Review of Passenger Car Equivalence Studies inIndian Context

MahendrakumarMetkari
Post Graduate student
Department of Civil Engineering
IIT Guwahati, Assam-781039.

Anuj Kishor Budhkar
Post Graduate student
Department of Civil Engineering
IIT Guwahati, Assam-781039.

Akhilesh Kumar Maurya
Assistant Professor
Department of Civil Engineering
IIT Guwahati, Assam-781039

ABSTRACT
Passenger Car Equivalent (PCE) or Passenger car unit (PCU) is the metric used to assess traffic-flow rate or volume on a heterogeneous traffic highway. Developed countries devised several methods for calculating PCUs. These PCU values (devised in developed countries)are not suitable for Indian heterogeneous traffic conditions, where traffic is more diverse in nature, and driver do not follow lane discipline. This paper reviews the existing basic methods and their applicability for Indian traffic streams. This paper also identifiesthe gapsin research areas which needs further research in Indian traffic condition.

General terms
Traffic Engineering, Traffic volume, Passenger car unit.

Keywords
Passenger car equivalence, Heterogeneous traffic, Indian traffic.

1. INTRODUCTION
Traffic in the country is of the mixed nature. To assess the different types of vehicles on common basis,idea of passenger car unit developed. Passenger Car Equivalent (PCE) or Passenger car unit (PCU) is thus a metric used to assess traffic-flow rate on a highway. In 1965 *Highway Capacity Manual* [1] introduced the term Passenger Car Equivalent for thefirst time.PCE defined as "The number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions". This definition of PCE was for relative homogeneous traffic conditions (only bus, car and trucks) prevailing in developed countries. Many methods exist for determining passenger car units like those based on headway, delay, density, platoon formation, extra vehicle hours, etc.

For Indian conditions, such homogeneous traffic is not prevalent. The Indian Roads Congress (IRC) code specifies the PCU values for other vehicle types also such as tractors, rickshaws, hand carts, bullock carts, etc. However, these PCU values are fixed and only depend on traffic composition.

This paper reviews the existing basic PCU methodsalong with methods used for Indian traffic streamswhich are characterized as heterogeneous and no lane discipline traffic. The researches for better assessment of PCU in Indian scenario arecontinuing. This paper also identifies the gaps in PCU related researches in Indian traffic condition. Initially the literature review is presented for developed and Indian conditions, followed by the identification of gap area for future research. Final section presents the conclusion of this study.

2. LITERATURE REVIEW:
As the traffic pattern in developing countries like India is different than traffic in developed countries. Therefore, existing literature on passenger car unit can broadly classified in two parts: (i) PCEs studies done for developed countries and (ii) PCEs studies for traffic streams present in developing countries like India.

2.1 PCEstudies in developed countries
The term Passenger Car Equivalent (PCE) was first introduced in the 1965 *Highway Capacity Manual* [1]. Today, the definition remains relatively unchanged [2] as "The number of passenger cars that are displaced by a single heavy vehicle of a particular type under prevailing roadway, traffic, and control conditions" [8]. A brief review of all the PCE calculation methods is presented in the following paragraphs.

2.1.1 HCM (Highway Capacity Manual) Method
In HCM, for two-lane highways, PCEs were calculated from speed distributions of cars and trucks for given volume and grade[3]. For multilane highways, PCEs were based on the relative delay [3].

2.1.2 Methods Based on Headways
The headway method uses the relative amount of space "consumed" by a vehicle as the basis for calculating PCE values[3]. Heavy vehicles take up more space.Werner and Morrall(1976) [4] suggested the formula for calculation of PCE on low terrain level and at low level of service using headway as,

$$E_T = \left(\frac{H_M}{H_B} - P_C\right)/P_T \qquad \ldots (1)$$

H_M is the average headway for mixed traffic conditions, H_B is the average headway for cars only traffic, P_C is the proportion of cars in the traffic, and P_T is the proportion of trucks on level grade and low level of service. Presence of trucks in the traffic stream of a freeway increases the average headways as observed by Cunagin and Chang [5]. This is used by Seguin *et al.* [6] for calculating PCEs in 1982. They defined PCE as,

$$E_T = H_{ij}/H_B \qquad \ldots (2)$$

Where, H_{ij} is the mean lagging headway of vehicle type i under conditions j and H_B is the mean lagging headway of passenger cars.

Krammes and Crowley (1986) [7] noted that spatial headway method was most appropriate for level freeway segments because this method considers the effect of psychological impact of trucks on drivers of other vehicles. They defined PCE values based on lagging headway. Lagging headway is

defined as the time or space from the rear of the leading vehicle to the rear of the vehicle of interest. Krammes and Crowley [7] suggest that PCE should be calculated as,

$$E_T = [(1 - P_T)H_{TP} + pH_{TT}]/H_P \ldots (3)$$

Where P_T is the proportion of trucks, H_{TP} is the lagging headway of trucks following passenger cars in the mixed vehicle stream, H_{TT} is the lagging headway of trucks following trucks in the mixed vehicle stream, and H_P is the lagging headway of cars following either vehicle type in the mixed vehicle stream.

A drawback of the headway method is that it assumes that drivers are exhibiting steady state, in lane behavior. However,it is difficult to separate the headways observed from drivers who are either not in steady state, or are not maintaining the lane (continuously following the same vehicle). It is less likely to occur that cars will continue to follow trucks given the first opportunity to pass on multilane highways.

2.1.3 Methods Based on Delays

Another method for calculation of PCE for trucks is based on delay [8] as per the following equation:

$$PCE_{ij} = (D_{ij} - D_{base})/D_{base} \quad \ldots (4)$$

Where, *PCEij* = PCE of vehicle type *i* under conditions *j*, *Dij*= delay to passenger cars due to vehicle type *i* under conditions *j*; and D_{base} = delay to standard passenger cars due to slower passenger cars.

A similar approach was used by Craus *et al.* [9] for calculating PCEs on two-lane highways based on the Walker method and delay to vehicles due to opposing traffic. A linear combination of assumptions of Walkers method for low volumes (no obstruction for faster vehicles since they can freely overtake) and delay method for high volumes (faster vehicles are always impeded by slower vehicles, and thus queues form) was made.Cunagin*et al*. [3] also combined the Walker method and the delay method in their research of two-lane highways. They studied three different grade conditions (flat, moderate & steep), proportion of trucks and volume levels corresponding to each of the five LOS categories. The PCEs increased with proportion of trucks and volume levels in flat and moderate grade conditions. However, in steep grade conditions, the PCEs decreased for increasing proportion of trucks.

2.1.4 Methods Based on Platoon Formation

Platooning is caused by high speed of following vehicle and not being able to overtake the slow moving leading vehicle. Heavy vehicles have a higher individual tendency to become platoon leaders than the passenger cars [8]. These leadership tendencies were examined by Van Aerde*et al.* [10] using the ratio of percentage leads to percentage of total main-line traffic count, by vehicle type. Number of followers was calculated using multiple regression models for all types of vehicles.PCE values are calculated as the ratio of coefficient of regression model of asubjected vehicle type and passenger cars [8]. Al-Kaisy*et al.* [11] calculated PCE using measurements of queue discharge flow (field observations and linear programming). They hypothesize that effect of trucks on traffic is greater during congestion.

2.1.5 Methods Based on Speed

Van Aerde and Yagar [10] developed a methodology to calculate PCEs which is based on relative speed reduction rates of each vehicle type. They proposed a multiple regression model to estimate the free-speed and the speed reduction coefficients for various percentile speeds.

Percentile speed = free speed + C_1 (number of passenger cars) + C_2 (number of trucks) + C_3 (number of RVs) + C_4 (number of othervehicles) + C_5 (number of opposing vehicles) …(5)

Coefficients C_1 to C_5 indicate the relative sizes of speed reductions due to the respective vehicle type or direction of travel. PCE values were determined as

$$PCE \text{ for vehicle type } n = C_n/C_1. \quad \ldots (6)$$

John [12] and John and Kobett [13] formulated a nonlinear relationship for calculating PCEs by simulating 13 different types of vehicles. The measure of equivalence was the mean speed of passenger cars [8]. They developed a concept termed the equivalence *kernel*. Kernels were subjected to a nonlinear process before equivalence in the usual sense was quantified [8]. Linzer *et al.* [14] also developed simulation model for multilane highways considering influences of grade, vehicle population, and flow rate. Messer [15] also used speed as the measure of PCE calculation. TWOWAF was used to compare traffic streams composed of various classes of vehicles to traffic streams composed only of passenger cars.

Hu and Johnson [16] described how to use HCM (1965) to find PCEs based on speed. PCEs are used to convert a mixed vehicle flow into a passenger car only flow with the same operating speed. In 1982, Huber [20] formulated an equation relating PCE to the flow of a passenger car only traffic stream and mixed vehicle traffic stream as

$$E_T = \frac{1}{P_T}\left(\frac{q_B}{q_M} - 1\right) + 1 \quad \ldots (7)$$

whereP_T is the proportion of trucks in the mixed traffic flow, $q_B$and$q_M$are base (cars only) and mixed flow rates.

In 1984, Sumner *et al.* [17] expanded the Huber's relationship to calculate the PCE of a single truck in a mixed traffic stream, which includes multiple truck types. This calculation requires an observed base flow, mixed flow, and flow with the subject vehicles. The equal impedance measure would cut across all three flow curves. The relationship described by Sumner *et al* is formulated as,

$$E_T = \frac{1}{\Delta P}\left(\frac{q_B}{q_M} - \frac{q_B}{q_M}\right) + 1 \quad \ldots (8)$$

Where, ΔP is the proportion of subject vehicles that is added to the mixed flow and subtracted from the passenger car proportion, q_B, $q_M$and$q$sare base, mixed and flow rate including the added subject vehicles.

2.1.6 Methods Based on Vehicle Hours

Sumner *et al*. [17] developed a method of calculating PCEs based on vehicle-hours for urban and suburban arterial roads by using NETSIM. Number of extra vehicle-hours on a section of roadwayis estimated caused by introducing heavy vehicles. This formed the basis for PCE values.

2.1.7 Methods Based on Travel Time

Keller and Saklas [18] used TRANSYT/7N to estimate PCE for heavy vehicles travelling on urban arterial streets as a function of traffic volume, vehicle classification and signal timing. PCEs were defined as ratio of total travel times of heavy vehicles to passenger cars travelling through an urban network.

2.1.8 Methods Based on Density

In 2003, Demarchi and Setti [19] calculated an aggregate PCE formulated for density of various types of trucks as,

$$E_T = \frac{1}{\sum_i^n P_i}\left[\frac{q_B}{q_M} - 1\right] + 1 \quad \ldots (9)$$

Where, P_i is the proportion of trucks of type i out of all trucks n in the mixed traffic flow, q_B is the base flow rate (passenger cars only), and $q_M$is the mixed flow rate.

2.2 PCEstudies in Indian traffic conditions

Indian road traffic is characterized by the following significant characteristics:

- Indian traffic streams consist of heterogeneous trafficwhich also includes non-standard vehicles.*Non-Standard vehicles* refer to non-conventional vehicles that exhibit abnormal stream and queuing behavior usually assumed in analysis [21]. Effect of non-standard vehicles on Indian traffic cannot be neglected.
- Lane discipline is quite weak which makes lane by lane analysis impossible and incorrect.

Next few paragraphsdescribe the PCU studies carried out for traffic similar to India.

2.2.1 PCU by Indian Roads Congress (IRC)

Indian Roads congress (IRC) suggested PCU values and their usages (refer IRC SP 41 for at –grade intersections and IRC 106 for mid-block sections). The PCU variation with terrain is adjusted as per the capacity of roads. IRC 70-1977 states that segregation in the form of physical, time-based, or by one-way systems or a combination of these can effectively reduce interference due to slow moving vehicles in a mixed traffic situation.

2.2.2 PCU Studies inUrbanAreas:

They are characterized by higher intersections and less length of mid-block sections. Traffic can be of all the levels of service. Predominant research on urban heterogeneous traffic conditions include

a) PCU of bicycles on urban road intersections

Wang *et al.*[22]made an analysis of interaction between bicycles and motor vehicles. A set of models of bicycle conversion factor were established for different situations. The suggested PCU values (i)for through bicycle at intersections was0.28; (ii) for left-turning bicyclewas0.33; (iii) for bicycle on the road section without physical separation was 0.24; and (iv) for bicycle on the road sections with physical separation was 0.22. For left turning vehicles, PCU was calculated as a ratio of average delay caused due each bicycle and average headway for successive vehicles. For other types, the PCU was calculated on basis of ratio of saturation flow rates of bicycles and other vehicles for the same road width.However, the study included only three sites and hence effect of road width and ratio of road widths of each road of intersection is not studied satisfactorily.

b) PCU of cycle rickshaw at mid-block section

Rahman and Nakamura [23] studied thePCU of non-motorized rickshaw (or cycle rickshaw) of mid-block sections of non-congested road in Dhaka, Bangladesh; by speed reduction method. Average stream speeds were calculated from 12 hr field video data. Basic speed calculation is done from those one-minute intervals video data which contained only cars. Effect of decrease in speed due to increase in rickshaws was studied. However, effect of buses and trucks (4 to 5 % of total traffic) was neglected. The study showed a linear relationship between PCU of rickshaw and traffic volume as well as percentage of rickshaws.

c) PCU of non-standard vehicles at saturated conditions at intersections

Saha*et al.*[24] had performed the calculation of PCU at a saturated intersection of Dhaka city (in Bangladesh) by headway ratio method. The roads had no entry for trucks, no bus stoppages nearby and no parking zone. PCU values of 0.86, 1.42, and 2.16 were obtained for auto rickshaws, minibuses and buses respectively.

2.2.3 PCU studies in SemiUrban and Rural Areas

The semi urban and rural areasare characterized by several highway types.

a) PCU for heterogeneous traffic on various roads

This was studied by Tiwari *et al.* [25] using 'modified density method'. In this study, authors evaluated 'conversion factors'. Here,

$$(PCU_{Xi})_j = \left[\frac{k_{car}/W_{85car}}{(q_{Xi}/u_{Xi})/W_{85Xi}}\right]_j \quad \ldots (10)$$

For the highway type *j*, entity group *Xi* in heterogeneous traffic,$q_{xi}$is the flow of traffic (entities/hour) and $u_{xi}$is the space mean speed (km/h) and $W_{85Xi}$is the 85th percentile distribution width (m). The vehicles were classified based on Indian conditions. The data recording was done at rural as well as urban traffic locations at highways with different conditions of lanes and shoulder.

b) *Effect of various factors studied for heterogeneous traffic conditions*

Factors affecting heterogeneous traffic conditions were studied in various researches and a brief listing is presented in Table1.

Table 1. Studies related to impact of various factors on PCU for Heterogeneous traffic conditions

Author	Factor studied	Methodology adopted	Conclusion
Botma, H. (1988) [27]	Slow moving vehicles	A macroscopic model was developed	PCU increases with increase in % slow moving vehicles
Chandra S, Kumar P (1996) [28]	Shoulder conditions	Shoulders were classified in 4 types based on quality	PCU increases with increase in quality of shoulder
Sikdar P.K., Chandra S (2000) [29]	Proportion of a vehicle	Composition of traffic was changed with other conditions remaining the same	PCU value decreases with increase in proportion of vehicle in traffic
Chandra, *et al.* (2001) [30]	Directional split	Effect on two lane, intermediate lane and single lane roads were studied	PCU decreases as directional split of traffic deviates from 50/50 %
Chandra S. (2004) [31]	Road Roughness	Roughness and free flow speed data was collected	PCU decreases with increase in roughness index. This effect is more for cars than slow moving vehicles.

Mallikarjunach (2006) [32]	Area occupancy	Area occupancy is measured over time and space, and entire road width is considered	PCU increases with increase in area-occupancy and decrease in proportion of traffic
Tiwari *et al*. (2008) [25]	Road width	Study of area occupancy of each vehicle based on road width was made	PCU value increases with more number of lanes and easier maneuverability
Arasan T. and Krishnamoorthy K, (2008) [34]	Traffic volume	PCU calculation was done based on basic HCM definition for various categories of vehicles	With increase in volume, PCU value of a particular vehicle increases upto a certain limit and then decreases since overall traffic speed decreases.
Tiwari *et al*., (2008) [25]	Modal split of 2 and 3 wheelers	Traffic data is collected and analyzed for various locations, densities and lane widths for free flow rural and suburban traffic	PCU values of 3-wheelers have very high values when modal share is less than 5%
Arkatkar, S.S. (2011) [34]	Upgrade and V/C ratio	HETEROSIM simulate traffic corresponding to V/C ratios for different grades and from definition, PCU was evaluated for each flow levels so average stream speed is constant.	PCU increases with increase in magnitude of grade and its length (more for heavy vehicles due to inferior performance on grades)

c) PCE for rural roads

On rural roads, the traffic intensity is less and the number of fast moving vehicles is also less. Thus the calculations for highways shall not be used for rural roads [26]. Based upon road usage and road nature for rural roads, the modified density method proposed by Tiwari *et al*. [25] can be used for Indian conditions. The method of platoon formation by Van Aerde and Yagar [10] can be studied for single lane village roads.

3.GAPS IN PCU RESEARCH PERTAIN TO INDIAN TRAFFIC CONDITION

Pertaining to Indian conditions, research on the following areas may be looked upon for further research:

(i) *Effect of grade on PCU on Indian roads/highway for saturated traffic and car-following conditions:* This study is important for analyzing capacity of roads/highways in hilly regions of India. The accuracy of data shall be used for road improvements and future road widening schemes. Work done by Arasan and Arkatkar[34]is limited to free flow conditions and wider roads only.

(ii) *PCU values of Para transit vehicles in semi urban areas:*Para transit vehicles are mostly used in fringe areas of Indian cities- plying on the main roads, their routes and trips per day are mostly fixed. Vehicles such as six seatersVikrams, transit vans (like Tata magix models), and transit jeeps (with open doors) have never been studied although they have a significant share of traffic in and near Indian cities. Most of these vehicles are classified as 'Light commercial vehicles' in a single group and assigned a PCU value of 1 in IRC codes.

(iii) The PCE for vehicles in heterogeneous traffic at rotaries is not investigated till date.

(iv) Similarly, PCE for vehicles in heterogeneous traffic at merging sections on highways is also not explored. Thedensity method used by Ahuja [35]can be used in this context.

(v) Effect of land use on the PCU factors can be established based upon vehicle composition and vehicle speed changes as per different land use.

(vi) For calculating PCU values of vehicles for noting capacity of Indian highway tunnels, the method adopted by Feng-Bor Lin *et al*. [36]in Taiwan's undersea tunnel may be extended for use in Indian highway conditions for trucks as well as buses assuming standard vehicles.

4. CONCLUDING REMARKS

This paper presented literature review on PCE (Passenger car equivalent) values for different conditions. In developing countries like India, there exist heterogeneous traffic stream resulting due to interference of non-standard vehicles.

For analysis of trip assignment in travel demand modelling, dynamic PCU values shall be applied to represent actual conditions while assigning trip matrices to the travel network. Significant research has been made to the extent of development of softwares like HETEROSIM for studying heterogeneous traffic conditions. Most papers in this context are focused on calculating PCE at particular sections of the road. The PCE of vehicles as a generalized model considering all effects of factors such as grade, shoulder condition, roughness, percentage of vehicle, percentage of slow moving vehicles has not been calculated universally. Such a model which can incorporate all effects of factors is yet to be developed. By doing so, the PCE could be calculated based upon single statistic equations for particular factor. Separate changes for special conditions like tunnels can be excluded from the generalized model.

The paper underlines the missing research for various conditions and the possible ways to carry it. Proper research for PCE for all vehicle types, at all conditions and covering all the sections can be looked upon. Finally, a model can be built which can evaluate PCU of a vehicle for universal adoptionin such context.

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