REVISITING PCU VALUES OF VARIOUS VEHICLES IN MIXED TRAFFIC CONDITIONS: ESTIMATION AND COMPARISON

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Resume

This study is an attempt to derive and to compare the Passenger Car Unit (PCU) values of vehicle types present in the stream, obtained using the Chandra's method, homogeneous coefficient method, speed-based modelling, and multiple linear regression method. Using the data collected from five sites of Sonipat City with varying traffic and geometric characteristics, it was found that Chandra's method is the best method to derive the PCU values in heterogeneous traffic conditions on divided urban roads. The PCU values obtained from Chandra's method are closer to IRC (Indian Roads Congress) code values. The PCU value of e-rickshaw was also estimated in this study, and it was found that it is smaller than one using the Chandra's method. The result of the comparison of obtained PCU values and values given in the IRC code points to conclusion that the IRC codes pertaining to PCU values need revision.

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1 Introduction

The passenger car unit (PCU) is an equivalency factor assigned to each kind of a vehicle in the flow, to convert each vehicle category to a single homogeneous unit. It is critical to establish the Passenger Car Unit (PCU) values for each vehicle type for the building and analysis of various traffic facilities, as well as for managing the traffic control. The adoption of appropriate PCUs for diverse vehicle types will accurately quantify the homogenous volume of traffic in the mixed transportation environment. There are various approaches available for estimating the PCUs for each vehicle category, namely, Chandra's Method [1], Homogeneous Coefficient Method [2], Headway Method [3], Multiple Linear Regression [4-5], Speed based Modelling [6], Density method [7], Huber's Method [8], Simulation technique [9-10]. However, different methods are used for different traffic and roadway conditions.

In this study, the PCU values of each vehicle category were derived and compared to the values given in the IRC (Indian Roads Congress) code (IRC: 106-1990). The PCU value for e-rickshaw was developed in this study, as well. E-rickshaw is a new vehicle type. It is a substitute for cycle rickshaw and is different from auto rickshaws in terms of speed and capacity. Auto-rickshaw has relatively higher speed because it is powered by fuel (CNG, petrol or diesel), the while e-rickshaw is driven by a battery. E-rickshaws are gaining popularity, especially in Asian developing countries like India, Bangladesh etc. because of low operating and maintenance costs. The PCU value of this type of vehicle is not available in the literature. Chandra's method, homogeneous coefficient method, speed-based modelling, and multiple linear regression methods were used to derive PCU values of vehicle types present in the stream. It is a case study of Sonipat City. Five sites of varying traffic and geometric parameters were selected, and by videography method, classified speed and volume data were collected and processed with the help of a VLC media player. The aims of this study were as follows.

1. To derive the PCU values of vehicle types present in the stream using different methods.
2. To compare the PCU values derived using different methods.
3. To compare the PCU values with the values given in IRC: 106-1990 and other literature.
4. To derive the PCU value of e-rickshaw (PCU value of e-rickshaw is not available in the IRC code)

The results of this study will benefit planners and engineers in dealing with heterogeneous traffic, and it will also be helpful in revising the IRC code pertaining to PCU values.

2 Review of published research

Dhananjaya et al. (2023) applied Chandra's method to get the passenger car unit of vehicle types for four different stretches in Sri Lanka's Colombo district. Field surveys were used to collect data, speed and vehicle area. Obtained results were compiled and compared to existing values with the goal of proposing a fresh set for generalized transport investigations in the nation of Sri Lanka [11].

Zero et al. (2022) collected data on passenger car unit for various vehicle types in Erbil City under mixed traffic conditions. Results showed significant variations in passenger car unit with traffic volume and roadway width. Buses had a PCU value of 2.92, similar to Iraq but different from the UK. Highway capacity increased with shoulder areas, positively affecting passenger car unit for vehicle types. Passenger car units were evaluated using Headway, Density, and Homogeneous Coefficient methods [12].

Ali et al. (2021) used Chandra's method and modified it (the modified version of Chandra's method uses average headway along with the average speed and projected rectangular area) for the estimation of PCUs on NHs (National Highways) as:

$$(PCU)_a = Headway\ factor \times Area\ Factor \times \times Speed\ Factor. \tag{1}$$

It was concluded that the Modified Chandra Method gives a higher value for more vehicle types [13].

The PCE (Passenger Car Equivalency of e-rickshaw was developed by Khan and Singh (2021) using Chandra's method of PCE determination and speed-based modelling on urban roads of Sonepat city of Haryana. Parameters considered for this study were the speed of vehicles, traffic volume, traffic composition, and average rectangular area of vehicles present in the stream. It was concluded that PCE of e-rickshaw changes with the change in traffic parameters. The PCE value of e-rickshaw increases positively with the composition of e-rickshaw and decreases as the traffic volume builds up in the stream. However, carriageway width has no significant impact on the PCE of e-rickshaw [14].

Ballari (2020) reviewed various research with respect to methods of estimation of passenger car units in terms of the trucks with different performance measures at the midblock sections [15].

Dasani et al. (2020) used different methods, namely Chandra's method, homogeneous coefficient method, headway method, and multiple linear regression method, to estimate dynamic equivalency factor (DEF) (a term used for Passenger car unit) for different vehicles on mid-block sections of Porbandar city. The study's characteristics included headway, the width of the road, the composition of traffic, and average speed. It was found that the Headway method yields higher dynamic equivalency factor values for MAV (Multi-Axle vehicle), truck, and bus and lower values for bike and autos than IRC standards, the Multiple Linear Regression method produces values for LCVs (Light Commercial Vehicles) that are almost identical to IRC standards, and the Homogenization Coefficient method produces equivalent values for all classes of vehicles. Chandra's approach produces outcomes that are more similar to IRC codes [2].

Sharma and Biswas (2021) examined passenger car units on city roads. They examined various methods for determining the PCU or PCE values and demonstrated how their effectiveness varies depending on the field situation. The estimated PCU values proposed in various research were also highlighted in the current paper. Some researchers suggested static PCU values, while others investigated its dynamic facets [16].

Pooja et al. (2019) examined methods for estimating PCU or PCE values. This paper provided an in-depth examination of methods for estimating the PCU/PCE values for homogeneous and heterogeneous conditions. An attempt was made to identify the limitations of existing PCU estimation methods and to identify potential solutions to these limitations [17].

Parth et al. (2018) calculated dynamic PCU/PCE for vehicles on urban roads with varying traffic conditions. In the current study is shown the dynamic nature of passenger car unit values on two different roads with highly varying traffic conditions. Using Chandra's method, the PCU values were calculated for both roads. Both roads' PCU factors were found to be extremely sensitive to changes in the traffic stream, whether in terms of traffic composition or traffic volume. The type of road also has an impact on it [18].

The PCU values using data from six highway locations of Andra Pradesh were calculated and compared by Rao and Yadav (2018). The speed and area of vehicles were considered to derive PCU values. Speed volume relations were also developed to check the effect of traffic parameters. The obtained PCU values were later compared to the recommended values of IRC: 106-1990 [6].

Barve and Sugandhi (2017) examined a highway-capable passenger car unit (PCU). They attempted to cover the most critical and recent research work in the advancement of PCE or PCU in both homogeneous and heterogeneous traffic conditions. In this study authors addressed and gathered multiple methods for estimating the PCU values. For the calculation of PCU, each method has its own set of factors, such as traffic conditions, geometric factors, headway time, speed, delay, and so on. The PCE or PCU values were found to vary based on traffic situation [19].

Mondal et al. (2017) estimated PCU or PCE values for mixed traffic streams on Kolkata's urban arterials. Author aimed to determine the passenger car unit values for various vehicle categories under non-homogenous traffic conditions on the mid-block section of inter-city arterials, as well as evaluate the variation of PCE values to different traffic stream parameters. Based on the variation of passenger car unit or equivalency, mathematical relationships were developed and validated using statistical analysis [20].

***Table 1** Summary of past research related to PCU estimation*

Author	Year	Method Used	Nature of Traffic	Type of road	No of Sites	Country of Study	Traffic Parameters considered
Dhananjaya et al. [11]	2023	Chandra's method	Mixed	Urban road	4	Sri Lanka	Speed
Zero et al. [12]	2022	Headway, Density and Homogeneous Coefficient method	Mixed	Urban road	5	Iraq	Speed, Volume
Ali et al. [13]	2021	Chandra's method and Modified Chandra's method	Mixed	National Highway	1	Pakistan	Headway, Speed
Dasani et al. [2]	2020	Chandra's method, Homogenization coefficient method, Multiple regression method and Headway method	Mixed	Urban road	3	India	Speed, composition and headway
Vijay et al. [31]	2019	Chandra's method	Mixed	2 lane Highway	12 sites	India	Speed
Rajesh and Rao [32]	2018	Chandra's method and speed-volume relationship	Mixed	2 lane urban road	3	India	Speed and Volume
Parth et al. [18]	2018	Chandra's method	Mixed	Urban road	2	India	Speed, Volume and Composition
Chand [21]	2016	Chandra's method, Density method, and Headway method	Mixed	Plain and hilly roads	2	India	Speed, headway and Density

***Table 2** Summary of past research related to PCU estimation*

Author	Year	Method Used	Nature of Traffic	Type of road	No of Sites	Country of Study	Traffic Parameters considered
Dhamaniya and Chandra [22]	2016	Chandra's method and speed-volume relationship	Mixed	Urban road	8	India	Speed, Volume and Composition
Shalkamy et al. [33]	2015	Chandra's method	Mixed	2 lane rural road	6	Egypt	Speed
Khanorkar and Ghodmare [27]	2014	Chandra's method and speed-volume relationship	Mixed	2 lane highway	4	India	Speed and Volume
Kumar et al. [34]	2018	Area Occupancy method, TRRL definition	Mixed	Multilane	8	India	V/C ratio
Biswas et al. [35]	2017	Kriging based approach	Mixed	Six lane divided road	1	India	Speed
Jassal et al. [36]	2025	Axle based mapping approach	Mixed	Two lane dual carriageway	1	India	Speed and Flow
Behzadi and Shakibaei [37]	2016	Headway and Density method	Mixed	Urban roads	1	Iran	Density, headway and speed
Sugiarto et al. [38]	2018	Time occupancy method	Mixed	Roundabout	1	Indonesia	Time occupancy
Subotic et al. [39]	2016	Time Headway	Mixed	Two lane roads	3	Serbia	Headway

Chand (2016) determined and compared the Passenger Car Unit (PCU) values on both hilly and plain urban roads. In this paper author considered a 3.2 km long section of a road in Visakhapatnam city, of which 1.9 km is plain and 1.3 km is hilly. PCE values were estimated using different methods. In both plain and hilly terrains, Chandra's method was found to produce more accurate results [21].

Simultaneous Equations and Chandra‘s method were used by Dhamaniya and Chandra (2016) to estimate dynamic Passenger Car Units on city roads. To illustrate the dynamic nature of the passenger car unit factor, data obtained on eight city road roads in India were analyzed. To determine the speed of different vehicles, all vehicles in the stream of traffic were classified into five categories, and simultaneous equations were developed. The PCU/PCE values obtained by using Chandra‘s method and simultaneous equations are very similar. Passenger car unit values for a vehicle were found to increase with the vehicle‘s share in the traffic stream [22].

Mahidadiya and Juremalani (2016) examined the global scenario for PCU estimation. A literature review on PCU or PCE values was discussed in this work. The majority of papers in this field concentrate on evaluating PCU at particular parts of the road as well as at intersections. The PCU or PCE values have been observed to fluctuate in response to traffic patterns. PCU values have not been calculated universally, taking into consideration all effects such as gradient, shoulder condition, road roughness, vehicle percentage, and share of slow-moving vehicles [23].

Nokandeh et al. (2016) used the method proposed by Chandra and simultaneous equations based on linear regression to derive passenger car unit values for highly heterogeneous situations [24].

The status of highway capacity research was described by Chandra (2015) in India on all types of highways. This paper presented a view of capacity-related studies [25].

In India, Mardani et al. (2015) calculated the Passenger Car Unit (PCU) values of vehicle types on undivided interurban roads. The purpose of this study was to investigate the influence of carriageway width on passenger car unit of various vehicle types. Data were obtained from ten stretches of various Indian roads. According to the findings, the PCU or PCE value for a type of vehicle tends to vary with traffic volume and composition, as well as the carriageway width of the street that is used [26].

Khanorkar and Ghodmare (2014) developed passenger car unit values for vehicles operating in mixed traffic on congested highways in cities. Data in this study were gathered using videography at 5 stretches of the two-lane highways in and around Nagpur to measure the effects of lane width and shoulder condition on the capacity of the 2-lane highways. Chandra‘s method was used to calculate PCU or PCE values. The PCU or PCE value of a vehicle was found to alter significantly depending on the traffic volume and roadway width based on a study of traffic volume and roadway conditions. It was discovered that as lane width increases, so does the PCU or PCE value of a vehicle type. The PCU or PCE is linearly changed as a function of the lane width [27].

Khanorkar et al. (2014) estimated the effect of lane width on the capacity on congested highways of Nagpur city with heterogeneous traffic. Data for this research were obtained at six locations to measure the influence of lane width and shoulder condition on the capacity. The PCU or PCE values for various vehicle types were determined separately for each of the selected locations. The newly calculated equivalency values differed significantly from the IRC code values [28].

Minh et al. (2005) used a modified version of Chandra‘s method. They considered a motorcycle as a base vehicle instead of a car due to the high proportion of motorcycles in the stream. The PCU values of a vehicle types were derived as:

$$(PCU)_a = \frac{V_{mc}/V_a}{A_{mc}/A_a}, \tag{2}$$

where: V and A are the speed and area, respectively, and mc and a stand for motorcycle and vehicle type ”a”, respectively, [29].

Omar et al. (2020) review the methods of PCU estimation. In this study, publications devoted to works on PCU estimation were summarised and different methods were discussed in detail [30].

A summary of some past research pertaining to PCU estimation is shown in Tables 1-2.

3 Data collection and methodology

The methodology followed in this study is presented in Figure 1. Five different road sections of Sonipat city with different carriageways and shoulder widths were selected to calculate the PCU values of vehicles present in the stream using Chandra‘s method, Homogeneous Coefficient method, Speed-based modelling, and multiple linear regression method. Description of the selected sites is presented in Table 3. All selected sections are located in the main city Sonipat. The estimated population of Sonipat city is 382000. This city is in the Haryana state of India and is located at just 46 km distance from Delhi (Capital of India).

For the data collection, three hour-long videos were captured from the selected road sections, and desired data (classified volume and speed of vehicle types) were extracted using the VLC media player. Data collection was done for every 15-minute interval. The composition of different types of vehicles observed on these sites is shown in Figure 2. The speed of vehicles was calculated by measuring the time taken by the vehicle to cross a section of predefined length. Speed and volume data for site 1 is presented in Figure 3. Similarly, data from other sites were collected and interpreted. Speed ratios of car with respect to other vehicle types are presented in Table 4. The length and width of vehicle types were also noted. Area ratios of standard vehicle (car) with respect to different types of vehicles, which is required for Chandra's method, and length ratios of standard vehicle (car) with respect to different types of vehicles , which is required for the Homogeneous Coefficient method, are presented in Table 5. Data was collected on sunny days. Stretches selected to collect data were away from any intersections and other obstructions like parking, pedestrian flow etc. The composition of cycles in the stream ranges from 2.49% to 6.77% and their movement was mostly in singles. The share of bike, auto-rickshaw and e-rickshaw is ranged from 43.24% to 70.83%.

Table 3 *Description of Selected Sites*

Site	Carriageway Width (m)	Shoulder Width (m)	Location
1	6.71	Raised footpath	29°00'05"N, 77°00'22"E
2	4.11	2.54	29°00'13"N, 77°01'44"E
3	6.75	Raised footpath	28°59'47"N, 77°00'31"E
4	7.2	5.80	28°59'22"N, 77°02'15"E
5	4.73	1.75	28°58'40"N, 77°01'45"E

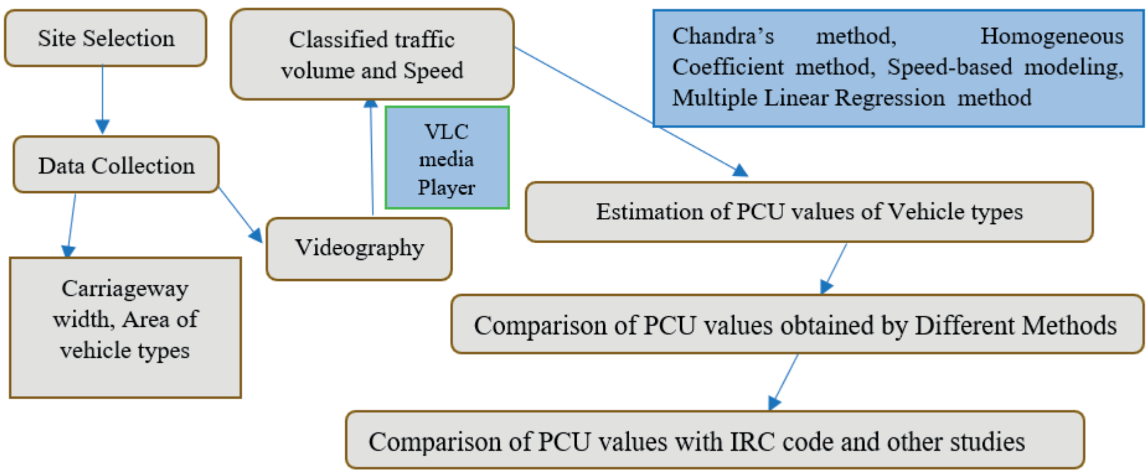


Figure 1 *Followed methodology for this study*

Table 4 *Speed ratios of vehicle types*

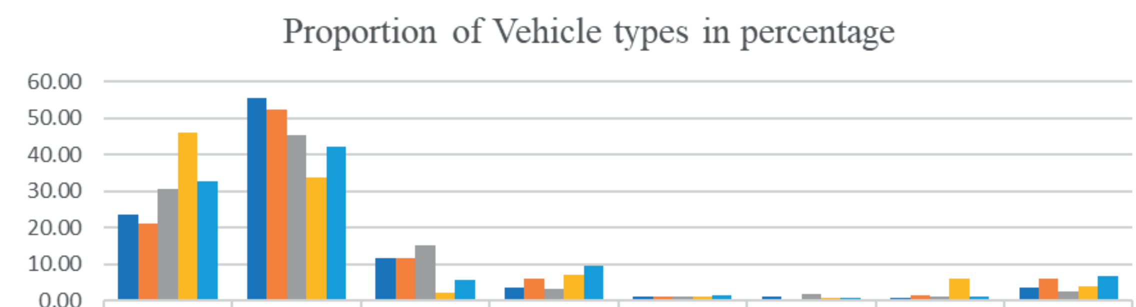
Site	Vc/Vb	Vc/Var	Vc/Ver	Vc/Vl	Vc/Vcy	Vc/Vbs	Vc/Vtr
1	0.974	1.105	1.571	1.164	2.320	1.123	1.917
2	1.016	1.027	1.487	1.155	2.281	1.019	1.374
3	1.050	1.081	1.617	1.136	2.259	1.013	1.522
4	1.054	1.231	1.499	1.116	2.034	1.080	1.265
5	0.977	1.106	1.396	1.050	1.966	1.116	1.344

where, V = Speed
c = car, b = bike,
ar = auto-rickshaw,
er = e-rickshaw, l = LCV,
cy = cycle, bs = bus,
tr = truck

Table 5 *Area and length ratio of vehicle types*

Area Ratios		Length Ratios	
Ac/Ab	4.621	Lc/Lb	1.989
Ac/Aar	1.196	Lc/Lar	1.163
Ac/Aer	1.971	Lc/Ler	1.333
Ac/Al	0.418	Lc/Ll	0.610
Ac/Acy	6.269	Lc/Lcy	1.958
Ac/Abs	0.218	Lc/Lbs	0.368
Ac/Atr	0.307	Lc/Ltr	0.496

Notations:
A, L are area and length of vehicles respectively.
C = car, b = bike, ar = auto-rickshaw, er = e-rickshaw, l = LCV, cy = cycle, bs = bus, and tr = truck.



	Car	Bike	Auto-rick	E-ricksh	LCV	Bus	Truck	Cycle
Site 1	23.57	55.66	11.53	3.64	1.06	1.11	0.64	3.46
Site 2	21.28	52.42	11.73	5.93	1.13	0.37	1.41	6.07
Site 3	30.47	45.16	15.07	3.20	1.17	1.69	1.00	2.49
Site 4	46.10	33.88	2.24	7.12	1.27	0.60	6.11	4.02
Site 5	32.79	42.34	5.85	9.57	1.32	0.79	1.10	6.77

Figure 2 *Proportion of Vehicle types on different sites in percentage*

Intervals	Speed of Vehicle types (in m/s)								Volume of Vehicle types							
	V_c	V_b	V_{ar}	V_{er}	V_l	V_{cy}	V_{bs}	V_{tr}	Nc	Nb	Nar	Ner	Nl	Ncy	Nbs	Ntr
1 interval	9.65	10.17	7.96	6.28	7.68	4.33	9.12	5.71	93	213	44	10	8	8	4	2
2 interval	8.63	10.11	8.63	5.55	8.02	3.91	0.00	5.39	107	224	46	13	3	15	0	2
3 interval	9.77	9.40	7.71	5.67	7.69	3.86	8.20	0.00	92	243	45	10	2	13	2	0
4 internal	9.77	10.25	7.94	6.07	6.73	4.16	8.84	5.39	85	192	46	10	1	16	4	1
5 interval	8.71	9.09	8.02	6.30	6.98	3.87	9.20	6.46	92	233	47	16	4	16	4	3
6 interval	8.79	8.55	8.57	5.68	8.34	4.13	8.38	6.28	83	228	46	17	5	21	2	3
7 interval	9.50	8.77	8.65	6.08	7.21	3.75	8.47	5.54	101	220	48	10	3	17	2	2
8 interval	9.14	9.11	8.85	6.03	9.55	4.09	8.91	7.54	90	205	60	15	4	11	7	2
9 interval	8.59	8.69	7.87	5.41	8.44	4.35	9.67	4.90	94	237	40	21	3	16	2	3
10 interval	8.29	9.13	8.25	5.25	7.94	3.96	9.92	5.35	105	248	53	32	4	17	3	2
11 interval	9.82	8.89	8.25	5.62	7.66	3.82	7.44	0.00	111	268	43	12	4	14	5	0
12 interval	9.15	10.56	8.69	5.96	8.08	4.38	9.67	4.71	111	239	49	16	6	6	2	1
Average	9.15	9.39	8.28	5.83	7.86	4.05	8.15	4.77	97	229	47	15	4	14	3	2

Where, V is the average speed and N is the number of vehicles in each interval. And c = car, b = bike, ar = auto-rickshaw, er = e-rickshaw, l = LCV (light commercial vehicle), cy = cycle, bs = bus, and tr = truck

Figure 3 *Speed and Volume data for Site 1*

4 Estimation of PCU values of vehicle types

Data were analyzed using different methods of PCU calculation. PCU of vehicle types were determined using Chandra‘s method, homogeneous coefficient method, speed-based modelling, and multiple linear Regression method.

4.1 PCU determination using Chandra‘s method

This method was proposed by Chandra [1]. As per this method, Passenger car unit of vehicles under heterogenous traffic conditions can be calculated as:

$$(PCU)_x = \frac{Speed\ ratio\ of\ car\ vehicle\ type\ x}{Are\ ratio\ of\ car\ vehicle\ type\ x}. \quad (3)$$

The speed ratio and area ratio are given in Table 4 and Table 5, respectively. Calculated PCU values using this method are listed in Table 6 with the help of interpreted data.

4.2 PCU determination using Homogeneous coefficient method

This method was proposed by Permanent International Association of Road Congress (PIARC) [2]. This method is very similar to Chandra‘s method. Instead of area ratio, length ratio is used in this method. PCU can be calculated as:

$$(PCU)_x = \frac{Speed\ ratio\ of\ car\ vehicle\ type\ x}{Length\ ratio\ of\ car\ vehicle\ type\ x}. \quad (4)$$

***Table 6** Developed PCU values of vehicle types using Chandra's and Homogeneous coefficient method*

Site	Method	Passenger Car Unit values using Chandra's and homogeneous coefficient method							
		Car	Bike	Auto-rickshaw	E-rickshaw	LCV	Bus	Truck	Cycle
1	CM	1	0.211	0.921	0.797	2.765	4.754	5.175	0.37
	HCM	1	0.49	0.948	1.178	1.895	2.814	3.203	1.185
2	CM	1	0.219	0.854	0.752	2.788	4.695	4.446	0.364
	HCM	1	0.509	0.879	1.111	1.911	2.779	2.752	1.165
3	CM	1	0.227	0.904	0.816	2.437	4.622	3.703	0.36
	HCM	1	0.528	0.93	1.206	1.67	2.736	2.292	1.154
4	CM	1	0.228	1.029	0.76	2.669	4.956	4.122	0.324
	HCM	1	0.53	1.059	1.124	1.829	2.936	2.551	1.039
5	CM	1	0.211	0.924	0.708	2.513	5.119	4.377	0.314
	HCM	1	0.491	0.951	1.048	1.722	3.032	2.709	1.004

Notations: CM = Chandra's method, HCM = Homogeneous Coefficient method.

Length ratios of car to different vehicle types are given in Table 5. The PCU developed using homogeneous coefficient method is listed in Table 6.

4.3 PCU determination using Speed-based modelling

In this approach, the speed of vehicles is modelled in terms of classified volume and speed as:

$$V_x = a_0 + \sum_{x=1}^{n} a_x \frac{N_x}{V_x}. \quad (5)$$

All the selected sites have eight vehicle types in the traffic stream, so the speed of each vehicle class will be modelled as Equations (6) to (13). These equations were solved for each selected site to get the PCU values.

$$\begin{aligned} V_c = {} & a_{0-c} + a_{1-c}(n_c/V_c) + a_{2-c}(n_b/V_b) + \\ & + a_{3-c}(n_{ar}/V_{ar}) + a_{4-c}(n_{er}/V_{er}) + \\ & + a_{5-c}(n_l/V_l) + a_{6-c}(n_{cy}/V_{cy}) + \\ & + a_{7-c}(n_{bs}/V_{bs}) + a_{8-c}(n_{tr}/V_{tr}), \end{aligned} \quad (6)$$

$$\begin{aligned} V_b = {} & a_{0-b} + a_{1-b}(n_c/V_c) + a_{2-b}(n_b/V_b) + \\ & + a_{3-b}(n_{ar}/V_{ar}) + a_{4-b}(n_{er}/V_{er}) + \\ & + a_{5-b}(n_l/V_l) + a_{6-b}(n_{cy}/V_{cy}) + \\ & + a_{7-b}(n_{bs}/V_{bs}) + a_{8-b}(n_{tr}/V_{tr}), \end{aligned} \quad (7)$$

$$\begin{aligned} V_{ar} = {} & a_{0-ar} + a_{1-ar}(n_c/V_c) + a_{2-ar}(n_b/V_b) + \\ & + a_{3-ar}(n_{ar}/V_{ar}) + a_{4-ar}(n_{er}/V_{er}) + \\ & + a_{5-ar}(n_l/V_l) + a_{6-ar}(n_{cy}/V_{cy}) + \\ & + a_{7-ar}(n_{bs}/V_{bs}) + a_{8-ar}(n_{tr}/V_{tr}), \end{aligned} \quad (8)$$

$$\begin{aligned} V_{er} = {} & a_{0-er} + a_{1-er}(n_c/V_c) + a_{2-er}(n_b/V_b) + \\ & + a_{3-er}(n_{ar}/V_{ar}) + a_{4-er}(n_{er}/V_{er}) + \\ & + a_{5-er}(n_l/V_l) + a_{6-er}(n_{cy}/V_{cy}) + \\ & + a_{7-er}(n_{bs}/V_{bs}) + a_{8-er}(n_{tr}/V_{tr}), \end{aligned} \quad (9)$$

$$\begin{aligned} V_l = {} & a_{0-l} + a_{1-c}(n_c/V_c) + a_{2-l}(n_b/V_b) + \\ & + a_{3-l}(n_{ar}/V_{ar}) + a_{4-l}(n_{er}/V_{er}) + \\ & + a_{5-l}(n_l/V_l) + a_{6-l}(n_{cy}/V_{cy}) + \\ & + a_{7-l}(n_{bs}/V_{bs}) + a_{8-l}(n_{tr}/V_{tr}), \end{aligned} \quad (10)$$

$$\begin{aligned} V_{cy} = {} & a_{0-cy} + a_{1-cy}(n_c/V_c) + a_{2-cy}(n_b/V_b) + \\ & + a_{3-cy}(n_{ar}/V_{ar}) + a_{4-cy}(n_{er}/V_{er}) + \\ & + a_{5-cy}(n_l/V_l) + a_{6-cy}(n_{cy}/V_{cy}) + \\ & + a_{7-cy}(n_{bs}/V_{bs}) + a_{8-cy}(n_{tr}/V_{tr}), \end{aligned} \quad (11)$$

$$\begin{aligned} V_{bs} = {} & a_{0-bs} + a_{1-bs}(n_c/V_c) + a_{2-bs}(n_b/V_b) + \\ & + a_{3-bs}(n_{ar}/V_{ar}) + a_{4-bs}(n_{er}/V_{er}) + \\ & + a_{5-bs}(n_l/V_l) + a_{6-bs}(n_{cy}/V_{cy}) + \\ & + a_{7-bs}(n_{bs}/V_{bs}) + a_{8-bs}(n_{tr}/V_{tr}), \end{aligned} \quad (12)$$

$$\begin{aligned} V_{tr} = {} & a_{0-tr} + a_{1-tr}(n_c/V_c) + a_{2-tr}(n_b/V_b) + \\ & + a_{3-tr}(n_{ar}/V_{ar}) + a_{4-tr}(n_{er}/V_{er}) + \\ & + a_{5-tr}(n_l/V_l) + a_{6-tr}(n_{cy}/V_{cy}) + \\ & + a_{7-tr}(n_{bs}/V_{bs}) + a_{8-tr}(n_{tr}/V_{tr}), \end{aligned} \quad (13)$$

where: V = speed, n = number of vehicle (volume), a_0 = intercept, a_1, a_2, ……….. , a_8 are the coefficients for car (c), bike (b), auto-rickshaw (ar), e-rickshaw (er), LCV (l), cycle (cy), bus (bs), and truck (tr), respectively.

With the help of SPSS software and Microsoft Excel, these equations were solved. After the solving, the modelled speed of different vehicles for Site 1 and the ratio of speed of car to speed of different vehicles are presented in Table 7. Then, the modelled speed is directly used for PCU determination using Chandra's method and Homogeneous coefficient method. A similar process was employed for other sites. The PCU values of vehicle types using this approach are listed in Table 8.

***Table 7** Modelled speed of vehicles and speed ratio*

Modelled Speed (m/s)		Speed ratio (car to different vehicle type)	
Vc	9.156		
Vb	9.385	Vc/Vb	0.979
Var	8.285	Vc/Var	1.107
Ver	5.822	Vc/Ver	1.573
Vl	7.863	Vc/Vl	1.17
Vcy	4.049	Vc/Vcy	2.261
Vbs	8.156	Vc/Vbs	1.123
Vtr	4.778	Vc/Vtr	1.632

***Table 8** Developed PCU values of vehicle types using Speed-based modelling*

Site	Method		Passenger Car Unit values using Speed-based modelling							
			Car	Bike	Auto-rickshaw	E-rickshaw	LCV	Bus	Truck	Cycle
1	SBM	CM	1	0.212	0.925	0.799	2.799	5.039	5.316	0.362
		HCM	1	0.492	0.952	1.181	1.918	2.844	3.29	1.158
2	SBM	CM	1	0.221	0.859	0.755	2.855	4.742	4.612	0.371
		HCM	1	0.512	0.883	1.116	1.957	2.807	2.721	1.187
3	SBM	CM	1	0.228	0.906	0.824	2.654	4.656	4.008	0.383
		HCM	1	0.529	0.932	1.221	1.819	2.756	2.481	1.226
4	SBM	CM	1	0.228	1.037	0.761	2.676	5.016	4.106	0.342
		HCM	1	0.529	1.067	1.127	1.834	2.969	2.541	1.096
5	SBM	CM	1	0.312	0.925	0.71	2.545	5.081	4.396	0.307
		HCM	1	0.725	0.952	1.052	1.819	2.756	2.481	0.983

Notations: CM = Chandra's method, HCM = Homogeneous Coefficient method, SBM = Speed based modelling

***Table 9** Obtained Regression Coefficients for Site 1*

Regression Coefficients	Obtained value
a_0	12.179
a_c	-0.003
a_b	-0.006
a_{ar}	-0.022
a_{er}	-0.036
a_{bs}	0.077
a_{tr}	-0.363
a_{cy}	0.022
a_l	0.064

***Table 10** Developed PCU values of vehicle types using Multiple Linear Regression method*

Site	Method	Passenger Car Unit values using Multiple Linear Regression Method							
		Car	Bike	Auto-rickshaw	E-rickshaw	LCV	Bus	Truck	Cycle
1	MLR	1	1.596	6.404	10.561	18.659	22.305	105.275	6.368
2	MLR	1	0.13	0.338	0.362	0.733	3.165	5.352	1.127
3	MLR	1	0.006	1.1	1.901	12.345	6.822	4.899	5.598
4	MLR	1	2.465	2.584	7.699	0.193	16.098	0.256	2.611
5	MLR	1	1.953	0.458	4.826	0.463	14.607	46.786	1.219

Notations: MLR = Multiple Linear Regression Method

4.4 PCU determination using Multiple linear regression method

This method can be used for mixed types of traffic conditions having any number of vehicle types. In this method, the average speed of car is presented in terms of classified traffic volume as Equation (14). Extended form as per the number of vehicle types in the traffic stream can be expanded as Equation (15).

$$V_c = a_0 + \sum_{x=1}^{n} a_x N_x , \quad (14)$$

$$V_c = a_0 + a_1 N_c + a_2 N_b + a_3 N_{ar} + a_4 N_{er} + + a_5 N_l + a_6 N_{cy} + a_6 N_{cy} + a_7 N_{bs} + a_8 N_{tr}, \quad (15)$$

where: V = speed, N = classified volume, and a_0, a_1, ... , a_8 are the regression coefficients. PCU of a vehicle type x can be calculated as:

$$(PCU)_x = \frac{a_x}{a_1} , \quad (16)$$

where: a_1 is the regression coefficient for car and a_x is for vehicle type x.

Equation (15) was regressed using SPSS software to calculate regression coefficients. The coefficients obtained for Site 1 are listed in Table 9. Then, the PCU values were determined using Equation (16), and are presented in Table 10.

5 Comparison of PCU values obtained from different methods

In this study, the PCU values of vehicle types were estimated using the Chandra's method, Homogeneous Coefficient method, Speed-based modelling, and multiple linear regression method. A comparison of PCU values obtained from Chandra's method, homogeneous coefficient method, and speed-based modelling is shown in Figures 4-10. Comparison of PCU values of bike, auto-rickshaw, e-rickshaw, LCV, bus, truck and cycle using different methods are shown in Figures 4, 5, 6, 7, 8, 9 and 10, respectively. From the Figures, it is clear that the PCU values of light vehicles (bike, auto-rickshaw, e-rickshaw, and cycle), estimated using Homogeneous coefficient method, are relatively higher, and PCU values of Heavy vehicles (LCV, bus, and truck) are lower than the PCU values obtained using the Chandra's method. The PCU values estimated using speed-based modelling are similar to values obtained without modelling the speed of vehicles with minor variations. The PCU values developed using multiple linear regression methods are not relevant. Out of all these methods, values obtained from Chandra's method are the most suitable.

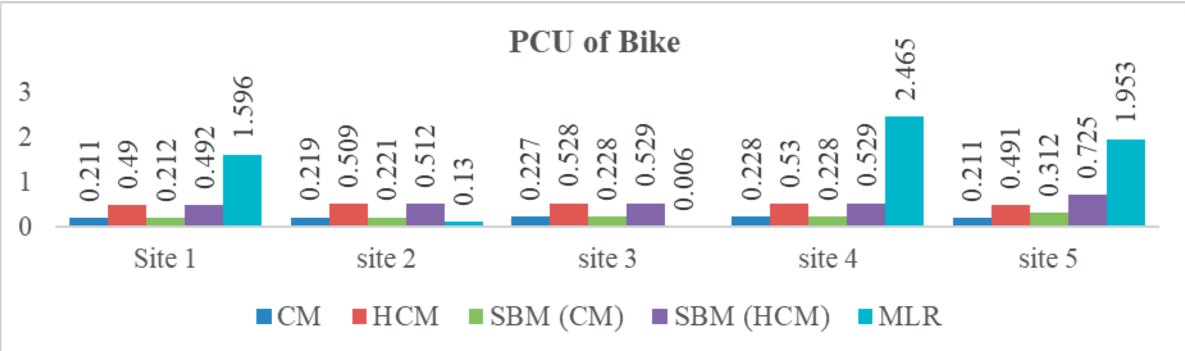


Figure 4 *Comparison of PCU values of Bikes*

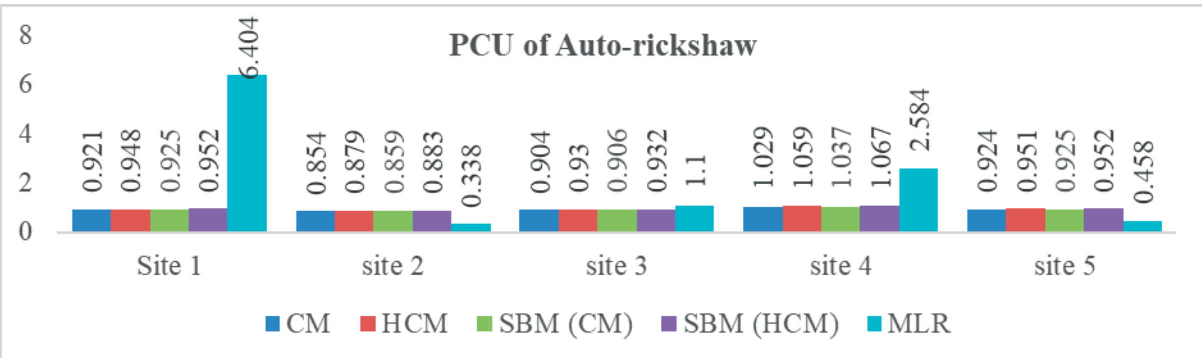


Figure 5 *Comparison of PCU values of Auto-rickshaws*

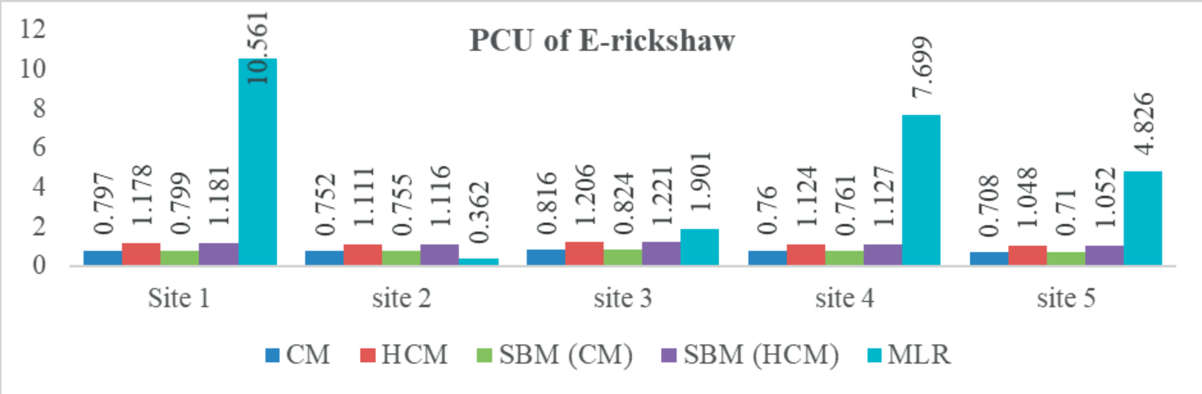


Figure 6 *Comparison of PCU values of E-rickshaws*

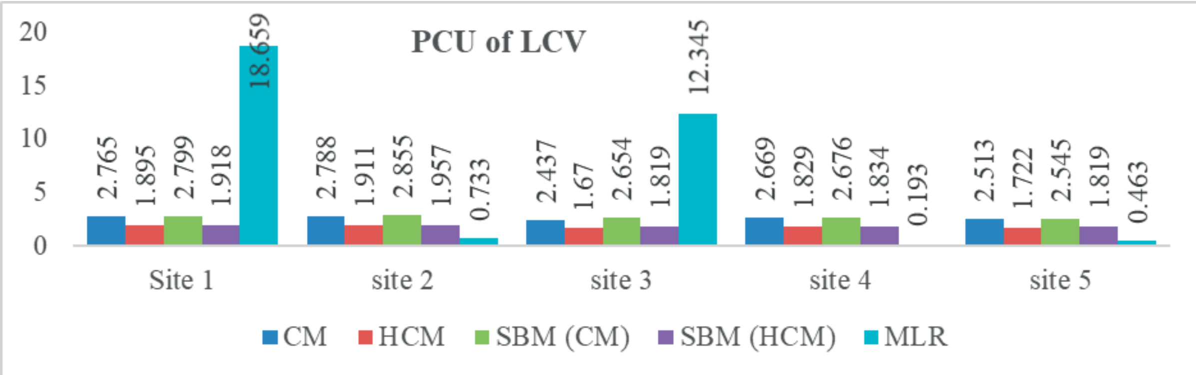


Figure 7 *Comparison of PCU values of LCVs*

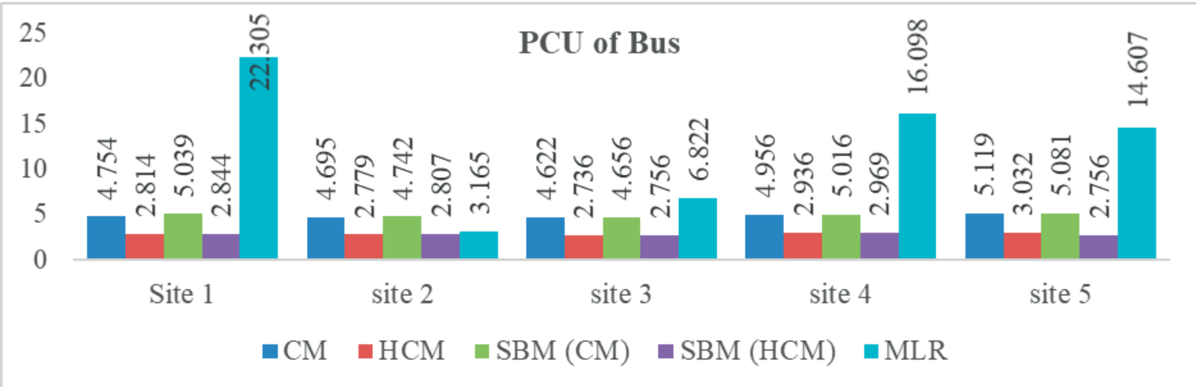


Figure 8 *Comparison of PCU values of Buses*

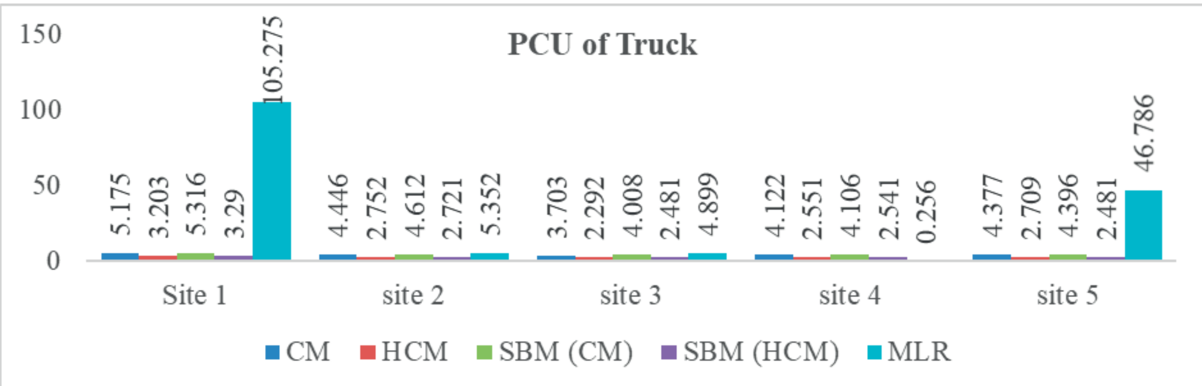


Figure 9 *Comparison of PCU values of Trucks*

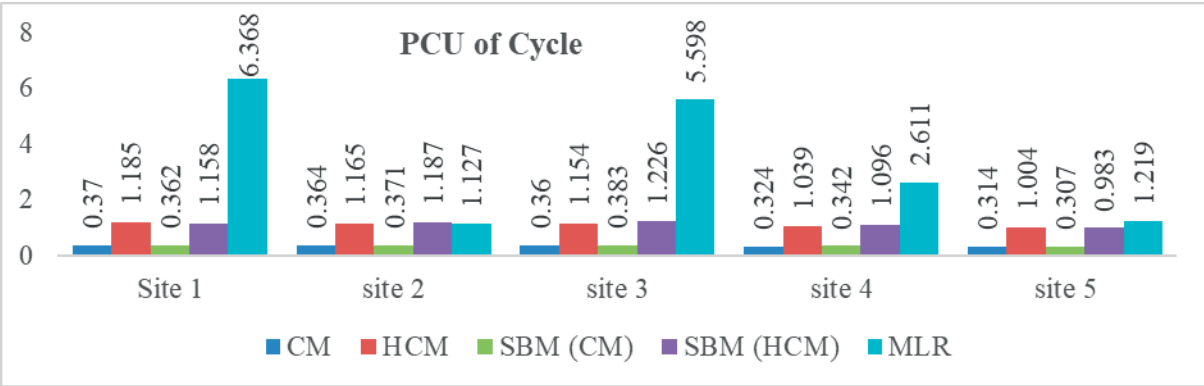


Figure 10 *Comparison of PCU values of bicycles*

Table 11 *Comparison of obtained PCU values to IRC:106-1990 and other study*

Vehicle Types	Passenger Car Unit using Chandra's Method					IRC 106:1990	Rao and Yadav 2018
	Site1	Site2	Site3	Site4	Site5		
Car	1	1	1	1	1	1	
Bike	0.211	0.219	0.227	0.228	0.211	0.5 - 0.7	0.231-0.250
Auto-rickshaw	0.921	0.854	0.904	1.029	0.924	1.2 - 2	0.963-1.04
E-rickshaw	0.797	0.752	0.816	0.76	0.708	-	-
LCV	2.765	2.788	2.437	2.669	2.513	1.4 - 2	2.74-3.02
Bus	4.754	4.695	4.622	4.956	5.119	2.2 - 3.7	5.33-5.76
Truck	5.175	4.446	3.703	4.122	4.377	2.2 - 3.7	4.19-4.52
Cycle	0.37	0.364	0.36	0.324	0.314	0.4 - 0.5	-

6 Comparison of PCU values to IRC 106:1990

A comparison between obtained PCU values using Chandra's method and values given in IRC 106:1990 is shown in Table 11. It is clear that the PCU values of bikes, auto-rickshaws, and cycles are smaller than the values given in the IRC code, while the values of LCVs, buses, and trucks are relatively higher. Rao and Yadav (2018) also obtained similar result [6].

7 Results, discussion and conclusion

The PCU of vehicle types is required to calculate capacity, signal designing, flow measurements, etc. Thus, the PCU is an important parameter and it can be calculated using many methods. In this study, PCU of every vehicle class was calculated using the Chandra's method, homogeneous coefficient method, speed-based modelling, and multiple linear regression. To calculate the PCU values, classified speed and volume data from 5 sites of Sonipat city having different traffic and geometric parameters were collected with the help of the videography method. After calculating the PCU of vehicle types, a comparison was made between values obtained from different methods (Figure 4-10), and it was found that values obtained from the Chandra's method are most suitable, while values obtained from the multiple linear regression are irrelevant. Later, the PCU values obtained from the Chandra's method and values given in IRC: 106-1990 were compared, and it was found that the PCU values obtained from the Chandra's method of slower vehicles (bike, auto-rickshaw, and cycle) are relatively lower and the PCU values of heavy vehicles (LCV, bus, and truck) are relatively higher. It can be concluded that the PCU values mentioned in IRC codes are old and outdated. A revision of the IRC code pertaining to the PCU values is required to meet technological advancements in vehicles and roads.

The PCU value of e-rickshaw obtained from this study can be used directly by urban planners to design different traffic facilities where the similar type of traffic condition prevails and more studies with different roadway and traffic conditions are required to precisely determine equivalency value of e-rickshaw.

One distinctive feature of this work is the Chandra technique, which provides a novel way to calculate Passenger Car Unit (PCU) values in mixed traffic situations. This approach can give a more realistic depiction of traffic flow and vehicle interactions, particularly in areas like India where there is a wide variety of vehicle types. It can take into consideration various vehicle classifications, such as auto-rickshaws and e-rickshaws.

The share of bike, auto-rickshaw and e-rickshaw is ranged from 43.24% to 70.83% on the analysed locations. Bikes, rickshaws, and e-rickshaws are predominant vehicle types ply on the city roads (urban roads) of India. The shares of these vehicles are generally smaller on the rural roads. The PCU values of vehicles are different for rural and urban roads. Different sets of PCU values for rural and urban roads are available in IRC codes (Indian Roads Congress code).

There are large differences in PCU values of trucks between different measurement locations (from 3.7 to 5.180) because out of five roads, two roads were connected to highways and rest were within the city only. So, the difference in PCU values may be due to change in given conditions in the analyzed locations.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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