

Influence of Operating Speed on Capacity of Urban Arterial Midblock Sections

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Abstract The present study demonstrates the influence of operating speed on capacity of a midblock section of urban road. Speed–flow data collected at 12 midblock sections of 6-lane and 4-lane divided urban arterials in four metropolitan cities of India are analyzed to determine their capacity. Lane capacity was found to vary from 1482 to 2105 PCU/h. This variation is explained on the basis of city size and driving behavior, which would influence the free flow speed on the road. 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 of standard car) on the road. Lane capacity was found to be strongly related to operating speed on a road and a second-degree polynomial model is developed between the lane capacity and operating speed. This model is further validated by collecting speed flow data at two new sections and their capacity was estimated from field data and from the model developed in the study. The predicted capacity was found to be matching with field capacity and the maximum error was 0.10 percent. Operating speed on a road can vary due to road surface condition, side friction or similar other factors. All these will have influence on capacity of the road. The capacity model suggested in the present study can be a useful tool to determine capacity of an urban road from its operating speed data.

Keywords Urban arterial · Capacity · Operating speed · Free flow speed

1 Introduction

Urban roads are defined in different manners in different countries. An arterial in the United States is often characterized by a series of signalized intersections at close intervals and high density of access points [1]. Urban roads in Indonesia, on the other hand, are those having continuous permanent development along all or almost all of its length, on at least one side of the road, whether or not it is ribbon development [2]. Urban roads in India are classified either on the basis of the number of lanes provided within an undivided or divided cross section or in accordance with their functions in the total urban road network [3]. An urban arterial in India is a general term denoting an urban street primarily for through traffic, usually on a continuous route. The arterials are generally divided highways with full or partial access. The distance between intersections on an urban road in India is generally large but speeds are low due to mixed nature of traffic. Due to long distances between the intersections and larger speed differential amongst vehicles, platoons get dispersed in the midportion between the intersections and the midblock section typically operates similar to a suburban section but with mixed traffic of urban characteristics. The HCM [1] do not categorically specify capacity values for urban roads. However, capacity of a midblock section will be important when grade separations are provided for through traffic on signal controlled intersections on an urban arterial. The capacity of urban roads is mainly dependent on the ratio between duration of a green phase and cycle length at the signalized intersection on the end of the link [4]. A

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computer simulation model relating average speeds of the traffic stream, the traffic volume and composition of traffic stream and found that the stream speed is highly influenced by the composition of traffic stream [5]. The model could recognize eight different categories of vehicles in the stream and it could be run for any combination of slow and fast moving vehicles. Traffic stream models, relating speed of vehicle type with flow and percentage of slow moving vehicles, were developed for each vehicle type. Headway data on urban roads was analyzed using artificial neural network for estimating the capacity. The headway between all cars was estimated 1.72 s giving per lane capacity of 2093 PCU/h/lane [6]. A simulation program was developed for modeling heterogeneous traffic flow on urban roads. The program was first run for homogeneous traffic and capacity of the road was obtained as 2000 PCU/h/lane. The calibrated model was further used to analyzed mixed traffic flow on urban roads [7]. The capacity values were reported as 3250 PCU/h for a 7.5-m-wide road using simulation [8]. The capacity values of urban roads in Hanoi, Vietnam are reported in terms of the Motorcycle Equivalent Unit (MEU) because of predominance of motorcycles on these roads. The capacity values on urban roads with two, three and four lane per direction were estimated at 13,358, 21,725 and 24,335 MEU/h, respectively [9]. A relation was developed between traffic speed, flow and density under various rainfall conditions on urban roads in Hong Kong and found that capacity reduced by 22 percent from dry to heavy rain conditions (more than 6.5 mm/h) whereas free flow speed reduces by 10% [10]. In a very recent study speed is considered as a measure to evaluate consistency in alignment. The alignment has been considered as good, fair and poor based on operating speed. Further, the outcome shows that the desired speed, posted speed and design speed can influence

the results [11]. In another study it has been revealed that design speed of the road plays an important role in determining the amplitudes of the lateral acceleration and deceleration when vehicles are negotiating a curve. Smaller the design speed, the greater the lateral acceleration and deceleration and as a result, the ride comfort in the horizontal and vertical direction decreases accordingly [12]. A study conducted on curved section of 2-lane highways to develop the regression models to predict operating speed. Continuous speed profile data was recorded with the help of VBox (GPS based device) which was attached with a vehicle to detect vehicle position through satellite signals. The validation of developed model shows compatibility with the experimental data [13].

The present study was taken up with the objective of determining midblock capacity of urban arterial roads in different cities of India having no side frictions. These capacity values are found to be different in different cities and also across the sections in a city. A strong relation is found between the lane capacity and operating speed on the road.

2 Data Collection

Data for the present study were collected on eight midblock sections of 6-lane divided urban roads and four midblock sections of 4-lane divided urban roads in different cities located in north, west and south India. All the sections are located in plain area with no rise and fall (R/F), i.e., (R/F=0). Cities where these sections were selected are New Delhi and Chandigarh in the north, Jaipur in the west and Bengaluru in South India. Table 1 gives details of test sections in these cities. Three digit

Table 1 Study sections and observed traffic composition

Section ID	City	Number of lanes	Traffic composition (%)				
			Small car (CS)	Big car (CB)	Heavy vehicle (HV)	Three-wheeler (3W)	Two-wheeler (2W)
D-6-1	Delhi	6	46.49	7.55	3.64	12.70	29.62
D-6-2	Delhi	6	38.30	5.10	2.60	20.60	33.40
D-6-3	Delhi	6	46.54	7.11	1.65	16.63	28.06
J-6-1	Jaipur	6	30.81	6.06	3.28	7.65	52.20
J-6-2	Jaipur	6	24.51	8.66	3.57	8.72	54.54
J-6-3	Jaipur	6	26.50	4.00	1.52	10.48	57.50
B-6-1	Bengaluru	6	30.12	10.38	10.35	15.43	33.72
C-6-1	Chandigarh	6	32.80	3.65	2.28	8.00	53.27
D-4-1	Delhi	4	58.08	11.04	2.03	7.71	21.14
D-4-2	Delhi	4	49.00	8.80	2.50	18.90	20.80
D-4-3	Delhi	4	45.76	5.76	4.13	18.41	25.94
J-4-1	Jaipur	4	24.29	10.05	5.19	8.31	52.17

section identification (ID) mentioned in Table 1 represents the name of the city (like D for Delhi), type of the road (6-lane or 4-lane) and the section number in a city.

The basic consideration in selection of a section was that it should be free from the effect of intersection, bus stop, parked vehicles, curvature, gradient, pedestrian movement and any other side friction. Also, the sections should have wide variations in proportions of different categories of vehicles. Traffic studies were planned to determine the traffic volume, composition of traffic stream, and the speed of different types of vehicles at selected road sections. A section of about 500 m was selected having uniform traffic operating conditions with no access point and a longitudinal trap of 60 m was made in the middle of this section for measurement of flow and speed. Since it was not possible to cover the entire stretch of 500 m in the camera view, the speed measured on this trap length was taken as the average speed on the entire section length. The data were collected through video camera at each section on a typical weekday during 6:00 AM to 6:00 PM. The video camera was placed at a vantage point to cover the entire length of the trap. The recorded film was replayed in the laboratory to extract the desired information. All vehicles in the traffic stream were divided into five categories as shown in Table 2. Even in the same category of car, there are several models plying on Indian roads. Therefore, cars are also divided into two categories as small car (standard car) and big car. Small car in Table 2 represents all cars having their engine power equivalent to that of engines with up to 1400 cc displacement and average length and width of 3.72 and 1.44 m, respectively. This is also taken as the standard car in the present study and passenger car unit (PCU) factors were derived for all vehicles with respect to this car. The big car is the one having engine power equivalent to that of engines with 2500 cc displacement. The size of a vehicle was measured in field by taking its maximum length and maximum width. In case where more than one type of vehicle is included in a category (for example, motorized two-wheeler) the average dimensions were considered. Table 2 shows the observed vehicle categories and their physical sizes.

3 Analysis of Data

Traffic data collected in field were analyzed to draw speed–volume curves for estimation of capacity of mid-block sections of urban roads. Traffic on Indian roads is heterogeneous in nature with wide variation in static and dynamic characteristics of different types of vehicles. It requires to convert all vehicles in the traffic stream into equivalent number of passenger cars using the concept of passenger car unit (PCU). The PCU factors for different types of vehicles are derived in the next section.

3.1 Estimation of PCU Factors

Various researchers have used different approaches for the estimation of PCU values of vehicles. The criteria used are delay [14], speed [15, 16], density [17, 18], headway [19] and queue discharge flow [20]. Truly speaking, the basis for PCU estimation should be the same as used for defining the level of service (LOS) for a roadway type. It is due to the reason that the variables that are used to define LOS reflect the factors that influence the driver's perception [19]. Speed is a performance measure, which is accurately measurable and easily perceived by all users of a roadway. Moreover, any change in geometry of the road or in traffic condition will culminate in change in the speed. Therefore, speed is considered a prime variable to determine the relative effect of individual vehicles on the traffic stream in terms of the PCU. The basic concept used to estimate the PCU in the present study is that it is directly proportional to the ratio of the speed, and inversely proportional to the space occupancy ratio with respect to the standard design vehicle which is a car [21].

$$PCU_i = \frac{V_c/V_i}{A_c/A_i} \quad (1)$$

where V_c is the speed of a car (km/h), V_i speed of a vehicle of type i (km/h), A_c projected rectangular plan area of car, and A_i projected rectangular plan area of vehicle i (m^2).

In the above equation, the first variable of speed ratio will be the function of composition of traffic stream as the

Table 2 Vehicle categories and their sizes

Vehicle type	Vehicles included	Length (m)	Width (m)	Rectangular plan area (m^2)
Small car (CS)	Car	3.72	1.44	5.36
Big car (CB)	Big utility vehicles	4.58	1.77	8.11
Heavy vehicle (HV)	Standard bus	10.10	2.43	24.54
3-wheeler (3 W)	Auto-rickshaw	3.20	1.40	4.48
2-wheeler (2 W)	Scooters, Motorcycles	1.87	0.64	1.20

speed of any vehicle type depends upon its own proportion and types and proportions of other vehicles. Hence, speed of any vehicle type will be true representation of overall interaction of vehicle type due to the presence of other vehicles. The second variable of space ratio indicates maneuverability and size of the vehicle (pavement occupancy) with respect to car, which are crucial in mixed traffic conditions.

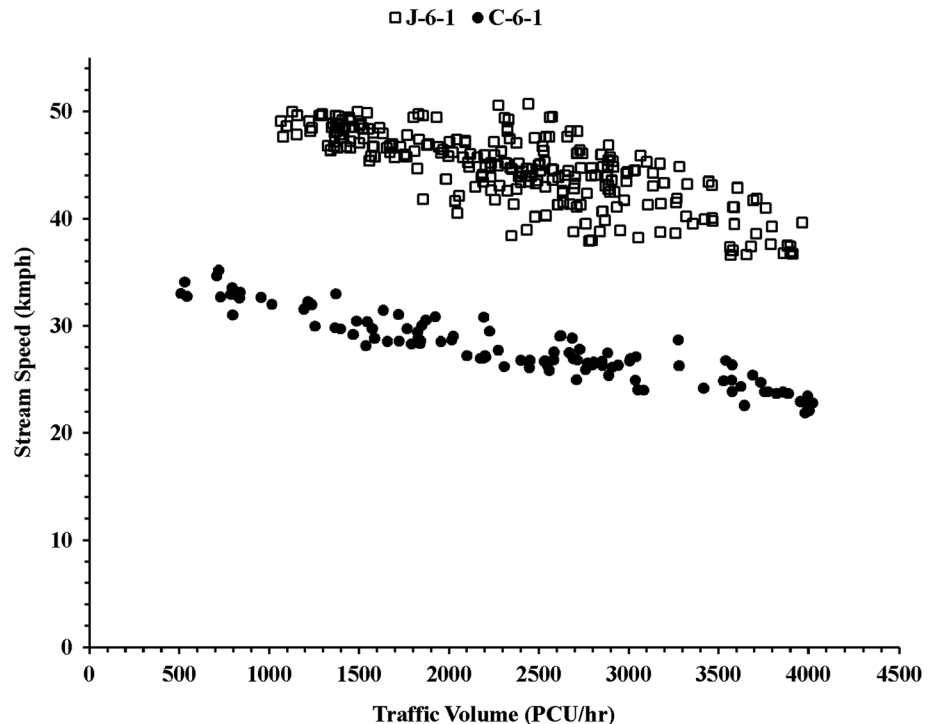
Traffic data collected in field were used to derive PCU values for different types of vehicles on different sections. The recorded film was replayed on a large screen monitor and 5-min classified traffic volume counts were made. To

ensure accuracy in the count, vehicles of one particular category were counted in one round of play of the film and the film was rewound as many times as the number of vehicle categories in the count. Traffic composition on different sections is shown in Table 1. For measurement of speed of vehicles included in the 5-min count, time taken by a vehicle to cover the trap length of 60 m was noted with an accuracy of 0.01 s using a software developed for this purpose. Speed data were used to derive PCU values for different types of vehicles using Eq. (1). These PCU values were found to be different in different count periods and also at different sections. Table 3 gives

Table 3 PCU factors at different urban road sections

Section no.	Name of the city	Average PCU factors				Standard deviation			
		CB	HV	3W	2W	CB	HV	3W	2W
D-6-1	Delhi	1.65	6.34	0.97	0.21	0.08	0.76	0.04	0.01
D-6-2	Delhi	1.66	6.28	0.97	0.21	0.07	0.60	0.05	0.01
D-6-3	Delhi	1.65	6.31	0.97	0.21	0.07	0.72	0.05	0.01
J-6-1	Jaipur	1.57	6.15	1.11	0.24	0.07	1.11	0.06	0.01
J-6-2	Jaipur	1.56	6.20	1.08	0.23	0.08	1.08	0.04	0.01
J-6-3	Jaipur	1.56	6.24	1.10	0.24	0.08	1.10	0.06	0.01
B-6-1	Bengaluru	1.60	6.38	1.00	0.23	0.10	1.15	0.08	0.01
C-6-1	Chandigarh	1.54	6.47	1.12	0.23	0.08	0.89	0.14	0.01
D-4-1	Delhi	1.54	5.91	1.00	0.23	0.11	0.60	0.05	0.01
D-4-2	Delhi	1.53	5.68	1.04	0.24	0.07	0.72	0.03	0.01
D-4-3	Delhi	1.56	6.00	1.02	0.24	0.10	0.56	0.04	0.01
J-4-1	Jaipur	1.55	6.10	0.99	0.21	0.05	0.66	0.08	0.01

Fig. 1 Speed–flow plots at sections J-6-1 and C-6-1



the average and standard deviation in PCU values calculated at different sections. The variation in PCU values for different types of vehicles is attributed to change in the composition of traffic stream and driver behavior in different cities.

3.2 Estimation of Capacity

Derivation of PCU factors enabled the expression of traffic flow in terms of passenger car units. It was thus possible to plot speed versus flow for every analysis period of 5 min. Speed in these plots was taken as the average of

Fig. 2 Speed–density relationship at section D-6-1

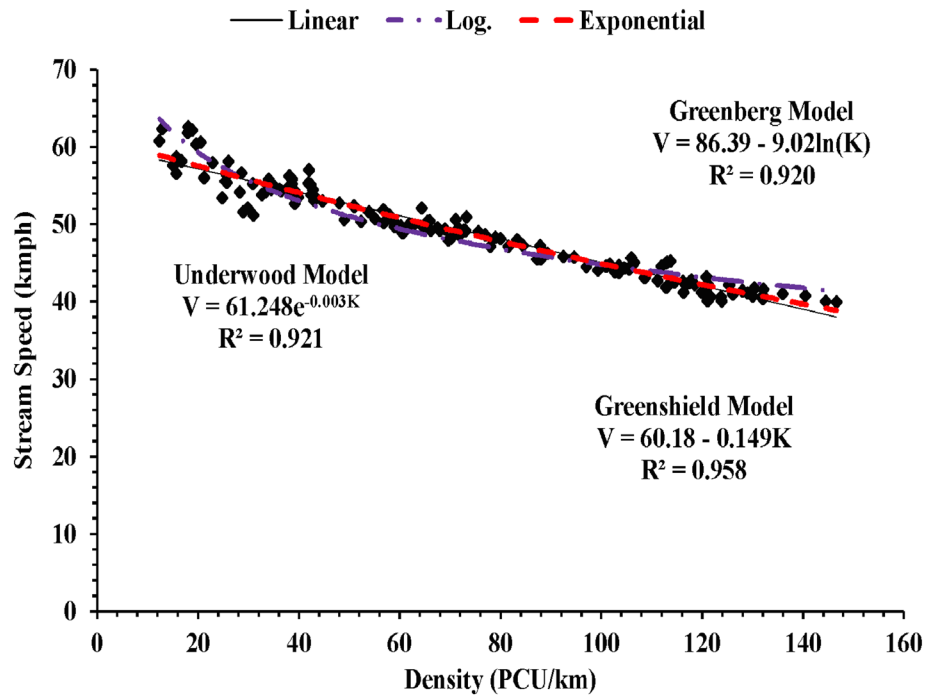
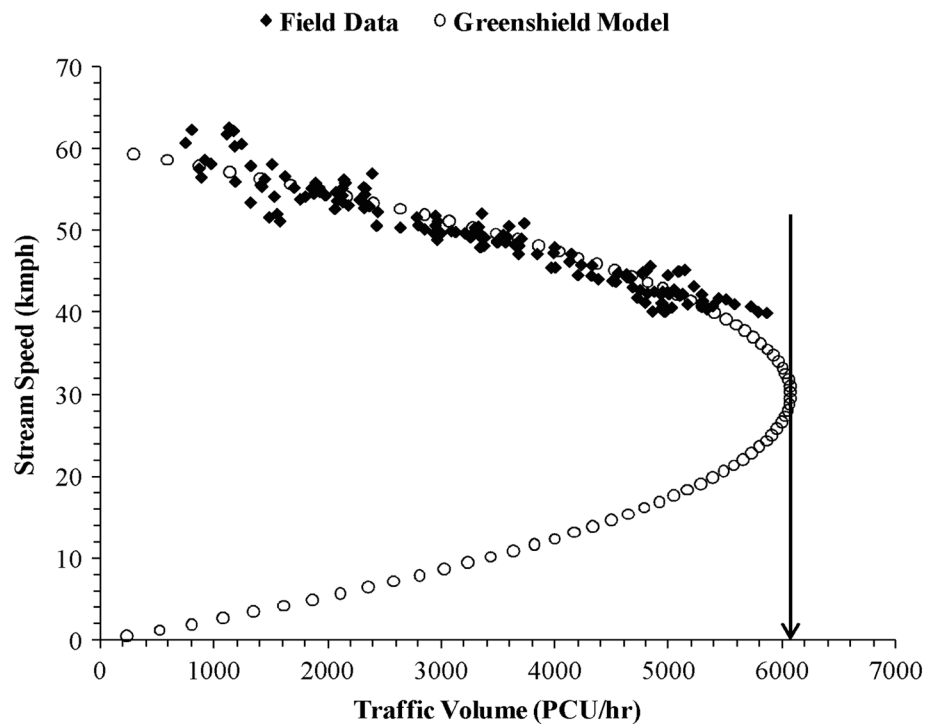


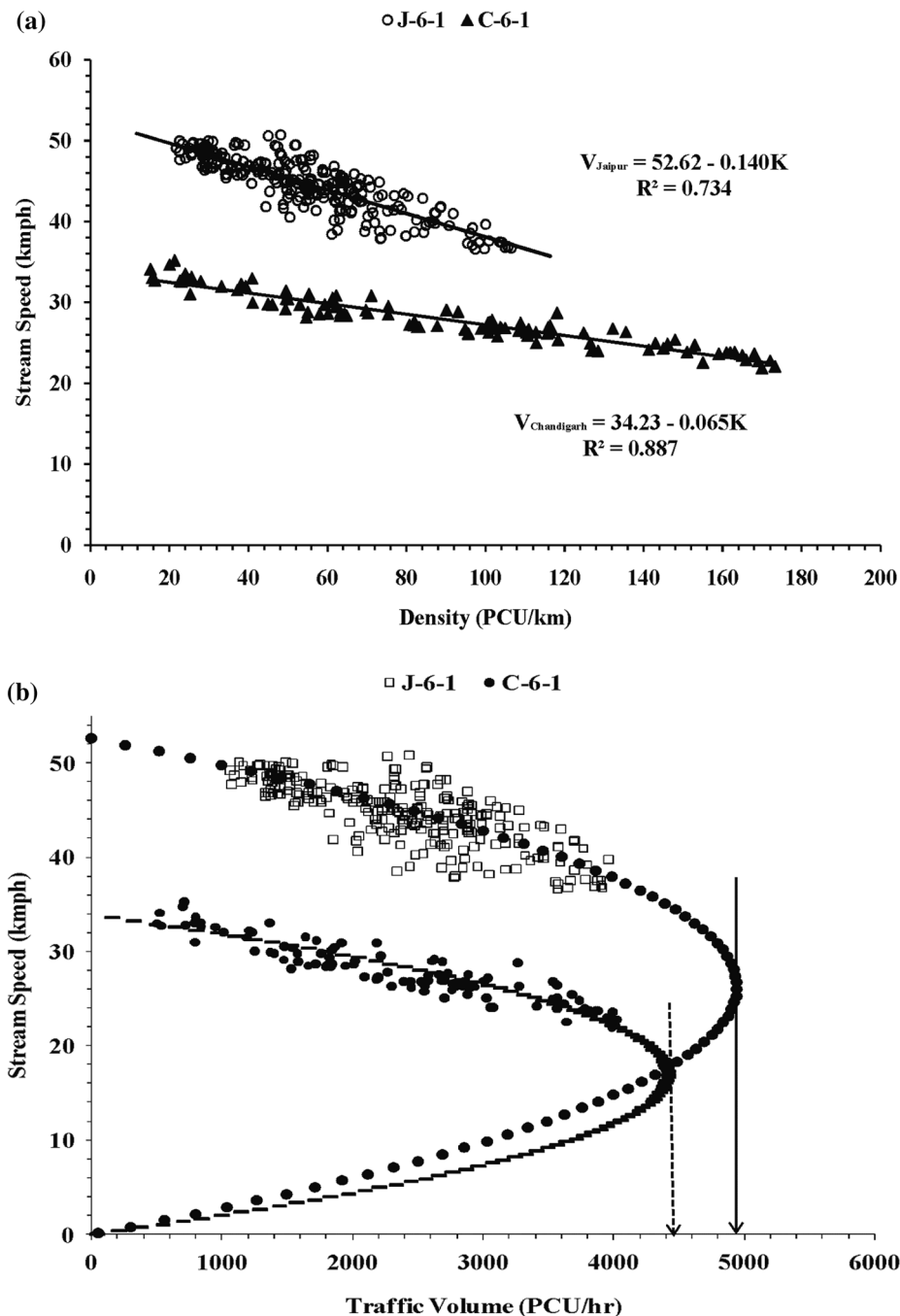
Fig. 3 Speed–volume relationship at section D-6-1



speeds of all vehicles included in the 5-min counts and this speed is referred as mean stream speed (V_m) in subsequent discussion. Speed–flow plots for two sites are shown in Fig. 1. Similar plots were made at other sites also and it was noticed that capacity flow was not approached on most of the sites, and speed–flow data followed a linear trend on some sections and non-linear at others. However, one common feature of all these plots was that stream speed depends on flow right from start of the curve. It intuitively suggested that speed–density data under mixed traffic flow

would follow either Greenshield linear model or Greenberg logarithmic model. Therefore, speed–flow data were converted to speed–density data using fundamental relationship between speed, density and flow. These data for Section D-6-1 are shown in Fig. 2. Various models like Greenshield, Greenberg and Underwood models were tried to fit these data. Greenshield model was found the best to describe speed–density curve, based on R^2 value, as shown in Fig. 2 and, therefore, straight line speed–density relation was used to develop complete speed–volume curve as

Fig. 4 Typical speed–density flow curves



shown in Fig. 3. It gave capacity of 6075 PCU/hr in one direction of flow at the section.

Similar exercise was done at all other sections also. Greenshield model was found fitting the speed–density data better than other models at all the sections. Few typical curves are shown in Fig. 4. Table 4 provides the capacity values on different sections of 6-lane and 4-lane roads. As may be observed, capacity of 6-lane roads varies from 1500 PCU/h/lane for section C-6-1 to 2105 PCU/h/lane for section D-6-3 whereas capacity of 4-lane road sections varies from 1482 PCU/h/lane (section J-4-1) to 2043 PCU/h/lane (section D-4-1). This variation might be the effect of city size on capacity. The last column in Table 4 shows the average per lane capacity as estimated in different cities. Figure 5 shows the effect of city size on midblock capacity of urban roads.

4 Relation Between Capacity and Operating Speed

Capacity values given in Table 4 indicate variation in lane capacity with city size. However, it is different on different sections in the same city also. For example, three sections of 4-lane roads in Delhi have substantially different capacity values and hence the variation in capacity cannot be attributed to the driving behavior only. As mentioned earlier, all sections were identical in terms of geometry and there was no side friction which can influence the capacity. Therefore, variation in capacity is due to some other factors like surface condition of the road or driving habits of the drivers. Both of these characteristics are reflected in free flow speed (FFS) of a vehicle. Therefore, FFS of standard cars was measured at each site when traffic volume was less than 1000 vehicle/h. Measuring speeds at low flow rates ensure that preceding vehicle speeds do not affect speeds of following vehicles and headways are more than 7 s [22]. Free speed data were used to determine 85th percentile speeds of standard cars on the road. This speed is termed as the operating speed of the road section. Figure 6 shows the plot between operating speed and lane capacity at all the 12 sections. A second-degree polynomial relation as given in Eq. (2) was found to be the best fit between lane capacity and operating speed. The statistical parameter of Eq. (2) is given in Table 5.

$$\text{Lane capacity} = 2694 - 49.53 V_{os} + 0.496 V_{os}^2 \quad (R^2 = 0.98) \quad (2)$$

The ‘*t*’ values of coefficients are found more than 1.96 at 95% confidence level which signifies that the parameters are statistically significant similarly the ‘*p*’ value of coefficients is also found significant. As may be seen from Eq. (2), the capacity of a road is strongly related

with operating speed with R^2 of 0.98. It explains the reason of higher values of capacity in New Delhi and lower value of capacity in Jaipur and Chandigarh. It is important to mention here that the lane capacity data fit well with operating speed for both 6-lane and 4-lane roads without any distinction.

5 Model Validation

To check the validity of the proposed model given in Eq. 2 field data were collected at two more sections; one section of 6-lane road in Delhi (D-6-7) and another of 4-lane road in Jaipur (J-4-2). Capacity of these two sections was determined in the same manner as discussed earlier in the section of capacity estimation. Speed–density and speed–flow relationships on section D-6-7 are shown in Fig. 7. Operating speed of standard cars at these two sections are estimated 86.20 and 62.22 km/h, respectively. Table 6 compares the capacity values as estimated from field data and predicted from Eq. (2). As may be seen, the difference between the estimated values and predicted values is less than 1 percent. It suggests that Eq. (2) predicts capacity values quite accurately from operating speed data on an urban arterial.

6 Conclusions

Capacity of midblock section of an urban arterial road is of great interest in situations where signalized intersections on the arterial are converted into conventional grade separation like road over bridge or underpass to

Table 4 Capacity and FFS on urban arterial roads

Section	Total capacity in one direction (PCU/h)	Operating speed (km/h)	Lane capacity (PCU/h)	Average lane capacity (PCU/h/lane)
D-6-1	6075	82.85	2025	2044
D-6-2	6000	80.80	2000	
D-6-3	6315	86.60	2105	
J-6-1	4944	68.74	1648	1645
J-6-2	4902	68.00	1634	
J-6-3	4956	69.65	1652	
B-6-1	5250	75.35	1750	1750
C-6-1	4500	63.50	1500	1500
D-4-1	4086	84.79	2043	1745
D-4-2	3142	61.71	1556	
D-4-3	3272	69.08	1636	
J-4-1	2964	54.91	1482	1482

Fig. 5 Variation in average lane capacity with city size

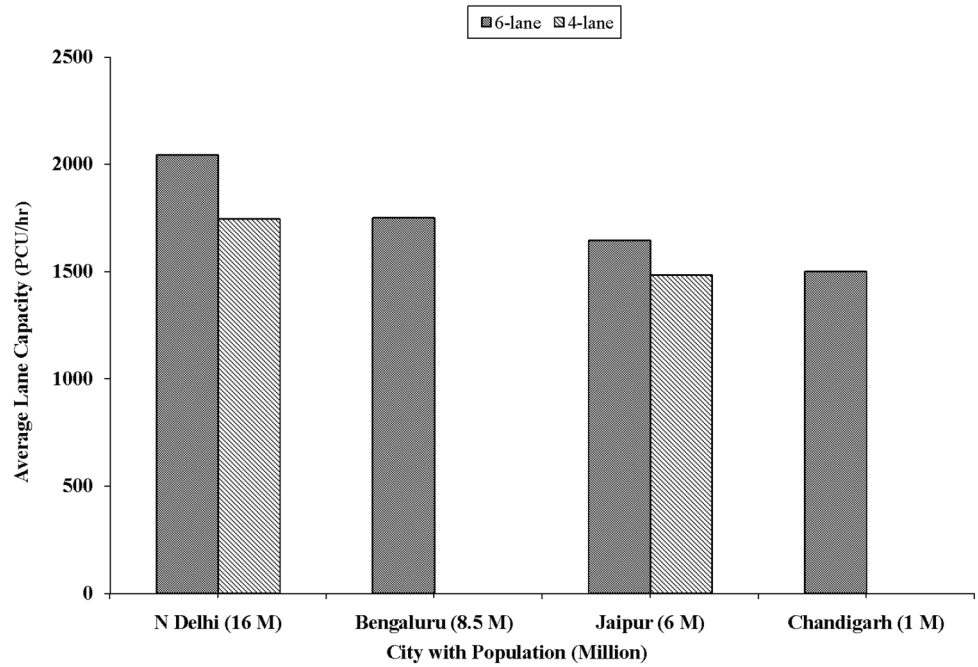
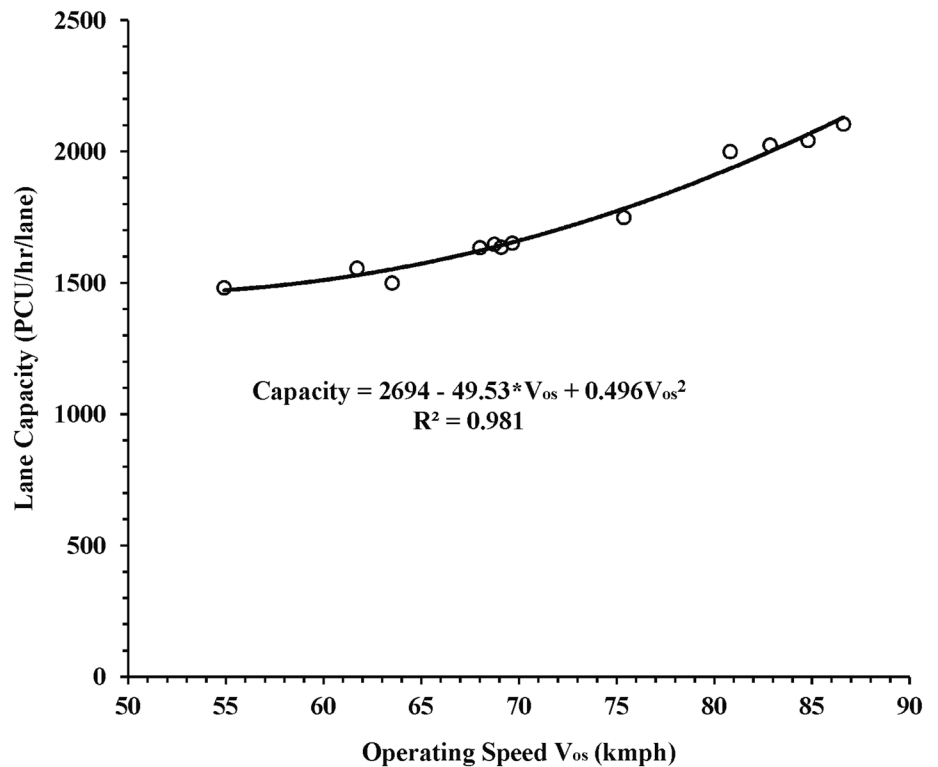


Fig. 6 Relation between operating speed and lane capacity



facilitate uninterrupted flow of through traffic. In mixed traffic situations like those prevailing in India and many other developing nations, speed differential among vehicles of different category is large and platoons released from the intersection gets dispersed very soon. It creates

the situation where traffic in sections between the intersections can move without much influence of intersections, particularly in locations where distance between the intersections is quite large. Data collected at 12 midblock sections of urban roads in four major cities of

Table 5 Statistical parameter of Eq. 2

Parameter	Coefficient	<i>t</i> statistics	<i>p</i> value	<i>R</i> ² of Eq. 2
Intercept	2694	4.64	0.0012	0.98
Operating speed (<i>V</i> _{os})	49.53	3.04	0.011	
(Operating speed) ² (<i>V</i> _{os} ²)	0.497	4.41	0.0017	

India are analyzed to determine their capacity. The mid-block capacity was found to vary from 1482 PCU/hr/lane to 2105 PCU/hr/lane. This variation is attributed to the

different operating speeds on different sections. A relationship is developed between lane capacity and operating speed on the road and this relation is validated at two new sections; one of 6-lane and another of 4-lane divided road. The maximum error in estimated and predicted value was 0.10 percent.

Operating speed on a road can change due to many reasons like road condition, side frictions, speed humps, etc. Drop in the operating speed will have influence on capacity of the road. Many researchers and manuals have recognized this fact that the capacity of a road is influenced by its operating speed. However, the quantification of this influence

Fig. 7 Speed–density–volume curves at D-6-7

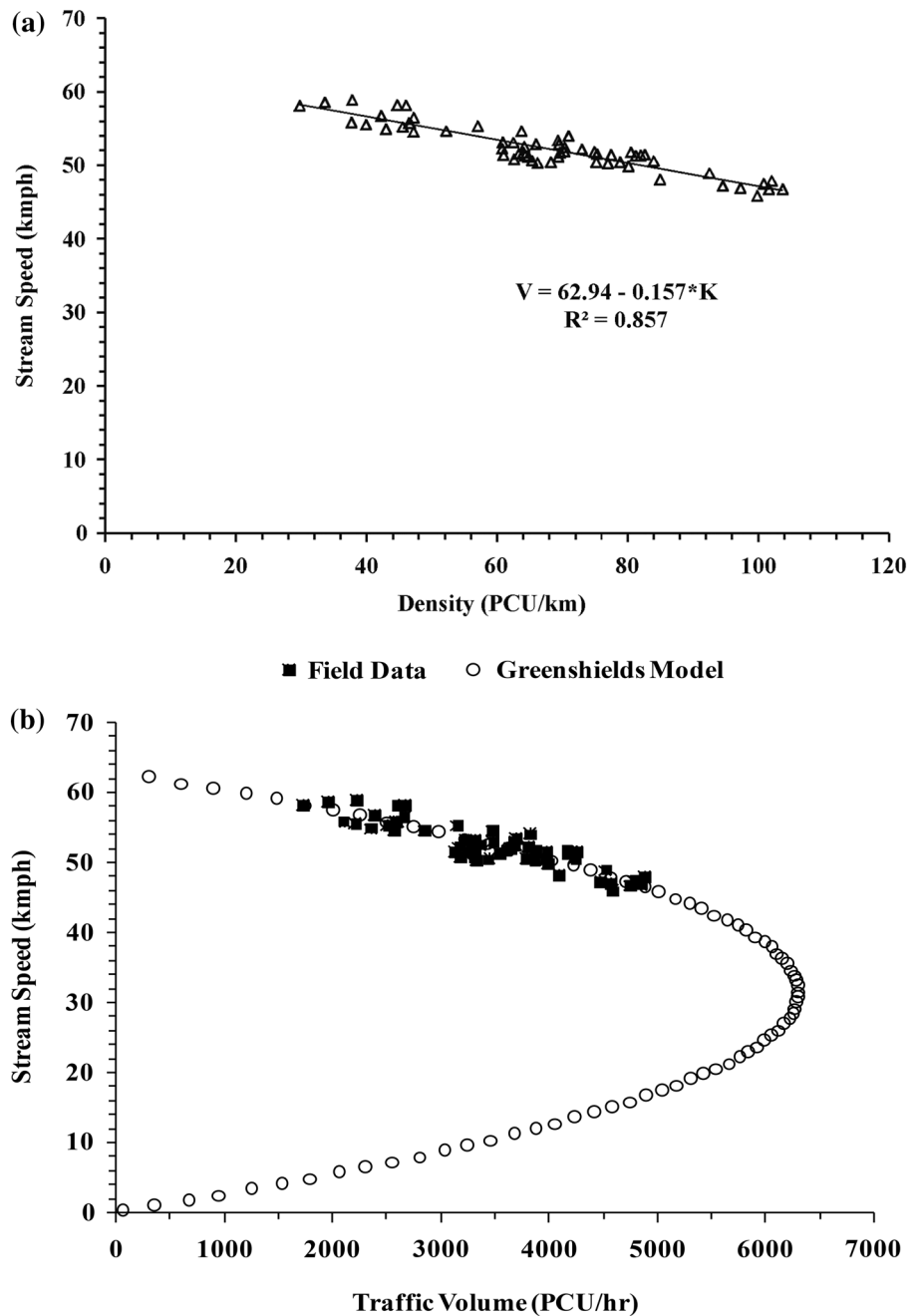


Table 6 Validation of the model

Section	Operating speed of standard car (km/h)	Directional capacity from field data (PCU/h)	Lane capacity from field data (PCU/h/lane)	Lane capacity from Eq. 2 (PCU/h/lane)	Percent difference
D-6-7	86.20	6300	2100	2110	0.10
J-4-2	63.22	3100	1550	1545	0.05

has not been given in literature. The major contribution of this research is the development of a relation between operating speed and the lane capacity. This relationship will be extremely useful to field engineers and planners to get the capacity of a section from operating speed data alone. It will save lot of time and money spent on data collection.

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