ESTIMATION OF CAPACITY FOR SINGLE, INTERMEDIATE AND TWO-LANE INTER-URBAN ROADS

Ph.D. THESIS

by

MOHAMMAD MARDANI NOKANDEH

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE – 247 667 (INDIA)
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A THESIS

Submitted in partial fulfilment of the requirements
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**ESTIMATION OF CAPACITY FOR SINGLE, INTERMEDIATE AND TWO-LANE INTER-URBAN ROADS**", in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Department of Civil Engineering if the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during the period from January, 2013 to October, 2015 under the supervision of **Dr. Indrajit Ghosh**, Assistant Professor, Transportation Engineering Group, Civil Engineering Department, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other institute.

(MOHAMMAD MARDANI NOKNADEH)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Indrajit Ghosh)

Date: Supervisor

ABSTRACT

Estimation of capacity is one of the fundamental requirements for designing, operation and layout planning of a road network system. The knowledge of capacity is helpful to determine the maximum amount of traffic flowing in an hour and level-of-service (LOS) of a road section.

More than 50 per cent of the length of National Highways in India is constructed two-lane and 24.13 per cent is of intermediate lane roads. Being a substandard two-lane road, the quality of service and performance level of an intermediate lane road can be highly improved by increasing the width of the carriageway. Also, as per IRC: 64-1990 some of the roads in rural areas are constructed merely with a single lane with at least 3.75 m width of paved surface due to lesser population or limited budget. Since augmentation projects are inter-related with funding and budgeting policies, prioritizations are made based on the studies conducted on the present and future demand state of a road system. This requires similar amount of consideration towards the importance of the knowledge over the capacity of single and intermediate-lane roads as required for two-lane inter-urban roads.

The heterogeneous nature of traffic stream in India and many other developing countries makes the task of traffic analysis for a traffic engineer a complicated one. Different vehicle categories, which are the obvious characteristic of a heterogeneous traffic, impose consideration of different vehicular physique-related variables while studying the traffic flow behavior on a section of road. Generally, such variables can be considered by taking account of variation in speed, acceleration capability, area occupied on the road surface and the influence of all these variables on other vehicles present in the same traffic stream.

This study is focused on determining the capacity of single, intermediate and two-lane inter-urban roads under heterogeneous traffic condition. Addressing the dynamic state of PCU values of different vehicles present in a heterogeneous traffic, the study further makes an attempt to derive relationships between capacity and operating speed of passenger cars travelling the proposed road types. The aim of developing such relationships is to measure the effect of width of carriageway and contribution of paved shoulder as well as the joint effect of gradient and curvature to their capacity.

Data were collected at eleven sections of two-lane, seven sections of intermediate-lane and five sections single-lane roads in different parts of India to get information on traffic volume, vehicle composition and the speed of different vehicles present in the traffic stream. Parameters of the traffic stream like traffic volume and speed of different types of vehicles were extracted from the video data.

The PCU value is the amount of interaction caused by a particular vehicle type to the traffic stream of passenger cars. This interaction will be different at different traffic volume levels. It will change with composition of the traffic stream as well. The amount of such interactions is measured using speed volume equations. But, development of PCU values using the speed volume equations has limitations. Such equations are effective in providing PCU values for all vehicle categories provided that all those categories are present with acceptable proportion in the traffic stream since the nature of such equations necessitates that presence of different vehicles must impose an impedance to the traffic. Such necessity is not met if all categories are not present or are very low in number. Added to this, is the large number of graphical representations handling of which can be very complicated and time consuming for a traffic engineer. To overcome such complexity, The concept of stream equivalency factor was used to provide a simple and fast method to calculate the flow of traffic in terms of PCU per hour based on the proportion of the individual vehicles present in the traffic stream on any given sections of two-lane, intermediate-lane and single-lane roads instead of going through the complicated method of manual data extraction and calculation of PCU values.

After dealing with the PCU values, the capacity was estimated for sections where data collection was performed using Greenshields model. According to HCM the capacity of road varies with the FFS on the road but unlike multilane freeways, such influence is not quantified for two-lane roads in the manual. Therefore an attempt was made to develop a relationship between the 85th percentile FFS as the operating speed of passenger cars and capacity of different road categories in this study. By developing the cumulative frequency distribution of free flow speed of passenger cars the operating speed of passenger cars on each section was obtained. Plotting these operating speeds against the capacity values which were already estimated using the field data, an equation was formed for each road type. One section from each category was kept for validation of developed models and the results showed low difference between field data and theoretical models. The developed models provide the base section capacity of two-lane, intermediate-lane and single-lane interurban roads using the operating speed of passenger cars.

As the capacity of a road is influenced by many factors, the effect of any single or multiple factor on the capacity of the proposed road types may be evaluated with regards to the change they inflict on the operating speed of those sections. The effect of width of carriageway for every 1.0 m increase was found to be 320.0 PCU/hr. Using the operating speed the effect of provision of 1.0 m paved shoulder to the both sides of a two-lane road was found to be 20.0 %.

A model was also developed which related the operating speed to gradient and curvature data on hilly roads. Road construction on hilly areas is different from plain and level grounds. Due to environmental and budgetary concerns, such roads are generally constructed with less carriageway width. Therefore, to measure the influence of the proposed geometric factors, the operating speed-capacity model developed for intermediate-lane roads were used. Such models were also validated by comparing the results obtained using the developed model and those from manual field data collection. It was found that in the absence of curvature, the capacity of a hilly road decreases 2.0 percent for 1.0 percent increase in the gradient. On the other hand, on level ground, for every 10 degree/100 m increase in curve deflection angle, the capacity decreased 2.0 percent.

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GLOSSARY OF TERMS

$\Delta C_{\%PSH}$	Percent Variation in The Capacity Due to Added Paved Shoulder
ΔC_{PSW}	Capacity Variation Due to Added Paved Shoulder
$\Delta C_{w\%}$	Capacity Variation Due to Change in the Width of Carriageway
ΔC_{wPCU}	Capacity Variation Due to Change in the Width of Carriageway
2W	Motorized Two Wheelers
3W	Motorized Three Wheeler
AASHTO	American Association of State Highway and Transportation Officials
A_c	Projected Rectangular Area of Passenger Car
ADV	Animal Driven Vehicle
A_i	Projected Rectangular Area of Vehicle Type i on the Road
ARRB	Australian Road Research Board
ARSS	Automated Road Survey System
ASCE	American Society of Civil Engineering
BC	Big Car
C_H	Capacity of Hilly Roads
$C_{intermediate\text{-}lane}$	Capacity of An Intermediate-Lane Inter-Urban Road
CRRI	Central Road Research Institute
$C_{single\text{-}lane}$	Capacity of A Single-Lane Inter-Urban Road
CSIR	Central Scientific and Industrial Research
$C_{two\text{-}lane}$	Capacity o A Two-Lane Inter-Urban Road
Cw	Variation in Total Carriageway Width Compared to a Standard 7.0 m Width
CYC	Cycle

d	Trap Length
DA	Curve Deflection Angle
DCU	Dynamic Car Unit
f	Frame Number
FFS	Free Flow Speed
G	Gradient
HCM	Highway Capacity Manual
HRB	Highway Research Board
HV	Heavy Vehicle
IHCM	Indonesian Highway Capacity Manual
IRC	Indian Roads Congress
K	Stream Equivalency Factor
k	Traffic Density
km/hr	Kilometer per hour
$K_{single\text{-}lane}$	Stream Equivalency Factor for Single-Lane Roads
$K_{two\text{-}lane,\ intermediate\text{-}lane}$	Stream Equivalency Factor for Intermediate and Two-Lane Inter-Urban Roads
LCV	Light Commercial Vehicle
LOS	Level of Service
m	Meter
MATLAB	Matrix Laboratory
MAV	Multi-Axle Vehicle
MDR	Major District Road
MEU	Motor Cycle Equivalent Unit
MHRD	Ministry of Human Resources Development
MORTAB	Model for Depicting Road Traffic Behavior
MoRTH	Ministry of Road Transport and Highways

MRI	Midwest Research Institute
N	Traffic Flow in vehicle per hour
NCHRP	National Cooperative Highway Research Programme
NH	National Highway
NSV	Network Survey Vehicle
ODR	Other District Road
P_{2W}	Proportional Fraction of Two-Wheelers in Traffic Stream
P_{3w}	Proportional Fraction of Three-Wheelers in Traffic Stream
P_{BC}	Proportional Fraction of Big Cars in Traffic Stream
P_{BUS}	Proportional Fraction of Buses in Traffic Stream
PCE	Passenger Car Equivalent
PCU	Passenger Car Unit
PHF	Peak Hour Factor
P_{LCV}	Proportional Fraction of Light Commercial Vehicles in Traffic Stream
P_{MAV}	Proportional Fraction Of Multi-Axle Trucks in Traffic Stream
P_{TK}	Proportional Fraction of 2-3 Axle Trucks in Traffic Stream
P_{TT}	Proportional Fraction of Tractors with Trailer in Traffic Stream
PWD	Public Works Department
q	Traffic Volume
QDF	Queue Discharge Flow
RCK	Rickshaw
RUCS	Road User Cost Studies
s	Second
SC	Standard Car
SEF	Stream Equivalency Factor
SH	State Highway

SMV	Slow Moving Vehicle
SUV	Sport Utility Vehicle
TK	Truck
TT	Tractor Trailer
u	Space Mean Speed
V/C Ratio	Volume-Capacity Ratio
V_c	Speed Of Passenger Car
VDF	Vehicle Damage Factors
veh/hr	Vehicle per hour
V_i	Speed Of A Vehicle Type i
VMS	Vehicle Moving Space
v_{os}	Operating Speed
V_{OSH}	Operating Speed on Hilly Roads
vps	Vehicle per second
W_{PSH}	Width of Added Paved Shoulder

CHAPTER – 1

INTRODUCTION AND RESEARCH METHODOLOGY

1.1 GENERAL

Transportation is one of the key elements of any economy without which a dynamic and sustainable growth is not possible. Transportation infrastructure links urban and non-urban areas and creates equal opportunity of growth for all the people across a country. It facilitates the transportation of people and goods and development in this sector provides balance in growth of population and infrastructure availability. As per Ministry of Road Transport and Highways, Government of India, (MoRTH 2012), the length of road network in India is more than 4.8 million km which makes it the second largest road network after the US. The 2009-10 statistics show that 85.2 per cent of the total passenger movement and 62.9 percent of freight in India were carried by roads. However the growth in road network development has not matched up with the rate at which the motor vehicle service demand has increased. While the number of motorized vehicles grew 9.9 percent from 2001 to 2011, the increase in road network was only 3.4 percent (MoRTH 2012).

A comparison between India and other countries shows that the density of Indian Highways is 1.42 km of road length per square km of land which is higher than that of USA, China and Brazil with 0.67, 0.40 and 0.21 km/square km respectively. Also the proportion of the length of paved road in India is 53.83 per cent which is lower than that of developed countries (MoRTH 2012).

Rural road network in India is consisted of the following categories as per IRC 73-1980

- National Highways
- State Highways
- Major District Roads
- Other District Roads
- Village Roads

As per MoRTH (2012), the largest proportion of road length in India is constituted by Rural roads with a share of 59 per cent. It is followed by other PWD roads (21%), Urban roads (9%), Project roads (6%), State Highways (3%) and National Highways (2%) as on 31st March 2011. The length and percentage of surfaced roads on Indian road network are given in Table 1.1.

Table 1.1 The Indian road network (MoRTH 2012)

Indian Road Network	Length (km)	Surfaced Road (km)	Surfaced Road (%)
National Highway	76,818	76,818	100
State Highway	164,360	162,950	99.14
Rural Roads	1,938,220	929,789	47.97
Urban Roads	464,294	339,131	73.04
Other Roads	1,747,864	1,327,889	75.97
Total	**4,865,394**	**2,698,590**	**55.46**

As indicated from the above table, although National Highways constitute the least proportion of the total road network in India, they carry a significant amount of road based traffic volume across the country. The inter-urban movement of traffic is made possible through National Highways (NHs) which are connected via State Highways (SHs), Major District Roads (MDRs) and Other District Roads (ODRs). Two-lane roads comprise more than 50 percent of the length of National Highways while 22.81 per cent are four-lane and 23.14 percent are intermediate lane roads (MoRTH 2012). As per IRC: 64-1990 some of the roads in rural areas are constructed merely a single lane with at least 3.75 m width of paved surface due to lesser traffic volumes or limited budget.

1.2 SPECIFICATIONS OF THE PROPOSED ROAD TYPES

1.2.1 Two-Lane Roads

The predominant portion of State and National Highways in India is composed of two-lane highways. Two-third of National Highways and more than half of the State Highways in India are still two-lane roads according to the latest Ministry Data (MORTH, 2014). The traffic operation on two-lane two-way highways is different from other types of roads. One single carriageway of about 7.0 m width is utilized by two-directional traffic. The traffic on each direction travels on a single lane and lane changing and overtaking maneuvers are, to a great extent, influenced by the traffic in the opposite direction making such maneuvers only possible when no vehicles are coming from opposite direction. If overtaking is not possible, the fast vehicle decelerates to the speed of the slow vehicle in front and follows it (Arasan and Vedagiri 2009).

1.2.2 Intermediate-Lane Roads

Wherever service is needed but sufficient funds are not available to road construction agencies, roads in India are made with 5.5 m carriageway width and these are called intermediate lane roads. These roads are substandard two-lane roads since the traffic movement on them is similar to that on a two-lane road. A considerable portion of National Highways, State Highways and District Roads in India are composed of intermediate-lane roads.

1.2.3 Single-Lane Roads

Unlike two-lane and intermediate-lane roads which provide separate lanes for each direction of traffic flow, single-lane roads are constructed for at least 3.75 m of carriageway width. While vehicle speeds on two-lane roads are less influenced by the opposing volume (Van Aerde and Yagar 1983) – than on single-lane roads, and they can use the carriageway in both directions at the same time, even with reduced speed and increased precaution, on single-lane roads however there are several occasions that vehicles need to leave the pavement and use the shoulder to allow the flow in the opposite direction. For instance, buses have dominant size and weight and less operational capability compared to passenger cars or a three-wheeler which justifies it for them to maintain their road occupancy (Mardani et al. 2015). This means that the speed of vehicles on single-lane roads is liable to more reduction than intermediate-lane and two-lane roads.

1.3 TRAFFIC CHARACTERISTICS ON INTER-URBAN ROADS IN INDIA

The present work is undertaken to study the traffic on single-lane, intermediate-lane and two-lane inter-urban roads in India. Operating factors on inter-urban roads like roughness, presence of horizontal and vertical curves and gradients influence the speed of the vehicles. The heterogeneous traffic on Indian roads are composed of slow to fast moving vehicles with substantial differences in their static and dynamic characteristics including size and engine power. A wide range of motorized and non-motorized vehicles use the same roadway and lane discipline is interrupted rapidly.

The bi-directional traffic on these single carriageway roads share the same facility without any segregation and occupy any lateral position on the road space depending on the availability. Figure 1.1 shows the heterogeneity of the traffic on a two-lane interurban road section located in a rural area near Surat (NH-165). As it may be clearly seen, there are six vehicle categories using the road section at the instance the image was taken. The vehicles on these roads rapidly change their position to obtain a clear view in order to find the opportunity to perform an overtaking maneuver. Such condition is prevailing in all Indian Highways. On a typical inter-urban road in India, passenger cars may constitute only 30 percent of the traffic stream.

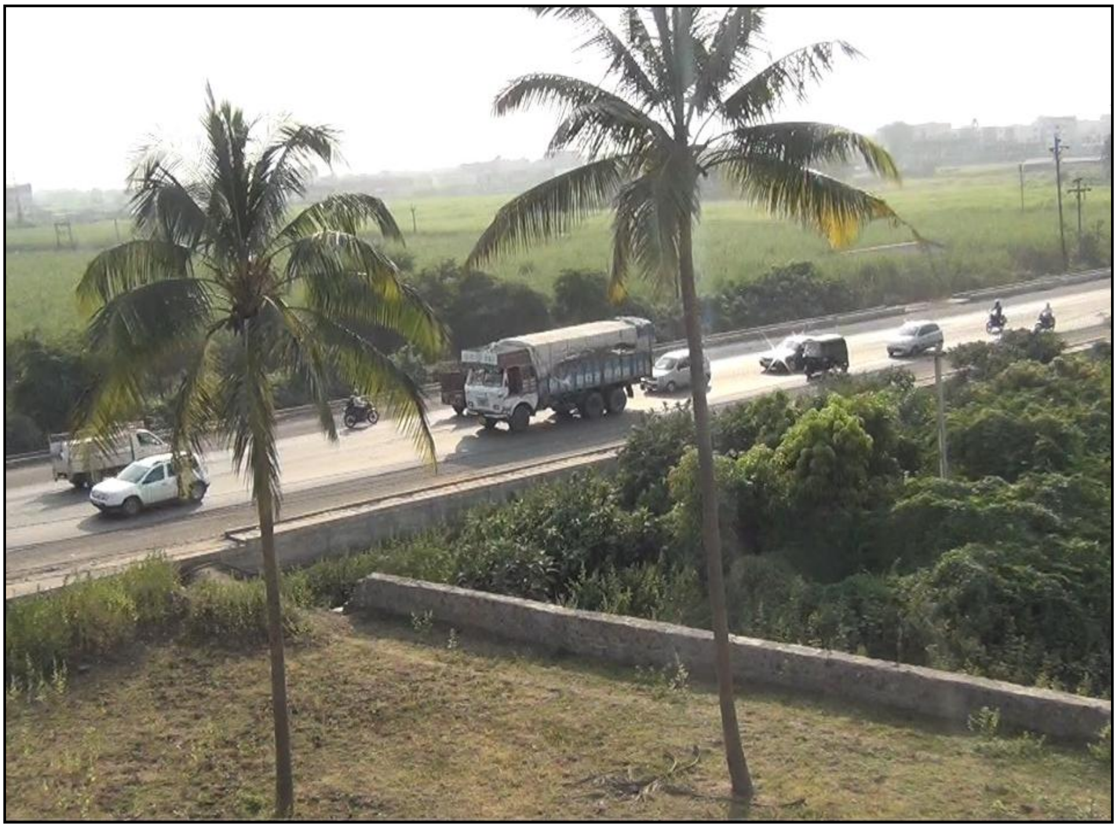


Figure 1.1 Heterogeneous traffic on Indian highways

The varying size and operational capabilities of different categories of vehicles create a complex traffic operation. The sizes vary from 0.4 m to 2.6 m in width and the speed of vehicles range from 10 km/hr for bicycles to 90 km/hr for passenger cars (under free flow conditions). Studies by Fildes and Lee (1993) and Karlaftis and Golias (2002), show that the heterogeneity of traffic affects the speed behavior of vehicles on two-lane roads. Such behavior varies from one state to another. Due to the heterogeneity in the traffic stream, with increase in the flow, there is an increasing demand for overtaking (Saha et al., 2015) with reduced passing and overtaking opportunities. In other words, as suggested by HCM (1985), as volume increases, passing demands exceeds passing capacity.

1.4 PCU AND INFLUENCING FACTORS

The changing condition of traffic stream under heterogeneous condition creates a number of problems to the traffic engineers which if not considered and addressed properly, makes it impossible to develop traffic models to study the capacity of roads that generate accurate and reliable outputs. In order to study a heterogeneous traffic, it is required to convert it to a homogeneous one. In order to do so, Highway Capacity Manual (1965) of the US introduced the concept of Passenger Car Unit (PCU) and defined it as the number of passenger cars displaced by a vehicle in the traffic stream under given conditions. It is a measure of relative interaction caused by a vehicle to the traffic stream compared to a passenger car. PCU value of a vehicle is influenced by several factors that may be grouped mainly as vehicular characteristics, traffic stream and roadway conditions.

1.4.1 Vehicular Characteristics

The size of a vehicle indicates its maneuverability and the space it occupies on a road surface. It will also affect the movement of other vehicles that use the same facility. The opportunity for passing and overtaking is highly related to the length and width of a vehicle. PCU is also influenced by the engine power and acceleration/deceleration capability of a vehicle which has a determining effect on its speed.

1.4.2 Traffic Condition

The interaction between different vehicles changes with both traffic volume and proportional composition of traffic stream. Presence of small sized or slow moving vehicles on the road with considerable proportion creates a poor lane discipline and vehicles tend to utilize any space available on the road. In such condition the distribution of transverse gap and longitudinal clearance of vehicles at different speeds will be affected.

1.4.3 Roadway Condition

The passenger car unit of a vehicle may also be influenced by road way characteristics. Factors like the type of the road, urban or inter-urban, number of lanes and lane width, shoulder type and width, roadway alignment including horizontal or vertical curves, gradient and its length and magnitude, type of pavement and surface condition have considerable effect on the PCU of a vehicle.

1.5 CAPACITY AND INFLUENCING FACTORS

Highway Capacity Manual (2010) defines capacity as the number of vehicles passing through a certain point or a section of roadway in a specified time interval under the prevailing roadway and traffic conditions. On inter-urban roads, this number can be changed due to various roadway, environmental, traffic and control conditions.

1.5.1 Environmental and Roadway Conditions

Inter-urban roads are spread across the country connecting areas with different topographic features. These roads may pass through level terrains as well as hilly areas. The land features to a high extent affect the alignment of the roads. Geometric characteristics of a road like presence of curves and gradients along with width of carriageway are greatly dictated by the land features. Drivers tend to increase the speed on downgrades provided enough sight distance is available. On upgrades, depending on the vehicles engine power and operating characteristics the speed will decrease. Also the capacity of roads with higher curve radius (less curve deflection angle) is higher than those with less curve radius mainly due to safety concerns. Also the weather affects the capacity. Under foggy, rainy or snow conditions the sight of drivers and their headway controlling performance get affected. Also the road surface condition forces the drivers to reduce the speed of the vehicle in order to have safe control on its movement. Added to these conditions are the drivers' behavior and their reaction to different situations. It is a parameter which depends upon the age, sex, experience as well as the mental and emotional status of the driver.

1.5.2 Traffic and Control Conditions

Capacity of inter-urban roads is affected by the composition of vehicles and proportion of individual vehicle types with their unique operating characteristics. Under heterogeneous traffic condition prevailing on Indian highways the increase in the number of small or slow moving vehicles reduces capacity. Small vehicles like motor cycles increase the safety related risks and reduce the speed of other commuters. Slow moving vehicles like motorized three-wheelers create obstruction to fast moving vehicles and increase the number of times a fast vehicle driver is forced to hit the brakes and cause overall speed reduction in the traffic stream. Large commercial vehicles like trucks and buses occupy greater space on the carriageway and their operation is more affected by roadway geometric conditions. The speed of such vehicles is less on curves and upgrades due to their size and weight which limits their operational capabilities. Also due to the large size of these vehicles, overtaking maneuvers become difficult for smaller and faster vehicles as they block the sight and their length necessitates longer headway in the opposite direction on two-lane inter-urban highways. Road sections with speed control and limits have less capacity than sections where vehicles are free to choose their desired speed. Road humps and barricades reduce the speed of vehicles and decrease the number of vehicles that can pass the section in a specified time interval which leads to loss of capacity.

All above factors influence the capacity of single, intermediate and two-lane inter-urban roads. The factors discussed above may be present on these types of roads in a combined form and studying the effect of each factor becomes more difficult and complex when traffic is heterogeneous. Therefore an attempt is made to study the variation in the PCU of different vehicles in a mixed traffic and converting it to a homogeneous one as well as the influence of different geometric factors on capacity of two-lane, intermediate-lane and single-lane roads to find a solution to Indian conditions.

1.6 NEED OF THE RESEARCH STUDY

The traffic on Indian roads is heterogeneous and different types of vehicles use the facility while having different sizes and operating characteristics. To address this issue, the Indian Roads Congress (IRC:64-1990) has adopted the concept of Passenger Car Unit (PCU) and suggested PCU values for different vehicle categories found on Indian inter-urban roads. However, the single sets of PCU values provided by this guide line seem to have lost adequacy and applicability as the road condition and vehicle manufacturing technology has improved drastically over the years. The guide lines are more than 20 years old and using same PCU values have resulted in values for volume to capacity ratio more than unity (Vagadia and Joshi 2012). Therefore there is a need to revise and improve the available guidelines to make them updated and adoptable for present needs.

There are several methods of estimating the capacity of a roadway. Most of the methods are focused on field data while others use simulation models. For all the methods the traffic is or is assumed to be homogeneous which is not applicable to Indian traffic conditions. The highway capacity manual of US (HCM 2010) has indicated that capacity of a two-lane road varies with the free flow speed on that road. However, the quantification of this influence is not addressed in the manual. It will also be interesting to see how the influence changes under heterogeneous traffic condition prevailing on Indian highways. The free flow speed on a road will be an indication of road surface condition and hence any enhancement or reduction in the capacity due to improvement or deterioration in the road condition will be useful information for planners as well as road maintenance engineers. Therefore the aim of the present study is to develop relationships between operating speed (which is taken as the 85^{th} percentile of free flow speed of passenger cars) and capacity of a two-lane, intermediate and single-lane roads. The advantage of these relations is the removal of expensive and long term data collection which is required for development of speed-flow curves. The models will be extremely useful to field engineers as the capacity can be estimated only by using the operating speed of passenger cars.

Further they may be used to study the effect of varying roadway geometric related conditions on capacity compared to basic conditions that the models were generated upon.

1.7 OBJECTIVES OF THE RESEARCH

The present study is aimed at studying the PCU variation for different vehicle categories on two-lane, intermediate-lane and single-lane inter-urban roads in India. The adequacy of single sets of PCU values for different traffic volume and composition will be criticized by showing the dynamic nature of these values. Also an attempt will be made to provide a generalized solution that would encompass the heterogeneity of traffic in terms of volume and composition and produce traffic flow in terms of PCU/hr without needing to calculate the PCU value of each vehicle category separately.

Also, the capacity of the above mentioned types of roads will be estimated using the operating speed (85^{th} percentile free flow speed) of passenger cars for basic conditions. Further the effect of geometric conditions on the capacity of these roads will be studied using the outputs of the relationship between capacity and operating speed of passenger cars for applicable conditions.

The objectives of this research work are thus listed as below:

(i) To determine PCU values for different types of vehicles found on two-lane, intermediate-lane and single-lane inter-urban roads in India and to study the variation in PCU for different traffic volumes and traffic compositions.

(ii) To apply the concept of Stream Equivalency Factor (SEF) which converts heterogeneous traffic stream into equivalent number of passenger cars without using PCU values of individual vehicle types.

(iii) To develop a relationship between capacity and operating speed of passenger cars for the mentioned road types under base conditions.

(iv) To study the influence of carriageway width, addition of paved shoulders and presence of gradient and curvature on capacity.

1.7 SCOPE OF THE WORK

The research work presented here is focused on estimation of capacity of two-lane, intermediate-lane and single-lane inter-urban roads in India. The scope of the work is limited to sections located on plain areas as base sections and sections located on hilly areas where the influence of variation in geometric conditions will be studied in terms of deviation from base conditions. The total work is accomplished in five stages as given below:

a. Field data collection from two-lane, intermediate-lane and single-lane interurban roads under base conditions from different states to develop curves showing the dynamic nature of PCU values for different vehicle categories on different types of roads
b. Further using the field data to develop speed-flow curves to estimate the capacity of the selected sections

c. Derive a relationship between capacity and operating speed of passenger cars on each type of roads
d. Study the Effect of variation in carriageway width and provision of paved shoulders to the either side of two-lane roads in terms of PCU and percent increase in capacity of these roads
e. Derive a relationship between operating speed and geometric parameters (gradient and curvature) and further using it to propose a model to estimate the capacity of different road types in hilly area

1.8 REPORT ORGANIZATION

Chapter 1

A brief background of the topic and its importance in Indian traffic is presented in the first chapter of this thesis. The need of the study and the objectives along with the scope of the work are given in this chapter.

Chapter 2

All the literature relevant to the work presented here is reviewed in this chapter based on the year they were published from the early 50's up to present. The objective of such accumulation of literature was to project the distinguished methods undertaken in this study despite partial similarities with other methods available in the literature.

Chapter 3

This chapter deals with the strategy of selecting sites for field data collection on base sections. The criteria for identifying base sections and method of data collection and extraction are elaborated in this chapter.

Chapter 4

The PCU values of different vehicles on different types of roads are calculated and their variation with change in traffic volume and composition is studied by solving simultaneous equations developed for speed and density of different sets of vehicle categories. Further, the concept of Stream Equivalency Factor will be applied which provides a factor to convert a heterogeneous traffic stream into a homogeneous one based on traffic volume and composition avoiding individually calculation of PCU values for different types of vehicles in the traffic stream.

Chapter 5

The capacities of base sections are estimated using field data and a relationship between these values and operating speed of passenger cars on corresponding base sections are developed in this chapter. The models provided in this chapter are used as a base for studying the capacity of sections where geometric specifications deviate from that of base sections.

Chapter 6

This chapter is aimed at studying the effect of width of carriageway on capacity of inter-urban roads. It also provides the variation in the capacity of a two-lane road if paved shoulder is provided to either side of the road in terms of percent increase in capacity per meter width of paved shoulder.

Chapter 7

The capacity of a road varies with geometric conditions of a road. On hilly areas the combined effect of gradients and curvatures are prevalent along the stretch. The effect of these parameters on operating speed and thus capacity of hilly roads are studied in this chapter and corresponding models are proposed accordingly.

Chapter 8

The conclusions of the undertaken study are presented in this chapter. The contributions of the research as well as the scope for future work are also discussed and highlighted.

The overall structure of the present work is presented in the flowchart given in Figure 1.2.

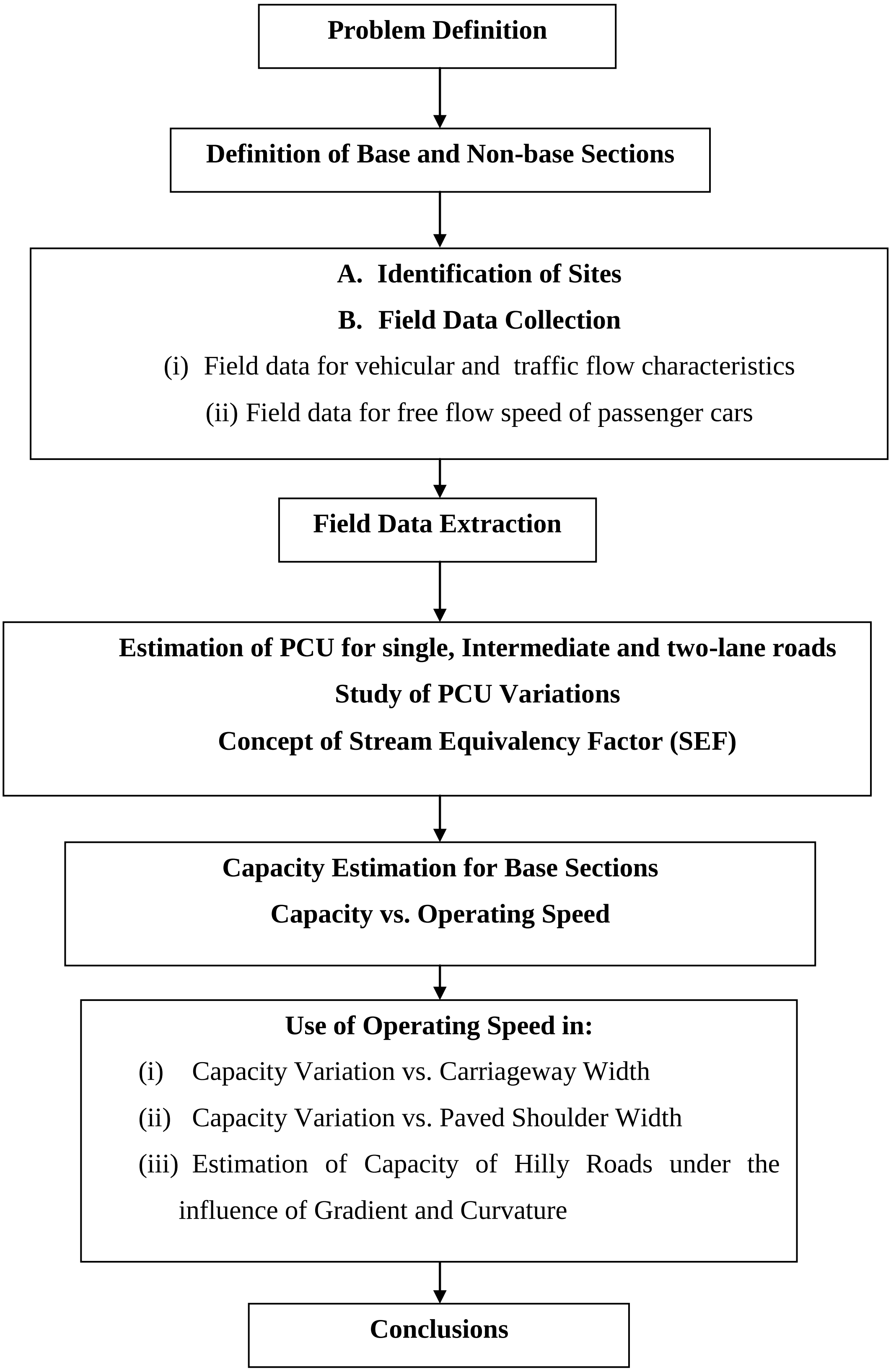


Figure 1.2 Flow chart of the research work structure

CHAPTER – 2

LITERATURE REVIEW

2.1 GENERAL

As stated in the previous chapter, parameters like PCU, Capacity and influencing factors such as lane width, shoulder width, gradient and curvature will be studied in this research work. It is also stated that the above parameters will be studied with regards to single, intermediate and two-lane inter-urban roads under heterogeneous traffic. Therefore the earlier researches and available literature related to the above subjects are reviewed. This will demonstrate the efforts of other scholars who have scrutinized the subject prior to this research work and clears out the points where the present work is sharing or in contrast with earlier works.

Primarily, the literature on the term PCU and its generation method will be reviewed. Then, as per the organization of this research work which was stated in Chapter 1, studies on capacity of proposed inter-urban road types and influencing factors will be referred in this chapter.

2.2 STUDIES ON PCU

Werner and Morall (1976) used walker's method to derive passenger car equivalencies (PCU) for heavy vehicles including trucks, buses and recreational vehicles for rolling and mountainous terrains. The basis of measurements to estimate PCU values were the number of overtaking maneuvers performed by passenger cars and mentioned heavy vehicles. The number of overtaking can be expressed as:

$$N = \sum_{i=1}^{n} \sum_{j=1}^{m} x_i y_j \left[\frac{1}{S_{2i}} - \frac{1}{S_{1j}} \right] \tag{2.1}$$

The estimation of the effect of grades on PCU for different vehicle categories was made under various levels of service (LOS). To check the sensitivity of PCU values with speed changes, they used a simulation model and found that PCU values are very sensitive to small changes in speed of vehicles and that this relationship is indirect.

Craus et al. (1980) evaluated the PCU estimation methodology developed by highway capacity manual **(HCM 1995)**. The measure for estimation of PCU was based on the delay in the traffic due to presence of slow moving trucks and opposing flow of traffic. The ratio of delay that a truck creates in a traffic stream to the delay created by a passenger car was taken as the PCU of a truck. The concept of such delay was the basis to develop an equation to measure the PCU of trucks. The authors suggest that despite taking in to account the physical size of vehicles and their operational performance, yet the obtained results appeared to be unrealistic.

Huber (1982) studied two types of traffic streams and attempted to relate them to estimate PCU values of the vehicles. They took the average travel time of vehicles in a traffic stream where trucks were mixed with passenger cars and in a traffic stream composed only with passenger cars. They suggested that average travel time as a measure of impedance is a function of traffic flow and can relate the two types of traffic streams as described. They considered different levels of traffic volumes where same impedance was observed in the traffic and estimated the PCU. They found that the effect of slow moving vehicles on traffic flow where traffic volumes are at low levels is minimal. PCU values increased with higher traffic volume levels where more interactions between vehicles were observed.

Central Road Research Institute, New Delhi (CRRI, 1982) suggested that traffic volume and composition in a mixed traffic stream have considerable effect on PCU values indicating that there can not be a universal set of PCU values for vehicles. The number of PCU values for a vehicle type depends on type of the road, traffic volume, composition of traffic mix and vehicle speed. They found that vertical gradient and road width have significant effect on PCU values of vehicles in a traffic stream.

Yagar (1984) considered highway speed as a combined function of several factors such as traffic volume and geometric and environmental conditions. They developed a procedure for estimating highway speed by applying a general set of PCU values for different vehicle categories to convert a mixed traffic to a homogeneous traffic. Equations were generated for 10^{th}, 50^{th}, and 90^{th} percentile speeds. They found that the above speeds were affected by factors like variation in traffic volume, direction of flow, type of vehicles, speed limits, extra lanes and grades.

Justo and Tuladhar (1984) analysed various factors that affect PCU values on urban roads. They identified speed and headway and effective width of vehicles as most important factors and utilized them to form a model to calculate and provide a set of PCU values which is given in Equation 2.2.

$$(PCU)_i = \left(W_i / W_c \right) * \left(U_c / U_i \right) * \left(t_i / t_c \right) \qquad (2.2)$$

Where;

W_i = effective width of vehicle class i, m

W_c = effective width of passenger car, m

U_i = mean speed of vehicle, km/hr

U_c = mean speed of passenger car, km/hr

t_i = mean time headway of vehicle class i, s

t_c = mean time headway of passenger car, s

Krammes and Crowley (1986) made an attempt to develop a method to obtain passenger car equivalents for trucks on level freeways. They suggested that a PCU estimation procedure should basically take in to account the variables that project the importance of factors that consider the overall effect of trucks on the roadway. They found that the most appropriate method for level freeway segments is headway method since it accounts for the accepted effect trucks due to size and lower performance. The method also recognizes the psychological effect of presence of trucks in the traffic stream on drivers of other vehicles using the roadway as a significant element. Such concept was also followed by **Hutchinson (1990)** where the average time required by various vehicle types to complete different types of intersection movements was taken as the basis for estimating PCU values.

Ramanayya (1988) examined the PCU and capacity values recommended by **Ministry of Transport (1966) and Indian Roads Congress (1980)** and suggested that due to variations in traffic stream from place to place in India there is no consistency and rationale in the capacity standards and developed PCU values with a method of their own. They developed a two-stage simulation model to depict road traffic behavior (MORTAB) under mixed traffic conditions. The impact of slow-moving vehicles (SMV) was analysed by comparing the graphs modeled for 100% passenger car and mix of car and SMV proportions separately. It was found that the impact of SMV is more pronounced on four wheeler fast-moving vehicles than on motorized two-wheelers. The study recommends a number of PCU factors for different levels of service under mixed traffic conditions.

Indian Roads Congress (IRC 64: 1990) provided PCU values for different vehicle categories for Indian roads and highways. Presence of slow moving vehicles is the basis for concept of equivalency factors for rural roads in India. This results in a single set of PCU factors which is only applicable to plain road sections and effect of many other roadway and traffic characteristics have not been considered. The PCU values of different types of vehicles on Indian two-lane rural highways as recommended by IRC are given in Table 2.1.

Table 2.1 Recommended PCU factors for various types of vehicles on rural roads (IRC 64: 1990)

Vehicle Type	Equivalency Factor
Fast Moving Vehicle	
Two-wheelers, Motor cycle, Scooter etc.	0.5
Passenger Car, Pick-up Van	1.0
Light Commercial Vehicle (LCV)	1.5
Truck or Bus	3.0
Agricultural Tractor Trailer	4.5
Slow Moving Vehicle	
Bicycle	0.5
Cycle Rickshaw	2.0
Tonga (Horse Driven Vehicle)	4.0
Hand cart	3.0

Tanaboriboon and Aryal (1990) studied the traffic in Thailand and suggested that PCU value for vehicles of medium size like cars should be assumed as 1.0.

Accordingly, they deduced the PCU for bus, trucks, tractor trailers and other large size vehicles as 1.5.

Fan (1990) derived PCU values for different types of vehicles in Singapore Expressway. A multiple linear regression technique was used based on 15-minute intervals of traffic volume data when the volume to capacity ratio was at least 0.67. The PCU value obtained for motorcycles was 0.4 by this method. This value for motorized two-wheelers was previously taken as 0.75 which was used in Britain. They suggest that PCU values provided in HCM are suitable mainly for the U.S and U.K and may not suit the traffic in Asian countries.

Chandra et al (1995) evaluated different methods of PCU estimation and found that the PCU value of vehicles depends also on the method of derivation. Area occupancy was considered by **Mallikarjuna and Rao (2006)** as an equivalency criteria to estimate the PCU values for buses, trucks and motor cycles using a simulation model.

Elefteriadou et al. (1997) used a simulation model to develop a methodology for calculating passenger car equivalents for freeways, two-lane highways and arterials.

Al-Kaisy et al. (2002) assumed that if the traffic stream was uniform and composed only with passenger cars, the queue discharge flow (QDF) would show the least fluctuations. They used QDF to develop a new approach to derive PCU values and measure the effect of heavy vehicles in a traffic stream. A non-linear programming problem was formulated using vehicle counts from the observations of capacity over QDF. The problem was mainly formulated to minimize the variation in capacity of QDF by developing PCUs when the variation was measured in terms of PCUs.

Chandra and Kumar (2003) considered the relative area requirement of a vehicle type to that of a passenger car as the basis of measuring and estimating dynamic PCU values. They proposed this new methodology by developing a mathematical model for PCU estimation as the ratio of speed and area ratio of passenger car and subject vehicle type. They took the projected rectangular area of a vehicle type to account for the area that a vehicle occupies on the road surface. The mathematical form of the proposed model is given in Equation 2.3.

$$PCU_i = \frac{V_c / V_i}{A_c / A_i} \tag{2.3}$$

Where;

V_c= speed of passenger car, km/hr

V_i= speed of a vehicle type i, km/hr

A_c= the projected rectangular area of passenger car, m^2, and

A_i = the projected rectangular area of vehicle type i on the road, m^2

They used the model and derived PCU factors for various vehicle types. Unlike the single set of PCU values provided by Indian Roads Congress for different road types, the proposed method has the potential to produce PCU values under various traffic and roadway conditions that affect the speed of a vehicle type.

Al-Kaisy et al. (2005) used empirical and microscopic traffic simulation data to develop a set of PCU factors on level terrain and upgrades on freeway and multilane highways during congestion. The process consisted of generating simulation data using traffic simulation model INTEGRATION, assuming that queue discharge flow capacity is constant except for the effect of presence of trucks in the traffic stream. They found that increase in grade length and magnitude increases the PCU while increase in proportion of trucks in the traffic stream decreases PCU values.

Zhang et al. (2006) identified vehicle moving space (VMS) as a measure to derive PCU values for different categories of vehicles in china. They estimated PCUs under different roadway and level of service conditions on two-lane and four-lane highways. They suggested that increase in number of lanes and level of service (LOS) from A to E will increase the PCU values.

Rakha et al. (2007) considered physical characteristics and operational performance of vehicles as a basis to estimate PCU values. They developed PCU values for a broad range of vehicle weight to power ratio using INTEGRATION software following HCM procedure. PCUs were then studied under influence of grades and different LOS levels. They developed PCUs for trucks for 2 to 6 percent grades at different levels of LOS in situations where the proportion of trucks in the traffic mix was more than 25 percent.

Dey et al. (2007) simulated the traffic of a two-lane road at 50/50 directional distribution with varying volume capacity ratios and different proportions of vehicles. They used the dynamic PCU estimation model provided by **Chandra et al. (1995)** to derive PCU values for different PCU values for vehicle types under specified conditions. Figure 2.1 displays the curves drawn for varying proportion of cars and two-wheelers.

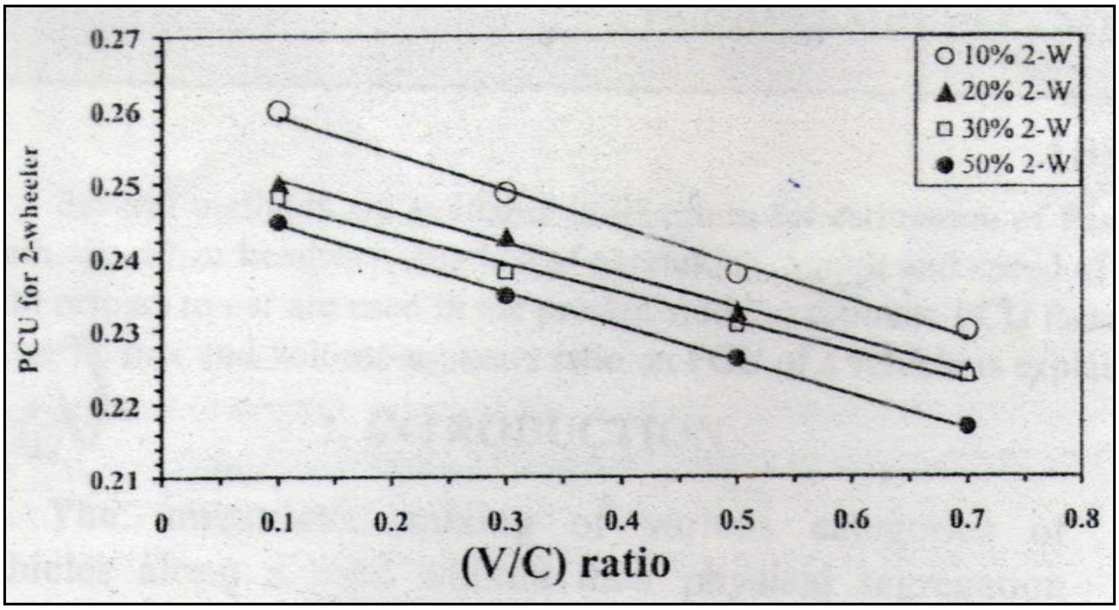


Figure 2.1 Variation in PCU for 2-wheelers with (V/C) ratio (Dey et al. 2007)

The above figure was selected as a representative of the similar curves drawn for other types of vehicles in the simulated mixed traffic. They found that PCU value for a vehicle type decreases with its own proportion in traffic stream. The study also showed that they decrease with increase in V/C ratio, the extent of which depends on traffic volume levels

Arasan and Krishnamurthy (2008) used a microscopic simulation model called HETEROSIM to develop PCU factors for different vehicle types on four-lane divided urban roads. Traffic was heterogeneous as it is prevailing on Indian roads. Average stream speed was taken as the measure of performance to estimate PCU values at different volume levels. They found that for low volume levels between 500 veh/hr to 2000 vph the PCU values showed increasing trend while for higher volumes (4000 vph) began to reduce.

Krishnamurthy and Arasan (2008) studied the effect of traffic volume on PCU values of vehicles. The results showed an increase in the PCU values with increase in volume at low volume levels and decrease in PCU values with an increase in volume at high volume levels.

Carrignon and Colin (2009) generated the heterogeneous traffic conditions in London using microscopic traffic simulation VISSIM and estimated PCU values for two-wheelers.

Geistefeldt (2009) introduced a new approach to empirical estimation of PCU values for heavy vehicles (trucks) on German freeways based on the concept of stochastic capacities. Regarding freeway capacity as a random variable, the method allows for estimation of capacity distribution functions based on volumes in PCU per hour. They suggested that the method can assess the impact of heavy vehicles on capacity during fluid traffic conditions. Only passenger cars and trucks were differentiated to transform the mixed traffic volume in to PCUs. The objective in such method was to determine PCU for which the variance of the capacity distribution function becomes minimal. The method was applied to eight data samples collected from freeways either with or without speed limits, different day time traffic peaks and varying average proportion of heavy vehicles in traffic composition. PCUs for heavy vehicles with this method ranged between 1.3 and 2.6. It was observed that with increasing number of lane, PCU values tend to decrease. The Author suggested that to reimburse for the drawback of this method which is the necessity for large sample size for obtaining realistic estimates, simulation approaches should be adopted.

Arasan and Arkatkar (2010) used micro-simulation technique to describe the effect of traffic volume and road width on PCU of vehicles under heterogeneous traffic conditions. They found that PCU for vehicles larger than passenger car decreases with increase in traffic volume at low volume levels. The trend at high traffic volume levels was found to be reverse. For vehicles smaller than passenger car the opposite behavior was observed.

Brooks (2010) estimated PCU values for different vehicle types by simulating traffic flow on different road widths. They used trial and error method to find PCU values by calculating the ratio of number of cars removed from a homogeneous traffic stream and the equivalent number of a different vehicle type replacing them to maintain the stream speed. They developed a number of graphical relationships between the average speed and traffic volume and measured the effect of different volume to capacity ratio and lane widths on PCU of vehicles in the traffic mix. They found that increase in road width increased the PCU values. Increase in traffic volume increases the PCUs at lower volume levels and decreases the PCUs at higher volume levels. Traffic volumes at or near capacity level yielded lesser PCU values. It was observed that PCU for two-wheelers, SUVs and heavy vehicles under specified conditions ranged from 0.2 to 0.65, 1 to 2.3 and 0.8 to 2.8 respectively.

Arkatkar (2011) studied the vehicular interactions at micro-level using a simulation model named as "HETEROSIM" developed by **Arasan and Koshy (2005)** mainly for different traffic volume levels and road upgrades under heterogeneous traffic conditions on Indian intercity roads. The simulation model considered the entire road space as a single unit and the vehicles as rectangular blocks, the width and breadth of which representing the overall length and breadth of vehicles respectively. Traffic flow was simulated to develop a speed-distance relationship for vehicle types moving along upgrades. They found that the decreasing effect of upgrades on vehicle speed is neutralized when the distance travelled is beyond 1600 m. They considered different volume levels and estimated PCU by dividing the number of passenger cars removed by equivalent number of vehicle-types added to traffic. PCU being calculated by this method was estimated by simulating traffic flow for different road widths and upgrades. They found that PCU value of all vehicles increase with increase in magnitude and length of upgrades.

Cao and Sano (2012) studied the traffic on urban roads in Hanoi in Vietnam and suggested that due to dominant proportion of motor cycles in the traffic stream, motor cycle equivalent units (MEU) should be used instead of PCU. They studied the effect of speed and space occupancy of a vehicle type on movement of surrounding motor cycles in a mixed traffic. The proposed values for cars, buses, mini-buses and bicycles were 3.4, 10.5, 8.3 and 1.4 respectively.

Bains et al. (2012) assessed the effect of vehicle composition with focus on proportion of heavy vehicles and light commercial vehicles on PCU values on expressways in India. PCU values were evaluated at different volume levels using VISSIM micro-simulation model. The analysis of results indicated that increase in

V/C ratio or decrease. However the study does not account for the effect of traffic heterogeneity in terms of vehicle composition in the traffic stream.

Joshi and Vagadia (2013) derive the Dynamic Car Unit (DCU) and Dynamic Two-wheeler Unit (DTU) for 10.5 m urban roads in India. Data were collected in seven metropolitan cities and modified homogenization coefficients approach is used to find the variation in DCU and DTU values. The observed variation in DTU from 3 to 4 for car, 15 to 21.5 in case of bus and 2.5 to 2.8 for three wheelers.

Dhamaniya and Chandra (2013) introduced stream equivalency factor (SEF) which converts a heterogeneous traffic on a six-lane urban arterial road in India to a homogeneous traffic in terms of PCU/hr while avoiding calculation of PCU values for each vehicle type. SEF (K) was defined as the ratio between traffic volume in veh/hr and traffic volume in PCU/hr. the method for estimating PCU values of each vehicle type was adopted from **Chandra and Kumar (2003)**. In order to avoid dampening of variation in traffic volume, 5-minute counts were considered instead of 15-minute data count offered by HCM 2010. They developed a curve displaying the plot between flow in veh/hr and flow in PCU/hr. The average value for K was observed to be 0.856 in a range of 0.8 to 2.04. Higher K values were observed for traffic streams with higher proportion of heavy vehicles and lower K values were obtained for traffic streams with higher proportion of motor cycles. They used linear regression technique to form a mathematical relation between K and composition of traffic stream. The effect of traffic composition on K was evaluated by simulating the traffic using VISSIM and several curves were developed to show the effect of proportion of different vehicle types on K values. They provided a table displaying regression coefficients of equations that relate K to different traffic compositions. The authors concluded that the PCU is a multidimensional parameter and needs to be estimated at different congestion levels and traffic composition.

Krishnamurthy and Arasan (2014) made an attempt to quantify the extent of vehicular interactions under heterogeneous traffic conditions on Indian roads in terms of PCU values. They used a micro-simulation technique to study the effect of traffic volume and road width on PCU value of a vehicle. The logic for the simulation was to consider the road space as a single unit, and the road space as a surface consisting square cells. This would transform the whole space into a matrix, leaving vehicles as rectangular blocks covering specified number of cells, coordinates of which have been defined with reference to a fixed origin. They found that at same volume to capacity ratios, increase in road width yields higher speeds of vehicle types. It was also observed that percentage increase in speed of passenger cars is higher than that of other vehicle types on wider roads. The analysis of the simulation results indicated that PCU values in a heterogeneous traffic increase with increase in width of road space.

Mehar et al. (2014) used VISSIM to determine PCU values at different levels of service to analyze the capacity of multi-lane highways in India. They used the microscopic simulation to generate the traffic flow and speed data where field observation and data collection was difficult to obtain. They calibrated VISSIM to draw speed-flow curves. They found that PCU of a vehicle type decreases with increase in volume to capacity ratio.

2.3 STUDIES ON TRAFFIC FLOW

Linzer et al. (1979) used the simulation model developed by Midwest Research Institute (MRI) on the effect of trucks on freeway flow and calibrated it to produce operating speed versus volume capacity ratios that would be observed in real traffic. The parameter used to determine the performance characteristics of the trucks was weight-to-power ratio and the speed of subject vehicles were analysed during movement on upgrades. They developed equivalency factors for trucks considering its proportion in the traffic mix. First set of equivalency factors for trucks were made under assumption of 10% truck in a traffic flow on a 4 percent sustained grade and the second set where derived with the assumption that the 10% truck population has proceed 600 m along the same specified grade. To find equivalency factors for recreational vehicle Walker's method which is exclusively for two-lane roads was employed. The authors recommended that the values provided by HCM (1965) should be taken for bus equivalency factors. The study however does not include measurement of the speeds of faster trucks on grades.

Hoban (1987) stated that in most cases a linear speed-volume relationship could be used to represent speed-volume data. Yet the slope of the speed volume curve varies with several factors. The ratio between maximum volume speed and free flow speed as proposed by **HCM (1985)** decreases with increase in free flow speed. It determines the rate at which speed drops in speed-flow diagram when flow rate increases. It is further implied that after the flow rate exceeds a certain limit, the increase in flow rate beyond that limit and towards the capacity flow rate, decreases the speed below free flow speed down to capacity speed due to increased interactions between the vehicles in traffic stream.

Persaud and Hurdle (1988) examined the upper high-speed part of speed-flow diagrams presented by **HCM (1985)** in Figure 2.2 using data collected in the vicinity of a free-way bottleneck in Toronto, Canada.

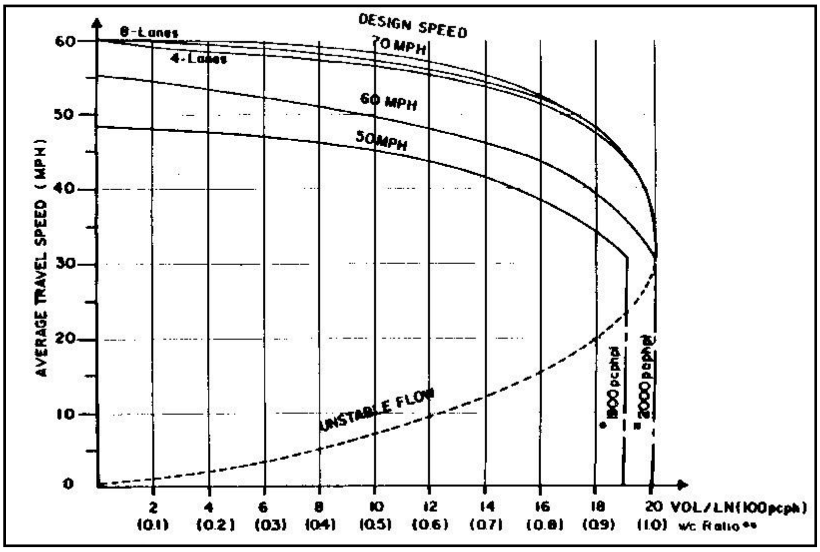


Figure 2.2 Speed-flow curves from HCM 1985

They confirmed that at low to moderate traffic flows. Speed is not sensitive to the flow unlike what was implied by **HCM 1985**. From the several curves that were drawn to show the relationship between speed sand flow. They opined that unlike what was implied by Figure 2.2 speed is not sensitive to flow at low to moderate traffic flows. However at higher flows it was suggested that speed does decrease with increase in flow but the fall-off may not be nearly so abrupt as it is generally believed. They related such abrupt drop in speed at high flow to the misinterpretation of data acquired by noticing that the speed of vehicles discharged from a queue depends on the location in the bottleneck while the flow does not.

Hall et al. (1992) introduced an alternative to represent the speed-flow model using a three-regime model and applied it to a freeway section in the U.S. The model is presented in Figure 2.3.Three different traffic flow regimes are displayed in the figure. The upper part of the curve shows that the speed remains unchanged for two-third of the flow and immediately begins to fall off almost linearly with such increasing rate. Data points in this region are scattered and represent the portion of speed-flow curve before the congestion stage. The second part or the vertical line represents the collected data at downstream of the formed queue. Speed in this portion is more associated with the point of measurement. Lower speeds are observed where the measurement point is closer to the front end of the queue since it takes time for a vehicle to regain speed. However it is not explained why there should be such a large variation in speed at this constant flow. They suggest that the chances of observing the whole three-regime pictures at any one location are low.

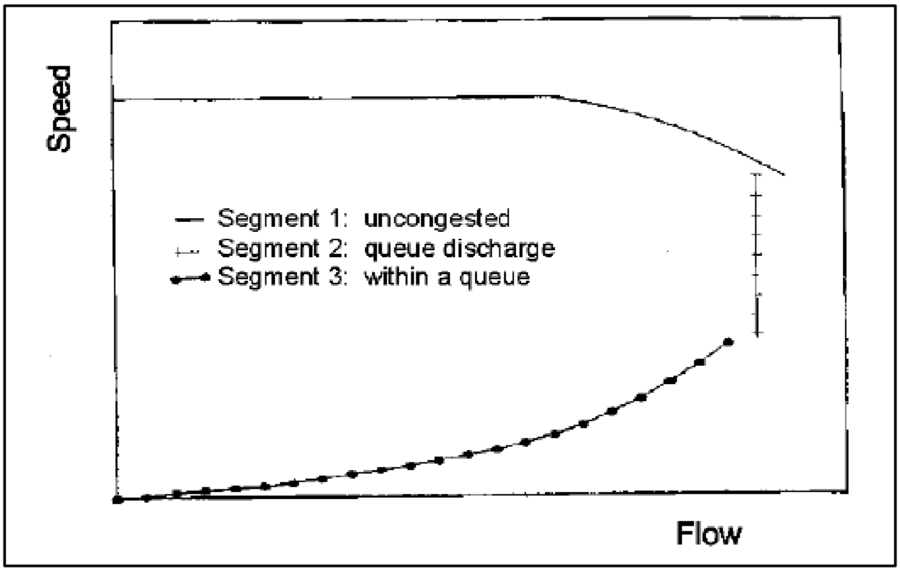


Figure 2.3 Generalized shape of speed-flow curve (Hall et al. 1992)

This indicates that combining observations from a number of different down-stream locations does not imply whether the "queue discharge" regime can be observed through its whole range of speed. The lower part has been subject to less study but the general shape was considered to be broadly correct. Speeds are lower as they include delay while waiting in the queue itself.

Webster and Elefteriadou (1999) studied the effect of grade and grade length as well as presence of trucks in the traffic stream on basic freeway sections in the U.S. They estimated the PCU values of trucks by developing a six-step simulation model (FRESIM) based on traffic density which considered the dynamics of interaction between passenger cars and trucks.

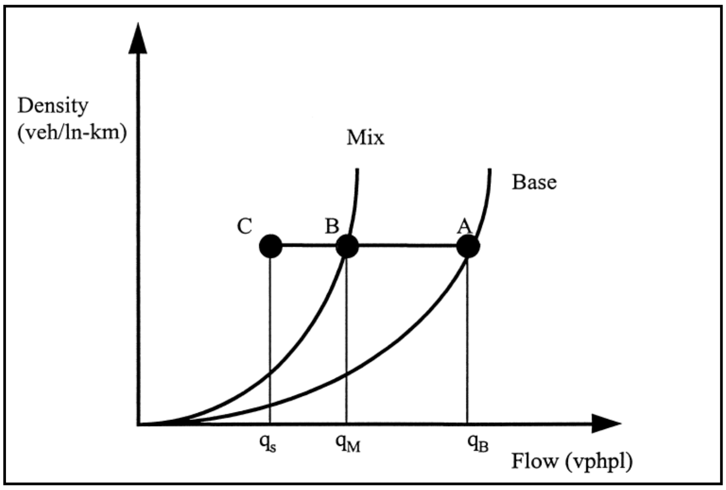


Figure 2.4 Method of PCU calculation (Webster and Elefteriadou 1984)

They generated flow-density curves for two types of traffic; one composed only with passenger cars and the other with a mix of passenger cars and trucks represented as base and mixed curves respectively. The procedure consisted of adding a number of trucks to the mixed-traffic while removing the same number of passenger cars. The model then simulated the traffic mix operation at a selected traffic flow (q_S) and found the corresponding density in Figure 2.4. Accordingly the flow rate for the mixed (q_M) and base traffic (q_B) would be obtained by drawing a horizontal line representing the same density which intersects with mix and base curves. The PCU values were then calculated using an equation developed by **Sumner et al. (1984).** It was found that PCUs have direct relation with traffic flow, free-flow speed, grade and grade length. The relation between PCU and presence of trucks in the traffic stream was found to be indirect.

2.4 STUDIES ON CAPACITY

McLean (1983) found that the capacity of two-lane roads is mainly influenced by directional split, speed and proportion of heavy vehicles. The equivalent capacity of two-lane roads is given by Equation 2.4.

$$C_E = K_1 K_2 C_{EO} \quad (2.4)$$

Where

C_E = Equivalent capacity (PCU/hr)

K_1 = Adjustment factor for uneven directional split

K_2 = Adjustment factor for lateral obstruction which are within 2.0 m of carriageway

C_{EO} = Basic Capacity (PCU/hr) = 1900PCU/hr

The actual capacity is given by Equation 2.5.

$$C = P_E C_E \tag{2.5}$$

Where

C = Actual capacity (PCU/hr)

P_E = Equivalency factor, which is based on speed of heavy vehicles and their proportion. The Swedish Capacity Manual (SCM) adjustment factors for uneven directional split are given in Table 2.2.

Table 2.2 Swedish Capacity Manual, adjustment factors for uneven directional Split (McLean 1983)

Percent Flow in Primary Direction	Adjustment factor
50-55	1.0
55-65	0.98
65-75	0.95
75-85	0.90

Chandra and Sinha (2001) studied the effect of directional split and slow moving vehicles on capacity of two-lane roads and found that as the directional distribution deviates from 50/50 state, the capacity starts to decrease. They also observed that as the proportion of slow moving vehicles in the traffic stream increases, the traffic speed and thus the capacity decreases.

Chandra (2004) studied the effect of road surface condition on capacity of two-lane roads. The study suggests that the HCM (2000) does not take in to account the road roughness as a factor affecting the free flow speed or capacity of a two-lane road maybe due to good condition of the U.S. roads, in general. They examined eight different sections of two-lane roads in India to study such effect on capacity and displayed the results in Figure 2.5.

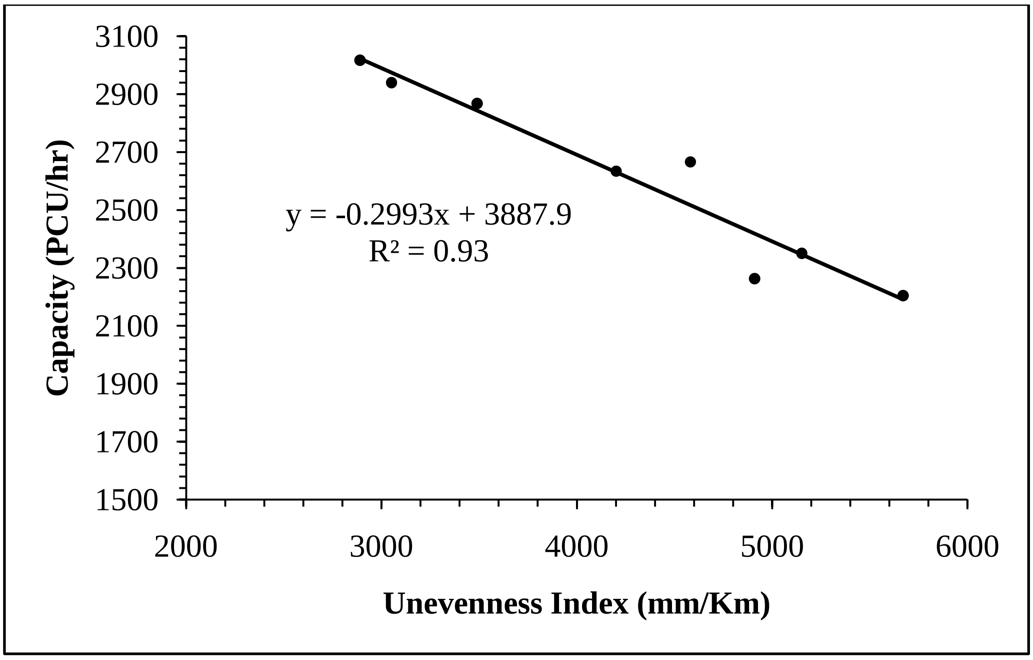


Figure 2.5 Effect of road roughness on capacity of a two-lane road (Chandra 2004)

The linear relation between capacity and road unevenness index was obtained which is given by Equation 2.6.

$$C = 3888 - 0.2993(UI) \quad (2.6)$$

$R^2 = 0.93$

Where;

C = Capacity in PCU/hr

UI = Unevenness index in mm/Km

The study recommends that the capacity of a two-lane road decreases by 300 PCU/hr, when the road roughness increases by 1,000 mm/Km. It concluded that the capacity of a two-lane road can be augmented by 10-15 percent by providing a good riding surface.

Ben-Edigbe and Ferguson (2005) studied the influence of road pavement distress on traffic capacity and capacity loss during day light in Nigeria. They also examined the effect of weather conditions on roads with and without pavement distress from eight sites in Nigeria. They extrapolated the fundamental diagram of traffic flow and density and developed a method to estimate the capacity. They compared the estimated capacities of sections with and without pavement distress and found that road distress causes and average speed drop of approximately 40 km/hr. They observed that low quality of road surface conditions adversely affects the capacity.

Dey (2006) estimated the capacity of two-lane roads through simulation studies as 2860 PCU/hr. The capacity of two-lane road was also determined for homogeneous type of traffic stream consisting of 2-wheelers, 3-wheelers, tractors and heavy vehicles and the capacity values as estimated are given in Table 2.3. The capacity for any given composition of traffic stream can be estimated using Equation 2.7.

$$\frac{100}{C_m} = \frac{P_C}{2860} + \frac{P_{HV}}{780} + \frac{P_{Tractor}}{580} + \frac{P_{2-W}}{5600} + \frac{P_{3-W}}{1850} \tag{2.7}$$

Where;

C_m = capacity of two-lane road in PCU/hr under mixed traffic conditions

P_c = Percentage of cars present in the traffic stream

P_{Hv}= Percentage of Heavy Vehicles in the traffic stream

$P_{Tractor}$ = Percentage of Tractors present in the traffic stream

P_{2-w} = Percentage of 2-wheelers in the traffic stream

P_{3-w} = Percentage of 3-wheelers in the traffic stream.

Table 2.3 Capacity of two-lane road (Dey 2006)

Type of Vehicle	Capacity (PCU/hr)
Car	2860
2-wheeler	5600
3-wheeler	1850
Heavy Vehicle	780
Tractor Trailer	580

Kim and Eleftriadou (2010) estimated the capacity of two-lane two-way highways by developing a simulation model called TWOSIM. The model integrates Akcelic's arrival headway distribution model developed by **Akcelic and Chung (2003)**, and car-following model by **Gipps (1981)** and provides capacity estimations under influence of factors like the presence of horizontal curves, upgrades and presence of trucks in traffic composition. The model shows that the reduction due to presence of horizontal curves was estimated to range between 3-17 percent depending on the curve radius. The combined effect of increase in proportion of trucks in the traffic stream (10-20 percent) and presence horizontal curves and upgrades caused the capacity to decrease by 3-36 percent and 11-40 percent respectively. It was observed that the capacity values obtained based on field data did not match the estimated capacities much frequently and the authors relate such mismatch due to very limited number of sites that operate at capacity. They suggested that the above values should be considered in HCM analysis for various geometric and traffic conditions.

Ben-Edigbe and Mashros (2012) compared roads with and without road humps to estimate the extent of capacity loss due to presence of such traffic calming devices. Despite decreasing impact of such devices have on accident rates these vertical deflections disturb the traffic speed substantially. The authors suggest that road humps, speed cushions and junction tables should also be considered as pavement distress along with potholes, edge subsidence, cracking and uneven road surface, they followed the fundamental relationship between speed and flow to derive speed-density equations and estimate PCU values for both road types to measure the capacity loss incurred due to road humps. It was observed that percent capacity loss in such cases ranges between 4.5 to 34.5 percent.

2.5 STUDIES ON SPEED

Farouki and Nixon (1976) carried out an investigation on untroubled roads in Northern Ireland to study the effect of width of sub-urban roads on the mean free speed of cars and to derive a quantitative expression for such effect. They measured the spot speeds of cars under free flow conditions using a video camera to film their passage along streets with different widths. They placed the camera in a side street which was perpendicular to the line of travel in order to prevent it from being seen and thus affecting drivers’ behavior. The results showed that the mean free speed increased linearly with carriageway width within the range of 5.2 m to 11.3 m. Speeds were measured in dry conditions during off peak periods on Friday afternoons. The measurements made on wet roads showed a decrease in speed by 10 percent.

Karan et al. (1978) classified the factors that affect the operating speeds of vehicles in five groups including driver, vehicle and roadway characteristics and traffic and environmental conditions. Attempt was made to establish initial relationships between speed and road surface roughness for two-lane rural highways. They chose riding comfort index (RCI) as the indicator of roughness. Speed limits for the selected highways were 80 km/hr and 96 km/hr to also determine the effect of speed limit or actual highway speed. They used HCM (1965) guide lines to calculate capacity and volume capacity ratio. Speed data was obtained using electronic radar speed meter. Pavement roughness was measured by BPR Roughometer on a 0.4 km section stretch. Observations were made during day time when heavy volume was not present to avoid the effect of traffic volume on speed. They developed a model using regression to relate average highway speed to pavement roughness which is given in Equation 2.8.

$$Y= 30.74 + 1.04 X_1 - 11.24 X_2 + 0.006X_3^2 \quad (2.8)$$

Where;

Y= average highway speed (km/hr)

X_1= RCI

X_2= V/C ratio

X_3= speed limit (km/hr)

They found that speeds of vehicles on two-lane highways are significantly affected by pavement condition.

Yagar and Van Aerde (1983) found a reduction in speed of 1.80 km/h for every 0.30 m reduction in the width of two-lane roads in Canada. They observed that the mean speed with a pavement width of approximately 6.10 m is about 80 km/hr and it increases from 88 to 90 km/h for a width of 7.80 m. Both driving lanes and extra pavement strips on the left and right side of the road, for instance an emergency lane or a shoulder, contribute to the total amount of pavement width. This additional space decreases drivers' uncertainty which usually leads to higher speeds. They also found that increasing the volume by 1000 passenger cars results in approximate 5 km/hr drop in traffic speed. Higher reduction in speed was observed by adding 1000 trucks to the stream.

Nagraj et al. (1990) studied the linear and lateral spacing of vehicles and developed relationship of speed and dimensions of the vehicles under mixed traffic conditions in India. They considered linear and lateral placement of vehicles as a function of stream speed. It was observed that the lateral spacing of the vehicles increases to an optimal extent with increase in stream speed and then decreased.

Kadiyali et al. (1991) conducted a study on basic desired speed, free speed and speed flow relationships on rural highway sections in India. Data was collected using Enoscope and digital electronic watches. They designed a 60 m trap and a minimum of 70 observations were made on each section for each vehicle class to increase the statistical accuracy. A two-lane rural section was selected for basic speed studies. They observed that irrespective of technological up-gradations, the free speeds of vehicles did not change due to narrow lane widths on single and intermediate-lane roads. However the 10 to 40 percent increase in speed of vehicles on two-lane and four-lane divided roads was related to technological improvement and enhanced road conditions. They suggested that IRC guidelines for capacity values need to be reviewed.

Kumar (2001) studied the effect of surface conditions (dry, wet and rainy) on speed of two-lane roads. To determine their effects on speed he has collected data at three road sections. He observed the speeds of vehicles in the three conditions i.e., dry, wet and rainy. He reported the percentage reductions in the speed of vehicles with respect to dry condition, given in Table 2.4.

Table 2.4 Percentage reduction in speed with respect to dry condition of pavement (Kumar 2001)

Condition	Car	Bus	Truck	LCV	2-wheeler	3-wheeler
Wet	10-15	15-18	15-18	10-15	6-8	18-20
Rainy	20-25	25-30	25-30	20-25	10-15	30-35

It is observed that the speed of a vehicle decreases in wet and rainy condition with respect to that in dry condition. Speed of a car and LCV decreases by 10-15% in wet and 20-25% in rainy condition. Effect of climatic condition is more pronounced in case of 3-wheeler and less pronounced in case of 2-wheeler. Hence the climatic conditions have a considerable effect on capacity of two-lane roads which varies with speed of vehicles.

Kumar and Madhu (2004) assessed the effect of motorized 3-wheelers (Auto rickshaws) on traffic stream in the city of Thiruvananthapuram of Kerala state, south of India. They developed a regression model to relate percentage of such form of public transport on the road and change in the speed of other vehicles due to its presence. They compared data on arterials with and without Auto rickshaws during peak hours and non-peak hours. They used registration number method to study the speed. It was found that speed reduction for 14 to 16 percent proportion of Auto rickshaws in the traffic stream is negligible. For proportions higher than 19 to 30 percent the speed reduction ranged from 3 to 25 percent.

Asamer and Reinthaler (2010) conducted studies on capacity and free flow speeds under normal and adverse weather conditions. The traffic flow parameters are studied under rainy and snow weather conditions. The results indicated that both capacity and free flow speed are considerably reduced during adverse weather conditions. The reduction of capacity is higher during rainy weather compared to snow conditions.

Pérez-Zuriaga et al. (2013) used GPS devices to collect continuous speed data instead of spot speed data to measure the speed changes for tangent to curve transition on two-lane rural roads in Spain. They developed a deceleration rate model that showed the effect of curve radius on operating speed which is displayed in Figure 2.6.

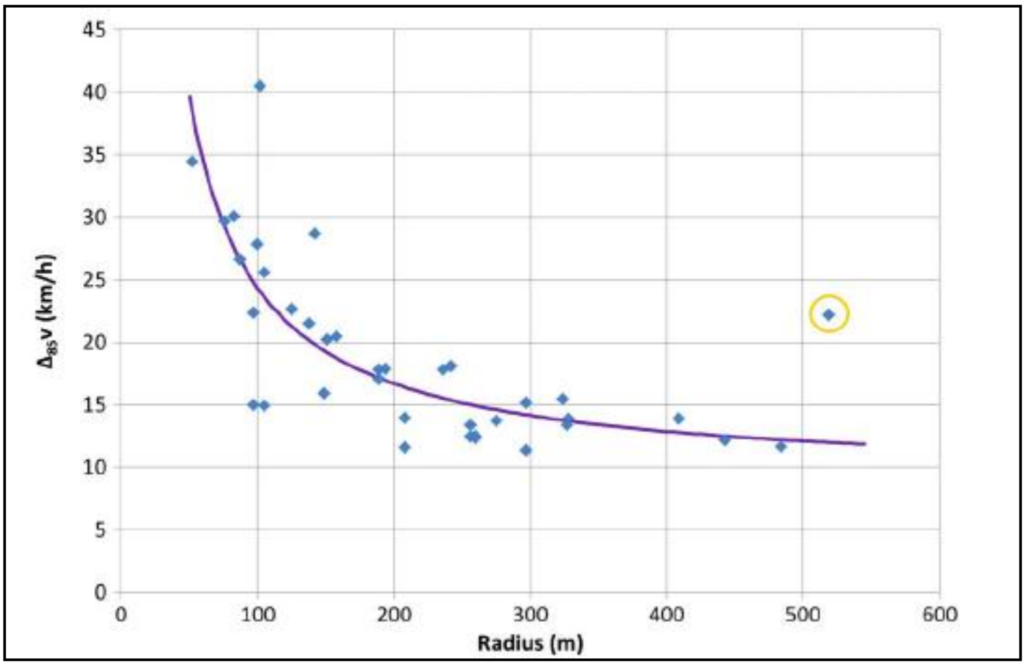


Figure 2.6 85th Percentile speed differential Model with Horizontal Curve Radius (Pérez-Zuriaga et al 2013)

2.6 STUDIES ON EFFECT OF LANE WIDTH ON SPEED AND CAPACITY

Harwood (1990) stated that lanes narrower than 3.65 m reduce the capacity of a road section. Sections having 3.3 m lane width have 3% less capacity than the sections with 3.65 m lane width. Likewise, sections with 3.05 m lane width have 7% less capacity and 2.7 m lane width sections have 10% less capacity than the sections with 3.65 m lane width.

Nakamura (1994) studied highway traffic in Japan with regard to lane width and how it affects the capacity and proposed adjustment factor for determining capacity for different lane widths as given by Equation 2.9.

$$Y_L = 0.24*W_L + 0.22 \qquad (2.9)$$

Where

Y_L= Adjustment factor for lane width (W_L).

Chandra and Kumar (2003) examined the effect of lane width on the capacity of a two-lane road under mixed traffic conditions. They collected data on ten sections of roads in different parts of India where the carriageway ranged from 5.5 m to 8.8 m in width. They found that narrow lanes do not provide enough margin of error for vehicles and therefore the speeds of vehicles drop. They also showed that lane width has a linear effect on PCU values. They used the second degree equation between the capacity and total carriageway to derive the adjustment factors for capacity in substandard lane width.

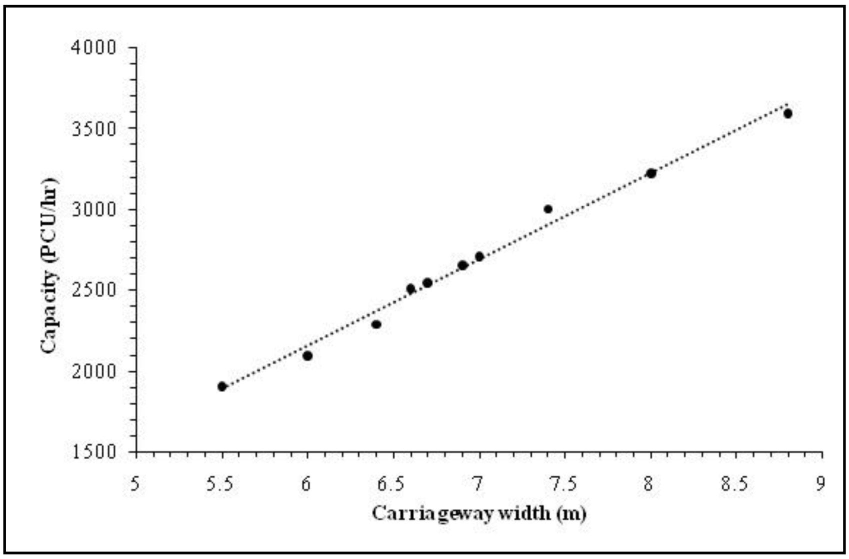


Figure 2.7 Variation of Capacity with Carriageway Width

They found that the capacity in PCU per hour of two-lane roads increase with total width of the carriageway (Figure 2.7), and their relationship follows a second degree curve given by Equation 2.10.

$$C=2184-226W^2+8574W \quad (2.10)$$

Where;

C= capacity (PCU/hr)

W= Total carriageway width (m)

Such relationship can provide a capacity estimate for two-lane roads with a range of carriageways as mentioned above.

Chandra (2004) evaluated variables like lane and shoulder width, traffic composition, grade and directional distribution that influence the capacity of two-lane roads in India and proposed a systematic approach to estimate capacity of two-lane roads in heterogeneous traffic conditions. Traffic on more than 40 sections of two-lane roads was observed and analysed and several relationships that relate the mentioned parameters to capacity were developed. The study provides adjustment factors for different directional distribution of traffic. Presence of slow moving vehicles (SMV) in traffic composition was analysed and a second degree equation was developed to show the decreasing impact of proportion of SMV on capacity. The method for calculating the PCU value of vehicle types in order to study the capacity was adopted from **Chandra and Kumar (2003)**.

Yang and Zhang (2005) surveyed three highway segments with two, three and four lanes In China. They showed that average capacity per lane on highway is 2014, 1971 and 1848 PCU, respectively and hence average capacity per lane decreases with increase in the lane number. They assumed the reason of this decrease may be the effect of increasing lane-changing opportunities and cars' interaction with increasing number of lanes on highways. They found it necessary to bring about the changes of car interaction and driver behavior which result in the difference of average capacity per lane on highway. Their findings show that the marginal decrease rate of average capacity per lane by increasing the number of lanes is around 6.7 percent.

2.7 STUDIES ON EFFECT OF SHOULDERS ON SPEED AND CAPACITY

Taragin and Eckhardt (1953) studied the effect of 1.2 m wide shoulders on speed and lateral placement of vehicles in different parts of the U.S. Their analysis showed the width of gravel shoulder did not increase the effective pavement widths for moving vehicles. They further observed that minimum 1.2 m paved shoulder width adjacent to 5.5 m to 6.0 m pavement increases the effective carriageway approximately by 0.6 m. They suggested that in case the grass shoulders are well-maintained their effect on speed and lateral placement of vehicles will be same as shoulders constructed with well-maintained gravel.

Armour and McLean (1961) suggested two major benefits of paved shoulders. One, they increase highway capacity in rural highways where paved shoulders serve as an extra lane for slow moving vehicles to pass or as an auxiliary lane during peak period to ease the traffic. Second, they provide more uniform speed by allowing motorists to leave the traffic lane at higher speeds so that following vehicles do not have to slow down considerably.

Prakash (1970) observed that type and width of shoulder has a considerable influence on highway capacity. Accordingly if capacity of 7.5 m wide pavement without shoulder is assumed as 100 units, then its corresponding capacity with 1.8 m wide shoulder is 138.9 units. Thus the capacity can be increased by 38.9 percent by extending the roadway with 1.8 m wide shoulders on either side of a two lane road. Similarly, presence of 1.2 m wide shoulder will increase the capacity by 29.2 percent.

Turner et al. (1981) carried out a study on effectiveness of shoulders in reducing the accidents on U.S. rural highways. They studied the attitude of drivers and police towards using of shoulders on two lane highways with and without paved shoulders and four-lane undivided highways without paved shoulders. It was discovered that in normal circumstances, 5-13 percent of vehicles used the shoulders. However, if the road markings were changed to imply the paved shoulder as traffic lane, then between 65 and 75 percent could use this lane.

Turner et al. (1982) studied the effects of paved shoulders on operating characteristics of vehicles. They performed field studies at 18 sites in United States for two-lane roadways with and without shoulders and four-lane undivided roadways.

They collected data on vehicle type, use of shoulder, speed and platooning for at least 2100 vehicles. The analysis of data indicated that increase in traffic volume would increase the benefits of fully paved shoulders. For volumes above 200 vehicles per hour the average speed of vehicles increased more than 10 percent on roadways with paved shoulder. Due to use of shoulder the number of vehicles in platoons reduced down to 20 percent. Only less than 5 percent of vehicles never used the shoulders at the selected sites. They found that converting shoulders to an additional lane has significant effect on improving the operational benefits only when the volume is more than 150 vehicles per hour. The results suggest that the average speeds could be expected to increase up to 5 percent while limiting the platooning down to 5 percent if the volume was higher. The conversion also leads two-third of vehicles to use the shoulders.

Taragin (1995) carried out a study on the effect of objects parked on the shoulders of two and four-lane roads. They realized that on narrower pavements, the traffic tends to shift away from the object of the shoulder. The results of the analysis show that for a two-lane highway with 4.8 m surface width, the shift was 1.0 m and on 7.2 m surface width, the shift was 0.54 m. the greatest effect on lateral placement was observed when the object was placed at the pavement edge.

Chandra and Kumar (1996) studied the effect of shoulder condition on speed of different types of vehicles and their placement on road during passing and overtaking maneuvers on single and two-lane highways. Their observations showed that vehicles do not prefer to come closer than 0.2 m to the pavement edge on a single lane road with badly damaged shoulders. The capacity of a 3.75m, 6.5 m and 7 m wide road was found to have decreased by 10.7, 15.4 and 15.7 percent respectively due to poor maintenance of shoulder.

Taragin (1998) observed lateral placement of vehicles on two-lane rural highways with regard to width and type of shoulders. They compared 0.9 m to 1.5 m wide gravel shoulders with those of 1.8 m to 3.0 m width. They found that the average position of vehicles was 0.12 farther to the left for the latter. But with provision of 1.2 m bituminous shoulders different in appearance from the pavement between carriageway and 1.2 m to 1.8 m gravel shoulder, the average position was 0.12 m farther to the left than on the sections with 1.8 m to 3.0 m gravel shoulders.

Hossain and Iqbal (1999) carried out a linear regression analysis with pavement and shoulder width on two-lane tow-way highways in Bangladesh. They developed an equation to show such relationship which is given in Equation 2.11.

$$V = a_1w_1 + a_2w_2 \qquad (2.11)$$

Where,

V = free speed (km/hr)

a_1,a_2 = regression coefficients

w_1 = pavement width (m)

w_2 = shoulder width (m)

They found that for pavement widths ranging from 5.8 m to 7.5 m, the drivers increased their free speed in a range of 7.25 to 10.29 km/hr for each meter increase in width of pavement. It was observed that due to presence of higher number of slow moving ability of local buses, the increase in shoulder width did not increase the free speed of such vehicles.

Chandra et al. (2005) studied the effect of shoulder condition on placement, speed and capacity of single, intermediate and two-lane roads in India where the traffic is heterogeneous. They divided the shoulders based on physical conditions in to four different categories. The assessment of the condition of shoulders was based on the method suggested by the shoulders were classified as good, average, poor and bad. They measured the percent loss in speed and effective width of the pavement during passing and overtaking maneuvers between cars, light commercial vehicles and heavy vehicles. They identified the width of the carriageway and shoulder condition as main factors affecting the lateral placement of vehicles in a traffic stream. It was observed that the percent loss in width of a carriageway varied from 8 to 35.4 percent. The variation depended upon the type of vehicles involved in the passing/overtaking maneuver and the type of shoulder. They found that for single-lane roads the percent reduction in speed of a vehicle during passing/overtaking maneuver is more than that of two-lane roads. This is mainly because vehicles on single-lane roads are forced to use the shoulders during such maneuvers. The study shows that the capacity of a two-lane road is reduced from 2650 PCU/hr to 1830 PCU/hr when the shoulder condition changed from average to bad. They suggested that increasing the quality of shoulders on both sides of an intermediate-lane road can increase the capacity up to 40 percent.

Fitzpatrick et al. (2005) studied the effect of functional classification, edge condition (whether it is shoulder or curb/gutter) and speed limit on the operating speed from 79 tangent sections of different type of roads in rural, urban and suburban areas in Italy. The study showed that the speed limit was the only variable statistically significant, affecting the operating speed while the next major influencing factor was the number of accesses. They also observed that pedestrian activity, road side parking and type of the median affected the 85th percentile free-flow speed.

Pandey (2008) proposed that the capacity of an intermediate lane road ranges from 2050 to 2155 PCU/hr for a shoulder width ranging from 1.5 to 2.0 meters. He found that the capacity of an intermediate lane road increases by 450 PCU/hr when the shoulder width is increased from 0.5 to 2.0 meters and the capacity increases with an increase in 2-wheeler and cars due to their better speed and maneuverability.

Chandra et al. (2010) analysed traffic flow on intermediate-lane roads in India under mixed traffic conditions. The aim of their study was to measure the effect of shoulder width and traffic composition on capacity of intermediate-lane roads. They used video recording technique and five minute categorized volume and composition data counts respectively to collect and extract the data from specified road sections. They observed that increase in shoulder width from 0.5 m to 2.0 m will increase the capacity up to 804 PCU/hr. They also found that every 5 percent increase in the proportion of motor cycles will increase the capacity by 71 PCU/hr. The method for obtaining the PCU values was taken from Chandra and Kumar (2003). The capacity was calculated using traffic volume and mean stream speed as per IRC: 64-1990 and the results were compared with that recommended by Road User Cost Study (RUCS, 2001) and HCM (2000). It was found that the obtained capacity value ranged between 2000 PCU/hr and 2300 PCU/hr for intermediate-lane roads with 1.5 to 2.0 m shoulder on both sides which was higher than the capacity suggested as 1200 PCU/hr in IRC: 64-1990.

Singal (2013) obtained PCU values by multiplying traffic volume of each vehicle category with the corresponding Vehicle Damage Factors (VDF) offered by IRC: 37-2001. They suggested that since higher traffic speed offers lower peak hour factors (PHF), then higher PHFs represent lower traffic speed and thus lower capacity. They observed that if the PHF is reduced from 10 percent to 5 percent the capacity would increase by 66 percent. They identified the number of lanes, condition of pavement and shoulders, type of shoulder and its width, traffic type and speed, geometric design of roads, directional traffic and peak hour concentration as measures for augmenting capacity of highways in India. Improving such factors helps maintaining the design speed and reducing PHF and thus increasing the capacity. They recommend that paving the shoulders can increase the capacity of a highway up to 20 percent. They suggest that construction of additional lanes should be considered only if the volume forecast for 20 years is above 30000 PCU.

2.8 STUDIES ON EFFECT OF GRADIENT AND CURVATURE ON SPEED AND CAPACITY

Leong (1968) studied the influence of gradient, pavement and shoulder width on free speed of vehicles on 31 two-lane rural highway sections in New South Wales during mid-sixties. The selected locations were of bitumen and concrete surface, different pavement and gravel shoulder width and gradients ranged between 0 to 10 percent. They used multiple regression method to analyze the data and suggested that gradients, shoulders and pavement widths and sight distance affected free speeds. They found that in general, gradient increase either upgrade or downgrade decreased speed and increase in sight distance, shoulder and pavement width increase the free speed.

Krammes et al. (1995) developed an equation to estimate 85th percentile speed of rural two-lane highway under effect of curve geometry, cross section and approach tangent condition the equation was formulated as given by Equation 2.12.

$$V_{85} = 102.45 - 1.57D + 0.003L - 0.10I \qquad (2.12)$$

Where,

V_{85} = 85th percentile speed on the curve (km/hr)

D = degree of curvature (degrees)

L = length of curvature (m)

I = deflection angle (degree)

Goyal (2000) studied the effect of grade on capacity of two-lane roads. The author considered five sections to study such effect of which one was a level terrain. He observed that the free flow speed of a vehicle declines uniformly with gradient and capacity of a two-lane road having two-way movement is more than that of the road having a one-way movement. He estimated the capacity of two-lane two-way road on level terrain as 2620 PCU/hr. He concluded that for every one percent increase of the upgrade, the capacity decreases by 2.61 percent and for every one percent increase of downgrade, the capacity increases by 3.09 percent.

Fitzpatrick and Collins (2000) observed that drivers could accelerate to maintain the desired speed for a range of 93 to 104 km/hr on long tangents and that 85^{th} percentile speed was sufficient for such maneuvers on two-lane rural roads in the U.S.

Donnel et al. (2001) predicted the operating speed of trucks on two-lane rural highways by developing a model to be used in design consistency. They developed several regression models to estimate 85^{th} percentile speed along a horizontal curve. Design characteristics that were considered for this study included curve radius, grade and length of approach and departure tangent.

Chandra and Goyal (2001) studied the effect of grade on capacity of two-lane roads. The study was aimed at determining the effect of gradient on PCU values and free speed for different types of vehicles. Data was collected at locations of two-lane roads where effect of gradient could be assessed along with 5 locations on level ground for comparison purposes. The data were collected using video recording technique. The results showed that PCU for a vehicle type increases on upgrade and decreases on downgrade. The effect of grade on PCU is linear and the slope of linearity depends on type of vehicle. It was observed that every one percent of downgrade increases the capacity value by 3.09 percent. Also free speed of a vehicle decreases uniformly with gradient. Finally the capacity of two-lane two-way road on level surface was estimated to be 2620 PCU/hr in both ways which is comparable to HCM values for 60:40 directional split.

Misaghi and Hassan (2005) conducted studies on two-lane rural highways in Canada. By using OLS linear regression method 85th percentile speed difference between the approach tangent and midpoint of a horizontal curve were estimated. They found that the average longitudinal grade, the presence of an intersection on the horizontal curve, and the deflection angle of horizontal curve were positively correlated with the speed differential.

Medina and Tarko (2007) studied the driver behavior in the vicinity of curves with reduced standards. They investigated driver behavior before and after horizontal curves and developed speed models for transition section to calibrate mean deceleration and acceleration rates and the portion of the transition section that occurs on the approach tangent to a curve. The models were used to design transition sections and to assess the design consistency of two-lane rural roads. They measured free-flow speeds and collected highway geometry information on undivided two-lane rural roads with diverse configurations, cross-sectional dimensions, roadside clear zones, horizontal curvature, and other features. A total of 158 spots were located in horizontal curves, tangents, and transition sections at different distance from the curves. The percentile speeds from the 5^{th} to the 95^{th} percentile at increments of five have been estimated for each measurement spot. The results indicated that 66 percent of the speed reduction and 72 percent of the speed increase occurs on the tangents preceding and following the curves, respectively. Also the mean deceleration rate and the mean acceleration rate are 0.033 and 0.022 ft/s^2 respectively; or approximately 0.732 and 0.488 m/s^2, respectively, for 16.1 km/h reduction.

Abbas et al. (2011) presented an empirical model to predict the 85^{th} percentile operating speed for horizontal curves on Malaysian Two-lane highways by developing multi-linear regression analysis on curve radius and speed at the tangent line. Geometric featured considered included the curve radius, curve length and length of approach tangent. They collected data on six sites using laser gun to collect spot speed data at mid-curve. However the model lacked any evaluation for actual condition.

Praticò and Giunta (2012) studied the effect of road features and alignments like curvature, gradient and the length of such elements on the operating speed of vehicles. They carried out an experimental survey on a two-lane road in Italy. Speed data was collected at 74 sites for individual geometric features (curve and gradient) using a speed laser gun from both flow directions under free flow conditions. They proposed an operating prediction model and concluded that gradient specifically has great influence on the operating speed.

D'Andrea et al. (2012) surveyed the speed of vehicles in 45 mid-curve sections on a two-lane rural road in Italy to calculate the operating speed. They considered factors such as curve radius, deflection angle, design speed, available sight distance offered, stopping sight distance required, pavement roughness etc, and applied a neuro-fuzzy technique to find the most important single or inter-related variables that actually influence the 85th percentile speed. It was observed that visibility provided by the facility and the stopping sight distance required were the most influential factors in this regard.

Hashim and Abdel-Wahed (2013) studied the changes in capacity when horizontal alignment of a road changes from tangent to curve in one direction of travel on a two-lane rural road in Egypt (Figure 2.8).

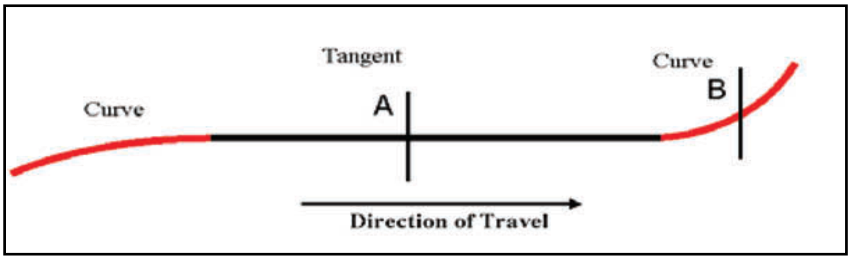


Figure 2.8 Horizontal tangent to curve transformation (Hashim and Abdel-Wahed 2013)

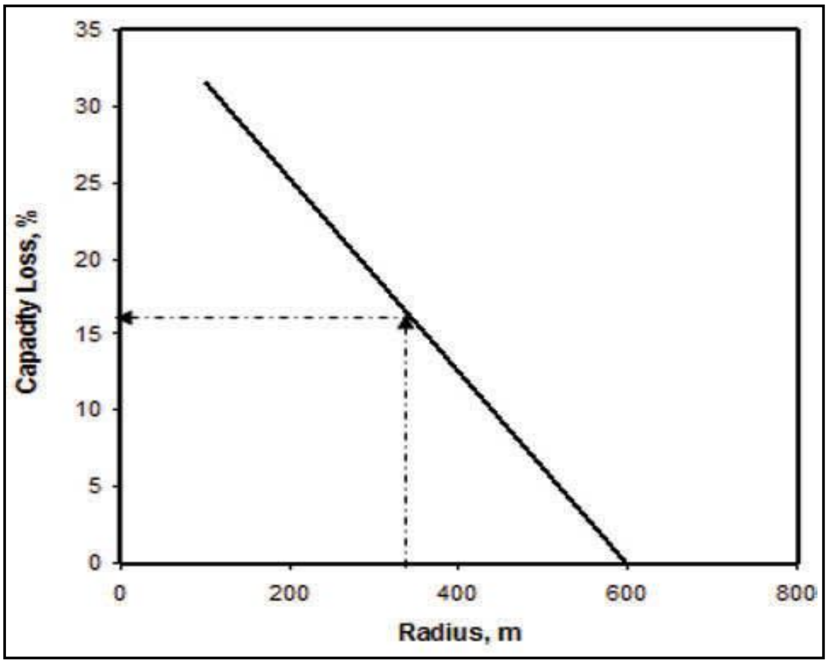


Figure 2.9 Effect of curve radius on capacity loss (Hashim and Abdel-Wahed 2013)

They classified the vehicles in different categories and calculated PCU values for each vehicle category for both tangent and curve separately. They used linear regression to model the effect of geometric characteristics on capacity loss. The model examines the effect of curve radius on difference in lane and shoulder width between tangents and adjoining curves the result of which was plotted in a graph displayed in Figure 2.9. They observed that due to rather poor performance of the roads, the capacity values were lower than those provided in HCM 2000. They suggested that the curve radius and lane width have direct effect on capacity of a two-lane road. The analysis of their results showed that capacity loss in a two-lane road when it transforms from tangent to a horizontal curve ranged between 4.1 to 35 percent. They also found that the minimum curve radius to diminish the capacity loss between a tangent and a horizontal curve is 600 m.

2.9 SUMMARY

A number of studies related to the subject of this research work were addressed and reviewed in this chapter. Several methods have been used by different scholars in the field of capacity estimation and influencing factors.

Different methods were adopted by various authors for development and estimation of PCU values. They identified several factors affecting the PCU value of a vehicle including roadway and traffic conditions. However the variation of PCU values for the types of inter-urban roads selected for this study under different traffic volume and composition and the heterogeneous traffic stream have not been studied before.

Also, several methods of capacity estimation, including use of simulation techniques and manual procedures, were addressed in this chapter. It is understood that capacity is influenced by many traffic and roadway conditions. Some methods consider single factors while others consider combined effect of a number of factors.

Speed has been considered as a determining factor in estimation of capacity by many researchers and studied its variation under different traffic and roadway conditions. The findings of previous works reviewed in this chapter will be compared with the results of this research work wherever applicable.

CHAPTER – 3

DATA COLLECTION

3.1 GENERAL

The most important part of a traffic study is the data collection. It should provide a strong base for further analysis. It is also important that data collection be performed with extra care as a considerable portion of the total budget is allocated to data collection. This will require the project team to be fully aware of the techniques and complexities of the work as well as the locations where data is to be collected from. The approach implemented in this study required manpower having knowledge of traffic volume, traffic composition, speed of individual vehicles and geometric layout of the road section. As mentioned in chapter 1, the objective of the present research is to develop capacity norms for single-lane, intermediate-lane and two-lane roads in India. Therefore, it was necessary to select the test sections in different parts of the country to cover as much variation in traffic and driver behavior characteristics as possible. Therefore, attempt was made to choose the sections in different parts of the country. This chapter describes the conditions of base sections on these types of roads, details of the sites, selected and method of data collection for the present study.

3.2 SITE SELECTION

The sites for data collection were selected in two stages. In the first stage, sections on single lane, intermediate lane and two lane roads satisfying the conditions of base sections were selected. The conditions for base sections for two-lane roads are summarized below.

- The carriageway width should be 7.0 m with two-way traffic.
- The section should be straight and level, not influenced by interruptions due to presence of intersections, slip roads, gradients and curvatures.
- Physical restrictions such as speed breakers or rumble stripes which affect the traffic stream should not be present at least 500 m length of the road.
- Earthen shoulder of at least 1.8 m width should have been provided on each side of the road.

- Roads should be free from any side frictions activity.

Added to the traffic interrupting factors was the bus stop as it reduces the average traffic speed which is discussed by Koshy and Arasan (2005) and Black et al. (1988). Similar conditions were observed for intermediate lane roads with carriageway width of 5.5 m to 6.0 m.

The single lane roads were not found with a standard carriageway width of 3.75 m and hence sections with less than 5.5m width located in plain area with no curvature/gradient and free from the effect of any access point were considered as base sections for this category of the road.

By considering the above criteria, the study sections were selected on different categories of roads as provided by IRC: 52-1981 such as National Highway, State Highway, District Roads and Village Roads across India. Table 3.1 provides the list of two lane, intermediate lane and single lane road sections selected for the present study. Figures 3.1 – 3.3 display typical snapshots of three types of roads.

Figure 3.1 Sample photo of a two-lane road (NH-88)

Figure 3.2 Sample photo of an intermediate-lane road (SH-22A)

Figure 3.3 Sample photo of a single-lane road (Mirza-Palashbari road-ODR)

Table 3.1 list of selected sections of two, intermediate and single lane inter-urban roads

Sec. ID.	Sec. details	Location of the road	Road type	Carriageway width (m)
T-1	NH-47	Salem (Kerala)	Two- lane	7.1
T-2	SH-31	Etah-Tudla Road (U.P)		7.0
T-3	NH-88	Bardoli (Surat)		7.0
T-4	NH-58	Roorkee-Meerut (U.P)		7.0
T-5	SH-59	Delhi-Yamunotri (Uttarkhand)		7.0
T-6	SH-15	Howrah (West Bengal)		7.0
T-7	MDR	Vijianagaram-Palakonda Road (AP)		7.0
T-8	NH-37A	Tezpur (Assam)		7.0
T-9	SH-02	Hajo-Barpeta-Guwhati Road (Assam)		7.0
T-10	NH-37	Near Kaziranga Park - (Assam)		7.0
T-11	NH-344	Roorkee-Punchkula (Haryana)		6.5
I-1	MDR	Vettu road-Perumathura (Kerala)	Intermediate-Lane	5.5
I-2	NH-73	Bhagawanpur-Roorkee Bypass road		5.5
I-3	NH-74	Roorkee-Haridwar (Uttarkhand)		6.0
I-4	SH-22A	Palwal-Aligarh (Haryana)		5.5
I-5	MDR	Valiyathura-Beemapally (Kerala)		5.5
I-6	SH-161	Dabhoi-Sinor (Gujarat)		5.5
I-7	SH-26	Hamidpur, Km 3 (U.P)		5.5
S-1	ODR	Dharapur-Palahbari (Assam)	Single-lane	3.7
S-2	ODR	Mirza-Palashbary (Assam)		4.3
S-3	ODR	S.Kota – Kothavalasa (A.P)		3.8
S-4	ODR	Manglore-Roorkee (Uttarkhand)		4.0
S-5	ODR	PMGSY Road (Sardhana-Meerut)		4.2

In the second stage of data collection, the sites with one or more of the influencing factors like paved shoulders (for two-lane roads only), gradient and curvature were selected. The details of two-lane sections with paved shoulders where the roads were located on plain area are given in Table 3.2. Intermediate-lane roads are not provided with paved shoulders, rather upgraded to two-lane sections. The details of sections selected to study the effect of gradient and curvature are discussed in Chapter 7.

Table 3.2 Details of two-lane sections with paved shoulders

Section ID	Section details	Location of the road	Carriageway width (m)	Shoulder width (m)
T-12	NH-04	Mumbai to Goa	7.5	0.6
T-13	SH-05	Ambala to Saha	8.0	0.9
T-14	NH-165	Bardoli to Surat	7.0	1.0
T-15	NH-235	Meerut to Hapur	6.9	1.4

3.3 VEHICLE CLASSIFICATION

All the motorized and non-motorized vehicles generally present in a heterogeneous traffic stream in India were divided in to twelve categories as shown in Table 3.3. Cars were also divided into two categories of Standard Cars and Big Cars (SUVs). Different vehicle categories and their abbreviations are Standard car (SC), big car (BC), motorized two-wheelers (2W), motorized three-wheelers (3W), light commercial vehicle (LCV), bus (BUS), truck (TK), tractor trailer (TT), and multi-axle vehicle (MAV) as well as Pedal cycle (CYC), Pedal Rickshaw (RCK) and animal driven vehicles (ADV). Standard Car represents taxis and passenger cars which have engine powers of 1400 cc and average length and width of 3.72 m and 1.44 m respectively. The standard cars are taken as the base for estimating the PCU factors and capacity values are calculated with respect to this vehicle in this study. Big cars are those of 4.58 m length and 1.77 m width whose engine power is around 2500 cc. The dimensions of all vehicles were measured by taking their maximum length and width. In case there were various types of vehicles in a category the average dimensions were considered. Typical samples of each vehicle category are shown in Figures 3.4 to 3.15.

Table 3.3 Vehicle categories and corresponding dimensions

Vehicle Type	Notation	Applicable vehicles	Length (m)	Width (m)	Rectangular Area (m^2)
Standard Car	SC	Passenger cars, Taxi	3.72	1.44	5.36
Big car	BC	Jeep, SUV	4.58	1.77	8.11
Two-wheeler	2W	Motor bikes, Scooter	1.87	0.64	1.20
Three-wheeler	3W	Auto-rickshaw	3.20	1.40	4.48
Light commercial vehicle	LCV	Mini bus, large van, mini trucks	6.10	2.10	12.81
Truck	TK	2 and 3-axle truck	7.50	2.35	17.48
Heavy commercial vehicles	MAV	Multi-axle trucks	15.24	2.44	37.16
Bus	Bus	Bus	10.10	2.43	24.54
Tractor trailer	TT	Tractor with trolley	7.40	2.20	16.28
Cycle	CYC	Bicycle	1.90	0.45	0.86
Rickshaw	RCK	Pedal rickshaw, carts	2.70	0.95	2.57
Animal driven vehicle	ADV	Bullock-cart, Horse cart	5.50	1.75	9.63

Figure 3.4 Typical Truck

Figure 3.5 Typical Tractor Trailer

Figure 3.6 Typical Big Car

Figure 3.7 Typical Bus

Figure 3.8 Typical MAV

Figure 3.9 Typical LCV

Figure 3.10 Typical Three-Wheeler

Figure 3.11 Typical Standard Car

Figure 3.12 Typical Two-Wheeler

Figure 3.13 Typical Cycle

Figure 3.14 Typical Rickshaw

Figure 3.15 Typical Animal Drawn Vehicle (ADV)

3.4 DATA COLLECTION AND EXTRACTION

Field data collection program for the present research was designed to have information on traffic flow, traffic composition, individual vehicular speed and free-flow speed. Since automated traffic detectors are not available on Indian highways, the videography technique was used to collect the data. Weather conditions can adversely affect the traffic movement (Kyte et al. 2000 and Hablas 2007). To avoid this, the recordings took place on normal sunny days. A uniform section of 500 m length was selected on each site and a trap of 60 m length was made using adhesive tape and white cement in order to make it visible and resistant to vehicle movements. Video recording technique was used as a primary method to capture the data of traffic flow characteristics which included the traffic volume, traffic composition and speed of vehicles. Data extraction was done by playing the recorded video in the laboratory on a large screen monitor.

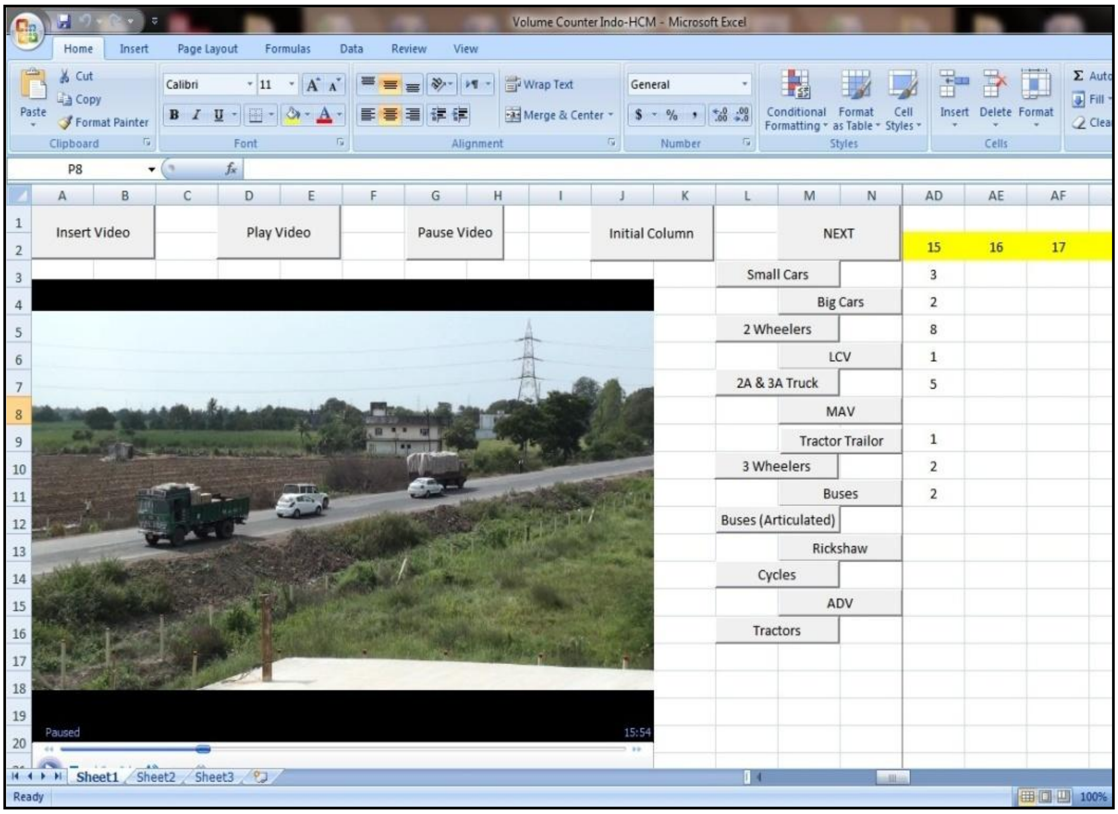


Figure 3.16 Excel volume counter

Figure 3.17 Frame number as the individual vehicle enters the trap

Figure 3.18 Frame number as the individual vehicle exits the trap

Five minute data counts including traffic volume and composition were made using an excel program where vehicle categories were completely defined and the counting was performed by clicking the corresponding vehicle category as it passed the trap during play back. A snapshot of the program interface is shown in Figure 3.16.

The video was recorded at the rate of 25 frames per second. Using the Media player classic from K-Lite Codec pack version 7.6.0.0 which provided the option of showing the frame numbers during video play back, the speed of each individual type of vehicle was calculated using the Equation 3.1. Figure 3.17 and 3.18 display snapshots of the contents that the following equation is comprised of.

$$V= \frac{d}{\frac{f_2 - f_1}{25}} \tag{3.1}$$

Where;

V= speed (m/s)

d= trap length (m)

f_1 = the frame number when the front wheels of a vehicle touch entry line of the trap (refer to Figure 3.17)

f_2 = the frame number when the front wheels of a vehicle touch the exit line of the trap (refer to Figure 3.18)

The extracted data were sorted and organized separately for each section located on single, intermediate and two-lane roads. The range and the average proportion of each vehicle category present in the traffic stream during the data collection time period (4 to 8 hours) for each study section are shown in Table 3.4 to 3.6.

Table 3.4 Traffic volume and composition on two-lane roads

Sec. ID.	Traffic Volume (Veh/hr)	Composition Parameter (%)	Vehicle Categories								
			SC	BC	2W	LCV	TK	MAV	3W	Bus	TT
T-1	2623	Average	27.41	8.10	42.35	2.08	5.22	-	12.97	1.87	-
		Maximum	35.6	14.66	59.25	5.00	11.29	-	22.16	5.24	-
		Minimum	18.49	4.15	30.37	0.00	0.91	-	7.07	0.00	-
T-2	842	Average	8.00	6.44	67.88	5.68	3.38	-	2.16	2.85	3.54
		Maximum	16.42	14.52	87.14	24.18	10.29	-	7.25	6.45	8.33
		Minimum	1.45	0.00	51.22	0.00	0.00	-	-	0.00	-
T-3	1242	Average	23.77	10.89	34.37	8.64	12.49	-	6.02	3.82	-
		Maximum	45.98	20.29	52.44	16.24	26.67	-	10.99	9.82	-
		Minimum	11.3	0.00	18.56	2.08	0.93	-	0.97	0.00	-
T-4	876	Average	26.53	14.22	31.02	3.07	11.05	-	0.16	9.50	3.45
		Maximum	38.2	25.00	45.16	8.82	19.35	-	3.03	15.79	10.84
		Minimum	14.47	5.62	23.29	0.00	1.72	-	0.00	3.61	-
T-5	739	Average	18.98	10.00	41.96	8.21	17.07	-	-	1.76	2.03
		Maximum	34.69	19.51	63.49	17.86	33.33	-	-	6.12	10.94
		Minimum	4.76	1.28	28.57	0.00	5.88	-	-	0.00	-

Table 3.4 Traffic volume and composition on two-lane roads (continued)

Sec. ID.	Traffic Volume (Veh/hr)	Composition Parameter (%)	Vehicle Categories								
			SC	**BC**	**2W**	**LCV**	**TK**	**MAV**	**3W**	**Bus**	**TT**
T-6	710	Average	6.06	4.80	61.05	13.89	1.54	-	9.67	2.98	-
		Maximum	16.33	11.67	72.00	29.03	5.63	-	20.34	7.14	-
		Minimum	1.64	0.00	48.33	6.38	0.00	-	3.23	0.00	-
T-7	1220	Average	5.37	1.50	56.34	3.07	1.81	-	28.06	2.29	1.23
		Maximum	12.00	4.35	66.67	9.33	5.26	-	44.44	8.70	6.85
		Minimum	1.03	0.00	44.12	0.00	0.00	-	14.67	0.00	0.00
T-8	303	Average	28.47	8.96	17.35	17.48	14.14	0.15	7.04	6.49	-
		Maximum	52.38	38.89	38.10	40.74	44.12	10.53	19.05	21.74	-
		Minimum	4.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-
T-9	797	Average	23.81	5.66	35.12	18.30	2.43	-	12.71	1.74	0.23
		Maximum	41.07	15.79	57.89	30.51	12.24	-	24.69	8.21	5.00
		Minimum	9.43	0.00	14.29	6.45	0.00	-	3.51	0.00	0.00
T-10	302	Average	27.08	10.80	12.44	16.72	25.77	0.22	0.31	6.53	0.12
		Maximum	50.00	33.33	35.29	33.33	55.88	8.33	4.55	23.81	5.88
		Minimum	10.00	0.00	0.00	3.33	0.00	0.00	0.00	0.00	0.00

Table 3.4 Traffic volume and composition on two-lane roads (continued)

Sec. ID.	Traffic Volume (Veh/hr)	Composition Parameter (%)	Vehicle Categories								
			SC	BC	2W	LCV	TK	MAV	3W	Bus	TT
T-11	1058	Average	9.31	2.83	68.89	3.55	1.23	0.16	9.85	0.84	3.33
		Maximum	17.57	15.63	83.33	11.43	4.88	2.17	20.41	4.11	12.36
		Minimum	1.28	0	52.7	0	0	0	3.37	0	0

Table 3.5 Traffic volume and composition on intermediate-lane roads

Sec. ID.	Traffic volume (veh/hr)	Composition Parameter (%)	Vehicle Categories								
			SC	BC	2W	LCV	TK	MAV	3W	Bus	TT
I-1	712	Average	12.39	2.90	52.54	7.15	1.56	-	22.96	0.50	-
		Maximum	15.20	5.60	42.40	9.60	3.20	-	21.60	2.40	-
		Minimum	5.26	5.26	57.89	5.26	5.26	-	15.79	5.26	-
I-2	548	Average	16.17	5.00	60.56	7.26	8.37	-	1.06	-	1.78
		Maximum	39.02	13.51	71.43	18.52	18.75	-	4.35	-	8.51
		Minimum	3.70	0.00	38.46	0.00	0.00	-	0.00	-	0.00
I-3	626	Average	23.00	16.19	37.46	3.66	11.22	-	0.71	6.82	0.74
		Maximum	44.78	28.99	56.36	10.64	24.53	-	4.88	20.93	6.00
		Minimum	6.38	5.26	17.91	0.00	1.56	-	0.00	0.00	0.00
I-4	496	Average	16.77	14.29	41.47	3.25	18.24	-	3.75	2.23	-
		Maximum	44.44	27.91	60.00	11.11	41.94	-	11.43	8.57	-
		Minimum	2.86	0.00	20.00	0.00	6.67	-	0.00	0.00	-
I-5	763	Average	9.39	-	59.37	-	-	-	28.05	3.19	-
		Maximum	33.33	-	100.00	-	-	-	62.50	33.33	-
		Minimum	0.00	-	0.00	-	-	-	0.00	0.00	-

Table 3.5 Traffic volume and composition on intermediate-lane roads (Continued)

Sec. ID.	Traffic Volume (Veh/hr)	Composition Parameter (%)	Vehicle Categories								
			SC	BC	2W	LCV	TK	MAV	3W	Bus	TT
I-6	379	Average	10.44	7.42	54.05	3.85	8.42	-	11.20	3.06	1.56
		Maximum	66.67	66.67	100.00	33.33	33.33	-	50.00	25.00	20.00
		Minimum	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
I-7	650	Average	12.80	8.65	56.62	2.91	10.34	-	4.37	1.42	2.89
		Maximum	23.21	19.70	71.43	8.33	22.92	-	12.24	6.67	12.07
		Minimum	2.08	1.64	32.65	0.00	0.00	-	0.00	0.00	0.00

Table 3.6 Traffic volume and composition on single-lane roads

Sec. ID.	Traffic volume (veh/hr)	Composition Parameter (%)	Vehicle Categories										
			SC	**BC**	**2W**	**LCV**	**TK**	**3W**	**Bus**	**TT**	**CYC**	**RCK**	**ADV**
S-1	313	Average	9.65	3.12	66.67	9.21	0.99	5.11	-	-	2.84	2.40	0.01
		Maximum	29.41	14.29	90.48	23.53	13.64	13.64	-	-	20.00	9.38	-
		Minimum	0.00	2.50	47.06	3.03	2.50	0.00	-	-	4.76	3.57	-
S-2	574	Average	10.79	2.36	69.28	3.83	0.27	12.75	0.71	-	-	-	0.01
		Maximum	31.25	28.57	81.69	18.75	6.25	29.41	28.57	-	-	-	-
		Minimum	4.23	0.00	28.57	0.00	0.00	0.00	0.00	-	-	-	-
S-3	523	Average	13.62	1.62	59.71	3.39	1.50	6.49	-	0.94	12.72	-	0.01
		Maximum	28.57	7.14	78.57	16.33	10.53	53.57	-	4.76	33.33	-	-
		Minimum	0.00	0.00	32.14	0.00	0.00	0.00	-	0.00	0.00	-	-
S-4	631	Average	26.07	7.36	63.23	-	-	-	-	-	3.33	-	0.01
		Maximum	39.34	21.79	83.33	-	-	-	-	-	17.39	-	-
		Minimum	8.33	0.00	41.03	-	-	-	-	-	0.00	-	-
S-5	619	Average	17.80	2.23	68.26	4.62	1.99	3.40	0.10	1.59	-	-	0.01
		Maximum	33.33	13.51	85.37	17.39	10.00	10.26	2.44	6.12	-	-	-
		Minimum	5.13	0.00	51.11	0.00	0.00	0.00	0.00	0.00	-	-	-

3.5 SUMMARY

The data provided in Table 3.4 to Table 3.6 are summarized in Table 3.7 as the average for each road type. The conditions for base sections of single-lane, intermediate-lane and two-lane roads were given in this chapter along with the traffic volume and composition. As tabulated in this chapter and reviewing the data extraction output it can be understood that the heterogeneous traffic existing on Indian roads consists of wide variety of slow and fast moving vehicles.

The data provided in this chapter will be used to estimate PCU factors for base sections of the subject types of roads and thereby the capacity in the following chapters.

Table 3.7 Average traffic volume and composition on different road types

Road Type	Traffic volume (veh/hr)	Vehicle category											
		SC	**BC**	**2W**	**LCV**	**TK**	**MAV**	**3W**	**Bus**	**TT**	**CYC**	**RCK**	**ADV**
Two-lane	974	17.3	8.0	46.3	7.1	8.1	0.1	8.1	3.5	1.5	-	-	-
Int.-lane	596	17.1	11.0	49.2	4.3	12.0	-	2.5	2.6	1.4	-	-	-
Single-lane	532	15.6	3.3	65.4	4.2	1.0	-	5.6	0.2	0.5	3.8	0.5	0.01

CHAPTER – 4

ESTIMATION OF PCU

4.1 GENERAL

The heterogeneous nature of traffic stream in India and many other developing countries makes the task of traffic analysis for a traffic engineer a complicated one. Different vehicle categories, which are the obvious characteristic of a heterogeneous traffic, impose consideration of different vehicular physique-related variables while studying the traffic flow behavior on a section of road. Generally, such variables can be considered by taking account of variation in speed, acceleration capability, area occupied on the road surface and the influence of all these variables on other vehicles present in the same traffic stream.

Many literature studies have been reviewed in the chapter 2 of this report. The overall aim of the various methods introduced and implemented in literature is to analyse the traffic in order to establish the grounds on which a heterogeneous traffic could be explained. To achieve such objective, the attempts were mostly made to define the traffic stream in terms of one standard vehicle category. Highway capacity manual (HCM 1965) of USA introduced the concept of Passenger Car Unit (PCU) to express the volume or capacity of a road section in terms of passenger cars per hour. As per the manual, the PCU of a vehicle is equal to the number of passenger cars displaced by that vehicle in the traffic stream under given conditions. The rest of the literature on this subject has been oriented towards estimation of PCU values for various types of vehicles operating on different types of roads in different countries.

In the past, various approaches have been adopted for estimation of PCU of vehicles. The bases used for the estimation process are Delay (Craus et al. 1980), Speed (Elefteriadou et al. 1997), Density (Webster and Elefteriadou, 1999), Headway (Krammes and Crowley, 1986), and Queue Discharge (Al-Kaisyet al. 2005). All these studies, however, are mainly related to estimation of PCU for heavy vehicles (Trucks and Buses) under homogeneous traffic conditions and hence, the results of these studies are not applicable for Indian conditions (Tiwari et al 2000, Praveen and Arasan 2013).

The dynamic state of traffic and the dynamic nature of the vehicle industry in terms of improvements to vehicular operational capabilities, necessitate the change of perception over the subject of PCU. Most of the standards like American HCM, Indonesian HCM (1996), Indian Roads Congress (1990) and standards in other developing countries where the traffic is heterogeneous provide only single sets of PCU values with very limited and controlled variations. Many researchers have shown that PCU for a vehicle type is not a constant value; rather it varies with traffic and roadway conditions. The dynamic nature of PCU on single, intermediate and two-lane roads is explored in this chapter, and based on the analysis carried out on PCU evaluation, a generalized solution is presented for converting mixed traffic stream into homogeneous equivalent.

4.2 STUDY OF VARIATION IN PCU VALUES

4.2.1 Method for Estimation of PCU Values

The PCU of a particular vehicle category can be expressed as the amount of interaction of that vehicle type to the traffic stream with respect to passenger car. This interaction gets changed with both traffic volume and proportional composition of traffic stream. It also varies with the length and weight to horsepower ratio of the vehicle (Elefteriadou et al 1997). These interactions are reflected in speed of a vehicle type and therefore speed is considered as one of the basic parameters for estimation of PCU factors. The physical size of the vehicle indicates its maneuverability, area occupied on the road and impedance caused to other vehicles in the traffic stream. In a mixed traffic stream where small size vehicles like motorized two wheelers are in good proportion, the lane discipline becomes extremely poor. When vehicles do not follow the lanes, the occupancy is better reflected by area than merely the length which has been suggested frequently in the literature as stated by Chandra and Sikdar (2000). In such situations Chandra and Kumar (2003) suggested the use of physical area of the vehicle as an important variable for the estimation of PCU factors. Therefore, in the present study, PCU of a particular vehicle category “i” is estimated by using Equation 4.1.

$$PCU_i = \frac{\left(\frac{V_c}{V_i}\right)}{\left(\frac{A_c}{A_i}\right)} \qquad (4.1)$$

Where;

V_c = Speed of passenger car (m/s),

V_i= Speed of a vehicle type i (m/s),

A_c = Projected rectangular area of passenger car, (m^2) and

A_i=Projected rectangular area of vehicle type i on the road, (m^2).

The speed ratio in Equation 4.1 depends on the composition of traffic stream as the speed of any vehicle varies with its own proportion and proportions of other vehicles in the stream. The second ratio is space ratio, which indicates the maneuverability of a vehicle with respect to passenger car.

The vehicle dimensions are already provided in Table 3.3. Accordingly, the data from the field observation on each section in chapter 3 were analysed and PCU values for each vehicle category present in the traffic stream of those sections were calculated using Equation 4.1 and presented in Table 4.1, 4.2 and 4-3 for two-lane, intermediate-lane and single-lane roads respectively.

The overall operating characteristics of traffic stream on two-lane and intermediate-lane roads are almost same and the major difference is the width of lanes. The traffic behavior on single-lane roads is different from that of two-lane and intermediate-lane roads. On single-lane roads vehicles arriving from both directions use only one lane and the width of the carriageway affects the driver performance and vehicle operation of different size and dimension. This is because there is very limited space available on carriageway and when traffic is streaming on both directions, one of the opposing vehicles is forced to leave the pavement and use the shoulder and this will extensively influence the speed of vehicles. For example a passenger car can cross a 3-wheeler with difficulty but both can use the carriageway while in case of a bus or any vehicle of greater dimension, the smaller vehicle is forced to use the shoulder and give room to the larger vehicle. To show this, two sections of two-lane and two sections of intermediate-lane roads, where the traffic composition was similar were selected and the mean PCU values of each vehicle category for both types of roads were calculated and compared. Further on, a z-test was carried out to assess the similarity of the PCU values for different vehicle categories obtained on each type of roads. The results are shown in Table 4.4 and Table 4.5. Also, the same test was carried out to compare the PCU values of different vehicles for two-lane and single-lane roads as well as intermediate-lane and single-lane roads which are presented in Table 4.6 and 4.7 respectively.

As it can be seen from the Table 4.4 and 4.5, the z-test values are all less than 1.96 at 95% confidence level for different vehicle categories on the subject sections. Such results imply the similarity of the compared PCU values. However, no such similarity was observed either for two-lane and single-lane or intermediate/and single-lane roads as indicated in Table 4.6 and 4.7. The Z values obtained from these comparisons were not significant. Therefore, it can be concluded that same PCU values may be applicable to motorized vehicles on intermediate and two-lane roads. Hence variation of PCU values with traffic volume and composition is studied for different sections of two lane roads as the vehicle interactions increase due to higher traffic volume on such roads and provides reliable results.

Table 4.1 PCU range of motorized vehicles on two-lane sections

Sec. ID	Vehicle Categories							
	BC	**2W**	**LCV**	**TK**	**MAV**	**3W**	**Bus**	**TT**
T-1	1.23– 3.07	0.20– 0.28	1.99– 2.91	3.03– 4.33	-	0.69– 1.42	3.68– 11.04	-
T-2	0.91– 2.18	0.19– 0.37	2.01– 4.70	2.86– 7.13	-	0.87-2.06	3.61-7.39	3.54 – 9.29
T-3	1.19 – 1.87	0.22 – 0.32	2.16 – 3.43	3.28 – 5.78	-	0.94 – 1.66	4.04 – 8.07	-
T-4	0.92 – 3.06	0.17 – 0.34	-	3.29 – 6.36	-	0.94 – 1.73	4.45 – 10.30	2.96 – 13.00
T-5	1.11 – 2.32	0.25 – 0.42	2.46 – 6.88	3.85 – 5.92	-	-	4.01 – 10.80	4.79 – 15.60
T-6	1.07 – 2.30	0.19 – 0.48	2.23 – 4.62	3.04 – 6.56	-	0.97 – 2.51	3.33 – 7.32	-
T-7	1.0 – 2.0	0.20 – 0.30	1.80 – 3.70	2.60 – 6.20	-	0.80 – 1.20	3.20 – 8.10	3.00 – 7.50
T-8	0.80 – 0.28	0.20 – 0.70	2.20 – 4.80	3.20 – 9.30	-	0.90 – 2.80	3.80 – 8.10	-
T-9	0.50 – 2.90	0.20 – 0.40	1.40 – 4.80	2.40 – 8.90	-	0.80 – 1.70	2.80 – 7.20	4.50 – 9.70
T-10	0.77 – 3.48	0.21 – 0.66	1.74 – 6.32	2.88 – 8.05	5.92 – 10.05	0.98 – 2.66	3.43 – 10.22	12.56 – 13.28
T-11	0.85 – 3.29	0.18 – 0.43	1.79 – 7.27	2.98 – 13.90	4.20 – 8.08	0.96 – 1.94	3.50 – 12.20	3.53 – 11.20
T-12	1.30 – 1.66	0.20 – 0.32	2.10 – 3.61	3.80 – 5.36	-	0.90 – 1.65	4.00 – 7.20	-
T-13	1.31 – 1.73	0.21 – 0.31	2.45 – 3.13	2.90 – 6.58	4.83 – 7.68	1.08 – 1.33	3.68 – 7.83	4.00 – 8.06
T-14	1.14 – 1.72	0.22 – 0.28	2.38 – 3.04	3.34 – 4.56	-	0.86 – 1.15	3.87 – 5.94	4.33 – 7.18
T-15	1.25 – 1.75	0.26 – 0.31	2.49 – 3.36	3.50 – 6.23		1.09 – 1.56	4.37 – 6.53	-

Table 4.2 PCU range of motorized vehicles on intermediate-lane sections

Section ID	Vehicle Category							
	BC	**2W**	**LCV**	**TK**	**3W**	**MAV**	**Bus**	**TT**
I-1	0.96 – 3.39	0.17 - 0.32	2.12 – 4.17	2.55 – 8.64	0.66 – 1.06	-	4.38 – 7.03	-
I-2	0.90 – 2.65	0.20 – 0.40	2.20 – 4.30	2.90 – 5.97	0.90 – 1.51	-	-	4.30 – 11.67
I-3	1.16 – 1.80	0.20 – 0.36	1.74 – 7.52	3.25 – 6.24	0.63 – 1.35	-	3.53 – 8.01	2.81 – 8.22
I-4	1.10 – 1.90	0.20 – 0.38	2.0 – 5.43	3.0 – 8.14	0.90 – 3.20	-	4.50 – 8.16	-
I-5	-	0.16 – 0.40	-	-	0.58 – 1.46	-	2.83 – 6.34	-
I-6	0.66 – 2.03	0.14 – 0.43	1.49 – 3.91	1.90 – 5.83	0.54 – 1.71	-	3.34 – 12.08	2.52 – 9.23
I-7	1.20 – 1.82	0.20 – 0.34	1.90 – 3.82	2.60 – 5.26	0.80 – 1.90	-	2.80 – 6.19	3.0 – 9.09

Table 4.3 PCU range of motorized vehicles on single-lane sections

Sec. ID.	Vehicle Category						
	TT	**Bus**	**3W**	**TK**	**LCV**	**2W**	**BC**
S-1	-	-	0.65– 1.56	2.64 – 4.02	1.89 – 5.58	0.16 – 0.32	0.93 – 1.94
S-2	-	3.44 – 7.04	0.67 – 1.29	1.57 – 4.95	1.99 – 5.04	0.16 – 0.30	1.02 – 2.30
S-3	4.51 – 10.24	-	0.62 – 1.86	2.10 – 7.61	1.69- 5.69	0.16 – 0.39	0.72 – 3.16
S-4	-	-	-	-	-	0.20 – 0.34	1.03 – 1.87
S-5	4.12 – 10.24	-	0.79 – 1.85	2.95 – 8.36	1.69- 5.69	0.18 – 0.32	0.74 – 3.12

Table 4.4 z test 1 for PCU values for two and intermediate-lane roads

Data	**Section type/name**	**Vehicle Categories**						
		2W	**3W**	**BC**	**LCV**	**TK**	**BUS**	**TT**
Traffic Composition (%)	Two-lane/T-4	31.02	0.16	14.22	3.07	11.05	9.50	3.45
	Intermediate-lane/I-3	37.46	0.71	16.19	3.66	11.22	6.82	0.74
Number of observations	T-4	45	6	46	34	45	45	36
	I-3	47	19	47	37	47	45	14
Average PCU	T-4	0.28	1.24	1.59	3.39	4.38	5.83	7.94
	I-3	0.28	0.94	1.49	3.37	4.57	5.55	6.27
Standard Deviation	T-4	0.04	0.23	0.21	0.87	0.61	0.94	1.51
	I-3	0.4	0.19	0.15	1.09	0.67	0.93	4.08
Degree of Freedom $(n_{T-4} + n_{I-3} - 2)$	-	90	19	91	69	90	88	48
Z	-	**-0.13**	**1.93**	**1.71**	**0.09**	**-1.44**	**1.05**	**1.23**

Table 4.5 z test 2 for PCU values for two and intermediate-lane roads

Data	Section type/name	Vehicle Categories					
		2W	**3W**	**BC**	**LCV**	**TK**	**BUS**
Traffic Composition (%)	Two-lane/T-3	34.37	6.02	10.89	8.64	12.49	3.82
	Intermediate-lane/I-4	41.47	3.75	14.29	3.25	18.24	2.23
Number of observations	T-3	74	74	73	74	74	71
	I-4	46	34	45	28	46	22
Average PCU	T-3	0.27	1.23	1.50	2.83	4.40	5.25
	I-4	0.26	1.33	1.55	3.21	4.25	5.85
Standard Deviation	T-3	0.02	0.14	0.16	0.29	0.46	0.73
	I-4	0.05	.39	0.21	0.57	0.95	1.08
Degree of Freedom $(n_{T-3} + n_{I-4} - 2)$	-	118	106	116	100	118	91
Z	-	**0.10**	**-1.44**	**-1.17**	**-1.46**	**0.99**	**-1.92**

Table 4.6 z test for PCU values for two and single-lane roads

Data	**Section type/name**	**Vehicle Categories**					
		2W	**3W**	**BC**	**LCV**	**TK**	**TT**
Traffic Composition (%)	Two-lane/T-7	56.34	28.06	1.50	3.07	1.81	1.23
	Single-lane/S-3	59.71	6.49	1.62	3.39	1.50	0.95
Number of observations	T-7	44	44	32	42	38	26
	S-3	76	63	43	57	31	31
Average PCU	T-7	0.24	0.96	1.45	2.59	3.85	5.21
	S-3	0.23	0.94	1.46	2.66	4.95	5.3
Standard Deviation	T-7	0.02	0.12	0.27	0.46	0.74	0.91
	S-3	0.03	0.24	0.39	0.69	1.22	1.70
Degree of Freedom $(n_{T-7} + n_{S-3} - 2)$	-	118	105	73	97	67	55
Z	-	**-4.57**	**-7.53**	**-2.06**	**-3.05**	**-2.29**	**-6.97**

Table 4.7 z test for PCU values for intermediate and single-lane roads

Data	Section type/name	Vehicle Categories					
		2W	**3W**	**BC**	**LCV**	**TK**	**TT**
Traffic Composition (%)	Intermediate-lane/I-2	60.56	1.06	5.0	7.26	8.37	1.78
	Single-lane/S-5	68.26	3.4	2.23	4.62	1.40	1.60
Number of observations	I-2	46	43	43	46	47	28
	S-5	32	18	61	79	47	43
Average PCU	I-2	0.31	1.19	1.51	3.24	3.66	7.6
	S-5	0.26	1.29	1.58	2.90	4.42	6.85
Standard Deviation	I-2	0.04	0.21	0.30	0.48	0.65	1.98
	S-5	0.03	0.15	0.39	0.68	0.61	1.71
Degree of Freedom $(n_{\mathrm{I-3}} + n_{\mathrm{S-5}} - 2)$	-	138	59	102	123	92	69
Z	-	**7.0**	**-2.01**	**-1.025**	**3.22**	**-5.80**	**1.58**

4.2.2 PCU Value for Non-Motorized Vehicles

Edquist et al. (2009) stated that presence of other road users like bicycles influence the drivers' choice of speed. At some sections, non-motorized vehicles like bicycles, cycle rickshaws and animal driven karts (vehicles) were also observed. Such vehicles usually drive on the side of the pavement and have very negligible speed variation. Since the number of these vehicles are very less in number it was decided to provide single PCU values for such vehicles in Table 4.8, 4.9 and 4.10 for two-lane, intermediate-lane and single-lane roads respectively.

Table 4.8 PCU values for non-motorized vehicles on two-lane roads

Vehicle category	Cycle	Rickshaw	ADV
PCU factor	0.67	2.53	12.3

Table 4.9 PCU values for non-motorized vehicles on Intermediate-lane roads

Vehicle category	Cycle	Rickshaw	ADV
PCU factor	0.51	2.18	10.64

Table 4.10 PCU values for non-motorized vehicles on Single-lane roads

Vehicle category	Cycle	Rickshaw	ADV
PCU factor	0.42	1.45	10.20

4.2.3 Development of Speed Equations

It is understood that the speed of a particular vehicle type will be influenced to different extents by the vehicles of different categories on the road. For a given road, the geometric features like cross-section, lane width, gradient, curvature, road surface conditions remain unaltered during the period of data collection. Therefore, traffic volume and its composition must be able to explain the variation in speed (or PCU factors) for a vehicle type. Speed of a vehicle type is modeled with volume and speed of different categories of vehicles on the road. As such, as many equations can be written as the number of vehicle categories present in the traffic stream. For a traffic stream consisting of 4 vehicle categories like standard cars (SC), motorized two wheelers (2W), heavy vehicles (HV) and three wheelers (3W), the four simultaneous equations for evaluating speed of these vehicles will be as given below.

$$V_{SC} = a_{0-SC} - a_{1-SC}\left(\frac{n_{SC}}{V_{SC}}\right) - a_{2-SC}\left(\frac{n_{2W}}{V_{2W}}\right) - a_{3-SC}\left(\frac{n_{HV}}{V_{HV}}\right) - a_{4-SC}\left(\frac{n_{3W}}{V_{3w}}\right) \qquad 4.2)$$

$$V_{2W} = a_{0-2W} - a_{1-2W}\left(\frac{n_{SC}}{V_{SC}}\right) - a_{2-2W}\left(\frac{n_{2W}}{V_{2W}}\right) - a_{3-2W}\left(\frac{n_{HV}}{V_{HV}}\right) - a_{4-2W}\left(\frac{n_{3W}}{V_{3w}}\right) \qquad (4.3)$$

$$V_{HV} = a_{0-HV} - a_{1-HV}\left(\frac{n_{SC}}{V_{SC}}\right) - a_{2-HV}\left(\frac{n_{2W}}{V_{2W}}\right) - a_{3-HV}\left(\frac{n_{HV}}{V_{HV}}\right) - a_{4-HV}\left(\frac{n_{3W}}{V_{3w}}\right) \qquad (4.4)$$

$$V_{3W} = a_{0-3W} - a_{1-3W}\left(\frac{n_{SC}}{V_{SC}}\right) - a_{2-3W}\left(\frac{n_{2W}}{V_{2W}}\right) - a_{3-3W}\left(\frac{n_{HV}}{V_{HV}}\right) - a_{4-3W}\left(\frac{n_{3W}}{V_{3w}}\right) \qquad (4.5)$$

Where

V = Speed of a vehicle (m/sec)

n = Number of vehicles crossing the measurement point per second (veh/sec), and SC, 2W, HV and 3W represent different vehicle categories in the traffic stream.

The variable $\frac{n_i}{v_i}$ in the above equation represents 5 minute average density of ith category of the vehicles on the road and hence all coefficients except the constant term are expected to be negative. While a_{0-i}, the constant, is considered as the free-flow speed of the vehicle category i, a_{j-i} represents the jth coefficient obtained regressing the speed of ith vehicle category with the densities of all vehicle categories. (j varies with the number of vehicle categories). For each of the sites, classified count of vehicles entering and exiting the trap in 5 minute period provided the information on traffic volume. The speed of each vehicle included in the count was estimated by measuring the time taken by the vehicle to cover the total trap length through frame by frame analysis of the video. The traffic count (n_i) and vehicular speed (v_i) data were used to determine the coefficients in speed equations using regression analysis.

Development of speed equations requires that all categories of vehicles are present in good proportions (at least 8-10 percent) so that independent variables do not get the zero values (in a 5-minute count period) very frequently. It may require grouping of vehicle categories of similar operational characteristics whose proportion in the traffic stream is less than 5 percent. For example, at the section of NH-47, seven vehicle categories are present with individual proportion of truck and bus being less than 8 percent. Therefore, these two categories are grouped together as heavy vehicles (HV). Similarly, big cars are merged with standard car and LCV with 3-wheeler to have four broad vehicle categories at this section.

Therefore the four speed equations for section T-1 developed through linear regression analysis are as given below.

$$V_{SC} = 17.09 - 69.87\left(\frac{n_{SC}}{V_{SC}}\right) - 61.06\left(\frac{n_{2W}}{V_{2W}}\right) - 194.89\left(\frac{n_{HV}}{V_{HV}}\right) - 37.47\left(\frac{n_{3W}}{V_{3w}}\right) \quad (4.6)$$

$$V_{2W} = 13.59 - 39.51\left(\frac{n_{SC}}{V_{SC}}\right) - 19.39\left(\frac{n_{2W}}{V_{2W}}\right) - 57.19\left(\frac{n_{HV}}{V_{HV}}\right) - 3.35\left(\frac{n_{3W}}{V_{3w}}\right) \quad (4.7)$$

$$V_{HV} = 14.69 - 8.91\left(\frac{n_{SC}}{V_{SC}}\right) - 48.45\left(\frac{n_{2W}}{V_{2W}}\right) - 183.77\left(\frac{n_{HV}}{V_{HV}}\right) - 73.16\left(\frac{n_{3W}}{V_{3w}}\right) \quad (4.8)$$

$$V_{3W} = 12.32 - 32.80\left(\frac{n_{SC}}{V_{SC}}\right) - 3.91\left(\frac{n_{2W}}{V_{2W}}\right) - 62.89\left(\frac{n_{HV}}{V_{HV}}\right) - 43.61\left(\frac{n_{3W}}{V_{3w}}\right) \quad (4.9)$$

All coefficients are obtained with negative signs which indicate that speed decreases with increase in volume (or density). Similarly, equations for section T-12 with 5 categories of vehicles after combining bus and truck into a single category of HV and 3W and LCV into the category of LCV are given below.

$$V_{SC} = 19.24 - 73.38\left(\frac{n_{SC}}{V_{SC}}\right) - 38.00\left(\frac{n_{BC}}{V_{BC}}\right) - 0.41\left(\frac{n_{2W}}{V_{2W}}\right) - 29.11\left(\frac{n_{LCV}}{V_{LCV}}\right) - 60.54\left(\frac{n_{HV}}{V_{HV}}\right) \quad (4.10)$$

$$V_{BC} = 20.45 - 42.54\left(\frac{n_{SC}}{V_{SC}}\right) - 113.14\left(\frac{n_{BC}}{V_{BC}}\right) - 15.07\left(\frac{n_{2W}}{V_{2W}}\right) - 0.07\left(\frac{n_{LCV}}{V_{LCV}}\right) - 73.01\left(\frac{n_{HV}}{V_{HV}}\right) \quad (4.11)$$

$$V_{2W} = 18.50 - 60.98\left(\frac{n_{SC}}{V_{SC}}\right) - 0.11\left(\frac{n_{BC}}{V_{BC}}\right) - 105.24\left(\frac{n_{2W}}{V_{2W}}\right) - 62.85\left(\frac{n_{LCV}}{V_{LCV}}\right) - 37.61\left(\frac{n_{HV}}{V_{HV}}\right) \quad (4.12)$$

$$V_{LCV} = 21.21 - 24.48\left(\frac{n_{SC}}{V_{SC}}\right) - 38\left(\frac{n_{BC}}{V_{BC}}\right) - 0.33\left(\frac{n_{2W}}{V_{2W}}\right) - 31.72\left(\frac{n_{LCV}}{V_{LCV}}\right) - 61.55\left(\frac{n_{HV}}{V_{HV}}\right) \quad (4.13)$$

$$V_{HV} = 15.38 - 18.01\left(\frac{n_{SC}}{V_{SC}}\right) - 4.55\left(\frac{n_{BC}}{V_{BC}}\right) - 0.24\left(\frac{n_{2W}}{V_{2W}}\right) - 54.06\left(\frac{n_{LCV}}{V_{LCV}}\right) - 84.95\left(\frac{n_{HV}}{V_{HV}}\right) \quad (4.14)$$

All coefficients are found to be significant based on their "t" values. Similar speed equations can be developed for other sites also. It is observed that the speed equations for different categories of vehicles obtained for all study locations look similar, but the coefficient values are different at different sites. It shows that the speed of a vehicle type would depend on the number and type of vehicle categories present on a section.

4.2.4 Variation in PCU with Traffic Composition and Volume

The PCU value is the amount of interaction caused by a particular vehicle type to the traffic stream of passenger cars. This interaction will be different at different traffic volume levels. It will change with composition of the traffic stream as well. Therefore, speed equations given above are solved for different compositions of traffic stream keeping total volume (N) on the road at a predefined value and also for different values of traffic volume having same composition of traffic stream. Figure 4.1 and 4.2 show the variation in speed of 2W and SC with variation in traffic volume and composition of 2W and 3W respectively. Proportions of 2W and 3W are varied in a complimentary manner while proportion of SC and HV are kept at constant values. Traffic volume is varied from 1000 veh/hr to 3000 veh/hr in a step of 500 veh/hr to generate different curves in Figure 4.1 and Figure 4.2. It is observed that for a given traffic volume, variation in speed of 2W and SC are almost equal. The influence of increase in the proportion of 2W in the traffic stream on speed of cars or 2W is very marginal. However, the speed of these two types of vehicles reduces considerably with the increase in the traffic volume on the road. Therefore, PCU for 2W is more affected by traffic volume (Figure 4.4 and 4.5) than by traffic composition (Figure 4.3) as they are less sensitive to traffic conditions (Terdsak and Chanong 2005), and able to move abreast any other vehicle (Arasan and Koshy 2005).

Figures 4.6 to 4.10 show the speed and PCU variation for 3W by displaying the 3W proportions against 2W. It should be noted that the proportions of 3W and 2W are varied in a complimentary manner. It means increase in the proportion of 3W in the traffic stream is associated with decrease in the proportion of 2W by the same amount. The physical size of 3W is more than that of a 2W but their operating conditions are poorer than those of standard cars. Therefore for a given traffic volume, increase in the proportion of 3W (and corresponding decrease in the proportion of 2W) will create more congestion. 3W due to their poorer operating conditions will be affected more by their congestions than the standard cars. It can be seen from Figure 4.6 and 4.7 that within a given volume, the speed of 3W shows more change than standard cars and as a result, as per Equation 4.1, the PCU value for 3W shows increasing trend with traffic composition in Figure 4.9. On the other hand the overall increase in traffic volume level creates different effect on the PCU values for 3W. As the increase in the traffic volume affects both 3W and standard cars, the individual standard car having more accelerating and operating capabilities will be affected more compared to a slow-built 3W. Hence as displayed in Figure 4.6 and 4.7, the speed drop for each step increase in traffic volume is more than that of a 3W and as per Equation 4.1, the PCU values for 3W show decreasing trend in Figure 4.8. The combined effect of both traffic volume and composition is displayed in Figure 4.10.

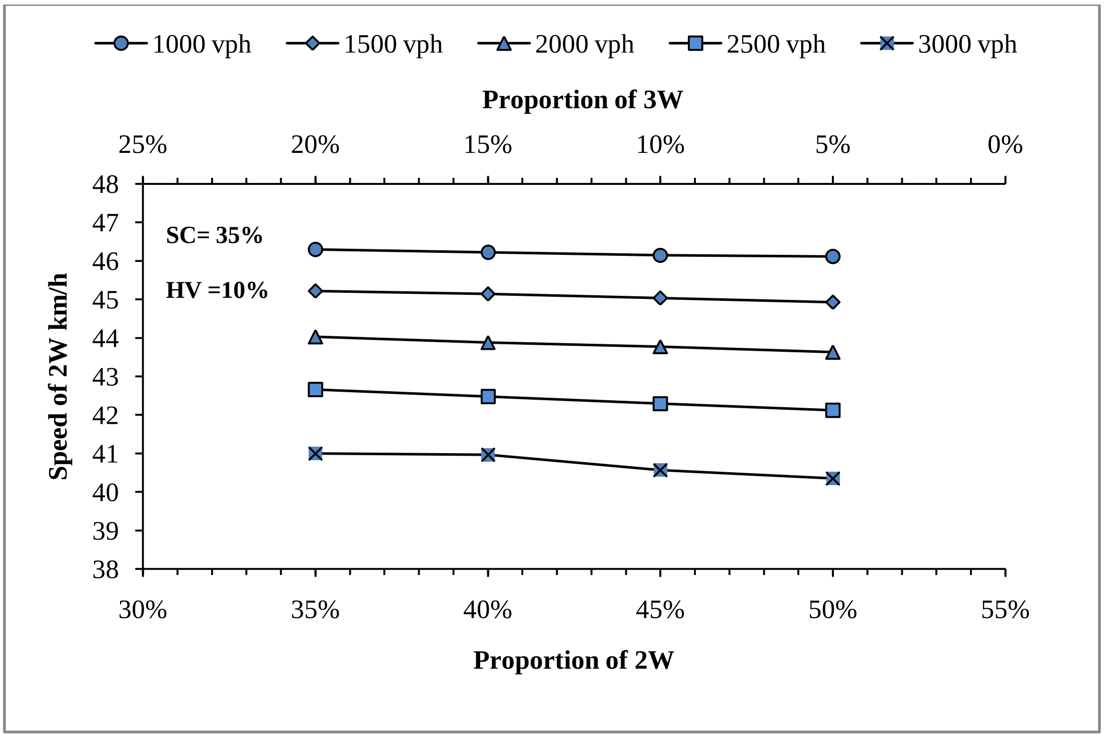


Figure 4.1 Variation in speed of 2W with traffic volume and composition on T-1

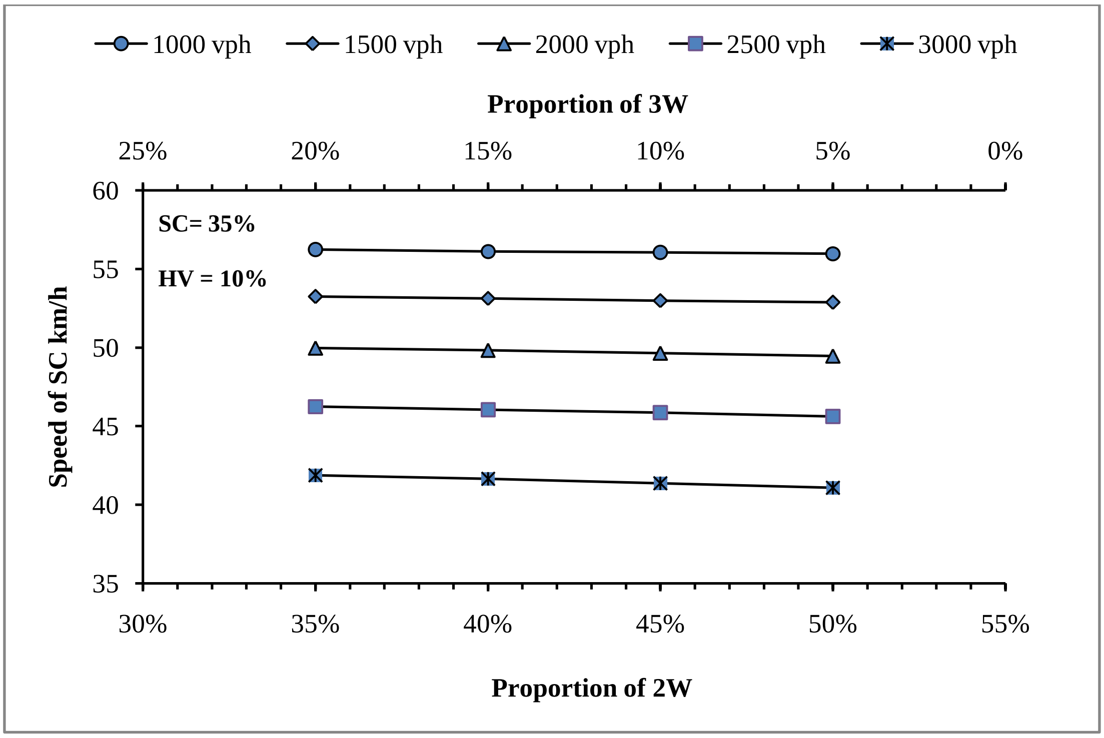


Figure 4.2 Variation in speed of SC with traffic volume and composition of 2W on T-1

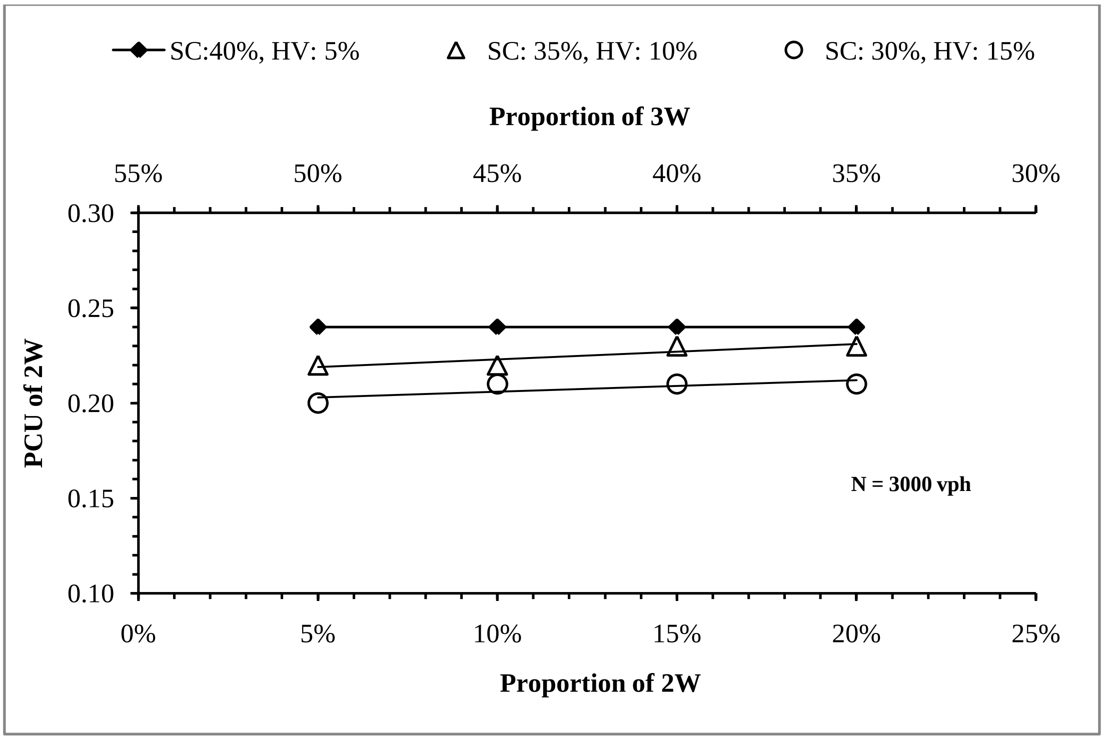


Figure 4.3 Variations in PCU of 2W with Traffic Composition on T-1

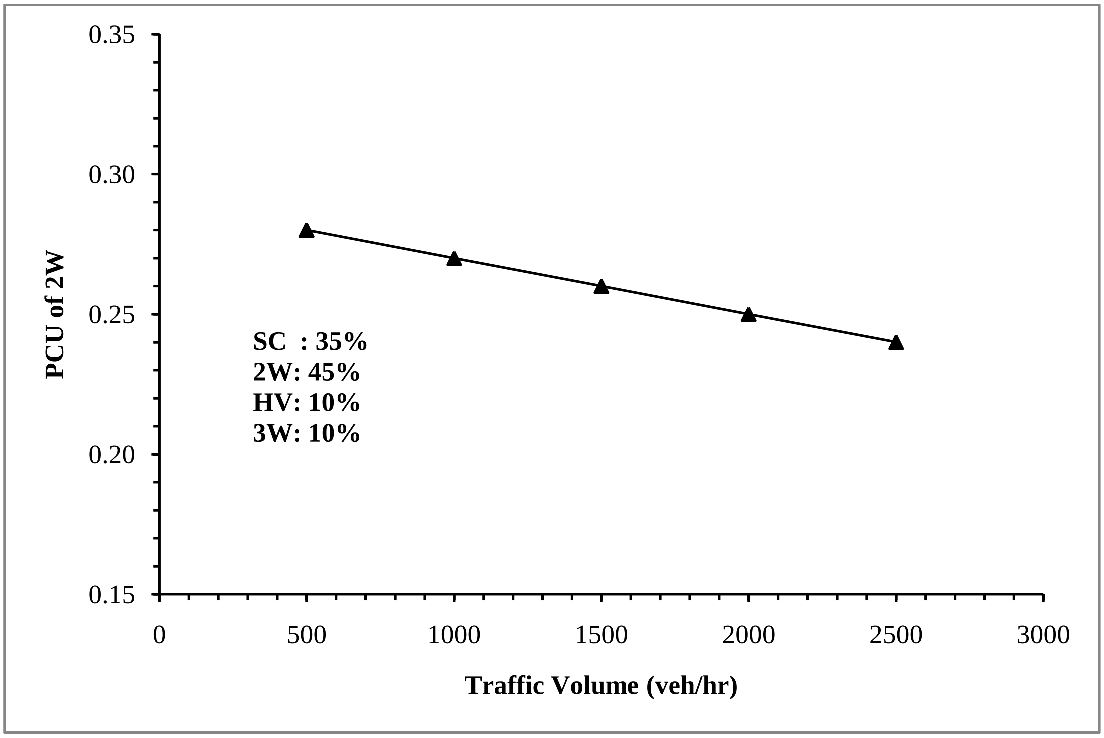


Figure 4.4 Variations in PCU of 2W with Traffic Volume on T-1

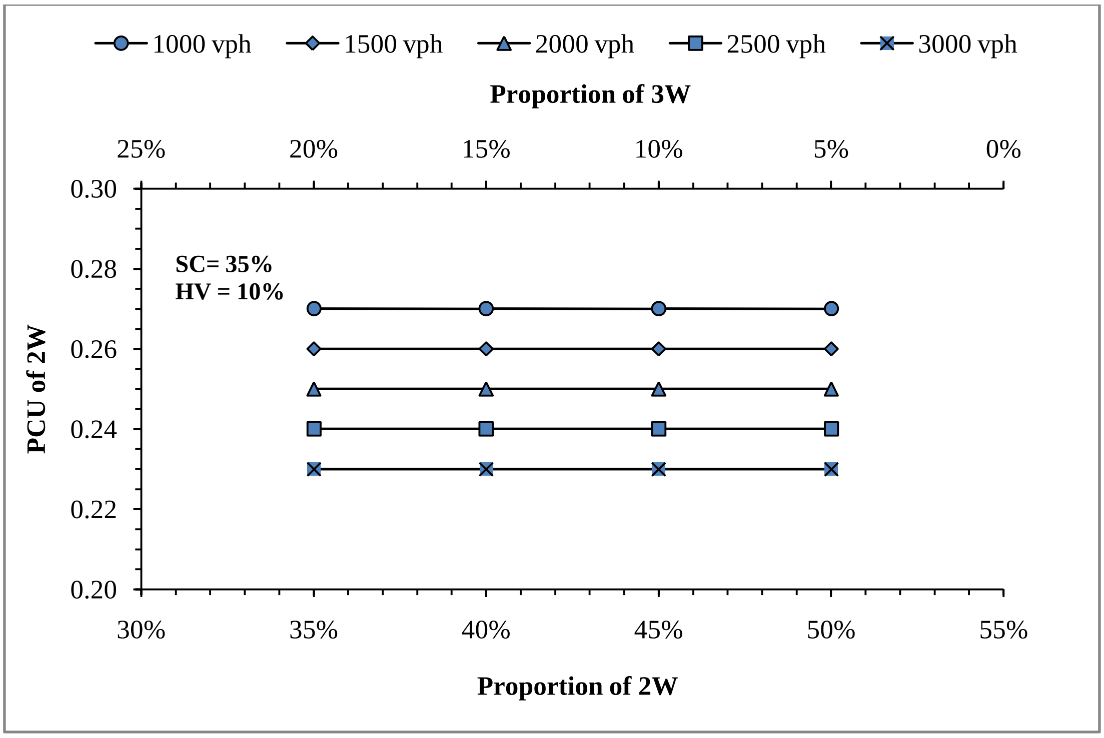


Figure 4.5 Variation in PCU of 2W with traffic volume and composition on T-1

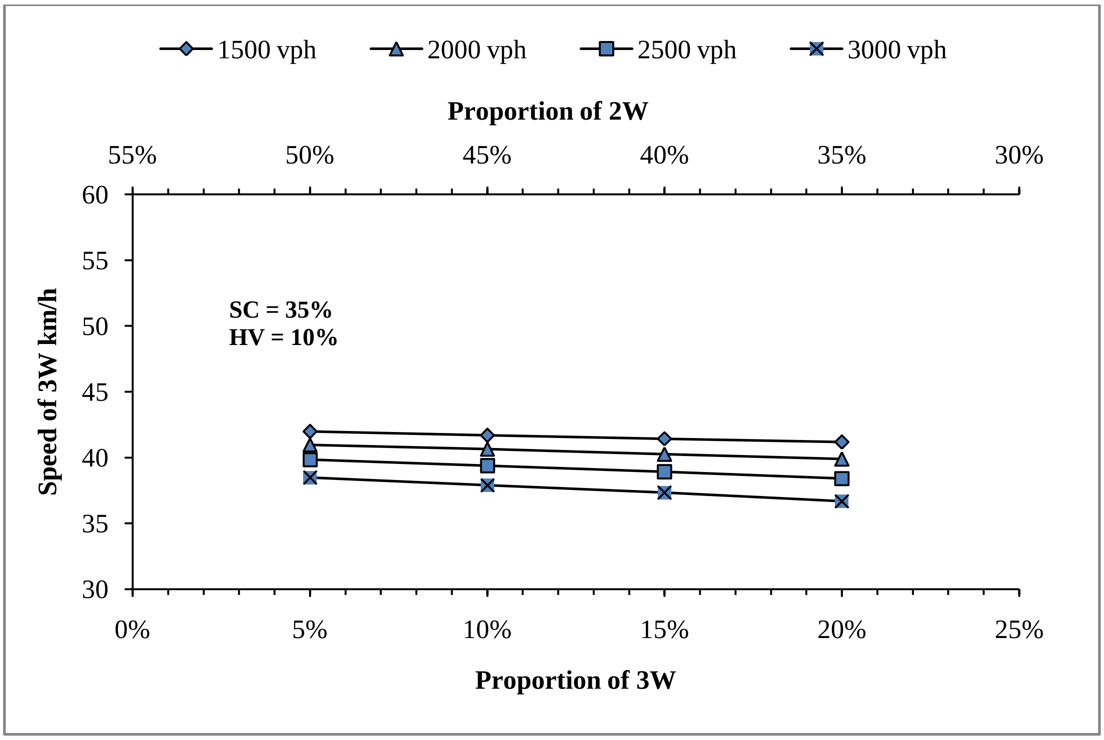


Figure 4.6 Variation in speed of 3W with traffic volume and composition on T-1

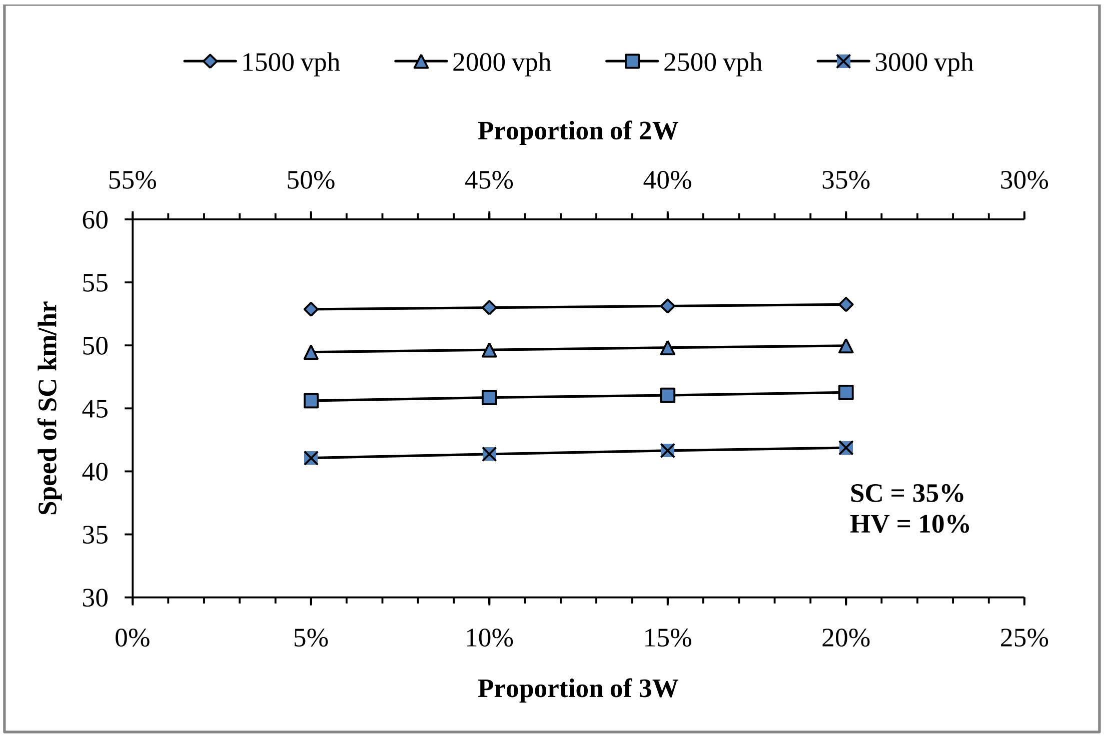


Figure 4.7 Variation in speed of SC with traffic volume and composition corresponding to 3W on T-1

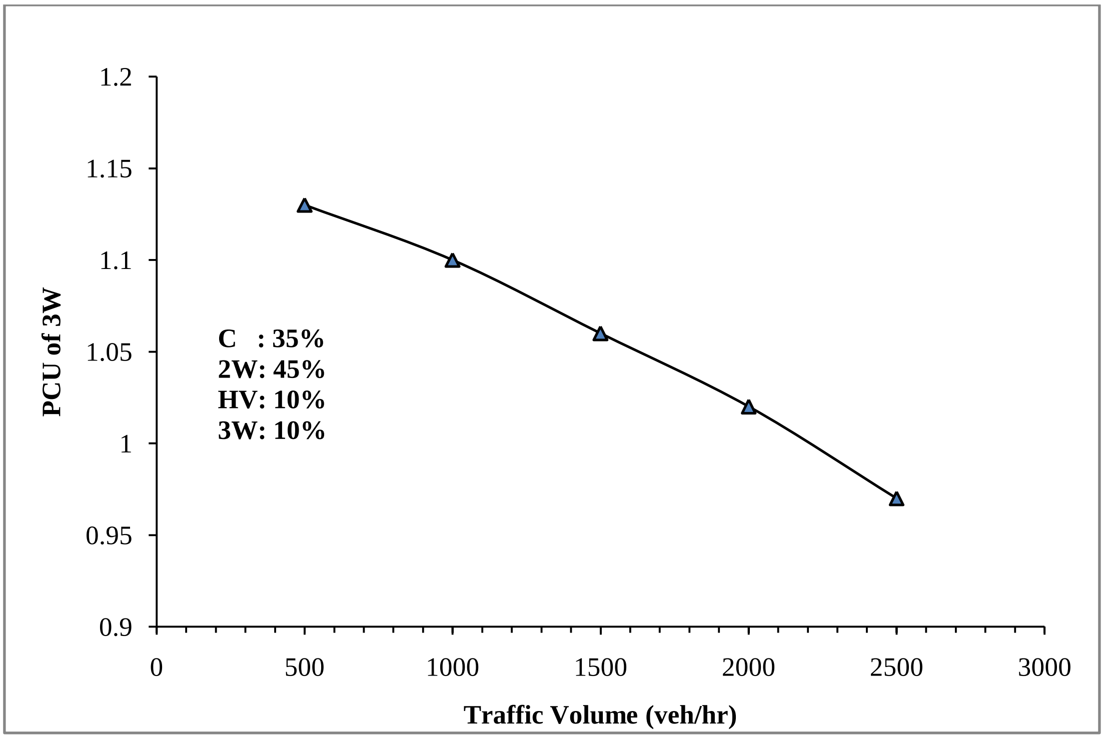


Figure 4.8 Variation in PCU of 3W with traffic Volume on T-1

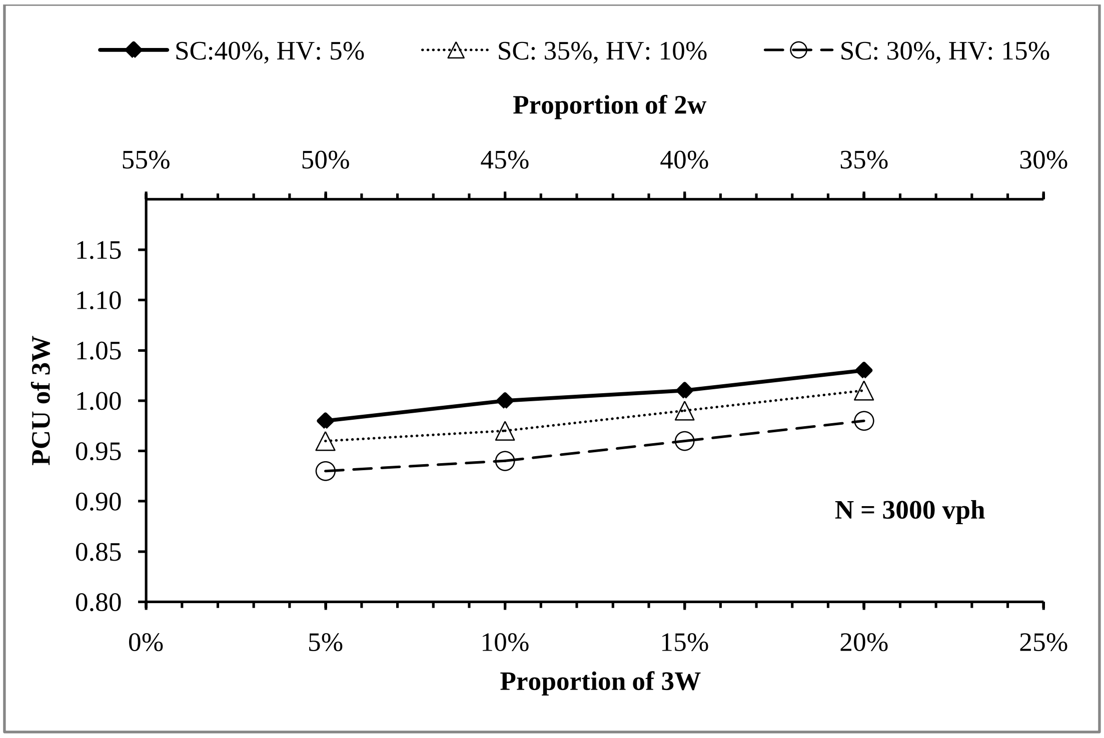


Figure 4.9 Variation in PCU of 3W with traffic composition on T-1

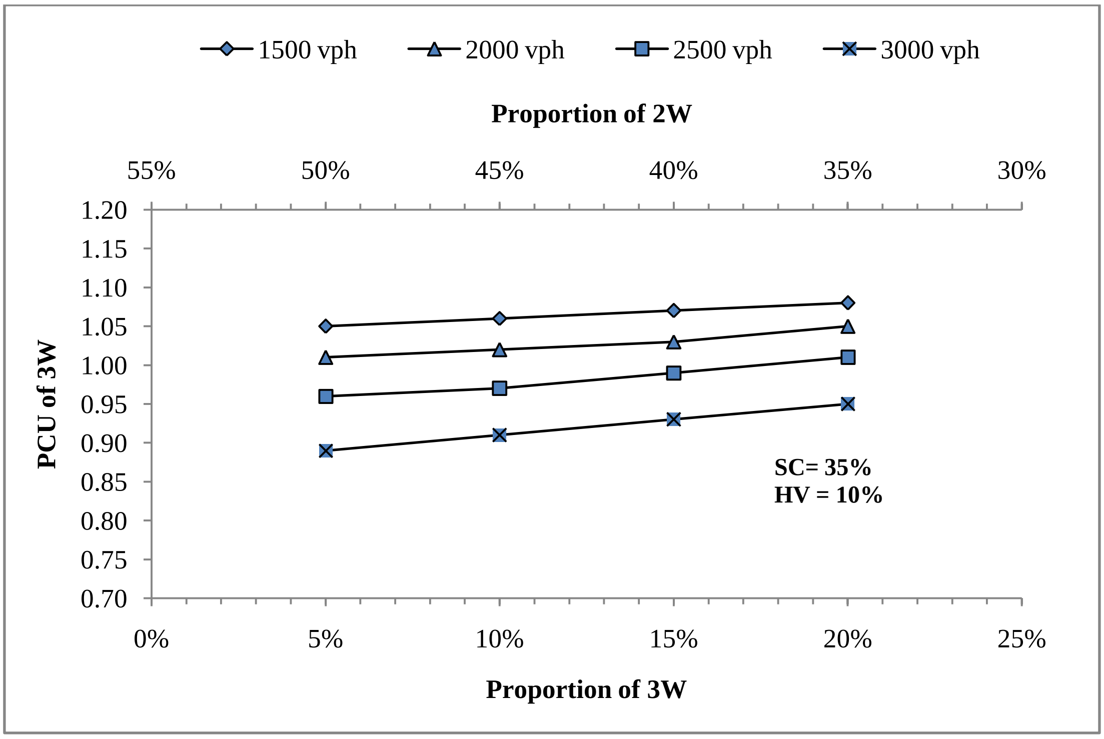


Figure 4.10 Variation in PCU of 3W with traffic volume and composition on T-1

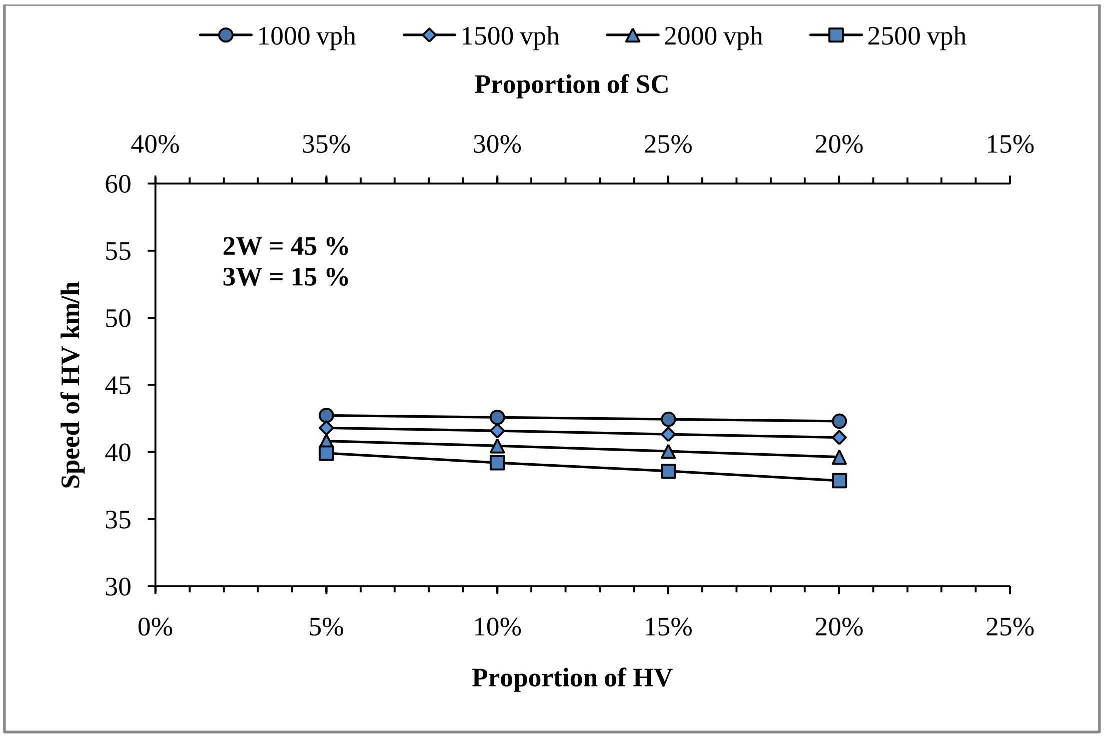


Figure 4.11 Variation in speed of HV with traffic volume and composition on T-1

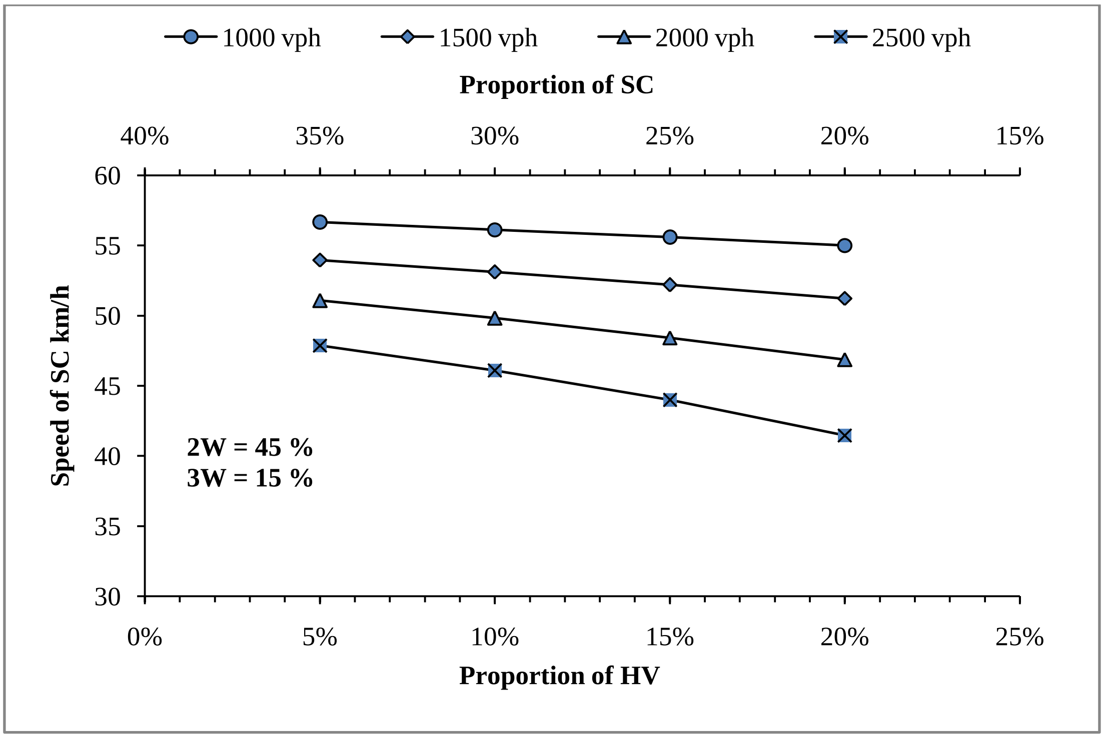


Figure 4.12 Variation in Speed of SC with traffic volume and composition on T-1

At lower volume levels, the opportunity of overtaking for HV using the adjacent lane has higher possibility. However, at higher volume levels, as the number of HV increases in the traffic stream, both directions on a two lane road are affected. HV being the largest among all other vehicle categories fully occupies a lane, and the average speed of all vehicles in the traffic is inevitably forced to be adjusted to HV movement speed. Operational capability of HV is limited and provided high traffic volume is present on the section, the average speed of HV will reduce. But since this reduction takes place in traffic stream which is following trucks as main impediments, the PCU values of trucks are not much affected by traffic volume and hence Figure 4.13 shows only slight reduction in PCU versus volume. On the other hand as it can be seen in Figure 4.12, for a given increase in proportion of HV, the reduction in speed of SC is more than that of HV. This will result in higher PCU values for HV as it is displayed in Figures 4.14 and 4.15.

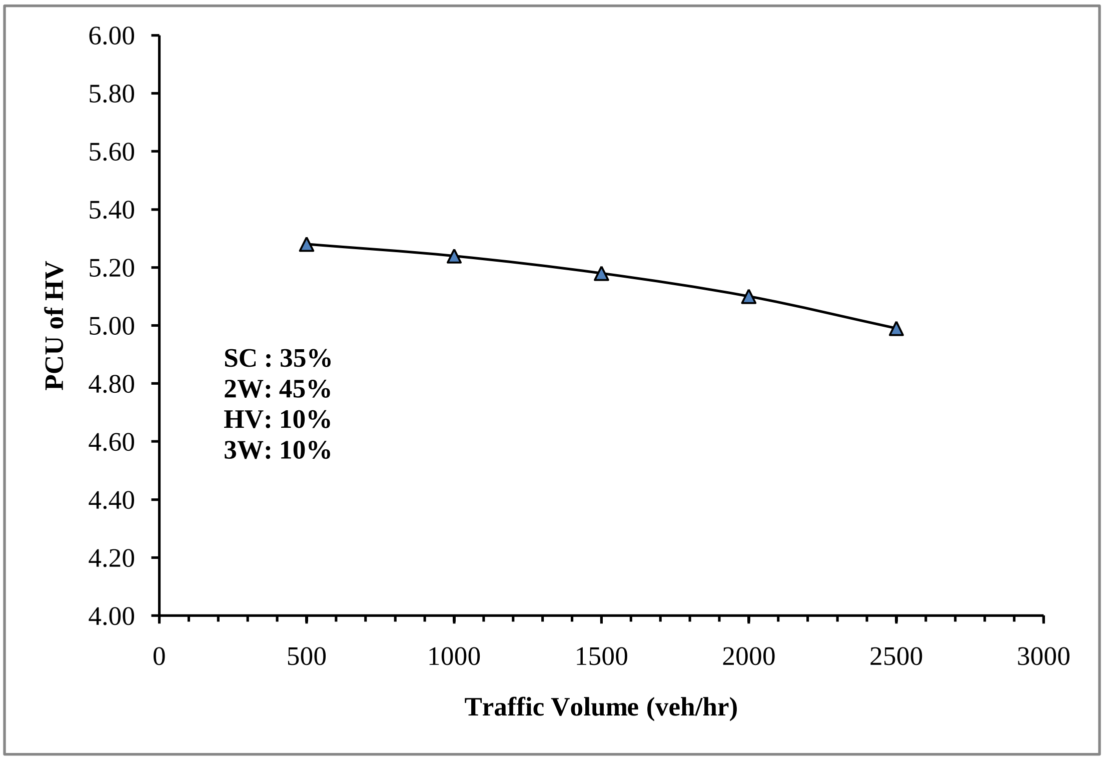


Figure 4.13 Variation in PCU of HV with traffic volume on T-1

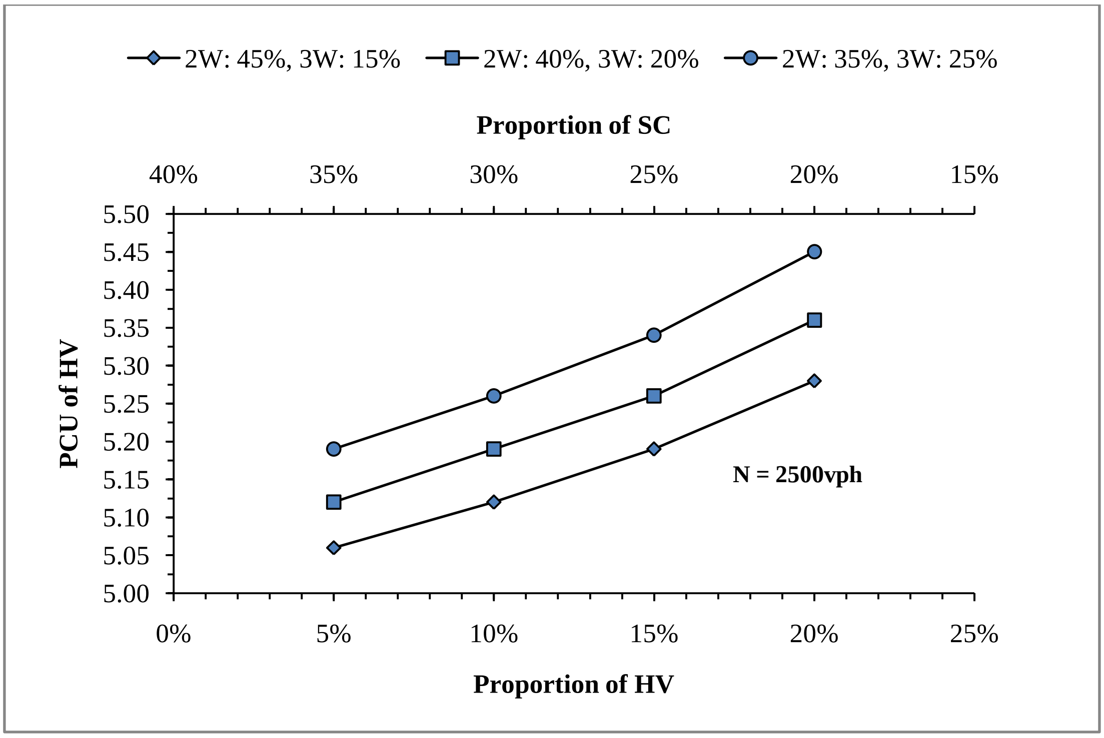


Figure 4.14 Variation in PCU of HV with traffic composition on T-1

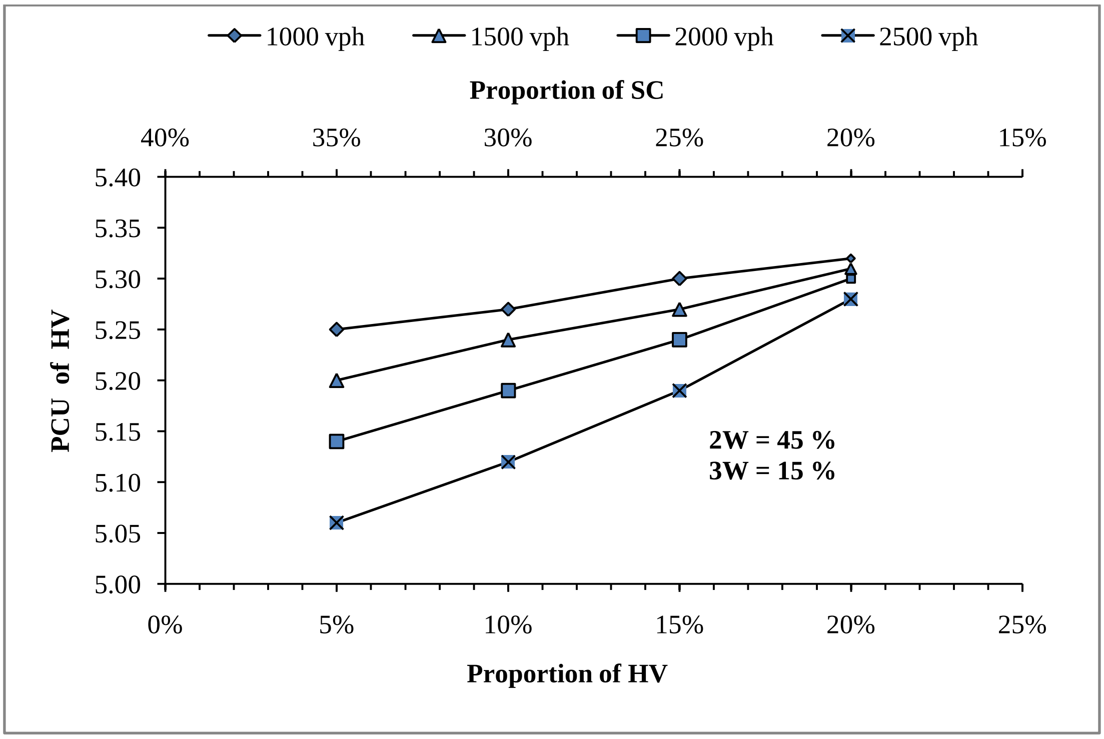


Figure 4.15 Variation in PCU of HV with traffic volume and composition on T-1

A few curves displaying the PCU of BC and LCV on another site (T-12) are plotted in Figure 4.16 to Figure 4.24. As may be seen, the trend of PCU variation is similar to that reported on T-12.

Since the engine power of BC is higher than that of SC, such vehicles drive generally faster than standard car and hence in Figure 4.16 higher values for speed of BC is displayed comparing to speed values of SC in Figure 4.17. With the increase in the traffic volume, as well as the proportion of BC in the traffic stream, due to the larger size of this vehicle type, the reduction in speed of BC will be higher than that of SC. Figure 4.18 displays the effect of variation in traffic volume on PCU of BC. So, although the speed of SC decrease with increase in traffic volume and proportion of BC, due to higher reduction in speed of BC, speed differential between the two increases and therefore PCU values for BC shows increasing trend in Figure 4.19. The combined effect of variation in traffic volume and composition is displayed in Figure 4.20.

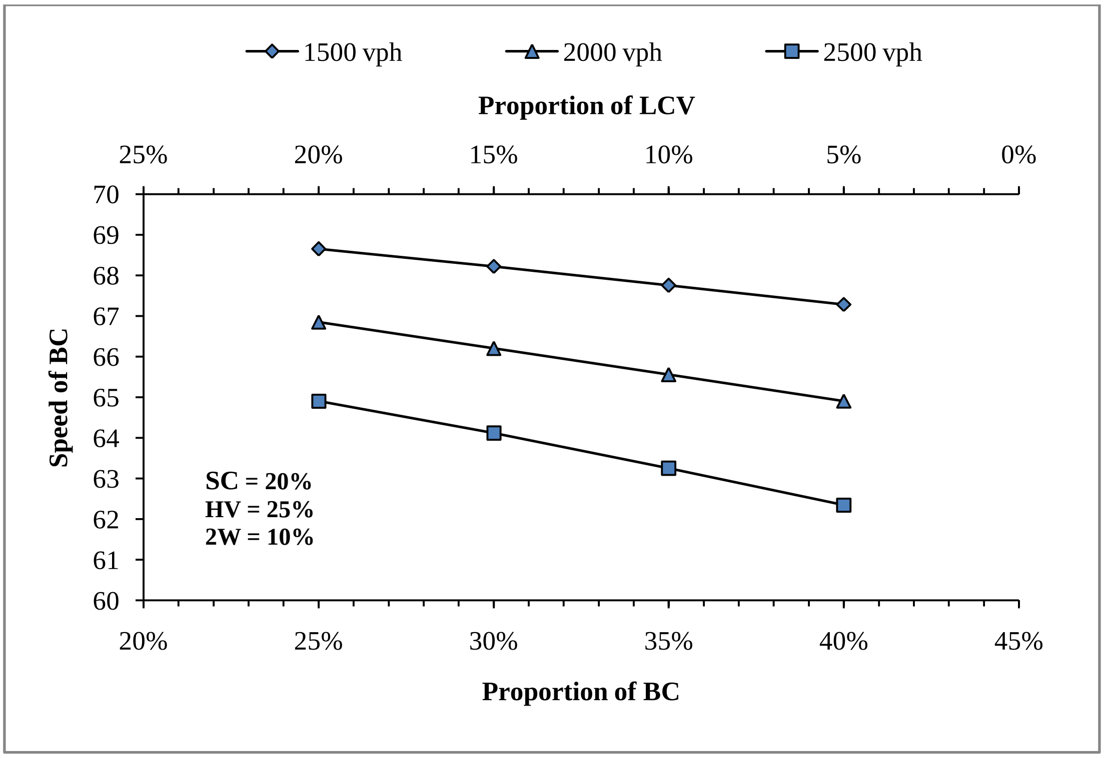


Figure 4.16 Variation in Speed of BC with traffic volume and composition on T-12

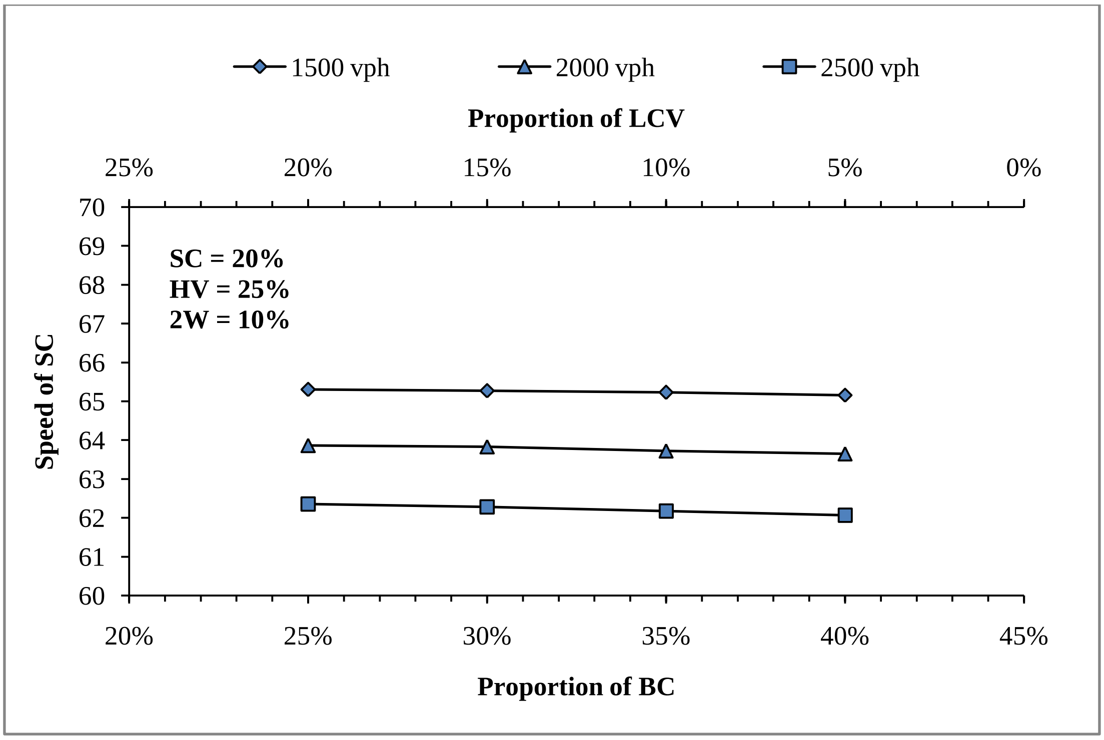


Figure 4.17 Variation in speed of SC with traffic volume and composition corresponding to BC on T-12

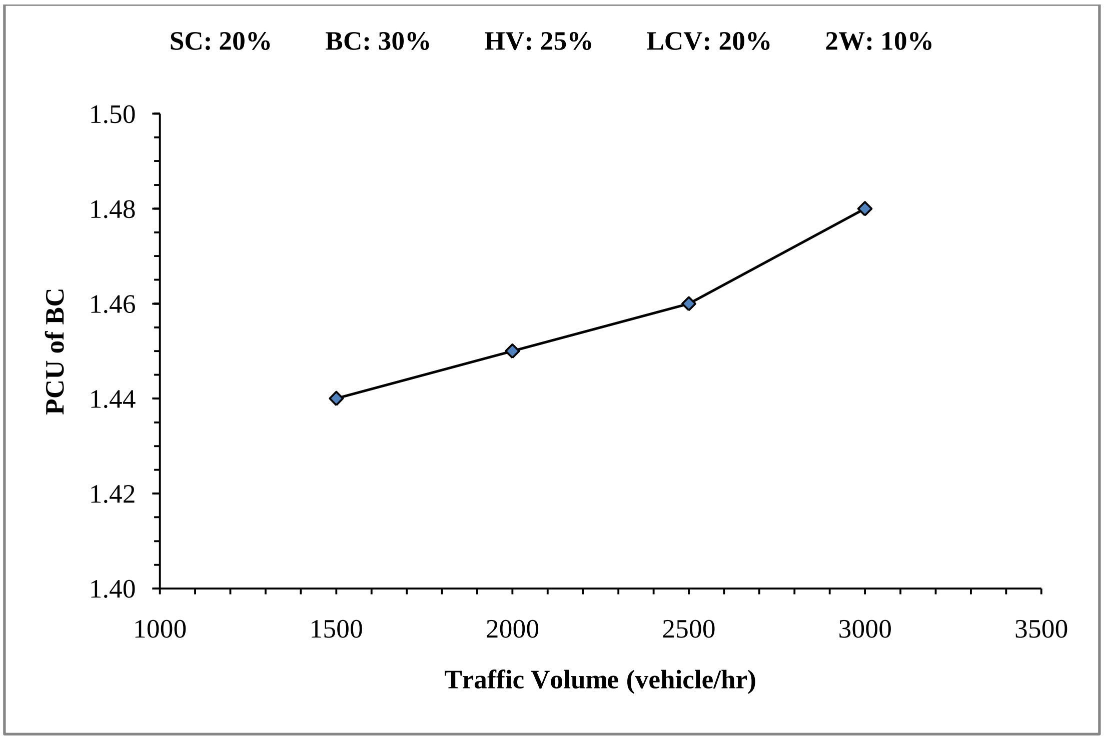


Figure 4.18 Variation in PCU of BC with traffic Volume on T-12

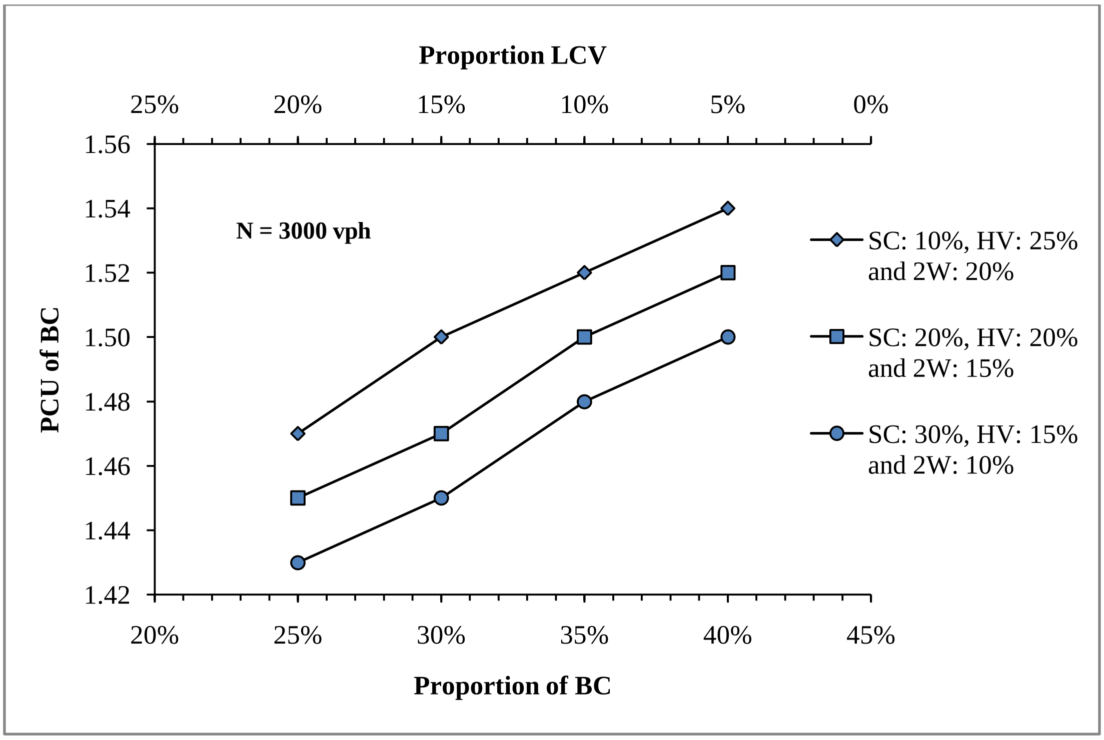


Figure 4.19 Variations in PCU of BC with Traffic Composition on T-12

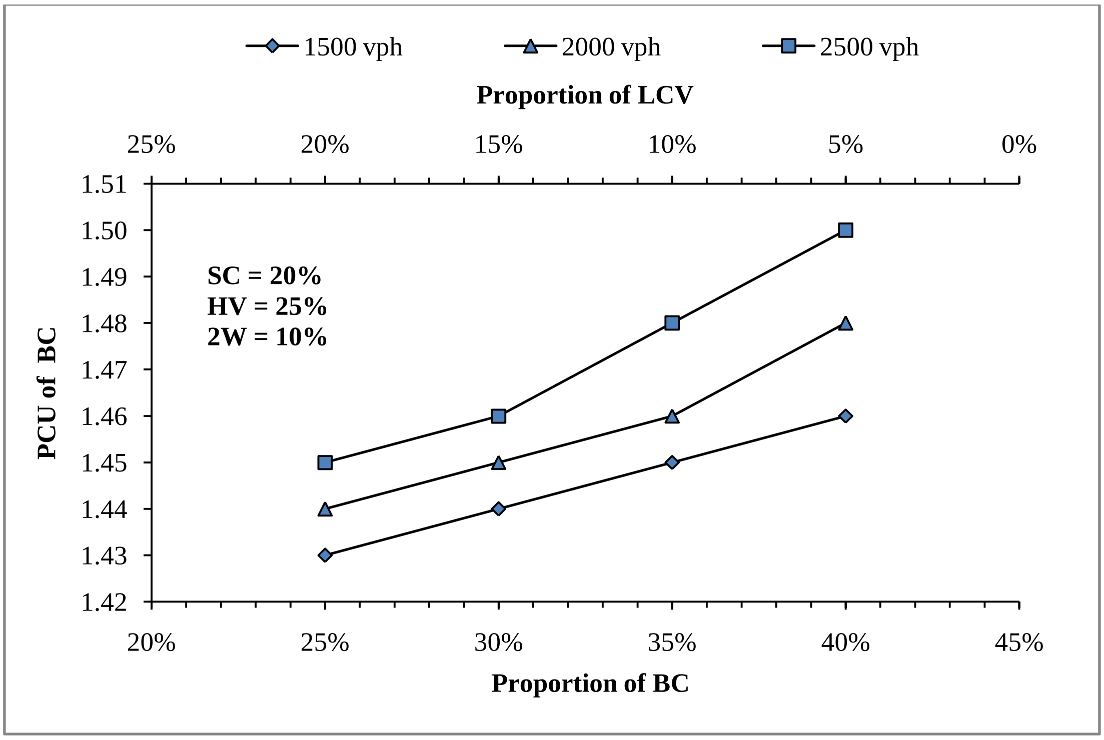


Figure 4.20 Variations in PCU of BC with Traffic Volume and Composition on T-12

Similar procedure was undergone for LCV. The size of this vehicle type is larger than SC and less than HV but the speed of LCVs are higher than SC. It occupies considerable space on the road surface and as the number of LCVs increase within a traffic stream, the opportunity for speeding up and overtaking becomes more difficult. The speed of such large size vehicles is highly affected by slow moving vehicles such as 3W and HV due to limitation on finding the appropriate gap on the opposite direction to overtake. Figure 4.21 displays the speed variation in LCV under varying traffic composition. The decrease in proportion on smaller vehicles with increase in percentage of HV causes the curve to show a descending trend while within the same situation, as displayed in Figure 4.22, SC due to better maneuverability shows higher speed values. The effect of volume alone was also studied by applying different volumes to a traffic stream with constant proportions of different vehicles. According to Figure 4.23, the higher interaction between vehicles in a traffic stream due to higher volume levels decrease the speed of individual vehicles. The result of such variation is reflected in Figure 4.24. As the increased volume decreases the speed ratio between SC and LCV the PCU values for LCV decrease with each step of increase in traffic volume. But since it was shown that at a same volume, the speed of SC, unlike the speed of LCV has an ascending trend and Speed ratio between SC and LCV increases and the increased PCU values for LCV are explained as such and volume levels. As it could be expected, as the traffic volume increases, as well as proportion of LCV within traffic stream, the speed of LCV starts to drop while the speed of SC increases due to better maneuverability and acceleration capability in using the gap in the opposite direction which is shown in Figure 4.22. The increase in speed differential between LCV and SC causes the PCU of LCV to increase.

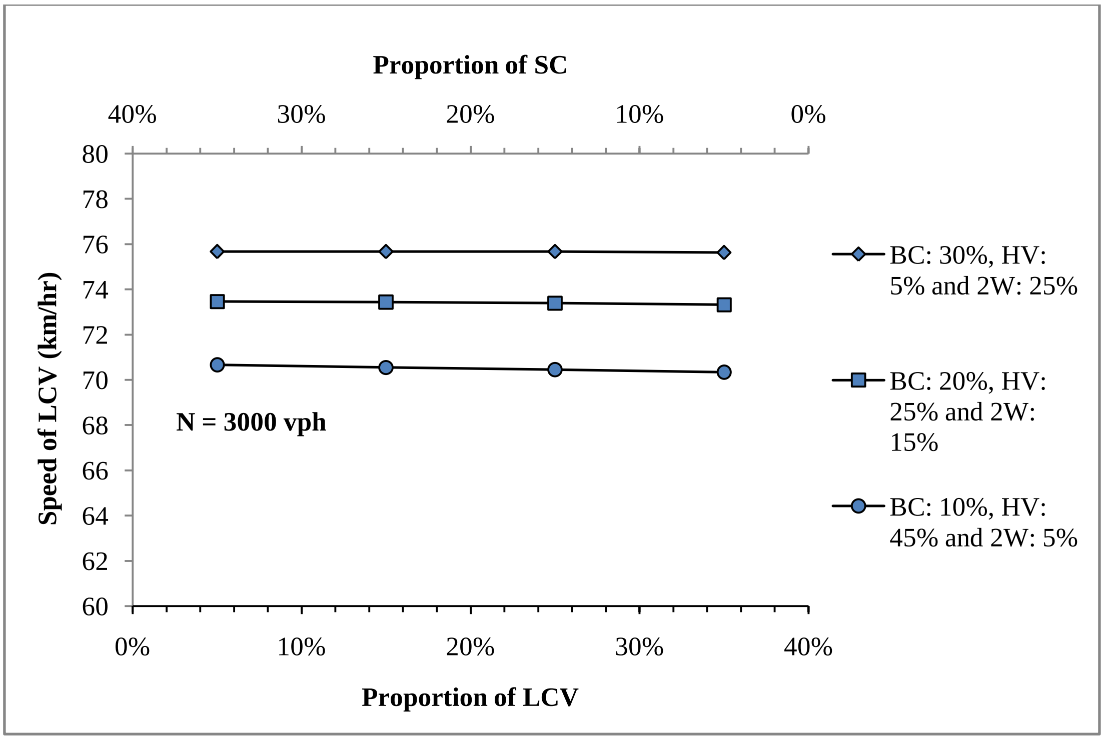


Figure 4.21 Variation in speed of LCV with traffic composition on T-12

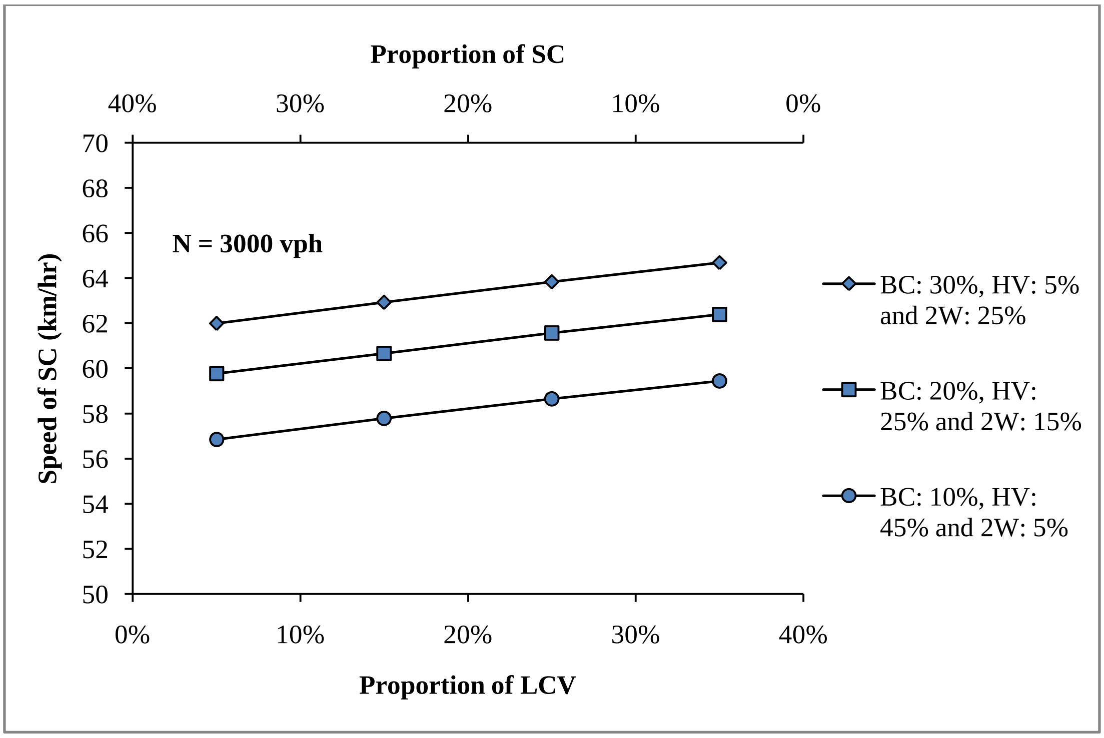


Figure 4.22 Variation in Speed of SC with traffic volume and composition corresponding to LCV on T-12

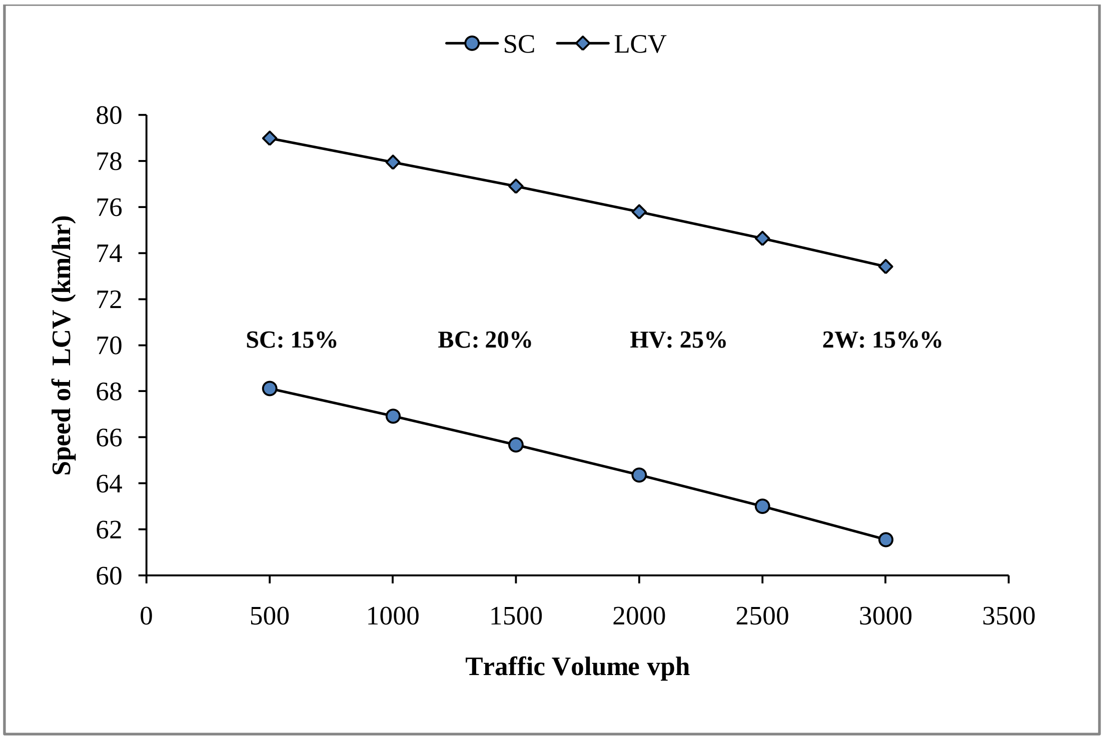


Figure 4.23 Variation in speed of LCV and SC with Traffic volume on T-12

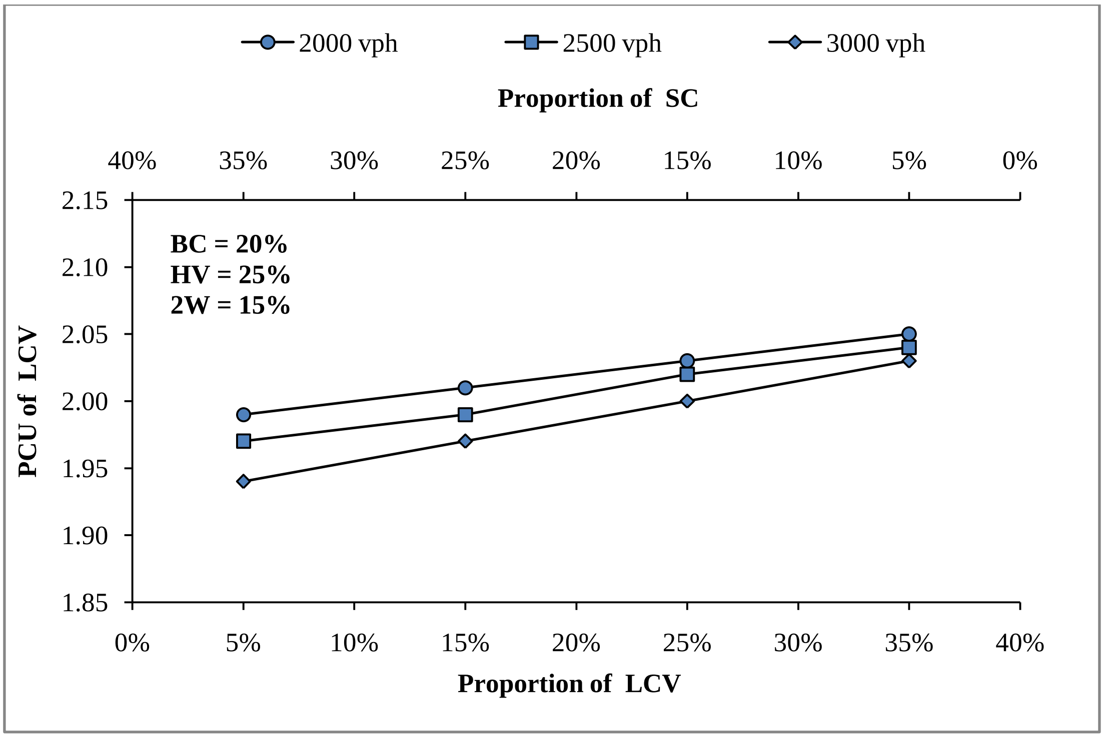


Figure 4.24 Variation in PCU of LCV with traffic volume and composition on T-12

4.3 STREAM EQUIVALENCY FACTOR (SEF)

Development of PCU values using the speed volume equations has limitations. The figures developed in this chapter show the sensitivity of PCU factors to traffic volume and composition variables. But developing such equations, as explained earlier, are effective in providing PCU values for all vehicle categories provided that all those categories are present with reasonable proportion in the traffic stream since the nature of such equations necessitates that presence of different vehicles must impose an impedance to the traffic. Such necessity is not met if all categories are not present or are very low in number. Added to this, handling of such large number of graphical representations can be very complicated and time consuming for a traffic engineer. The concept of stream equivalency factor as introduced by Dhamaniya and Chandra (2013) eliminates the limitations of speed volume equations. Stream equivalency factor (K) is the ratio of flow in PCU per hour to the flow in vehicle per hour as given below.

$$K = \frac{Flow\ in\ PCU/hr}{Flow\ in\ Vehicle/hr} \qquad (4.15)$$

An attempt is made in the present research to develop the concept of SEF for these categories of roads.

4.3.1 SEF for Intermediate and Two-Lane Roads

To obtain the flow in PCU/hr and veh/hr, five minute data on classified volume count and speed of individual type of vehicle from 13 sections of two and intermediate-lane roads were used. As displayed in Figure 4.25 the data points are scattered across the plot area. A straight line relation with zero constant shows an average value of K as 1.10 with R^2 value being 0.58.

The scattered points in the plot area in Figure 4.25 explain the dependence of K-factor on composition of the traffic stream. There are many values of flow in PCU/hr corresponding to the same value of flow in veh/hr and vice a versa. The range of K-factor in the data is from 0.43 to 4.59.

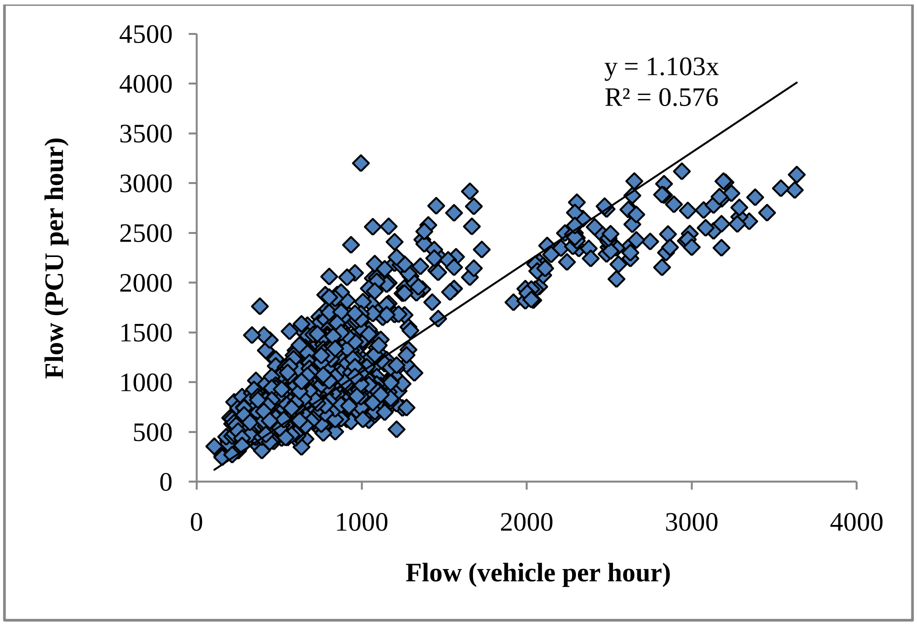


Figure 4.25 Traffic flow in vehicle per hour versus flow in PCU per hour

For a stream consisting of greater proportions of heavy vehicles the K factor will be higher than that of a traffic stream composed of higher percentage of 2-wheelers. Therefore K is related with traffic composition and traffic volume as shown in Equation 4.16. The corresponding t-values along with equation R^2 are presented in Table 4.11.

$$K_{two\text{-}lane,\ intermediate\text{-}lane} = 1 + 0.350*P_{BC} - 0.826*P_{2W} - 0.282*P_{3W} + 1.895*P_{LCV} + 3.905*P_{BUS} + 3.301P_{TK} + 5.571P_{TT} + 8.971*P_{MAV} + 73.191*\frac{1}{N} \quad (4.16)$$

Where;

$K_{two\text{-}lane,\ intermediate\text{-}lane}$ = Equivalency factor

P_i= the proportion of vehicle category i in the traffic stream

Table 4.11Statistical information of Equation 4.16

	Vehicle categories									R^2
	BC	2W	3W	LCV	BUS	TK	TT	MAV	1/N	
t-values of the coefficients	2.91	30.32	2.18	19.39	23.51	32.95	18.24	5.57	8.82	0.92

SEF indicates overall PCU of the stream. The constant term in above equation is intentionally kept unity, which will be the value of K for car-only situation in the traffic stream. Vehicles which are smaller than standard car having PCU values smaller than one decrease the SEF. On the other hand, vehicles like BC, TK and LCV that have larger physical size than standard car increase SEF. This explains the negative/positive signs of the coefficients. All coefficients are significant at 0.95% level of confidence. The proportion of standard car is not considered in the above relation equation to avoid the problem of co-linearity.

4.3.2 Validation

The relation given in Equation 4.16 is validated using the field data at two sections of two-lane roads which were not considered in developing this equation. K value is determined in two different manners. In the first method, each 5-min data is converted into equivalent number of PCUs by calculating PCU for each type of vehicles using Equation 4.1. K value is then calculated by taking the ratio of 5-min volume in PCU to the 5-min volume in the number of vehicles. This is called as $K_{calculated}$. In the second method, K is directly calculated using Equation 4.16 for observed traffic volume (N) and proportion of each 5-min data. This is called $K_{estimated}$. The plot between these values of K is shown in Figure 4.26 and 4.27.

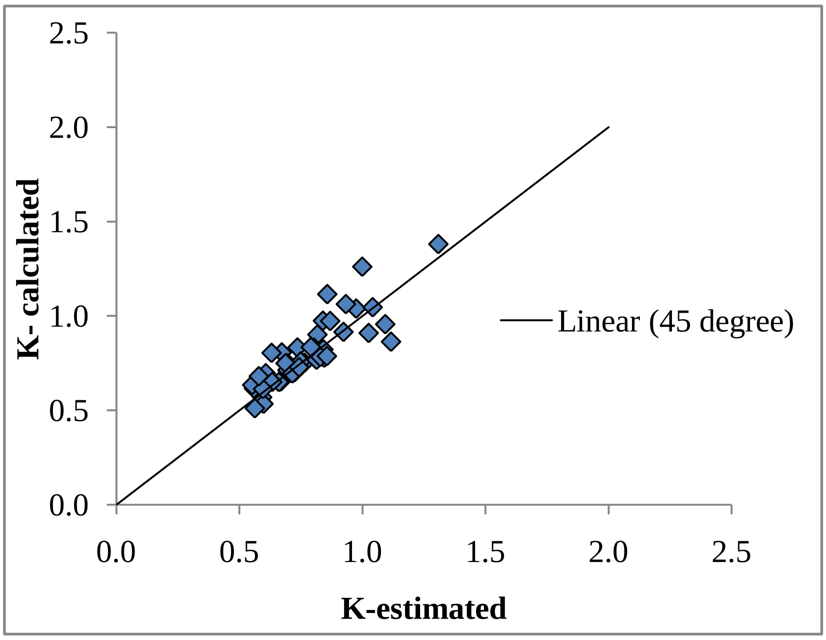


Figure 4.26 Estimated and calculated values for K on T-7

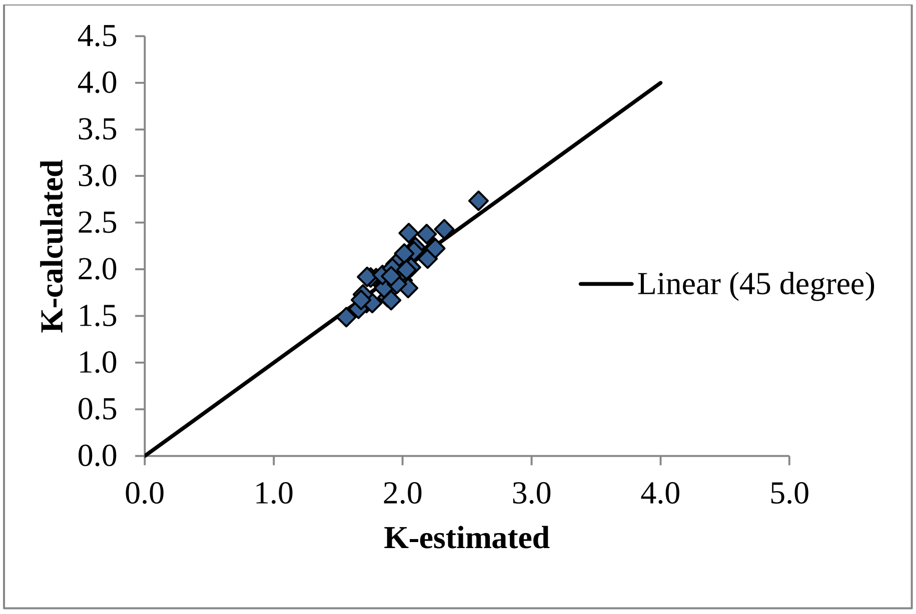


Figure 4.27 Estimated and calculated values for K on T-12

As may be seen, all the data points are very close to the line drawn at 45° indicating that K-value estimated from Equation 4.16 matches with K-value calculated as per its definition. It validates the Equation 4.16 and hence it could be used for estimation of PCU values for any two-lane or intermediate inter-urban roads.

4.3.3 SEF for Single-Lane Roads

The same procedure which was implicated for two-lane and intermediate-lane road was used for single-lane roads. The proportions of individual vehicles were regressed with K-factors from single lane road sections. The equation thus developed is given in Equation 4.17.

$$K_{single\text{-}lane} = 1 + 0.128*P_{BC} - 0.690*P_{2W} - 0.363*P_{3W} + 1.447*P_{LCV} + 3.544*P_{BUS} + 0.757P_{TK} + 6.385P_{TT} + 2.540*\frac{1}{N} \quad (4.17)$$

Where;

$K_{single\text{-}lane}$ = Stream Equivalency factor for single-lane roads

P_i= the proportion of vehicle category i in the traffic stream

4.4SUMMARY

The PCU values are estimated for different categories of motorized and non-motorized vehicles in the heterogeneous traffic present on over 20 sections of single, intermediate and two-lane roads in different parts of India. The PCU values for two-lane and intermediate-lane roads were shown to be similar through use of z-test on two sections of two-lane and two-sections of intermediate-lane roads. Vehicle maneuvers being different on single-lane roads from that of former road types necessitated calculation and development of PCU values separately for these roads.

It was observed that PCU values on all study sections were dynamic. Several plots were made to show the influence of variation in traffic volume and composition on PCU value of individual vehicles using an equation which was developed between speed and density of different vehicles on section T-1 and T-12.

The concept of stream equivalency factor was used to provide a simple and fast method to calculate the flow of traffic in terms of PCU per hour based on the proportion of the individual vehicles present in the traffic stream on any given sections of two-lane, intermediate-lane and single-lane roads instead of going through the complicated method of manual data extraction and calculation of PCU values. The proposed model was validated with two sections of two-lane roads and a good match was observed among the ‘estimated’ K and ‘calculated’ K from field data. The data from both methods were plotted against each other in Figure 4.26 and Figure 4.27 where data points fell on a 45 degree line.

The data provided in this chapter will be used to estimate the capacity of base sections of two-lane, intermediate-lane and single-lane roads in Chapter 5 of this research work.

CHAPTER – 5

ESTIMATION OF CAPACITY FOR BASE SECTIONS

5.1 GENERAL

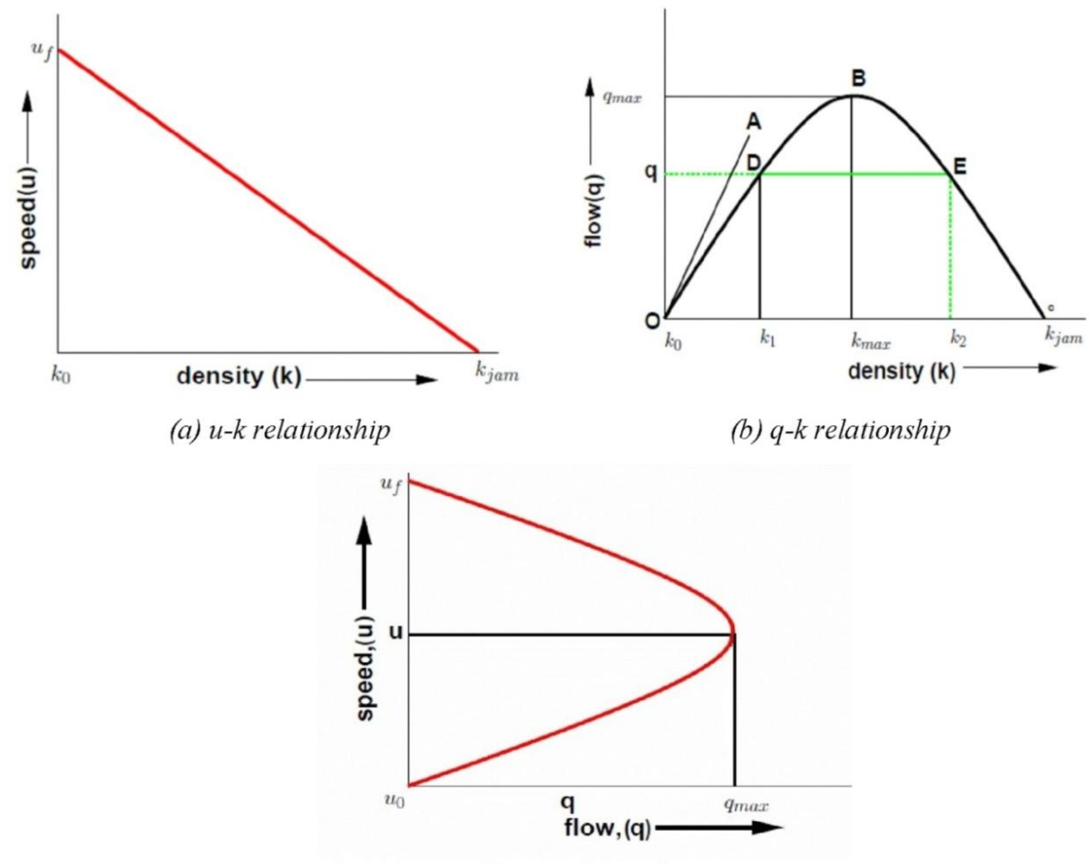
Estimation of capacity is one of the fundamental requirements for designing, operation and layout planning of a road network system. The knowledge of capacity is helpful to determine the maximum amount of traffic flowing in an hour and level-of-service (LOS) of a road section. It also helps in determining the number of lanes and width of lane to be provided at that location.

Different methods have been used by the researchers to estimate capacity of roads. Some methods require simulation of the traffic using the computer based softwares while others are based on guidelines provided by standards like Highway Capacity Manual of the U.S and the Indian Roads Congress in India. The headway method, volume-speed and volume-speed-density method are direct empirical methods that are used by various researchers to obtain capacity of different types of urban and inter-urban roads.

All studies as mentioned earlier in Chapter 1, including Linzer et al (1979) McLean (1983), Hoban (1987), Sarna et al (1989), Lum et al (1998), Bang and Heshen (2000), Chandra and Kumar (2003), Chandra (2004), Kim and Elefteriadou (2010), Velmurugan et al (2010) and Ben-Edigbi and Mashros (2012) have focused on estimation of capacity of a road using field data. Due to heterogeneity of traffic on Indian highways, the simulation models (e.g. Arasan and Vedagiri 2009 and Himes and Donnell 2010) which assume a homogeneous traffic with clear lane discipline may not be directly applicable to the heterogeneous conditions (Arkatkar 2011). The Highway Capacity Manual of US (HCM 2010) has indicated that capacity of a two-lane road varies with the free flow speed on that road. However, the manual does not quantify the influence of free flow speed on capacity. Also it is worthwhile to see how the influence changes under mixed traffic condition. The FFS on a road will be an indication of road surface condition and hence any enhancement or reduction in the capacity due to improvement or deterioration in the road condition will be useful information for planners as well as road maintenance engineers. The present study was therefore undertaken to develop relationships between operating speed (while is taken as the 85th percentile of FFS) of standard cars and capacity of two-lane, intermediate-lane and single-lane roads. Such relations will be extremely useful to field engineers as they would remove the necessity for collection of excessive data required for the development of speed-flow curve on a road. Capacity can be found by making use of operating speed of standard cars only.

5.1.1 Speed-Flow Relationships

The fundamental relationship between flow and speed proposed by Greenshields (1935) became the basis for a huge number of researches and literature over the years. The basic fundamental parameters of the traffic flow; speed (u), density (k) and flow (q) and the generalised relationship between these factors are shown in Figure 5.1.



(a) u-k relationship *(b) q-k relationship*

(c) u-q relationship

Figure 5.1 Generalized relations between q, k and u for an uninterrupted flow facility

The proposed model has a linear form and is given in Equation 5.1.

$$u = a + b.k \quad (5.1)$$

The other model known as the Logarithmic model was introduced by Greenberg (1959) based on the theory of one-dimension compressible fluid flow and it takes the form of Equation 5.2.

$$u = a.\ \ln\left(\frac{b}{k}\right. \quad (5.2)$$

The drawback of this model was that as k reduces down towards zero, u will move towards infinity which implies that the model is not very good in predicting speed at low densities and traffic volume levels.

The third model which was tried in this study to find the relation between flow and speed – to be used for further analysis of capacity at each section – was the method proposed by Underwood (1961) which took an exponential form for the relation between u and k as given in Equation 5.3.

$$u = a.\ e^{-b^{-1}(k/c)^{b}} \quad (5.3)$$

However the drawback of this method was that “u” becomes zero only when k is infinite which implies that the jam density can be infinite.

5.2 TWO-LANE ROADS

5.2.1 Data Collection

Data were collected at ten sections of two-lane roads in different parts of India to get information on traffic volume, vehicle composition and the speed of different vehicles present in the traffic stream. Sections were away from intersections and presence of access roads which reduce the operating speed and data were collected during typical weekdays to avoid possible weekend or holiday congestion (Jun 2010). The details of each section along with the traffic volume and composition are given in chapter 3 (Table 3.1 and 3.4 respectively) of this study. Parameters of the traffic stream like traffic volume and speed of different types of vehicles were extracted from the video data as discussed in section 3.4 of chapter 3.

5.2.2 Data Extraction and Analysis

Traffic on Indian roads is heterogeneous with several categories of vehicles sharing the road space without any physical segregation. Therefore, it is important to convert a mixed traffic stream into a homogeneous equivalent by making use of passenger car unit (PCU) value for different types of vehicles. When different vehicles with varying sizes and operating characteristics are in good proportion in a stream, the lane discipline becomes extremely poor. Under such circumstances, Chandra and Kumar (2003) suggested the use of physical area that a vehicle occupies on the road as an important variable for estimation of PCU factors which is discussed in Chapter 4 of this research work. The details of the vehicle categories observed at the selected sections are given in Table 3.3. Therefore in the present study the mixed traffic flow was converted into equivalent number of Passenger car units (PCU) by calculating the PCU factors for each type of vehicle in the five minute counts using the equation proposed by Chandra and Kumar (2003) which is given by Equation 4.1.The range of calculated PCU values are given in Table 4.1.

It was observed that a large variation exits in PCU value of a vehicle on different road sections. The values are different from those provided by IRC: 64-1990. The reason could be due to car manufacturing and upgraded technology. The PCU values calculated 25 years ago were based on the passenger car (Ambassador) of larger dimensions with less operating capabilities of current standard cars. Fildes and Jarvis (1994) and Horswill and Coster (2002) showed that due to the improved technology and enhanced maneuverability the drivers feel free to select the headway and maintain the speed of their desire .

5.2.3 Speed-Volume Relationships

The basic parameters of traffic flow; speed, volume and density are used to estimate the capacity of a road. Since the measurement of traffic density in a heterogeneous traffic condition is a difficult task, attempts have always been concentrated to develop speed-volume relationship instead. In order to determine the speed-flow relationship in a mixed traffic situation, the volume calculated by the data extracted from recorded videos in each five minute counting was converted into equivalent number of PCUs using Equation 4.1.

Maximum volume is reached at a certain traffic speed on a road section and then decreases (Greenshields 1960). But since the field data do not provide congested part of speed-volume curve on a road section, a complete speed-volume curve should be developed using the theoretical formulations. The popular fundamental relationships between speed, density and flow were used to convert the speed-volume data into speed density data. Such data are shown for section T-1, T-5 and T-7 in Figures 5.2, 5.3 and 5.4 respectively. The classic models like Greenshields, Greenberg and Underwood were tried to fit these data. As it can be seen from the above figures, there was not much variation observed between the R^2 values obtained from the three models. It was observed from the field data, that stream speed starts to decline right from the beginning as traffic volume increases under heterogeneous traffic condition. On the other hand, field data do not provide the congested condition of the traffic flow. Therefore, the Greenshields model which uses a simple straight line speed-density relationship to develop a complete speed-volume curve was selected to estimate the capacity. Figure 5.5, 5.6 and 5.7 display the speed-volume relationship for section T-1, T-5 and T-7 respectively based on the Greenshields model for speed-volume relationships.

It should be noted that the upper part of the developed curves (shown with solid line) represent the condition where field data were available. The lower part (shown with dotted line) however, represents the derived (theoretical) data which is provided by using assumed density values as input to developed speed-density relationship. The same pattern is followed to develop all speed-volume curves presented in this research work.

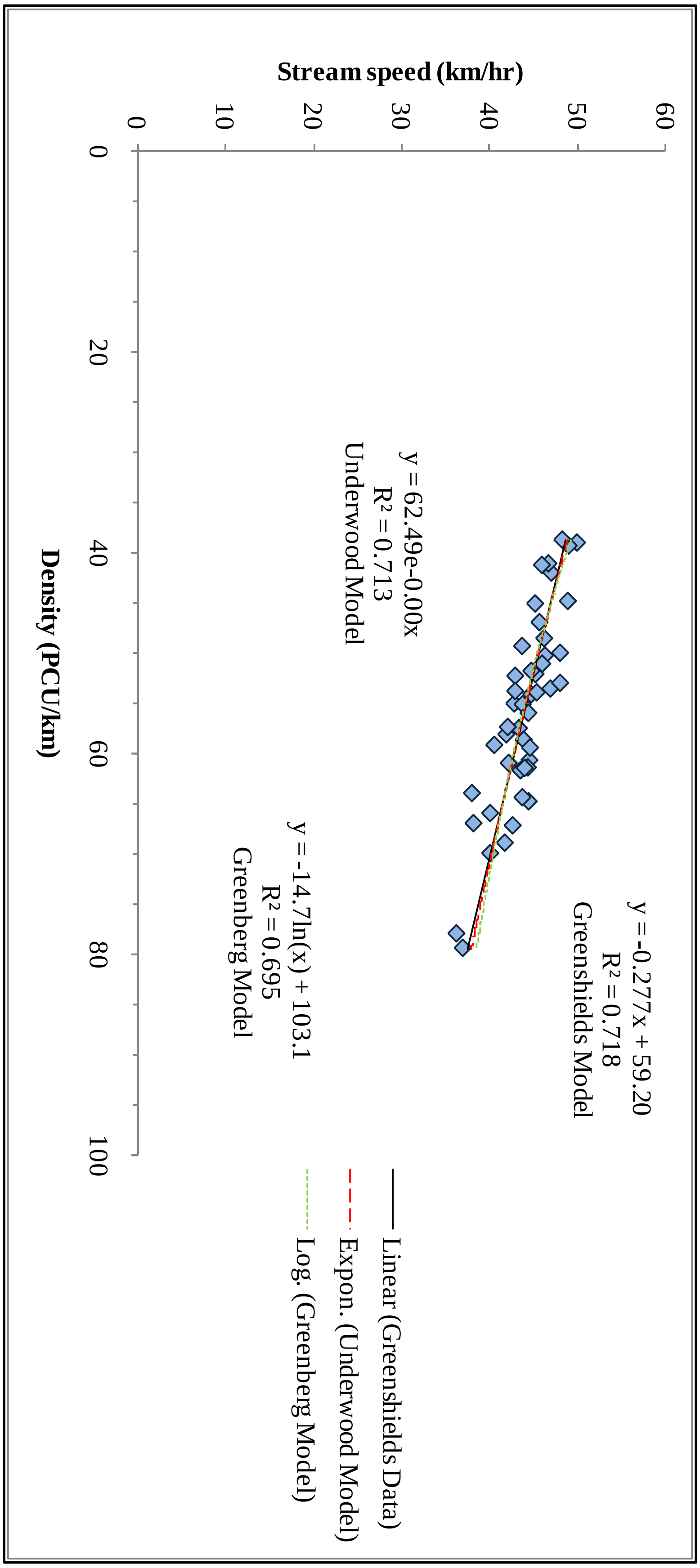


Figure 5.2 Speed-density relationships on section T-1

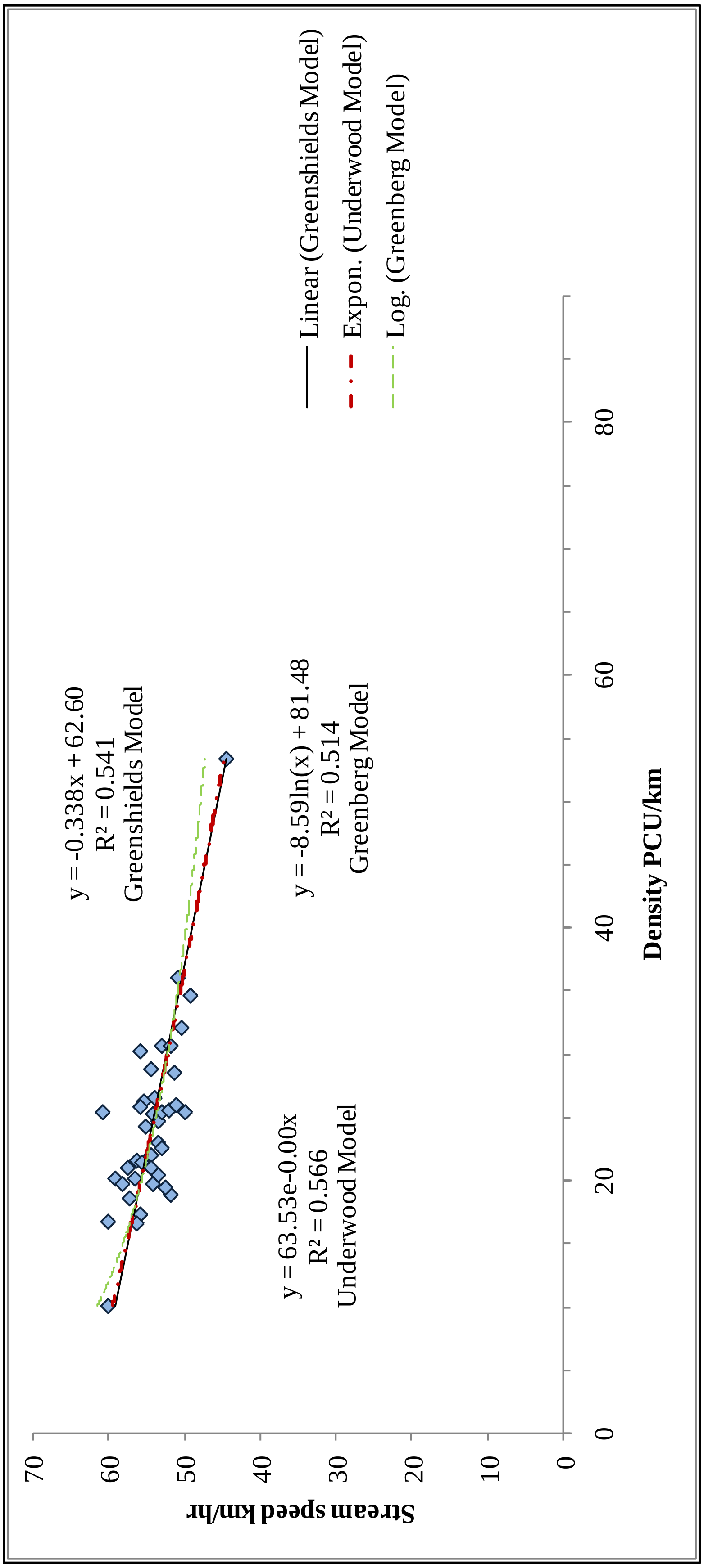


Figure 5.3 Speed-density relationships on section T-5

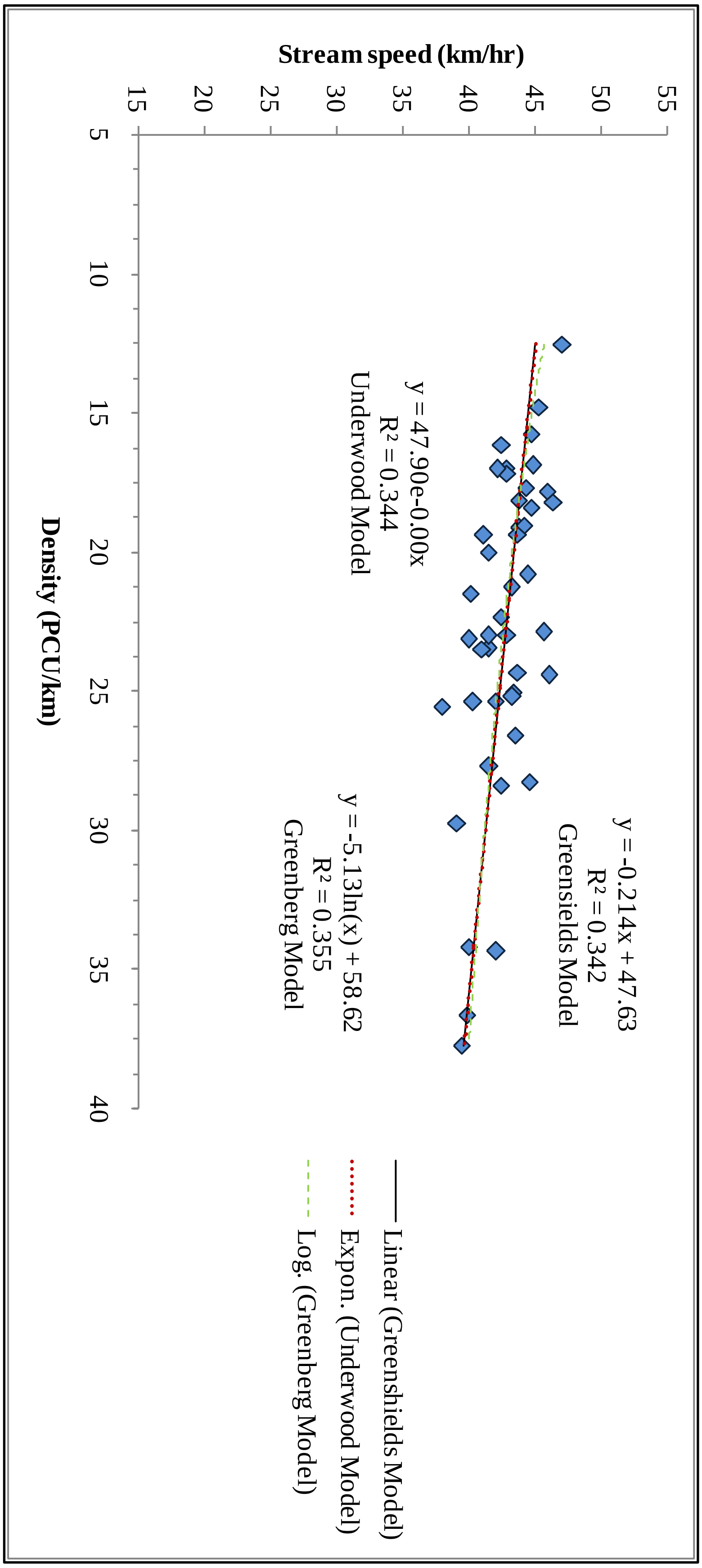


Figure 5.4 Speed-density relationships on section T-7

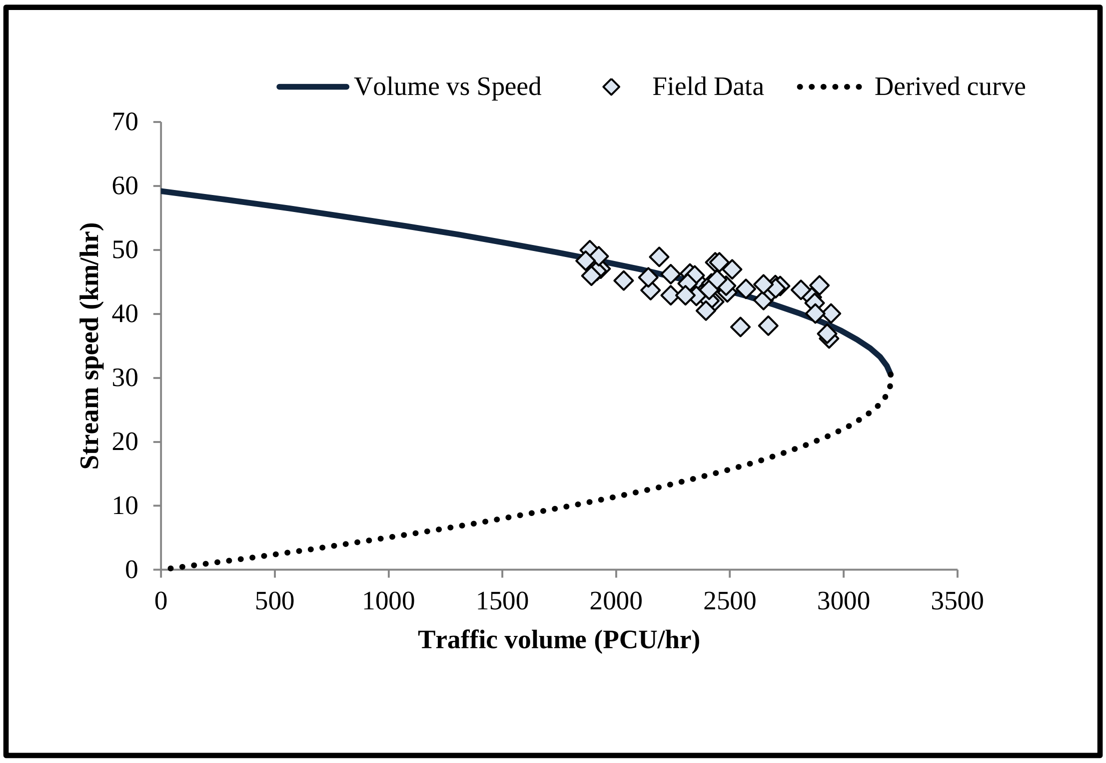


Figure 5.5 Speed – volume relationship on section T-1

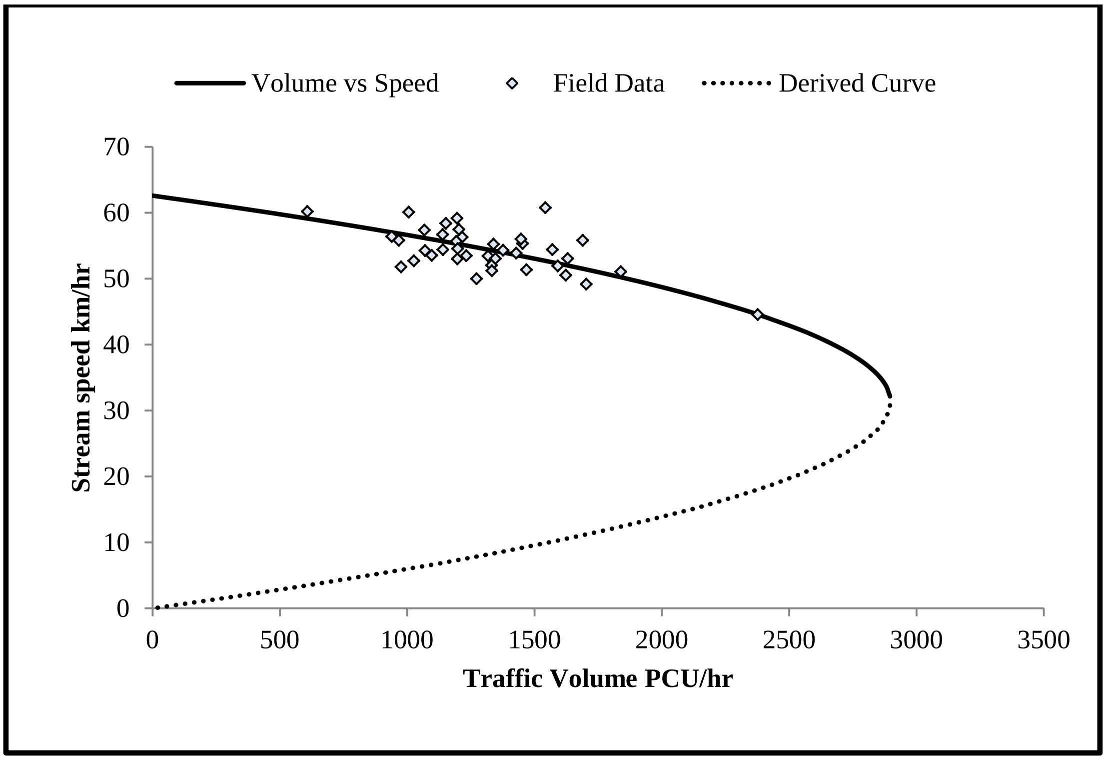


Figure 5.6 Speed - volume relationship at section T-5

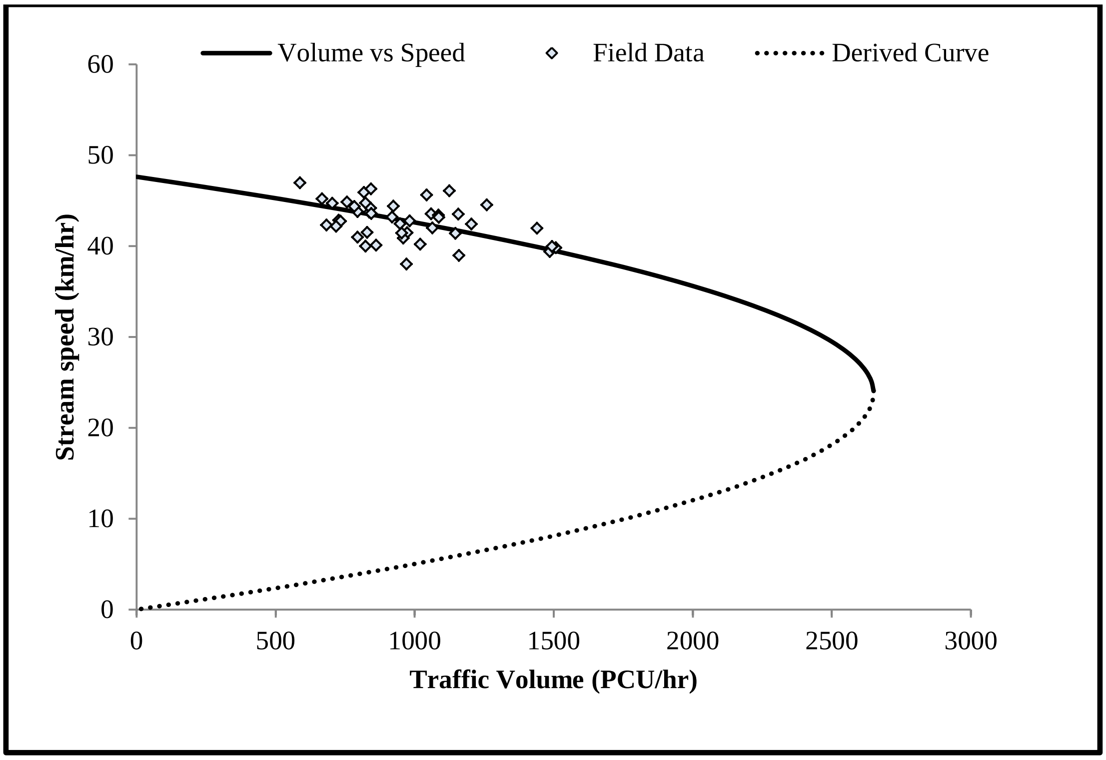


Figure 5.7 Speed - volume relationship at section T-7

Similar procedure was followed to estimate the capacity of all sections of two-lane roads and the results are shown in Table 5.1.

Table 5.1 Capacity values at different sections of two-lane roads

Section ID	Capacity (PCU/hr)
T-1	3162
T-2	2802
T-3	3163
T-4	2710
T-5	2897
T-6	2429
T-7	2650
T-8	3294
T-9	2450
T-10	2948

5.2.4 Free Flow Speed and Operating Speed

The aim of this study was to develop a relationship between the operating speed of standard cars. American Association of State Highway and Transportation Officials (AASHTO 2004) defined operating speed as the speed at which drivers are observed operating their vehicles during free-flow conditions. Some authors use specific time headway between two consecutive vehicles to describe free movement of a vehicle (Katja 2002, Bham and Ancha 2006, Ossen et al. 2006, Ossen and Hoogendoorn 2007, Kim et al. 2007, Al-Kaisy and Karjala 2010) and whether or not a vehicle is in a following condition and its speed is influenced by the leading vehicle. HCM (2010) defined free flow condition as a situation where the vehicle passing the section is not influenced by the movement of any other vehicle present either in the same or opposing direction under low traffic volume condition equal or less than 200 vehicles per hour. The 85th percentile free flow speed is frequently used worldwide as the model to predict the operating speed in this regard. For example McLean (1979) in Australia, Kerman et al. (1982) in the United Kingdom, Setra (1986) in France, Lamm (1993) in Germany, Lamm et al. (1995c) in Greece, Andueza (2000) in Venezuela, Gibreel et al (2001) in Canada and Poe et al. 1996), Otessen and Krammes (2000) and Jessen et al. (2001) in the United States, Dey et al. (2006) in India and Azad and Behbahani (2010) in Iran and many others across the world have used the 85th percentile speed as the operating speed of vehicles. The drivers' choice of speed reflects their response to the geometric characteristics of a road (Lobo et al. 2013). Under such conditions the effect of all factors that influence the capacity of a section will be projected in the free flow speed of a standard car and therefore a relationship between the capacity and such speed could be sought. In this regard the free flow speed data of standard cars at each section were collected and speed frequency and cumulative frequency distribution curves were plotted to find the 85th percentile speed for each section. Figure 5.8 (a and b) and 5.9 (a and b) show the frequency and cumulative frequency distribution of free flow speed for section T-2 and section T-3 respectively. The first and last speed values given in the free speed frequency distribution figures represent the minimum and maximum observed free speeds on each section respectively. The 85th percentile speeds of all other sections were obtained following the similar procedure and are presented in Table 5.2. It should be noted that the desirable design speeds for National Highways in India as per IRC: 73-1980 and IRC: 52-1981 are 100 km/hr for plain terrain and 50 km/hr for mountainous terrains. The upper speed limit on National Highways for standard cars is 85 km/hr. Therefore it may be concluded that the free flow speeds observed on the study sections were not influenced by the speed limits.

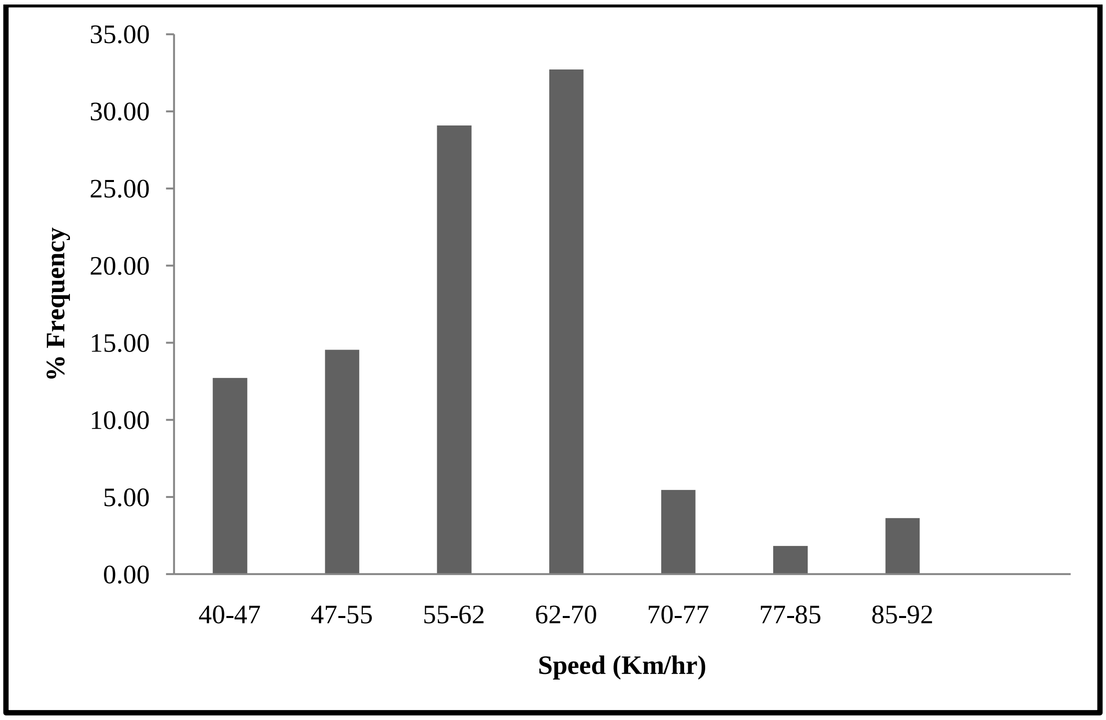


Figure 5.8.a Frequency distribution of free-flow speed at T-2

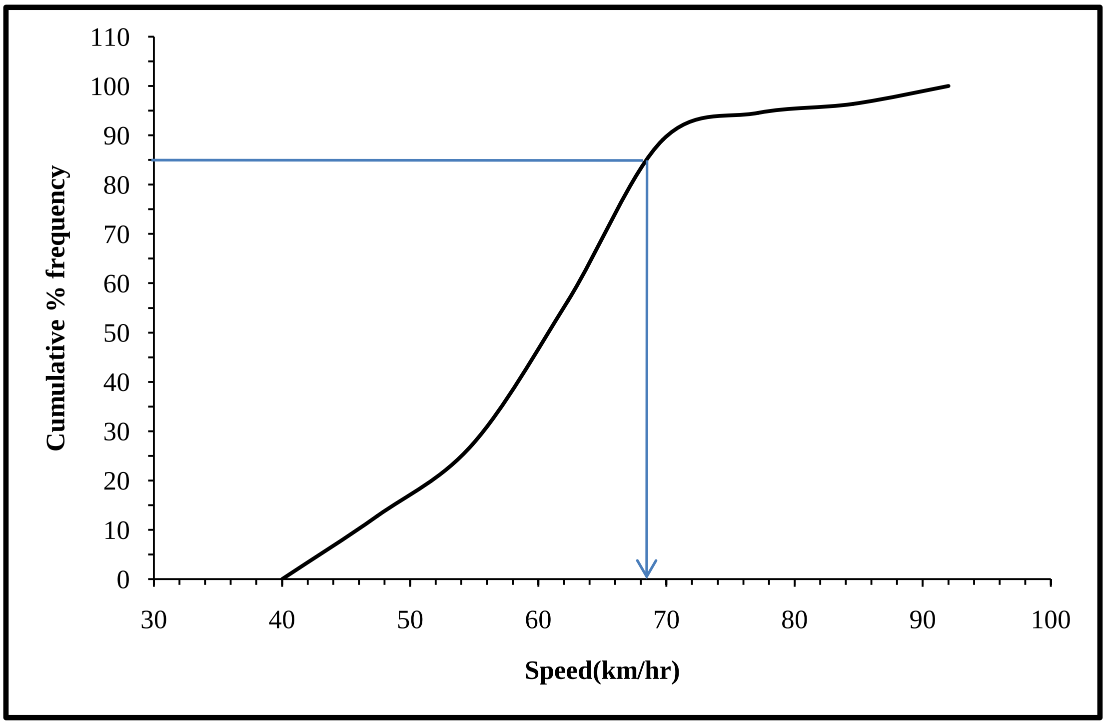


Figure 5.8.b Cumulative frequency distribution of free-flow speed and 85th percentile speed at T-2

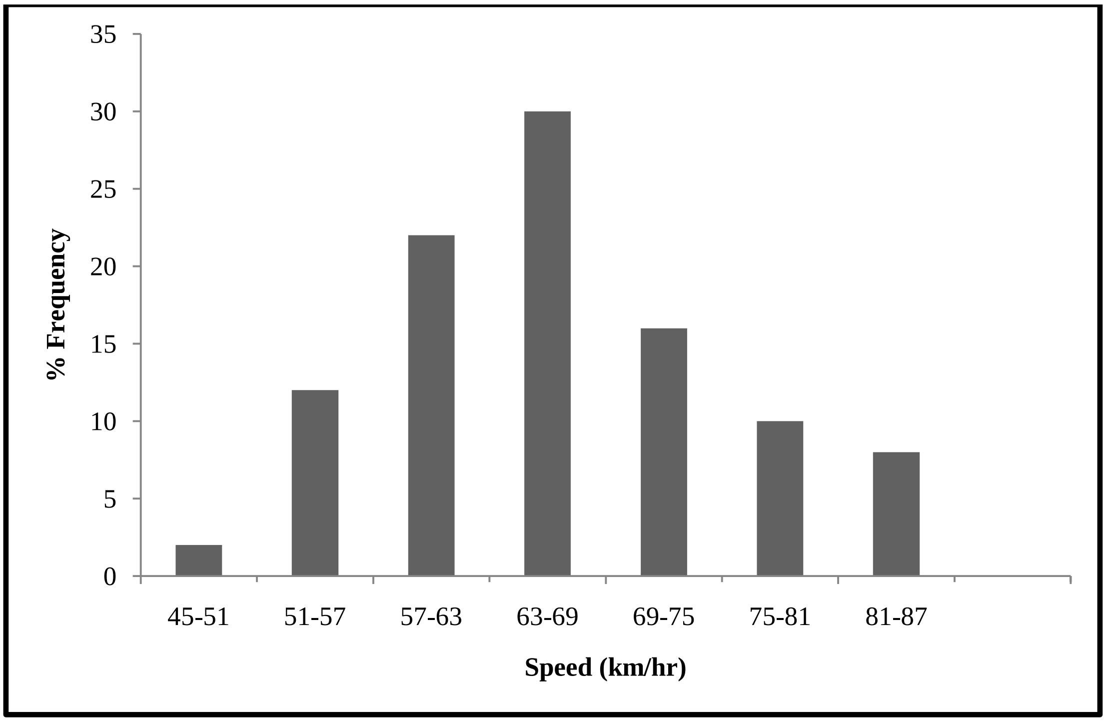


Figure 5.9.a Frequency distribution of free-flow speed at T-3

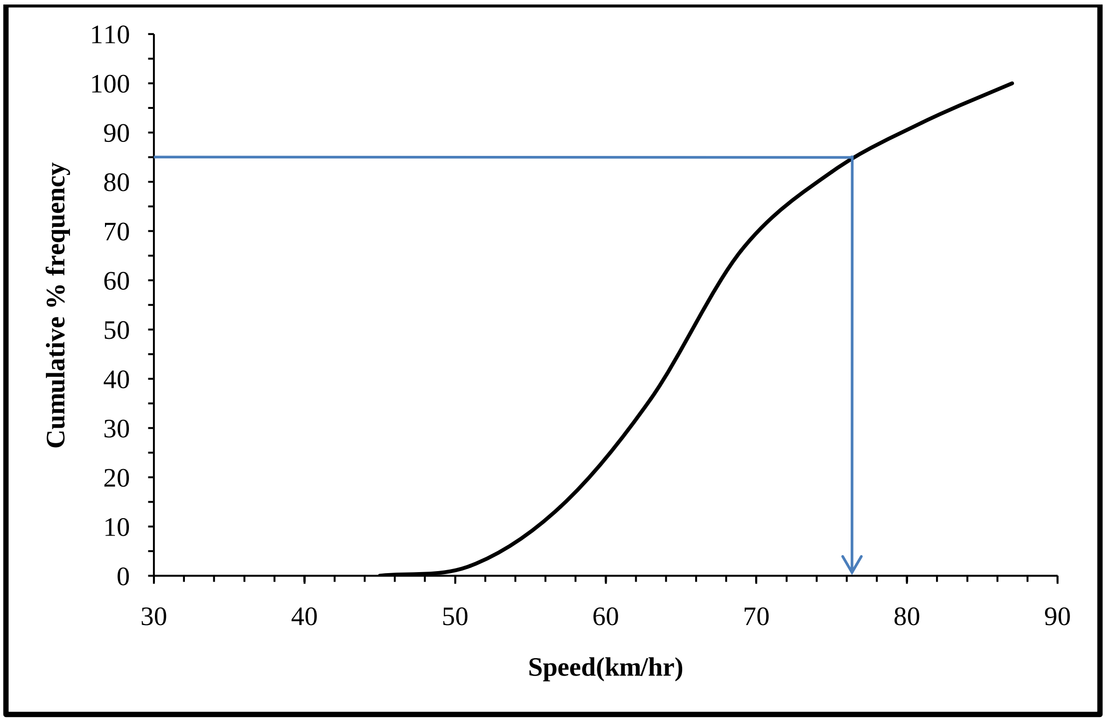


Figure 5.9.b Cumulative frequency distribution of free-flow speed and 85th percentile speed at T-3

Table 5.2 Speed distribution characteristics on two-lane roads

Section ID	Capacity (PCU/hr)	85th Percentile FFS of Standard Car (km/hr)
T-1	3162	72.91
T-2	2802	68.50
T-3	3163	76.50
T-4	2710	71.26
T-5	2897	73.06
T-6	2429	64.83
T-7	2650	66.75
T-8	3294	80.0
T-9	2450	67.80
T-10	2948	75.50

It can be observed that the capacity and the corresponding operating speed at a road section vary for different highways located in different parts of India. This variation could be attributed to traffic composition and driver behavior observed at different states in India.

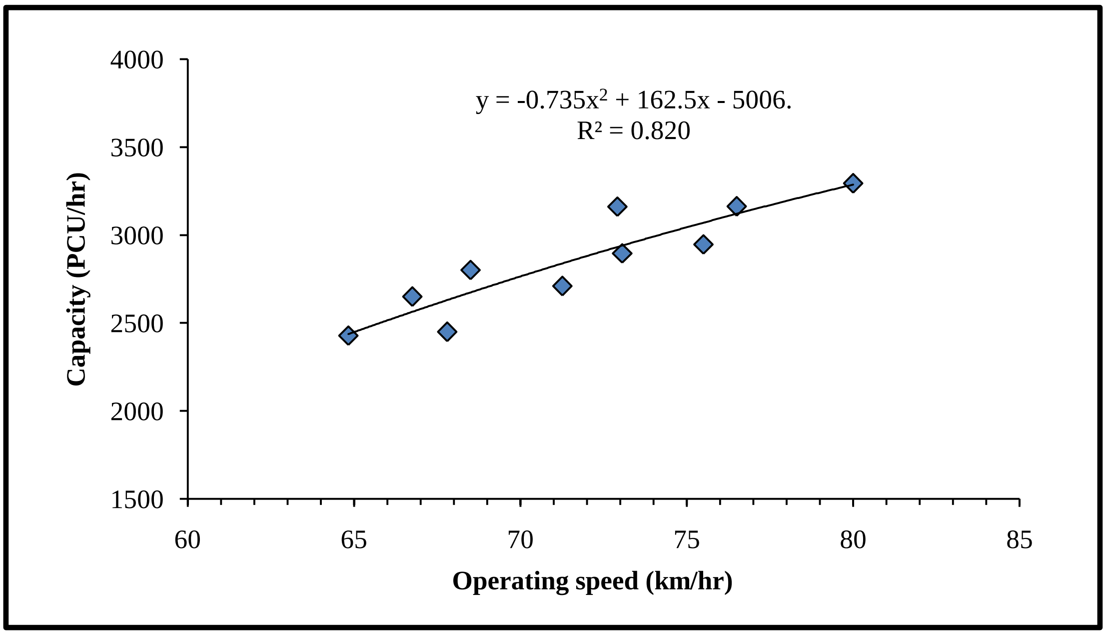


Figure 5.10 Relationship between operating speed and capacity at two-lane sections

The operating speed was plotted against the capacity of each section and a best fit line was drawn. A second degree polynomial curve with a R^2 value of 0.820 was obtained. Figure 5.10 displays the developed plots for the two-lane highways and the relationship obtained in this manner is given in Equation 5.4.

$$C_{two\text{-}lane} = -0.735v_{os}^2 + 162.5v_{os} - 5006 \quad (5.4)$$

Where;

$C_{two\text{-}lane}$ = capacity of a two-lane inter-urban road (PCU/hr)

v_{os} = operating speed (km/hr)

5.2.5 Model Validation

Data were collected on one more section of two-lane road to test the reliability of the relationship shown in Equation 5.4. The capacity value of the new section T-11 was estimated using Greenshields model. Initially the heterogeneous traffic at this section was converted to a homogeneous traffic by converting all vehicle types into passenger car units using Equation 4.1. Figure 5.11 (a and b) shows the speed-volume relationship for the field data collected at T-11. The capacity for this section was estimated as 2641 PCU/hr. Then the cumulative distribution curve for free-flow speed of standard cars was developed and the 85^{th} percentile speed (operating speed) of standard cars traveling on this section was found to be 72.5 km/hr (Figure 5.12.a and 5.12.b).

By putting the operating speed obtained from section T-11 in Equation 5.4 new value was obtained for the capacity of this section. The results are presented in Table 5.3.

Table 5.3 Capacity obtained from field data and from Eq. 5.4

Section ID	Total capacity from field data (PCU/hr)	Operating speed, (km/hr)	Capacity Eq. 5.4 (PCU/hr)	% difference
T-11	2641	72.8	2929	9.82

From the Table 5.3 it can be observed that the percent difference between the capacity values obtained from field data and Equation 5.4 is very low and this validates the capacity-operating speed model developed in this study for two-lane roads.

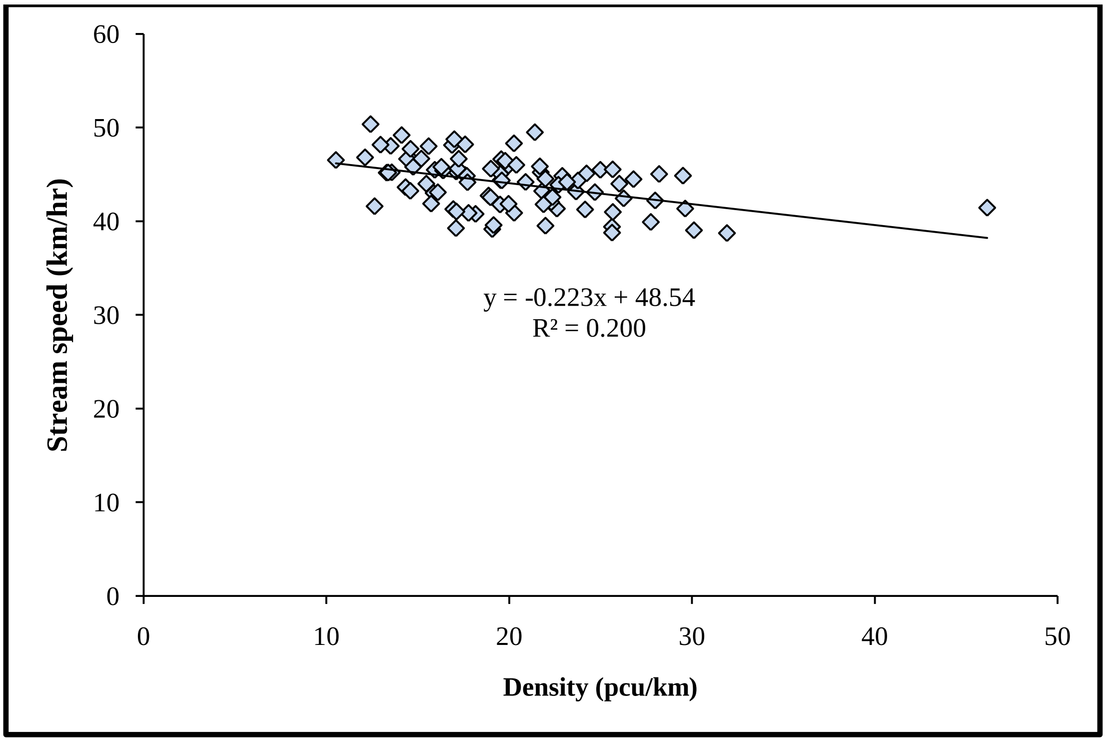


Figure 5.11.a Speed-Density relationship on section T-11

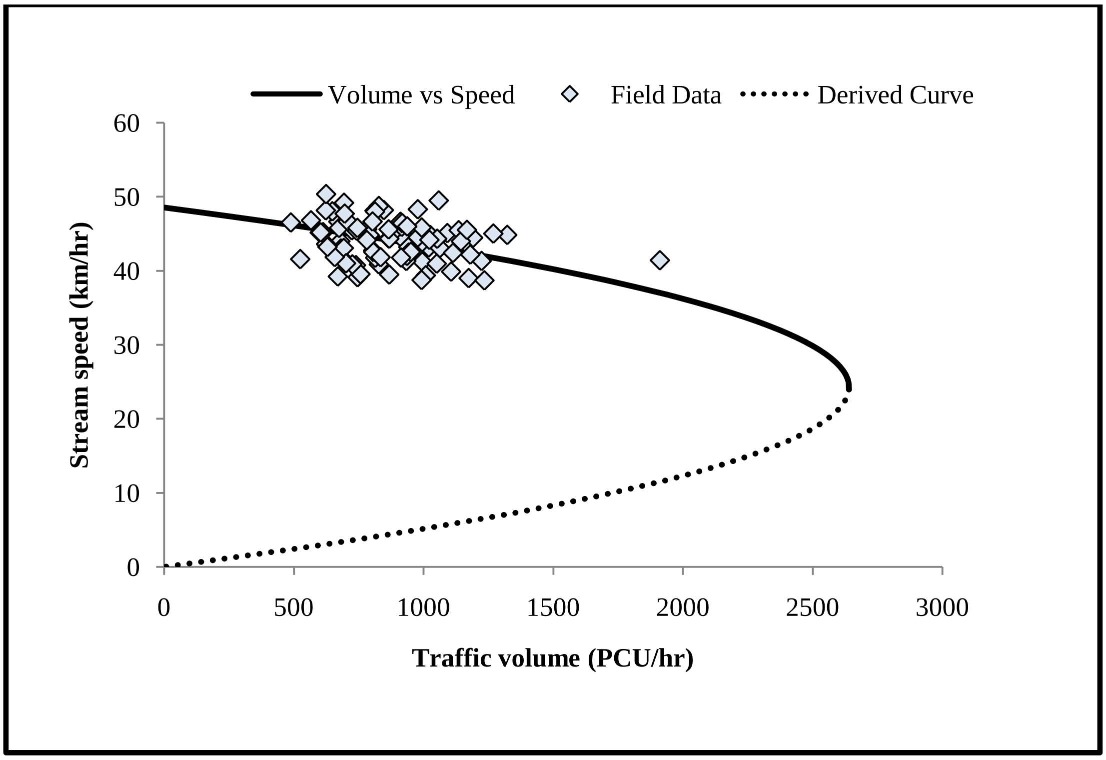


Figure 5.11.b Speed-volume relationship on section T-11

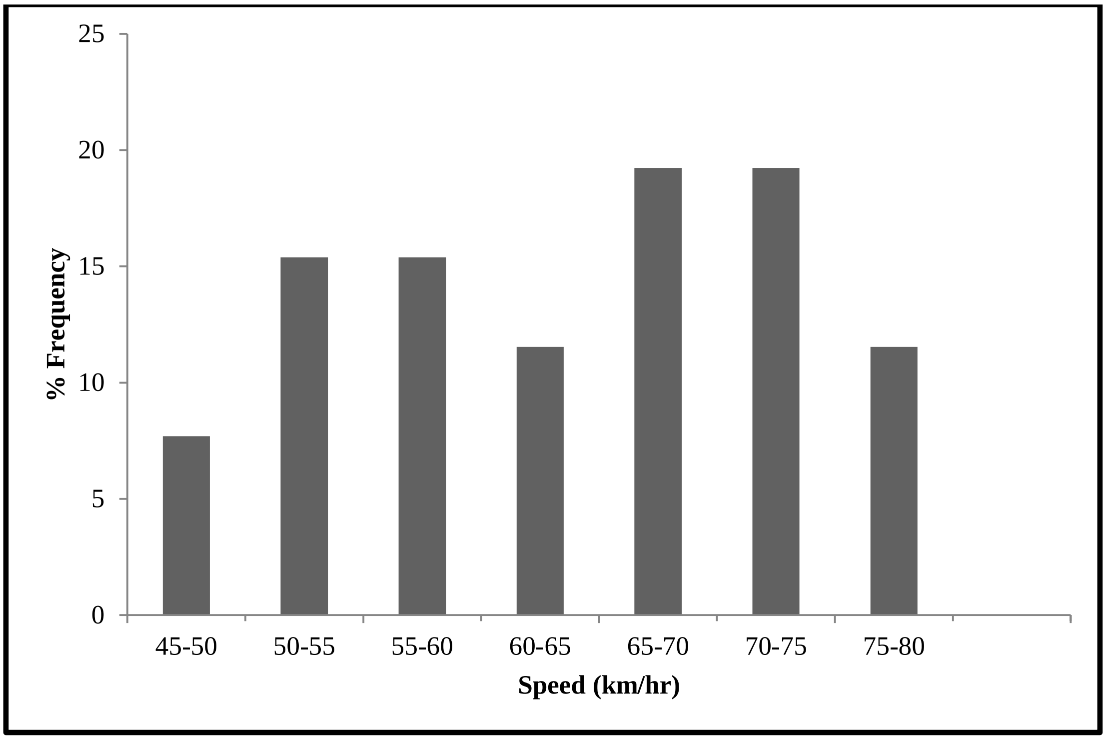


Figure 5.12.a Frequency distribution of free-flow speed at T-11

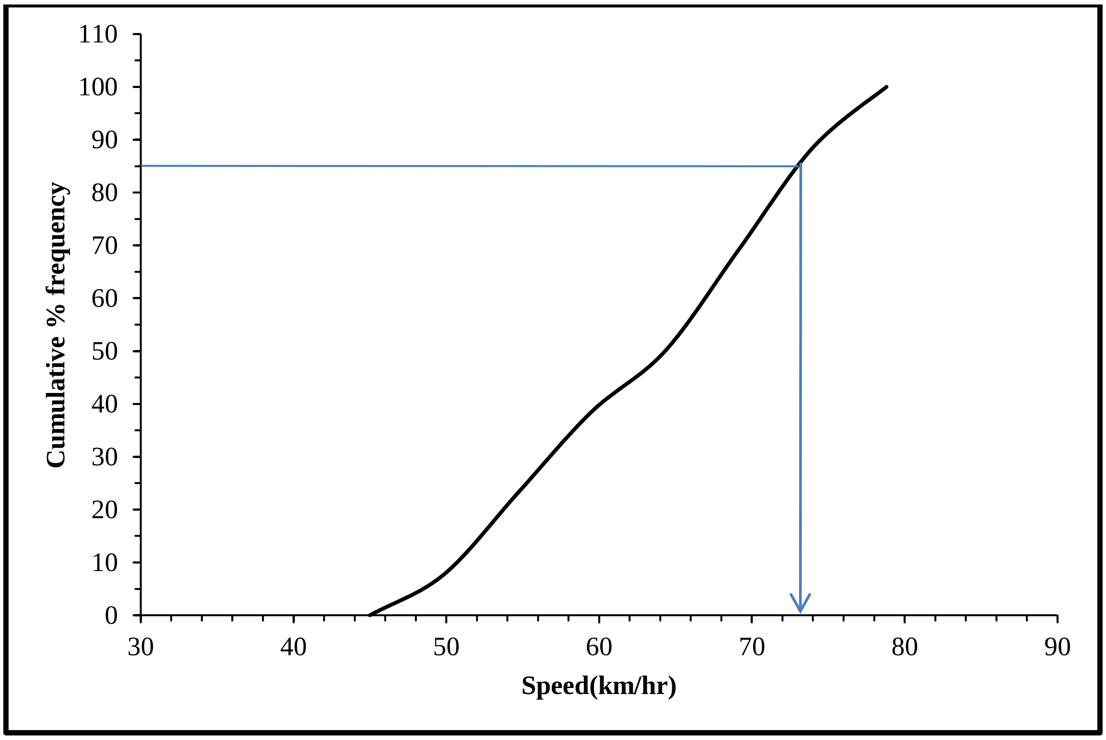


Figure 5.12.b Cumulative frequency distribution of free-flow speed and 85th percentile speed at T-11

5.3 INTERMEDIATE-LANE ROADS

5.3.1 General

Being a substandard two-lane road, the quality of service and performance level of an intermediate lane road can be highly improved by increasing the width of the carriageway. Since augmentation projects are inter-related with funding and budgeting policies, prioritizations are made based on the studies conducted on the present and future demand state of a road system. This brings about the importance of the knowledge over the capacity of intermediate lane roads in India.

The literature on estimating the capacity of intermediate lane roads as substandard two lane roads is very few. Majority of the researchers have considered the influencing geometric factors and traffic conditions related to two lane roads only. Yet the methods implemented by researches could be considered for studying intermediate lane roads as they provide service for two directions of traffic on a single lane. HCM (2000) suggested the capacity of intermediate lane roads (5.50 m) as 2240 PCU/hr provided that 1.80 m earthen shoulder is available at both sides. The manual does not consider the effect of traffic composition on capacity. As per the Road User Cost Study (RUCS, 2001) which is provided by CRRI, New Delhi, the maximum capacity of an intermediate lane road with earthen shoulders is suggested to be about 1600 PCU/hr using static PCU values for different vehicle types under mixed traffic condition on Indian roads. The design service volume under LOS B is recommended as 6000 PCU/day for intermediate lane roads by IRC-64-1990. Chandra et al. (2010) analysed the traffic flow on intermediate-lane roads in India using the dynamic PCU factor for different vehicle types and developed the speed-flow relationship to study the effect of road geometry and traffic composition on the flow and capacity on these roads.

As the necessity of a reliable method which estimates the capacity of a road without huge amount of data collection and analysis was discussed for two-lane roads, it is intended to estimate the capacity of intermediate-lane roads using the 85th percentile FFS (operating speed).

5.3.2 Data Collection and Analysis

Field data was collected for 6 sections of intermediate-lane roads from different parts of India. The details and the traffic volume and composition of each section are given in chapter 3 (Table 3.1 and 3.5 respectively) of this study. Similar procedure was followed to convert the heterogeneous traffic on intermediate-lane roads to a homogeneous traffic as discussed for two-lane roads. Accordingly the capacity values on each section were estimated by developing the speed-flow curves using Greenshields method which are given in Table 5.4. Figures 5.13 (a and b) and Figure 5.14 (a and b) display such diagrams for section I-1 and I-4 respectively.

The estimated capacities of the selected sites ranged between 1456 PCU/hr and 2082 PCU/hr. This variation in capacity is attributed to the variation in traffic composition and driver behavior in different parts of the country.

The study was aimed at finding a relationship between the operating speed of standard cars and capacity. The effect of all factors that influence the capacity of a section will be projected in the free flow speed of a standard car and therefore a relationship between the capacity and operating speed could be developed. The frequency distribution curve of free flow speeds were plotted to find the 85th percentile speed for all six sections. Figure 5.15 (a and b) and 5.16. (a and b) show the frequency and cumulative frequency distribution diagram of free flow speeds for section I-1 and I-4 respectively.

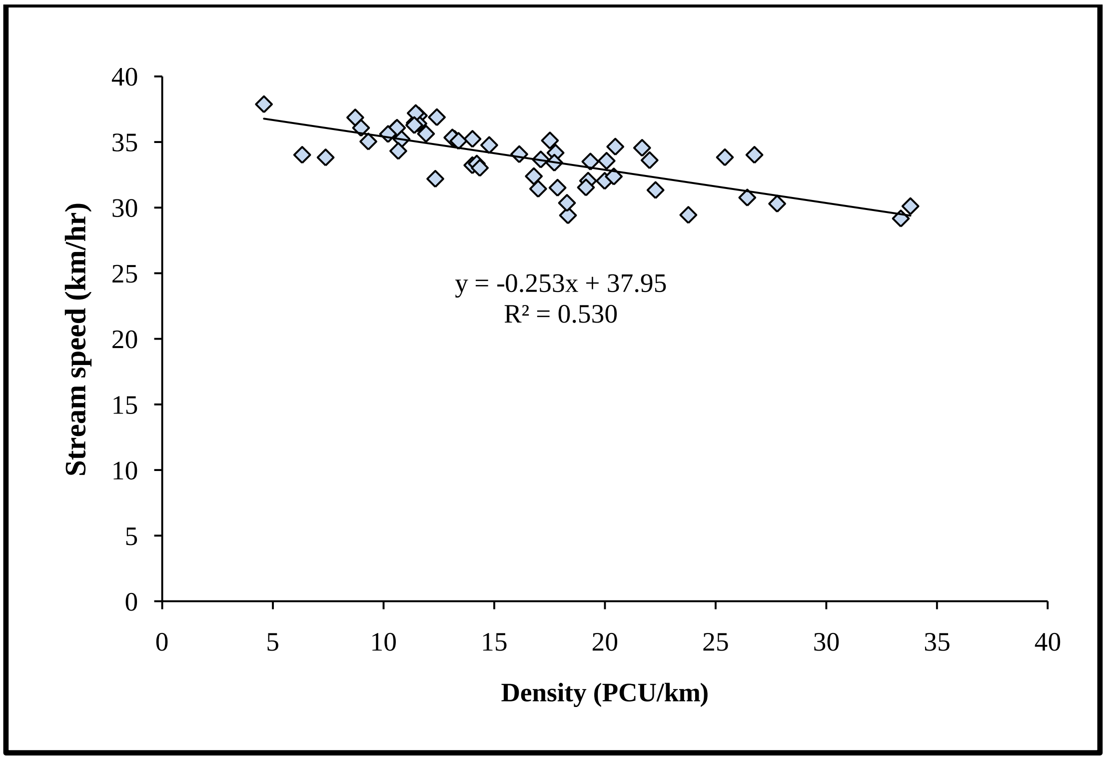


Figure 5.13.a Speed - density relationship at section I-1

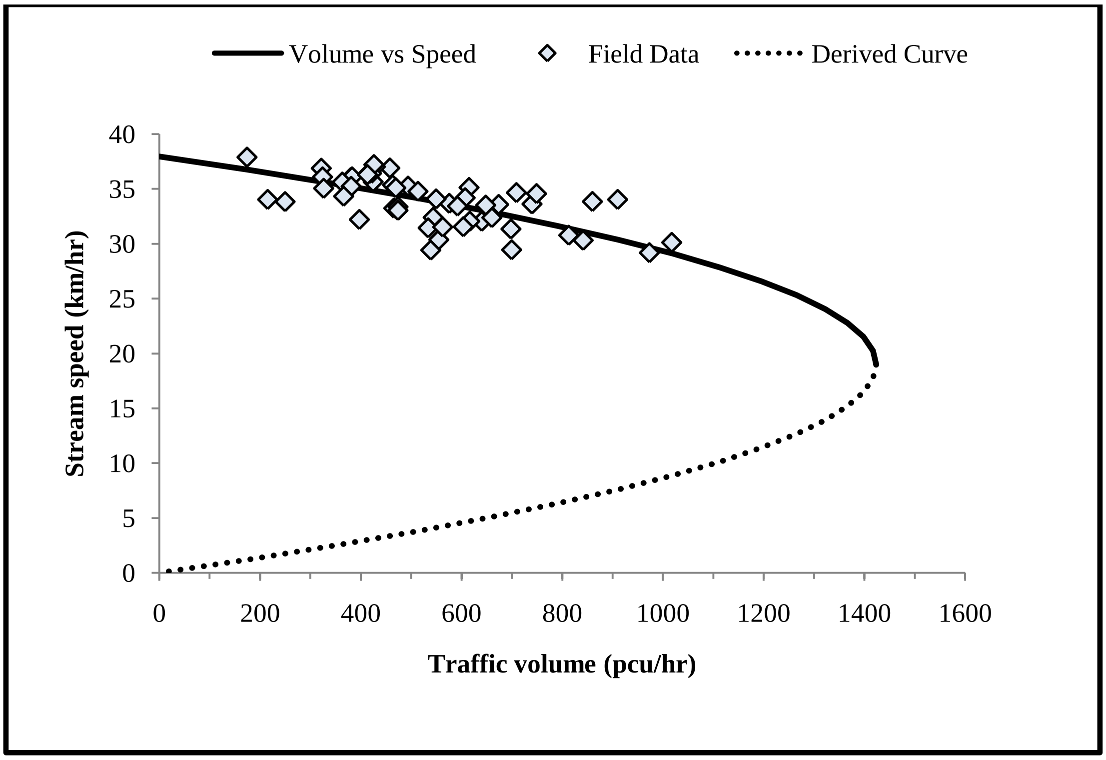


Figure 5.13.b Speed-volume relationship at section I-1

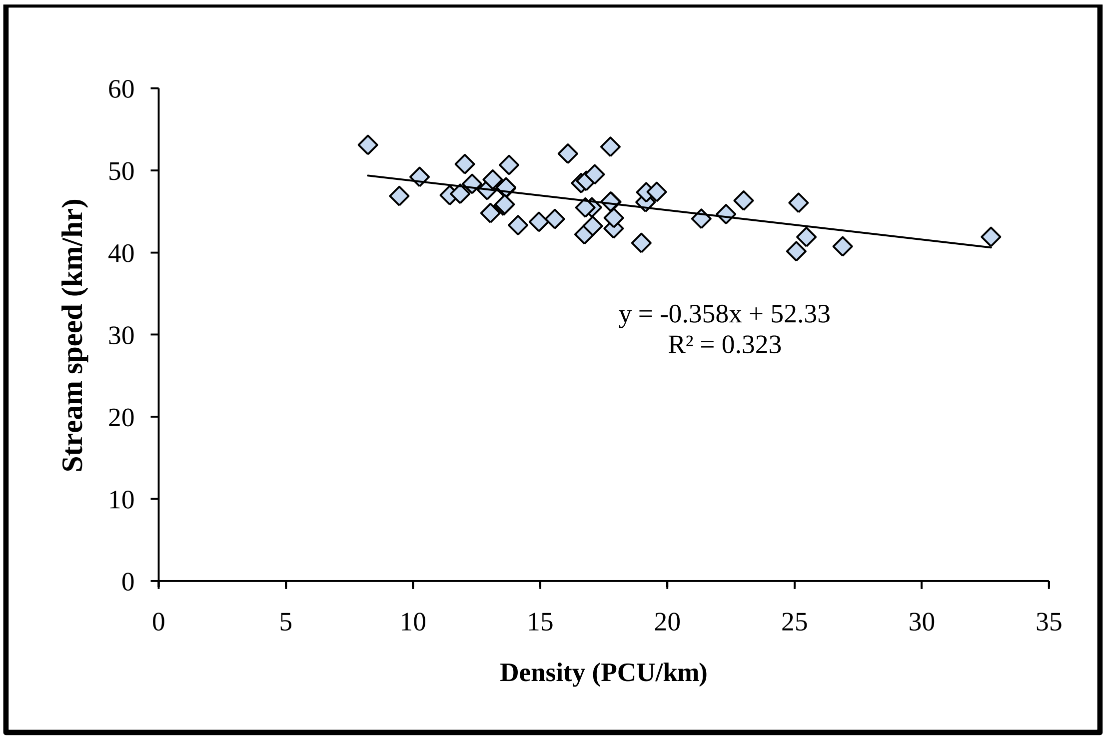


Figure 5.14.a Speed - density relationship at section I-4

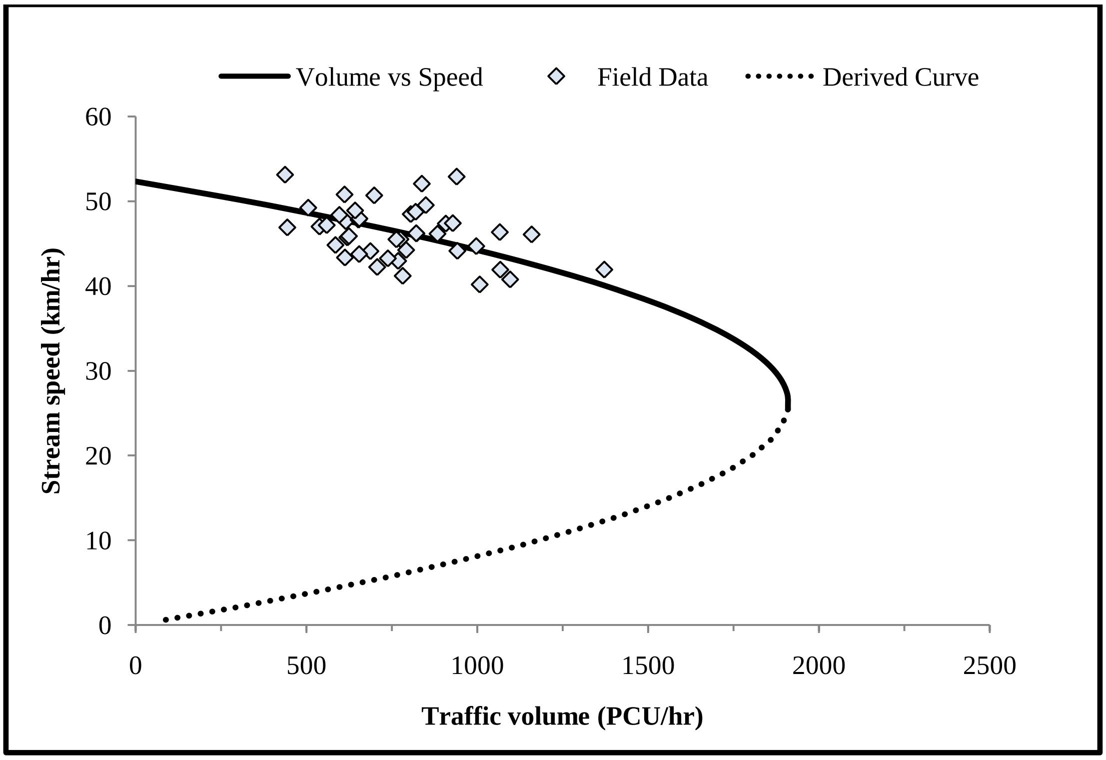


Figure 5.14.b Speed - volume relationship at section I-4

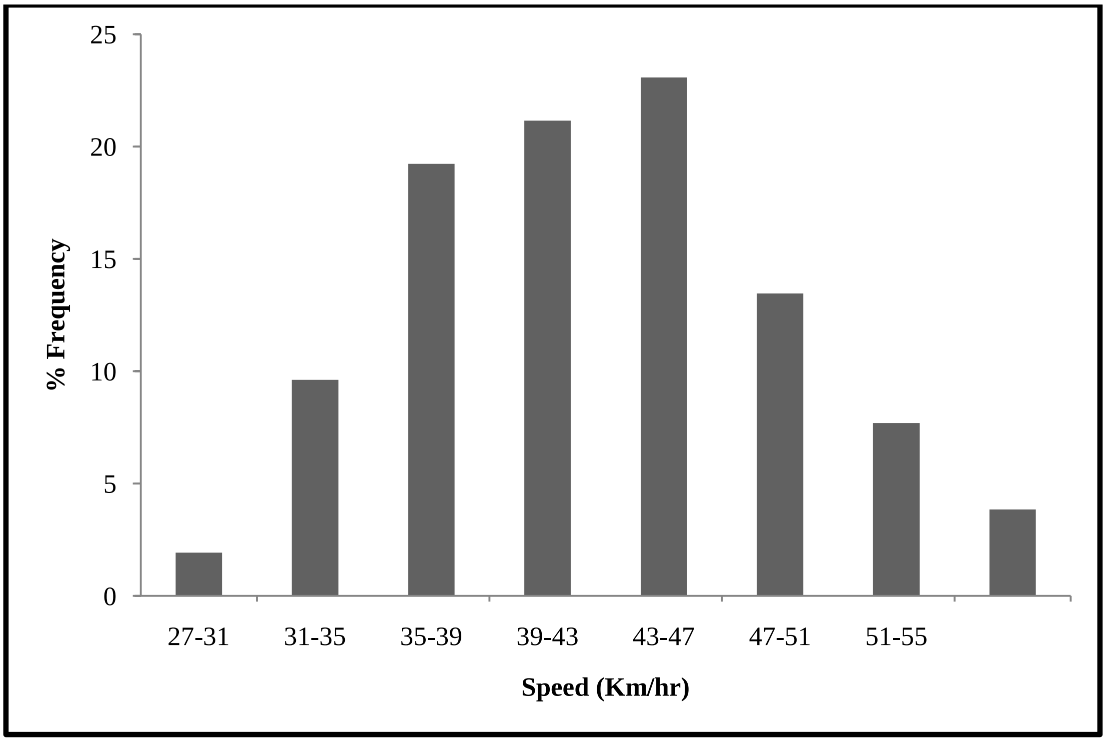


Figure 5.15.a Free-flow speed frequency distribution at section I-1

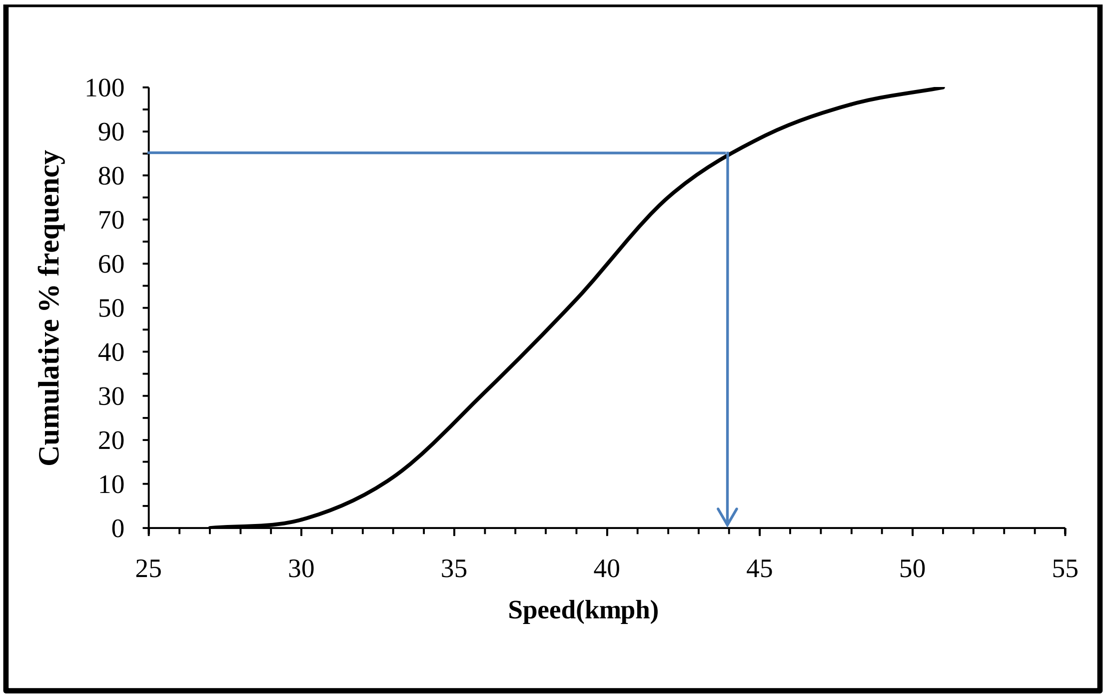


Figure 5.15.b Cumulative frequency distribution of free-flow speed and 85th percentile speed at section I-1

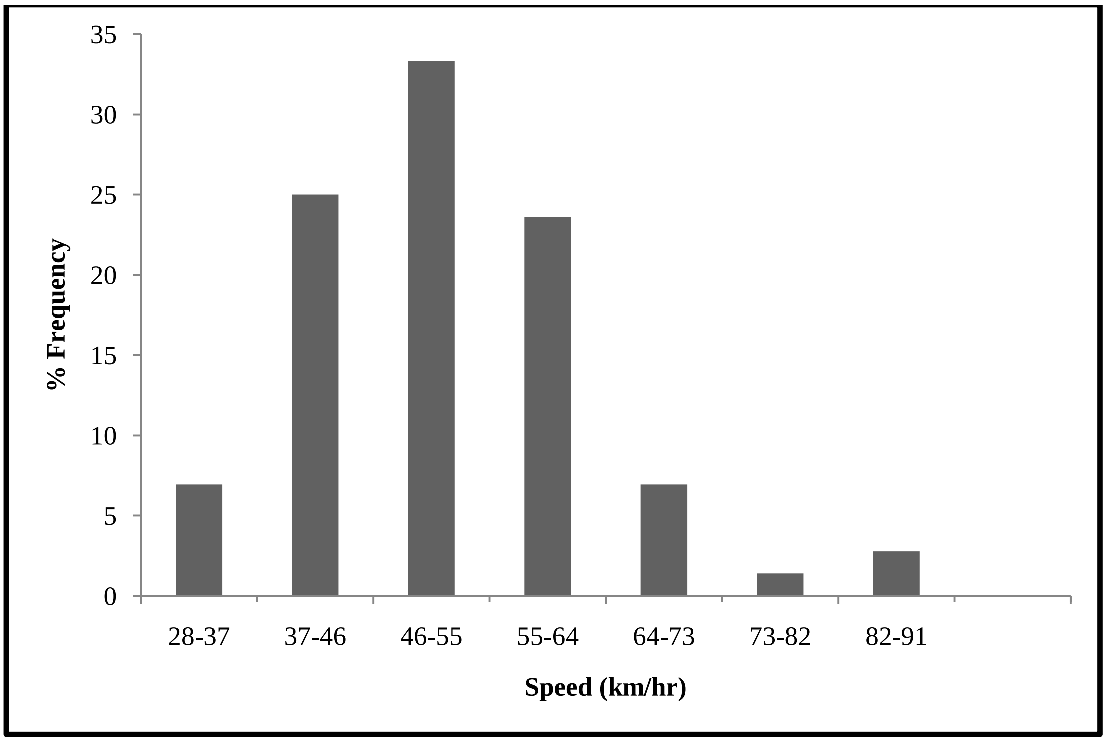


Figure 5.16.a Free-flow speed frequency distribution at section I-4

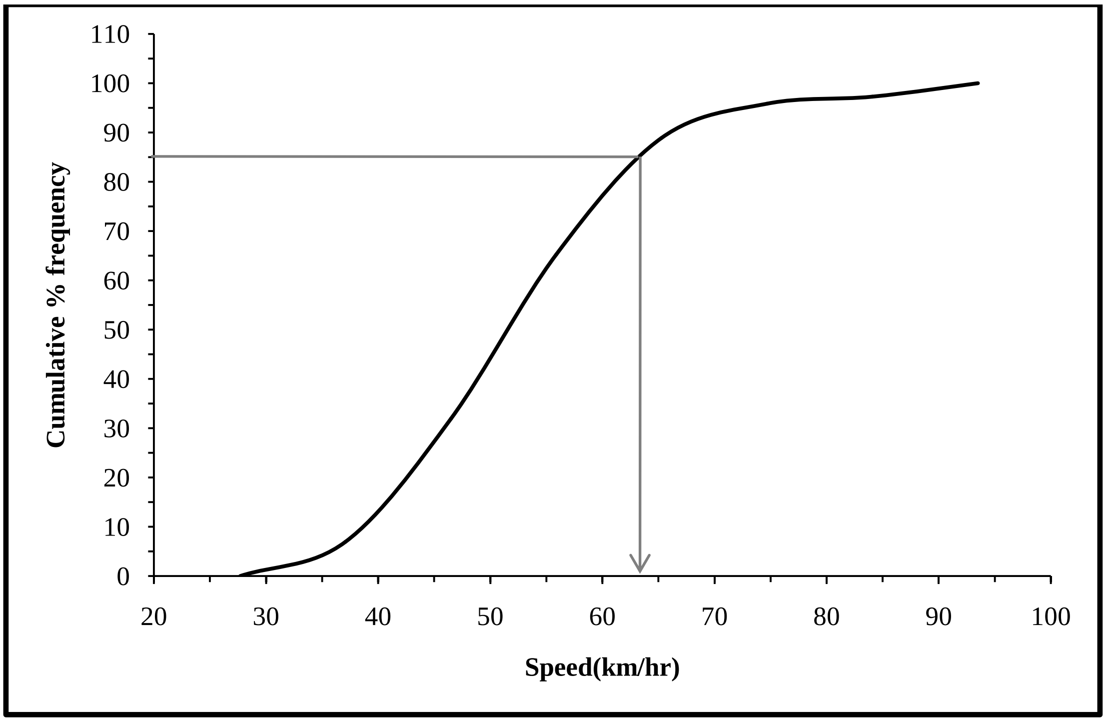


Figure 5.16.b Cumulative frequency distribution of free-flow speed and 85th percentile speed at section I-4

The 85th percentile speed of all sections were found following the similar procedure as displayed in above figures and presented in Table 5.4. It can be observed that the capacity and the corresponding operating speed of a road section vary for different highways located in different parts of India.

Table 5.4 Speed distribution characteristics on intermediate-lane roads

Section ID	Capacity (PCU/hr)	Operating speed of Standard Car (km/hr)
I-1	1423	44
I-2	2082	72
I-3	2000	59
I-4	1909	63
I-5	1456	37
I-6	1850	53

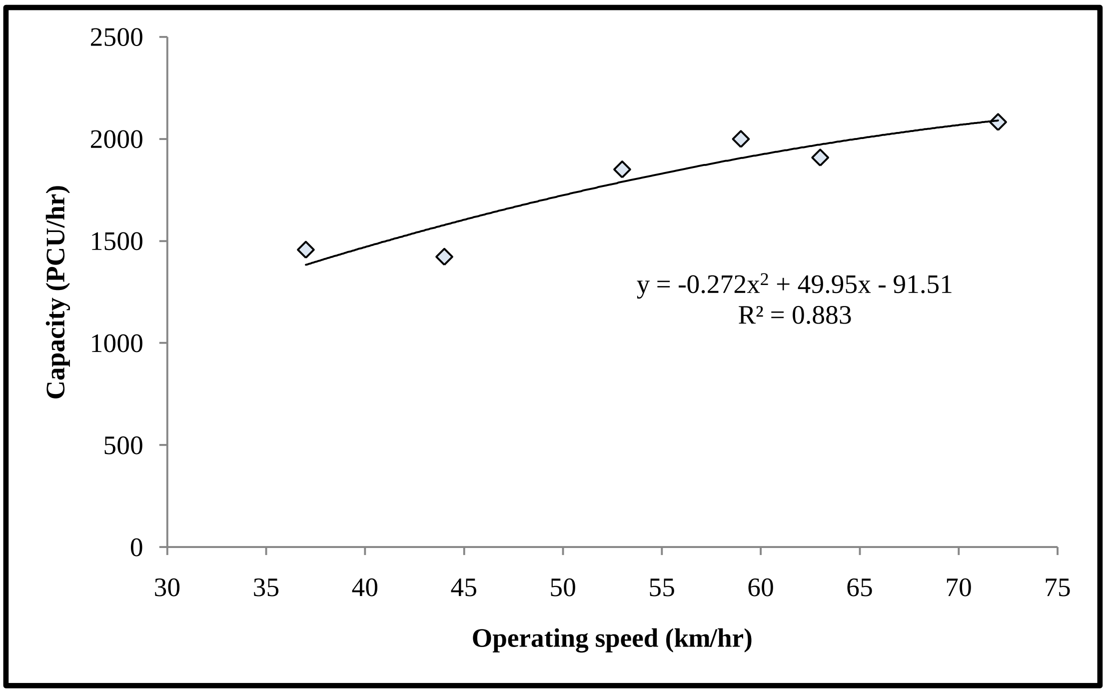


Figure 5.17 Relationship between operating speed and capacity at intermediate-lane sections

The capacity values were plotted against the corresponding operating speeds and a polynomial relationship was found to be best-fit to describe such relation which is given in Equation 5.5.

$$C_{intermediate\text{-}lane} = -0.272\, v_{os}^{2} + 49.95\, v_{os} - 91.51 \qquad (5.5)$$

Where;

$C_{intermediate\text{-}lane}$ = capacity of an intermediate-lane inter-urban road (PCU/hr)

v_{os} = operating speed (km/hr)

5.3.3 Model Validation

In order to test the validity and reliability of the model thus obtained, data were collected for one more section of intermediate-lane road the details of which is presented in Table 5.5. The procedure to estimate the capacity using the plot between traffic speed and volume was repeated. Figure 5.18 (a and b) shows the speed-volume relationship for the field data collected at SH-26. The capacity value for the new section was estimated to be 1979 PCU/hr. The free flow speed of standard cars at this section was also observed to find the operating speed. The 85th percentile free flow speed for SH-26 was found to be 68 km/hr (Figure 5.19.a and 5.19.b).

Table 5.5 Capacity obtained from field data and from Equation 5.5

Section name	Carriageway width (m)	Total capacity from field data PCU/hr	Operating speed (km/hr)	Capacity from Eq. 5.5	% difference
SH-26	5.50	1979	68	2047	3

The difference between the field capacity and the capacity estimated using Equation 5.5 as given in Table 5.5 is very low which validates the model developed between operating speed and capacity on intermediate-lane roads.

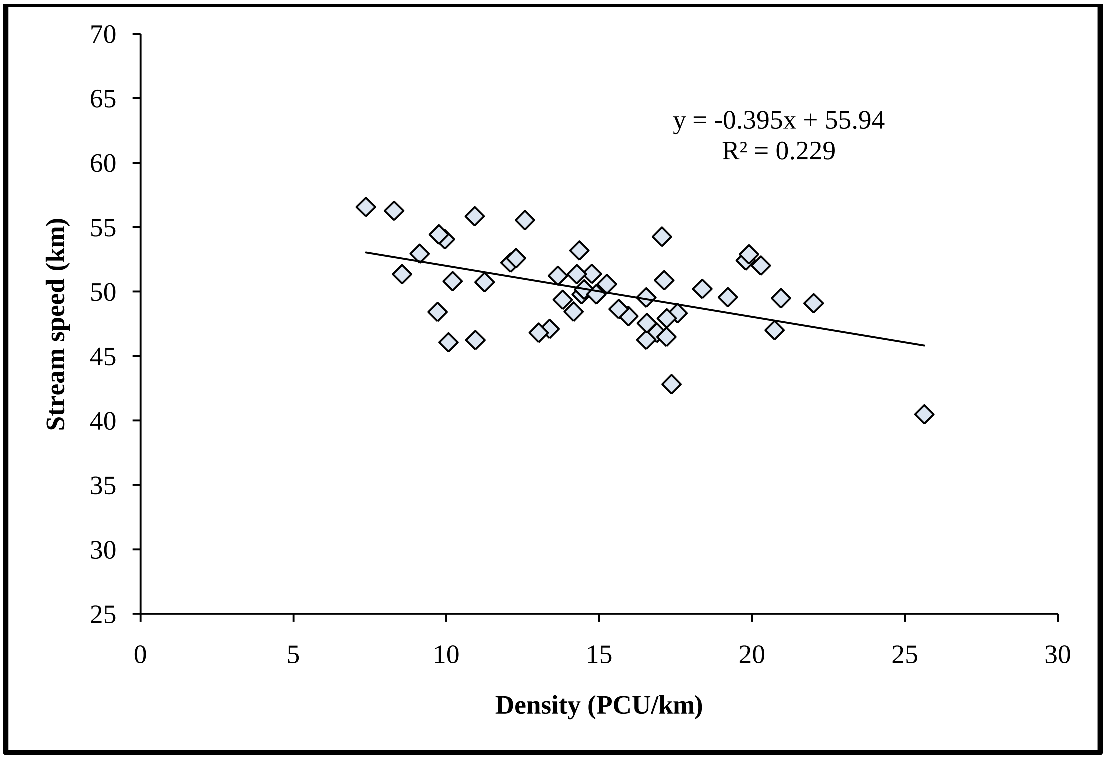


Figure 5.18.a Speed - density relationship at I-7

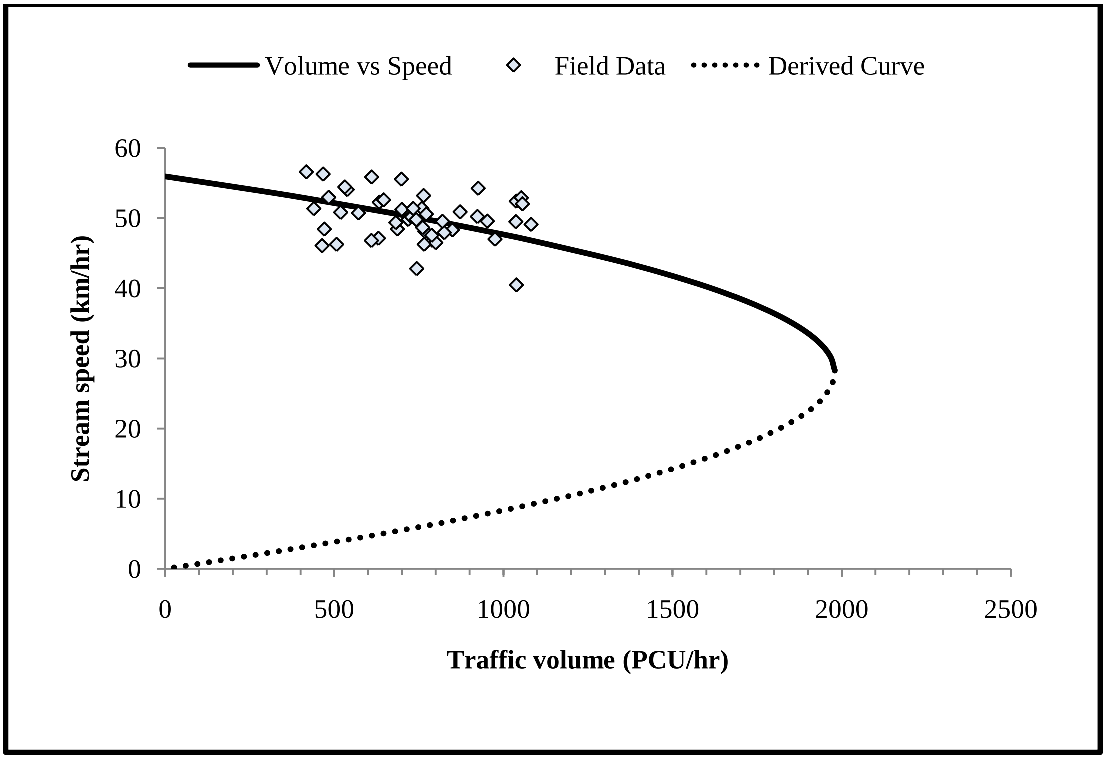


Figure 5.18.b Speed-volume relationship at I-7

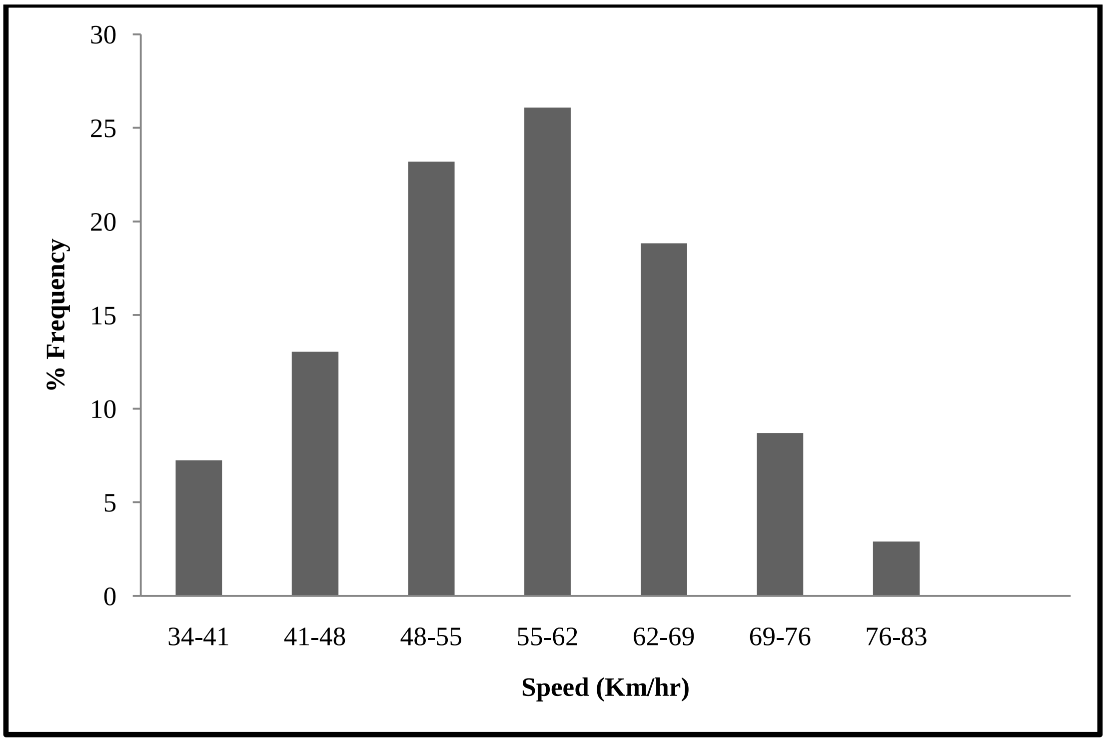


Figure 5.19.a Free-flow speed frequency distribution at section I-7

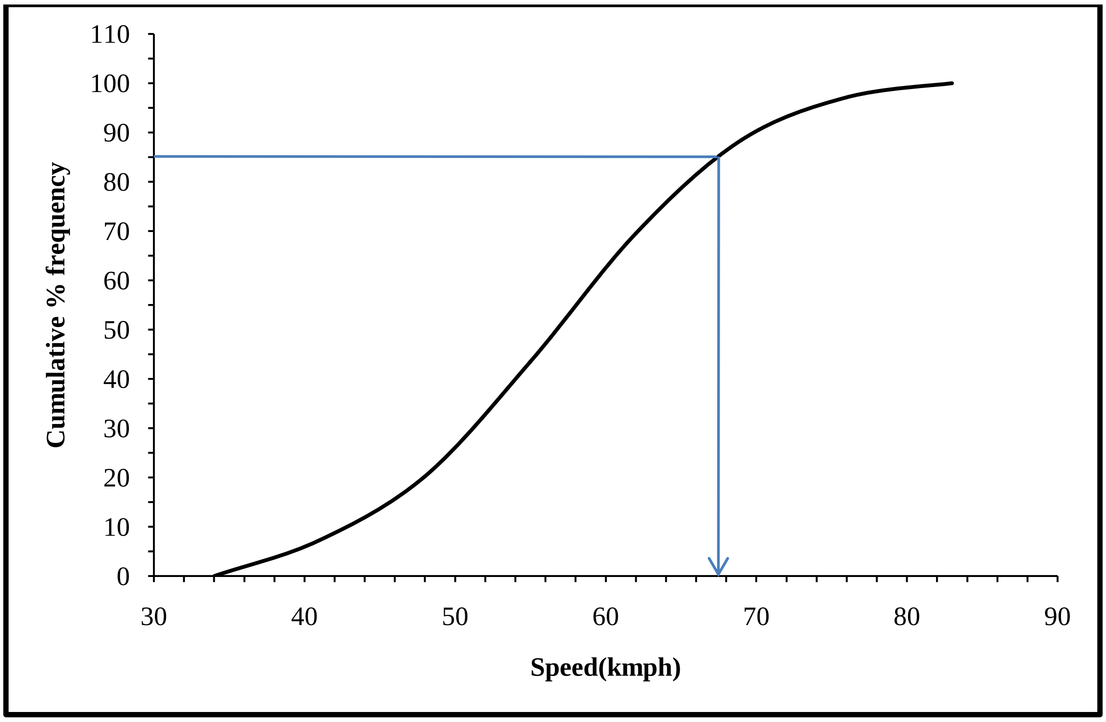


Figure 5.19.b Cumulative frequency distribution of free-flow speed and 85th percentile speed at I-7

5.4 SINGLE-LANE ROADS

5.4.1 General

The road surface occupancy on single-lane roads are generally governed by the size and weight and operating capability of vehicles. Therefore the speed of vehicles in the traffic stream on such roads is liable to excessive change as smaller vehicles are sometimes forced to leave the pavement and use the shoulder in order to make way for larger vehicles. As a result of the increased frequency of using the brakes, the stream speed will decrease and so will the capacity. Free flow speed is also expected to decrease as the drivers tend to accelerate less on single-lane roads due to safety concerns that a narrow carriageway necessitates along with other parameters. Hence the objective here is to find if there is a trend between the operating speed of standard cars and the capacity of single-lane roads.

5.4.2 Data Collection and Analysis

The details of the sections selected for this study are given in Chapter 3 (Table 3.1 and 3.6). Speed-flow diagrams were developed using the Greenshields method and field capacities were estimated for the selected sections. Figure 5.20 (a and b) and

Figure 5.21 (a and b) displays the speed-flow diagrams for section S-1 and S-2 respectively. The operating speed of standard cars was also obtained using the 85th FFS of these vehicles for all the sections. The details of single-lane section capacities and corresponding operating speeds obtained in this manner are given in Table 5.6

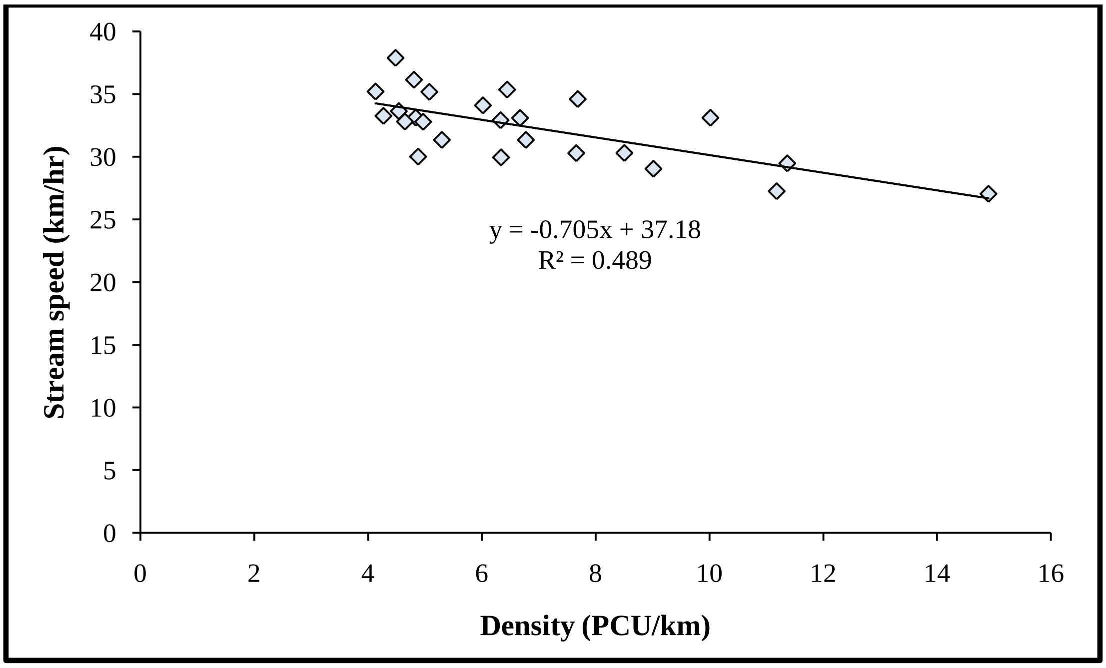


Figure 5.20.a Speed - density relationship at S-1

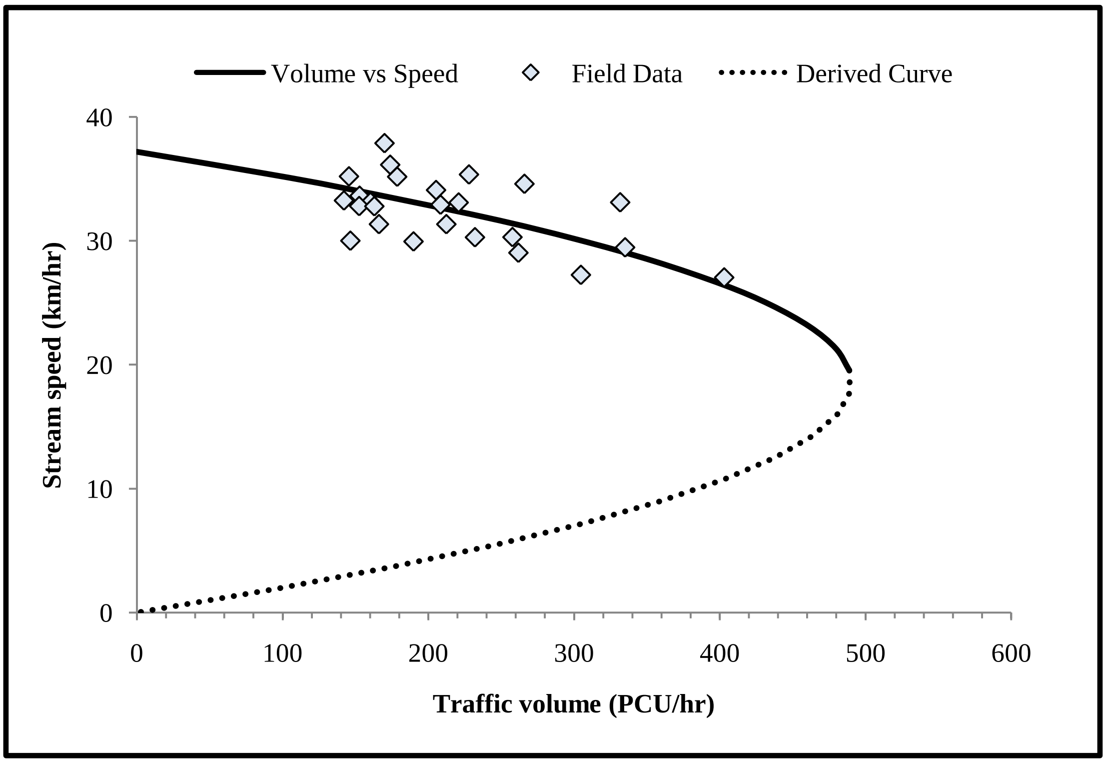


Figure 5.20.b Speed-volume relationship at S-1

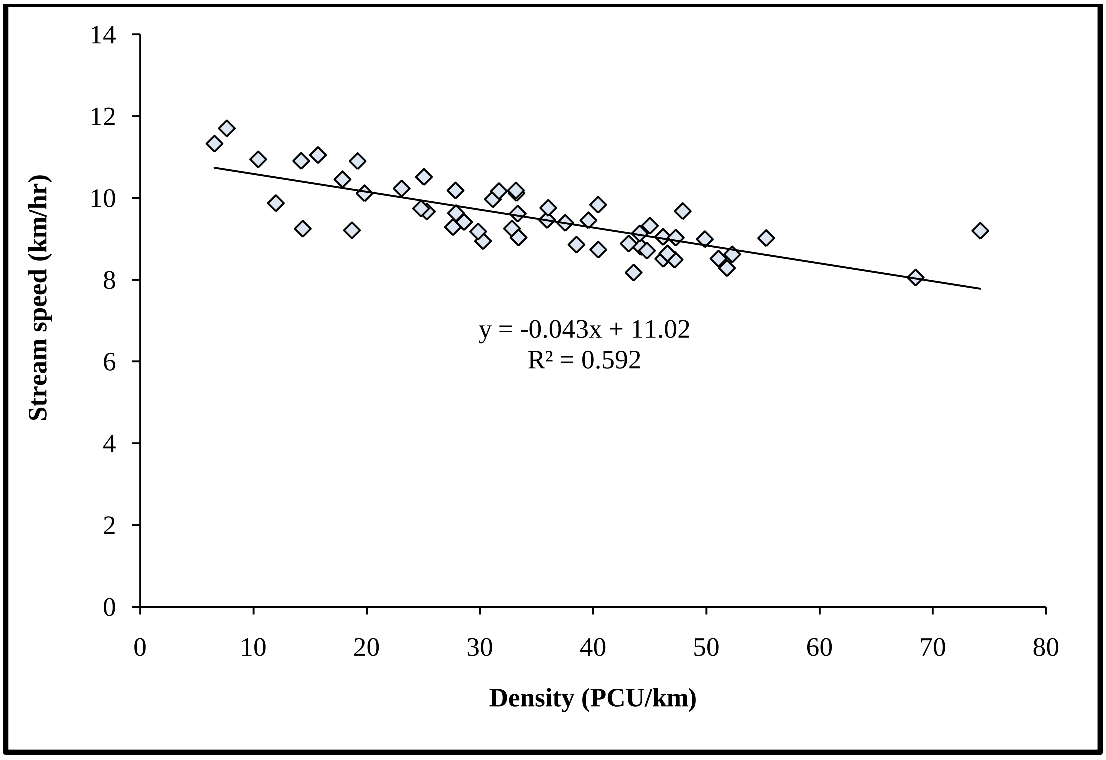


Figure 5.21.a Speed - density relationship at section S-2

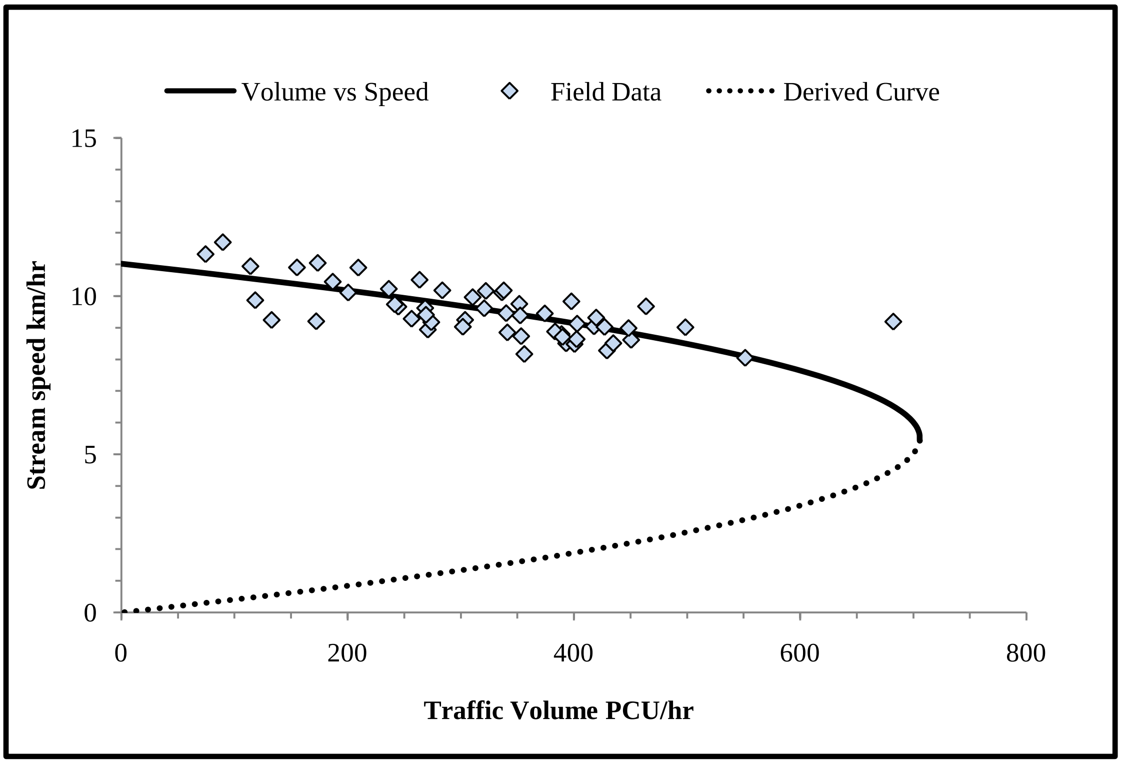


Figure 5.21.b Speed - volume relationship at section S-2

Table 5.6 Speed distribution characteristics on single-lane roads

Section ID	Capacity (PCU/hr)	85^{th} Percentile FFS of Standard Car (km/hr)
S-1	488	32
S-2	706	43
S-3	893	42
S-4	1090	65

The operating speeds were plotted against the capacity values at each section and a best fit line was drawn. A second degree polynomial curve was obtained which is displayed in Figure 5.22. Therefore the relationship between operating speed and capacity on single-lane roads may be expressed as in Equation 5.6.

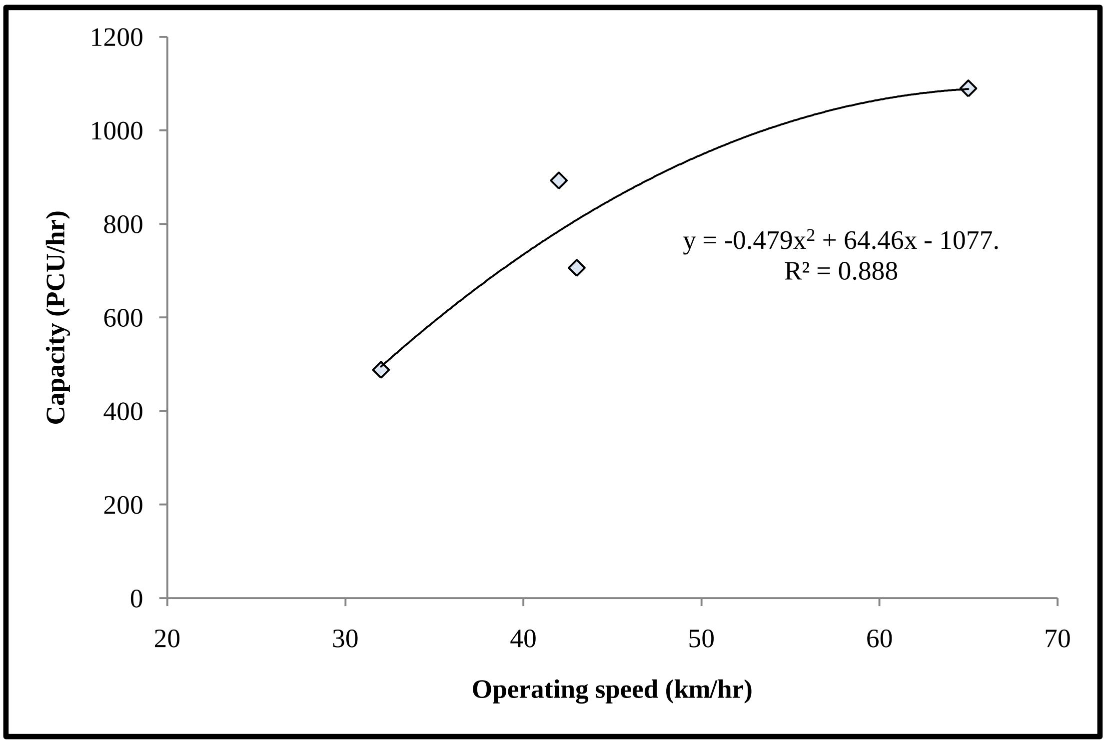


Figure 5.22 Relationship between operating speed and capacity at single-lane sections

$$C_{single\text{-}lane} = -0.479v_{os}^2 + 64.46\ v_{os} - 1077.0 \qquad (5.6)$$

Where;

$C_{single\text{-}lane}$ = capacity of a single-lane inter-urban road (PCU/hr)
v_{os} = operating speed (km/hr)

5.4.3 Model Validation

In order to test the reliability of the model thus obtained, field data was collected for one more section of single-lane road. The capacity of the new section was estimated using speed-flow diagrams as displayed in Figure 5.23 (a and b). The operating speed of the standard cars was also calculated (Figure 5.24.a and 5.4.b) to find the capacity using Equation 5.5. The details of the selected section and the result of the comparison between the capacity values obtained from classic speed-flow method and the operating speed-capacity model are presented in Table 5.7. The low difference between the two capacity values (9.90 %) validates the above model.

Table 5.7 Capacity obtained from field data and from Equation 5.6

Section ID	Operating speed (km/hr)	Capacity from field data (PCU/hr)	Capacity from operating speed (PCU/hr)	% difference
S-5	64	1078	1087	0.83

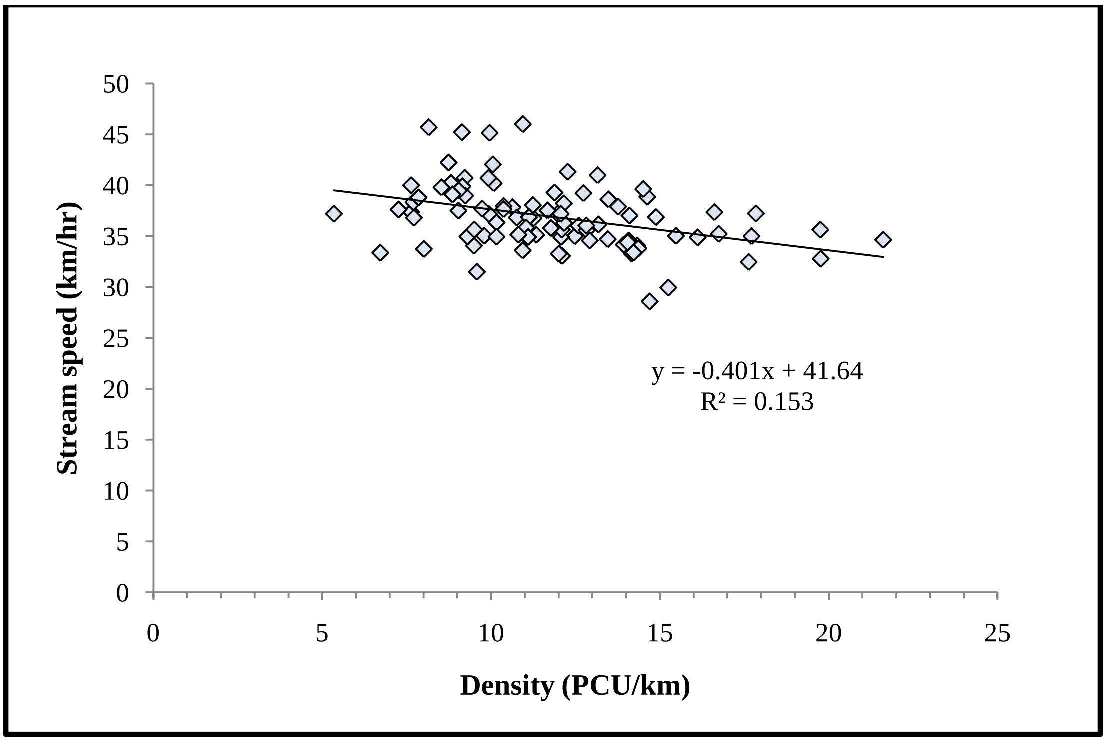


Figure 5.23.a Speed - density relationship at S-5

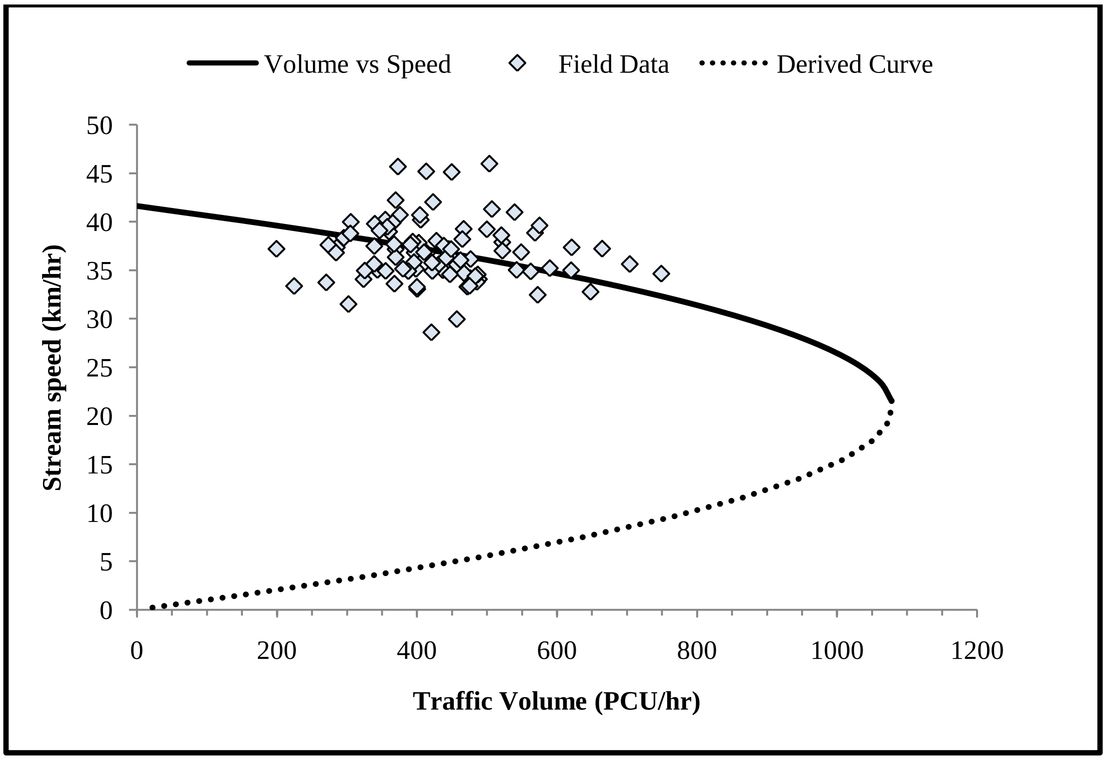


Figure 5.23.b Speed-volume relationship at S-5

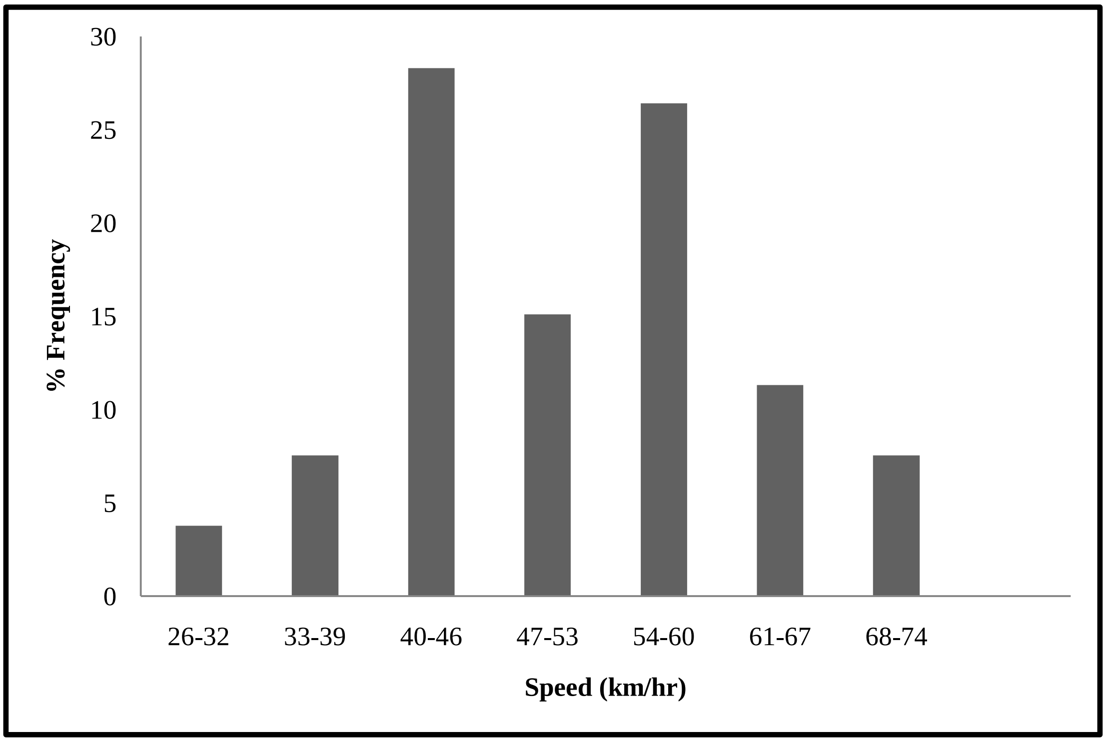


Figure 5.24.a Free-flow speed frequency distribution at section S-5

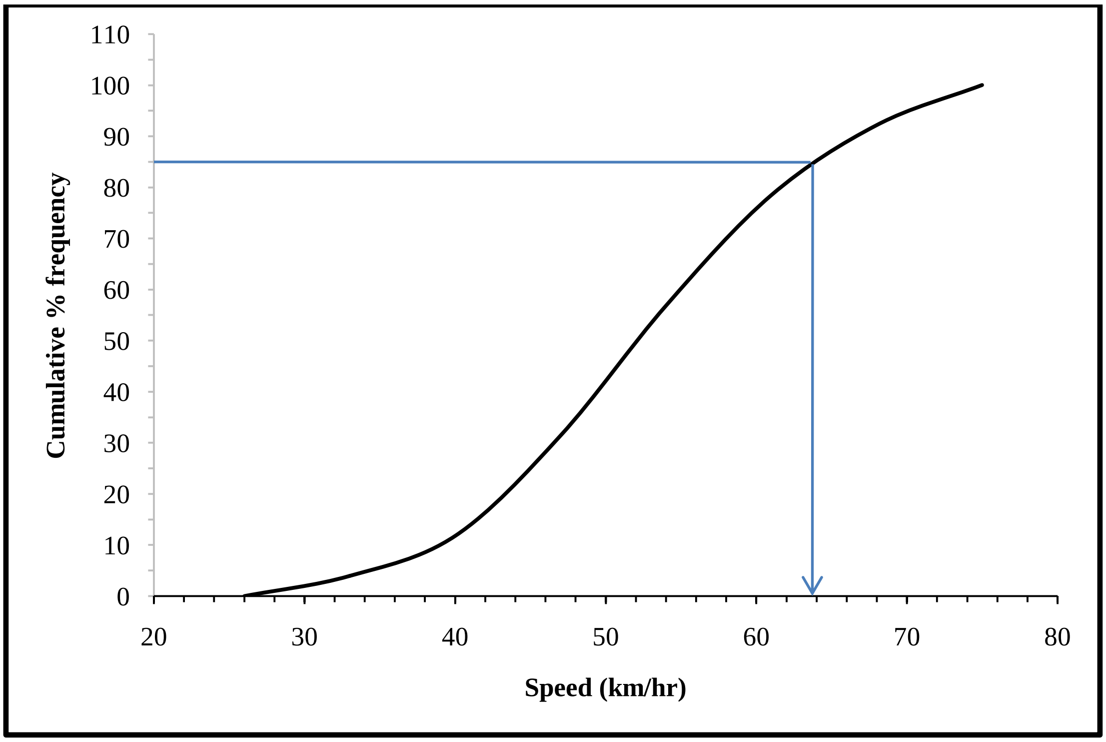


Figure 5.24.b Cumulative frequency distribution of free-flow speed and 85th percentile speed at S-5

5.5 SUMMARY

The capacity was estimated for ten sections of two-lane, six sections of intermediate-lane and five sections of single-lane inter-urban roads in different parts of India using Greenshields model. The capacity values for each highway category were different which may be attributed to different traffic composition and driver behavior or road surface conditions. The overall effects of such influencing factors result in the speed of vehicles passing these sections. According to HCM the capacity of road varies with the FFS on the road but unlike multilane highways, such influence is not quantified for two-lane roads in the manual. Therefore an attempt was made to develop a relationship between the 85^{th} percentile FFS as the operating speed of standard cars and capacity of different road categories in this study.

By developing the cumulative frequency distribution of free flow speed of standard cars the operating speed of standard cars on each section was obtained. Plotting these operating speeds against the capacity values which were already estimated using the field data, an equation was formed for each road type. These equations relate the capacity of two-lane, intermediate-lane and single-lane inter-urban highways. Further, one more section of each road type was selected in order to test the reliability of the developed equations. The capacity for each section was again estimated using the Greenshields model and 5.0 minute volume counts. It was also estimated using the models developed which incorporates the operating speed of standard cars. It was observed that the difference between capacity values obtained from the two methods were very low which validates the equations developed in this study.

The models developed in this chapter provide the base section capacity of two-lane, intermediate-lane and single-lane inter-urban roads. As the capacity of a road is influenced by many factors, the effect of any single or multiple factor on the capacity of the proposed road types may be evaluated with regards to the change they inflict on the operating speed of those sections.

It should be noted that the capacity-operating speed models developed in this research work were developed on sections where operating speeds varied between certain values with respect to the type of the roads. Therefore extrapolations of these equations should be done cautiously.

The factors selected as the subject of study for the following chapters of this research work are the carriage way width, paved shoulder width and presence of gradients and horizontal curves.

CHAPTER – 6

EFFECT OF CARRIAGEWAY AND PAVED SHOULDER ON CAPACITY

6.1 EFFECT OF CARRIAGEWAY WIDTH

6.1.1 General

As per HCM (2010) capacity is defined as the maximum hourly rate at which standard cars can be accommodated for by a given segment of a road facility under prevailing roadway, traffic and control conditions. With this definition such maximum number of standard cars can be disturbed by variation in the roadway and traffic and control conditions. The capacity of two-lane, intermediate-lane and single-lane inter-urban roads was studied under uninterrupted flow conditions and away from intersections and speed breakers in chapter 5 of this research work.

The heterogeneous characteristics of the traffic on Indian highways were discussed in previous chapters. One of the associated driving behaviors due to traffic mix is that vehicles tend to utilize the whole carriageway width which occasionally includes use of the opposite direction (Chandra and Kumar 2003). Also the importance of knowing the capacity and factors affecting its variations was discussed in previous chapters. The objective of this chapter is to study the effect of carriageway-width on the capacity of two-lane roads. When budget is available, some two-lane roads are provided with paved shoulders on either side. Since lane discipline is not much respected on Indian highways due to mixed traffic, the paved shoulders are also utilized by many drivers when required and hence contribute to whole carriageway width. Single and intermediate-lane roads are excluded from this study as the reason for construction of such substandard roads are either economic or environmental concerns.

From the literature it is understood that increase in the lane width generally results in increase of capacity. Chandra and Kumar (2003) observed the variation of PCU values of different vehicles due to change in the road width and suggested that 0.6 lane widening increases the capacity of a two-lane road up to 0.24 percent for carriageway widths ranging from 5.5 to 8.8m. Leong (1968) showed that capacity drops 28 percent due to decrease in lane width from 3.7 to 2.75. In this chapter an attempt is made to quantify the effect of lane width variation on capacity by comparing capacity from field data and capacity obtained from Equation 5.4 which incorporates the operating speed as a determining variable.

6.1.2 Field Data

Six sections of two-lane roads, the width of which ranged from 6.5 m to 9.8 m were selected. The pavement material used for shoulder on sections with such provision was same as the carriageway. The site details of these sections are given in Table 3.1 and 3.2. The same procedure of video recording, data extraction and analysis procedure adopted in chapter 5 was performed to develop speed-density relationship for these sections. Then speed-volume curves were plotted for each section and the corresponding capacities were estimated. Figure 6.1 (a and b) and 6.2 (a and b) show the speed-density and speed-volume curves for sections T-12 and T-15 respectively. The capacity values and the carriageway and shoulder width at each section are given in Table 6.1.

Table 6.1 Capacity of two-lane sections with varying carriageway widths

Section ID (1)	Carriageway width excluding shoulder (m) (2)	Width of paved shoulder on either side (m) (3)	Total Carriageway width (m) (4)	Capacity (PCU/hr) (5)
T-1	7.1	0.0	7.1	3162
T-11	6.5	0.0	6.5	2641
T-12	7.5	0.6	8.7	3274
T-13	8.0	0.9	9.8	3843
T-14	7.0	1.0	9.0	3496
T-15	6.9	1.4	9.7	4357

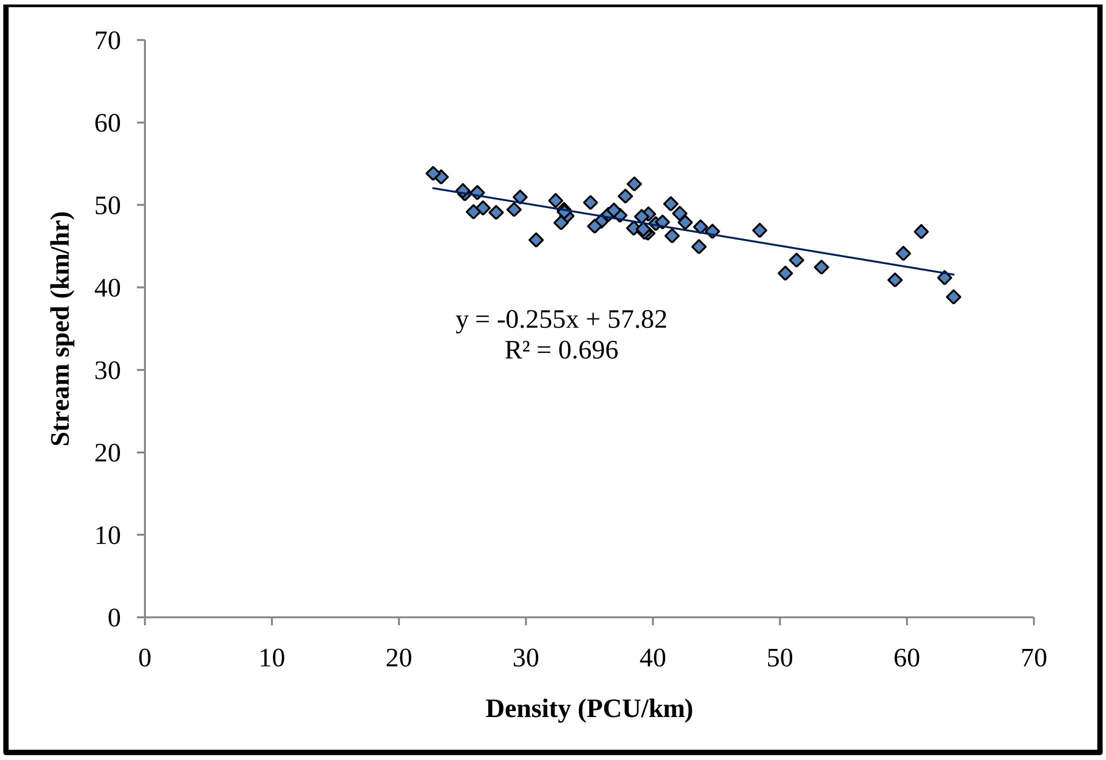


Figure 6.1.a Speed-density relationship at section T-12

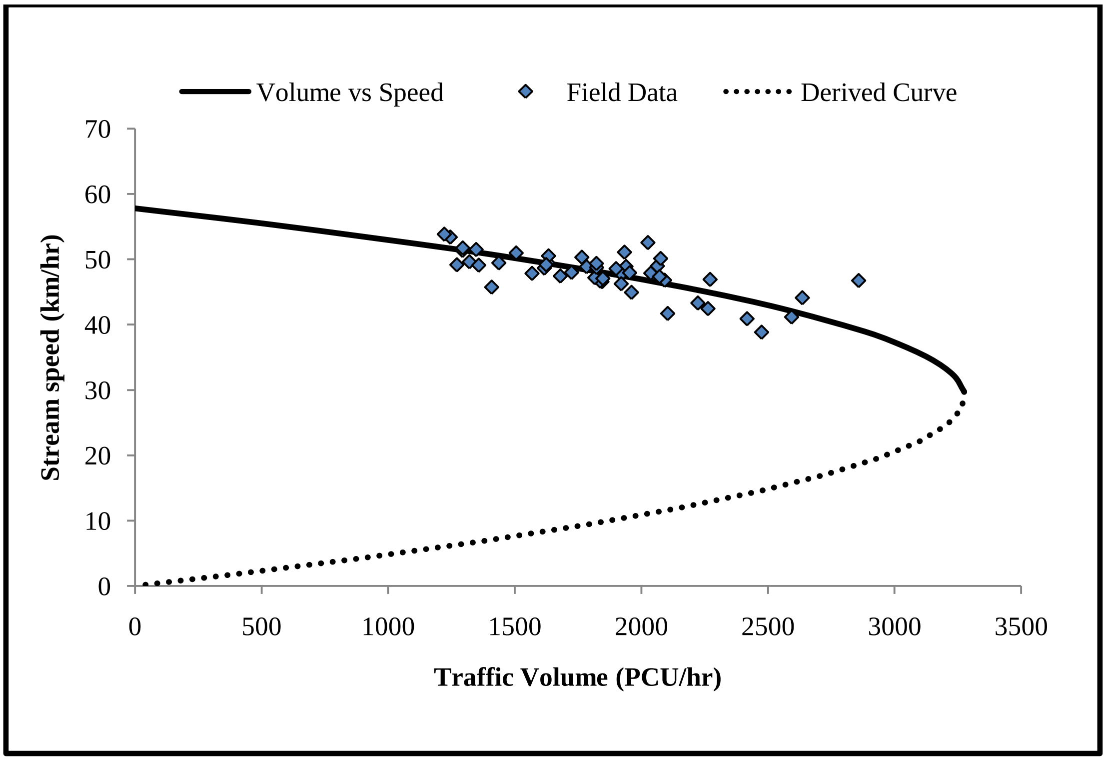


Figure 6.1.b Speed-volume relationship at section T-12

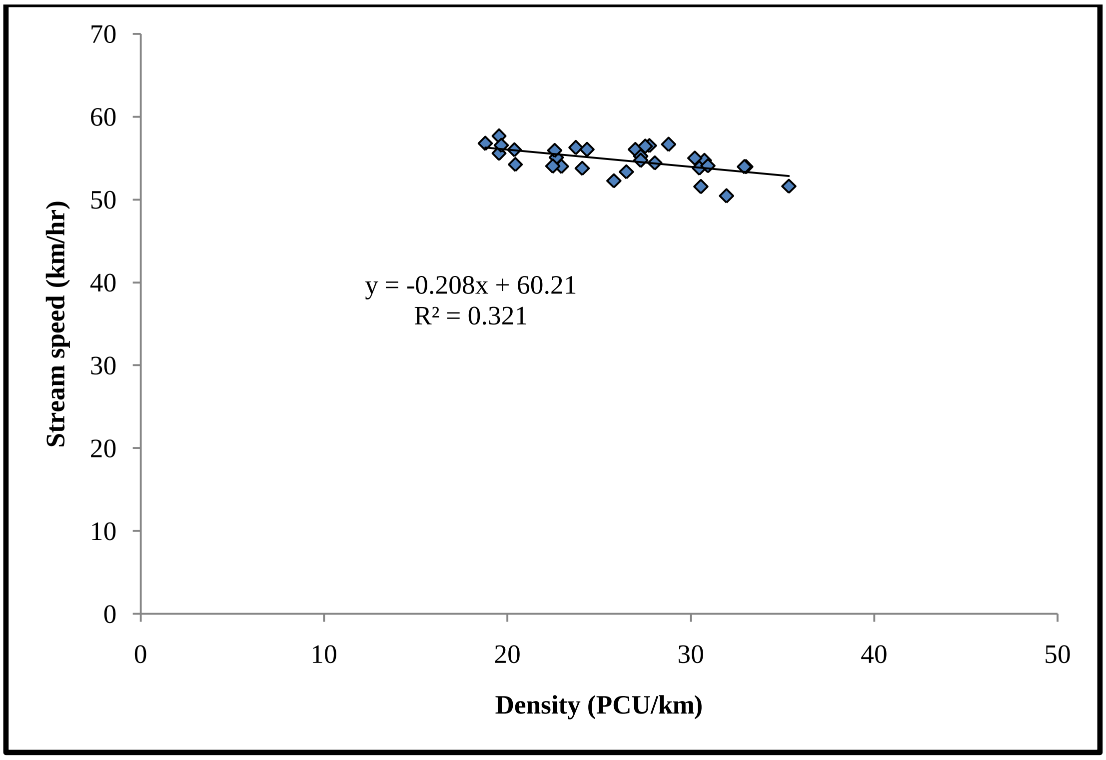


Figure 6.2.a Speed-density relationship at section T-15

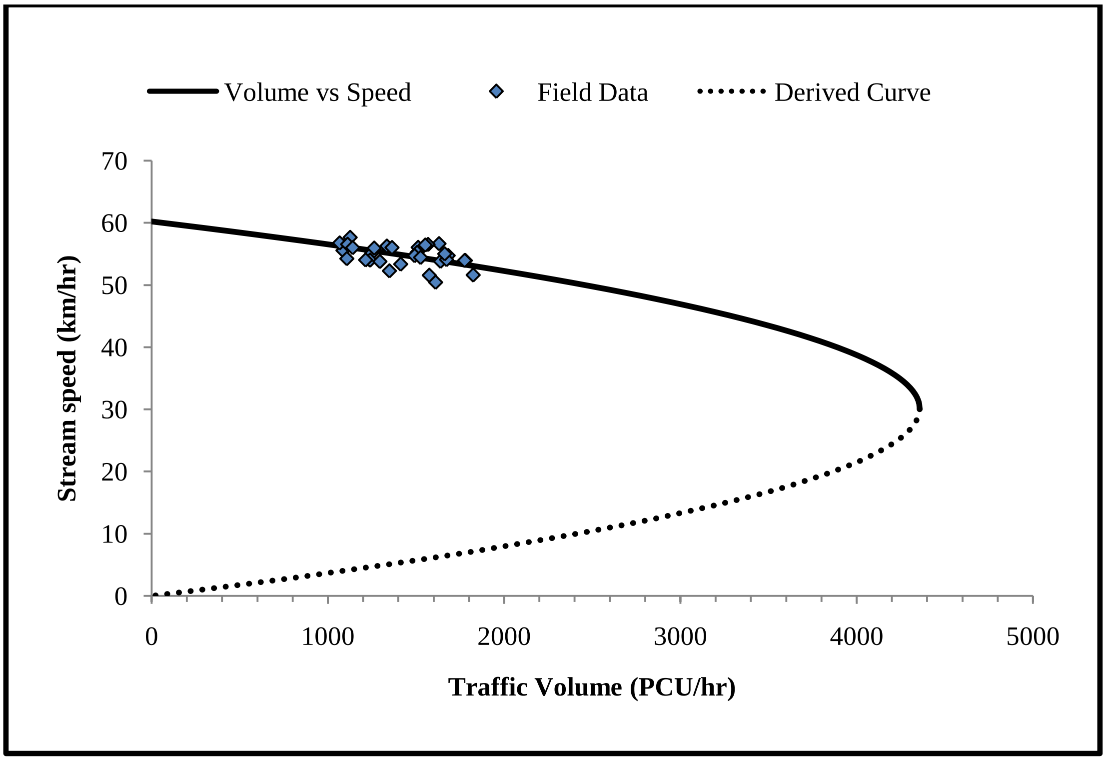


Figure 6.2.b Speed-volume relationship at section T-15

In order to find the effect of variation in the total width of the carriageway (including shoulders) on capacity, the capacity values obtained from speed-flow diagrams for each section were compared with the capacity of the same section assuming that the section is 7.0 m wide and only earthen shoulders are provided to the both sides of the road. The difference of carriageway width with such assumption is given in Column 2 of Table 6.2. With this assumption, the capacity of a road with 7.0 m width may be estimated using Equation 5.4. Therefore the 85th percentile free flow speed was estimated at each section by developing cumulative distribution of free flow speed. The capacity values estimated using Equation 5.4 are given in Column 4 of Table 6.2 for each section. The difference between the capacities from field data (Table 6.1) and Equation 5.4 which is given for each section in Column 6 of Table 6.2 can therefore explain the influence of variation in carriageway width on capacity.

Table 6.2 Variation in capacity due to change in total carriageway width

Section ID (1)	**Change in carriageway width with respect to 7m wide two-lane road (m) (2)**	**Operating speed (km/hr) (3)**	**Estimated Capacity using Equation 5.4 (PCU/hr) (4)**	**Field capacity from Table 6.1 (PCU/hr) (5)**	**Change in Capacity due to assumed change in carriageway width (PCU/hr) (6)**
T-1	0.10	72.91	2935	3162	227
T-11	-0.5	72.80	2929	2641	-288
T-12	1.7	71.0	2826	3274	448
T-13	2.8	77.50	3173	3843	670
T-14	2.0	69.80	2756	3496	740
T-15	2.7	80.30	3303	4357	1054

6.1.3 Carriageway Width and Capacity

The difference between capacity values obtained from field data and Equation 5.4 (Column 6 of Table 6.2) were plotted against the assumed variation in the total carriageway width with respect to a 7.0 m wide carriageway (Column 2 of Table 6.2) and displayed in Figure 6.3. A linear relationship between the two variables was found to be best fit. The capacity variation is equal to zero when there is no change in the width of a 7.0 m wide standard two-lane road. Such relationship between total carriageway width and the associated capacity variation is given in form of Equation 6.1.

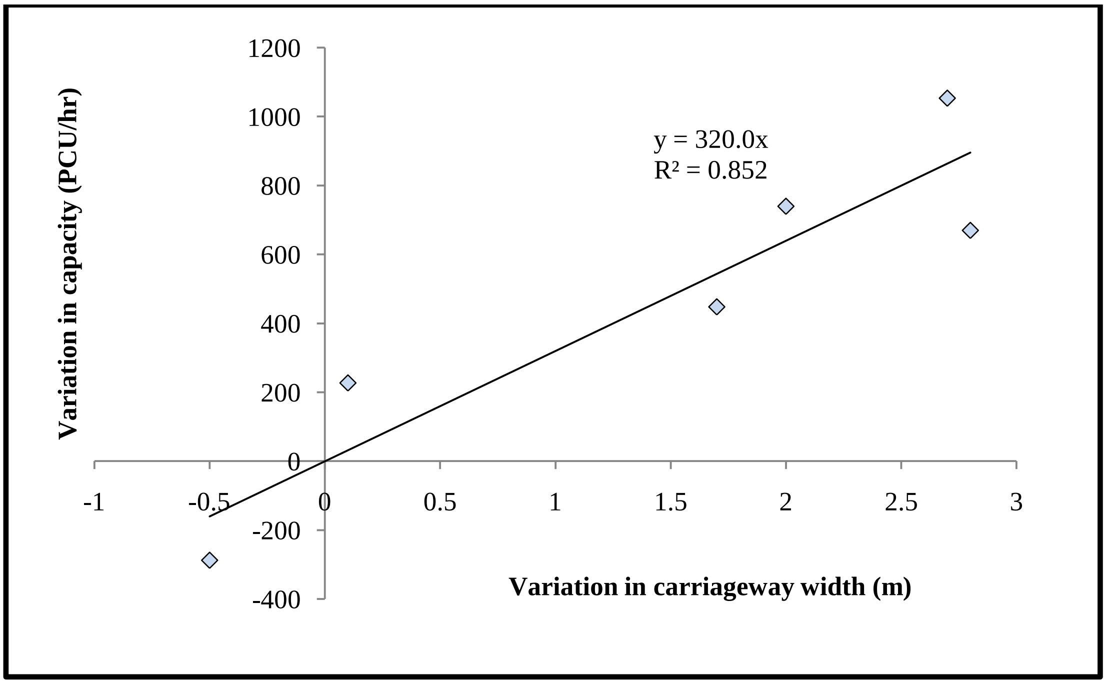


Figure 6.3 Variation in Capacity due to change in total carriageway width

ΔC_{wPCU} = 320.0*CW (6.1)

Where;

ΔC_{wPCU} = capacity variation due to change in the width of carriageway (PCU/hr)
CW = variation in total carriageway width compared to a standard 7.0 m width (m)

According to the model developed above, the capacity of a two-lane road increases about 320 PCU/hr for 1.0 m increase in the carriageway width. It is also observed that for a 0.50 m decrease in the width, the capacity decreases 160 PCU/hr.

Such variation is also depicted in Figure 6.4 as percent variation in capacity due to change in the width of carriageway in meters. The model derived in this manner in given in Equation 6.2. For 1.0 m increase in carriageway width, the capacity increases near ten percent. The results of this study contradict the findings of Leong (1968) and

Chandra and Kumar (2003) as mentioned earlier in this chapter. However, the amount reduction in capacity due to decrease in carriageway width was similar to the findings of Harwood (1990).

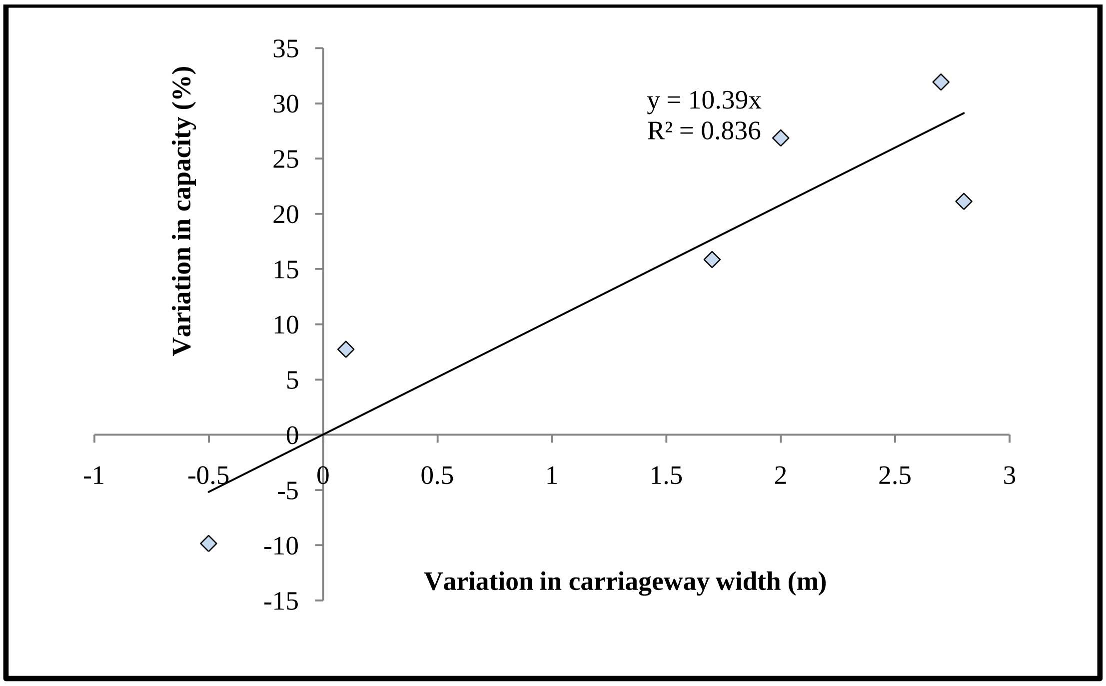


Figure 6.4 Percent variation in Capacity due to change in total carriageway width

$\Delta C_{w\%} = 10.39*CW$ (6.2)

Where;

$\Delta C_{w\%}$ = capacity variation due to change in the width of carriageway (%)
CW = variation in total carriageway width compared to a standard 7.0 m width (m)

6.2 EFFECT OF WIDTH OF PAVED SHOULDER ON CAPACITY

6.2.1 General

Shoulders create a sense of space openness to the drivers (Chandra 2005) and allow the traffic flow to benefit full service of the facility depending on the type and quality it is provided for. When shoulders are of earthen or any other type except paved type, vehicles tend to travel towards the centerline which reduces the effective lane width (Singal 2013). Also In case of congestion or obstruction due to presence of slow moving vehicles or a demand for overtaking, the paved shoulders if available can perform as an additional width to the carriageway allowing for the traffic stream to maintain its speed as well as security and space for correcting errors (Ben-Bassat and Shinar 2011).

It is acknowledged that paved shoulders contribute as an extension to total carriageway which leads to increase in the capacity of a two-lane road. But the effect of the width of paved shoulders is still not quantified. In order to study the effect of adding paved shoulders to the both sides of a two-lane inter-urban road on the capacity, 4 sections of two-lane roads where such provision was present (from Table 6.1) were selected. A sample image from one of the selected sections is given in Figure 6.5.

Some may challenge the fact that such provision could not be considered as a shoulder as the paved space beyond the road markings are just part of the running way and the white lines are merely helping the drivers to stay in the line. IRC: 35-1997 which provides guide lines for road markings, to the contrary, states that pavement edge lines are desirable where the shoulder is paved and is of similar texture to the main carriageway. Therefore the paved area beyond the lane marking "is" the paved shoulder provision.

Figure 6.5 Sample image of section T-12 with paved shoulder

6.2.2 Paved Shoulder Width and Capacity

It should be noted that the width of carriageway between shoulder markings are different at each section. In order to study the contribution of paved shoulder to increase in the capacity, first, with respect to the width of carriageway between the shoulder line markings, the theoretical capacity values obtained from Equation 5.4 (Column 4 Table 6.2) were adjusted for the width of carriageway between shoulder lines at each section using Equation 6.1.For example, the width of carriageway between shoulder lines on section T-12 is 7.5 m (Column 2 Table 6.1). Equation 5.4 is developed for sections with 7.0 m carriageway width. Therefore the capacity of section T-12 which is obtained from Equation 5.4 is adjusted for 0.5 m increase in width using Equation 6.1 (Column 3 of Table 6.3). The difference between the theoretically adjusted capacities and capacity values obtained from field data (Column 5 of Table 6.2) represents the effect of the added paved shoulder on capacity for this section as presented in Column 4 of Table 6.3. Similar procedure was repeated for the remaining three sections. Eventually, to measure the contribution of paved shoulders to variation in capacity, the values in Column 4 of Table 6.3 were plotted against the width of paved shoulders given in Column 2 of the same Table and a linear relationship was obtained. The model provides the increase in capacity with respect to the increase in width of paved shoulder in terms of PCU/hr as Figure 6.6 represents. Similarly, the variation in width of paved shoulder was modeled in terms of percent variation in capacity and presented in Figure 6.7.

Table 6.3 Effect of width of paved shoulders on capacity of two-lane roads

Section ID (1)	Width of paved shoulder (m) (2)	Adjusted capacity using Eq. 6.1 (PCU/hr) (3)	Difference between Field capacity and adjusted capacity (PCU/hr) (4)
T-12	0.60	2986	288
T-13	0.90	3493	350
T-14	1.0	2756	740
T-15	1.40	3271	1086

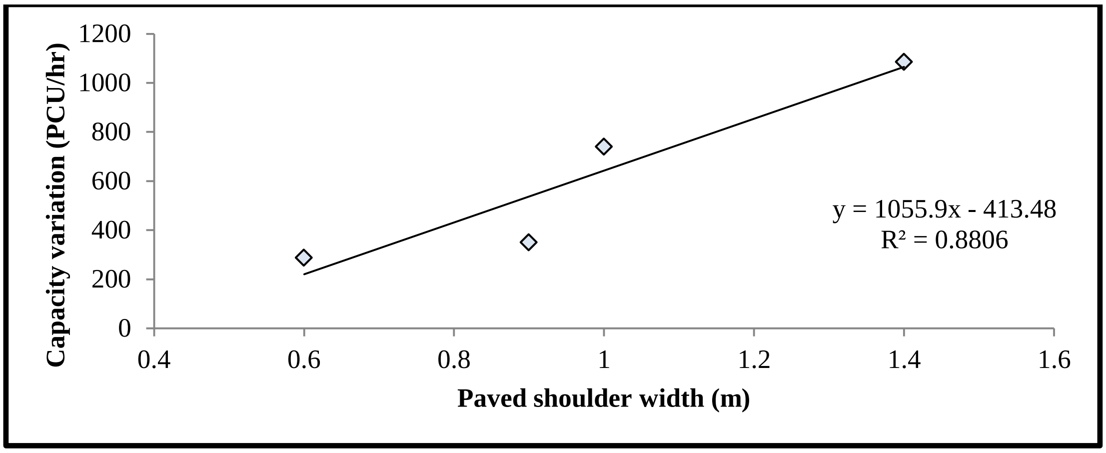


Figure 6.6 Variation in capacity of a two-lane road with provision of paved shoulder

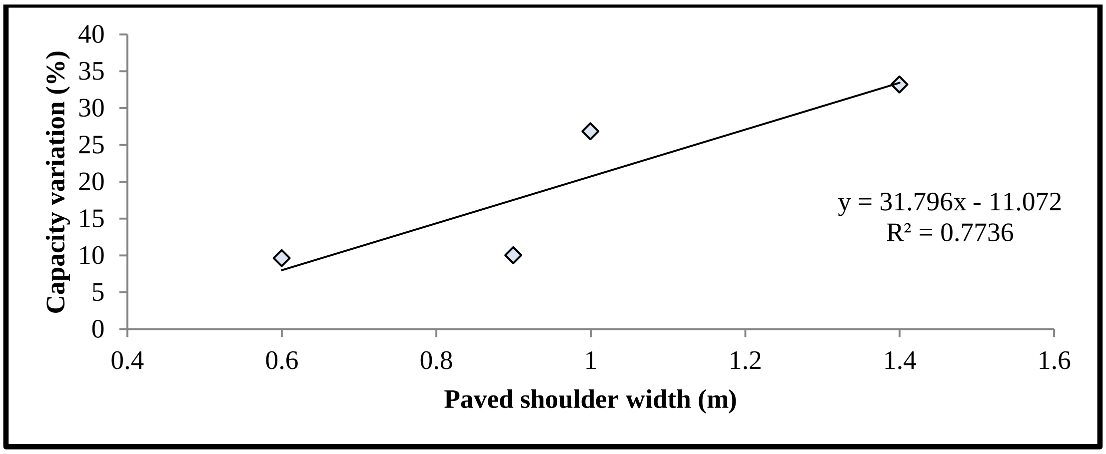


Figure 6.7 Percent variation in capacity of a two-lane road with provision of paved shoulder

Therefore the relationship between the width of added paved shoulder and increase in the capacity in terms of PCU/hr and percent variation in capacity may be expressed as Equation 6.3 and Equation 6.4 respectively. It should be noted that the following equations are valid only for paved shoulder widths ranging from 0.5 m to 1.4 m.

$$\Delta C_{PSW} = 1055.0 * W_{PSH} - 413.4 \quad (6.3)$$

$$\Delta C_{\%PSH} = 31.79 * W_{PSH} - 11.07 \quad (6.4)$$

Where;

ΔC_{PSW} = capacity variation due to added paved shoulder (PCU/hr)

$\Delta C_{\%PSH}$ = percent variation in the capacity due to added paved shoulder (%)

W_{PSH} = width of added paved shoulder (m)

The increase in capacity of a two-lane road due to presence of 1.0 m paved shoulder as displayed in Figure 6.7 is around 20.0 percent. The measured variation in capacity due to the width of paved shoulder is similar to the findings of Prakash (1970) which suggests 38.0% increase in capacity for 1.8 m width of paved shoulder. The amount of increase in capacity for the same width of paved shoulder as per Equation 6.4 is 46.0 %.

6.3 SUMMARY

The heterogeneous traffic on Indian highways greatly causes poor lane discipline and as a result, vehicles tend to use the whole pavement at any chance. Hence to study this effect, the total carriageway width was considered instead of lane width which is common in developed countries where traffic is homogeneous and lane discipline is strictly respected. The study shows that decrease/increase in total carriageway width below/above of a 7.0 m wide two-lane road decrease/increases the capacity of the facility and there is a linear relationship between the two variables.

IRC: 64-1990 suggests that when there is shoulder provision, provided the width of the shoulder is at least 1.5 m on the both sides of the road, capacity could increase up to 15 percent. The present study shows that the capacity of a two-lane road increases 20.0 percent when 1.0 m paved shoulder is provided on either side. This may be due to improvement in vehicle manufacturing technology which has improved the vehicle maneuverability greatly over the years.

CHAPTER – 7

EFFECT OF CURVATURE AND GRADIENT ON CAPACITY

7.1 GENERAL

This chapter is focused on estimation of the effect of curvatures and gradients on capacity of two-lane inter-urban roads. Finding curved sections where the speed of vehicles would be influenced only by this factor on plain areas free from gradients was very difficult. Same condition was found for separately measuring the effect of gradients. Therefore the only way to study these two geometric factors on Indian highways for the purpose of this research work was to consider the hilly roads where a mixed influence of curvatures and gradients was present simultaneously. Figure 7.1 and 7.2 show sample images from such sections on NH-72.

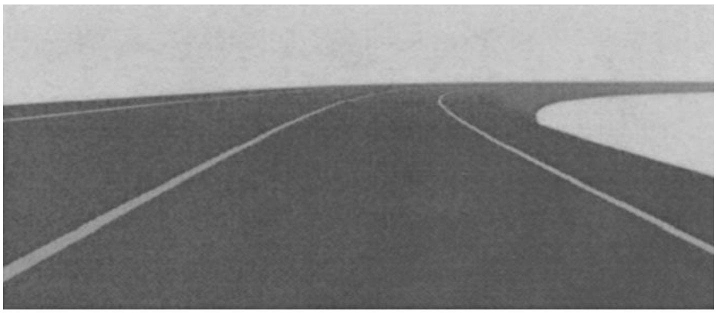
Figure 7.1 Gradient and curvature on hilly roads (NH-72)

Road construction on hilly areas is different from plain and level grounds. It is difficult to connect different points located at different altitudes with merely straight lines and thus the alignment of the roads should be in form of a chain of tangents and curves with different slopes. Under such circumstances the road alignment is primarily governed by the topography of the area. It is also restrained by the size of vehicles that travel these roads which includes long commercial vehicles like trucks and buses (Chai 2013). Such elements make the road designers to consider gradient and curvatures of different magnitudes. At many occasions such features occur simultaneously and at an uphill or downhill direction the road alignment may make it difficult for the drivers to choose the correct speed as the combined effect of horizontal and vertical alignment create different visual perception (Smith and Lamm 1994). While overlapping of a sag curve makes the curve to look flatter than it is, the crest curve creates a sharper appearance of the horizontal curve (Figure 7.3).

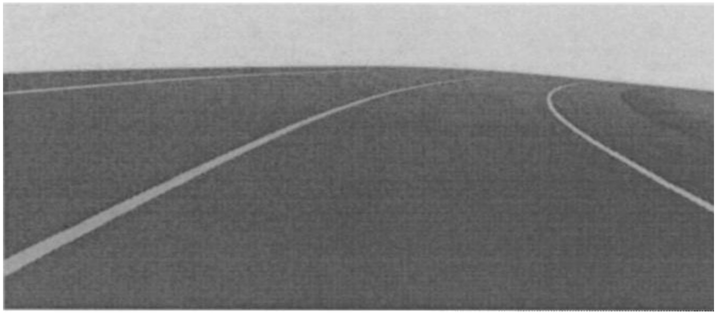
Figure 7.2 Gradient and curvature on hilly roads (NH-72)

Such geometric elements influence the performance of the vehicle running pattern. High gradients on uphill direction reduce the speed of vehicles due to engine power of different types of vehicle. On downhill direction on the other hand, the high value of gradient will force the drivers to use the break in order to guarantee the control and safety of driving. Such effect gets even more complicated when there are curves on the direction of traffic flow. In such cases, sight distance which is addressed by Van Valkenberg (1977), Glennon (1988), Hassan et al. (1996), Wang and Carmell (1998), Figueroa and Tarko (2004) Wang et al. (2013) and Lobo et al. (2013) gains more importance as it decreases by the reduction in the curve radius (or increase in deflection angle in a short distance) – which increases the probability of black spots

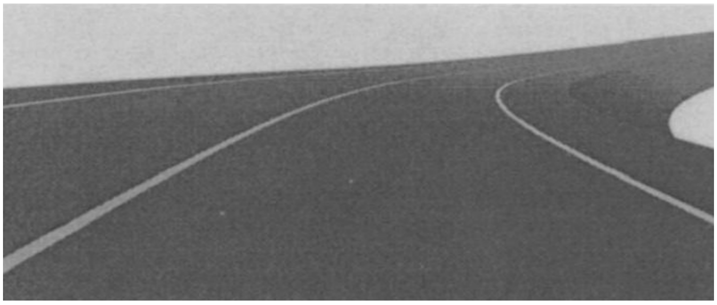
(Qiao et al 2011) - and drivers will adopt lesser speeds to assure the safety of drive (Lin 1990, McFadden and Eleftriadou 2000, Robinson and Knapp 2009, Montella 2009, de Ońa et al. 2014).



Horizontal curve



Horizontal curve overlapped with crest vertical curve



Horizontal curve overlapped with sag vertical curve

Figure 7.3 Effect of road vertical alignment on curve sharpness perception (Hassan and Easa 2003)

7.2 SITE SELECTION AND FIELD DATA EVALUATION

Earlier in this research work it was observed that the capacity of different types of roads may be estimated with operating speed of standard cars. The model developed for this purpose was validated for different sections of two-lane, intermediate and single lane roads. The model was also used to study the influence of adding paved shoulders to the both sides of two-lane inter-urban roads. Since any considerable change in the operating speed indicates a substantial change in the geometry of layout element of the road (Garach et al. 2014), the aim of this chapter is to measure the influence of curvatures and gradients on the operating speed of standard cars travelling on hill roads and thus the capacity of such roads. Using the latest version of an online software – Google Earth – the National and State highways located on hilly areas were spotted. The details of these highways are given in Table 7.1.

Table 7.1 Details of the sections selected for NSV data collection runs

Section no	Details of the road	Location
1	SH-15A, Haryana	5th to 22nd km of Farukhnagar-Wazirpur Road
2	NH-72, Uttarkhand	21st to 35th km of Chhutmalpur-Dehradun Road
3	NH-73, Haryana	31st to 115th km Roorkee-Ambala Road

A state of the art designed vehicle was used to collect the data on three national and state highways. The IRSM Hawkeye 2000 professional network survey vehicle also known as the Automated Road Survey System (ARSS) – Figure 7.4 – was provided by CRRI to obtain various data on the proposed roads. The system mounted on this vehicle was developed in collaboration with Australian Road Research Board (ARRB).

Table 7.2 Sample data provided by NSV runs

Chainage (km)		IRI (m/km)	Grade (%)	Curvature (Degree/ km)	Cross Slope HDM4 (%)	Speed (km/h)	Survey Day
2.000	2.050	3.7	-4.0	353.5	1.1	32.0	2/14/2015
2.050	2.100	8.0	-1.0	151.3	4.0	34.2	2/14/2015
2.100	2.150	4.7	-1.7	28.1	1.1	42.2	2/14/2015
2.150	2.200	4.9	-3.6	92.8	2.3	43.1	2/14/2015

Figure 7.4 Network Survey Vehicle

The Network Survey Vehicle (NSV) can be used to study pavement features such as roughness, rutting, texture, cracking, potholes, patches etc. It can also be used to measure roadway characteristics such as lane width, shoulder width, clearance, hazards, horizontal curvatures and vertical gradients. A sample of the data provided by this vehicle is given in Table 7.2. By reading the data provided by such equipment, only NH-72 was found to have several locations with different curvature and gradients, the magnitude of which ranged from low to high values and in good numbers. Therefore it was selected for the purpose of this study.

As per IRC: SP: 30-2009, the horizontal curvature is measured by the average degree of curvature (CV) per kilometer (Equation 7.1). Figure 7.5 depicts the method of quantification of the same.

Average curvature of section AB, CV = ($Ø_1$+ $Ø_2$+ $Ø_3$+ …+ $Ø_n$)/Distance AB (km); expressed as degrees/km, (IRC: SP:30-2009) (7.1)

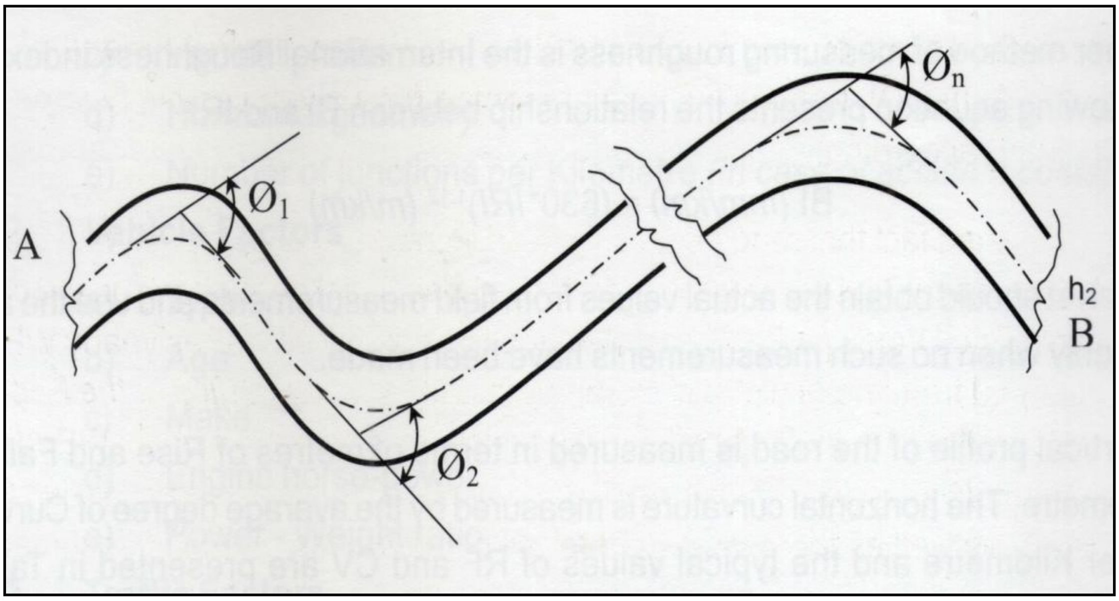


Figure 7.5 Method of specifying the curvature profile of a road section (IRC: SP: 30-2009)

Praticò and Giunta (2012) showed that statistically, the geometric features present at the study location have prevailing influence on the speed compared to the features before or after the same location. Therefore, despite the method suggested by IRC: SP: 30-2009 which measures the curves as an average of curve deflection angles per kilometer, to address the curves in this study, the deflection angle of the curvature was measured within a 100 m of road length.

Abbas et al. (2011) and Jacob and Anjaneyulu (2013) observed the speed changes on curves between approach tangent and mid-curve. But for this study free flow speed data were collected from standard cars exiting the selected locations – where the curvature ends and vehicle enters the tangent – to assure complete effect of the desired geometric factors according to Perez-Zuriaga et al. (2013) which is shown in Figure 7.6. Data was collected from 26 points on NH-72 using a Speed Gun (Figure 7.7) for both upgrade and downgrade directions. The locations of each spot where the free flow speed and geometric data were collected are given in Figure 7.8.

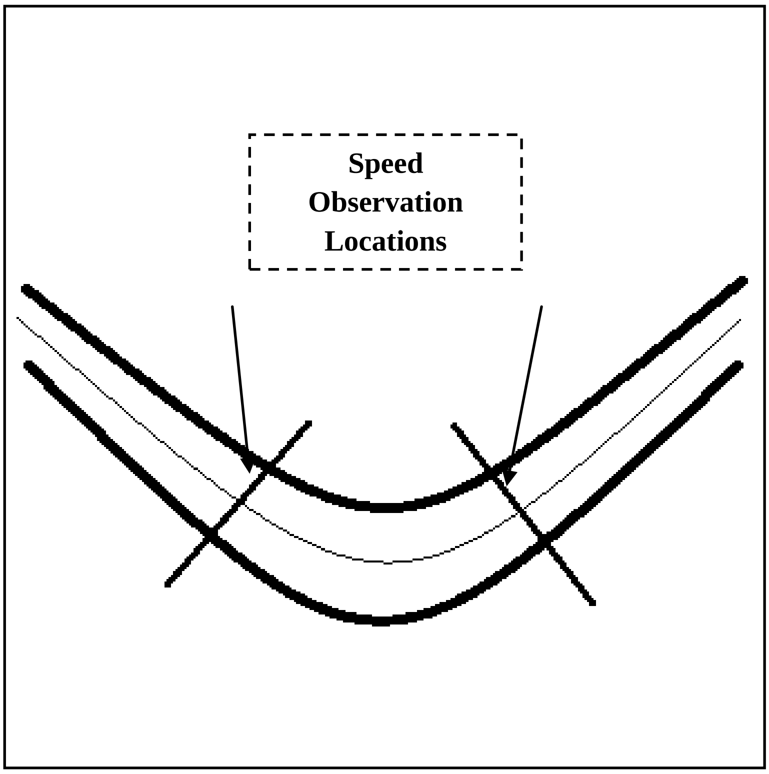


Figure 7.6 Speed observation locations for speed data collection

Figure 7.7 SPEEDAR speed gun used for measuring FFS

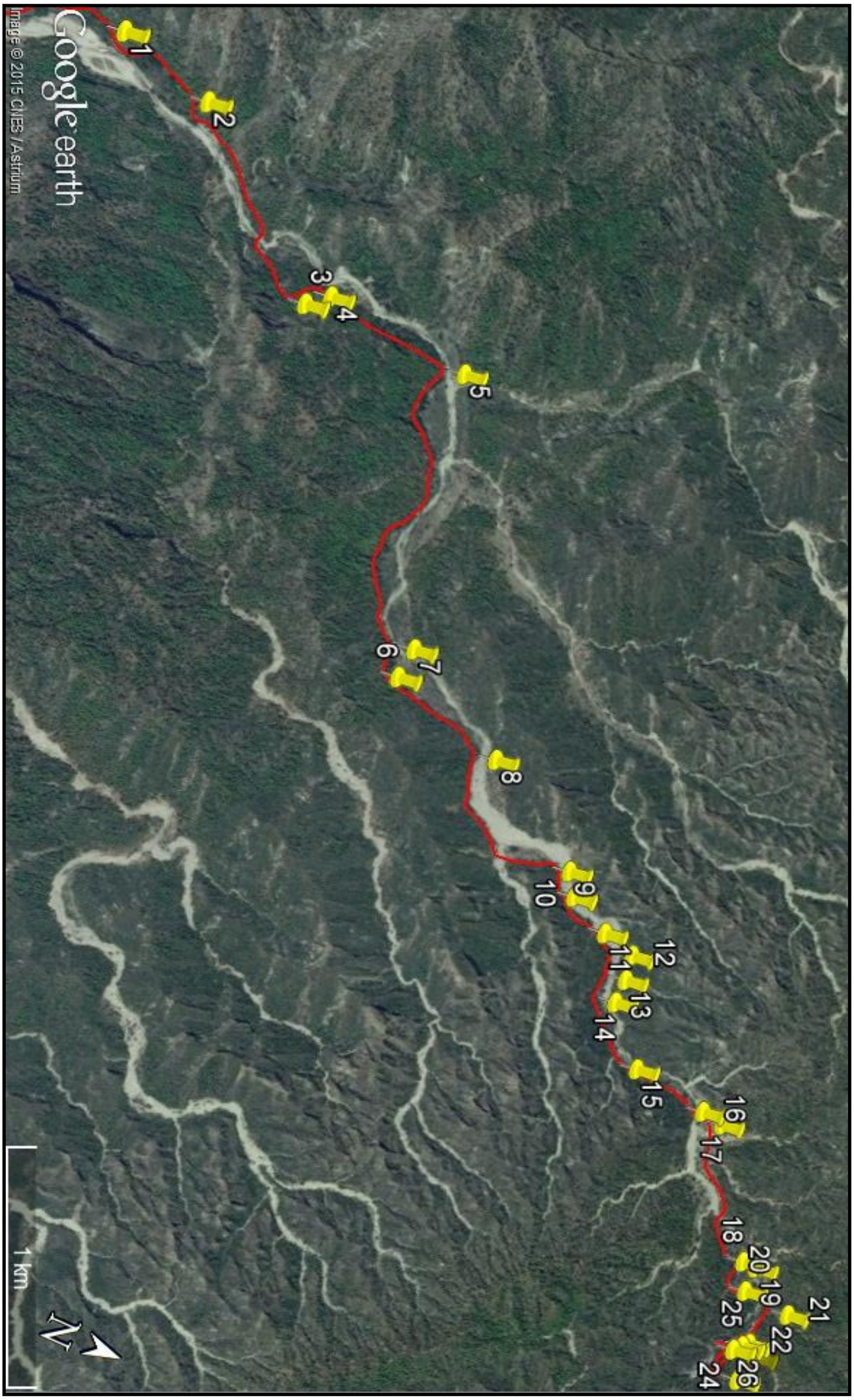


Figure 7.8 Data collection spots on NH-72

Table 7.3 Geometric characteristics of different chainages on NH-72

S. No.	Chainage (km)	Operating Speed (km/hr)	Deflection Angle (DA) (degree/100m)	Gradient (G) %
1	24.350	49.0	29	4.1
2	24.750	41.0	83	3.2
3	25.700	46.5	74	5.3
4	25.800	51.0	28	4.1
5	26.450	35.1	70	6.7
6	27.950	53.9	15	5.9
7	28.050	41.8	55	5.9
8	28.600	49.7	46	4.2
9	29.400	32.9	73	5.2
10	29.550	47.0	50	5.0
11	29.800	52.6	32	3.5
12	29.900	53.5	63	2.8
13	30.000	47.0	28	6.8
14	30.100	49.1	75	7.6
15	30.500	56.5	27	5.0
16	30.800	63.5	20	3.1
17	30.950	39.1	57	6.4
18	31.600	49.0	47	3.7
19	31.750	42.3	37	7.3
20	31.850	41.2	45	6.2
21	32.150	39.0	62	7.6
22	32.300	26.0	105	11.3
23	32.350	32.5	98	10.0
24	32.500	31.5	121	8.7
25	32.700	38.5	102	9.4
26	32.750	35.0	105	8.8

It may be argued that vehicles tend to gain speed due to gravity on downhill direction and drivers are not inclined to apply the brakes (Fildes et al. 1987). However due to reduction of sight distance and centrifugal force imposed by the presence of the curves, drivers are forced to adjust their speeds for safety concerns.

The operating speeds were obtained from the free flow speed data. Based on the location of each section the corresponding Gradient and DA values were obtained from the NSV data. The details of the locations and corresponding geometric data as well as the operating speeds are presented in Table 7.3.

A linear regression analysis was run over the data from Table 7.3 and Equation 7.2 was developed. This equation estimates the operating speed of standard cars under the influence of gradients and curvatures.

$$V_{OSH} = 62.97 - 0.159*DA - 1.562*G \qquad (7.2)$$

Where;
V_{OSH}= Operating speed on hilly roads (km/hr)
DA= Curve deflection angle (degrees/100m)
G= gradient (%)

Table 7.4 shows the statistics of the parameters of the Equation 7.2

Table 7.4 Statistical information of Equation 7.2

Parameter	**Constant**	**DA**	**G**
t-value	22.56	3.63	2.75
Standard Error	2.79	0.04	0.57
Observations	26		
R-squared	0.72		

7.3 EFFECT ON CAPACITY

It was observed that the carriageway width of the selected National Highway (NH-72) ranged between 5.5 to 6.9 m on tangents and increased up to 8.0 m on the curves with earthen shoulders at the both sides of the road which – even regardless of the curve radius – comply with the guide lines recommended by and IRC: SP-48-1998 as presented in Table 7.5.

Table 7.5 Widening of Pavement at Curves (IRC: SP-48-1998)

Radius of Curve	**<20**	**21 - 40**	**41-60**	**61-100**	**101-300**	**>300**
Extra width (m) Two-lane	1.5	1.5	1.2	0.9	0.6	Nil
Single-lane	0.9	0.9	0.6	Nil	Nil	Nil

Two-lane roads in mountainous areas are usually constructed with less road bed or carriageway width (Zhang et al. 2010). The reason for such low widths could be economical and environmental concerns. Therefore for the purpose of this study, such two-lane roads fall in the substandard (intermediate-lane) category.

The relationship between operating speed and capacity on an intermediate-lane road was expressed by Equation 5.5. Therefore in order to obtain the capacity of the hilly roads, the operating speeds obtained from each chainage as given in Table 7.3 were used as input values in Equation 5.5. The estimated theoretical capacity values were regressed with gradient and curvature data at each section and Equation (7.3) was developed. The statistical information of this model is presented in Table 7.6.

$$C_H = 2063.61 - 4.15*DA - 42.42*G \quad (7.3)$$

Where;

C_H= Capacity of hilly roads (PCU/hr)
DA= Curve deflection angle (degrees/100m)
G= Gradient (%)

Table 7.6 Statistical information of Equation 7.3

Parameter	**Constant**	**DA**	**G**
t-value	29.39	3.76	2.96
Standard Error	70.20	1.10	14.31
Observations	26		
R-squared	0.75		

7.4 MODEL VALIDATION

In order to validate the model developed between the operating speed/capacity and geometric characteristics of a hilly road, a section was selected and using the videography technique, the five-minute volume count and speed measurement were performed for three hours on a typical week day. The geometric details of this section are given in Table 7.7. The speed density and speed-volume diagrams were plotted to obtain the capacity and displayed in Figure 7.9 and Figure 7.10 respectively. The operating speed of standard cars was also obtained by determining the 85^{th} percentile free flow speed of these vehicles (Figure 7.11). Utilizing the geometric data, the theoretical operating speed and capacities were obtained using Equation 7.2 and 7.3 respectively. Here also the carriageway width of the proposed section was 5.70 m which puts it under intermediate-lane category. Therefore Equation (5.5) was applied and using the operating speed measured from field data, the capacity of the given section was estimated in this manner as well. The results of the comparison between theoretical and field data for operating speed and capacity are given in Table 7.8 and 7.9 respectively.

Table 7.7 Geometric details of the section selected for model validation

location	Deflection Angle (degrees/100m)	Gradient (%)
24.900 km NH-72	56.5	4.5

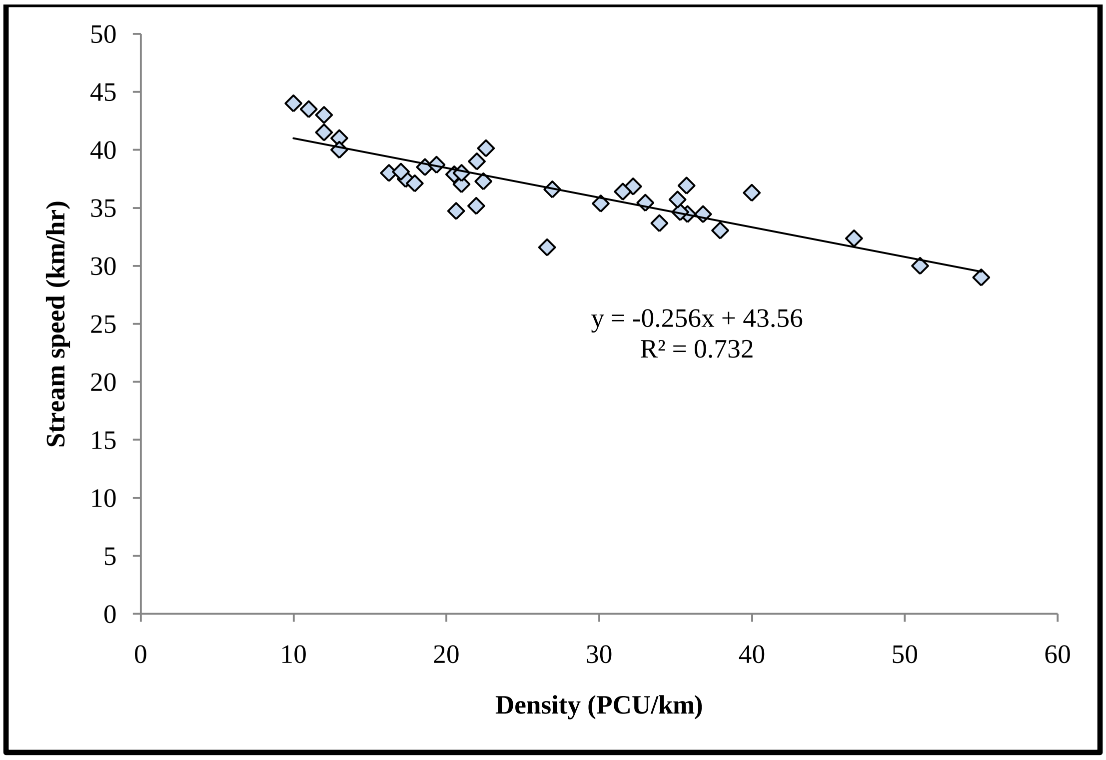


Figure 7.9 Speed-Density relationship at 24.900 km of NH-72

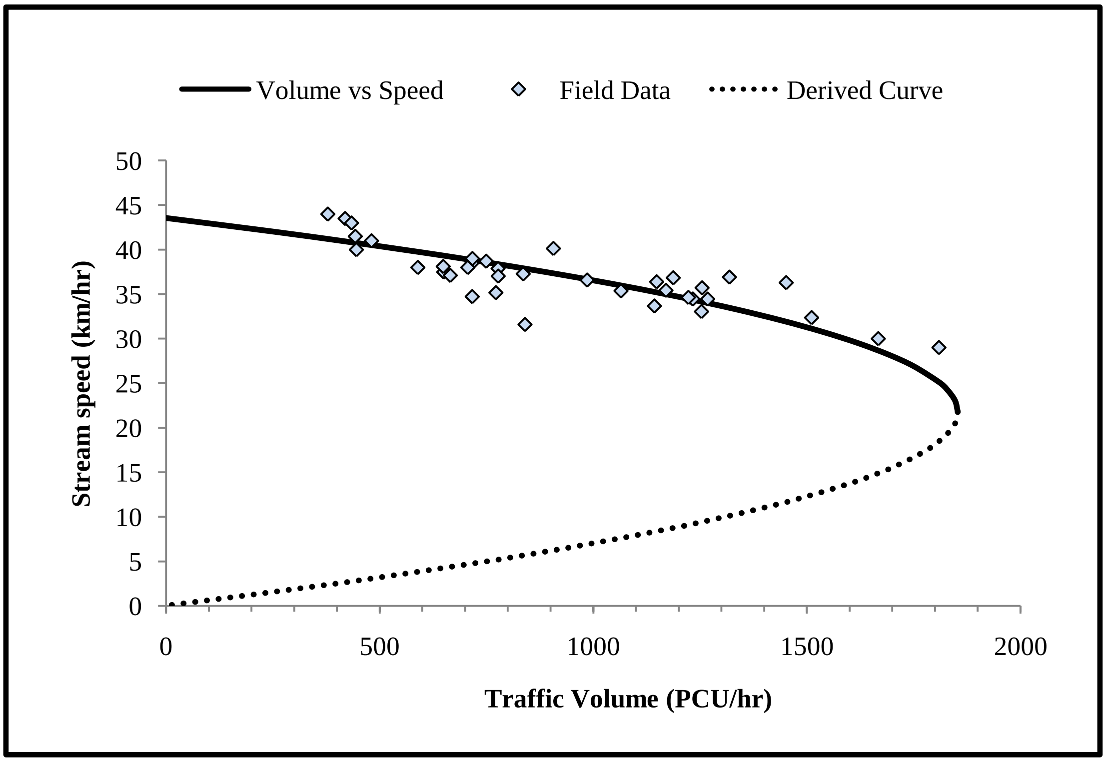


Figure 7.10 Speed-Volume relationship at 24.900 km of NH-72

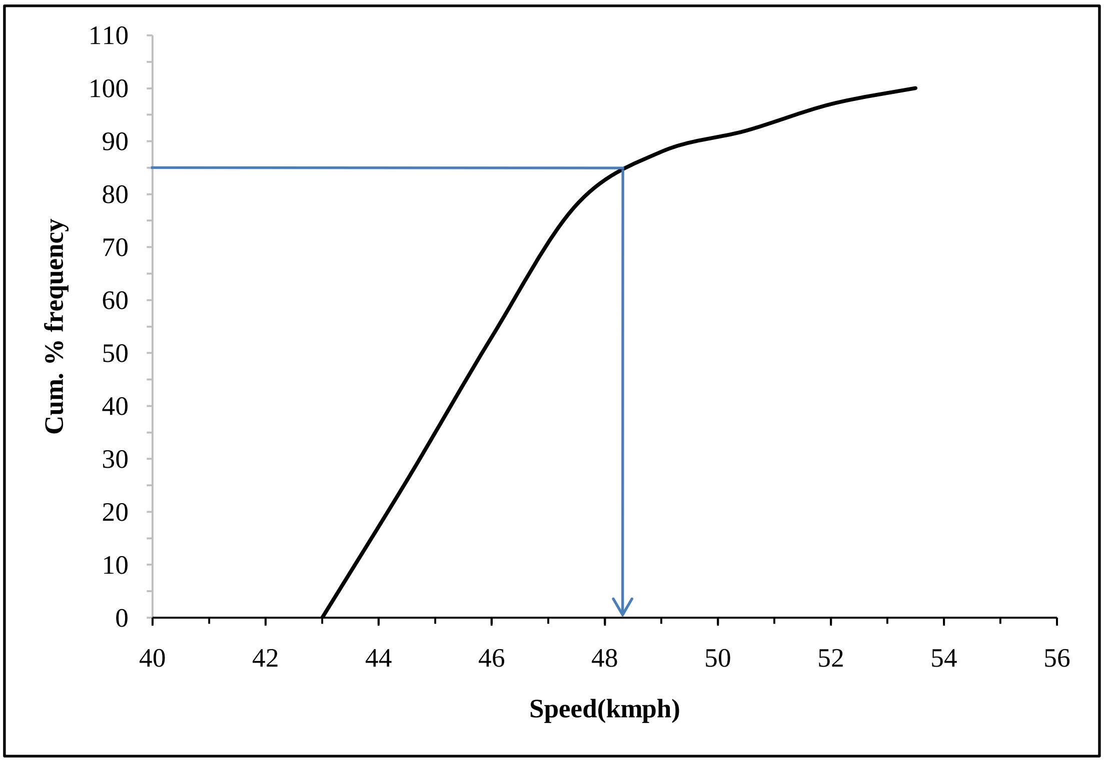


Figure 7.11 85th percentile free flow speed of standard cars at 24.900 km of NH-72

Table 7.8 Comparison of the operating speed from field data and Equation 7.2

Parameters	**Operating speed (km/hr) From field data**	**Operating speed (km/hr) From Eq. 7.2**
Parameter values	48.30	46.95
Percent difference	3.2	

Table 7.9 Comparison of the capacity from field data and Equation 5.5 and 7.3

Parameters	**Field capacity (PCU/hr)**	**Capacity from Eq. 7.3**	**Capacity from Eq. 5.5**
Parameter values	1853	1638	1686
Difference with field capacity (%)	-	11.60	9.01

The low percent difference between the results from theoretical models and field data presented in Table 7.8 and 7.9 validates the models developed between operating speed and capacity and the geometric parameters (curvature and gradient). The capacity-operating speed model given in Equation 5.5 is a second degree polynomial relationship while Equation 7.3 is linear. This may also explain the higher difference of theoretically estimated capacity using Equation 7.3 with field data, than the theoretically estimated capacity obtained from Equation 7.2 and Equation 5.5.

7.5 DISCUSSION

According to Equation 7.3, the increase in the gradient of a hilly road by 1.0 %, on sections with no curvature, will decrease the capacity by 2.0 %. Such result complies with the findings of Chandra and Goyal (2001). The operating speeds observed on the hilly road sections selected for this study ranged between 26 km/hr and 63.5 km/hr which give capacity values of 1142 PCU/hr and 1882 PCU/hr respectively, based on the capacity estimation model developed in Chapter 5 (Equation 5.5). Although IRC: 64-1990 does not consider the effect of gradient, these values are still generally two-times greater than the values given in the code as presented in Table 7.10. The reason could be that vehicle technology and road construction equipment have improved over the years. This requires a revision in the manual as it is shown in this chapter that gradients have considerable influence on the capacity of such roads.

Table 7.10 Recommended capacity values for Hill Roads (IRC: 64-1990)

Sr. No.	Type of Road	Capacity in PCU/hr		
		Carriageway Width (m)	For low curvature (0-200 degrees per km)	For high curvature (above 200 degrees per km)
1.	Single-Lane	3.75	230	200
2.	Intermediate-Lane	5.5	740	640
3.	Two-Lane	7.0	1000	715

7.6 SUMMARY

Data were collected on 26 points throughout NH-72 in state of Uttarkhand, north of India. These data included information on gradient, curvature and operating speed of standard cars. A model was developed to estimate the operating speed of standard cars using the proposed geometric data. Also the operating speed values obtained from these points were used as input in Equation 5.5 to estimate the corresponding theoretical capacity values. By regression of the estimated capacities with gradient and curvature of the chainages where these operating speed data were collected from, a linear relationship was also developed. The low percent difference between theoretical and field data validated the above models.

CHAPTER – 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 GENERAL

The present research was undertaken with the objective of estimating the capacity of single, intermediate and two-lane inter-urban roads in India. Data were collected on several sections of the above categories using videography technique. The recorded videos were played in a computer lab and information on speed and flow were extracted. The mixed traffic which is prevailing on Indian highways was converted to a homogeneous traffic using PCU values for different categories of vehicles. It was shown that PCU values are dynamic and affected by the variation in the traffic volume and traffic composition.

The concept of Stream Equivalency Factor (SEF) which was originally developed for urban roads was modified for the proposed types of roads in this study. The method converts the heterogeneous traffic stream to a homogeneous traffic in terms of PCU/hr. This model is suggested to be used to remove the complexities of calculating the PCU values for individual vehicles present in a traffic stream.

The capacity of the study sections on level terrain were estimated using the fundamental speed-flow diagrams. It was observed that capacity values are different for different roads in different states. For each type of proposed roads, a mathematical model was developed which related the capacity to operating speed of passenger cars. Further the effect of geometric factors like gradient and curvatures on capacity of two-lane roads located in hilly areas were studied by making use of the models developed between operating speed and capacity on level terrains.

8.2 CONCLUSIONS

The following includes the major findings from the present study.

1. Under similar traffic volume and composition, the PCU values of different vehicle categories are almost same for intermediate-lane and two-lane inter-urban roads provided that earthen shoulders in good condition are available on either sides of the road. However, due to different traffic characteristics, such values are significantly different from those on single-lane roads.

2. PCU values are dynamic in nature and depend on traffic volume and traffic composition on the road. It was observed that significant variation is created in PCU value of a vehicle under low and high traffic volume levels as well as different proportions of the same or other vehicle categories in the traffic stream.

3. To estimate the speed of a vehicle type in the traffic stream under different traffic volume and composition, a mathematical equation is developed which can further be used to calculate PCU values. The proposed model of this mathematical equation for a traffic stream with five vehicle categories is given below.

$$V_i = a_0 - a_1 \frac{n_{SC}}{V_{SC}} - a_2 \frac{n_{2W}}{V_{2W}} - a_3 \frac{n_{TK}}{V_{TK}} - a_4 \frac{n_{3W}}{V_{3w}} - a_5 \frac{n_{lcv}}{V_{lcv}}$$

Where;

V_i = the speed of a given vehicle type in m/sec

n = the number of vehicles of each vehicle category in the traffic stream expressed as vehicles per second and,

SC, 2W, 3W, TK and LCV are the vehicle categories which are explained in Chapter 3.

The above equation is developed separately for different vehicle categories in the traffic stream using the field data and speed is considered as the determining factor in developing PCU factors. It shows the variation in the PCU values due to change in the interaction between different vehicles categories imposed by variation in traffic volume level as well as the proportion of each vehicle category in the traffic stream.

4. The concept of Stream Equivalency Factor (SEF) is proposed in this research work which converts the heterogeneous traffic flow to a homogeneous equivalent. The difference between this method and other methods of homogenizing the mixed traffic is that it removes the difficult task of calculating PCU values for each vehicle categories in a given traffic stream. The mathematical form of the developed model for the proposed road types are given below.

$$K_{\text{two-lane, intermediate-lane}} = 1 + 0.350*P_{BC} - 0.826*P_{2W} - 0.282*P_{3W} + 1.895*P_{LCV} + 3.905*P_{BUS} + 3.301P_{TK} + 5.571P_{TT} + 8.971*P_{MAV} + 73.191*\frac{1}{N}$$

$K_{single\text{-}lane} = 1 + 0.128*P_{BC} - 0.690*P_{2W} - 0.363*P_{3W} + 1.447*P_{LCV} + 3.544*P_{BUS} + 0.757P_{TK} + 6.385P_{TT} + 2.540*\frac{1}{N}$

Where;

$K_{two\text{-}lane,\ intermediate\text{-}lane}$ = Stream Equivalency Factor for intermediate and two-lane inter-urban roads

$K_{single\text{-}lane}$ = Stream Equivalency Factor for single-lane roads

P_{BC} = Proportional fraction of big cars in traffic stream

P_{2W} = Proportional fraction of two-wheelers in traffic stream

P_{3w} = Proportional fraction of three-wheelers in traffic stream

P_{LCV} = Proportional fraction of light commercial vehicles in traffic stream

P_{BUS} = Proportional fraction of buses in traffic stream

P_{TK} = Proportional fraction of 2-3 axle trucks in traffic stream

P_{TT} = Proportional fraction of tractors with trailer in traffic stream

P_{MAV} = Proportional fraction of multi-axle trucks in traffic stream

N = Total flow in vehicle per hour

5. The capacity range of base sections was found to be between 2429 PCU/hr and 3294 PCU/hr for two-lane, 1423 PCU/hr and 2082 PCU/hr for intermediate-lane and 488 PCU/hr and 1090 PCU/hr for single-lane inter-urban roads.

6. The PCU of vehicles larger than a passenger car (big car, LCV, TK …) increases and PCU value of motorized vehicles smaller that the passenger car (2W and 3W) decreases the K factor. Since the value of K is unity if all the vehicles in the traffic are passenger cars, the PCU value of vehicles smaller than passenger cars decrease the K factor and vice a versa.

7. Several factors affect the capacity of a road. The effect of different characteristics of a road may be reflected in the free speed of a vehicle travelling on it. The operating speed of passenger cars, which is the 85^{th} percentile free flow speed of such vehicles as described by HCM (2010) was plotted against the field capacity value of each section. Therefore the capacity of two-lane, intermediate-lane and single-lane inter-urban roads may be estimated using the following equations.

$C_{two\text{-}lane} = -0.735v_{os}^2 + 162.5v_{os} - 5006.0$

$C_{intermediate\text{-}lane} = -0.272v_{os}^{2} + 49.95v_{os} - 91.51$

$C_{single\text{-}lane} = -0.479v_{os}^{2} + 64.46v_{os} - 1077.0$

Where;

$C_{two\text{-}lane}$ = capacity of a two-lane inter-urban road (PCU/hr)

$C_{intermediate\text{-}lane}$ = capacity of a intermediate-lane inter-urban road (PCU/hr)

$C_{single\text{-}lane}$ = capacity of a single-lane inter-urban road (PCU/hr)

v_{os} = operating speed of passenger cars on the corresponding type of road(km/hr)

8. Based on the effect on operating speed, the increase or decrease in the capacity of a two-lane inter-urban road due to change in the width of carriageway may be estimated using the following equations.

$\Delta C_{wPCU} = 320*CW$

$\Delta C_{w\%} = 10.39*CW$

Where;

ΔC_{wPCU} = capacity variation due to change in the width of carriageway (PCU/hr)

$\Delta C_{w\%}$ = capacity variation due to change in the width of carriageway (%)

CW = change in total carriageway width with respect to a standard 7.0 m width (m)

The capacity of a two-lane road increases about 320 PCU/hr for one meter increase in the carriageway width. It is also observed that for a 0.50 m decrease in the width, the capacity decreases 160 PCU/hr.

9. It is found that paved shoulders contribute to the total carriageway of a two-lane road and therefore increase the capacity. The amount of increase in the capacity value is quantified using the following models developed in this research.

$\Delta C_{PSW} = 1055.0*W_{PSH} - 413.4$

$\Delta C_{\%PSH} = 31.79*W_{PSH} - 11.07$

Where;

ΔC_{PSW} = capacity variation due to added paved shoulder (PCU/hr)

$\Delta C_{\%PSH}$ = percent variation in the capacity due to added paved shoulder (%)

W_{PSH} = width of added paved shoulder (m)

10. It is shown in this research work that any change in the characteristics of a road of proposed types will be reflected in the operating speed of the passenger cars. Gradient and curvature of roads in hilly areas are geometric factors that adversely affect the speed of vehicles and thus the capacity. A linear regression analysis was performed between operating speed and geometric features over 26 locations on NH-72. The relationship between operating speed and geometric factors are given in the following equation.

$$V_{OSH} = 62.97 - 0.159*DA - 1.562*G$$

Where;
V_{OSH}= operating speed on hilly roads (km/hr)
DA= curve deflection angle (degrees/100m)
G= gradient (%)

It has been demonstrated in this research that there are different relationships between operating speed and capacity for each type of inter-urban roads. The width of hilly roads where data was collected ranged between 5.0 m and 6.0 m which classify it as an intermediate-lane road on the level ground. By inputting the operating speed data collected from the hilly road section, the corresponding capacity values were calculated. Using regression analysis a model is developed that incorporates the effect of curvature and gradient on the capacity of hilly roads which takes form of the following equation.

$$C_H = 2063.61 - 4.15*DA - 42.42*G$$

Where;

C_H= capacity of hilly roads (PCU/hr)
DA= curve deflection angle (degrees/100m)
G= gradient (%)

8.3 CONTRIBUTIONS

The major contributions of this study which is one of the comprehensive researches performed on inter-urban roads in India are summarized below.

a. The simultaneous equations developed in this study (Equation 4.2 to 4.5) determine the speed of a vehicle type at different traffic volume levels. They provide a thorough insight to the dynamic state of PCU values. The proposed model is easy to use and merely requires classified traffic volume data. It will remove a huge amount of cost and time required to develop a complete range of speed variation of a given vehicle type. The model can be easily modified in case more categories of vehicles are observed in the traffic stream.

b. PCU values may be derived from the proposed simultaneous equations which predict speed of different vehicle categories at different traffic volume levels and traffic composition.

c. The Stream Equivalency Factor developed for each type of roads provides the homogeneous equivalent of the heterogeneous traffic which is prevailing on Indian highways with no need of going through individual calculation of PCU values. No such studies have been done for inter-urban roads so far which makes this effort as a state of the art in the Indian traffic survey methods. The model is easy to use and gives a quick estimation of the traffic flow based on the proportion of vehicles in the traffic stream at the site.

d. The relationship between capacity and operating speed of passenger cars developed in this study eradicates a huge portion of the time and cost of studies required to estimate the capacity of proposed road types. The models suggested in this study (Equation 5.4, 5.5 and 5.6) provide a fast estimation of the capacity of two-lane, intermediate-lane and single-lane inter-urban roads without compromising the accuracy of the results.

e. The relationships between capacity and operating speed were developed for base sections of each type of roads which is described in chapter 3 of this study. Therefore the effect of any deviation from the proposed descriptions (in terms of change in width, adding paved shoulders and change in geometric features) on capacity may be measured by the influence they impose on the operating speed of passenger cars travelling on such roads.

f. IRC provides single sets of PCU values for different vehicle categories regardless of traffic volume and traffic composition. This study shows that such provision does not fulfill the traffic survey requirements adequately as PCU values are dynamic. Therefore it is suggested that PCU estimation method should be revised accordingly.

g. Although IRC: 64-1990 does not include the effect of gradient on capacity of hilly roads, the capacity values estimated in this study were nearly two times greater than the capacity values suggested by this code. Therefore it is also suggested that effect of gradients must be considered in the IRC standards.

8.4 RECOMMENDATIONS FOR FUTURE STUDIES

The speed prediction models developed in this study consider only four or five categories of vehicles. This was due to lower proportion of other vehicle types present at the study section which does not provide interaction with other vehicles high enough to develop a model for. Therefore finding sections where traffic stream is composed of different vehicle categories with nearly equal proportional distribution will help to have speed prediction models for more vehicle categories.

The present study provides models to estimate the capacity of single, intermediate and two-lane inter-urban roads based on the operating speed of passenger cars. To enhance the accuracy of capacity-operating speed relationships developed on the proposed road types, especially for single and intermediate-lane roads it is recommended that the number of sites having the corresponding roadway characteristics to be increased. Doing so will increase the number of data points and leads to stronger equations.

It was observed that the effect of provision of paved shoulder with respect to operating speed of passenger cars was nearly half the values proposed by other scholars who have worked on this topic. However, adding more sections of two-lane roads where such provision is present strengthens the conclusions of this study.

Effect of provision of hard shoulders on capacity of single-lane roads may be an interesting field of research as it may influence the traffic behavior on such roads.

Hilly roads are generally constructed with less carriageway width than those located on plain areas. The model proposed in this study was developed on sections with widths less than 6.0 m. As explained in the introduction of this research work, such roads are referred to as intermediate-lane roads and thus may be applied only to hilly roads of similar widths. However, there are locations where budget is enough and environmental concerns still allow for wider two-lane roads. Therefore, by collecting free speed and geometric data, the capacity of hilly roads which are constructed with 7.0 m width may be estimated using the capacity-operating speed developed for two-lane roads in chapter five of this study. Naturally, the obtained values are adjustable using the carriageway width-capacity model developed in this research work if the study sections have higher widths.

Although 9 categories of motorized vehicles and 3 categories of non-motorized vehicles were identified and grouped for analysis in this study, there are still few more vehicle categories in different states of India whose physical size and operational characteristics do not fit with the specifications addressed in this research work. Therefore a more comprehensive traffic survey across this country is required to enhance the methods provided in this work from details point of view.

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APPENDIX – A

MATLAB 4-CATEGORY SIMULTANEOUS EQUATIONS SOLUTION PROGRAM

```
close all;
clear all;
clc
%eps=0.1
disp(' Solution of Non linear 4-Category Equations')
disp('--------------------------------------------')
reply='Y';
while (reply =='Y'||reply =='y')
close all;
clear all;
clc
disp(' Solution of Non linear 4-Category Equations')
disp('--------------------------------------------')
%entry = input('ENTER THE VALUES OF COEFFICIENTS SEPARATED BY COMMAS
','s')
var1(5)=input('ENTER THE VALUE OF Total N=');
var1(1)=input('ENTER THE VALUE OF FIRST COEFFICIENT (in %) Nsc=');
var1(2)=input('ENTER THE VALUE OF SEC COEFFICIENT (in %)N2w=');
var1(3)=input('ENTER THE VALUE OF THIRD COEFFICIENT (in %)Nhv=');
var1(4)=input('ENTER THE VALUE OF FOURTH COEFFICIENT (in %)N3w=');
fprintf(1,'\n Ncs = %8.3f, N2w = %8.3f, Nhv = %8.3f, N3w = %8.3f
\n',var1(1)*var1(5)/100,var1(2)*var1(5)/100,var1(3)*var1(5)/100,var1(
4)*var1(5)/100)
var(1)=var1(1)*var1(5)/360000;
var(2)=var1(2)*var1(5)/360000;
var(3)=var1(3)*var1(5)/360000;
var(4)=var1(4)*var1(5)/360000;
var
% var6=1;
%
% var(1)=var1
% var(2)=var2
% var(3)=var3
% var(4)=var4
% var(5)=var5

% var(1)=1000;
% var(2)=1000;
% var(3)=1000;
% var(4)=1000;
% var(5)=1000;


Vsc=10;
V2w=30;
Vhv=30;
V3w=30;
```

```
% Vscr=Vsc-17.09-69.87*(var1/Vsc)-61.06*(var2/V2w)-194.89*(var3/Vhv)-
37.47*(var4/3w) %
% while Vscr<eps
% Vsc=Vscr
% Vscr= Vsc-17.09-69.87*(var1/Vsc)-61.06*(var2/V2w)-
194.89*(var3/Vhv)-37.47*(var4/3w)
% end

x0=[10 10 10 10]';
fprintf(1,'\n\n')
disp(' Initial guess for the problem is')
fprintf(1,'\n Vsc = %8.3f, V2w = %8.3f, Vhv = %8.3f, V3w = %8.3f
\n',x0)
fprintf(1,'\n\n')
ask1 = input('DO YOU WANT TO CHANGE THE INITIAL GUESS (Y/N)','s');
if(ask1 =='Y'||ask1 =='y')
x0(1)=input('ENTER THE First guess VALUE OF Vsc=');
x0(2)=input('ENTER THE Second guess VALUE OF V2w=');
x0(3)=input('ENTER THE Third guess VALUE OF Vhv=');
x0(4)=input('ENTER THE Fourth guess VALUE OF V3w=');
disp('\n Initial Changed guess for the problem is')
fprintf(1,'\n Vsc = %8.3f, V2w = %8.3f, Vhv = %8.3f, V3w = %8.3f
\n',x0)
end

%options = optimoptions('fsolve','Display','iter'); % Option to
display output
%options = optimset('Display','iter'); % Option to display output

options = optimset('Display','off'); % Option to display output
%[x]=fsolve(@nlefour,x0,options,var);

[x]=myfunsix(x0,var)

%[x,fval,exitflag]=fsolve(@nle,x0,options,var)
%[x,fval,exitflag]=fsolve(@nle,x0)
% disp('The value of Vsc =')
%x
%fval
fprintf(1,'\n\n')
disp('The output converged values of Vsc V2w Vhv V3w  are given
below:')
fprintf(1,'\n Vsc = %8.2f, V2w = %8.2f, Vhv = %8.2f, V3w = %8.2f
\n',x)
px(1)=1;
px(2)=(x(1)/x(2))/4.466666667;
px(3)=(x(1)/x(3))/0.218418908;
px(4)=(x(1)/x(4))/1.196428571;
disp('The corresponding values of Psc P2w Phv P3w  are given below:')
fprintf(1,'\n Psc = %8.2f, P2w = %8.2f, Phv = %8.2f, P3w = %8.2f
\n',px)

%end
fprintf(1,'\n\n')
reply = input('\n DO YOU WANT TO CALCULATE FOR ANOTHER DATA SET
(Y/N)','s');
end
close all;
clear all;
clc
```

```
disp(' Thanks for running the program :)')
```

Functions

```
function [ f ] = myfunsix( x,var )
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here
eps=0.001;
itr=0;
flag ='Y';
fprintf(1,'Solution of non linear equation has started \n')
while (flag =='Y')
itr=itr+1;
fprintf(1,'Iteration number =%5i \n',itr)

f(1)=17.091-69.869*(var(1)/x(1))-61.062*(var(2)/x(2))-
194.888*(var(3)/x(3))-37.467*(var(4)/x(4));
f(2)=13.386-39.509*(var(1)/x(1))-19.394*(var(2)/x(2))-
57.189*(var(3)/x(3))-3.349*(var(4)/x(4));
f(3)=14.693-8.907*(var(1)/x(1))-48.499*(var(2)/x(2))-
183.769*(var(3)/x(3))-73.160*(var(4)/x(4));
f(4)=12.325-32.802*(var(1)/x(1))-3.914*(var(2)/x(2))-
62.892*(var(3)/x(3))-43.612*(var(4)/x(4));

if(abs(f(1)-x(1))<=eps || abs(f(2)-x(2))<=eps || abs(f(3)-x(3))<=eps
|| abs(f(4)-x(4))<=eps)
f(1)=x(1);
f(2)=x(2);
f(3)=x(3);
f(4)=x(4);
flag='N';

else
x(1)=f(1);
x(2)=f(2);
x(3)=f(3);
x(4)=f(4);
end

end
```

APPENDIX – B

MATLAB 5-CATEGORY SIMULTANEOUS EQUATIONS SOLUTION PROGRAM

```
close all;
clear all;
clc
%eps=0.1
disp(' Solution of Non linear 5-Category Equations')
disp('-------------------------------------------')
reply='Y';
while (reply =='Y'||reply =='y')
close all;
clear all;
clc
disp(' Solution of Non linear 5-Category Equations')
disp('-------------------------------------------')
%entry = input('ENTER THE VALUES OF COEFFICIENTS SEPARATED BY COMMAS
','s')
var1(6)=input('ENTER THE VALUE OF Total N=');
var1(1)=input('ENTER THE VALUE OF FIRST COEFFICIENT (in %) Nsc=');
var1(2)=input('ENTER THE VALUE OF SEC COEFFICIENT (in %)Nbc=');
var1(3)=input('ENTER THE VALUE OF THIRD COEFFICIENT (in %)Nhv=');
var1(4)=input('ENTER THE VALUE OF FOURTH COEFFICIENT (in %)Nlcv=');
var1(5)=input('ENTER THE VALUE OF FIFTH COEFFICIENT N2w)=');
fprintf(1,'\n Nsc = %8.3f, Nbc = %8.3f, Nhv = %8.3f, Nlcv = %8.3f,N2w
= %8.3f
\n',var1(1)*var1(6)/100,var1(2)*var1(6)/100,var1(3)*var1(6)/100,var1(
4)*var1(6)/100,var1(5)*var1(6)/100)
var(1)=var1(1)*var1(6)/360000;
var(2)=var1(2)*var1(6)/360000;
var(3)=var1(3)*var1(6)/360000;
var(4)=var1(4)*var1(6)/360000;
var(5)=var1(5)*var1(6)/360000;

% var6=1;
%
% var(1)=var1
% var(2)=var2
% var(3)=var3
% var(4)=var4
% var(5)=var5

% var(1)=1000;
% var(2)=1000;
% var(3)=1000;
% var(4)=1000;
% var(5)=1000;


Vsc=10;
Vbc=30;
Vhv=30;
Vlcv=30;
V2w=30;
```

```
% Vscr=Vsc-16.95-45.17*(var1/Vsc)-40.36*(var2/Vbc)-46.17*(var3/Vhv)-
46.17*(var4/Vlcv)-36.18*(var5/V2w)
%
% while Vscr<eps
% Vsc=Vscr
% Vscr=Vsc-16.95-45.17*(var1/Vsc)-40.36*(var2/Vbc)-46.17*(var3/Vhv)-
46.17*(var4/Vlcv)-36.18*(var5/V2w)
% end

x0=[10 10 10 10 10]';
fprintf(1,'\n\n')
disp(' Initial guess for the problem is')
fprintf(1,'\n Vsc = %8.3f, Vbc = %8.3f, Vhv = %8.3f, Vlcv = %8.3f,V2w
= %8.3f \n',x0)
fprintf(1,'\n\n')
ask1 = input('DO YOU WANT TO CHANGE THE INITIAL GUESS (Y/N)','s');
if(ask1 =='Y'||ask1 =='y')
x0(1)=input('ENTER THE First guess VALUE OF Vsc=');
x0(2)=input('ENTER THE Second guess VALUE OF Vbc=');
x0(3)=input('ENTER THE Third guess VALUE OF Vhv=');
x0(4)=input('ENTER THE Fourth guess VALUE OF Vlcv=');
x0(5)=input('ENTER THE Fifth guess VALUE OF V2w=');
disp('\n Initial Changed guess for the problem is')
fprintf(1,'\n Vsc = %8.3f, Vbc = %8.3f, Vhv = %8.3f, Vlcv = %8.3f,V2w
= %8.3f \n',x0)
end

%options = optimoptions('fsolve','Display','iter'); % Option to
display output
%options = optimset('Display','iter'); % Option to display output

options = optimset('Display','off'); % Option to display output
%[x]=fsolve(@nlefour,x0,options,var);

[x]=myfunsix(x0,var)

%[x,fval,exitflag]=fsolve(@nle,x0,options,var)
%[x,fval,exitflag]=fsolve(@nle,x0)
% disp('The value of Vsc =')
%x
%fval
fprintf(1,'\n\n')
disp('The output converged values of Vsc Vbc Vhv Vlcv V2w are given
below:')
fprintf(1,'\n Vsc = %8.2f, Vbc = %8.2f, Vhv = %8.2f, Vlcv = %8.2f,
V2w = %8.2f \n',x)
px(1)=1;
px(2)=(x(1)/x(2))/0.664612;
px(3)=(x(1)/x(3))/0.217866;
px(4)=(x(1)/x(4))/0.418423;
px(5)=(x(1)/x(5))/4.491667;
disp('The corresponding values of Psc Pbc Phv Plcv P2w are given
below:')
fprintf(1,'\n Psc = %8.2f, Pbc = %8.2f, Phv = %8.2f, Plcv = %8.2f,
P2w = %8.2f \n',px)

%end
fprintf(1,'\n\n')
```

```
reply = input('\n DO YOU WANT TO CALCULATE FOR ANOTHER DATA SET
(Y/N)','s');
end
close all;
clear all;
clc
disp(' Thanks for running the program:)')
```

Functions

```
function [ f ] = myfunsix( x,var )
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here
eps=0.001;
itr=0;
flag ='Y';
fprintf(1,'Solution of non linear equation has started \n')
while (flag =='Y')
itr=itr+1;
fprintf(1,'Iteration number =%5i \n',itr)

f(1)=19.24-73.38*(var(1)/x(1))-38*(var(2)/x(2))-60.540*(var(3)/x(3))-
29.11*(var(4)/x(4))-0.41*(var(5)/x(5));
f(2)=20.45-42.54*(var(1)/x(1))-113.14*(var(2)/x(2))-
73.01*(var(3)/x(3))-0.07*(var(4)/x(4))-15.07*(var(5)/x(5));
f(3)=15.38-18.01*(var(1)/x(1))-4.55*(var(2)/x(2))-
84.95*(var(3)/x(3))-54.06*(var(4)/x(4))-0.24*(var(5)/x(5));
f(4)=22.21-24.48*(var(1)/x(1))-38*(var(2)/x(2))-61.55*(var(3)/x(3))-
31.72*(var(4)/x(4))-0.33*(var(5)/x(5));
f(5)=18.5-60.98*(var(1)/x(1))-0.11*(var(2)/x(2))-37.61*(var(3)/x(3))-
62.85*(var(4)/x(4))-105.24*(var(5)/x(5));

if(abs(f(1)-x(1))<=eps || abs(f(2)-x(2))<=eps || abs(f(3)-x(3))<=eps
|| abs(f(4)-x(4))<=eps || abs(f(5)-x(5))<=eps)
f(1)=x(1);
f(2)=x(2);
f(3)=x(3);
f(4)=x(4);
f(5)=x(5);
flag='N';

else
x(1)=f(1);
x(2)=f(2);
x(3)=f(3);
x(4)=f(4);
x(5)=f(5);

end

end
```

APPENDIX – C

MATLAB STREAM EQUIVALENCY FACTOR SOLUTION PROGRAM FOR TWO-LANE AND INTERMEDIATE-LANE ROADS

```
close all;
clear all;
clc
reply='Y';
while (reply =='Y'||reply =='y')
%entry = input('ENTER THE VALUES OF COEFFICIENTS SEPARATED BY COMMAS
','s')
var1=input('ENTER THE VALUE OF 1st COEFFICIENT (in %)bc=');
var2=input('ENTER THE VALUE OF 2nd COEFFICIENT (in %)2w=');
var3=input('ENTER THE VALUE OF 3rd COEFFICIENT (in %)3w=');
var4=input('ENTER THE VALUE OF 4th COEFFICIENT (in %)lcv=');
var5=input('ENTER THE VALUE OF 5th COEFFICIENT (in %)bus=');
var6=input('ENTER THE VALUE OF 6th COEFFICIENT (in %)tk=');
var7=input('ENTER THE VALUE OF 7th COEFFICIENT (in %)tt=');
var8=input('ENTER THE VALUE OF 8th COEFFICIENT (in %)mav=');
var9=input('ENTER THE VALUE OF 9th COEFFICIENT N=');
var10=1
var1=Var1/100
var2=Var2/100
var3=Var3/100
var4=Var4/100
var5=Var5/100
var6=Var6/100
var7=Var7/100
var8=Var8/100

elsif (var1>0 & var2>0 var3>0 & var4>0 var5>0 & var6>0 var7>0 &
var8>0 & var9>0)
   a1=0.350
   a2=-0.826
   a3=-0.282
   a4=1.895
   a5=3.905
   a6=3.301
   a7=5.571
   a8=8.971
   a9=73.191
   result=var10+a1*var1+a2*var2+a3*var3+a4*var4+a5*var5+a6*var6+a7*va
   r7+a8*var8+a9/var9

end
reply = input('DO YOU WANT TO CALCULATE FOR ANOTHER DATA SET
(Y/N)','s');
end
disp(' Thanks for running the program :)')
```

APPENDIX – D

MATLAB STREAM EQUIVALENCY FACTOR SOLUTION PROGRAM FOR SINGLE-LANE ROADS

```
close all;
clear all;
clc
reply='Y';
while (reply =='Y'||reply =='y')
%entry = input('ENTER THE VALUES OF COEFFICIENTS SEPARATED BY COMMAS
','s')
var1=input('ENTER THE VALUE OF 1st COEFFICIENT (in %)bc=');
var2=input('ENTER THE VALUE OF 2nd COEFFICIENT (in %)2w=');
var3=input('ENTER THE VALUE OF 3rd COEFFICIENT (in %)3w=');
var4=input('ENTER THE VALUE OF 4th COEFFICIENT (in %)lcv=');
var5=input('ENTER THE VALUE OF 5th COEFFICIENT (in %)bus=');
var6=input('ENTER THE VALUE OF 6th COEFFICIENT (in %)tk=');
var7=input('ENTER THE VALUE OF 7th COEFFICIENT (in %)tt=');
var8=input('ENTER THE VALUE OF 9th COEFFICIENT N=');
var9=1
var1=Var1/100
var2=Var2/100
var3=Var3/100
var4=Var4/100
var5=Var5/100
var6=Var6/100
var7=Var7/100

elsif (var1>0 & var2>0 var3>0 & var4>0 var5>0 & var6>0 var7>0 &
var8>0)
   a1=0.128
   a2=-0.690
   a3=-0.363
   a4=1.447
   a5=3.544
   a6=0.757
   a7=6.385
   a8=2.540
   result=var10+a1*var1+a2*var2+a3*var3+a4*var4+a5*var5+a6*var6+a7*va
   r7+a8/var8

end
reply = input('DO YOU WANT TO CALCULATE FOR ANOTHER DATA SET
(Y/N)','s');
end
disp(' Thanks for running the program :)')
```

LIST OF PUBLICATIONS

Journals

Nokandeh, M.M., Ghosh, I, and Chandra, S. (2015). "Passenger Car Units on Two-Lane Intercity Highways under Heterogeneous Traffic Conditions." *Journal of Transportation Engineering, American Society of Civil Engineers (ASCE),* 04015040

Conferences

Mardani Nokandeh, M., Chandra, S., and Ghosh, I. (2015). "Passenger Car Unit of Vehicles on Undivided Intercity Roads in India." *Procedia Computer Science*, The 4th International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (AMBTRANS), London, No. 52, 926-931.

Mardani, N., Ghosh, I., and Chandra, S. (2016). "Estimation of Capacity of Two-lane Inter-Urban Roads in India from Free Speed data" Presented for *The 15th International Conference on Transportation and Traffic Engineering (ICTTE),* Tehran.