

Methodology of Calculating Heavy Vehicle Equivalents

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Abstract: Passenger car equivalents (PCE) present a very important parameter for capacity calculation and road service level as well as a planning segment of road capacity. There are many ways of calculating PCE and most of them are based on Greenshield's basic method. This paper studies the PCE calculation methodology and conditions under which it is applied. The first part of the paper is about role of PCE in analyzing traffic flow, and the rest of the paper is presenting methodologies for computation of PCE. Example of the latest method for determining PCE according to HCM-2010 is given in this paper. The goal of the research is presented by structural, parameter and functional analysis of methods. Further research directions of PCE are shown as well.

Key words: passenger car equivalents (PCE), analysis, heavy vehicle, flow.

INTRODUCTION

Many studies have been made in order to understand the effect of different categories of vehicles on traffic flow. PCE is used to evaluate the effect of different categories of vehicles on traffic flow. As traffic flow is made of more than one type of vehicle, PCE values are used to translate a real traffic flow through an equivalent of homogenous traffic. PCE is first mentioned in 1965, and since then many researchers have tried to determine a quantity effect of heavy vehicles in traffic flow during the development of HCM (*Highway Capacity Manual*) using different methodologies and equality criteria. According to the HCM-2000 [1] PCE is a number of passenger cars distributed according to a single category of units of vehicles depending on traffic conditions, i.e. an average number of passenger cars that would use the same percentage of capacity of the road as any other vehicle (HV, BUS, RV) in given road and traffic conditions. This also creates a unit of measurement of capacity as passenger car/hour (PC/h). Presence of heavy vehicles in traffic flow results in decreased capacity of traffic lanes in intersections, which is shown in [2]. Influence of heavy vehicles on traffic flow is also seen in the fact that heavy vehicles are larger than passenger cars and therefore occupy more space in traffic flow. Also, heavy vehicles are inferior comparing to passenger cars in terms of technical and usage abilities (acceleration and deceleration) and therefore require larger distances between vehicles. In [3] it is presumed that drivers of other types of vehicles are maintaining larger safe following distances comparing to heavy vehicles during driving.

HISTORICAL DEVELOPMENT OF EQUIVALENTS

Papers that have examined PCE were mostly trying to estimate PCE regarding different categories of vehicles under different conditions of traffic flow and roads ([4], [5], [6], [7]). There are different chronological methods in establishing PCE. For example, HCM-1965 uses *speed reduction method* to determine PCE for highways, also known as Walker's method. According to Huber [8] there are three performance measures of PCE: *speed, density and passenger car's speed in both lanes*. In 1980, Ramanyya [9] used the title „*equivalent of a car's design*“ instead of unit of a passenger car for traffic model observed in urban roads in India. This kind of study is the first that measures flow in metric values instead of PCE values. The study shows that PCE values are not constant due to heterogenous road conditions. This Indian model is trying to translate all vehicles to a unit of „*equivalent of a car's design*“. Raghava Chari and Badarinath [10] considered heavy vehicle equivalents through density, which they were calling „*areal density*“ (density observed in an area). This is the first study that was observing vehicle's area (the area that vehicle occupies) to measure density. This density is defined as a vehicle on the road per unit of the road section. Determining area density is done with a camera in time interval of one second. Cunagin and Messer [11] are using *delay* relations as a performance measure to evaluate PCE of heavy vehicles at highways with several lanes. Sumner and Shapiro [12] are using *a number of vehicles per hour* to present density equivalent because veh/h is in a function of vehicle's speed and its

length. Kumar [13] is using characteristics of traffic flow to study traffic on national roads in India. Al-Kaisy et al. [14] is using a factor of queue discharge flow as a measure to evaluate PCE during traffic congestion.

METHODOLOGY FOR DETERMINING PCE

In practice, many types of research were focused on defining the influence of different categories of vehicles on the capacity of roads. Basic method of establishment of this influence is based on the concept of determining PCE. Similarly, the method of relative relations of time headway in process of queue discharge flow is the most common and the most frequently used to determine PCE value. This method was developed by Greenshields in 1947 and it is known as "basic method of determining the time headway". The method is very simple and uses the following relation:

$$PCE_i = \frac{H_i}{H_{pc}}, \text{ where}$$

PCE_i - passenger car equivalent for i th vehicle category

H_i - average value of time headway for i th vehicle category

H_{pc} - average value of time headway for passenger car

Method recommended by HCM-1965

PCE values for basic sections of highways with several lanes are based on relative delay and are calculated as:

$$E_T = \frac{(D_{ij} - D_B)}{D_B}, \text{ where}$$

D_{ij} - delay of passenger car depending on type i under condition j ;

D_B - basic delay of standard passenger car due to passenger cars with lower speeds.

Besides this method based on delay, Cunagin and Messer [11] used the extended version of HCM-1965 to determine PCE of roads with several lanes based on relative delay. In their approach combination of Walker's method of relative number of passings and method of relative delay has been used. In their research, they recognized that at roads with several lanes passing or overtaking of vehicles is prevented only by traffic flow of other traffic lanes. PCE, in this case, is thus calculated as:

$$E_T = \frac{(OT_i / VOL_i) \cdot [(1 / SP_M) - (1 / SP_B)]}{(OT_{LPC} / VOL_{LPC}) \cdot [(1 / SP_{PC}) - (1 / SP_B)]}, \text{ where}$$

OT_i - number of overtaking of vehicles type i by passenger cars,

VOL_i - number of type i vehicles,

OT_{LPC} - number of overtaking of passenger vehicles with lower technical and exploitation characteristics by standard passenger cars,

VOL_{LPC} - number of passenger cars with lower technical and exploitation characteristics,

SP_M - average speed of mixed traffic in the lane,

SP_B - average speed of basic traffic flow made of passenger cars with higher technical and exploitation characteristics and

SP_{PC} - average speed of traffic flow in the lane only with passenger cars.

Linzer et al. [15] bring the utility of designers diagrams which are resulting in microsimulation which is done in MRI - Midwest Research Institute. Here, design connects the grade, mixed flow and percentage of heavy vehicles in capacity percentage (equivalent of V/C relation). Here, PCE, e.i. E_T is thus calculated as:

$$E_T = \frac{q_B - q_M(1 - P_T)}{q_M \cdot P_T}, \text{ where}$$

q_B - equivalent of flow of passenger cars for given relation V/C,

q_M - mixed traffic flow and

P_T - percentage of heavy vehicles in mixed traffic flow.

Huber [8] has developed an equation in a different functional form to show PCE for passenger car lane in relation to mixed flow lane. Heavy vehicle effect is expressed by a number, i.e. through connecting flow for the same level of service. Every equivalent of the level of service can be used for determining values. For example, if density would be used to define equal criteria of level of service, the relation flow-density could be used to connect flow with same density values. Huber's basic equation is:

$$E_T = \frac{1}{P_T} \left(\frac{q_B}{q_M} - 1 \right) + 1, \text{ where}$$

P_T - percentage of heavy vehicles in a mixed flow,

q_B - basic flow (passenger cars only),

q_M - mixed flow.

In 1984, Sumner et al. [6] have expanded Huber's equation to calculate PCE value for a single heavy vehicle in a mixed traffic flow, which includes different types of heavy vehicles. This calculation demands observation of basic flow, mixed flow and flow with appropriate vehicles. Equal level of service should be shown for all three flow curves. The relation which Sumner describes is thus presented as:

$$E_T = \frac{1}{\Delta P} \left(\frac{q_B}{q_S} - \frac{q_B}{q_M} \right) + 1, \text{ where}$$

ΔP - proportion of required vehicles added to mixed flow and deducted from proportions of passenger cars,

q_B - basic flow (passenger cars only),

q_M - mixed flow and

q_S - flow which includes added required vehicles.

PCE in HCM - 1985

According to Roess and Messer [16] PCE in HCM-1985 is calculated for heavy vehicles in category weight/power for 60,9 kg/kW, 121,8 kg/kW and 182,7 kg/kW, and 121,8 kg/kW is considered as an average heavy vehicle. Movement of a typical heavy vehicle of 182,7 kg/kW to 121,8 kg/kW is inspired by an indication that average heavy vehicle fleet on roads was between 76,1 and 103,5 kg/kW. Besides this change, the method of PCE calculation in V/C relation in TRB circular 212 stayed the same in HCM-1985. Same as in TRB circular 212, PCE was the biggest at long downgrades, but it was decreasing with the increase in the percentage of heavy vehicles.

Method of spatial distance is discussed as a replacement for density unit. Both methods affect the maneuver capabilities in traffic flow. With a change of equation in PCE chapter based on traffic velocity, designed by Huber, for calculation of PCE values is used equation based on distance. The equation uses keeping distance, as the perception of a driver of the following vehicle about maneuver capabilities influences on PCE value. Opposing these findings by Cunagin and Chang [17], the distance for heavy vehicles following other heavy vehicles is significantly smaller than distance for passenger car following heavy vehicle. Therefore, opposite to recommended equation of Seguin et al. [18], Krammes and Crowley [19] suggest PCE calculation as:

$$E_T = \frac{(1 - P_T) \cdot H_{TP} + p \cdot H_{TT}}{H_p}, \text{ where}$$

P_T - percentage of heavy vehicles,

H_{TP} - distance of heavy vehicle following passenger car in mixed traffic flow,

H_{TT} - distance of passenger car following heavy vehicle in mixed traffic flow and

H_p - distance of passenger car following any type of vehicle in mixed traffic flow.

Webster and Elefteriadou [7] have published a study to determine the influence of traffic flow on PCE for basic level road sections using FRESIM simulation model. They completed the calculation of PCE for five types of heavy vehicles, which are different in relation to weight/power, as well as in overall length of vehicles. Their study evaluated five types of heavy vehicles:

1. Truck with semi-trailer with five axles,
2. Truck without trailer with two axles,
3. Truck with semi-trailer with four axles,
4. Truck with two trailers and five axles and
5. Truck with three trailers.

Tested traffic flow was expressed in flows of 500, 1,000, 1,500 and 2,000 vehicles/h/lane. This classification determines PCE values for five controlled types of heavy vehicles. As previously mentioned, in 2002 Al-Kaisy et al. [14] have published a report describing the calculation of PCE values with usage a factor of queue discharge

flow (*QDF-Queue Discharge Flow*), as well as terrain sum of traffic flow of vehicles separated in their categories. Their hypothesis is based on an attitude that the effect of the influence of heavy vehicles is higher during traffic congestion rather than saturated conditions. The primary hypothesis of their research is that the capacity of discharging traffic flow is constant, except when it comes to influencing of heavy vehicles on traffic flow. Al-Kaisy used observation scope and linear programming for determining PCE.

Table 1. Effect of traffic flow on level road sections in ratio to PCE [7]

Traffic flow (veh/h/lane)	PCE				
	Truck with semi-trailer with five axles	Truck without trailer with two axles	Truck with semi-trailer with four axles	Truck with two trailers and five axles	Truck with three trailers
500	1.02	1.03	1.09	1.02	1.02
1,000	1.05	1.05	1.04	1.06	1.07
1,500	1.14	1.07	1.06	1.12	1.16
2,000	1.42	1.04	1.15	1.42	1.62

Huber [8] assumed that traffic flow q_B of basic flow (passenger cars only) and traffic flow q_M of mixed flow have a proportion p of heavy vehicles and proportion $1-p$ of cars that have same measure performances, and thus the following calculation can be made:

$$q_B = (1 - p) \cdot q_M + e \cdot p \cdot q_M, \text{ where}$$

e - PCE value for heavy vehicles.

However, the formula of Huber's followers Sumner and Shapiro [12] allows calculation of PCE value for a single heavy vehicle in a lane mixed with other vehicles. Applied to roads, the density is the most often equal to the level of service, so Webster and Elefteriadou [7] used this method to determine PCE for heavy vehicles. Their approach was using a simulation model for calculating relations between density and flow. Again researchers were examining the influence of prevailing traffic flow, truck dimensions (length and power/weight ratio), length and grade and a number of lanes on the road. The result of the analysis of Webster and Elefteraidu indicate an increase of PCE with the increase of flow on the road section and decrease of PCE with the increase of the percentage of heavy vehicles and traffic lanes. The most important conclusion is that the type of heavy vehicle toward length and power/weight ratio is a priority for determining PCE values.

Demarchi and Setti [20] have published a paper describing limitations in determining PCE values for traffic lanes for multiple vehicle types. In their algebra analysis, they have shown that PCE value is developed

for one type of heavy vehicle. However, in a mixed traffic flow made of several types of heavy vehicles, there is not enough attention dedicated to the interaction between heavy vehicles themselves. Their consideration they justified with next statement: „With an increase of the percentage of heavy vehicles in a lane, increase (decrease) of PCE value is neglected due to marginal effect of vehicles in the lane“. To the contrary, the influence of heavy vehicles in mixed traffic flow is overrated, as their proportions should be smaller than they are when adding a given vehicle. Demarchi and Setti also indicate the possibility of preventing this problem in order to avoid mistakes when calculating PCE values for each heavy vehicle individually by calculating mutual PCE formulated in this way:

$$E_T = \frac{1}{\sum_i P_i} \cdot \left[\frac{q_B}{q_M} - 1 \right] + 1, \text{ where}$$

P_i - proportion of trucks going from origin leg i to destination leg j in a mixed stream,
 q_B - base stream (passenger cars only),
 q_M - mixed stream.

This equation is basically made by Huber and it is modified for several types of heavy vehicles in a mixed lane. This approach of usage mutual PCE seems that is adopted in HCM-1994. and HCM-2000. PCE values in HCM-2000 and HCM-2010 are presented for *the percentage of grade, length of grade and percentage of heavy vehicles*. PCE decreases with the decrease in the percentage of heavy vehicles. There are many other worldwide researchers who worked on PCE methodology. Further, in this paper, it will be analyzed PCE methodology according to HCM-2010 for two-lane roads because of accommodation to conditions in the Republic of Srpska.

PCE IN HCM-2010 ON TWO-LANE HIGHWAYS IN TIPYCAL ROAD CONDITIONS

As the methodology of calculating capacity and level of service in HCM-2010 is consisted of 8 steps which determine values, the focus will be on PCE values only. Also, there are two cases related to one-way and two-way two-lane highways. Furthermore, it is necessary to determine the specific terms which are referred to road sections with grade of 3 percent or more and road sections at least 0.97 km (0.6 mi) long. Same as in HCM-2000, in order to convert volume for the full peak hour to passenger car equivalent flow rate (pc/h) there are necessary three correction factors: grade adjustment factor, heavy vehicle adjustment factor and peak-hour factor.

$$v_{i,ATS} = \frac{V_i}{PHF \cdot f_{g,ATS} \cdot f_{HV,ATS}}$$

According to HCM-2010 a heavy vehicle is defined as any vehicle (trailer) with more than four wheels. All commercial vehicles are categorized as heavy and recreational vehicles. Heavy vehicles consider small pickup and panel trucks with more than four wheels to double and triple tractor-trailer units. Small pickup and panel trucks with only four wheels are classified as passenger cars. Heavy vehicles also include all types of buses and recreational vehicles consider motorized campers, motor homes etc. In this case, PCE values are given for two-way two-lane highways.

Table 2. PCE for trucks and recreational vehicles for level terrain and specific downgrades and rolling terrain for two-way two-lane highways [21]

VEHICLE TYPE	FLOW RATE (vehicle/hour)	Terrain	
		Level terrain and specific downgrades	Rolling terrain
TRUCKS E_T	≤ 100	1.9	2.7
	200	1.5	2.3
	300	1.4	2.1
	400	1.3	2.0
	500	1.2	1.8
	600	1.1	1.7
	700	1.1	1.6
	800	1.1	1.4
	≥ 900	1.0	1.3
RECREATIONAL VEHICLES E_R	All flows	1.0	1.1

Heavy vehicle adjustment factor is calculated with following equation:

$$f_{HV,ATS} = \frac{1}{1 + P_T \cdot (E_T - 1) + P_R \cdot (E_R - 1)}, \text{ where}$$

P_T - percentage of trucks in traffic flow (decimal),
 P_R - percentage of recreational vehicles in traffic flow (decimal),
 E_T - passenger car equivalent for trucks from the previous figure,
 E_R - passenger car equivalent for recreational vehicles from the previous figure.

PCE values according to HCM-2010 [21] are defined for:

- Level terrain,
- Specific upgrades, and
- Specific downgrades

At one-way two-lane highways, it is a common occurrence of inability to overtake slow moving vehicles, due to the inability of entering the other lane. The meth-

odology is the same as in the case of two-way two-lane highways in HCM-2000, only that HCM-2010 suggests equivalent values as given in the figure below.

Table 3. PCE for trucks and recreational vehicles for level terrain and specific downgrades and rolling terrain for one-way two-lane highways [21]

VEHICLE TYPE	FLOW RATE (vehicle/hour)	Terrain	
		Level terrain and specific downgrades	Rolling terrain
TRUCKS E_T	≤ 100	1.1	1.9
	200	1.1	1.8
	300	1.1	1.7
	400	1.1	1.6
	500	1.0	1.4
	600	1.0	1.2
	700	1.0	1.0
	800	1.0	1.0
	≥ 900	1.0	1.0
RECREATIONAL VEHICLES E_R	All	1.0	1.0

CONCLUSION

In order to make the comparison useful, important parameters are selected which determine the method for establishing PCE values. In the interest of more detail observation of method of determining PCE, the methodology for determining PCE at two-lane highways according to HCM-2010 is highlighted, as road network of the Republic of Srpska is mostly covered with two-lane highways. Some of the segments of two-lane highway cannot be realistically compared for the reason that classified values are given in different criteria, but from a global point of view it is possible to make the selection using a unified criterion.

If equivalent values for computation of heavy vehicles into passenger car equivalents (PCE) were compared using HCM-1965 to HCM-2010 chronologically, it will be noticeable a great reduction in equivalent values. It is evident that the development of automobile industry, heavy vehicle industry and traffic economy have made an influence in traffic flow, specifically to dynamic and technical and exploitation characteristics of vehicles which resulted in a consequence, among others, of change of distance and time headway, and thus automatically to change of values of PCE equivalents. Phenomenon of decreasing of equivalent values for heavy vehicles is still actual. However, method for calculating these equivalents is still attached to the standard Greenshield's method, regardless of all the research papers and results presented in this paper. Further research should be much more focused on monitoring equivalents values

on roads, than to advancement of methods for calculating equivalents, as PCE values have major oscillations as they are highly influenced by traffic dynamics.

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