European Transport \ Trasporti Europei (2022) Issue 86, Paper n° 6, ISSN 1825-3997

https://doi.org/10.48295/ET.2022.86.6

Estimation of PCU Values for Urban Roads by Considering the Effect of Signalized Intersections under Mixed Traffic Conditions

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Abstract

Along with multiple classes of vehicles, frequent signalized intersections on the urban roads and the platoons thus created add complexity to the estimation of Passenger Car Units (PCU). Under such scenarios of interrupted traffic, a new approach based on platoon movement of vehicles is introduced for the realistic estimation of PCU values for urban roads by incorporating the appropriate vehicle behavior and interactions. The PCU values were derived by finding the trade-off between the speed reduction caused by the flow of passenger cars and other vehicle classes, as per the given definition by Transport Research Laboratory (TRL). However, the speed-flow, as well as the speed-density relations, were analyzed and found that later is preferred for the realistic estimation of PCUs for urban roads. The speed reduction is modeled using multiple linear regression with field data collected from typical urban roads characterized by platoon flow in Mumbai city (India).

Keywords: Urban Roads, Passenger Car Unit, Interrupted Traffic, Regression, Speed Reduction, Platoon

1. Introduction

Traffic volume is an essential input required for the planning, design, and operational assessment of any traffic facility. It is defined as the number of vehicles passing a particular point on a roadway during a given time period. For the conceptual representation of traffic volume, the volumes of different vehicle types must be converted into an equivalent volume of a standard vehicle. The conventional practice is to group vehicles into classes based on the similarity in physical and operational characteristics. The passenger car is considered the standard vehicle class in traffic analysis, and the traffic volume is usually depicted in terms of passenger cars per hour. This is achieved by finding an equivalency factor for other vehicle classes with respect to passenger cars, known as Passenger Car Equivalent (PCE) or Passenger Car Unit (PCU).

Highway Capacity Manual (HCM 2010) defines PCE as the number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under a specified roadway, traffic, and control conditions. Compared to homogeneous traffic, the estimation of PCU values in developing countries is complex due to the multiple classes of vehicles. Unlike developed countries, most urban roads in

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developing countries are characterized not only by passenger cars and heavy vehicles but by a wide variety of vehicle classes with different sizes and operational characteristics, moving in a laneless fashion. The vehicle classes, two-wheeler, three-wheeler, passenger car, light/heavy commercial vehicle, minibus, bus, bicycle, and animal-drawn vehicle, constitute the composition of mixed traffic. Moreover, in mixed traffic conditions, size, speed, maneuvering, and acceleration-deceleration characteristics of vehicle classes also vary widely.

HCM (2016) defines the urban street segment as the segment of roadway bounded by controlled intersections at either end that requires the street's traffic to slow or stop. An urban street facility is a set of contiguous urban street segments. These facilities are generally analyzed as segments due to the signalized intersections present throughout the roadway. But in countries like India, though urban roads are characterized by signalized and unsignalized intersections, urban roads are separately analyzed as mid-block sections and intersections. When such fixed and frequent interruptions dominate the urban roads, the traffic flow becomes non-continuous, leading to the platoon movement of traffic. Due to the change in operations of urban roads, the vehicles under such conditions will behave differently than a typical urban midblock with continuous flow. In this scenario, using the existing PCU values or the estimation approaches developed for the urban midblock section might lead to an inaccurate representation of traffic volume and capacity. Hence, there is a need to estimate PCU values for urban roads, considering them as segments influenced by signalized intersections, for the fair evaluation of the facility. So the objective of the study is to develop a methodology for the realistic estimation of PCU values for urban roads with the interrupted flow in mixed traffic conditions.

2. Literature Review

Several studies have been identified for the PCU estimation for different traffic facilities, as reported by Raj et al. (2019). These studies have used various methods to estimate PCU values, but most of them are done in the context of homogeneous traffic.

One of the earlier methods used for developing PCUs was based on passing time and headways. Craus et al. (1980) proposed the truck equivalency factor as the ratio of delay time (travel time required to complete the overtaking process) caused by one truck to delay time caused by one passenger vehicle. Sarraj and Jadili (2012) used the method suggested by Greenshield in 1947, known as the basic headway method, in which the ratio of headways gives the PCU values. Sun et al. (2008) also estimated PCU by finding the ratio of the average time headway of a truck to that of a passenger car. Keller and Saklas (1984) used travel time for deriving PCU values by comparing travel time with respect to passenger cars. These methods cannot be implemented directly in mixed traffic conditions due to the lack of lane discipline and platoon movement of vehicles on urban roads.

In a few studies, PCU estimation is carried out by comparing two traffic streams; the first stream has only passenger cars, and the other has mixed traffic - cars and trucks. The PCU factors are obtained by analyzing the change in a selected traffic parameter due to the introduction of the vehicle under consideration with respect to car-only traffic. These parameters can be traffic speed, headway, travel time, and density. This popularly used method for estimating PCU values is the method of equivalency criterion. Sumner et al. (1984) used Huber's relationship to estimate the PCU of a single truck in a mixed traffic stream based on travel time. As per this method, the PCU of a truck is the number of passenger cars that can produce the same effect as the truck without changing the quality of service. Studies by Cunha and Setti (2011) and De Luca and Dell'Acqua (2014) have used similar methods for developing PCU values.

The "cars only" traffic condition is generally not present in the Indian scenario, so a few studies have also used the simulation to obtain cars only traffic conditions to estimate PCU values. Al-Kaisy et al. (2005) developed PCU factors for heavy vehicles on freeways and multilane highways during congestion. Using the simulation method, Mehar et al. (2014) derived PCU values on interurban multilane highways in India at different service levels. Arasan and Arkatkar (2010) also used stream speed as an equivalency criterion for developing PCU values. Basu et al. (2006) developed PCU values by comparing the reduction in stream speed caused by a vehicle type to the reduction in stream speed caused by old technology cars for a base volume and base composition using traffic simulation. Webster and Elefteriadou (1999) modified the method for estimating PCUs of trucks on basic freeway sections using simulation. The main drawback of these methods is that homogeneous traffic streams obtained by simulation cannot be validated.

A few studies have also used vehicular characteristics to estimate PCU values. Anand et al. (1999) developed PCU factors based on lateral clearance, mean speed, and headway of the vehicle classes and passenger cars. Some studies have included the size of the vehicle as a parameter that affects PCU values. Cao and Sano (2012) used a speed and effective space for developing motorcycle equivalents. Chandra and Kumar (2003) used PCUs based on the speed and area of the vehicles. Indian Highway Capacity Manual (Indo-HCM, 2017) also uses this method for defining the PCU values for urban roads in Indian traffic conditions. Studies have also used and modified the speed-area-based method to estimate PCU values for urban roads (Mondal et al., 2017; Biswas et al., 2018). Area-based methods do not consider the effect of other vehicles in the stream to estimate PCU; hence realistic estimation cannot be guaranteed.

Studies have also considered the regression method for measuring the marginal effect of vehicle classes on traffic parameters for estimating PCU. Fan (1990) proposed that the maximum flow rate is PCU times the traffic volume at congested flow, and PCU values were developed by regressing maximum flow with respect to flow rates of the vehicle types. Van-Aerde and Yagar (1984) calculated PCUs based on the speed reduction of each vehicle type in the traffic stream, considering a linear relationship between speed and flow using regression. Yeung et al. (2015) and Raj et al. (2020) have also used the regression approach to derive PCU values. In general, the PCU estimation methods used for urban roads can be broadly classified, as shown in Table 1.

Table 1: Approaches used for PCU estimation on urban roads

Approach	*Selected Major Studies*
Ratio of Traffic Parameters (Greenshield's Method)	Craus et al. (1980)
Equivalency Criterion (Huber's Method)	Sumner et al. (1984)
Traffic Flow/Speed Modeling	Van-Aerde and Yagar (1984)
Simulation Method	Keller and Saklas (1984)
Speed-Area Method	Chandra and Kumar (2003)

The most commonly used PCU values for urban roads in Indian conditions are those in Indian Road Congress (IRC)-106 (1990), but it doesn't provide any methodology or background for the PCU values defined. Another essential factor that must be considered during the estimation of PCU values is the interaction of vehicles, which is not attempted widely in the existing studies. The urban roads in Indian conditions are characterized mainly by noncontinuous platoon flow due to frequent intersections. In the earlier studies, the urban roads affected by signalized intersections and the resulting platoon flow in urban roads are not generally considered for PCU estimation. This is an important parameter that must be included in the analysis as the number of intersections is more in most urban road stretches in developing countries. The estimation of PCU values was mainly carried out in uninterrupted facilities such as freeways or highways where the flow characteristics do not vary frequently. When the flow characteristics vary, the vehicles are forced to change their driving behavior which eventually affects the nearby vehicles. Hence, there is a need to estimate PCU values for vehicle types considering the platoon movement of vehicles caused due to fixed interruptions on urban roads under mixed traffic conditions. So the present study attempts to identify the variations in flow characteristics in interrupted conditions and thereby proposes a method for estimating PCU, incorporating the vehicle interactions, which can be used generally for urban roads where the platoon movement of traffic prevails.

3. Methodology

In HCM (2000), the concept of PCU is defined as the number of passenger cars that are displaced by a single heavy vehicle of a particular type under the specified roadway, traffic, and control conditions. So the present study attempts to figure out the number of passenger cars displaced by a specific type of vehicle, based on a traffic parameter as the equivalency criterion. From the literature survey, it is understood that methods based on speed are the most effective and commonly used for estimating PCU. In this respect, the definition of PCU as given by the Transport Research Laboratory (TRL) becomes handy. As per this definition, on any particular section of road under prevailing traffic conditions, the addition of one vehicle of a particular type per hour will reduce the average speed of the remaining vehicles by the same amount as the addition of, say x cars per hour, then one vehicle of this type is equivalent to x PCU. This definition of PCU based on speed is utilized in the present study to estimate PCU values for urban roads. If there is a linear relationship between speed and volume, the computation of the PCU value of any vehicle type becomes simple, as per the TRL definition. It gives a reasonable estimate of PCU when linear relation between speed and flow is assumed.

3.1 Existing Method for Estimation of PCU in Uninterrupted Flow Conditions

The traffic flow that is not affected by any fixed interruptions is known as uninterrupted flow. The existing studies have used the method for estimating PCU values for roads with an uninterrupted flow. According to the fundamental speed-flow relation, the traffic speed reduces with the increase in traffic volume in the uncongested regime. The regression method developed by Van-Aerde and Yagar (1984) calculated PCUs based on the speed reduction of each vehicle type in the traffic stream, considering a linear relationship between speed and volume. The average stream speed (v) and volume (n) over fixed time intervals like 15, 10, or 5 minutes were selected as dependent and independent variables, respectively, for the regression. This very well suits the definition given by TRL, that the increase in traffic volume will reduce the traffic speed. So the regression equation is modeled as shown in Eq. (1).

$$v = v_f + a_c n_c + a_1 n_1 + a_2 n_2 + a_3 n_3 + \cdots = v_f + \sum_{all\ i} (a_i\, n_i) \qquad (1)$$

where v is the average traffic stream speed, v_f is the free-flow speed, n_i is the volume of class i vehicles in the stream, and a_i is the marginal effect of respective vehicle classes on average stream speed. The number of vehicles added to the stream is an independent variable, and a linear regression is suitable for explaining the effects caused by each vehicle class. Based on this, the linear regression approach finds the marginal effect of each vehicle class in reducing speed from free-flow speed to stream speed. The trade-off between the marginals effects of a particular vehicle class, a_i and passenger cars, a_c gives the PCU of that vehicle class as shown in Eq. (2).

$$PCU_i = \frac{a_i}{a_c} \tag{2}$$

But it is crucial to notice that the fundamental speed-flow relation is not linear, and marginal effects vary with respect to the speed function. So the present study has proposed that the marginal effect of a vehicle class on average stream speed can be represented more realistically as the partial derivative of the speed function with respect to that vehicle class, as shown in Eq. (3).

$$a_i = \frac{\partial}{\partial n_i}(v) \tag{3}$$

As per TRL definition, for bringing about the same speed reduction brought by the vehicle class i, ${}^{a_i}/_{a_c}$ cars are needed to be introduced into the stream. Thus, the PCU of a particular vehicle class is the ratio of the partial derivative of speed function with respect to vehicle class i and with respect to passenger car c, as given in Eq. (4).

$$PCU_i = \frac{\frac{\partial}{\partial n_i}(v)}{\frac{\partial}{\partial n_c}(v)} \tag{4}$$

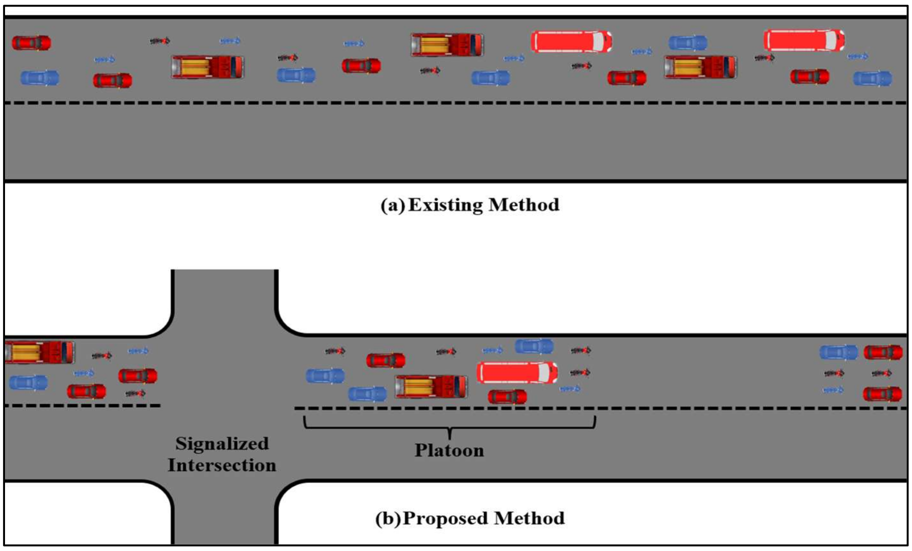

Figure 1: Schematic representation of the existing and proposed method

In Figure 1(a), the platoons are less likely to be formed due to sufficient spacing between the signals, or the platoons formed are dispersed as vehicles move forward. The average speed of the vehicles (v) and the number of vehicles (n) of different classes over a time period can be used to find the marginal effect of vehicle types on speed reduction. But in the present study, as shown in Figure 1(b), the platoons formed are met with another intersection before they could disperse due to more intersections in the corridor. The platoons formed at the signalized intersections move towards mid-blocks, and hence the presence of gaps within the flow will not satisfy the definition of speed reduction. Also, the method does not consider the effect of vehicle classes on speed reduction directly due to platoons generated from signalized intersections. The existing method was used to estimate the PCU values for highways with uninterrupted flow conditions where the flow characteristics and vehicle behavior does not vary frequently.

3.2 Vehicle Behaviour in an Interrupted Flow

According to HCM (2016), any street or roadway with signalized intersections, stop-controlled intersections, or roundabouts that are spaced no farther than 2 miles apart can be evaluated using the HCM methodology for urban streets. So the influence of platoons on the urban street operation is very likely to be negligible when segment length exceeds 2 miles (≈3.2 km). However, studies have suggested the need for analyzing urban roads as segments due to frequent signalized intersections in Indian scenarios (e.g., Raj and Vedagiri, 2022). Hence, the urban streets in Indian conditions are characterized by vehicles arriving in the platoon, which is used to understand the speed reduction more precisely in the present study.

(a) Vehicles arriving between two platoons (b) Vehicles at the beginning of a platoon

(c) Vehicles arriving as a part of platoon (d) Vehicles arriving in bunches within platoon

Figure 2: Different cases of vehicle behavior in interrupted flow

Four cases of vehicle behaviors were identified on the interrupted urban traffic flow under mixed traffic conditions and are explained using Figure 2. (i) Case 1: In Figure 2(a), vehicle 1 is randomly arriving in between two platoons. The speed of these vehicles is relatively very high as the vehicle is not disturbed due to the absence of other vehicles around it. (ii) Case 2: In Figure 2(b), vehicle 2 is arriving as a part of the platoon but at the beginning of the platoon. The vehicle’s speed is relatively higher but less than in the previous case as the vehicle is affected by the immediate vehicles on the sides. (iii) Case 3: In Figure 2(c), vehicle 3 is arriving as a part of the platoon, either at the middle or towards the end of the platoon. The speed of that vehicle is less compared to the previous cases as the vehicle is interrupted by other vehicles in the platoon. (iv) Case 4: In Figure 2(d), vehicle 4 is arriving as a part of the platoon, but there is a gap within the platoon. So the speed of these vehicles may or may not be affected by the vehicles in the bunch ahead.

So, from the preliminary analysis, it is observed that the stream speed varies rapidly in a wide range, unlike the uninterrupted flow conditions. The traffic volume also showed variation frequently. Since the flow and speed characteristics differ from normal uninterrupted flow conditions, such urban roads have to be treated separately as different traffic facilities. Hence, rather than a macroscopic approach, microscopic analysis is required to understand the speed reduction and marginal effect on urban roads characterized by platoon flow.

3.3 Proposed Method for Estimation of PCU in Interrupted Flow Conditions

Even though the existing method was suitable for estimating PCU, the main issue with the approach while using it for urban roads with the interrupted flow is the identification of platoon flow. The time intervals in terms of minutes cannot be used for the analysis, as the length of platoons will be mostly in seconds characterized by the signal timings. A preliminary investigation was conducted for the traffic volume for different time intervals such as 60, 30, 20, and 10 seconds. The analysis inferred that the higher time intervals could not identify the platoons and the gaps in the traffic flow. But when the volume was represented in smaller intervals, the gaps in the traffic flow due to the signalized intersections were identified. Considering this, the extraction interval was decided to be as minimum as possible, 10 seconds, which can very well take into account the platoon flow.

Based on the existing methodology, the speed of the stream is affected by the number of vehicles in the stream. Hence the average speed of the stream is considered the dependent variable, and the vehicles affecting the average speed will be the independent variables for the regression. Accordingly, the regression Eq. (1) is modified as Eq. (5).

$$v = v_o + \sum_{all\ i} (a_i\, q_i) \tag{5}$$

Where v is the average stream speed, v_o is the operating speed of the stream, q is the number of class i vehicles in the stream for a given time period or simply flow rate, and a_i is the marginal effect of the respective vehicle class on average speed. In the formulation, free-flow speed is replaced with the term operating speed, as most vehicles will not travel at maximum speed on urban roads due to signalized intersections, even if there are no other vehicles in the stream. AASHTO Green Book (2011) defines operating speed as the speed at which drivers are observed operating their vehicles during free-flow conditions. It is the 85th percentile value of the observed free-flow speeds, which is the most frequently used measure of the operating speed associated with a particular location or geometric feature.

Two methods were implemented for modeling the speed reduction- (i) Method 1: Based on flow, and (ii) Method 2: Based on density. In both methods, the marginal effect on speed reduction of each vehicle class is modeled using the field data. For method 1, the average stream speed over 10 seconds is regressed over the corresponding traffic flow of different vehicle classes. It is assumed that the average speed is affected by the number of different types of vehicles over a fixed time interval for interrupted flow conditions, thereby considering the vehicle interactions in that time interval. Therefore, the marginal effect of any vehicle type on speed reduction accurately depicts the interaction of that vehicle type during that time interval.

Even though most studies have used traffic flow as the criterion for PCU estimation, some studies have used traffic density, such as Webster and Elefteriadou (1999). For the case of speed-density relation, the number of influencing vehicles is considered for a fixed length instead of the time interval. The density used for the study is measured from the field using the video data collected. The density of the stream is analyzed at every 10th second of the traffic flow and is used for modeling the speed-density relation. So, the concept for estimating the PCU value is that adding the number of vehicles in a given length of roadway (traffic density) will reduce the speed of the vehicles linearly. In the same way, the marginal effect of each vehicle class on speed reduction can be calculated and used for estimating PCU values. Since the speed-flow relation is non-linear, the concept of estimating the PCU value can be altered in such a way that the addition of a number of vehicles in a given length of roadway (traffic density) will reduce the speed of the vehicles linearly. Hence the average speed of the passenger cars will be the dependent variable for linear regression. The corresponding vehicles per length affecting the average speed will be the independent variables. Therefore, Eq. (1) is modified as shown in Eq. (6) for method 2.

$$v = v_o + \sum_{all\ i} (a_i\ k_i) \tag{6}$$

Where v is the average stream speed, v_o is the operating speed of the stream, k is the number of class i vehicles in the stream for a given length, and a_i is the marginal effect of the respective vehicle class on stream speed.

4. Data Collection

Based on the proposed method, data has been collected as part of the project, namely the 'Development of Indian Highway Capacity Manual' sponsored by CSIR-CRRI. Video data were collected for urban midblock sections in Mumbai city, considering the geometric variations. The one-hour video data at peak periods from four locations, namely Jogeshwari-Vikhroli Link Road- Location 1 (JVLR 1), Jogeshwari-Vikhroli Link Road- Location 2 (JVLR 2), Lala Lajpat Rai Road (LLR), and Swami Vivekananda Road (SVR) were used for the analysis of the present study. The videographic data is collected during morning peak hours around 10 AM to 12 PM. The locations were selected to represent typical Indian urban roads where platoon flow constantly occurs and has varying road widths. The snapshots of the video from the four locations are shown in Figure 3.

(a) Jogeshwari-Vikhroli Link Road, Location 1 (JVLR1) (b) Location 2 (JVLR2)

(c) Lala Lajpat Rai Marg (LLR) (d) Swami Vivekananda Road (SVR)

Figure 3: Snapshot of video data collected

4.1 Data Extraction

Traffic volume was extracted every 10 seconds by replaying the collected video data for different vehicle classes to test the speed-volume relation. Compared to the field observed traffic flow, the traffic volume varies significantly when 10 seconds interval is considered. This is due to the different cases of vehicle behaviors observed in interrupted urban traffic flow. The corresponding stream speed was measured with the help of a known trap length (50m) marked at the locations. Since the speeds varied in a wide range over time, the average speed was estimated for every 10 seconds interval to understand speed reduction more effectively.

For interrupted flow conditions, the traffic density measured over one kilometer does not represent the real traffic scenario due to the presence of platoon movement of vehicles. Since the vehicles are moving in platoons, the gaps thus created cause underestimation of traffic density. Hence, smaller stretches are more suitable for measuring traffic density in interrupted flow conditions than long stretches. Therefore, the traffic density for the present study is measured within a small stretch of 50m. The vehicles occupied over a fixed length for every 10^{th} second were extracted using the trap length marked on the video to model the speed-density relation. The same vehicle classes used for the speed-volume relation were also considered for density extraction. The corresponding stream speed was measured based on the same trap length.

The extracted samples of average speed and the corresponding volume or density make one data point. According to the proposed methodology, when volume increases, the stream speed reduces, but in some cases, even though there is a very low or zero number of vehicles, the average speed is very low. This can be explained with the help of the presence of intersections and platoon flow on the urban roads. So the data points with low speed values and fewer vehicles were also considered outliers and were removed from the analysis.

4.2 Traffic Composition

Six vehicle classes were considered in the study – i. Motorized Two-wheeler (TW), ii. Motorized Three-wheeler (ThW), iii. Passenger Car (C), iv. Light Commercial Vehicle (LCV), v. Heavy Commercial Vehicles (HCV), and vi. Bus (B). Some vehicle classes are found to be significantly less in the composition and hence cannot contribute to the development of the model. So the vehicle classes that are very few were not considered for the analysis separately (e.g., minibusses). The vehicle class minibus was added to the vehicle class, namely light commercial vehicle, for the study considering the similar physical characteristics. The vehicle composition and other aspects of the selected locations are shown in Table 2.

Table 2: Details of the selected urban road locations

Characteristics	*JVLR1*	*JVLR2*	*LLR*	*SVR*
Number of lanes (per direction)	3	3	4	2
Roadwidth (in m, per direction)	10.8 m	11.0 m	13.5 m	5.8 m
Segment length (m)	550	230	650	350
Speed range (km/h)	20-60	20-60	30-70	20-50
Flow rate (pcphpl)	1030	1120	980	1250
Percent Composition (%)				
Motorized Two-wheeler (TW)	25	22	15	21
Motorized Three-wheeler (ThW)	25	24	0	32
Passenger Car (C)	36	33	80	43
Light Commercial Vehicle (LCV)	6	8	3	2
Heavy Commercial Vehicles (HCV)	5	5	1	1
Bus (B)	3	8	1	1

Note: m = metres; km/h = kilometre per hour; pcphpl = passenger cars per hour per lane (PCU based on Indo-HCM, 2017)

5. Modeling Speed Reduction

Speed is modeled using Multiple Linear Regression (MLR) in the present study. MLR is an extension of simple linear regression for modeling the relationship between a scalar dependent variable and scalar independent variables. So, the objective of the MLR is to estimate the coefficients of the independent variables in predicting the dependent variable. The coefficients are calculated using the method of least squares, in which the best fit is obtained by minimizing the sum of the squares of the residuals of all data points. The linear regression model in the present study tries to explain the relationship between the dependent variable – average speed and the independent variables – the number of vehicles. The coefficients of regression represent the marginal effect of speed reduction. Method 1 analyzes the variation of speed with respect to flow, whereas, in method 2, the speed variation with respect to vehicles per kilometer (traffic density) is investigated.

5.1 Method 1: Speed–Flow Relation

Even though the speed-flow relation is not linear, the data revealed an approximately linear relationship between speed and volume. According to the TRL definition for PCU estimation, it is assumed that the speed is linearly varying with the flow. This assumption is checked by modeling the linear speed-flow relation in method 1. The speed model obtained for the location JVLR1 is as shown in Eq. (7).

$$v = 45.16 - 0.16\, q_{tw} - 1.62\, q_{thw} - 1.28\, q_c - 1.05\, q_{lcv} - 3.16\, q_{hcv} - 6.44\, q_b \tag{7}$$

Where v is the speed of the stream, 45.16 is the operating speed in km/h. q is the number of vehicles in unit time and subscripts, tw, thw, c, lcv, hcv, and b represents different vehicle classes. The coefficients represent the marginal effect of each vehicle class on speed reduction. Eq. (7) is specific to a particular location, and to ensure robustness, similar models are developed for other locations and are shown in Table 3.

Table 3: Coefficients of the variables obtained from regression analysis

Regression Coefficient of	*JVLR1*	*JVLR2*	*LLR*	*SVR*
Method 1: Speed-Flow Relation				
Intercept (Operating Speed)	45.16	57.50	63.58	37.81
Motorised Two-Wheeler (TW)	-0.16*	-0.87	-0.41	-0.16*
Motorised Three-Wheeler (ThW)	-1.62	-1.10	-	-0.67
Passenger Car (C)	-1.28	-1.13	-1.22	-1.14
Light Commercial Vehicle (LCV)	-1.05*	-2.05	-1.24	-1.40*
Heavy Commercial Vehicle (HCV)	-3.16	-3.45	-3.16	-1.89*
Bus (B)	-6.44	-4.06	-3.57	-4.72
Method 2: Speed-Density Relation				
Intercept (Operating Speed)	47.56	56.61	61.41	34.87
Motorised Two-Wheeler (TW)	-0.23*	-1.23	-2.10	-0.17*
Motorised Three-Wheeler (ThW)	-1.96	-2.13	-	-0.55
Passenger Car (C)	-2.42	-2.70	-4.60	-1.33
Light Commercial Vehicle (LCV)	-3.15	-3.80	-7.19	-1.82
Heavy Commercial Vehicle (HCV)	-6.53	-6.76	-8.51	-2.62
Bus (B)	-7.38	-7.91	-10.3	-3.90

Note: ThW is not allowed at LLR (0%); *Not significant at 95% confidence level (p-value > 0.05)

5.2 Method 2: Speed–Density Relation

Apparently, from the speed-density data, it can be inferred that the relationship between speed and density can be better approximated by a linear relationship than the relationship between speed and flow. So, the relation between the dependent variable- traffic speed and independent variables- classified density is studied in this method. The speed-density model obtained for the location JVLR1 is as shown in Eq. (8).

$$v = 47.56 - 0.23\, k_{tw} - 1.96\, k_{thw} - 2.42\, k_c - 3.15\, k_{lcv} - 6.53\, k_{hcv} - 7.38\, k_b \tag{8}$$

Where v is the speed of the stream, 47.56 is the operating speed in km/h. k represents the number of vehicles in unit length, and subscripts represent different vehicle classes. The results obtained for all the locations based on method 2 are also shown in Table 3.

According to this method, adding one two-wheeler into the stream of 50m length of a three-lane road will reduce the average speed by 0.36 km/h. At the same time, the addition of 1 two-wheeler per 10 seconds will reduce the average speed by 0.16 km/h as per method 1. This is in line with the definition given by TRL. It can also be observed that the speed reduction caused by vehicles increases with the increase in the physical size of the vehicles.

5.3 Statistical Analysis

The regression coefficients were negative for all the cases proving that the increased number of vehicles will reduce the speed. Table 4 shows the statistical results obtained for the MLR method. The multiple-R value suggests the existence of a linear relationship between speed and flow as well as speed and density. The R square values are found to be higher for method 2 compared to method 1, indicating relatively better goodness of fit for the speed-density model. From the statistical results, the density-based method is found to be more significant even though the TRL defines speed reduction based on speed–flow relation for the estimation of PCU values.

Table 4: Statistical analysis of the MLR models

Measures		*JVLR1*	*JVLR2*	*LLR*	*SVR*
Method 1: Speed-Flow Relation					
Observations		211	198	239	195
Multiple R		0.54	0.64	0.71	0.66
R square		0.29	0.41	0.51	0.44
Significance		0.000	0.000	0.000	0.000
p-value (VIF)†	Intercept	0.000	0.000	0.000	0.000
	TW	0.617* (1.03)	0.001 (1.02)	0.019 (1.02)	0.281* (1.01)
	ThW	0.000 (1.00)	0.000 (1.05)	-	0.000 (1.03)
	Car	0.000 (1.12)	0.000 (1.13)	0.000 (1.01)	0.000 (1.03)
	LCV	0.165* (0.92)	0.000 (1.05)	0.038 (1.03)	0.077* (0.98)
	HCV	0.001 (1.01)	0.000 (1.07)	0.048 (1.01)	0.103* (1.02)
	Bus	0.000 (1.00)	0.000 (1.10)	0.000 (1.06)	0.000 (1.20)
Method 2: Speed-Density Relation					
Observations		205	168	192	167
Multiple R		0.82	0.76	0.76	0.76
R square		0.68	0.58	0.57	0.57
Significance		0.000	0.000	0.000	0.000
p-value (VIF)†	Intercept	0.000	0.000	0.000	0.000
	TW	0.443* (1.14)	0.010 (1.07)	0.002 (1.04)	0.359* (1.06)
	ThW	0.000 (1.08)	0.000 (1.05)	-	0.000 (1.04)
	Car	0.000 (1.14)	0.000 (1.23)	0.000 (1.08)	0.000 (1.04)
	LCV	0.000 (1.05)	0.000 (1.02)	0.000 (1.08)	0.008 (1.07)
	HCV	0.000 (1.03)	0.000 (1.13)	0.007 (1.03)	0.005 (1.09)
	Bus	0.000 (1.05)	0.000 (1.17)	0.000 (1.07)	0.000 (0.98)

Note: TW = Motorized Two-Wheeler; ThW = Motorized Three-Wheeler; LCV = Light Commercial Vehicle; HCV = Heavy Commercial Vehicle; ThW is not allowed at LLR (0%).
*Not significant at 95% confidence level (p-value > 0.05), †Values in parentheses is VIF

The operating speeds obtained from the models were compared with the operating speeds obtained from actual speed data collected from the field to check the accuracy of the models. The 85th percentile speeds in km/h were obtained around 45, 55, 60, and 35 for the locations JVLR1, JVLR2, LLR, and SVR, respectively. The operating speeds of the locations predicted by the models were close to the field measured speeds.

The developed models are required to be tested for the problem of endogeneity. If the variables are endogenous, they will correlate with the error terms of each data point. The endogeneity can happen due to the following cases: (a) omitted variables and (b) simultaneity. As per the methodology, the addition of any vehicle type causes a reduction in the average speed of the traffic stream. Thus, the volume of each vehicle class is the independent variable, and all the vehicle classes were considered for the analysis. Since modeling speed reduction aims to estimate the PCU values, the independent variables can be only these vehicle classes, and none of the vehicle classes are omitted from the analysis. So, the chance of the Type I endogeneity due to omitted variables is removed. Type II endogeneity or simultaneity occurs when independent variables cause the dependent variable and the dependent variable causes the independent variable. But for the present modeling, the average speed cannot exist if there are no vehicles. So, it can be inferred that speed is caused due to vehicles, and speed cannot cause vehicles. However, this can be statistically proved by finding the correlation between error terms (actual speed – predicted speed) and independent variables. The Pearson correlation is obtained in the range of -0.1 and 0.1, ruling out the endogeneity problem. The intercorrelation of variables has also been checked using the Variance Inflation Factor (VIF) and found to be slightly higher than 1, implying very little correlation.

6. Derivation of PCU and Comparison of Methods

The marginal effect on speed reduction caused by each vehicle class with respect to the passenger car gives the PCU of that vehicle class. The marginal effect of the two-wheeler at JVLR1 is -0.16, and that of the passenger car is -1.28. Hence, the PCU for the two-wheeler is calculated as 0.16/1.28, which gives 0.13. Similarly, the PCU derived for the vehicle classes at the locations using both methods are shown in Table 5.

Table 5: Estimated PCU values

Location	*TW*	*ThW*	*LCV*	*HCV*	*Bus*
		Method 1: Speed-Flow Relation			
JVLR 1	0.13*	1.27	0.82*	2.47	5.03
JVLR 2	0.77	0.97	1.81	3.05	3.59
LLR	0.34	-	1.02	2.59	2.93
SVR	0.14*	0.59	1.23*	1.66*	4.14
Range of PCU	0.13 - 0.77	0.59 - 1.27	0.82 - 1.81	1.66 – 3.05	2.93 - 5.03
		Method 2: Speed-Density Relation			
JVLR 1	0.10*	0.81	1.30	2.70	3.05
JVLR 2	0.46	0.79	1.41	2.50	2.93
LLR	0.46	-	1.56	1.85	2.24
SVR	0.13*	0.41	1.37	1.97	2.93
Range of PCU	0.10 - 0.46	0.41 - 0.81	1.30 - 1.56	1.85 – 2.70	2.24 - 3.05

Note: TW = Motorized Two-wheeler; ThW = Motorized Three-wheeler (not allowed at LLR); LCV = Light Commercial Vehicle; HCV = Heavy Commercial Vehicle. *Not significant at 95% confidence level

The PCU values for two-wheelers at two locations are found to be not significant and vary in a wide range due to the high-speed characteristics and smaller size. They also have the ability to move towards the starting of the queue at intersections during the red time, and for that reason, two-wheelers are mostly seen at the starting of the platoon or in between platoons with higher speeds. The PCU values of the three-wheeler and bus at most of the locations obtained from method 1 are very high compared to method 2. Whereas the PCU values of LCV and HCV are found to be not statistically significant in method 1. In general, the range of PCU values obtained from method 1 is found to be varying more and had less statistical significance compared to method 2. This is because speed-density data fitted linear relations better than speed-flow data. Therefore, the linear regression is suited well for the speed-density relation in finding the speed reduction in urban roads characterized by platoon flow.

7. Discussion

Due to frequent signalized intersections, the vehicles move in platoons on most Indian urban roadways. The platoons created at the signalized intersections are not allowed to disperse as the traffic has to go through other intersections. So the vehicles are constrained to move along with their nearby vehicles in an interrupted flow resulting in more speed reduction than uninterrupted flow. The PCU values developed for the Indian conditions do not account for the effect of platoon movement caused due to the signalized intersections on urban roads and the vehicle interactions on roadways. Hence, the PCU values reported from some existing studies conducted on highways and freeways cannot be directly used where interrupted flow conditions exist. In the present study, PCU values are developed for such urban roads based on speed reduction for the vehicle classes – motorized two-wheeler, motorized three-wheeler, light commercial vehicles, heavy commercial vehicles, and buses.

In uninterrupted flow conditions, the vehicles will be moving in a steady flow where the variation in speed and flow will be very gradual. Whereas in the present study, the interrupted flow conditions have frequent variations in flow and speed and can be utilized for modeling speed reduction more accurately. Also, when vehicles are moving in platoons, they are forced to move at speed according to their position in the platoon. So the reduction caused to the stream speed by a particular vehicle class will be more in an interrupted flow than in uninterrupted flow conditions. Hence, the PCU values in the present study are slightly lesser than the values given by IRC-106 (1990) and Indo-HCM (2017). A comparison of PCU values with some of the existing studies is also shown in Table 6. The freeways do not have any platoon flow condition, and existing studies in multilane highways do not account for the platoon flow; hence the present study has contributed to PCU estimation, considering that peculiar aspect of urban roads. Overall, the estimated PCU values are found to be logical with respect to the physical size as well as operating characteristics of different types of vehicles. Hence, the methodology can be used to estimate accurate PCU values for urban roads characterized by platoon movement.

Table 6: Comparison of PCU values with some of the existing studies

Studies/Manuals	*TW*	*ThW*	*LCV*	*HCV*	*Bus*
			Freeways		
Fan (1990)	0.40	-	1.30	2.60	2.70
Yeung et al. (2015)	0.65	-	1.53	2.75	-
			Multilane Highways		
Chandra & Kumar (2003)	0.25-0.30	1.24-1.75	2.49-2.81	3.66-4.04	5.17-5.64
Arasan & Arkatkar (2010)	0.34-0.89	0.50-0.99	1.24-1.67	1.90-2.80	1.70-2.90
			Urban Roads		
IRC-106 (1990)	0.50, 0.75	1.20, 2.0	1.40, 2.00	2.20, 3.70	2.20, 3.70
Indo-HCM (2017)	0.10-0.45	0.38-2.11	2.10-4.50	2.70-7.50	1.90-6.00
Method 1: Speed-Flow Relation	0.13-0.77	0.59-1.27	0.82-1.81	1.66-3.05	2.93-5.03
Method 2: Speed-Density Relation	0.10-0.46	0.41-0.81	1.30-1.56	1.85-2.70	2.24-3.05

Note: TW = Motorized Two-Wheeler; ThW = Motorized Three-Wheeler; LCV = Light Commercial Vehicle; HCV = Heavy Commercial Vehicle

The PCU values were estimated for different vehicle classes based on two methods based on speed-flow relation and speed-density relation. The PCU values obtained from the speed-density relation are more logical than the speed-flow relation. This is due to the linear relationship between the speed and density, whereas the speed-volume relation is non-linear, and hence linear regression suits the former well. According to TRL, PCU has to be estimated based on the speed reduction with respect to vehicles per hour, but the present study has also analyzed the speed reduction based on vehicles per kilometer, and significant improvements were observed. Since density is a measure of the proximity of other vehicles in the stream, the vehicular interaction of passenger cars with respect to other vehicles can be explained better compared to traffic flow. If the speed-flow relation is used for estimating PCU values, dynamic PCU values must be developed for different flow conditions. This drawback can be overcome by adopting a speed-density relation for estimating static PCU values. The PCU values estimated using the speed-density relation can take care of variations in different density conditions, as the speed and density are more towards a linear relation. Hence the method based on density is comparatively better than the flow-based method for estimating the PCU values for urban roads characterized by platoon flow. However, the flow-based method can be preferred when accurate density data is unavailable.

8. Conclusions

The Indian urban roads mostly have the platoon movement of vehicles on the urban roads due to frequent intersections. The segment-level analysis of urban roads for PCU estimation is not considered widely in earlier studies. Hence, estimating PCU values at such road sections where the interrupted flow is dominating is a challenging task. So, the study has developed a new methodology for deriving the PCU values for Indian urban roads with interrupted flow conditions. The methods discussed in this study appear to be promising for generating PCU factors for mixed traffic where multiple class of vehicles and interrupted traffic flow exists. The approach considers the platoon flow occurring significantly in Indian conditions and uses the concept of speed reduction, which best suits the definition given by TRL for the estimation of PCU values. The marginal speed reduction of different vehicle classes is calculated based on the speed model developed. This marginal speed indirectly accounts for the vehicle interactions of various vehicle classes with respect to passenger cars, which is not considered for PCU estimation in most existing studies. Two methods were also proposed and compared to estimate PCU values in urban roads with interrupted traffic based on the same concept. Thus, the current study has made a significant contribution in two aspects related to PCU estimation. The first one is the development of a suitable methodology for deriving more truthful PCU values for urban roads with interrupting traffic flow. Another is that the study has revealed density-based method has an advantage over the flow-based method while using the speed modeling approach in deriving realistic static PCU values. As a result, a revision of the popular TRL definition of PCU is recommended; to substitute vehicles per kilometer in place of vehicles per hour in case of static PCU definition.

The significantly lower percent composition of some vehicle classes in the data is a limitation of the study. Similarly, the study does not consider the effect of factors such as traffic composition and road width while estimating PCU, which is another limitation of the study. For a more detailed investigation of different factors affecting PCU values, such as truck type or heavy vehicle percentage, or percentage composition, simulation approaches can be considered. Nevertheless, the PCUs and the methodology developed in the study can serve as a guideline for traffic engineers and practitioners. Subsequently, the analysis of volume and capacity based on accurate and reliable PCU values leads to efficient planning and design of urban road facilities.

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Acknowledgments

The video data for this study was collected as part of the project named 'Development of Indian Highway Capacity Manual' sponsored by CSIR – Central Road Research Institute (CRRI), New Delhi. The authors acknowledge the whole team of the project.