Modelling Dynamic PCUs Using Occupancy Time Approach at Urban Signalised Intersections Under Mixed Traffic Conditions

Pinakin Patel and Ashish Dhamaniya

Abstract At signalised intersections, the mixed traffic flow is converted to corresponding car flow using a passenger car unit. Earlier studies showed that PCU value is not static but depends on the interaction of vehicles for a particular traffic stream. This study suggests a methodology to find the PCU value at urban signalised intersections based on the PCU value obtained by time occupancy method during the saturation condition with varying interaction between the vehicles. For the analysis, traffic data have been collected with the help of videography at Ahmedabad and Surat, Gujarat. Traffic flow discharge and clearance time of different vehicular categories have been extracted from the video during the saturated green time. The variation in PCU values with respect to traffic composition and discharge rate is carried out in this study. Regression-based PCU models are developed to estimate the PCUs for different category of vehicles considering the traffic flow and compositions. Further, a stream equivalency factor has been developed to convert the heterogeneous traffic into homogeneous traffic without making use of PCU values.

Keywords Passenger car units · Mixed traffic · Signalised intersection

1 Introduction

The signal system is provided in urban area to manage the adverse movements of pedestrian and vehicles. The passenger car unit (PCU) values play an important role to convert different static and dynamic behaviour of mixed flow into homogenous equivalent flow for the capacity estimation of signalised junctions. The traffic and roadway factors are affecting on a PCU value of particular vehicle category. For the exact derivation of PCU values, it is essential to study precisely the influence of traffic and roadway factors on vehicular movement.

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T. V. Mathew et al. (eds.), *Transportation Research*, Lecture Notes in Civil Engineering 45, https://doi.org/10.1007/978-981-32-9042-6_34

To represent the buses and trucks in a traffic stream to an equivalent passenger car unit, the concept of PCU was introduced in 1965 by the US Highway Capacity Manual [1]. IRC SP: 41 [2] had recommended static PCU values for each category of vehicles. There are different methods used for the derivation of PCUs. Branston and Van Zuylen [3] suggested a method to estimate PCUs using regression technique. In regression method, saturated green time is considered as depending variable on number of different class of the vehicles approaching stop line. The similar approach was used by Arasan and Jagadeesh [4], Minh and Sano [5]. The statistical technique of headway ratio process has developed by Vien et al. [6] for finding the PCU values at signalised intersection in Malaysian traffic conditions. The concept of area occupancy is incorporated by Arasan and Dhivya [7] for finding the PCU on urban roads. The derived PCU values of homogenous traffic are not suitable for heterogeneous traffic, where the traffic is composed of different vehicles categories, static and dynamic characteristics and absence of lane discipline. Hence, the suitable method is developed incorporating mixed traffic attributes for the PCU estimations. Chandra and Kumar [8] proposed a method to estimates the PCU of different vehicles category considering speed and area occupancy ratio. In the present study, the speed ratio is replaced by the clearance time ratio for each movement. The present method measures the occupied time taken by a vehicle for the deriving PCUs which includes delay indirectly, which is performance assessment parameter for categorising level of service as per US Highway Capacity Manual (HCM-2010). The objective of this research is to estimate PCU for different category of vehicles under different level of interaction of mixed traffic during saturated green time at the signalised intersections. The mathematical models are developed considering mixed traffic flow behaviour to estimate the PCUs for each vehicular category.

2 Methodology

2.1 Time Occupancy Method

The small car is considered as a standard vehicle for the determination of PCU values. The idea of dynamic PCU was developed by Chandra and Kumar [8] considering the several traffic and flow characteristics. The clearance time between the stop lines is taken as time occupancy. The variable clearing-time includes the effect of several roadway geometry and traffic aspects disturbing the movement of a vehicle in a given intersection [9]. The PCU for a vehicle can be determined using Eq. (1).

$$\mathrm{PCU_m} = \frac{\left(\frac{T_\mathrm{m}}{T_\mathrm{c}}\right)}{\left(\frac{A_\mathrm{c}}{A_\mathrm{m}}\right)} \tag{1}$$

where PCU_m = passenger car unit for the subject vehicle 'm' in the traffic; A_c/A_m = space ratio of the standard car (in m^2) to the subject vehicle 'm' (in m^2); T_m/T_c = clearing time ratio of subject vehicle 'm' (in seconds) to standard car (in seconds); The classification of vehicle is done based on their physical size. The physical dimensions for two-wheelers (2W), three-wheelers (3W), light commercial vehicles (LCV), heavy commercial vehicles (HCV), standard car (CS) and big car (CB) were measured in the field and found as 1.2, 4.48, 9.50, 24.54, 5.36 and 8.11 m^2, respectively [9].

2.2 PCU Models

The PCU models are developed based on the statistical significance of identified sensitive parameters. The models are validated for field conditions. Based on the data collected, PCU models have been developed for various modes considering the effect of compositions of mixed traffic through regression approach. The standard model is given in Eq. (2).

$$Y = 1 + a_1 P_{cb} + a_2 P_{3w} + a_3 P_{2w} + a_4 P_{lcv} + a_5 P_{hcv} + 1/N \qquad (2)$$

where Y = PCUs of different modes; P_{2w} = % share of 2W; P_{3w} = % share of 3W; P_{cb} = % share of CB; P_{lcv} = % share of LCV; P_{hcv} = % share of HCV in the traffic stream; and N = flow rate in vehicles/seconds.

3 Data Collection

The study is performed at three important urban signalised junctions of Ahmedabad and Surat, India. The particular intersections satisfy the norms of base conditions for signalised intersections. The lane formation varies from 2 to 4 lanes. The left-turning traffic is using separate lane without interrupting to through traffic. The camera is placed at vantage points to capture various aspect of mixed traffic behaviour by recording traffic movement at approaches. The queue formation and discharge patterns are extracted from the video using manual technique. In Webster's method [10], analysis period was fixed as 5 s at the signalised intersection. The numbers of each category of vehicles and time occupied by each vehicle category vehicles from one stop line to another stop line for straight moving and right-turning traffic during each 5 s of the effective green phase is extracted and later on used for the estimation of PCUs. This process is used for every cycle. The total of 75 cycles from five approaches is considered for analysis. The maximum traffic flow is detected on the particular approaches. Tables 1 and 2 summaries the statistics of data collected at signalised intersections.

Table 1 Observed intersection details

Intersection	Study approaches	Width (m)	Green time (s)	Cycle time (s)	Right turn (%)	Saturation flow (veh/h)
I-01	01	14	44	110	0	15,588
	02	7.2	17	146	0	9000
I-02	03	10.5	35	110	5	13,212
	04	10.5	41	115	20	15,804
I-03	05	10.5	35	125	31.78	10,770

Table 2 Observed traffic at approaches of junctions

Intersection	Study approaches	Composition (%)					
		2W	Auto/3W	Small car	Big car	LCV	HCV
I-01	01	63.24	18.62	5.20	9.42	1.23	1.21
	02	79.40	10.10	5.30	4.10	1.10	0.00
I-02	03	58.76	30.03	3.56	4.31	2.30	1.04
	04	72.92	14.98	4.10	3.80	1.10	0.49
I-03	05	63.78	16.36	9.12	9.28	1.06	0.41

4 Data Analysis

The variation in traffic characteristics and physical size are able to explain in PCU for a vehicle type. From the time occupancy data, higher the occupancy time of a particular category of vehicle with respect to standard car implicates higher value of delay and results in higher PCU. Whereas, lower occupancy time of vehicles having lesser physical dimension than small car implies lower value of delay and results in lower value of PCU. Figure 1 shows the extraction of time occupancy data using the software Avidemux-2.6.

The calculated PCU values using Eq. (1) for the different intersections are tested for their variance using the analysis of variance (ANOVA) at 5% level of significance. The results are shown in Table 3 which indicates that there is no variation in PCU values for different movements and intersection for the particular vehicle category.

Figures 2 and 3 show the box—whisker and normal plots for different vehicle categories.

From Fig. 2, it is clear that the decrease in physical size of vehicle will require less time to clear the junction compared to larger-size vehicle which have better manoeuvrability and low PCU values.

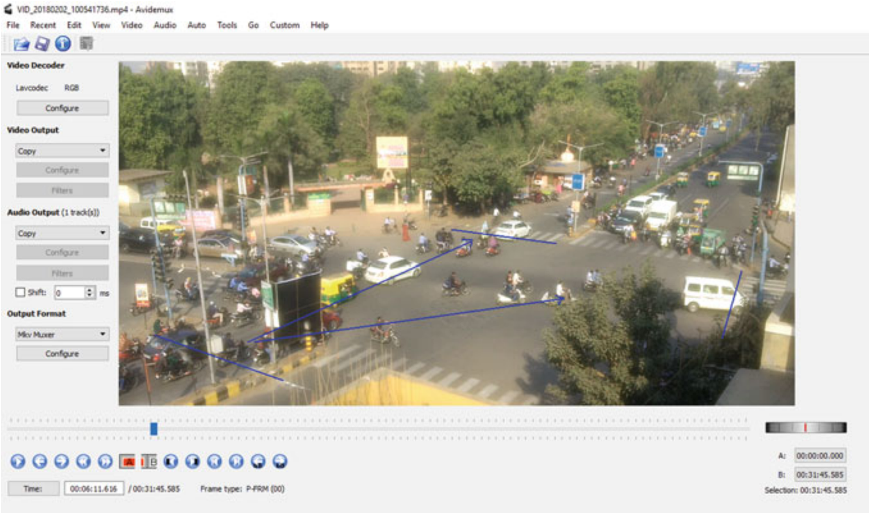

Fig. 1 Snapshot for extraction of time occupancy data

Table 3 Data of PCUs calculated for different vehicle classes

Type of vehicle	I-01	I-02	I-03	*p*-value	*F*	*F* critical	$F < F_{\text{critical}}$	Standard deviation	Average PCU
2W	0.22	0.18	0.20	0.7726	0.3730	2.6373	Yes	0.04	0.20
3W	0.68	0.69	0.71	0.1479	1.8379	2.7318	Yes	0.13	0.69
Small car	1	1	1	–	–	–	–	–	1.00
Big car	1.52	1.51	1.46	0.9708	0.0800	2.6407	Yes	0.27	1.51
LCV	1.97	1.93	2.14	0.1751	1.7171	2.7862	Yes	0.44	2.02
HCV	5.93	5.09	5.81	–	–	–	–	1.24	–

5 Developments of PCU Models

Mathematical models based on regression method were developed to allow easy and fast estimation of PCU values for the prevailing traffic conditions. The proposed regression models are shown in Eqs. (3)–(5). The *t*-values of model are significant at 95% level of confidence. Values in parenthesis show *t*-statistics and R^2-values. The proportion of LCV and HCV is very less, so that is not considered for the development of mathematical models.

$$\mathrm{PCU}_{2\mathrm{W}} = 1 - \underset{(57.11)}{0.0075 P_{2\mathrm{W}}} - \underset{(21.10)}{0.0077 P_{3\mathrm{W}}} - \underset{(17.98)}{0.0063 P_{\mathrm{cb}}} - \underset{(6.58)}{2.14/N} \quad \left(R^2 = 0.98\right) \tag{3}$$

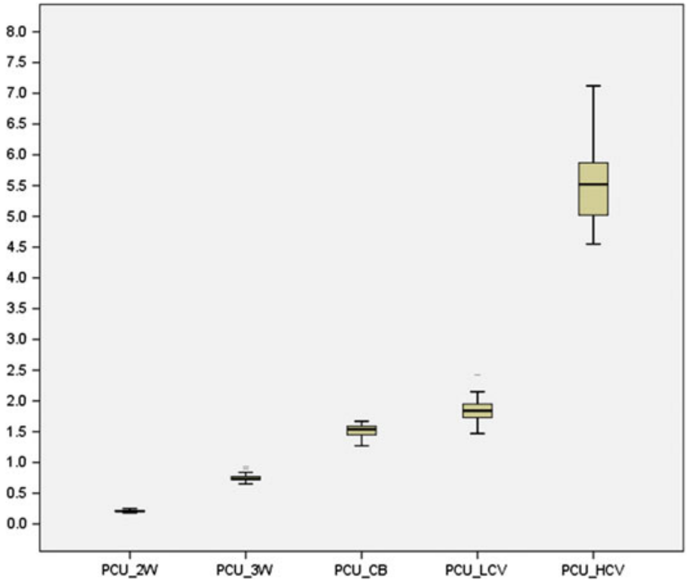

Fig. 2 Box plot of PCU

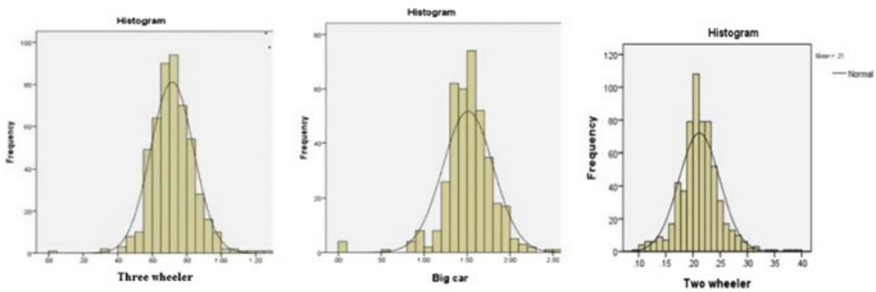

Fig. 3 Variation of PCU values with histogram plots of normal distribution

$$\underset{\;}{PCU_{3w} = 1 - \underset{(4.90)}{0.001P_{2W}} - \underset{(4.01)}{0.0035P_{3W}} - \underset{(7.59)}{0.0046P_{cb}} - \underset{(2.7)}{0.92/N}} \quad \left(\mathrm{R}^2 = 0.88\right) \tag{4}$$

$$PCU_{cb} = 1 + \underset{(3.79)}{0.0047P_{2W}} + \underset{(3.17)}{0.0044P_{3W}} + \underset{(5.83)}{0.00577P_{cb}} + \underset{(3.19)}{1.52/N} \quad \left(R^2 = 0.91\right) \tag{5}$$

where PCU_{2W} = PCU of motorised 2W, PCU_{3W} = PCU of motorised 3W, PCU_{cb} = PCU of CB, P_{2W} = Composition of 2W for a particular interval, P_{3W} = Composition of 3W for a particular interval, P_{cb} = Composition of CB for a particular interval and N = Total number of vehicles per 5 s.

Table 4 Significance test of PCUs at 5% level of significance

Type of vehicle	*t*-value	*t*-critical	*p*-value
2W	1.37	2.03	0.088
3W/auto	0.125	2.04	0.450
Big car	1.18	2.05	0.123

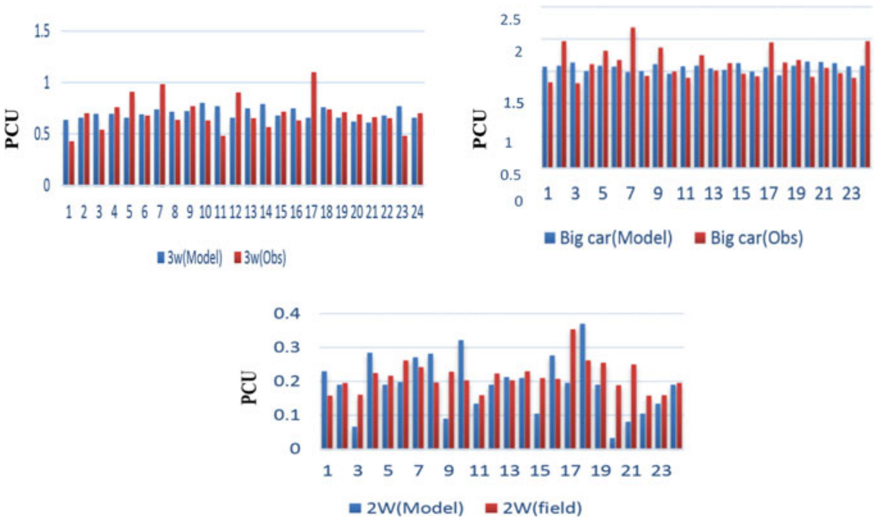

Fig. 4 Comparison of PCUs from model and observed/field

Developed models for PCU are validated for a different intersection by taking representative samples to observe the feasibility of the model having different traffic composition and geometrical characteristics. To check the likely change in variance of observed and model PCU values of 2W, 3W and CB statistically, paired *t*-test was done by equating the variance in PCU values for all the vehicle categories at 5% level of significance. It has been observed that variation in variance and PCU values is not significantly different in both the cases for the representative category of vehicles as *t*-statistics value is less than *t*-critical value and p-value also suggests the comprehensibility of the model. Test results are given in Table 4.

Figure 4 shows the comparisons of field and model PCUs. The variation observed is very less between field measured and model PCUs.

5.1 Variations of PCUs

The effect of discharge rate on PCUs is studied from the developed models of PCUs for different traffic volume and for a predefined composition of traffic. Figure 5 shows

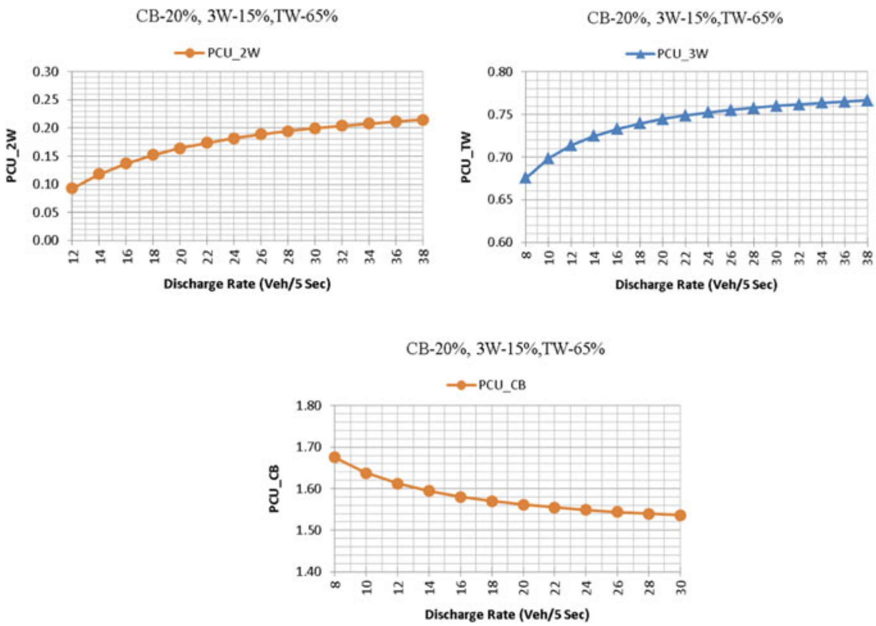

Fig. 5 Variation PCU with discharge rate for 2W, 3W and CB

the variation of PCU for different category of vehicles with the respective discharge rate.

From Fig. 5, it has been seen that the PCU of vehicles smaller than the reference vehicle increases with increase in discharge rate, whereas the PCU of vehicles larger than the reference vehicle decreases with increase in discharge rate. It is observed that, when the composition of small-size vehicles are high in the traffic stream, in that case, the tendency of small-size vehicle is to travel towards edge lane of roadway in a group of platoon and create poorer operating condition among themselves which, in turn, increases in average occupancy time and results in more PCU, but the scenario becomes opposite for big cars, and therefore, with less speed differential invariably reduces the PCU at the signalised intersections. The slope of graphs is flat, so less variation in PCUs with the discharge rate.

The proportion of two categories of vehicles is kept constant and the other two categories are varied in a contemporary manner. Figure 6 shows the various graphs of variation in PCU with their own vehicle proportion at the various saturation flow level of 7200, 14,400, and 21,600 veh/h which was observed in the field. It has been seen that the PCU of motorised two-wheeler and three-wheelers goes on decreasing with increase in their own proportions. PCU values for big cars showed a different trend. There is increase in dynamic PCU values with increase in particular vehicles proportion. At an intersection, it is also observed that small-size vehicles like 2W and 3W have more manoeuvrability and they can accept the gaps between the large-size vehicles and able to passage in any space accessible between big-size vehicles and

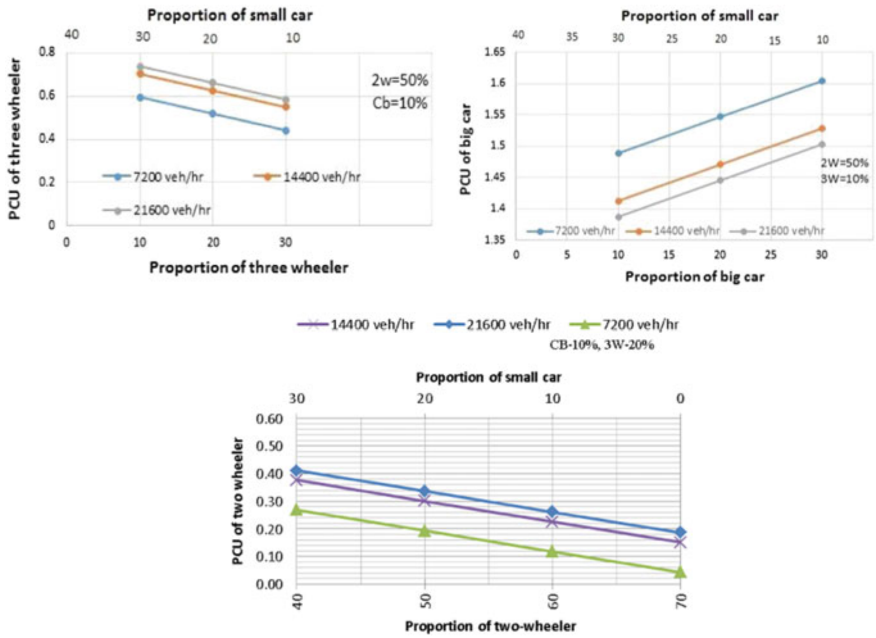

Fig. 6 Variation in PCU of 3W, CB and 2W with their proportions

thus they are minimum affected, but they make poorer operative conditions for other vehicles [11, 12]. The variation in PCU values during the saturation time is mainly due to the composition effect and their interaction among the vehicles. Increase or decrease in PCU values is attributed to speed of reference and subject vehicles during the discharging operations.

6 Stream Equivalency Factor

A stream equivalency factor has been suggested by Dhamaniya and Chandra [13] to convert mixed traffic flow to equivalent car flow. The derived stream equivalency factor (k) is for the stream conversion. The same concept is used by Patel and Dhamaniya [14] at signalised junction and derived the equivalency factor. It is flow ratio between PCUs and vehicles. In the current study, the estimated average PCU values from Table 3 are used for developing the stream equivalency factor (Fig. 7).

The linear regression model is developed to estimate the k-value by adopting the influence of heterogeneous traffic on k. The relation is given in Eq. (6).

$$k = 1 + 0.3793 \times \frac{1}{N} + 0.005 \times C_{\mathrm{CB}} - 0.0032 \times C_{\mathrm{3W}}$$

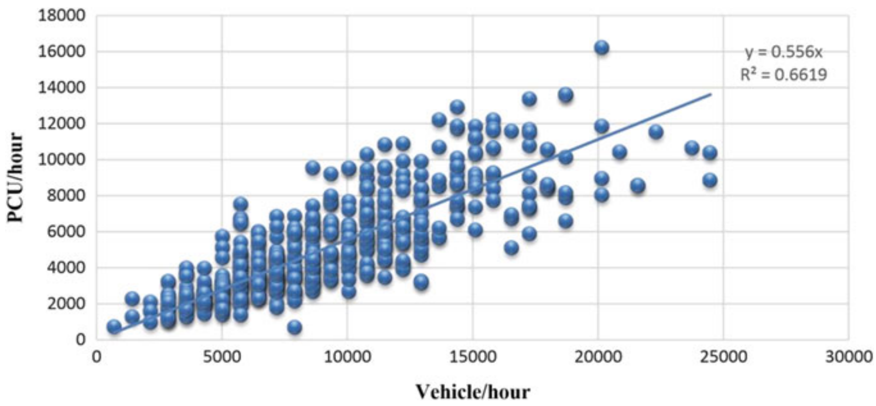

Fig. 7 Stream equivalency factor

$$- 0.0078 \times C_{2W} + 0.0479 \times C_{HCV} + 0.0081 \times C_{LCV},$$
$$R^2 = 0.96 \quad (6)$$

where N average of vehicles, C_{CB}, C_{3W}, C_{2W}, C_{HCV} and C_{LCV} are the average share of CB, 3W, 2W, HCV and LCV, respectively, for each 5 s. The R^2-value and t-value indicate good strength significant at the 95% level of confidence. The coefficients' signs are also logical for smaller-size and large-size vehicles.

7 Conclusions

The passenger car equivalent is most crucial parameter to address the mixed traffic condition mainly comprised of different static and dynamic characteristics of vehicles and absence of lane-disciplined driving. The several techniques are suggested by the researcher for PCU estimation and obtained values may vary to certain range. Still, all the approaches limit to a specific set of PCU value for different traffic environments. The current study explains the dynamic nature of PCU value in urban signalised junction. The PCU values are derived by new technique of occupancy time. Meanwhile, the occupancy time of a vehicle is influenced by the composition and flow rate on a stream, a set of equations is developed considering the above factors. Variation of PCU is denoted graphically for different discharge rate and traffic composition. PCU of two wheelers and three wheelers decreases with increase in its own due to their small size and higher manoeuvrability. Similarly, PCU of big car increases with increase in its own composition because of its lesser gap accepting behaviour. This study provides a methodology for estimation of dynamic PCU factors during the saturated green time. The equations are developed for PCU and stream equivalency for the different compositions level to predict PCUs and stream equivalent factors at signalised junctions under mixed traffic flow.

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