



REVIEW ON PASSENGER CAR UNIT STUDIES IN HOMOGENEOUS AND HETEROGENEOUS TRAFFIC FLOW-A PERSPECTIVE

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ABSTRACT

It is usually true that wise people get benefited in all the future endeavors, based on their learning's and accomplishment that were experienced in the past. In this paper many of the milestones in the development of Passenger Car Unit (PCU) are reviewed. An attempt has been made to cover the critical and the most current research work in the development of PCU in both homogeneous and nonhomogeneous traffic conditions, though the review is not exhaustive. Passenger Car Units or Passenger Car Equivalents (PCE) plays a vital role in studying the traffic flow of diverse vehicle types in the traffic stream and is used to transform traffic stream consisting of different vehicle types into traffic stream consisting of only passenger cars and they are worked out to analyze the relative effect of different type of vehicles on the road. The present paper reviews and compiles various methods that have been followed to estimate the value of PCUs. Each method has its own factors like density, headway, speed, delay etc. that are taken into account for calculation of PCU. In this context, present study also identifies the gaps in research areas which needs further work to be carried out in Indian traffic conditions.

Key words: Passenger Car Unit, Traffic flow, Nonhomogeneous Traffic, Homogeneous Traffic, Indian Traffic.

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1. INTRODUCTION

The traffic stream consists of wide variety of vehicle types with varying dynamic characteristics like high/low performance; engine output etc. and they tend to share the same space of the road without much speed control and lane discipline resulting in the reduction of allowable throughput. It also becomes difficult to study the traffic characteristics and to estimate the parameters like roadway capacity, density, level of service (LOS) etc., which are the basic fundamentals for design, planning, operation and layout of road sections. Hence traffic volumes containing a mix of vehicle types are converted into an equivalent flow of passenger cars (reference vehicle) using Passenger Car Unit.

Highway Capacity Manual (HCM) was first to introduce the concept of passenger car equivalent in the year 1965. PCU was 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 [1]. Since then, considerable research efforts have been directed towards estimation of PCU for different types of vehicles moving on different categories of roads in different parts of the world. In the recent edition of Highway Capacity Manual (2010), it defined passenger car equivalent as “The number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under specified roadway, traffic, and control conditions [2].

Apart from taking passenger car as a reference vehicle for converting all the vehicle types into equivalent vehicle of single type, some researchers took motorcycle and taxi as reference vehicle. Golias (2003) developed Taxi Equivalent Factors (TEF) instead of PCU because the author believed that the PCU values given by HCM cannot be used for taxis as taxis have different behavior in the traffic stream [3].

Similarly Cao & Sano (2012) considered motorcycle as reference vehicle instead of taking passenger cars and converted the traffic stream consisting of mixed vehicle types into traffic stream of motorcycles only by developing Motorcycle Equivalent Unit (MEU) for urban roads in Vietnam. The MEU values were obtained as 3.4 for cars, 1.4 for bicycles, 10.5 for buses and 8.3 for Minibuses [4].

$$MEU_k = \frac{\bar{V}_{mc}}{\bar{V}_k} \times \frac{\bar{S}_k}{\bar{S}_{mc}}$$

Where MEU_k = Motorcycle equivalent unit of vehicle type ‘k’,

\bar{V}_{mc} = Mean speed of motor cycles (m/s),

\bar{V}_k = Mean speed of vehicle type ‘k’ (m/s),

\bar{S}_{mc} = Mean effective space for motorcycles (m^2)

\bar{S}_k = Mean effective space for vehicle type ‘k’ (m^2)

In case of developing countries like India, mixed traffic is regnant. The Indian Road Congress (IRC) provided the PCU values for the estimation of capacity of urban roads and

rural roads in IRC 106: 1990 [5] and IRC 64: 1990 [6] respectively. These PCU values are static despite being dynamic in nature and depend only on traffic composition. Hence there is a great need for the further research to be carried out in the estimation of precise PCU values. This review paper helps in contributing a packed knowledge on the concept of PCU which would be helpful for more exploration in the present topic.

2. EVOLUTION OF PCU

From the past five decades, researchers around the world have developed many methods for the estimation of PCU values by taking several factors into consideration and the evolution is as follows:

- (i) In the first edition of Highway Capacity Manual, the term PCU was not used. Instead, two cars were randomly taken into account in place of a single truck.
- (ii) Passenger Car Equivalent (PCE) was first introduced in the 2nd edition of Highway Capacity Manual which was published in the year 1965 in which it defined PCE as “the number of passenger cars displaced in the traffic flow by a truck, or a bus, under the prevailing roadway and traffic conditions”.

2.1. Based on Headways

As heavy vehicles present in the traffic stream consumes more space, headway is considered as one of the primary effects. Hence headways are used as one of the methods for calculating PCU.

Greenshields et al., (1947) developed a method known as “basic headway method” and suggested the following equation for the estimation of PCU as [7],

$$PCU_i = \frac{H_i}{H_c}$$

Where PCU_i = Passenger car unit for vehicle type (i)

H_i = Average headway of vehicle type (i)

H_c = Average headway of passenger car

Webster & Cobbe (1966) obtained PCE value of 1.75 for medium and heavy goods vehicles [8].

Miller (1968) estimated PCE value by measuring additional time required by heavy vehicles over a passenger car to cross an intersection. He obtained a value of 1.85 for trucks [9].

Werner & Morrall (1976) suggested that headway method is best suited for the calculation of PCEs on low terrain level and at low level of service [10]. The formula for calculation of PCE is recommended as,

$$PCE = \frac{\frac{H_M}{H_B} - P_C}{P_T}$$

Where H_M = Average headway for the sample including all vehicle types,

H_B = Average headway for a sample of passenger cars only,

P_C = Proportion of cars in traffic,

P_T = proportion of trucks on level grade and low level of service.

Branston & Van Zulen (1978) defined “saturated” vehicles as one that came to complete stop/ near stop in queue before proceeding and by measuring the lagging headway of these vehicles as they crossed stop line and calculated PCE value for heavy vehicles as 1.74 [11].

Cunagin & Chang (1982) observed that the trucks present in the traffic stream of a freeway lead to increase in the average headways [12]. The formula for calculation of PCE is,

$$PCU_{ij} = \frac{H_{ij}}{H_B}$$

Where PCU_{ij} = Passenger car unit of vehicle type 'i' in condition 'j',

H_{ij} = Mean lagging headway of vehicle type 'i' under condition 'j',

H_B = Mean lagging headway of passenger cars.

Seguin et al., (1982) recommended the formula for calculation of PCE [13] as,

$$PCU_{ij} = \frac{H_{ij}}{H_{pcj}}$$

Where PCU_{ij} = Passenger car unit of vehicle type 'i' in condition 'j',

H_{ij} = Average headway for vehicle type 'i'

H_{pcj} = Average headway for passenger cars at condition 'j'

Krammes & Crowley (1986) compared constant volume to capacity method, spatial headway method and equal density method and concluded that spatial headway method was very appropriate for level free segments as this method also considers the effect of trucks due to low performance and size as well as effect of psychological impact of trucks on drivers of other vehicles. The PCE values were defined based on lagging headway [14]. The recommended formula for PCE is,

$$PCE = \frac{[(1-P_T)H_{TP} + pH_{TT}]}{H_p}$$

Where H_{TP} = Lagging headway of trucks following passenger car

H_{TT} = Lagging headway of trucks following trucks

H_p = Lagging headway of cars following either vehicle type,

P_T = Proportion of trucks.

Krammes and Crowley believed that an increase in proportion of trucks results in higher PCEs as the opportunity for interaction between cars and trucks increases. Drawbacks of this method are that, it must be assumed that in lane behavior, drivers' exhibits steady state. It is less likely to occur that cars will continue to follow trucks; given the first opportunity to pass on were multilane highways. Traffic volume, percentage of heavy vehicles and multiple heavy vehicles in the queue are not taken into account for calculation of PCE.

Molina (1987) considered that increased headways caused by large trucks and developed PCE value of large trucks at signalized intersections [15].

$$PCE = 1 + \frac{D_h}{H_b}$$

Where D_h = increased headway by queue caused by vehicle type 'i' (sec),

H_b = saturation flow headway of passenger car (sec).

2.2. Based on Density and Flow Rates

Traffic flow rate is the term used to indicate equivalent hourly rate of vehicles passing a point per unit time.

John & Glauz (1976) estimated the PCE values by considering percentage if grade, truck volume to capacity ratio and mixed vehicle flow [16].

$$PCE = \frac{q_B - q_M[1 - P_T]}{q_M \times P_T}$$

Where q_B = equivalent passenger cars only flow rate for given volume/capacity ratio,
 q_M = Mixed flow rate,
 P_T = proportion of truck in mixed traffic flow.

Huber (1982) introduced the concept of using equal density to relate base flow rate and mixed flow rate for calculation of PCE. At some common level of impedance, PCE values are related to ratio between the volumes of two streams [17]. The formula for calculation of PCE is,

$$PCE = \frac{1}{P_T} \left[\frac{q_B}{q_M} - 1 \right] + 1$$

Where q_B = equivalent passenger cars only flow rate for given volume/capacity ratio,
 q_M = Mixed flow rate,
 P_T = proportion of truck in mixed traffic flow.

But the drawback of Huber's computation is that it assumes mixed vehicle flow contains passenger cars and only one type of truck.

Sumner et al., (1984) further developed the concept proposed by Huber. Multiple truck types were also taken into account for the calculation of PCE of a single truck in mixed vehicle stream [18].

$$PCE = \frac{1}{\Delta P} \left[\frac{q_B}{q_S} - \frac{q_B}{q_M} \right] + 1$$

Where, q_S = additional subject flow rate,
 ΔP = proportion of subject vehicles that is added to mixed flow and subjected from passenger car proportions
 q_B = base flow rate (passenger cars only)
 q_m = mixed flow rate

Webster & Elefteriadou (1999) calculated flow vs. density relationships using simulation models for the estimation of PCE. They concluded that PCE increases with increase in traffic flow on freeway segments and decreases with increase in proportion of trucks and number of lanes. Truck type (defined by length and weight to power ratio) is critical for determination of PCE [19].

Mallikarjun & Rao (2006) used 'areal density' to quantify traffic density. In their study, they considered vehicle areas in measuring density. The sum of projected areas of vehicles on the ground per unit area of roadways is known as areal density [20].

Rahman & Nakamura (2005) stated that density should be the governing parameter for Level of Service, even though it is defined by density and speed stated as in 1965 HCM. They suggested that equal density method will be more appropriate for estimation of level of service [21].

Demarchi & Setti (2003) proved that the concept of Sumner do not fully account for interaction between trucks [22]. Hence in order to avoid errors associated with calculating PCE for each truck type separately, they suggested to calculate aggregate PCE which is formulated as,

$$PCE = \frac{1}{\sum_i^n P_i} \left(\frac{q_B}{q_M} - 1 \right) + 1$$

Where P_i = proportion of truck type 'i' out of all trucks 'n' in mixed flow,

q_B = base flow rate (Passenger cars only),

q_M = mixed flow rate.

2.3. Based on Speed

The PCE is determined as the rate of motion of vehicle in speed or distance per unit of time.

St. John (1976) proposed a non-linear truck factor which showed the smaller impact of trucks on traffic streams with increase in proportion of truck. The author found out that as the truck proportion increased, the interactions with cars get reduced. The truck factor was based on speed flow relationships and then later introduced the concept of 'equivalence kernel', which accounts for incremental effects of trucks in traffic stream and is used to calculate PCEs [23].

Hu & Johnson (1981) described how to use 1965 HCM to find PCEs based on speed. They used equation developed by John & Glauz (1976) to calculate PCE. Operating speeds were based on design charts obtained by research performance by the Mid-west Research Institute (MRI). The PCEs were calculated based on extended freeway segments [24].

Van Aerde & Yagar (1984) proposed a method for calculation of PCE based on relative rate of speed reduction. Speed flow relationships and field observations were taken as inputs to form multiple linear regression model which estimates percentile speed based on free speed and speed reduction coefficients for each type of vehicle [25]. The model was as follows,

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

Where C_1 - C_5 = relative sizes of speed reductions due to respective vehicle type or direction of travel.

$$PCE_i = \frac{C_i}{C_1}$$

Where C_i = speed reduction coefficient for vehicle type 'i'

C_1 = speed reduction coefficient for passenger cars

Chandra and Sikdar (2000) developed a methodology for estimation of PCE under mixed traffic conditions. They considered PCE as a function of vehicle area and speed [26].

$$PCE_i = \frac{V_c/V_i}{A_c/A_i}$$

Where V_c & V_i = mean speed of car and vehicle type 'i'

A_c & A_i = projected area of car and vehicle type 'i'

Rahman & Nakamura (2005) developed PCE for non-motorized vehicles along urban arterial at mid-block section on the speed difference of mixed traffic flow of passenger cars [27].

$$PCE_{max} = 1 + \frac{S_b - S_m}{S_b}$$

Where S_b = average speed of passenger car in basic flow (kmph),

S_m = average speed of passenger car in mixed flow (kmph).

2.4. Based on Delays

The delay method that is based on relative capacity reducing effect of heavy vehicles is directly related to additional delay caused by such vehicles when compared to all passenger car case.

Werner & Morrall (1976) determined PCE values using Walker method. The Walker method has assumption: there is no hindrance for faster vehicles in passing as they overtake slow moving vehicles, so that there is no formation of queues [28].

$$PCE = \frac{[OT_i/VOL_i][1/SP_M] - [1/SP_B]}{[OT_{LPC}/VOL_{LPC}][1/SP_{PC}] - [1/SP_B]}$$

Where OT_i = number of overtaking vehicle type 'i' by passenger car,

VOL_i = volume of overtaking vehicle type 'i' by passenger car,

OT_{LPC} = number of overtaking of lower performance passenger car by passenger cars,

VOL_{LPC} = volume of overtaking of lower performance passenger car by passenger cars,

SP_M = mean speed of mixed traffic stream,

SP_B = mean speed of base traffic stream with only high performance passenger cars,

SP_{PC} = mean speed of traffic stream with only passenger cars.

Craus et al., (1980) used equivalent delay method in which they considered that difference between delay caused by heavy vehicle to standard passenger cars and delay caused by slower passenger cars to standard passenger cars. The equivalent delay method assumes that faster vehicles are always resisted by slower vehicles causing queue formation [29]. The PCE is formulated as,

$$PCE = \frac{d_{kt}}{d_{kp}}$$

Where d_{kt} = average delay time caused by one truck,

d_{kp} = average delay time caused by one passenger car.

Cunagin & Messer (1983) determined PCE values using Walker spatial- headway and equivalent- delay methods. The PCE are estimated as the ratio of delay experienced by passenger car due to non-passenger vehicles to delay experienced by passenger car due to other passenger car [30].

$$PCE_{ij} = \frac{D_{ij} - D_{base}}{D_{base}}$$

Where D_{ij} = delay to passenger cars due to vehicle 'i' under condition 'j',

D_{base} = delay to standard passenger car due to slow passenger cars.

Zhao (1998) developed delay based PCE method for heavy vehicles at signalized intersections using headway data [31].

$$D-PCE_i = 1 + \frac{D_{di}}{d_o}$$

Where $D-PCE_i$ = delay based PCE for vehicle type 'i',

D_{di} = additional delay caused by vehicle type 'i' (sec),

d_o = average delay of passenger car queue (sec).

Rahman et al., (2003) suggested a method for calculation of PCE for large vehicles at signalized intersections based on increased delay caused by large vehicles. The effect of a large vehicle's position in the queue to estimate PCE is also included in this method [32].

$$PCE_{LVj} = 1 + \left[\frac{d_{LGj}}{D_o} \right]$$

Where PCE_{LVj} = PCE for large vehicles at j^{th} queue position,

d_{LGj} = increased delay due to large vehicles at j^{th} queue position,

D_o = base delay of passenger cars when all queued vehicles are passenger cars.

2.5. Based on Queue Discharge Flow

Al. Kaisy (2002) developed a new approach to quantify the effect of heavy vehicles on traffic which is great during congestion than during under-saturated conditions by deriving PCE using Queue Discharge Flow (QDF) capacity as equivalency criterion [33]. The optimization procedure to determine PCE is as follows,

Objective function: minimize $Z(C^*)$

(Z = Coefficient of variation = standard deviation/mean)

Design variable: PCE factor

Constraints: $C^* > X1$ ($X1 = 1600$ pcphpl at site 1, $X1 = 1400$ pcphpl at site 2)

$C^* = X2$ ($X2 = 2800$ pcphpl at site 1, $X2 = 2600$ pcphpl at site 2)

$PCE = X3$ ($X3 = 1.0$)

$PCE = X4$ ($X4 = 10.0$)

2.6. Based on V/C Ratio

Fan (1989) applied the method of constant V/C method for determination of PCU for expressway in Singapore. Traffic streams with an equal V/C ratio will not necessarily have equal speed, density and therefore LOS. Even though density was used to define LOS, the author used V/C method because these freeways operate at LOS E. the study focused in congested flow conditions or V/C ratio above 0.67 and mentioned that it is unnecessary to calculate PCE at uncongested flow conditions. Using multiple linear regression and multiplying observed flow by V/C ratio, he found that commercial vehicles (CV) such as light and heavy trucks, buses, trailers has higher PCE than PCE used in US, UK for level terrain [34].

2.7. Based on Travel Time

Keller & Saklas (1984) developed PCE for heavy vehicles on an urban arterial network using *TRANSYT/7N*. The PCE is taken as a function of traffic volume, vehicle classification and signal settings. The travel time method is based on statement that reduction in capacity is directly related to additional delay caused by large vehicles in traffic streams [35].

$$PCE = \frac{TT_i}{TT_o}$$

Where TT_i = total travel time of vehicle type 'i' over networks in hours.

TT_o = total travel time of base vehicle over networks in hours.

2.8. Based on Vehicle Hours

Sumner et al., (1984) suggested a procedure for calculation of PCE values on urban arterial roads between consecutive signalized intersections using NETSIM which is a microscopic

simulation. The values are obtained from the vehicle –hour utilization of road that is added when large vehicles are introduced to traffic stream [36].

3. GAPS IN PCU

The above mentioned methodologies and factors considered help in identifying the research gaps given below:

- PCU of different vehicles types are determined by taking passenger car as the basis. But, now-a-days, there are more variants of passenger cars with different dimensions, power to weight ratios etc. Hence for precise calculation of PCU, a standard passenger car's characteristics itself needs to be defined.
- Effect of grade on PCU in hilly terrains is to be determined, which further helps in analyzing of capacity of roads in hilly terrains.
- The method for calculation of PCU values should be determined at embankments, tunnels, underpass etc.
- PCU values for vehicles at merging and intersection of roads is not investigated yet.
- The PCU values of heterogeneous traffic at roundabouts should be investigated.

4. CONCLUSIONS

The primary aim of this study is to review and categorize developments in data and to forecast future research opportunities for further contribution to develop better PCE values. Also the missing criteria, which can be used for more promising PCE models, for further research can be looked upon.

In India, there exist heterogeneous traffic conditions because of intervention due to non-standard vehicles. Hence there is a much need for considering all the factors such as geometric elements of road, traffic conditions, vehicle compositions, vehicle conditions etc. to develop a model for deriving the most appropriate PCE values that can be adopted throughout the world.

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