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Traffic Flow Modeling and Capacity Estimation for Heterogeneous Traffic on Four Lane Divided Carriageway

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Abstract— In India, heterogeneous traffic condition due to various kinds of vehicles manoeuvres increase rapidly. Heterogeneous nature occurs due to different lane characteristics and driver behavior resulting in static and dynamic features. Therefore, traffic on the road varies and traffic volume exceeds normal range. Study on various traffic parameters is essentially required for manoeuvre of roadway facilities. Traffic flow fundamental diagrams can be used to characterize relation between traffic parameters such as speed, flow and density. Present study is concerned with macroscopic traffic flow characteristics observed on four lane divided carriageway. Traffic flow fundamental diagrams are used to characterize the relation between macroscopic parameters and compared with other multi-regime models such as Edie model, Modified Greenberg's model, Two regime linear model and Three regime linear model. Macroscopic models provide a general knowledge of vehicles and traffic as a continuum. Calibrated speed-density model under free-flow regime and congested flow regime can be used for predicting future scenario of traffic on four lane divided road. The speed-density models are modified based on percentage heavy motor vehicle composition. Capacity analysis of the roads is done using speed-flow diagram and compared with the capacity obtained from Indo-HCM method. Greater capacity shows better roadway structure that will improve the vehicular road traffic. At last the influence of operating speed on the roadway capacity is found and developed a new capacity model that can be used for predicting capacity for varying road sections.

Index Terms— Capacity, Edie model, Fundamental diagrams, Heterogeneous traffic, Indo-HCM method, Macroscopic models, Modified Greenberg's model, Three regime linear model, Traffic parameters, Two regime linear model.

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1 Introduction

TODAY's situation of congested road networks is a severe problem, which has to be addressed due to the increase in trend of transportation demand every year. Determination of road capacity is a major issue for transport planners. Capacity studies for heterogeneous traffic situations are very complex and only limited studies undertaken. There are several methods of estimation of capacity. However the major types of estimation can be classified under two broad categories as Direct Empirical Methods and Indirect Empirical (Simulation) Methods.

In this paper an attempt is made to study the fundamental diagrams of traffic flow and evaluate the capacity of urban mid block section, particularly for a four lane divided cross section. Macroscopic traffic flow models represent the traffic as a compressible fluid with the main properties flow, density and speed. Multi-regime models include two or three regimes to describe different traffic conditions.

Using the fundamental parameters, capacities of sections were evaluated and compared with the capacity estimated using Indo-HCM method. Free flow speed was also measured at each section and these speed data were used to determine operating speed 85th percentile of free flow speed on the road. Operating speed on a road can vary due to road surface condition, side friction or similar other factors.

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2 Objectives

1. To develop speed-density model and to derive relationship between flow-density and speed-flow, in order to assess the behavior of traffic flow.
2. To compare the developed model with other multi-regime models such as Edie model, Modified Greenberg's model, Two regime linear model and Three regime linear model.
3. To modify the developed speed-density model based on percentage heavy motor vehicle composition.
4. To estimate the roadway capacity using parameters obtained from fundamental diagrams of traffic flow.
5. To determine influence of operating speed on the roadway capacity, for develop a capacity model.
6. To compare the estimated capacity with the capacity found out using Indo-HCM method.

4 Literature Review

Hwang Zunhwan et. al. [7] developed DHCE (Dynamic Highway Capacity Estimation) methods and applied to real traffic data. Result shows DHCE methods showed excellent performance in explaining real traffic situations, which can vary dynamically. Dr. Mehdi I. Alkubaisi et. al. [2] focuses on studying the speed flow density relationships. The developed regression models may be used to predict the speed- flow-density relationships for urban highways and other similar areas. K. M. Lum et. al. [5] presented speed-flow modeling of arterial roads in Singapore. The developed models for radial and ring arterial roads in Singapore by taking minimum delay per intersection and number of intersections per kilometre as model parameters. J Roux et. al. [4] tested the relevance of overseas models to South African conditions. The ability of each model to describe the entire data range was evaluated with the aid of statistical methods based on two regimes of traffic flow, namely uncongested flow and congested flow. Separate curves were used to describe each regime. Examined speed-flow relationships for individual lanes and compared to relationships established for average lanes. Ashish Dhamaniya et. al. [1] developed speed density relations for different vehicle type on urban arterial roads under mix traffic conditions in Chandigarh, Jaipur and Delhi using a set of simultaneous equations and established speed prediction models and also compares the manoeuvrability of a vehicle type. Ashutosh Kantibhai Patel [6] aimed to model an urban corridor using Cellular Automata. Modeling and analyzing non-lane-based heterogeneous traffic at urban mid-block sections as well as signalized intersections. Results show that developed model can be used as an effective tool for heterogeneous traffic flow modeling. H. Hussain et. al. [3] establishes motorcycle speed flow and density relationships and capacities of exclusive motorcycle lanes in Malaysia. Motorcycle speed-density data were aggregated and plotted for two types of observable motorcycle riding behaviour patterns: headway pattern and space pattern. For both riding patterns, regression analysis of motorcycle speed-density data best fits the logarithmic model and consequently the motorcycle flow-density and speed-flow models are derived. Motorcycle lane capacities for headway and space riding patterns are estimated. Indo-HCM [8] the capacity of a four-lane road is influenced by the road conditions and drivers' behaviour. Hence a linear relation as typically presented as in Eqn. 1 is observed to exist between capacity and operating speed (V_{OS}) of standard cars plying on varying typologies of interurban and urban roads. In this context, the operating speed on a road is taken as the 85th percentile of free flow speeds of standard cars. A vehicle travelling with headway 8 seconds or more is considered as free flowing.

$$\text{Base Capacity} = A = B * V_{OS} \qquad (1)$$

Where,

V_{OS} = Operating Speed of Standard Cars, km/h

5 METHODOLOGY

1. Selection of suitable road stretch and time of survey.
2. Data collection using videographic technique.
3. Data extraction using Macro in Excel.
4. Analysis and calculation of basic parameters of traffic flow using statistical software SPSS.
5. Tabular and graphical representation of analyzed values of traffic flow parameters.
6. Development of speed-density relationship model.
7. Deriving flow-density and speed-flow relationship for the given road.
8. Compare the developed model with other multi-regime models.
9. Modify the developed speed-density model based on percentage heavy motor vehicle composition.
10. Validation of the developed model.
11. Estimation of roadway capacity using parameters obtained from fundamental diagrams.
12. Determine influence of operating speed on the roadway capacity.
13. Compare the estimated capacity with the capacity found out using Indo-HCM method.

6 DATA COLLECTION AND EXTRACTION

6.1 Determination of Study Section

The initial step was the selection of the road stretch, from which the data were collected. Four roads were selected under congested and congested regime conditions. A pilot study was organized on the selected road which covers both free-flow and congested-flow conditions in order to determine the place were predictable to get the data more precisely. The distance enclosed by the entry and exit point is noted as 1 km. The data were collected by videographic survey conducted on typical weekdays over peak and off-peak hour.

6.2 Data Processing

Video recordings were processed by tracing vehicle movement crossing the specified study section. The flow data is calculated at entry and exit points in such a way that the vehicles which are passing through the section in every five minute interval. The speed data is done by calculating the time by which vehicle which enters and exit the rectangular section. Initial density is determined using photographic technique along the entire section. By using initial density, the density is calculated at every five-minute interval as in (2).

$$k_t = k_{(t-1)} + N_{entry} - N_{exit} \qquad (2)$$

Where,

k_t is the density at time t

N_{entry} is the number of vehicles entered the stretch during the time from t-1 to t

N_{exit} is the number of vehicles going out the stretch during the time from t-1 to t

7 DATA ANALYSIS

7.1 Determination of Speed-Density Relationship

The model equations and breakpoints for different multi- regime models are shown in Table 1.

TABLE 1
EQUATIONS AND BREAKPOINTS FOR MULTI-REGIME MODELS

Multi-regime Model	Free-Flow Regime	Transitional Flow Regime	Congested Flow Regime
Edie Model	$u = 54.9e^{-k/163.9}$ (k≤50)	-	$u = 26.8\ln\left(\frac{162.5}{k}\right)$ (k≥50)
Two-regime linear Model	$u = 60.9 - 0.515k$ (k≤65)	-	$u = 40 - 0.265k$ (k≥65)
Modified Greenberg's Model	$u = 48$ (k≤35)	-	$u = 32\ln\left(\frac{145.5}{k}\right)$ (k≥35)
Three-regime linear Model	$u = 50 - 0.098k$ (k≤40	$u = 81.4 - 0.913k$ (40≤k≤65)	$u = 40.0 - 0.265k$ (k≥65)

The speed-density curve was plotted, density as independent variable and speed as dependent variable. The best fit curve was chosen for model development. The developed model was compared to multi-regime models such as Edie model, Modified Greenberg's model, Two regime linear model and Three regime linear model where shown in Figure 1, 2, 3, 4, 5 & 6.

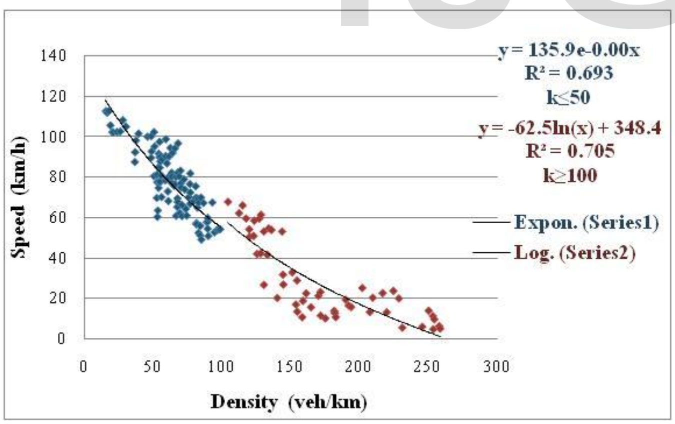

Fig. 1. Speed-Density Relationship using Edie Model

In Modified Greenberg's model it was assumed u= 48 km/h when the density is less than 35 veh/km. In the existing traffic condition this assumption cannot be considered. Thus a model was developed based on existing traffic conditions on four lane divided carriageways. The developed two regime model shows better goodness of fit than other multi regime models shown in Figure 5.

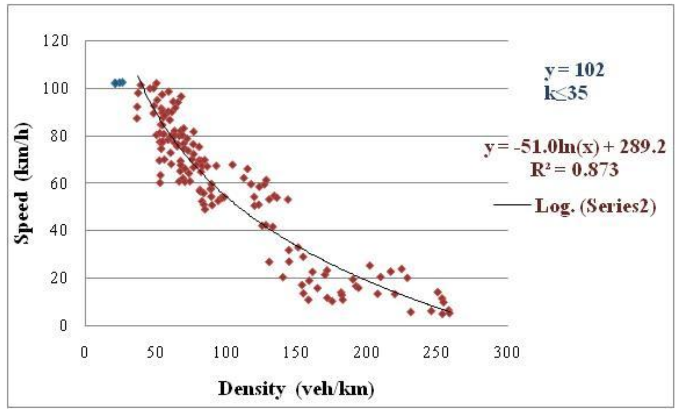

Fig. 2. Speed-Density Relationship using Modified Greenberg's Model

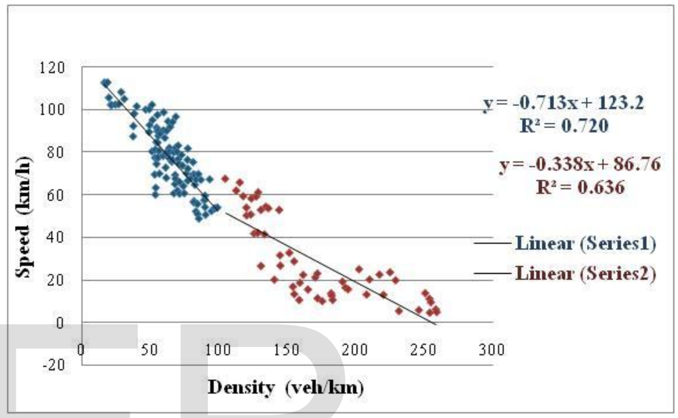

Fig. 3. Speed-Density Relationship using Two Regime Linear Model

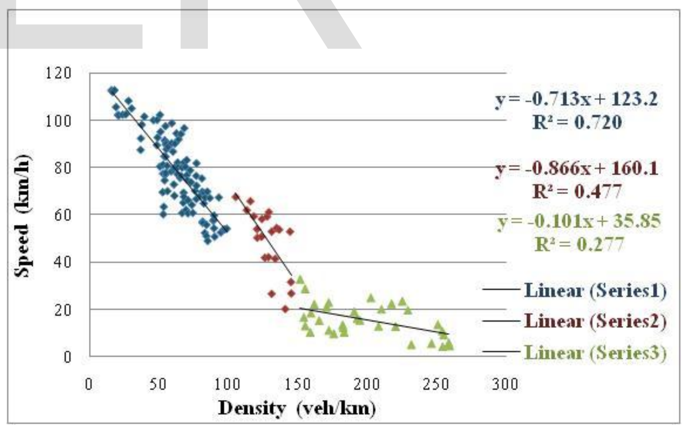

Fig. 4. Speed-Density Relationship using Three Regime Linear Model

In Figure 5, data was plotted based on free flow regime and congested flow regime. The data range was chosen based on the traffic flow conditions. The density below which maximum flow occurs was chosen as free flow regime (k≤100) and the density above maximum flow was taken as congested flow regime (k≥100). In Figure 6, the density below which maximum flow occurs was chosen as free flow regime (k≤100), density ranges from 100 to 150 taken as transitional flow regime and the density above 150 taken as congested flow regime.

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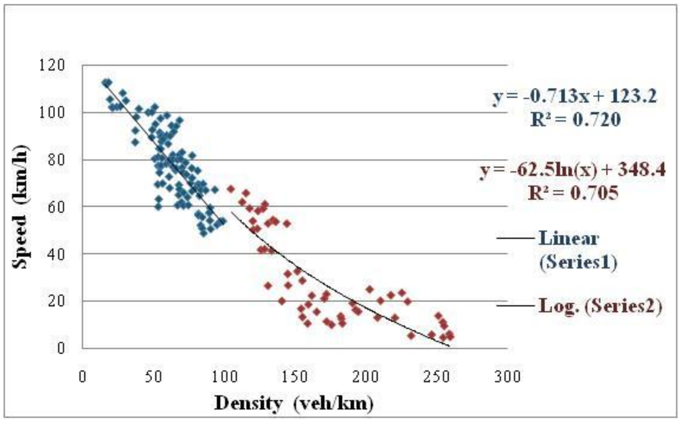

Fig. 5. Speed-Density Relationship using Developed Two Regime Linear Model

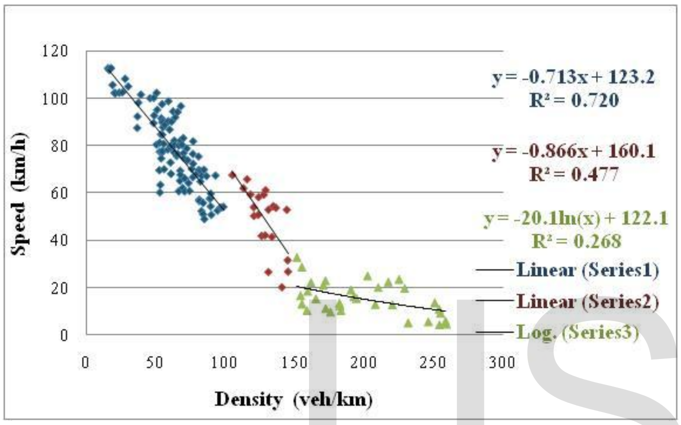

Fig. 6. Speed-Density Relationship using Developed Three Regime Linear Model

The final form of speed-density relationship model is presented as follows:

Free flow regime (k≤100),

$$u=-0.713*k+123.2 \quad (3)$$

Congested flow regime (k≥100),

$$u=-62.5*\ln(k)+348.4 \quad (4)$$

Where,

u is the speed in km/h
k is the density in veh/km

7.2 Flow-Density Relationship

The flow-density diagram is used to determine the traffic state of a roadway. The free-flow of a roadway at the origin of the flow-density graph and the congested has a negative slope, which implies that the higher the density on the congestion, lower the flow. The flow-density relationship can be derived as follows:

$$q=u*k \quad (5)$$

Free-flow regime (k≤100),

$$q=(-0.713*k+123.2)\,k \quad (6)$$

Congested flow regime (k≥100),

$$q=(-62.5*\ln(k)+348.4)\,k \quad (7)$$

Where,

q is the flow in veh/h
k is the density in veh/km

The obtained flow-density relationship was plotted, density is independent variable and flow is dependent variable.

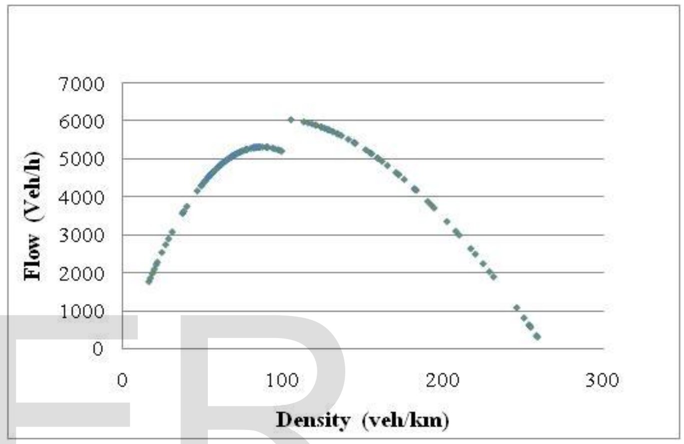

Fig. 7. Flow-Density Relationship

7.3 Speed-Flow Relationship

Speed–flow diagrams are used to determine the speed at which the optimum flow occurs. The speed-flow curve also consists of two branches, the free flow and congested branches.

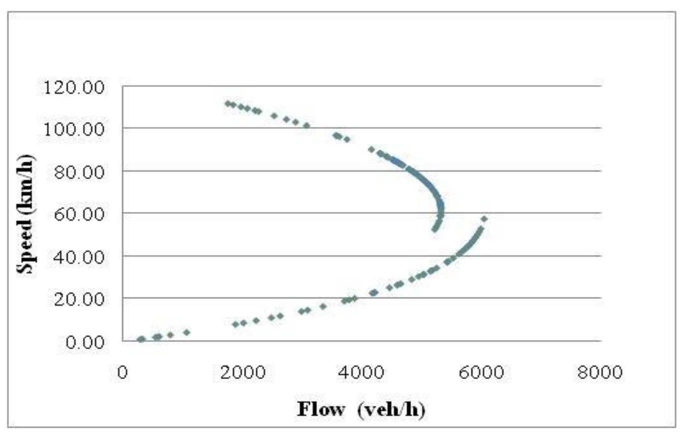

Fig. 8. Speed-Flow Relationship

8 Model Validation

The basic tool for statistical modeling is graphical residual analysis. The acceptability of various phases of the model is provided by different plots of the residuals from a fitted model. Numerical methods like R^2 statistic for model validation are

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also useful, but usually to a small extent than graphical methods. Graphical Residual Analysis and R^2 statistic for the given lanes (see Figure 9).

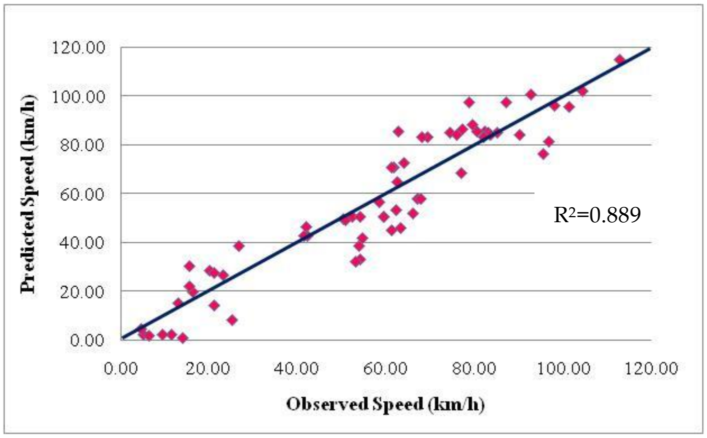

Fig. 9. Model Validation

9 Speed-Density Model Related to HMV Composition

Based on the results of exploratory analysis, different equations are considered for congested and free flow regime. It is possible that cut-offs may vary in view of different vehicle types. In this part the heavy motor vehicle composition related to speed is found out. The obtained speed-density model related to percentage heavy motor vehicle composition as in Eqn. 8 and 9.

Free-flow regime (k≤100),

$$u=-0.673x_1-0.055x_2+123.93 \quad (8)$$

Congested flow regime (k≥100),

$$u=-68.400x_1-11.206x_2+424.315 \quad (9)$$

Where,

u is the speed in km/h
x_1 is the density in veh/km
x_2 is the % HMV composition

10 Capacity Estimation

10.1 Capacity Estimation using Speed-Flow Curve

The maximum flow is taken as the capacity flow. Capacity varies with time, location, composition and other local factors. In the Fig. 8 maximum flow (q_{max}) obtained was 6042 PCU/h/lane among the whole data. Likewise, speed-flow diagrams are plotted for each lane at different location and the maximum flow is taken as the capacity of each lane represented as PCU/h/lane. Capacity and operating speed estimated on different lanes is shown in Table 2. Cumulative frequency distribution diagram of spot speeds for Lane 1-1 is illustrated in Figure 10. Similarly, graphs are plotted for remaining lanes and corresponding operating speeds are found out.

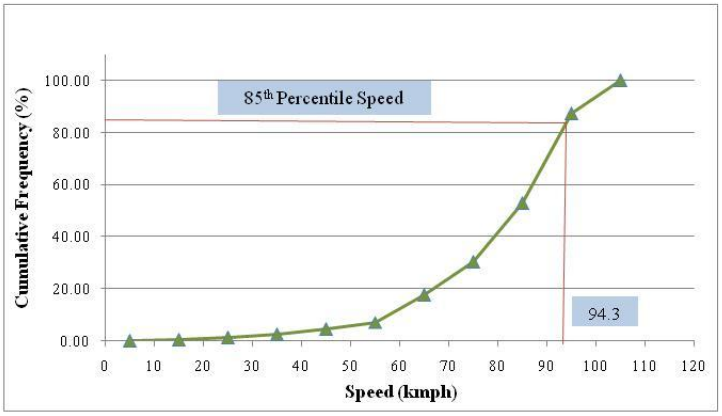

Fig. 10. Cumulative Frequency Distribution Diagram of Spot Speeds-Lane 1-1

TABLE 2
CAPACITY ON DIFFERENT LANES USING SPEED-FLOW CURVE

Lane	Capacity (PCU/h/lane)	V_{os} (km/h)
Lane 1-1	6042	94.3
Lane 1-2	5908	81.6
Lane 2-1	5900	65.3
Lane 2-2	5985	68.9
Lane 3-1	5817	52.6
Lane 3-2	6036	82.1
Lane 4-1	5320	23.2
Lane 4-2	5263	18.4

10.2 Relation between Capacity and Operating Speed

Table 4 indicates variation in lane capacity and operating speed with location. It is different on different sections in the same location also. The variation in capacity cannot be attributed to the driving behavior only. Therefore, variation in capacity is due to some other factors like surface condition of the road or driving habits of the drivers. Figure 11 shows the plot between operating speed and lane capacity at different sections. Logarithmic relation as given in Eqn. 10 was found to be the best fit between lane capacity and operating speed.

$$C= 504.4*\ln (V_{OS}) +3779 \quad (10)$$

Where,

C is the capacity in PCU/h/lane
Vos is the 85th percentile speed of standard passenger cars measured under low volume conditions in km/h

It can be seen from Figure 11, the capacity of the road is strongly related with operating speed with R2 of 0.971.

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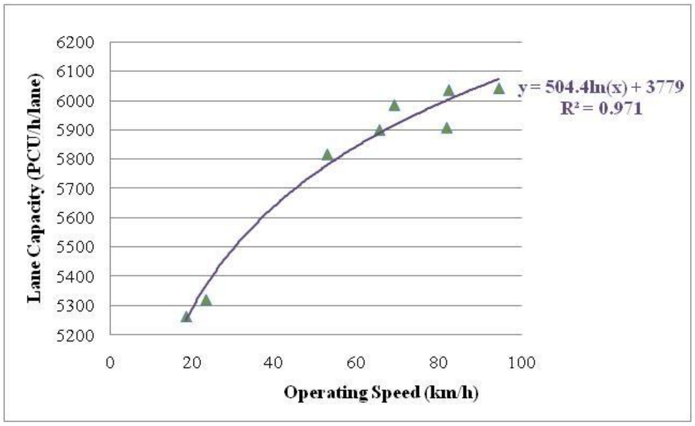

Fig. 11. Relation between operating speed and lane capacity

10.3 Capacity Estimation using Indo-HCM

Capacity estimated based on operating speed obtained on different lanes is shown in Table 3.

TABLE 3
CAPACITY ON DIFFERENT LANES USING Indo-HCM

Lane	Vos (km/h)	Capacity (PCU/h/lane)
Lane 1-1	94.3	4369
Lane 1-2	81.6	3988
Lane 2-1	65.3	3499
Lane 2-2	68.9	3607
Lane 3-1	52.6	3118
Lane 3-2	82.1	4003
Lane 4-1	23.2	2236
Lane 4-2	18.4	2092

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10 Conclusions and Future Scopes

In the modified Greenberg model it was assumed that the constant speed (u= 48 km/h) occurs when the density is less than 35 veh/km. In the existing Indian traffic condition this assumption cannot be considered as true. Thus the developed two regime model shows better goodness of fit. The best fit linear curve for free flow regime and logarithmic curve for congested flow regime was plotted. By using this developed speed-density model, flow-density and speed-flow relationship graphs are derived. The maximum flow obtained (qmax) is 6042 PCU/h/lane and the free-flow speed (u_0) is 57.73 km/h. The maximum density at lower flow, i.e. jam density (kj) is 259 veh/km.

The graphical residual analysis was used to statistically evaluate the mathematical model. The obtained value of R^2 is 0.889. The speed-density model related to heavy motor vehicle composition is developed by taking percentage heavy motor vehicle as a parameter. It can be used to predict speed based on heavy motor vehicle composition. Speed-flow diagrams are plotted for each lane at different location and the maximum flow is taken as the capacity of each lane represented as PCU/h/lane. Greatest capacity estimated on Lane 1-1, i.e. 6042 PCU/h/lane. Cumulative frequency distribution diagram of spot speeds for all lanes are plotted and the capacity is estimated using Indo-HCM method. Capacity estimated on Lane 1-1, i.e. 4369 PCU/h/lane is highest than other lanes. Relation between capacity and operating speed shows the capacity of the road is strongly related with operating speed with R^2 of 0.971. Thus the capacity model developed can be used for predicting capacity for varying road sections.

11 Future Scopes

1. The investigation of speed-flow relationships and capacity for various geometric conditions, terrain and traffic characteristics is required, in this study only one case was considered since all sections similar conditions.
2. In order to evaluate the effect of shoulder use on capacity, further study can be performed by comparing the value of capacity obtained on sections with good shoulder conditions to the capacity value of sections where the usage of shoulders is constrained.
3. Study can be extended to the estimation of capacity for Six-lane and Eight-lane divided Inter-Urban highways.

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