Review of Methods for Estimation of Passenger Car Unit Values of Vehicles

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Review of Methods for Estimation of Passenger Car Unit Values of Vehicles

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Abstract: Estimation of passenger car unit (PCU) values is very important for traffic capacity analysis and other relevant applications such as level of service (LOS) measures, determination of saturation flow rate, signal design and coordination, and development of traffic flow models. Because of such wide applications, the accuracy of PCU values is highly significant in traffic flow analysis. Many research works have been carried out on estimation of PCUs in the past few decades. In developed countries, various methods were developed for estimating PCU values for different types of facilities which carry trucks and buses of lesser composition. But these methods are not completely analogous for mixed traffic due to the presence of wide variety of vehicle types, nonlane discipline, intraclass variability of vehicles and their maneuverability. With this consideration, various methods used for estimating PCUs for different facility types under homogeneous and mixed traffic conditions are reviewed and the drawbacks of the existing methods are identified in this paper. The challenges in estimating PCU values and future directions for improving the PCU estimation methods are also presented. **DOI: 10.1061/JTEPBS.0000234.** © *2019 American Society of Civil Engineers.*

Author keywords: Passenger car unit; Passenger car equivalent; Passenger car unit (PCU) estimation methods; Facility type; Homogeneous traffic; Mixed traffic.

Introduction

The traffic flow characteristics and roadway system in developing and developed countries are basically different. The traffic in most of the developed countries, commonly referred as homogeneous traffic, follows lane discipline and is composed of large proportion of vehicles with not same similar dimensions—predominantly cars and a small proportion of trucks and other vehicles. In contrast, mixed traffic comprises of a wide variety of vehicles with different static and dynamic characteristics occupying the same road space without any confinements for maneuvering.

These differences between homogeneous and mixed traffic show the complications in implementing traffic operations and designing roads. To overcome this, a uniform measure of vehicles called passenger car unit (PCU), also referred as passenger car equivalent (PCE) is used for converting traffic stream composed of two or more vehicle types into an equivalent traffic stream composed of exclusively passenger cars. The PCU values can be used for capacity analysis, signal design, traffic management, determination of saturation flow rate and developing traffic flow models.

The *Highway Capacity Manual* (Highway Research Board 1965) first defined PCU as "the number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions." Later, it is redefined by Transportation Research Board: National Research Council (2010) as "the number of passenger cars which will result in the same operational condition as a single heavy vehicle of a particular type under specified roadway, traffic and control conditions." However, the TRRL (1965) in London defined PCU as "on any particular section of road under particular traffic condition, if 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 of average size per hour, then one vehicle of this type is equivalent to x PCU." For mixed traffic, the *Indonesian Highway Capacity Manual* (I-HCM) (Directorate General of Highways 1997) defined PCU as "conversion factor for different vehicle types with regard to their impact on capacity as compared to a passenger car (i.e., for passenger cars and other light vehicle PCU = 1.0)." Indian Roads Congress (IRC 1990) suggests static PCUs for different vehicle types in India based on traffic composition.

Because of the distinct nature of homogeneous and mixed traffic behaviors, different methods have been used for estimating PCU values for different facility types such as midblock section, signalized intersection, and uncontrolled intersection. Continuous research works have been carried out to overcome the complexities involved in accurate estimation of PCU. The review article by Metkari et al. (2012); Shalini and Kumar (2014); Kiran and Verma (2016); Rana and Bajaj (2016) have failed to examine all the existing methods of PCU estimation under homogeneous and mixed traffic and, failed to investigate them based on road facility types. The parameters influencing the PCU values are not same for all the road facilities and nature of traffic (homogeneous and mixed traffic). Hence, it becomes necessary to review PCU methods for each

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of the facility type under homogeneous and mixed traffic conditions and derive the best approach for each facility. Also, the drawbacks of most of the methods are not discussed in those review papers except Metkari et al. (2012) and Shalini and Kumar (2014). However, they have mentioned only the drawbacks of headway method.

Hence, this paper is intended to focus on different methods used for PCU estimation based on facility type (e.g., midblock section, intersection) under homogeneous and mixed traffic conditions. Moreover, this paper discusses the drawbacks of the existing methods used for PCU estimation and discusses the challenges and directions for future research in estimating PCUs.

Parameters Influencing Passenger Car Unit Values

Parameters used in estimation of PCU for various road facility types are different under homogeneous and mixed traffic. For homogeneous traffic, researchers have used several parameters such as speed (e.g., Aerde and Yagar 1984), headway (e.g., Greenshields et al. 1947), density (e.g., Huber 1982), delay (e.g., Craus et al. 1980), travel time (e.g., Keller and Saklas 1984), and queue discharge flow (QDF) (e.g., Al-Kaisy et al. 2002). Besides these parameters, for mixed traffic, Chandra et al. (1995) developed an equation considering speed-area ratio to estimate PCUs for different vehicle types. Other parameters such as density (e.g., Tiwari et al. 2000), queue discharge (e.g., Mohan and Chandra 2017), headway (e.g., Saha et al. 2009), area occupancy (e.g., Kumar et al. 2017), time occupancy (e.g., Mohan and Chandra 2018), influence area (e.g., Paul and Sarkar 2013), effective area (e.g., Pooja et al. 2018), and travel time (e.g., Mahidadiya and Juremalani 2016) are also used under mixed traffic conditions. Researchers have also estimated PCUs using several other parameters like vehicle hours (e.g., Sumner et al. 1984), platoon formation (e.g., Aerde and Yagar 1984), volume-to-capacity (V/C) ratio (e.g., Fan 1990), and directional split (e.g., Aggarwal 2011). It is inferred that each of the parameter is applicable only for respective facility type and may not be applicable for other facility types. This is the primary motivation of reviewing the research works based on the facility types.

Methods for Estimation of PCU on Midblock Sections

Several methods were used for estimating PCU values on midblock sections in both homogeneous and mixed traffic conditions. Midblock sections can be classified into urban midblocks (divided and undivided arterials, subarterials, etc.) and nonurban midblocks (divided and undivided highways, freeways, expressways, etc.). The various methods used for the estimation of PCUs for these facility types under homogeneous and mixed traffic conditions are discussed in this section.

Studies on Urban Midblock Sections

Speed Modeling

In mixed traffic conditions, Chandra et al. (1995) presented the new concept using speed as a primary variable to determine the PCU of vehicles on urban midblock. They mentioned that speed of any vehicle type is a true representation of overall interaction of that vehicle type with other vehicle types. According to their concept, PCU is directly proportional to speed ratio and inversely proportional to projected area ratio with respect to the standard vehicle as follows:

Table 1. Vehicle categories and their projected areas

Category	Vehicles included	Average dimension: Length (m)	Average dimension: Width (m)	Projected rectangular area on ground (m^2)
Car	Car, jeep	3.72	1.44	5.39
Bus	Bus	10.10	2.43	24.74
Truck	Truck	7.50	2.35	17.62
Light commercial vehicle	Minibus, vans	6.10	2.10	12.81
Tractor	Tractor, trailer	7.40	2.20	16.28
Three-wheeler	Three-wheeler	3.20	1.40	4.48
Two-wheeler	Scooter/motorbike	1.87	0.64	1.20
Cycle	Bicycles	1.90	0.45	0.85
Rickshaw	Pedal rickshaw/cart	2.70	0.95	2.56

Source: Reprinted from Chandra and Kumar (2003), © ASCE.

$$\mathrm{PCU} = (V_c/V_i)/(A_c/A_i) \tag{1}$$

where V_c and V_i = mean speeds of car and vehicle type i, respectively; and A_c and A_i = their respective projected rectangular areas on the road. Chandra and Sikdar (2000) and Chandra and Kumar (2003) considered the same concept to determine dynamic PCUs for different vehicle types on two-lane roads in India. Table 1 shows projected area of vehicles used in Chandra's method. Rahman and Nakamura (2005) introduced a method for estimating PCU for nonmotorized vehicle (Rickshaws) at urban midblock sections in Dhaka metropolis of Bangladesh based on speed reduction of passenger cars in the mixed flow due to the presence of nonmotorized vehicles. In this study, PCU values for rickshaws were estimated as follows:

$$\mathrm{PCU} = 1 + (S_b - S_m)/S_b \tag{2}$$

where S_b and S_m = average speed of passenger car in base flow and mixed flow (km/h), respectively. The same method was adopted by Adnan (2014) for heterogeneous traffic environment prevailing in urban arterials of Karachi City, Pakistan. Patil and Adavi (2015) estimated PCUs for urban midblocks in Pune, India using mean speed ratio of passenger cars to any vehicle class using the following equation:

$$F_u = U_c/U_v \tag{3}$$

where F_u = PCU factor for speed of vehicle class v; U_c = mean speed of car c; and U_v = mean speed of the vehicle class v.

Mardani et al. (2015) studied the effect of carriageway width on PCU of vehicle categories on urban roads in India by estimating PCU values using Chandra's method. Mondal et al. (2017) adopted the same method to estimate the dynamic PCUs for four and six lane divided urban arterials in Kolkata, India. Using the same method, Gunasekaran et al. (2015) analyzed capacity with traffic flow rate estimated for fixed time intervals (1, 5, 10, and 15 min) and platoon flow period, and Dhamaniya and Chandra (2016) developed simultaneous equations to determine the speed of a vehicle type for estimating PCU of multilane divided urban roads in India. A few studies were done on estimation of motorcycle unit (MCU) in those countries where motorcycles are found to be dominant. MCU is defined as the number of motorcycles that can be displaced for one vehicle of specified type running at the same speed. In mixed traffic conditions, Minh et al. (2005) used

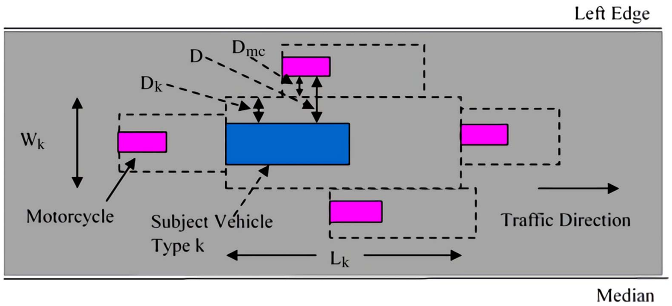

Fig. 1. Effective space of subject vehicle and surrounding motorcycles. (Adapted from Cao and Sano 2012, © ASCE.)

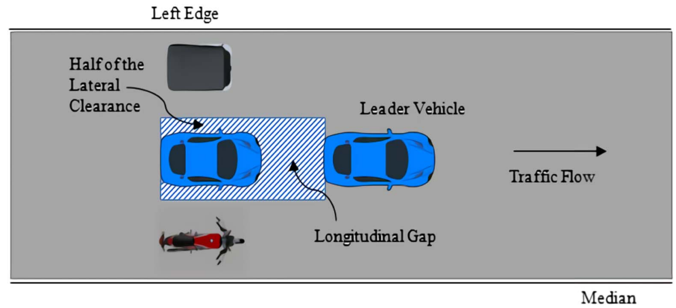

Fig. 2. Conceptual model for determining dynamic PCU values. (Adapted from Paul and Sarkar 2013.)

the Chandra's formula considering motorcycles instead of passenger cars to estimate MCUs of vehicles in Vietnam, as follows:

$$\mathrm{MCU}_i = (V_{mc}/V_i)/(A_{mc}/A_i) \tag{4}$$

where V_{mc} and V_i = mean speed of motorcycles and vehicle type i, respectively; and A_{mc} and A_i = the respective projected area of motorcycles and vehicle type i. Cao et al. (2010) and Cao and Sano (2012) also adopted the same formula given in Eq. (4), but effective space of vehicles was considered instead of projected area

$$\mathrm{MCU}_k = (V_{mc}/V_k)/(S_{mc}/S_k) \tag{5}$$

where V_{mc} and V_k = mean speed of motorcycles and vehicle type k, respectively; and S_{mc} and S_k = mean effective space for motorcycles and vehicle type k, respectively. The effective space of each vehicle type is computed considering the influences of speed, physical size of the subject vehicle, and the surrounding motorcycles. Fig. 1 shows the effective space of subject vehicle and surrounding motorcycles. In this figure, L_k is the effective longitudinal distance of running vehicle inclusive of vehicle length (m); W_k is the effective lateral distance of running vehicle inclusive of vehicle width (m); D_k is the effective space's lateral width of vehicle type (m); and D_{mc} is the effective space's lateral width of motorcycles (m). Similar attempt was made by Asaithambi and Mahesh (2016) to estimate MCU values for different vehicle categories in Indian traffic conditions.

Headway Method

Patil and Adavi (2015) estimated PCUs for urban midblock in Pune, India, using the following equation:

$$F_t = t_c/t_v \tag{6}$$

where F_t = PCU factor for time headway of vehicle class v; and t_c and t_v = mean lower time headway of cars and vehicle class v, respectively. The same method was adopted by Adnan (2014) for arterials of Karachi City, Pakistan. Swetha (2016) analyzed the characteristics of heterogeneous traffic flow to identify appropriate theoretical distributions for various traffic variables influencing the traffic stream characteristics, and study vehicular interactions at microlevel and wide fluctuations in speeds. They studied the effect of road width and traffic volume on PCU values of vehicles by estimating PCU values using time headway method. Suweda (2016) developed time headway distribution model and subsequently estimated the capacity of undivided urban roads in the city of Denpasar, Bali Province. In the study, time headways were used to estimate the PCUs for undivided urban roads.

Space Occupancy Method

Kumar et al. (2017) focused on PCU estimation using area occupancy as measure of base for different vehicle classes on multilane urban roads under mixed traffic conditions. Using TRRL's definition of PCU, they replaced stream speed with area occupancy at different V/C ratio. Paul and Sarkar (2013) have done a case study on urban arterial roads of Delhi City, India, where PCU was estimated considering speed and influence area as parameters. They modified Chandra's speed–projected area ratio method as shown in the following equation for estimating PCUs,

$$\mathrm{PCU} = (A_i \times V_c)/(V_i \times A_c) \tag{7}$$

where V_c and V_i = speeds of car and vehicle type i, respectively; and A_c and A_i = their influence areas. Fig. 2 presents the conceptual model developed for determining PCU values. Pooja et al. (2018) determined PCU for each type of vehicle considering speed and effective area of subject and neighboring vehicles. The basic formula developed by Chandra and Kumar (2003) is modified in which projected area is better reflected by effective area considering the influence of neighboring vehicles under mixed traffic conditions due to weak lane discipline. The adopted formula for determining PCU is given by

$$\mathrm{PCU}_k = (V_{\mathrm{car}}/V_k)/(A_{\mathrm{car}}/A_k) \tag{8}$$

where PCU_k = PCU of vehicle type k; V_{car} and V_k = mean speeds of passenger car (small car) and vehicle type k, respectively (m/s); and A_{car} and A_k = effective area of passenger car and vehicle type k, respectively (m^2).

Multiple Linear Regression Method

Regression analysis method is used in many studies to derive PCUs. Minh and Sano (2003) obtained the following equation for estimating PCE:

$$S = \mathrm{FFS} + a_1\mathrm{PC} + a_2\mathrm{BUS} + a_3\mathrm{MC} + a_4\mathrm{HV} \tag{9}$$

where S = average traffic stream speed; FFS = free flow speed; PC = number of passenger cars in traffic stream; BUS = number of buses in traffic stream; MC = number of motorcycles in the traffic stream; HV = number of heavy vehicles in the traffic stream; and a_1, a_2, a_3, a_4 = marginal effect of respective mode on average traffic stream speed. Based on the estimation of the above coefficients from Eq. (9), Adnan (2014) derived PCE factors for different types of vehicles on urban arterials by taking the ratio of coefficients obtained for each vehicle type (a_{ir}) with the coefficient obtained for reference vehicle, i.e., passenger car (a_1) using the following equation:

$$\text{PCE} = a_{ir}/a_1 \tag{10}$$

An attempt was made by Basu et al. (2006) to model stream speed as a function of dynamic control variables like traffic volume and its composition for estimating PCU values. The speed model was used to study the variation of PCE with base volume and composition. The effect of traffic volume and its composition on PCU of different vehicle types in a mixed traffic stream was investigated taking an urban divided midblock section as the case study. Patel et al. (2016) determined dynamic PCU values by expressing the speed-flow relationship in the form of multiple regression equation taking the speed of cars as the dependent variable and volume of different vehicle categories as the independent variables. The ratio of the regression coefficients of different vehicle categories to the regression coefficient of the car gives an estimate of PCU factors. The speed of car was regressed against the volumes of different vehicle types as follows:

$$V_1 = A_0 + A_1 Q_1 + A_2 Q_2 + A_3 Q_3 + \cdots + A_n Q_n \tag{11}$$

where V_1 = speed of cars; Q_1 = flow of cars; $Q_2, Q_3, \ldots, Q_n$ = flow of vehicle type $2, 3, \ldots, n$; $A_1, A_2, \ldots, A_n$ = regression coefficients; and A_0 = constant. Dynamic PCU of vehicle type n is given by

$$\text{DPCU} = A_n/A_1 \tag{12}$$

Other Methods

Praveen and Arasan (2013) used the microsimulation model HETEROSIM to derive PCU factors on a purely cars-only traffic stream as well as heterogeneous traffic stream for different vehicle categories over a wide range of traffic flow and compositions on four-lane divided urban roads in India. Mishra et al. (2017) developed a simulation model to study the PCU values on a multilane urban road in Delhi, India. Dhamaniya and Chandra (2013) proposed a new procedure for converting a mixed traffic stream into a homogenous traffic stream by employing a stream equivalency factor (K) rather than PCU values of vehicle types. Use of the K factor will provide quick estimation of volume in PCU per hour and thus V/C ratio on the road, which is considered a surrogate measure for congestion and level of service (LOS).

Studies on Nonurban Midblock Sections

Speed Modeling

Aerde and Yagar (1984) estimated PCU based on the relative rates of speed reduction for each vehicle type traveling in the ongoing direction and for all vehicles combined traveling in the opposing direction in two-lane two-way rural highways under homogeneous conditions. PCU for a vehicle type n (E_n) was determined using the following equation:

$$E_n = C_n/C_1 \tag{13}$$

where C_n = coefficient of speed reduction for vehicle type n; and C_1 = coefficient of speed reduction for passenger car.

Using Chandra's method, Mardani et al. (2015) studied the effect of carriageway width on PCU values of vehicles on Indian highways and found that PCU value for a vehicle type varies with traffic volume and composition on the road and the carriageway width of the road being used. Shalkamy et al. (2015) studied the influence of different geometric features of tangent and curved elements on PCUs of two-lane two-way rural roads in Egypt. Other researchers like Arun et al. (2016) studied the effect of the various roadway and operational factors on capacity of Indian highways, and Khanorkar et al. (2014) studied the traffic flow on Indian highways by evaluating PCU of different vehicle categories at different sections of two-lane highways around Nagpur City using Chandra's method.

Headway Method

Krammes and Crowley (1986) derived PCU equation in terms of variables that reflect the relative importance of three factors that contribute to the overall effect of trucks on the roadway type. They observed that spatial headway method was most appropriate for level freeway segments. Ahmed (2010) identified and quantified the characteristics of heavy vehicles that have an impact on freeway at different levels of congestion under homogeneous traffic conditions, with an emphasis on operations at LOS using headway ratio method as follows:

$$\text{PCE} = \text{HV}_{\text{headway}}/\text{PC}_{\text{headway}} \tag{14}$$

where $\text{HV}_{\text{headway}}$ = headway of heavy vehicle; and $\text{PC}_{\text{headway}}$ = headway of passenger car. Xue et al. (2014) proposed a model for estimating capacity of expressway based on dynamics and gap acceptance theory, considering lane-changing processes and time headway loss. Al-Obaedi (2016) used lagging headway method for estimating PCEs and capacity of freeways. To estimate lagging headway, the available time headway (h) was first converted to following headway considering the length of leader vehicle (L_L) and speed of following vehicle (S_F). The following headway was then added to ratio of length (L_F) and speed (S_F) of following vehicle for estimating the lagging headway

$$\text{Following headway} = h - (L_L/S_F) \tag{15}$$

$$\text{Lagging headway} = \text{Following headway} + (L_F/S_F) \tag{16}$$

Based on Flow Rates and Density

Huber (1982) suggested a model based on flow rate and calculated PCU values of trucks for multilane roads under free flow conditions as given

$$\text{PCU} = (q_B/q_M - 1)/(P_T) + 1 \tag{17}$$

where q_B = equivalent passenger-car-only flow rate for a given V/C ratio; q_M = mixed flow rate; and P_T = truck proportion in mixed traffic flow. Demarchi and Setti (2003) studied the impact of heavy vehicles on traffic streams, particularly on grades by deriving the PCEs for each truck type on multilane divided highways of the US. Al-zerjawi (2016) used the ratio of density of passenger cars (K_{car}) to density of trucks (K_{truck}) on multilane highways under homogeneous traffic conditions to determine the PCUs for trucks

$$\text{PCU} = K_{\text{car}}/K_{\text{truck}} \tag{18}$$

Tiwari et al. (2000) estimated PCU values for divided highways using modified density method. The modified density method recognizes the loose lane discipline characteristic of nonhomogeneous traffic

$$(\text{PCU}_{X_i})_j = \left[\frac{k_{\text{car}}/W_{85\text{car}}}{(q_{X_i}/u_{X_i})/W_{85X_i}}\right]_j \tag{19}$$

where for highway type j, PCU_{Xi} = PCU for traffic entity group X_i; k_{car} = density of passenger car (cars/km); $W_{85\text{car}}$ = 85th percentile distribution width (m) for passenger car; q_{Xi} = flow of traffic entity group X_i in heterogeneous traffic (entities/hour); u_{Xi} = space mean speed of traffic entity group X_i (km/h); and W_{85Xi} = 85th

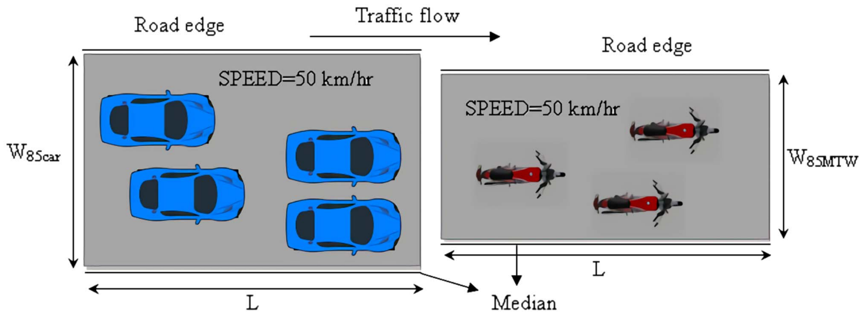

Fig. 3. 85th percentile width of passenger car and motorized two-wheelers used for PCU estimation in heterogeneous traffic. (Adapted from Tiwari et al. 2000.)

percentile distribution width (m) for traffic entity group X_i. Fig. 3 gives a clear picture on how they have considered 85th percentile distribution width.

Based on Delay

Craus et al. (1980) considered the difference between delay caused by heavy vehicle to standard passenger cars and delay caused by slower passenger car to standard passenger cars. They applied equivalent delay method considering the ratio of average delay time caused by one truck divided by average delay time caused by one passenger car. Cunagin and Messer (1983) estimated PCU values for 14 vehicle types under specified typical conditions for two-lane and four-lane rural highways using the delay experienced by a passenger car due to nonpassenger vehicles and the delay experienced by a passenger car due to other passenger cars

$$\mathrm{PCE}_{ij} = (D_{ij} - D_{\mathrm{base}})/D_{\mathrm{base}} \tag{20}$$

where PCE_{ij} = PCE of vehicle type i under flow condition j; D_{ij} = delay to standard passenger cars due to vehicle type i under flow condition j; and D_{base} = delay to standard passenger cars due to slower passenger cars under homogeneous traffic condition.

Space Occupancy Method

For estimating PCUs, area occupancy proposed by Mallikarjuna and Rao (2006) is used instead of density as it does not represent the mixed traffic characteristics appropriately. Area occupancy is defined as the sum of total vehicle area projected on the ground per unit area of roadway. Swamy et al. (2016) also estimated PCU based on influence area which is found to be more logical when estimated at different flow conditions on expressways. The PCU of the vehicle moving at a particular speed ($\mathrm{PCU}_{\mathrm{vehicle}}$) was calculated by finding the influence area of the vehicle using the relationship between the clearance, width and length of that vehicle using the equation

$$\mathrm{PCU}_{\mathrm{vehicle}} = \frac{\mathrm{Velocity}_{\mathrm{car}}/\mathrm{InfluenceArea}_{\mathrm{car}}}{\mathrm{Velocity}_{\mathrm{vehicle}}/\mathrm{InfluenceArea}_{\mathrm{vehicle}}} \tag{21}$$

where $\mathrm{Velocity}_{\mathrm{car}}$ and $\mathrm{Velocity}_{\mathrm{vehicle}}$ = velocity of car and a vehicle type, respectively; $\mathrm{InfluenceArea}_{\mathrm{car}}$ and $\mathrm{InfluenceArea}_{\mathrm{vehicle}}$ = influence area of the car and a vehicle type, respectively.

Based on Queue Discharge Flow

Al-Kaisy et al. (2002) developed a new approach based on QDF to determine PCE factors for heavy vehicles on congested freeways of the US. They considered an entrance ramp merge area and a long-term freeway reconstruction zone where bottlenecks were formed. They assumed that the fluctuation in QDF capacity observations would be minimal if the traffic stream was uniform and consisted of passenger cars only. The observed vehicle counts from QDF capacity were used to develop a nonlinear programming problem, where the objective function was to minimize the variation in QDF capacity.

Simulation Method

Elefteriadou et al. (1997) developed PCE values for different types of trucks on freeways and highways under homogeneous traffic conditions using the NETSIM (NETwork SIMulation) model and its revised version was used by Sumner et al. (1984). Webster and Elefteriadou (1999) determined PCEs for trucks using the simulation model, FREeway SIMulation (FRESIM) based on traffic density. It investigated the effect of several characteristics related to freeway design, vehicle performance, and the traffic stream on truck passenger car equivalents. The FRESIM model, developed by the Federal Highway Administration, was used in this study. Al-Kaisy et al. (2005) utilized microscopic traffic simulation to develop PCU factors for heavy vehicles on level terrain and specific upgrades of freeways and multilane highways during congestion. They used the traffic simulation model INTEGRATION to obtain PCU values based on QDF and studied their effect on traffic flow. Arasan and Arkatkar (2010, 2011) obtained PCU values for different vehicle types for a wide range of traffic volume and roadway conditions using the microscopic simulation model HETEROgenous SIMulation (HETEROSIM) for multilane highways. Bains et al. (2012) modeled traffic flow by determining PCU of vehicles at different volume levels on a level terrain using the microsimulation model VISSIM (Verkehr In Städten SIMulation model) for multilane expressways. They evaluated the capacity of expressways and studied the effect of vehicle composition on PCU values. Mehar et al. (2014) examined the application of VISSIM to determine capacity of multilane highways and to calibrate two major parameters of the model to suit mixed traffic conditions. It was used to generate the traffic flow and speed data for conditions that are difficult to obtain from field observations. They studied the effect of traffic mix on capacity of highway. Giuffre et al. (2015) estimated PCEs for heavy vehicles on freeway of Italy using the simulation model AIMSUN.

Other Methods

Fan (1990) studied PCU values for expressway in Singapore using V/C ratio instead of density or LOS because these freeways operate at LOS Aerde and Yagar (1984) determined PCEs in terms of both platoon leadership and follower creation under homogeneous traffic conditions. Aggarwal (2011) used MATLAB-based fuzzy model for PCU estimation of truck based on four factors such as width of pavement, type/quality of shoulder, directional split and traffic composition of highways. Mardani et al. (2016) demonstrated the dynamic nature of PCUs on two-lane intercity highways under heterogeneous traffic composition.

Summary of PCU Estimation Methods for Midblock Sections

Of the performance measures discussed in the preceding sections, speed (Aerde and Yagar 1984; Chandra et al. 1995; Arun et al. 2016), flow rate and density (Demarchi and Setti 2003; Tiwari et al. 2000), and delay (Craus et al. 1980; Cunagin and Messer 1983) were most often used for calculating PCUs on various highway types. Among them, speed-area ratio method can be used for calculating PCUs for highways. This method is simple in its construct, and speed data can be easily collected. Also, in nonurban roads like highways, the interactions among the vehicles are relatively lesser when compared to the urban roads. In case of freeways and expressways, spatial headway method (Krammes and Crowley 1986) and microscopic traffic simulation (Webster and Elefteriadou 1999; Bains et al. 2012) may be most appropriate. For urban roads, the mean effective area (Pooja et al. 2018) may be incorporated with the notion that space occupancy of vehicle is a function of operational behavior of a particular vehicle type in the traffic stream. Additionally, incorporation of space occupancy parameter may provide more thoroughness in estimation of PCU factors on urban midblock sections.

Methods for Estimation of PCU on Intersections

Studies on PCU estimation for intersections are discussed in this section with two subsections namely signalized intersections and unsignalized intersections. The reviewed studies in this section cover a wide range of PCU estimation methods under both homogeneous and mixed traffic.

Studies on Signalized Intersections

Headway Method

Greenshields et al. (1947) estimated PCU values based on basic headway using the following equation:

$$\mathrm{PCU}_i = H_i/H_c \tag{22}$$

where PCU_i = PCU of vehicle type i under homogeneous traffic condition; H_i = average headway of vehicle type i; and H_c = average headway of passenger car. Bhattacharya and Mandal (1980) developed a generalized model for PCE estimation based on headway at controlled intersection in Calcutta. Sarraj and Jadili (2012) estimated PCUs for different vehicle types at signalized intersections in Gaza using headway method. Saha et al. (2009) derived the PCE for four vehicle types of through vehicles at signalized intersections according to the traffic conditions of Bangladesh using the headway ratio method.

Based on Delay

Zhao (1998) developed a delay-based passenger car equivalent method for heavy vehicles at signalized intersections. Mathematically, PCE for a heavy vehicle type i based on delay is expressed by the following equation:

$$D\_\mathrm{PCE}_i = 1 + (\Delta d_i/d_0) \tag{23}$$

where D_PCE_i = PCE for a heavy vehicle type i based on delay; Δd_i = additional delay caused by a vehicle type i; and d_0 = average vehicle delay when the traffic is composed of passenger cars only. Benekohal and Zhao (2000) used delay as a parameter to estimate PCU for heavy vehicles at signalized intersections of the US. The delay-based PCE factor gives the number of passenger cars that would replace a heavy vehicle in the traffic stream and result in the same amount of delay as the original traffic stream. Cao et al. (2009) calculated motorcycle equivalents units (MEUs) of bus based on the delay at signalized intersections in urban roads in motorcycles dependent cities. MEU of bus based on the delay is defined as the ratio of delay caused by each bus in heterogeneous cases to the average delay of a motorcycle in homogeneous case. Rahman et al. (2003) developed a new method for estimating PCEs for large vehicles at signalized intersections based on the increased delay caused by the large vehicle. This study includes the effects of a large vehicle's position in the queue to estimate the PCE value.

Based on Queue Discharge Flow

Radhakrishnan and Mathew (2011) proposed a methodology based on QDF to develop a saturation flow model based on dynamic PCUs using microscopic analysis for mixed traffic conditions. They computed PCU at urban signalized intersections by minimizing the difference between the ideal and the observed flow profiles, considering saturation flow rate. For signalized intersections, Mohan and Chandra (2017) used queue clearance rate method which does not need saturation flow values and yielded good estimates of PCUs. PCU was estimated based on the assumption that the rate at which a queue of vehicles clears the intersection is a function of its composition.

Based on Travel Time

Modifying Chandra's method based on travel time, Mahidadiya and Juremalani (2016) estimated PCUs for signalized intersection from the following equation:

$$\mathrm{PCU}_i = (t_i/t_c)/(A_c/A_i) \tag{24}$$

where A_c and A_i = projected area of passenger car and vehicle type i, respectively and t_c and t_i = travel time of passenger car and vehicle type i, respectively. Various problems associated with delay estimation under mixed traffic conditions in India and the methods to overcome them were discussed by Kumar and Dhinakaran (2013). Attempting to improve the accuracy of delay estimation, they calculated PCU values using the ratios of travel time and static area of vehicle. Similarly, Bhatt and Patel (2017) estimated the dynamic PCUs for four-legged signalized intersection in mixed traffic conditions using the ratios of travel time and static area of vehicle and compared static PCU values to dynamic PCU values.

Multiple Linear Regression Method

Hadiuzzaman et al. (2008) and Parvathy et al. (2013) estimated PCU values using regression analysis at signalized intersections. The saturated green time was regressed against the number of each category of vehicles crossing the stop line during the saturated green time, assuming a linear relationship between the variables. Minh et al. (2010) estimated the delay of vehicles at pretimed signalized intersections under mixed traffic conditions. PCU was estimated using multiple linear regression analysis considering saturated green time as dependent variable. In Africa, Adams et al. (2015) evaluated PCU values using multiple linear regression analysis, in which the saturated green time is a function of vehicles passing the stop line during that green time. PCU factors of each group were obtained by dividing the coefficient of that group by the coefficient of the car group. Simha (2017) measured traffic flow characteristics at the signalized intersection. PCU values and saturation flow rates were estimated at 20 various study intersections in Mumbai City of India. From regression analysis, PCU values of two-wheeler, private buses, public buses, trucks, taxi, lorry were obtained, when the coefficient of respective vehicles were divided by the coefficient of passenger car.

Simulation Method

Keller and Saklas (1984) calculated PCUs for heavy vehicles as functions of traffic volume, vehicle classification and signal settings under homogeneous traffic conditions considering the ratio of total travel times of heavy vehicles to passenger cars using TRANSYT (TRAffic Network StudY Tool)

$$\mathrm{PCU} = TT_i/TT_b \tag{25}$$

where TT_i = total travel time of vehicle type i in hours; and TT_b = total travel time of base vehicle b in hours. Alex and Isaac (2015) used the microsimulation model TRAFFICSIM (TRAFFIC SIMulation) to estimate dynamic PCUs for signalized intersections for varying approach width, traffic composition, stream speed and traffic volume. Asaithambi et al. (2017) estimated PCUs using a simulation model developed specifically for a signalized intersection under Indian traffic conditions and examined the influence of traffic volume, traffic composition and road width on PCU values.

Studies on Unsignalized Intersections

Headway Method

Mohan and Chandra (2018) estimated PCU factor by the ratio of capacity of a priority movement in terms of standard passenger cars to that in terms of a vehicle type at two-way uncontrolled intersections. The capacity for a movement can be determined in terms of any vehicle type for known values of its critical gap and follow-up times. Critical gap is defined as the minimum time gap between the arrivals of major street vehicles when a minor street vehicle can safely execute the required maneuvers. Follow-up time is the time headway between the departures of minor street vehicles using the same gap in the major street, under a condition of continuous queuing on the minor street (Transportation Research Board: National Research Council 2000). PCU was estimated as the ratio of capacity of a priority movement in terms of standard passenger cars ($C_{p,cs}$) to that in terms of a vehicle type i ($C_{p,i}$) as follows:

$$\mathrm{PCU}_i = C_{p,cs}/C_{p,i} \tag{26}$$

Ahmad and Rastogi (2017) defined PCU as the ratio of the mean lagging headway of a subject vehicle divided by the mean lagging headway of the passenger car. The present study considered the width of the vehicle as an additional variable in the estimation of PCU. This was formulated as

$$\mathrm{PCU}_i = f_i \times (H_i/H_c) \tag{27}$$

where PCU_i = PCU of vehicle type i; f_i = width factor for vehicle i; H_i = mean lagging headway of vehicle type i; and H_c = mean lagging headway of passenger car c.

Based on Flow Rate

Lee (2015) developed PCEs for heavy vehicles at roundabouts of the US using flow rate. The PCE was developed such that the variation in the entry capacity in various mixes of cars and heavy vehicles was minimized. The PCE was also applied to the prediction of the entry capacity using a roundabout capacity model.

Time Occupancy Method

Occupancy time is the time elapsed between the front end of vehicle entering the conflict area and its rear end clearing the conflict area. Estimating PCU by time occupancy method was done by Mohan and Chandra (2018) from the following equation:

$$\mathrm{PCU}_i = (OT_i/OT_{cs}) \times (w_i/w_{cs}) \tag{28}$$

where OT_i and OT_{cs} = the occupancy times of vehicle type i and passenger car, respectively. w_i and w_{cs} = the widths of vehicle type i and passenger car. Sonu et al. (2016) estimated PCUs for four-legged roundabout in India based on time occupancy as follows:

$$\mathrm{PCU}_i = (T_i/T_c)/(A_c/A_i) \tag{29}$$

where T_c and T_i = average time occupancy of standard car and vehicle type i, respectively; and A_c and A_i = projected area of car and vehicle type i, respectively. Relationship between entry flow and circulatory flow has been plotted based on the observed data corresponding to the time period in which there was queue formation in the approach. The same method is used by Gorwadkar et al. (2016) to study the effect of geometrics on PCU values. Sonu et al. (2017) investigated the suitability of HCM equations for determining the entry capacity of a four-legged roundabout under mixed traffic condition and proposed a methodology for validating and calibrating HCM equations for performance evaluation by determining PCU values of roundabouts under mixed traffic conditions.

Simulation Method

Giuffre et al. (2016) determined PCE for heavy vehicles crossing turbo-roundabouts of Italy using the simulation model AIMSUN and studied the effect of heavy vehicles on operational characteristics of a turbo-roundabout. The capacity obtained was used to study the influence of percentage of heavy vehicles and circulating flows for each entry lane of the turbo-roundabout on PCE. When the traffic stream contained a significant number of heavy vehicles, a larger PCE effect was noticed.

Summary on PCU Estimation Methods for Intersections

Headway methods (Sarraj and Jadili 2012; Saha et al. 2009) are based on the notion that passenger-car following larger vehicles may have higher headways compared to time headway between two successive passenger cars at saturated flow conditions. However, the pattern of queue formation and discharge is unique in mixed traffic and widely varying acceleration characteristics of the different vehicles need to be taken in to account while measuring the headways. Methods based on travel time of vehicles did not gain popularity as the urban road segment analyses the midblock and intersection separately. Thus, for the signalized intersections, PCUs are generally estimated with the variables such as queue discharge, saturation flow and delay. Among them, queue clearance rate method (Mohan and Chandra 2017) which does not need saturation flow values may yield good estimates of PCU values. In case of unsignalized intersection, queuing and saturation flow parameters are not applicable. The methods on headway may hold the same drawback of that for signalized intersections. The methods on time occupancy may be realistic as it can capture the behavior of different vehicles in the conflict area, which is the critical space in case of the unsignalized intersection where the interaction of uncontrolled vehicles takes place. In addition, simulation method is the common method for both signalized and unsignalized intersections and can be a potential tool for evaluating the vehicular interactions in intersection facilities.

Discussion on PCU Estimation Methods for Different Facility Types

An overview of various methods for calculating PCU for different facility types is presented in the earlier sections. The approaches and corresponding parameters for different facility types under homogeneous and mixed traffic are tabulated in Table 2. From Table 2, it is observed that the researchers used either one parameter or a combination of parameters for estimating the PCUs of vehicle types for different facility types under homogeneous and mixed traffic conditions. The studies carried out in the countries where homogeneous traffic is present, used single parameter to estimate PCU values. But, majority of the studies carried out in developing countries, where traffic is mixed in nature, used a combination of parameters for PCU estimation (Chandra et al. 1995; Sarraj and Jadili 2012; Paul and Sarkar 2013; Mohan and Chandra 2017). A few researchers estimated PCU values for urban midblock sections using speed (Rahman and Nakamura 2005; Mardani et al. 2015) and space occupancy (Kumar et al. 2017; Paul and Sarkar 2013; Pooja et al. 2018) as the major parameters whereas other researchers calculated PCU for highways, expressways, and freeways using parameters such as speed, headway, density, delay, and space occupancy. In case of signalized intersections, researchers mainly

Table 2. Summary of study approaches and parameters used for PCU estimation

Approach	Parameters											Reference	Country	Facility type
	SP	TH	SH	FRD	DL	QD	PA	IA	AO	TO	TT			
Speed modeling	X	—	—	—	—	—	—	—	—	—	—	Aerde and Yagar (1984)	Australia and United States	H
	X	—	—	—	—	—	—	—	—	—	—	Rahman and Nakamura (2005)	Bangladesh	UM
	X	—	—	—	—	—	—	—	—	—	—	Adnan (2014)	Pakistan	UM
	X	—	—	—	—	—	—	—	—	—	—	Patil and Adavi (2015)	India	SI
Chandra's method	X	—	—	—	—	—	X	—	—	—	—	Chandra et al. (1995)	India	H
	X	—	—	—	—	—	X	—	—	—	—	Chandra and Sikdar (2000)	India	H
	X	—	—	—	—	—	X	—	—	—	—	Chandra and Kumar (2003)	India	H
	X	—	—	—	—	—	X	—	—	—	—	Khanorkar et al. (2014)	India	H
	X	—	—	—	—	—	X	—	—	—	—	Mardani et al. (2015)	India	H
	X	—	—	—	—	—	X	—	—	—	—	Gunasekaran et al. (2015)	India	UM
	X	—	—	—	—	—	X	—	—	—	—	Shalkamy et al. (2015)	Egypt	RM
	X	—	—	—	—	—	X	—	—	—	—	Dhamaniya and Chandra (2016)	India	UM
	X	—	—	—	—	—	X	—	—	—	—	Arun et al. (2016)	India	H
	X	—	—	—	—	—	X	—	—	—	—	Mondal et al. (2017)	India	UM
Flow rate and density	—	—	—	X	—	—	—	—	—	—	—	Huber (1982)	United States	H
	—	—	—	X	—	—	—	—	—	—	—	Tiwari et al. (2000)	India	RM
	—	—	—	X	—	—	—	—	—	—	—	Demarchi and Setti (2003)	United States	H
	—	—	—	X	—	—	—	—	—	—	—	Lee (2015)	United States	RO
	—	—	—	X	—	—	—	—	—	—	—	Al-zerjawi (2016)	Iraq	H
Delay	—	—	—	—	X	—	—	—	—	—	—	Craus et al. (1980)	Israel	H
	—	—	—	—	X	—	—	—	—	—	—	Cunagin and Messer (1983)	United States	H
	—	—	—	—	X	—	—	—	—	—	—	Zhao (1998)	United States	SI
	—	—	—	—	X	—	—	—	—	—	—	Benekohal and Zhao (2000)	United States	SI
	—	—	—	—	X	—	—	—	—	—	—	Rahman et al. (2003)	Japan	SI
Headway method	—	X	—	—	—	—	—	—	—	—	—	Greenshields et al. (1947)	United States	SI
	—	X	—	—	—	—	—	—	—	—	—	Bhattacharya and Mandal (1980)	India	SI
	—	—	X	—	—	—	—	—	—	—	—	Krammes and Crowley (1986)	United States	F
	—	X	—	—	—	—	—	—	—	—	—	Saha et al. (2009)	Bangladesh	SI
	—	X	—	—	—	—	—	—	—	—	—	Ahmed (2010)	United States	F
	—	X	—	—	—	—	—	—	—	—	—	Sarraj and Jadili (2012)	United States	SI
	—	X	—	—	—	—	—	—	—	—	—	Adnan (2014)	Pakistan	UM
	—	X	—	—	—	—	—	—	—	—	—	Xue et al. (2014)	China	E
	—	X	—	—	—	—	—	—	—	—	—	Patil and Adavi (2015)	India	SI
	—	X	—	—	—	—	—	—	—	—	—	Suweda (2016)	India	UM
	—	X	—	—	—	—	—	—	—	—	—	Mohan and Chandra (2018)	India	USI
	—	X	X	—	—	—	—	—	—	—	—	Al-Obaedi (2016)	UK	F
	—	X	—	—	—	—	—	—	—	—	—	Swetha (2016)	India	UM
	—	X	—	—	—	—	—	—	—	—	—	Ahmad and Rastogi (2017)	India	USI
Queue discharge	—	—	—	—	—	X	—	—	—	—	—	Al-Kaisy et al. (2002)	United States	F
	—	—	—	—	—	X	—	—	—	—	—	Radhakrishnan and Mathew (2011)	India	SI
	—	—	—	—	—	X	—	—	—	—	—	Mohan and Chandra (2017)	India	SI
Space occupancy	X	—	—	—	—	—	—	X	—	—	—	Paul and Sarkar (2013)	India	UM
	—	—	—	—	—	—	—	—	X	—	—	Mallikarjuna and Rao (2006)	India	RM
	X	—	—	—	—	—	—	X	—	—	—	Swamy et al. (2016)	India	E
	—	—	—	—	—	—	—	—	X	—	—	Kumar et al. (2017)	India	UM
	X	—	—	—	—	—	—	—	X	—	—	Pooja et al. (2018)	India	UM
Time occupancy	—	—	—	—	—	—	—	—	—	X	—	Mohan and Chandra (2018)	India	USI
	—	—	—	—	—	—	—	—	—	X	—	Sonu et al. (2016)	India	RO
	—	—	—	—	—	—	—	—	—	X	—	Gorwadkar et al. (2016)	India	RO
	—	—	—	—	—	—	—	—	—	X	—	Sonu et al. (2017)	India	RO
Travel time	—	—	—	—	—	—	X	—	—	—	X	Kumar and Dhinakaran (2013)	India	SI
	—	—	—	—	—	—	—	—	—	—	X	Mahidadiya and Juremalani (2016)	India	SI
	—	—	—	—	—	—	—	—	—	—	X	Bhatt and Patel (2017)	India	SI

Table 2. (*Continued*.)

Approach	Parameters											Reference	Country	Facility type
	SP	TH	SH	FRD	DL	QD	PA	IA	AO	TO	TT			
Multiple linear regression	X	—	—	X	—	—	—	—	—	—	—	Basu et al. (2006)	India	UM
	—	—	—	X	—	—	—	—	—	—	—	Hadiuzzaman et al. (2008)	Bangladesh	SI
	—	—	—	—	X	—	—	—	—	—	—	Minh et al. (2010)	Vietnam	SI
	—	—	—	X	—	—	—	—	—	—	—	Parvathy et al. (2013)	India	SI
	X	—	—	—	—	—	—	—	—	—	—	Adnan (2014)	Pakistan	UM
	—	—	—	—	—	X	—	—	—	—	—	Adams et al. (2015)	Africa	SI
	X	—	—	X	—	—	—	—	—	—	—	Patel et al. (2016)	India	UM
	—	—	—	X	—	—	—	—	—	—	—	Simha (2017)	India	SI
Simulation	—	—	—	—	—	—	—	—	—	—	X	Keller and Saklas (1984)	United States	SI
	X	—	—	—	—	—	—	—	—	—	—	Elefteriadou et al. (1997)	United States	F & H
	—	—	—	X	—	—	—	—	—	—	—	Webster and Elefteridou (1999)	United States	F
	—	—	—	—	—	X	—	—	—	—	—	Al-Kaisy et al. (2005)	United States	F & H
	—	—	—	—	—	—	—	—	X	—	—	Alex and Isaac (2015)	India	SI
	X	—	—	—	—	—	—	—	—	—	—	Arasan and Arkatkar (2010)	India	H
	X	—	—	—	—	—	—	—	—	—	—	Arasan and Arkatkar (2011)	India	H
	X	—	—	—	—	—	X	—	—	—	—	Bains et al. (2012)	India	E
	X	—	—	—	—	—	—	—	—	—	—	Praveen and Arasan (2013)	India	UM
	X	—	—	—	—	—	X	—	—	—	—	Mehar et al. (2014)	India	H
	—	—	—	X	—	—	—	—	—	—	—	Giuffre et al. (2015)	Italy	F
	—	—	—	X	—	—	—	—	—	—	—	Giuffre et al. (2016)	Italy	RO
	X	—	—	—	—	—	—	—	X	—	—	Mishra et al. (2017)	India	UM
	—	X	—	—	—	—	—	—	—	—	—	Asaithambi et al. (2017)	India	SI
Stream equivalency factor	X	—	—	—	—	—	X	—	—	—	—	Dhamaniya and Chandra (2013)	India	UM
	X	—	—	—	—	—	X	—	—	—	—	Mardani et al. (2016)	India	H

Note: X denotes the adopted approaches in each article. SP = speed; TH= time headway; SH = space headway; FRD = flow rate and density; DL = delay; QD = queue discharge; PA = projected area; IA = influence area; AO = area occupancy; TO = time occupancy; TT = travel time; UM = urban midblock; RM = rural midblock; H = highway; F= freeway; E = expressway; SI = signalized intersection; USI = unsignalized intersection; and RO = roundabout.

focused on headway (Saha et al. 2009; Sarraj and Jadili 2012), delay (Benekohal and Zhao 2000), queue discharge (Radhakrishnan and Mathew 2011; Mohan and Chandra 2017), and travel time (Mahidadiya and Juremalani 2016; Bhatt and Patel 2017) for estimating PCU values. On unsignalized intersections and roundabouts, researchers used headway (Mohan and Chandra 2018; Ahmad and Rastogi 2017) and time occupancy (Sonu et al. 2016; Gorwadkar et al. 2016) as the major parameters.

Advantages and Disadvantages in Various Methods of PCU Estimation

Based on the review of extensive literature available for different facility types under homogeneous and mixed traffic conditions, the advantages and disadvantages of the major methods are listed.

Speed Modeling

Speed is one of the important factors directly influencing mobility and LOS. PCU for a vehicle type depends upon traffic composition, total volume of the road and physical size of the vehicle. Any change in the traffic volume or composition of traffic stream influences the speed of individual vehicle type. Hence, the impact of increase in traffic or replacing a vehicle by another can be witnessed directly from the traffic stream speed. This method is simple and measuring speed from the field is relatively easier. Speed of traffic is usually measured as average speed of different vehicle types present in the stream (Elefteriadou et al. 1997; Chandra and Kumar 2003). Traffic stream speed-based methods are established on the aspect in which it quantifies the effect of a certain type of vehicle in changing the traffic stream speed compared to passenger cars. Thus, in the method of speed modeling, either average speed of each vehicle type or traffic stream is used. This imposes two problems: first, speed of each vehicle type varies significantly across traffic states and different facility types. Taking average of speeds of all vehicles across the traffic states to determine the stream speed suppresses the variations in speeds of various vehicle types. Second, at the congested traffic state, the difference in speeds of various vehicle types is lesser since the traffic is forced to move at reduced speed (Metkari et al. 2012). This causes PCU of a vehicle to vary significantly across the traffic states and produces inaccurate estimate when they are generalized to present a static PCU values. In mixed traffic, since the speed of each vehicle type is different for different facility types, speed modeling of traffic would be influenced by the composition of vehicles. Besides, the presence of any feature which acts as a friction to the traffic stream will govern the speed of traffic which is addressed by limited studies (Aerde and Yagar 1984).

Headway Method

One of the primary effects of heavy vehicles on the traffic stream is that they take up more space on the road; hence headways have been used to calculate PCUs. Headway-based methods are preferred over others as it is utilizing such a dynamic characteristic of traffic stream (i.e., headway) that explains driver behavior, roadway surroundings, traffic volume, and speed characteristics through a single parameter. However, PCU estimation using headway method is applicable only for steady state traffic conditions (Saha et al. 2009; Sarraj and Jadili 2012). Under unsteady state, the measurement of headway is difficult and chances for erroneous headway measurement are high. Also, segregating the headway of steady state traffic from the headway data collected for longer period is laborious. Besides, it is difficult to obtain the headway data for all vehicle types in the mixed traffic as the event of

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slow-moving vehicles following fast-moving vehicles occurs rarely in steady state traffic (Metkari et al. 2012).

Delay and Queue Discharge Flow Method

Delay is the additional travel time experienced by a driver, passenger or pedestrian due to circumstances that impede the desirable movement of traffic. In the equivalent-delay method, it is assumed that faster vehicles are always hindered by slower vehicles, such that queues form (Craus et al. 1980). With this assumption, the delay method is more appropriate at high volumes. However, this can be observed mostly in homogeneous traffic. Queue discharge flow governs the operation of the freeway or multilane highway after the onset of congestion. This QDF is considered to reflect the real long-term capacity of a recurrent or nonrecurrent bottleneck. In queue discharge flow method, the time that a vehicle spends within the intersection area indicates the impact of the vehicle on intersection operation. The time that a queue of vehicles takes to clear the intersection will also depend upon the interaction among vehicles within the queue, which is a function of its composition and relative sizes of the vehicles. In case of mixed traffic conditions, it can be observed that smaller size vehicles like two-wheelers try to occupy the front row in the queue by squeezing between gaps available on the road space due to their higher maneuverability. Hence, these methods may not give accurate PCU values for mixed traffic where lane discipline is compromised.

Platoon Method

PCU estimation based on platoon method is proposed in a number of studies (Aerde and Yagar 1984; Gunasekaran et al. 2015). For defining a platoon in traffic stream, many methods were proposed (Day and Bullock 2012; Mathew et al. 2013). This method is advantageous since the interaction among the vehicles can be easily observed when the traffic stream is analyzed as platoons. Based on several assumptions, the platoons are chosen and PCUs are estimated by quantifying the impact of inclusion of each vehicle type to the platoon. Trucks, recreational vehicles and buses often have lower speeds and poorer acceleration capabilities than standard passenger cars and are, therefore, more likely to affect the movement of faster vehicles than passenger cars. In addition, the larger vehicles are more difficult to pass because their height, width, or length impairs the follower's sight and necessitates longer passing distances (Aerde and Yagar 1984). Theoretically, it is proved that the PCU values must decrease with increase in heavy vehicle proportion as the interaction of heavy vehicle and fast-moving vehicles are more than that of two heavy vehicles (Al-Kaisy et al. 2002). This is unlikely to match with the results of other methods. In mixed traffic, little attention has been devoted to identifying the platoons.

Chandra's Method

Chandra et al. (1995) proposed a method for PCU estimation using speed and area ratio which is widely used in many studies pertaining to mixed traffic. They used speed as a primary variable to determine the relative effect of individual vehicles on traffic stream of urban roads. The speed of any vehicle type is a true representation of overall interaction of that vehicle type with other vehicle types. However, it does not consider the standard definitions of PCUs. Besides, this method considers only the projected area of vehicles whereas, in the field, vehicles will be influenced by larger area than its projected area, proportionate to the surrounding vehicle types. Accounting the effect of these influences on PCU estimation would be more realistic (Paul and Sarkar 2013). Moreover, in free traffic state, influence of a vehicle over others is relatively lesser and hence, PCU estimation by Chandra's method is influenced by speed and projected area. But, in congested traffic condition, speed of all vehicle types is almost equal and hence, the PCU value estimated is influenced only by area ratio of the vehicles.

Stream Equivalency Factor

Considering the complexities involved in estimation of PCUs for different vehicle types, the alternate methods for converting the mixed traffic into homogeneous equivalents are being attempted. One such attempt is the use of stream equivalency factor (K) which allows determination of traffic flow in terms of passenger cars using the compositions of different vehicle types (Dhamaniya and Chandra 2013). Use of the K factor will provide quick estimation of volume in PCU per hour and thus, V/C ratio on the road, which is considered a surrogate measure for congestion and LOS. But the equivalency factor is estimated from the dynamic PCUs calculated for different vehicle types and hence, this method possesses the same drawbacks as that of Chandra's method.

General Challenges in Estimation of PCU

The challenges in estimation of PCUs are discussed in this section. For the purpose of discussion, the challenges are categorized as follows:

Data Collection and Extraction

PCUs are estimated using various parameters of traffic. The use of automatic data collection systems, developed for homogeneous traffic, helps for the availability of abundant traffic data for PCU estimation. In case of mixed traffic with no lane discipline, since only a few sophisticated but costlier automatic data collection sensors are available for use, data collection becomes a challenging task. The commonly used data collection technique in mixed traffic is videotaping of traffic flow which involves huge amount of time and effort for extracting the traffic parameters for PCU estimation. Videotaping requires a suitable vantage point for installing cameras. Videos captured by placing cameras at a particular vantage point may cause parallax effect, distortion and occlusion due to camera angle which may affect data extraction. Also, videotaping during night time is another problem as headlight glaring may affect the extraction. A few attempts were made to develop semi-automated software tools (Munigety et al. 2014) that can be used for traffic data extraction. In recent decade, several sensors, loop detectors, and traffic cameras are introduced to the market and used by several studies. However, these are costlier solutions and hence, the use of these devices is very limited in the mixed traffic context. Similarly, a few advanced data collection techniques like in-built GPS devices like V-box (Bokare and Maurya 2011) are capable of providing the speed and position of the vehicles in less than a second accuracy but it is impossible to have these devices fitted in all the vehicles. Bluetooth sensors (Mathew et al. 2016) are advantageous for detecting the vehicles through their Bluetooth signals but the vehicle classification and traffic count cannot be achieved as not all the vehicles are equipped with Bluetooth transmitters.

Vehicle Types

Many new vehicles with different static and dynamic characteristics are introduced in the market every year. Addition of new vehicle types creates complexity in PCU analysis and hence, demands more amount of data. Also, the introduction of modern vehicles does not completely replace their predecessors and thus, forms a mix of vehicles with different capabilities even within same category, i.e., intraclass variability (Asaithambi et al. 2012).

Selection of Standard Mode

A few studies are found for estimation of motorized two-wheeler equivalences instead of passenger cars (Minh et al. 2005; Cao et al. 2010; Cao and Sano 2012). The concept of PCUs was introduced for accounting the trucks in homogeneous traffic as the trucks are affecting the speed of the cars. Over the decades, the estimation of PCU for trucks was studied in detail for homogeneous traffic conditions (Huber 1982; Benekohal and Zhao 2000). Similarly, for mixed traffic, the PCUs are estimated to represent different vehicle types in terms of a common vehicle type, i.e., mostly passenger car (Chandra and Sikdar 2000; Tiwari et al. 2000; Chandra and Kumar 2003; Bains et al. 2012; Dhamaniya and Chandra 2013; Mardani et al. 2016; Mohan and Chandra 2018). But, in the view of developments in vehicular technologies and volatile urban traffic conditions, the traffic becomes highly heterogeneous through the inclusion of new vehicle types over the years in addition to the existing vehicle types. Widely varying traffic composition across cities of various developing countries having mixed traffic complicates the selection of standard mode for PCU estimation. For example, in India, across different cities, the predominant vehicle type of traffic is either two-wheeler or car. In such circumstances, it is a complex discretion to select a 'standard vehicle'. An attempt was made by Asaithambi and Mahesh (2016) to estimate the Motor Cycle Unit (MCU) values for different vehicle categories considering motorcycle as a standard vehicle in Indian traffic conditions as the composition of motorcycles is the maximum.

Lane Discipline

The impact of lane discipline on PCUs is not well addressed in previous studies. There are very lesser number of studies available that investigate the effect of lane and nonlane-based traffic movements on PCUs of different vehicle types.

Dynamic PCUs versus Static PCUs

Influence of a vehicle type on a traffic stream is not same across the different traffic states. It is understood from many recent literature (Chandra and Sikdar 2000; Chandra and Kumar 2003; Bains et al. 2012; Dhamaniya and Chandra 2013; Mardani et al. 2016) that the application of dynamic PCUs are widely used nowadays. That means, each vehicle type will have a set of PCU values for different flow conditions, either in terms of V/C ratio or flow rates. This is another challenge as one needs to understand the LOS of the traffic before choosing appropriate PCU values from the suggested set of PCUs [Dynamic: Chandra et al. 1995; Paul and Sarkar 2013; Static: IRC 106 (IRC 1990)].

Various Factors Influencing PCUs

PCU is influenced by various factors such as road width (Chandra and Kumar 2003), presence of shoulders (Chandra et al. 1995), directional split (Aggarwal 2011), roughness of road (Arun et al. 2016), traffic composition (Basu et al. 2006), land use, and type of facility. which are already studied by researchers. But, roadside

Fig. 4. Different side frictions in mixed traffic: (a) parking; (b) bus stops; and (c) pedestrian crossing. (Images by Pooja Raj.)

frictions such as pedestrian sidewalks, undesignated pedestrian midblock crossings, bus stops, and roadside parking. also influence the PCU values of vehicles especially in mixed traffic conditions, which are not considered in the existing methods. Fig. 4 shows the different side frictions found in mixed traffic conditions. Also, there are many human and psychological factors influencing the driving behavior [lane changing, overtaking, acceleration, deceleration, desired speed of travel, and PIEV (Perception, Intellection, Emotion, Volition) time of drivers] whose effects on PCU are difficult to capture. Moreover, the data collected from field generally have the major drawback of being influenced by more than one factors present at the site, which makes it difficult to evaluate the effect of individual factors on PCU.

Validation of Result

Review of earlier research works make it clear that PCU values for various vehicle types estimated through different methods are dissimilar. To find out the accurate method of PCU estimation obtained from various methods, a proper validation method is required. The capacity estimation is the commonly adopted validation. In capacity estimation through speed-flow relationships, a curve is assumed to be base curve, i.e., developed from the data obtained through cars only traffic. Thus, the substitution of PCU value for each vehicle type moves the data points of mixed traffic stream in speed-flow diagram toward the corresponding data points of car only traffic. In homogeneous traffic, obtaining the speed-flow curve is easier as cars are predominantly present. In contrast, for mixed traffic, the number of observations with only cars is difficult to obtain and so is for obtaining the base speed-flow curve for mixed traffic. Moreover, the speed-flow or speed-density curve is a macroscopic traffic relationship. Hence, such aggregated traffic relationship may not capture effects of individual vehicles.

Conclusion and Future Directions

This paper presents a comprehensive review on various methods used for estimation of PCU values for different facility types under homogeneous and mixed traffic conditions. An attempt has been made to bring out the limitations in the existing PCU estimation methods and find the possible solutions to overcome such limitations. Based on the review of various studies, the important findings can be summarized as follows:

1. The parameters used in the estimation of PCUs for homogeneous and mixed traffic are different for almost all the facility types.
2. The studies carried out in the countries where homogeneous traffic is present, used single parameter to estimate PCU values. However, many studies on PCU estimation for mixed traffic used more than one parameter, i.e., static and dynamic parameters, for estimating the PCU values of vehicles. It may be attributed to the fact that use of both static and dynamic parameters can capture the effects of the variation in dimensions and their maneuverability.
3. More number of vehicle types, their intraclass variability and weak lane discipline make the mixed traffic more complex to analyze. Hence, the parameters required for PCU estimation under mixed traffic are relatively more complex to measure than that of homogeneous traffic conditions.
4. Dynamic PCU values might better define the influence of a vehicle type in the traffic stream over different traffic flow conditions.
5. Very little attention has been paid on the PCU estimation studies for freeway weaving sections, expressways, and roundabout facilities.
6. Validation of PCU values is widely performed using macroscopic parameters.

In addition to the above findings, from the detailed review of the past studies, the following future directions can be inferred:

1. In mixed traffic, the accurate estimation of PCUs relies on the collection of sufficient amounts of data representing the different traffic flow, composition and other influencing factors. The data limitation in mixed traffic is often encountered due to two factors. First, videographic method of data collection and extraction involves huge amount of time and effort and secondly, the existing automatic data collection systems are either unsuitable or costlier for mixed traffic. Nevertheless, infrared sensors (Yu et al. 2010, 2011), loop detectors (Ali et al. 2012), traffic cameras (Schoepflin and Dailey 2004), radar and laser guns (Adnan et al. 2013), Unmanned Aerial Vehicles (UAV) like drones (Chopade and Guru 2015), pneumatic mast (Kamyab and Storm 2001), Traficon video image detector (Kumar and Vanajakshi 2015) and software tools such as TRAZER, a video image processing software (Mallikarjuna et al. 2009; Padiath et al. 2009), Irfanview (Gowri 2011), and Traffic Data Extractor (Munigety et al. 2014) are used in recent years by researchers as they significantly reduce efforts of data collection and extraction.

   Most of these video image processing software tools require the traffic video to be recorded in certain angle. This cannot be achieved always as it highly depends on the vantage point availability in the site. This limitation can be overcome by using UAVs and pneumatic mast which do not require vantage points. UAVs are advantageous in capturing the traffic efficiently with minimal distortion and occlusion. Even though the use of UAVs can be encouraged for data collection, there is no cheaper solution available in the market for extracting the video data especially for mixed traffic as the requirements of already existing software tools pose certain limitations. The angle requirements remain the major issue in the extraction of traffic video by any of the automated extraction software tools. It can be inferred that more attention has to be paid by the researchers for developing efficient and cheaper version of automated video processing tool that can be used for extracting the mixed traffic from the video data recorded by UAVs.

   At the same time, attention is also to be given for developing cheaper and effective sensor solutions for automatically detecting and classifying the vehicles along with their speed and position on the roads accounting the nonlane discipline of mixed traffic. These directions can avoid the need for manual extraction of video data and save time on data collection and also, enable setting up of long-term data collection points.
2. For midblock sections carrying mixed traffic, the widely used method for PCU estimation (Chandra et al. 1995) considers the relative speed and projected area (length $\times$ width) of the vehicles, where the projected area of vehicle does not actually represent the effective area occupied by them due to the influence of surrounding vehicles. To overcome this limitation, a methodology is proposed (Pooja et al. 2018) for PCU estimation for urban midblock section carrying mixed traffic. PCU can be determined for each type of vehicle considering speed and effective area of subject and neighboring vehicles which is used by Cao et al. (2010) in their study for determining MCUs. The basic formula developed by Chandra and Kumar (2003) can be modified in which projected area can be better reflected by effective area considering the influence of neighboring vehicles

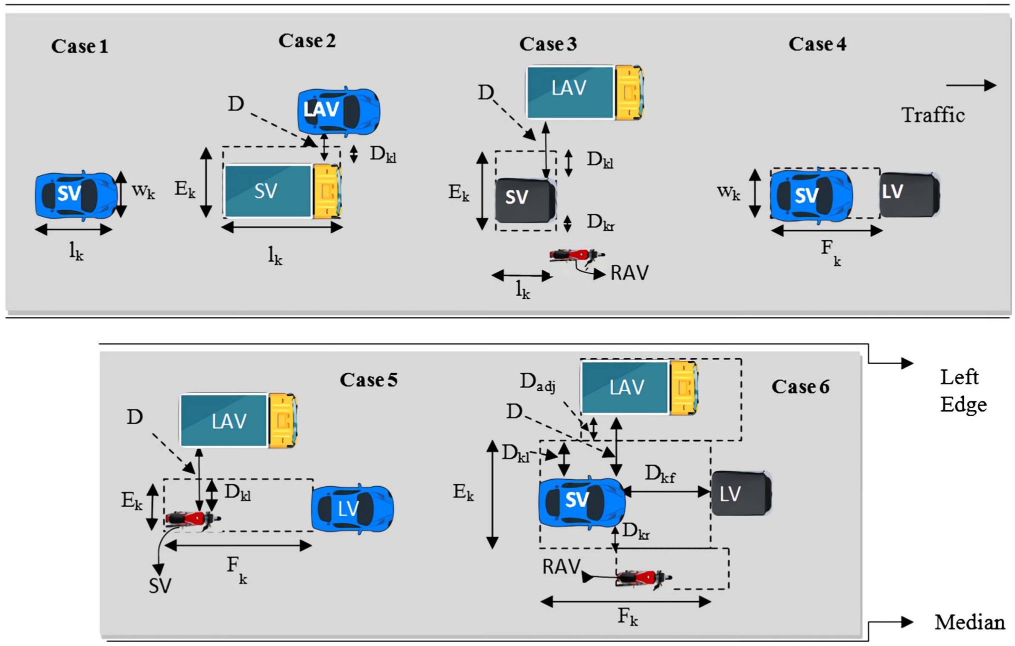

Fig. 5. Different cases considered for estimating PCU. (Adapted from Pooja et al. 2018.)

Table 3. Measuring effective area of subject vehicles under different situations of mixed traffic

Traffic situations	Description of effective area measurement
Case 1: Only subject vehicle	Effective area is the area of the subject vehicle (Case 1 in Fig. 5).
Case 2: Subject vehicle with constraint of one adjacent vehicle	The subject vehicle virtually occupies some distance (based on size ratio) on one side besides its actual width (effective lateral gap) due to the influence of adjacent vehicle. The effective area in this case is the product of length of subject vehicle and effective lateral gap (Case 2 in Fig. 5).
Case 3: Subject vehicle with constraint of two adjacent vehicles	The subject vehicle virtually occupies some distance (based on size ratio) on its both sides due to the influence of adjacent vehicles. So, effective area is the product of length of subject vehicle and effective lateral gap (Case 3 in Fig. 5).
Case 4: Subject vehicle with constraint of a leader vehicle	When the subject vehicle is constrained by a leader, the subject vehicle is assumed to occupy the virtual space of longitudinal gap besides its actual length (effective longitudinal gap). Hence, effective area is the product of effective longitudinal gap and the width of subject vehicle (Case 4 in Fig. 5).
Case 5: Subject vehicle with constraint of a leader and an adjacent vehicle	In this situation, effective area is the product of effective lateral gap and effective longitudinal gap (Case 5 in Fig. 5).
Case 6: Subject vehicle with constraint of a leader and two adjacent vehicles	In this situation, effective area is the product of effective lateral gap and effective longitudinal gap (Case 6 in Fig. 5).

Source: Adapted from Pooja et al. (2018).

under mixed traffic conditions due to weak lane discipline. The adopted formula for determining PCU is given by

$$\mathrm{PCU}_k = \frac{\left(\frac{V_{\mathrm{car}}}{V_k}\right)}{\left(\frac{A_{\mathrm{car}}}{A_k}\right)} \tag{30}$$

where PCU_k = PCU of vehicle type k; V_{car} and V_k = mean speeds of passenger car (small car) and vehicle type k, respectively (m/s); and A_{car} and A_k = effective area of passenger car and vehicle type k, respectively (m^2). Taking into consideration of surrounding vehicles, different cases (Fig. 5) may be considered such as presence of only subject vehicle (Case 1), subject vehicle with an adjacent vehicle (Case 2), subject vehicle with two adjacent vehicles one on each side (Case 3), subject vehicle following a leader (Case 4), subject vehicle with a leader and an adjacent vehicle (Case 5), and subject vehicle surrounded by leader and two adjacent vehicles one on each side (Case 6) for estimating PCU values.

The effective area of different vehicle types used for estimating PCU values varies with respect to different traffic flow conditions. The effective area of a vehicle can be influenced by size of the subject vehicle (SV), leader vehicle (LV) and adjacent vehicles on its right (RAV) and left side (LAV). Table 3 gives the description for calculating effective area for different cases. It can be assumed that effective lateral distance of subject vehicle (E_k) used for calculating effective area is a function of lateral width of the subject vehicle based on size ratio (D_k) and physical width of the subject vehicle (w_k). The lateral width of the subject vehicle depends on the ratio of physical sizes of subject vehicle and adjacent vehicle (size ratio). The physical sizes of different types of vehicles can be adopted from the study conducted by Chandra and Kumar (2003). In Fig. 5 (Cases 2, 3, 5, and 6), D is the total lateral gap between subject and adjacent vehicle

$$D = D_k + D_{adj} \tag{31}$$

Knowing the physical sizes (length × width) of subject vehicle (Z_k) and adjacent vehicle (Z_{adj}), total lateral gap (D) can be divided according to the ratio of physical sizes of subject and adjacent vehicles (Z_k/Z_{adj}) to obtain the lateral width of subject vehicle (D_k) and that of adjacent vehicle (D_{adj}). Thus, the equation obtained is as follows:

$$\frac{D_k}{D_{adj}} = \frac{Z_k}{Z_{adj}} \tag{32}$$

The lateral width of the subject vehicle k may be computed as given in Eq. (33)

$$D_k = \frac{Z_k}{Z_{adj}} \times D_{adj} \tag{33}$$

where D_k = lateral width of subject vehicle k based on size ratio (m); D_{adj} = lateral width of adjacent vehicle, *adj* based on size ratio (m); Z_k = total physical size (length × width) of subject vehicle k (m^2); and Z_{adj} = total physical size of adjacent vehicle, *adj* (m^2). Other than adjacent vehicles, the leader vehicle also influences the subject vehicle to great extent. The effective longitudinal distance of the subject vehicle (F_k) can also be computed to estimate the effective area. In an attempt by Pooja et al. (2018), the effective longitudinal distance of a subject vehicle was calculated as function of the longitudinal gap between the SV and LV (D_{kf}) and length of the SV (l_k). Effective longitudinal distance of a subject vehicle was calculated considering the average longitudinal gap maintained by the subject vehicle with all other leader vehicle types. The study may be extended in future to accurately observe the pair wise longitudinal gap between different types of SV and LV. This method accounts the predominant variations of traffic over time. Hence, the estimated PCU values for different types of vehicles considering the influence of surrounding vehicles may prove to be realistic estimates. Besides its application to the urban midblock section of mixed traffic, this method may be applicable to the midblock sections in highways carrying mixed traffic as the nonlane disciplined driver behavior may have influence over the effective area of the vehicles.

3. Literature review shows that the vehicle equivalents are estimated in terms of passenger cars and motorcycles. Studies on estimation of MCUs are mainly deployed where the composition of motorcycles is maximum (Minh et al. 2005; Cao et al. 2010; Cao and Sano 2012; Asaithambi and Mahesh 2016). The composition of a vehicle type need not be same across the country; for example, in India, the traffic composition is not same in different cities. Several cities have majority of passenger cars and some other cities have majority of motorcycles. In such cases, the estimation of vehicle equivalents solely in terms of passenger cars for the wide varying traffic compositions in different locations may lead to inaccurate results. To overcome this, the equivalency factors may be estimated in terms of the predominant vehicle type of the selected study location. Alternatively, there are few studies that analyzed the effects of composition on PCUs (Basu et al. 2006). Such effects may be provided in the form of adjustment factors to the PCU values of each vehicle type.
4. Intraclass variability of the vehicles is another challenging area which needs to be addressed by the researchers studying mixed traffic characteristics. PCUs of various vehicle types are estimated based on the prior classification of vehicle types. The intraclass variability causes the classification meaningless since behavior of each vehicle of a particular category is significantly different. The classification of vehicles based on their dynamic characteristics (speed, acceleration, deceleration, and headway) along with their static characteristics (length and width of vehicles) helps us in overcoming intraclass variability. The dynamic characteristics of the vehicles are not constant across traffic states, weather and geometric conditions. Varying dynamic characteristics helps in subcategorizing a vehicle type. There are few studies (Dhamaniya and Chandra 2013; Mardani et al. 2015; Mohan and Chandra 2018) that subclassified the passenger cars into small cars and big cars as they are different by dimensions and power to weight ratios (Dhamaniya and Chandra 2016). Similarly, motorized two-wheeler can be subclassified into three categories, viz., mopeds, bikes and sports bikes based on their power to weight ratios. However, the power to weight ratios of the vehicles is hard to be observed on the field and cannot be used as a measure for categorization. Still, the power to weight ratio can be indirectly observed by the speed of the vehicles in free flow and intermediate traffic situations. During the congested traffic/wet road surface, the speeds of all the motorized two-wheelers are nearly same despite their capabilities. Hence, it is proposed to develop a table with PCU values of each subclass (based on speed) of each vehicle type for different traffic conditions. Such tables may be separately developed for different weather and geometric conditions also. On other hand, Asaithambi et al. (2012) have used a simulation tool for evaluating the effects of intraclass variability of vehicles under different roadway and traffic conditions in mixed traffic scenario.
5. Effects of different factors on PCU values are always the limitation of the field data and are difficult to overcome, but it is not impossible. Roadside frictions such as pedestrian sidewalks, undesignated pedestrian midblock crossings, bus stops, and roadside parking. influence the PCU values of vehicles especially in mixed traffic conditions, which are not considered in the existing methods. In recent decade, many simulation studies attempted to quantify the impacts of the friction factors on PCU values. Adding complexity to this, the human and psychological factors play a significant role in estimation of the PCUs as they cannot be observed from the field. Driver simulator is proved to be the promising tool in capturing the human and psychological factors that influence the driving behavior (Lee et al. 2007; Tran et al. 2017). Also, there were studies that used eye-tracking sensors to study the drivers' eye movements, distractions, fatigue, etc. while they were being tested on simulators (Lee et al. 2007). Hence, it is suggested to develop the driver simulator integrated with simulation tools for mixed traffic conditions of nonlane discipline. Such driver simulator integrated simulation tool could be a viable solution in studying the impacts of human, psychological and other geometrical factors on PCUs by observing the interactions among vehicles under different driving scenarios.
6. In most of the studies, the speed-flow or speed-density curve which is a macroscopic traffic relationship, is used for validating the PCU values. Such aggregated traffic relationship may not capture effects of individual vehicles. Hence, a systematic procedure for validation of the estimated PCU values becomes imperative. Simulation-based validation of PCU values is suggested considering the robustness of the simulation tools as they can observe the interactions among the different vehicle types and hence, they can be the promising tools for validating the PCU values (Bains et al. 2012).

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