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Evaluation of Roadway Capacity of Four-Lane Divided Carriageway under Heterogeneous Urban Traffic Conditions

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***Abstract*— Traffic on urban road is heterogeneous when large varieties of vehicles operate in mixed mode condition. The performance of the urban roadway depends on the practical capacity and actual traffic volumes. To estimate the roadway capacity, traffic flow in terms of PCUs and speed of the stream of respective hours were evaluated. The speed flow equation was developed by using PCU volume and the speed. The study reveals that the polynomial form of curve was best fitted for the study area, for upper uncongested segment and linear form for lower congested segment. The capacity obtained was found to be relatively low than the IRC guidelines.**

***Keywords*— Capacity, Free Flow Speed, Traffic Flow, Level of Service, Design Service Volume, Manoeuvre, Congestion.**

I. Introduction

Frequent traffic jams and increasing journey times with growing traffic volume are major concerns in many Indian cities. The composition of traffic in the city is more complex in nature, as several modes of traffic using the same roadway having different acceleration and dimensional characteristics, like buses, cars, trucks, motorcycles, auto rickshaws, cycle rickshaws and bicycles, etc. Traffic on Indian urban roads is heterogeneous with a large variety of vehicles operating without any segregation. Traffic congestion and safety are a serious problem, with an impact on fuel economy, environmental pollution and the quality of journey times in our cities. In designing highways, traffic engineers must anticipate the amount and type of traffic that will use the road in order to make the highway match its anticipated use. Highway capacity is the maximum number of vehicles that can reasonably be expected to pass a section of road in a unit of time under prevailing roadway, traffic and control conditions. The design service volume is the maximum number of vehicles that can be accommodated at a specified level of service (LOS). The performance of the urban roadway depends on the practical capacity and actual volume of traffic on the roadway.

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II. Objective of The Study

The prime objective of the present study is to determine the roadway capacity of a divided four-lane carriageway under heterogeneous urban traffic conditions, and thus to ascertain the level of service that persists in the present scenario.

III. Background

There are different approaches to estimating the capacity of the road. Figure 1shows the various methods, which are based on direct and indirect empirical approaches (Minderhoud et al., 1997). There are four different methods available for capacity estimation under the direct empirical approach.

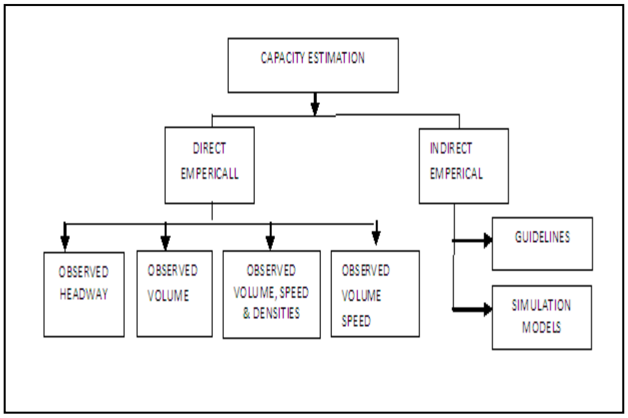

Figure 1. Methods of Capacity Estimation (source: Minderhoud *et al.*, 1997)

The observed headway models (e.g. Branston's generalized queuing model, Beckley's semi-Poisson model, etc.) are based on the theory that at the capacity level of flow on the road, all driver-vehicle elements are constrained. These models can be applied only for a single lane. In the case of multiple lane roads, the lanes are treated separately. An example of a capacity estimation technique based on observed traffic volume is the observed extreme value method, which estimates the capacity of a road by using only known maximum traffic volumes observed over a certain period of time. The product limit method is an example of road capacity estimation based on both traffic volume and speed data. This is an online procedure for capacity estimation based on traffic volume, speed and densities. The fundamental diagram method is based on the relationships between traffic flow, speed and density. It is sufficient to measure two of the three variables at different volumes to make a curve fitting possible. The capacity estimation guidelines issued by the Highway Capacity Manual (HCM), the Indian Roads Congress (IRC) and similar agencies are based on indirect empirical methods using appropriate theoretical techniques.

A. *Speed – Flow Study*

Speed, hourly flow (volume) data were used to build up the speed-flow relation. Different equations including linear, exponential, polynomial, logarithmic, power, Akcelik and Bureau of Public Roads (BPR) were attempted. The different forms of these models are selected based on the equations in Table 1.

TABLE 1. SPEED FLOW EQUATIONS

Name of the equation	Functional form
Linear	$v= \alpha\text{-}x+\beta$
Logarithmic	$v= \alpha \ln x+\beta$
Exponential	$v=\alpha v_f \exp(-\beta x)$
Power	$v=\alpha/x^{\beta}$
Polynomial	$v=\alpha x^2-\beta x+\gamma$
Bureau of Public Roads	$v=v_{f/(}(1+-\alpha(x)^{\beta}$
Akcelik	$v=L[L/vf+0.25\{(x-1)+SQRT\{(x-1)^2+\alpha x\}]$

V-speed; α, β,γ-global parameters for equation, $x= F/F_{cap}$; F = flow; F_{cap} = capacity flow;L- link length; V_f - free flow speed

Using the collected speed and flow data, the speed-flow relationship was explored by converting the different vehicles into PCU units as prescribed in IRC-106 (1990). Hourly traffic volumes in terms of PCUs are divided into two segments, as shown in Figure 2.

1. Uncongested segment – upper half of the curve
2. Congested segment – lower half of the curve

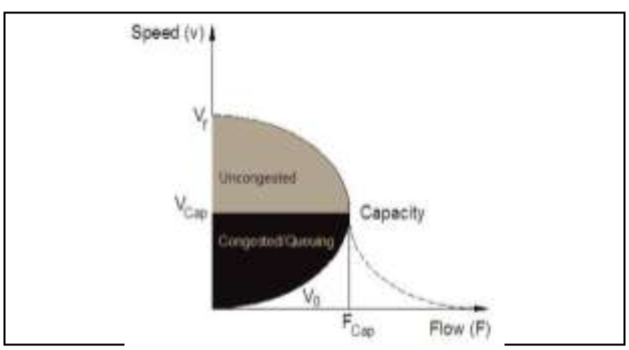

Figure 2. Capacity Estimation

The capacity estimation guidelines issued by the HCM, IRC and similar agencies are based on indirect empirical methods using appropriate theoretical techniques. Analysing the two parts (uncongested and congested) separately for developing the speed-flow equation under heterogeneous traffic conditions, roadway capacity (F_{cap}) is considered as the intersecting point of the best speed flow model developed for the upper and lower parts shown in Figure 2. The primary aim of the present study is to build up a speed-flow equation for an urban heterogeneous four-lane divided carriageway to determine the roadway capacity and level of service and to suggest the design service volume (DSV).

B. *Level of Service (LOS)*

Capacity standards are fixed normally in relation to the Level of Service (LOS) adopted for the design. Level of service is defined as the qualitative measures describing the operational conditions within a traffic stream and their perception by drivers/passengers. Level of service is broadly defined as the prevailing conditions under which the driver has to drive. This is a qualitative measure rather than a quantitative measure in the true sense. LOS is divided into six commonly recognised classes – LOS (A) to (F). The definition of the level of service generally describes this condition in terms of factors such as speed and travel time, freedom to manoeuvre, traffic interruptions, comfort, convenience and safety.

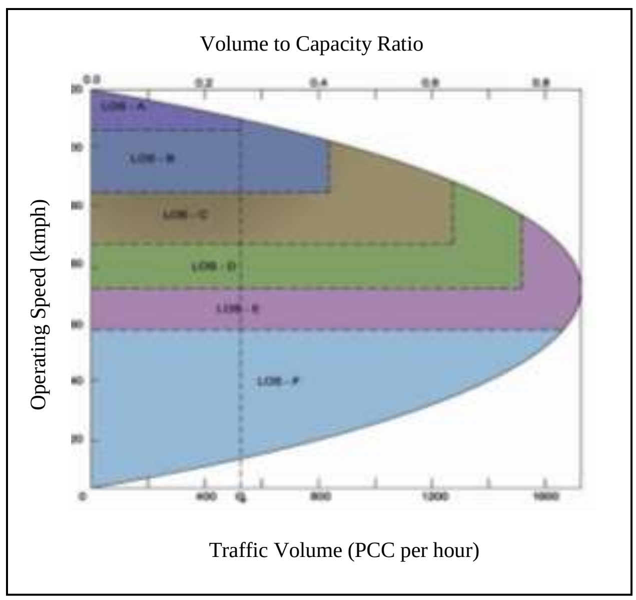

Figure 3. Level of Service

Usually, LOS (B) is considered for design purposes. But in exceptional circumstances LOS (C) is used. Figure 3 shows the various levels of service in the form of an indicative volume flow-relationship for urban conditions, and each of the levels of service can be described broadly as below. When driving conditions are at their best, the traffic moves in freely flowing conditions, and the driver faces absolutely no hindrances from other vehicles.

The volume of the road reaches capacity when the volume to capacity ratio approaches the maximum possible value of 1.0. The factors to be considered for the evaluation of a roadway in a comprehensive manner include the operating speed, travel time, traffic interruptions, freedom of manoeuvre, driving comfort, safety, economy etc. However, in order to simplify the level of service concept, two factors considered by the Highway Capacity Manual (HCM) are the ratio of service volume to capacity (v/qc) and the operating or travel speed. With increasing traffic volume, or the v/qc ratio, the operating speeds of faster vehicles and their opportunities to overtake decrease and the level of service falls to decreasing values of (B), (C), (D) and (E). Further increase in vehicle arrival causes a further decrease in stream speed, as well as in the maximum flow, resulting in undue congestion and the lowest level of service, (F), when the forced flow condition deteriorates until there is no flow due to stopping of vehicles. Hence the density attains the highest value (jam density) and there is a traffic jam.

In the Highway Capacity Manual (HCM) (2000) procedures, there is an implicit assumption that safety, an important measure of the service a facility provides, is automatically considered when the LOS is specified. This means that the better the LOS, the safer a facility will be and the usual practice of designing for a median LOS of (C)or (D) produces a desirable balance between cost, safety and operational measures. The IRC recommends that LOS (C) should be adopted for the design of urban roads (IRC-106, 1990). At this level, the volume of traffic will be around 0.7 times the maximum capacity, and this is taken as the design service volume for urban roads.

C. Design Service Volume

The design service volume (DSV) is defined as the maximum hourly volume of vehicles that can reasonably be expected to traverse a uniform section of a roadway under prevailing roadway, traffic and control conditions at a designated level of service (LOS). Design service volume is used to determine the carriageway width. From the viewpoint of smooth traffic flow, it is not advisable to design the width of the carriageway (or to determine the number of lanes) for a traffic volume equal to its capacity at LOS (E). At this level, speeds are low (typically half the free speed) and freedom to manoeuvre within the traffic stream is extremely restricted. Besides, at this level of service, even a small increase in volume would lead to a forced flow situation. Different DSV for different class of urban road are presented in Table 2.

D. Free Flow Speed Study

When the volume of the traffic is very low, the vehicle runs freely without any obstruction. This is referred to as the free flow condition, and speed in this condition is known as free speed. Free flow speed studies were conducted using a radar speed gun. This instrument directly displays the speed on triggering the gun on the moving vehicle. The observed free flow speeds of different vehicle types were classified into suitable intervals (kmph) to determine the frequency distribution of vehicles as per speed. The mean speed and standard deviation (SD) values were calculated from the frequency distribution. Further, these data were fitted to normal distribution and cumulative distribution curves, using the mean speed and standard deviation of the vehicle speed. From these distributions, important parameters such as the 15th percentile speed (V_{15}), 50th percentile speed (V_{50}), 85th percentile speed (V_{85}), 95th percentile speed (V_{95}) and spread ratio (SR) were calculated to check the validity of the data. The SR is used to explain the normality of the observed data and is defined by the relation:

$$SR = (V_{85}-V_{50}) / (V_{50}-V_{15}) \quad (1)$$

The estimated frequency curve will be truly normal when the SR is unity. It will tend to deviate from the normal distribution as the SR deviates from unity. As observed from the fitted normal distribution curves, speed data follow the normal curve only when the SR is between 0.69 and 1.355.

TABLE 2. IRC RECOMMENDED DSV (FOR URBAN ROAD)

Sl. No.	Type of Carraigeway	Total Design Service Volume for Different Categories of Urban Roads, PCU/Hour		
		Arterial	*Sub-Arterial*	*Collector*
1	2 Lane (one way)	2400	1900	1400
2	2 Lane (two way)	1500	1200	900
3	3 Lane (one way)	3600	2900	2200
4	4 Lane Undivided (two way)	3000	2400	1800
5	4 Lane Divided (two way)	3600	2900	---
6	6 Lane Undivided (two way)	4800	3800	---
7	6 Lane Divided (two way)	5400	4300	---
8	8 Lane Divided (two way)	7200	---	---

IV. Study Area & Selection of Site

This study was conducted in Silchar (longitude 24°52′46.4″ N & latitude 92°42′52.84″E) located in the north-eastern part of Assam, India. The determination of the roadway capacity in the study area as a case of urban heterogeneous traffic conditions was based on the very slow movement of the traffic during the peak hours. The traffic data required for the

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capacity study was collected from the Rangerkhari area of the Silchar Hailakandi Road. This is a four-lane divided carriageway and the layout plan of the study area is shown in Figure 4.

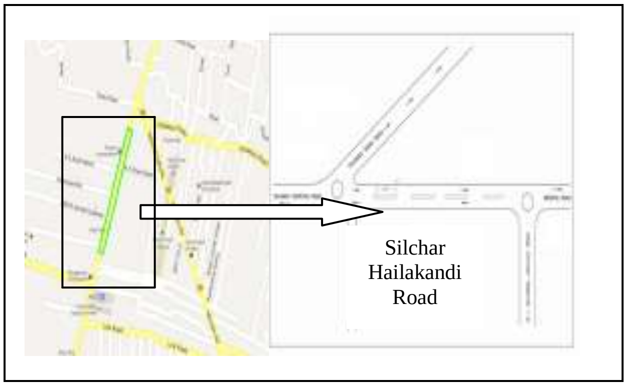

Figure 4. Layout Plan of the Study Area

Several criteria were used to select the site for study:

- Comparatively high traffic volume
- Equal width of the road
- Similar surface condition
- Reasonable quantity of non-motorized vehicles
- Level terrain
- Insignificant disturbance from parked vehicles
- Absence of bus stops

V. Free Flow Speed Survey and Analysis

Free flow speed data were collected during a lean period of traffic volume. The time selected for this study was in the early morning from 5 a.m. to 6 a.m. in order to experience free flow conditions. Free flow speed data were recorded with the help of a radar speed gun in order to capture a reasonable quantity of vehicles as shown in Figure 5. The observed free flow speed data were tabulated showing all the relevant parameters, such as sample size, standard deviation, percentile speed, mean free flow speed, maximum free flow speed and spread ratio for each class of vehicle, as indicated in Table 5.

Figure 5. Free Speed Data Collection by a radar speed gun

TABLE 5. FREE SPEED STATISTICS

Types of Vehicle	SS	MS	AS	SD	V_{15}	V_{50}	V_{85}	V_{95}	SR
Motor Cycle	76	65	55.2	4.08	50.0	53.6	57.6	60.5	1.11
Car	48	62	54.6	3.30	50.8	54.3	57.0	59.5	0.76
Auto Rickshaw	50	52	44.1	3.46	40.0	44.0	47.2	48.5	0.80
Bus/Truck	20	42	36.5	2.91	33.0	36.0	39.0	41.0	1.00

SS – sample size, MS – Maximum Speed, AS – Average Speed SD- Stand Deviation ,V_{15} -15th percentile speed in kmph,V_{50}- 50th percentile speed in kmph ,V_{85}-85th percentile speed in kmph ,V_{95}-95th percentile speed kmph , SR -spread ratio

VI. Traffic Volume Speed Survey

The aim of the traffic survey is to identify the required traffic volume and speed of the traffic stream at different hours of the day. The data were collected using a videographic technique as shown in Figure 6. Two video cameras were fitted, one at the entry point and the other at the exit point of the selected section of road. The cameras were enabled with time-recording devices. The distance between the entry and exit points on the roadway section was 600 m. All the vehicles crossing the section were recorded by the entry and exit cameras with their entry and exit times. The time taken to traverse the selected stretch was calculated for each vehicle and thus the speed of each individual vehicle was calculated. The count on the entry/exit camera gave the flow or the volume. The videographic survey was conducted for the period from 8 a.m. to 7 p.m.

Figure 6. Traffic Data Collection

Three sets of data were collected for five minute periods for each of the eleven hours of the study period. Therefore, the total duration of the video recording was 165 minutes. The recorded data were run in an audio-visual equipped laboratory. The vehicles were identified from their registration numbers. The necessary traffic volume and speed data of the respective hours for each set was obtained.

VII. Converting Traffic Volume to PCU Volume

Estimation of the traffic volume and capacity of the roadway under mixed traffic flow is difficult unless the different vehicle classes are converted into one common standard vehicle unit. It is common practice to consider the passenger car as a standard vehicle unit to which to relate the other vehicle classes, and this unit is called a Passenger Car Unit (PCU). The PCU factors for various classes of vehicle for urban areas are selected from Table 3 (IRC-106, 1990). The percentage of each class of vehicle is determined from the traffic volume. This average composition was then plotted in a pie chart as indicated in Figure 7.

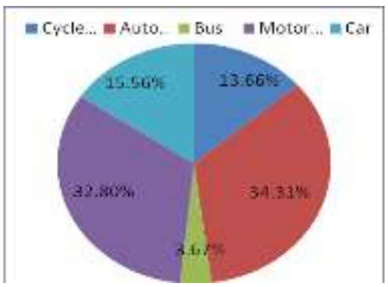

Figure 7 Percentage composition of vehicles for each class.

These percentages were used to select the appropriate PCU factor as indicated in Table 7. Then the traffic volume was converted into the PCU volume by multiplying by the respective PCU factor. These PCU volumes are the inputs for the speed-flow equation.

TABLE 7. PCU FACTORS FOR THE STUDY AREA

PCU Factor	**Traffic Composition (%) (Average of all three sets)**				
	Cycle Rickshaw	*Auto Rickshaw*	*Bus*	*Motorcycle*	*Car*
	2.00	2.00	2.20	0.75	1.00

VIII. Speed Data PCU Volume

Speed is the one of the most important parameter for speed-flow study. The video data recorded during the traffic survey were run on two computers simultaneously in slow motion mode. Recorded data from the entry and exit points were run simultaneously to identify every vehicle entering and leaving the road section. As the video cameras were able to display time, the actual times of entry and exit were identified for each of the vehicles. Based on this very simple methodology, namely the repeated running of video films, the entry and exit times of each class of vehicle in each hour for each set of data were extracted. Thus, the speed of individual vehicles was calculated by simply dividing the length of the segment by the time difference between the entry and exit points.

TABLE 8. AVERAGE SPEEDS (KMPH) OF CARS

Time	**1st Set of Data**	**2nd Set of Data**	**3rd Set of Data**
8-9	27.80	27.95	26.46
9-10	23.25	19.27	23.41
10-11	15.06	15.58	15.06
11-12	15.49	15.58	15.63
12-1	15.19	15.59	15.48
1-2	15.55	16.06	15.67
2-3	15.66	15.90	15.47
3-4	19.08	17.00	20.10
4-5	22.58	22.08	19.05
5-6	20.57	17.57	20.54
6-7	22.70	27.03	21.15

The speed of cars entering the roadway section during the hours of the survey for each set is calculated. Average speeds of different cars during the different hours are calculated and presented in Table 8.The speed data of cars is required to develop the speed-flow equation.

IX. Evaluation of Capacity

All three sets of data (Table 8) were converted into PCU volume. The first set of data was used to build up the model and the remaining two sets were used to validate the model. The speed data of cars and the PCU volumes in the respective hours were utilized to develop speed-flow graphs and thus the speed-flow equation for the study area. Methodologically, the first set of data was initially scrutinized and divided into two segments - uncongested and congested, based on speed and volume. The data in the uncongested segment showed higher speeds and lower to higher traffic volume. Similarly the data in the congested segment are of lower speeds and higher to lower traffic volume, as indicated in Table

The intersecting point of both the curves is the capacity of the roadway. The volume of the intersecting point is found to be 2138 PCU, which is the observed capacity of the roadway section in the present study. The equations derived for the speed-flow model are indicated in Figure 8.

TABLE 9. PCU VOLUME & SPEED

1st Set			2nd Set			3rd Set		
Time	*Volume (PCU)*	*Speed (kmph)*	*Time*	*Volume (PCU)*	*Speed (kmph)*	*Time*	*Volume (PCU)*	*Speed (kmph)*
Uncongested segment			*Uncongested segment*			*Uncongested segment*		
8-9 a.m.	1361	27.80	8-9 a.m.	1463	27.95	8-9 a.m.	1484	26.46
9-10 a.m.	1880	21.37	9-10 a.m.	1922	19.27	9-10 a.m.	1664	23.41
10-11 a.m.	2176	15.07	10-11 a.m.	1991	15.58	10-11 a.m.	2191	15.06
5-6 p.m.	1794	20.57	5-6 p.m.	1994	17.57	5-6 p.m.	1837	20.54
6-7 p.m.	1708	22.70	6-7 p.m.	1541	27.03	6-7 p.m.	1747	21.15
4-5 p.m.	1656	22.58	4-5 p.m.	1707	22.08	4-5 p.m.	1858	19.05
3-4 p.m.	1921	19.08	3-4 p.m.	1994	17.00	3-4 p.m.	1851	20.10
2-3 p.m.	2178	15.66	1-2 p.m.	2109	16.06	1-2 p.m.	2310	15.67
Congested segment			*Congested segment*			*Congested segment*		
2-3 p.m.	2178	15.66	1-2 p.m.	2109	16.06	1-2 p.m.	2310	15.67
1-2 p.m.	2056	15.55	2-3 p.m.	1987	15.90	2-3 p.m.	1923	15.47
12-1 p.m.	1708	15.44	12-1 p.m.	1726	15.64	12-1 p.m.	1876	15.48
11-12 a.m	1794	15.49	11-12 a.m.	1714	15.58	11-12 a.m.	2164	15.63

The upper uncongested segment and lower congested segment are plotted separately to get the graphical pattern using speed and flow data. Different forms of equations as indicated in Table 4 were tested to get the best fitted speed-flow equations.

The free flow speed wherever required for these equations was taken from Table 9. The parametric constant of each of the equations was determined and the respective R^2 value was checked for statistical validity.

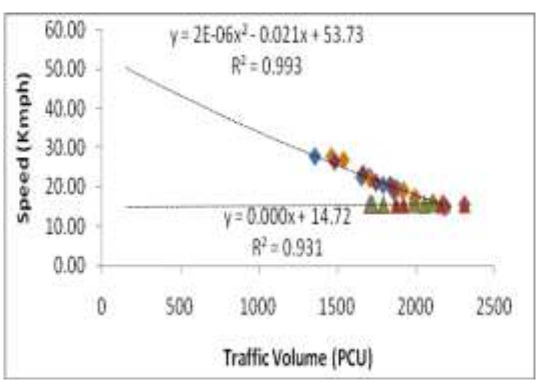

Figure 8. Speed Flow Model

The models were tried using the statistical package for social study (SPSS). It was found that the polynomial equation of second degree was the best fitted out of all the forms of equation considered (Table 4) in the upper congested segment, and the linear equation for the lower congested segment. The speed-flow curves are plotted as shown in Figure 8.

X. Level of Service and Design Service Volume

Considering the need for smooth traffic flow, it is not advisable to design the roadway section for a maximum traffic volume equal to the capacity of the road. At such volume level, the prevailing LOS is normally either (E) or (F) and the speeds are very low. The volume/capacity (v/c) ratios at different hours were calculated from the flow values of the respective hours. Next, plotting the v/c ratio versus the respective speed, two separate curves for both the upper and lower segments were obtained, as shown in Figure 9. The equations of the curves are indicated in Table 10.

The curves shown in Figure 9 are utilised to obtain the different level of service regions, i.e., LOS (A) to (F). The x-axis (abscissa) of the graph represents the volume to capacity ratio and at the same time y-axis (ordinate) represents the speed. Horizontal lines are drawn parallel to the x-axis from abscissa upto the length of v/c ratios for corresponding speeds. Now, vertical lines are drawn parallel to the y-axis at end of each of the horizontal lines till it touches the LOS curve. The area lying in between two horizontal lines are referred as LOS as indicated in Figure 9. Data obtained from the survey were mostly located in the region of LOS (E) or LOS (F), which are the zones of forced flow. It can be easily understood that the traffic during most hours of the day experiences traffic congestion or traffic jams.

TABLE 10. REPRESENTATION OF EQUATION FOR LOS CURVES

Segment	Type of equation	Form	Statistical validity (r^2) value
Upper Segment	Polynomial	$y= 8.292x^2 - 46.09x + 53.73$	0.993
Lower Segment	Linear	$y= 0.893x + 14.72$	0.931

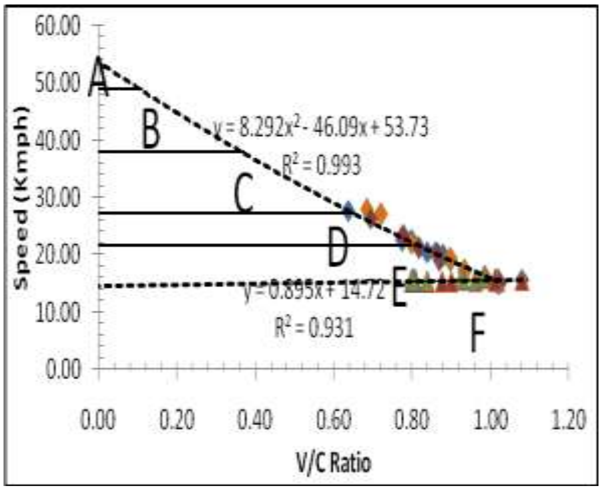

Figure 9. Level of Service Diagram

The design service volume is chosen considering a balance between economy and safety. It can be specified that LOS (A) and (B) are not viable due to the higher facility costs involved. LOS (E) and (F) are the zones of forced flow condition. Thus the design service volume is usually targeted to be such that the level of service can be maintained at (C). In the urban scenario, the LOS may be relaxed to LOS (D). It is desirable to have LOS (C) for comfort as well as for economic considerations. Beyond LOS (D) the traffic experiences traffic jams leading to a constant breakdown of traffic movement. The design service volume (DSV) has been identified at different v/c ratios as indicated in Figure 10.

The DSV at LOS (C) and LOS (D) are found to be 1496 PCU and 1924 PCU respectively. The values of the DSV obtained at different levels of service are considerably lower than the recommended IRC guidelines as indicated in Figure 10. The present scenario at the study area reflects the forced flow condition mostly during the peak hours.

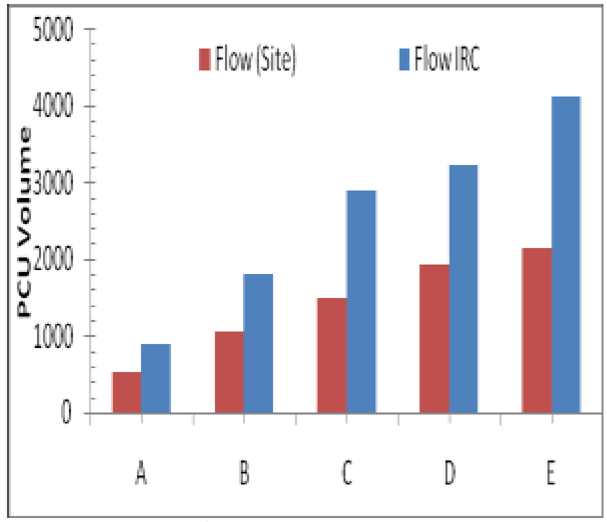

Figure 10. Comparison of DSV at study area and IRC recommended value

XI. Conclusions

Speed flow equation was attempted for heterogeneous urban traffic composition for the study area. The speed flow relationship for the upper uncongested and lower congested segment were plotted separately. The speed flow equations from the collected data suggest that the average speed of the vehicles remains within the range of 10Km/hr to 30 Km/hr when the traffic volumes were in between 1200 to 2100 PCU. The speed ranges are very low due to heterogeneity of the traffic composition. There was a significant composition of non-motorized vehicle in the traffic stream. The lanes were not segregated for motorized and non motorized vehicles in the study area. Vehicle mix behaviour of traffic would be the probable reason for low speed of vehicles and consequent under performance of the roadway section.

The capacity of the road at the selected section was observed as **2138 PCU,** which was considerably less than the prescribed IRC guidelines for similar class of road (IRC-106, 1999). The LOS diagram plotted from this study reflects that the level of service on the roadway was **LOS (E)** for most hours of the day, and was occasionally LOS (F). The **DSV** obtained from the study for **LOS (C)** was **1496.60** and **LOS (D)** was **1924**. The DSV is low, so there is an urgent need for improvement of the traffic capacity.

Since the traffic volume is going to increase day by day, the prevailing condition will further deteriorate in the years to come. This prevailing LOS in the present scenario is an alarming indication for the present as well as the future. Unless a comprehensive strategy is adopted to relieve the traffic congestion, the movement of vehicles is likely to jeopardize the entire traffic system in the years to come.

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