

A Comparison of Macroscopic Traffic Stream Models Under Non-lane-Based Heterogenous Highway Traffic



Sandeep Singh, Rajesh Kumar Panda, Anisha Biswal,
and S. Moses Santhakumar

1 Introduction

Many roads have insufficient capacity and often lead to congestion. Despite significant efforts, the Indian road network has not been able to keep pace with the high vehicular growth. This phenomenon can be attributed to the fact that Indian traffic is unique on its own [1]. It displays a much higher degree of heterogeneity against the traffic prevalent in other developing countries like China. Because of this considerable variation in the category of vehicles and different dynamic and static behavior, the movement of one vehicle is severely affected by the other [2]. Traffic speed is also a major controlling parameter contributing to the effective management of highways. The analysis of traffic flow on multi-lane roads is therefore vital. Traffic engineers can study and assess traffic systems on the basis of traffic flow metrics. Speed, flow, and density are the three most essential traffic parameters. Using these parameters, the highway system can be operated more efficiently.

Therefore, the researchers take advantage of traffic models to understand traffic characteristics and predict the traffic system's behavior. It is also fundamental for planning, designing road operations, and improving road serviceability. To account for the heterogeneous variability, the researchers use an equivalent unit, called passenger car unit (PCU), to interchange the traffic into a homogeneous one. In order to reduce heterogeneity variability in the traffic data, the dynamic passenger car unit (DPCU) values are calculated using the speed-area ratio method. This research has attempted to develop the relationships between speed, flow, and density using

S. Singh (✉) · A. Biswal · S. M. Santhakumar
Department of Civil Engineering, National Institute of Technology Tiruchirappalli, Tamil Nadu,
Tiruchirappalli 620015, India
e-mail: sandeepsingh.nitt@gmail.com

R. K. Panda
TATA Projects Limited, Pune, Maharashtra 411015, India

different macroscopic linear and nonlinear, single regime traffic flow models. Eventually, the basic principle of differentiation was used to find the maximum flow values for different models and based on statistical analysis, the best fit model was determined. Previous studies conducted on the same principles mainly focused on urban roads, limiting the application of macroscopic traffic stream models. The present study brings out the rational outcomes in terms of analyzing the macroscopic traffic parameters for the Indian highway traffic system.

2 Literature Review

Numerous approaches have been used in the past to estimate passenger car units (PCU) of vehicles. The basis used for most estimates is delay [3], speed [4], density [5], headway [6], and queue discharge [7]. However, these studies relate mainly to the PCU estimation of vehicles under uniform conditions of traffic. Hence, the results do not apply to the heterogeneous nature of traffic prevalent in India. Singh and Santhakumar [8] determined the DPCU and PCU for many vehicles under mixed traffic flow conditions. According to the study, the PCU values recommended by western countries' highway capacity manuals might not be applicable for capacity analysis in Asian countries.

Velmurugan et al. [9] investigated the free stream speed of various vehicles to evaluate the limit on multi-lane roadways in India. Mehar et al. [10] estimated multi-lane highway capacity through VISSIM models. They developed five different driver behaviors for various categories of vehicles based on their static and operating characteristics. Dhamaniya and Chandra [11] proposed a method to convert heterogeneous traffic volumes into homogeneous DPCUs without setting PCU factors. This study introduced a new term, the Stream Equivalency Factor (K): the ratio of traffic volume in PCU per hour to volume in vehicles per hour. A linear model proposed by Greenshields [12] was the earliest speed-density model. This model assumes speed and density to be linear, which is not valid for the entire road stretch. It can also be highly unsuitable for Indian roads due to the heterogeneity of vehicles on the roads.

Moreover, even in developing countries, there is a wide variation in traffic characteristics [13]. The vehicles have a vast difference in their physical appearance and performance abilities even though they share the same road [14]. The traffic conditions in India are therefore highly heterogeneous. For the capacity estimation, it is imperative to account for this heterogeneity under non-lane-based traffic conditions, and it is relatively tough to estimate traffic volume on the road. This discrepancy in capacity analysis instigates the need for this research work. Literature review reveals that research about the effect of heterogeneity of traffic on the performance and capacity analysis of multi-lane highways has been less and needs more studies. The major limitation of the greenshields' linear model (GLM) [12] is the linear relationship that is assumed between speed and density. Thus, in order to get an accurate speed-flow-density relationship on Indian highways, other non-linear models must be explored to arrive at the most optimal solution. Since the derived speed-density

relationship is different from the actual one, the relation between speed and density was more thoroughly examined by the Greenberg logarithmic model [15], Underwood exponential model [16], Drakes’s model [17], and Pipes’ generalized model. Furthermore, the estimated capacity from the best-fitted macroscopic traffic stream model based on the speed-area ratio method was compared to the capacity estimated using the DPCU and PCU values suggested by the Indian Highway Capacity Manual (Indo-HCM:2017) [18] and Indian Road Congress (IRC-64:1990) [19].

3 Data Collection

Traffic data was collected using the Transportable Infrared Traffic Logger (TIRTL)-An advanced IR sensors-based device. The traffic data was collected near Kancheepuram city on Chennai-Bengaluru National Highway (NH-48). The coordinates of the site were 12.90°N (Latitude), and 79.80°E (Longitude). Figures 1 and 2 illustrate the map and aerial view of the study spot, respectively.

The NH is a four-lane divided section. It is chosen for the study so that it is free from any impact of side friction. Figure 3 illustrates the vehicle detection mechanism using the TIRTL.

Figure 3 shows the detection mechanism of the TIRTL instrument. The TIRTL instrument was set up on the lane toward Chennai, with a receiver (RX) near the kerb side and a transmitter (TX) on the median side. The TIRTL detects the vehicles that cross the IR sensor detection zone. The TX unit forms two straight and two diagonal IR beam pathways. Two beam events such as the vehicle entry and exit are recorded for any vehicle identification. This also helps in deriving vehicle speed and headway.

Further, the beam events are used to determine the inter-wheel (inter-axle) spacing and the number of vehicle axles, based on which the correct vehicle classification is done. TIRTL calibrates automatically. The real-time field recorded traffic data can be

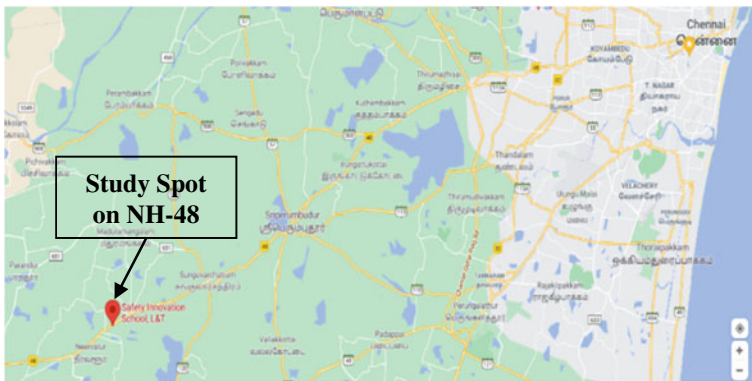


Fig. 1 Map showing the study spot on NH-48. Source Google maps



Fig. 2 Aerial view of the study spot on NH-48. Source Google earth



Fig. 3 Vehicle detection mechanism

viewed in the user-friendly interface, and the traffic data is stored as a.csv output file in the laptop device connected to the RX. Further, more details regarding the TIRTL instrument’s working and accuracy can be inferred from the studies by Singh et al. [20, 21]. Figure 4 shows the setup of the TIRTL instrument at the study spot.

The Indian traffic is marked by a high degree of heterogeneity. The details regarding geometrics were collected from the intercity highway (NH-48) connecting



Fig. 4 Setup of the TIRTL instrument

Chennai and Bangalore. The highway section has plain terrain with a traffic lane width of 3.5 m each. There are two lanes in each direction. A paved shoulder width of 2.0 m is also provided. The median width is 5.0 m.

From Table 1, it can be observed that there were nine different categories of vehicles. A total of 42,901 vehicles were recorded for 24 h of the data collection period. Table 1 shows the traffic characteristics of the vehicles.

4 Data Analysis, Modeling, and Results

4.1 Determination of DPCU

The Indian traffic carries vehicles with different static and dynamic features. Accounting for this diversity, the DPCU factor is used for transforming all vehicles into a standard unit. The DPCU is determined using Eq. (1).

$$DPCU_i = (V_c/V_i)/(A_c/A_i) \quad (1)$$

where V_c and V_i represent the speed of the Small Car (SC) and 'ith' vehicle, respectively, while, A_c and A_i represent the physical area of a SC and 'ith' vehicle, respectively.

For the evaluation of DPCU, SC was adopted as the standard vehicle category. The TIRTL records the spot speed, i.e., the time-mean speed of the vehicle; however, space mean speed calculated using the harmonic mean formula is used to represent the real-field conditions. Table 2 shows the DPCU values of each class of vehicles.

The estimated DPCU values are adopted to convert the heterogeneous traffic to homogeneous traffic and further analyze the macroscopic fundamental relationship diagrams (MFDs) using linear and nonlinear models.

4.2 Modeling Traffic Stream Parameters

Traffic flow parameters such as free-flow speed, optimum speed, jam density, and optimum density are necessary for finding the highway's capacity. The single regime and macroscopic traffic flow models were used for calculating capacity for four-lane divided road sections of the intercity highway. In this paper, the following models are used for calculating capacity,

- (i) Greenshields' Linear Model,
- (ii) Greenberg's Model,
- (iii) Underwood's Exponential Model,
- (iv) Drake's Model, and
- (v) Pipes' Model.

Table 1 Traffic characteristics of the vehicles

Vehicle class	Two-wheeler	Three-wheeler	Standard/small car	Big car	Small commercial vehicle	Light commercial vehicle	Medium commercial vehicle	Heavy commercial vehicle	Multi-axle vehicle
Length (m)	1.61	1.99	4.17	4.69	3.58	5.7	8.5	9.49	12.12
Width (m)	0.59	0.98	1.35	1.52	1.24	1.47	1.84	1.92	1.96
Area (m ²)	0.95	1.95	5.63	7.13	4.44	8.38	15.64	18.22	23.75
No. of vehicles	13,677	846	18,188	2498	492	1038	4230	946	986
Share (%)	31.8	1.97	42.29	5.81	1.14	2.41	9.84	2.2	2.29
Maximum speed (kmph)	122.47	117.38	134.31	133.22	87.55	125.33	100.61	99.65	74.54
Minimum speed (kmph)	14.04	19.14	16.86	31.39	16.71	14.63	22.75	24.95	15.9
Time mean speed (kmph)	59.12	51.56	73.56	73.17	54.41	63.35	56.58	50.16	45.74

Table 2 DPCU value of the vehicles

Vehicle class	Space mean speed (kmph)	Vehicle area (m ²)	Speed ratio (V _r)	Area ratio (A _r)	DPCU (V _r /A _r)
Two-wheeler	55.47	0.95	1.27	5.93	0.21
Three-wheeler	49.03	1.95	1.44	2.89	0.50
Standard/small car	70.43	5.63	1.00	1.00	1.00
Big car	69.62	7.13	1.01	0.79	1.28
Small commercial vehicle	52.78	4.44	1.33	1.27	1.05
Light commercial vehicle	60.11	8.38	1.17	0.67	1.74
Medium commercial vehicle	54.44	15.64	1.29	0.36	3.58
Heavy commercial vehicle	48.00	18.22	1.47	0.31	4.75
Multi-axle vehicle	44.47	23.75	1.58	0.24	6.58

The traffic data was plotted using Microsoft Excel, and the essential traffic parameters were found. The maximum flow values (q_{max}) using the traffic flow principle were estimated for the different models. The values found are tabulated in Table 3. Figures 5, 6, and 7 illustrate the different speed-density, speed-flow, and flow-density plots, respectively, developed using the macroscopic traffic stream models.

To compare the various models numerically, the speed-related R -squared (R^2) value along with two other measures (root mean squared error (RMSE) and the mean absolute percentage error (MAPE)) were used.

The R^2 value is a measure of the goodness of fit of the model. The higher the R^2 value, the closer the data is to the fitted regression line. But, R^2 value itself is not a reliable measure of the data fitting, and thus the researchers use other error-based measures like RMSE and MAPE.

The RMSE represents the size of a typical error since it is measured in the unit of the original data. The formula for RMSE is given in Eq. (2).

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N \frac{|x_{est} - x_{obs}|}{x_{obs}} \right] \times 100 \sqrt{\frac{\sum_{l=1}^N (x_{est} - x_{obs})^2}{N}} \tag{2}$$

The MAPE is another frequently used efficacy measure that gives us a general sense of the error. The formula for MAPE is given in Eq. (3).

Table 3 Model equations and traffic parameter results

Model	Model Equation	v_f (Km/h)	v_o (Km/h)	k_j (PCU/km)	k_o (PCU/km)	q_{max} (PCU/h)
Greenshields'	$v = v_f - \left(\frac{v_f}{k_j} * k\right)$	66.75	33.37	430.0	215	7177
Greenberg's	$v = v_o * \ln \frac{k_j}{k}$	-	29.41	283.4	-	3066
Underwood's	$v = v_f * e^{\frac{-k}{k_o}}$	66.79	-	-	333	8191
Drake's	$v = v_f * e^{\frac{-1}{2} \left(\frac{k}{k_o}\right)^2}$	63.63	-	-	129	4983
Pipes' $n = 2$ $n = 3$	$v = v_f * \left(1 - \left(\frac{k}{k_j}\right)^2\right)$	63.73	-	188.17	-	4616
	$v = v_f * \left(1 - \left(\frac{k}{k_j}\right)^3\right)$	62.70	-	127.86	-	3788

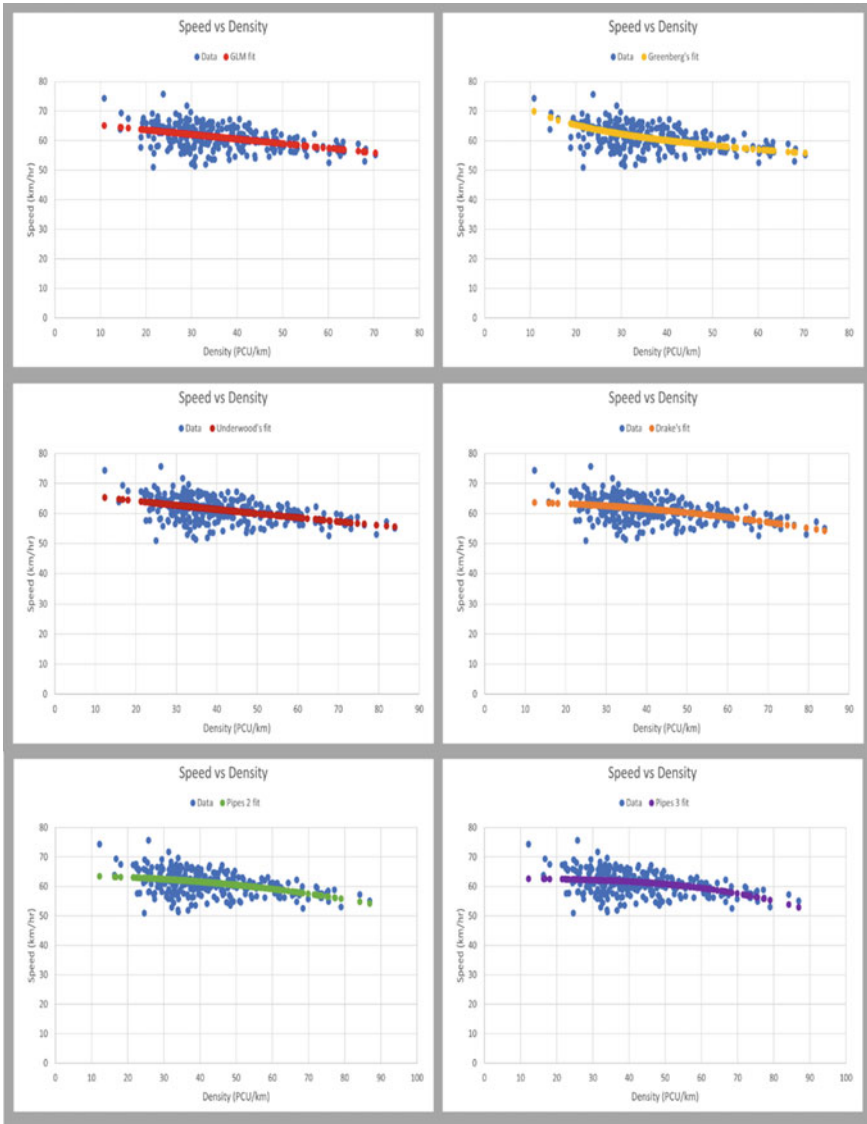


Fig. 5 Speed-density relationship plot

$$MAPE = \sqrt{\frac{\sum_{l=1}^N (x_{est} - x_{obs})^2}{N}} \tag{3}$$

Table 4 shows the RMSE and the MAPE values for all the models.

The GLM is a linear model that poorly maps the relationship between speed and density in real-time traffic. It is evident with the high error values of MAPE = 4.6425

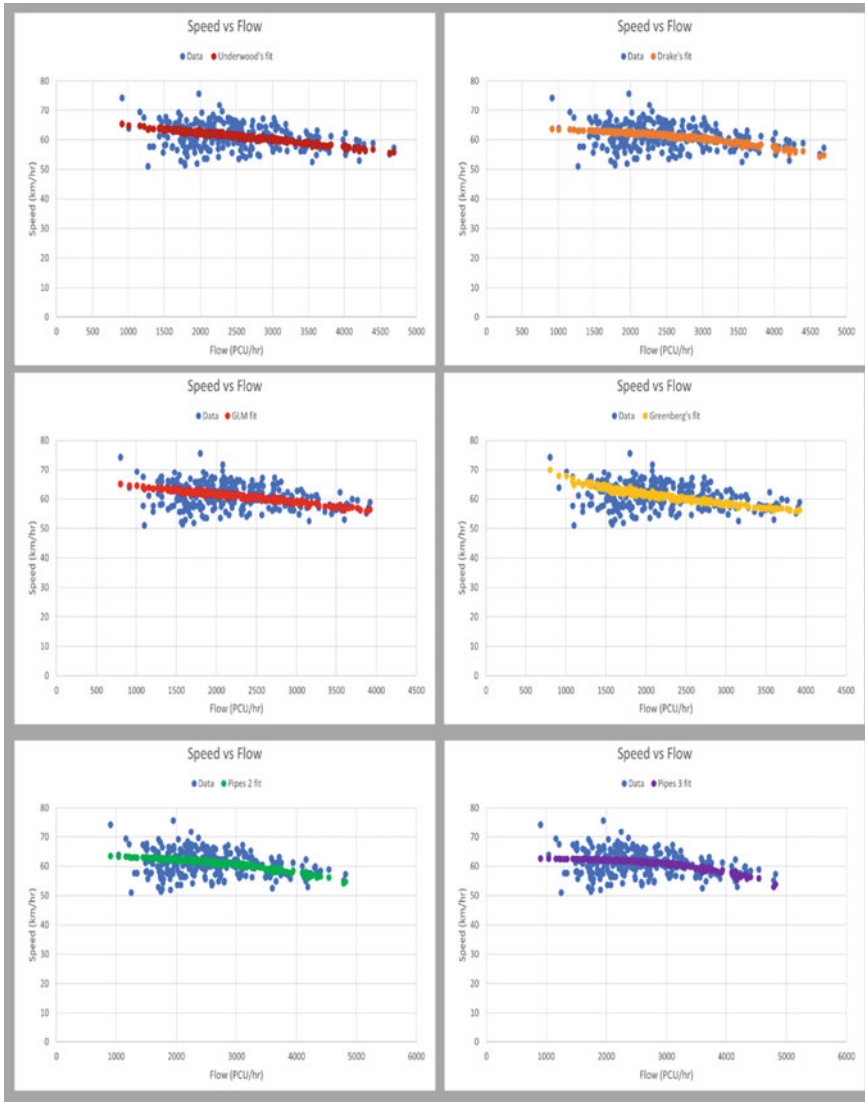


Fig. 6 Speed-flow relationship plot

and $RMSE = 3.63\%$ and low value of $R^2 = 0.39$. Several vehicle classes, intra-class variability, and weak-lane discipline make it more complicated to analyze mixed traffic assuming linearity. Greenberg's model too suffers from drawbacks due to its logarithmic nature, in which when density tends to zero, the speed tends to infinity, and vice versa. The traffic parameters, which are highly contrasting to other models, justify the high error values. This has been even stated in a paper by Khan et al. [22], which says that Greenshields' and Greenberg's model give unrealistic results for

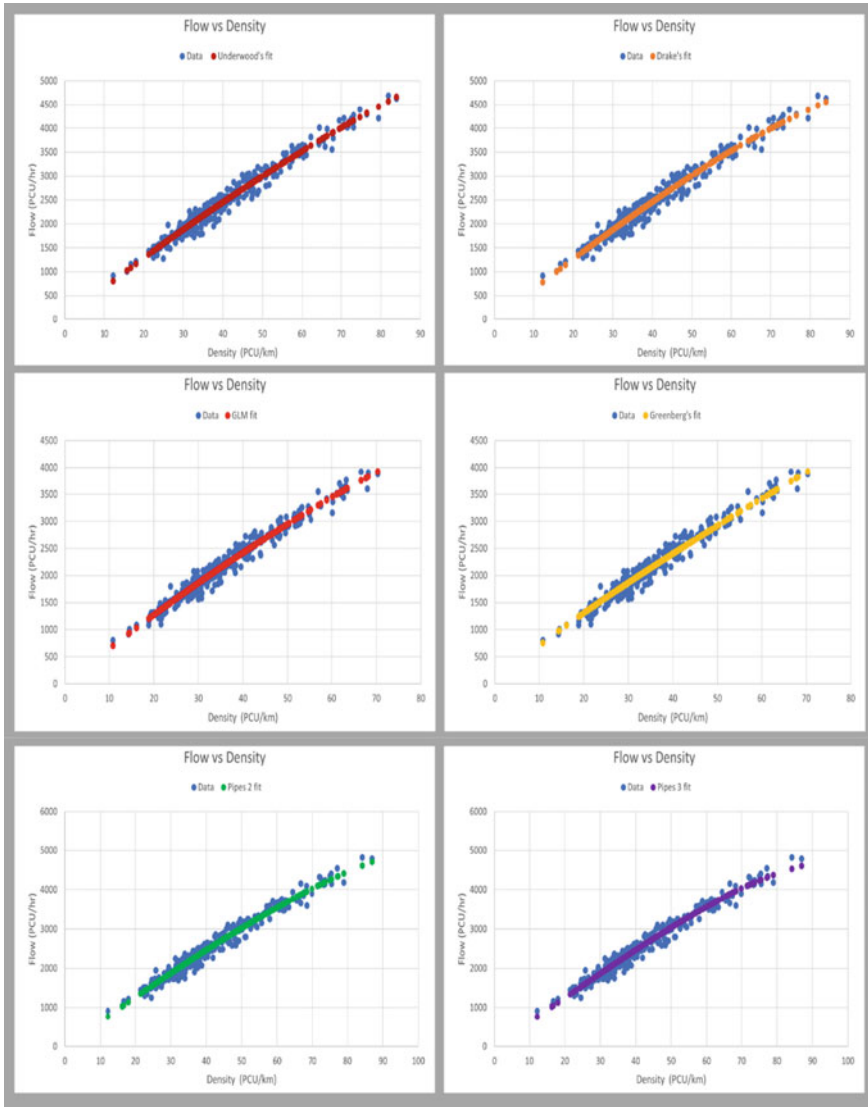


Fig. 7 Flow-density relationship plot

heterogeneous traffic. Thus, it can be inferred that those arbitrary results obtained from some of the models are due to the heterogeneous nature of the traffic under study.

The Greenshields', Greenbergs', and Underwoods' models show erratic values of optimum density and jam density. The jam density obtained for these models is above 350 PCU/km, which is impractical. However, Drake's and Pipe's generalized

Table 4 RMSE and the MAPE values for all the models

Model	R^2	MAPE	RMSE (%)
Greenshield's	0.39	4.6425	3.63
Greenberg's	0.30	10.234	8.26
Underwood's	0.44	4.6430	3.61
Drake's	0.53	3.8598	3.60
Pipes (2)	0.47	4.0038	3.61
Pipes (3)	0.56	3.5105	3.57

models show reasonable values in the range of 120 PCU/km to 200 PCU/km. Despite all these, it can be surmised that most of the characteristics of traffic data cannot be met by either of the existing functional forms. However, it can be concluded that Pipes' family models fit the traffic data the best and give the most realistic results with average free-flow speed, average jam density, and average capacity.

4.3 Comparison of Highway Capacity Using Different PCU Estimation Methods

Generally, the DPCU values are used for homogenizing the heterogeneous traffic [23]. The capacity of the highways was obtained using the best-fitted macroscopic model, i.e., the pipe's non-linear model ($n = 3$). This study estimated the capacity using the DPCU method, where indigenous DPCU values for each vehicle are used. Other PCU estimation methods which are widely used in the Indian context are the Indo-HCM (2017) and IRC:64 (1990) methods. The DPCU and PCU values for different classes of vehicles suggested by Indo-HCM (2017) and IRC:64 (1990), respectively, are shown in Table 5.

These DPCU and PCU values were used for capacity estimation, and the comparison of highway capacity was carried out. Table 6 shows the traffic parameters estimated using the DPCU values and static PCU values from Indo-HCM (2017) method and IRC:64 (1990) method, respectively, which are compared with the speed-area ratio method estimated traffic parameters.

The capacity value estimated using the DPCU values from the adopted speed-area ratio method was 3788 PCU/h. However, by adopting the Indo-HCM (2017) suggested DPCU values, the capacity value resulted in 4211 PCU/h, while by adopting the IRC:64 (1990) suggested static PCU values, the capacity value resulted in 3157 PCU/h. It can be clearly interpreted that the capacity value by the Indo-HCM (2017) DPCU values was overestimated, while the capacity value by the IRC:64 (1990) static PCU values was underestimated in comparison to the speed-area ratio method. This can be attributed to the result of the DPCU values suggested by the Indo-HCM (2017) being slightly higher than the static PCU values suggested by IRC:64 (1990). The use of DPCU and static PCU values may have amounted to

Table 5 DPCU and PCU values by Indo-HCM (2017) and IRC:64 (1990)

Vehicle class	Indo-HCM (2017) DPCU values range median		IRC:64 (1990) static PCU values
	range	median	
Two-wheeler	0.3–0.5	0.40	0.5
Three-wheeler	1.1–1.3	1.20	1.6
Standard/small car	–	1.00	1.0
Big car	1.4–1.5	1.45	–
Small commercial vehicle	–	–	–
Light commercial vehicle	2.7–3.3	3.10	2.8
Medium commercial vehicle	3.5–4.6	4.40	4.5
Heavy commercial vehicle	3.5–4.6	4.40	4.5
Multi-axle vehicle	6.3–7.0	6.60	6.0
Tractor	3.9–7.0	6.20	4.5
Bi-cycle	–	–	0.6

Table 6 Traffic parameters by the speed-area ratio, Indo-HCM (2017), and IRC: 64 (1990) methods

Traffic parameter	Speed-area ratio method	Indo-HCM (2017) method	IRC:64 (1990) method
Free flow speed (V_f) (Km/h)	62.70	64.57	60.12
Jam density (K_j) (PCU/km)	127.86	138.71	123.88
Capacity (Q_{max}) (PCU/h)	3788	4211	3157

overestimation and underestimation of traffic variables when they are homogenized, thus resulting in errors.

5 Conclusions

This study presents a comprehensive analysis of various methods used to model the traffic characteristics under mixed traffic conditions. This study is a case study of a national highway section in the southern part of India. For describing the traffic characteristics, five models were used. Using the different models, speed-flow-density relationships were formulated in graphs. Also, this research demonstrated the similarities and differences among the macroscopic traffic stream models. It was found

that the different parameters such as R-squared values, MAPE, and RMSE were the suitable error measuring units, which helped determine the best fit model. The R-squared values were very low for all the models. This is because of the data obtained from the highway conditions, which often do not follow any trend. Further, the current study suggests using an indigenous measure for DPCU estimates to avoid overestimation and underestimation of traffic parameters. The study results substantially contributed to the view that traffic characteristics modeling could be enhanced by differentiating not only based on methods of traffic stream models but also based on the method of determination of PCU. Overall, the study results point towards the significant concerns of not carrying out traffic studies considering the difference in the various method under the non-lane-based traffic conditions. Ultimately, the study shows that traffic capacity is critical to solving traffic problems.

Considering the identified issues from past research, this study makes significant contributions (i) by developing the regime-based equilibrium traffic flow models to account for the actual traffic dynamics, (ii) by showing that the MFDs can explain the traffic mix characteristics, and (iii) by capturing the variations of MFDs on in a mixed-traffic environment. The findings of this study reinforce the point that the estimation of the traffic capacity of uninterrupted highway facilities with a higher degree of accuracy can improve the analysis of traffic characteristics, thereby enriching the traffic flow theory. The present study is conducted only for one selected section. More sections and a more extended period of traffic data can be considered for further research for the entire day and night. This study can be further extended to the development of multi-regime models.

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