Influence of Carriageway Width and Horizontal Curve Radius on Passenger Car Unit Values of Two-lane Two-way Rural Roads

Amr Shalkamy[1], Dalia Said[2*], Laila Radwan[3]

1. Transportation Engineer, Dar Al Handasah (Shair and Partners), M.Sc., Department of Civil Engineering, Cairo University, Giza, Egypt
2. Assistant Professor, Highway and Traffic Engineering, Public Works Department, Faculty of Engineering, Cairo University, Giza, 12316, Egypt
3. Professor, Highway, Traffic, and Airport Engineering, Public Works Department, Faculty of Engineering, Cairo University, Giza, 12316, Egypt

* E-mail of the corresponding author: daliasaid@eng.cu.edu.eg

Abstract

Capacity is a central concept in design and operation of roadways. Studying roadway capacity and factors affecting this capacity is an important issue when transportation facilities are designed or upgraded. One of the main components for the estimation of roadway capacity is the passenger car unit (*PCU*). The main objective of this paper is to study the influence of different geometric features of tangent and curved elements on *PCU* values on two-lane two-way rural roads. Geometry and traffic data were collected from six sites located on Benisuif-Assiut Agricultural Road, Egypt. Each site was composed of two elements; a straight element (tangent) and a succeeding horizontal curve. *PCU* values were estimated using the speed-area method. Using regression analysis, different models were developed to model the influences of different geometric features on *PCU* values. The results show that the *PCU* values for different vehicle categories increase linearly with increase of carriageway width and horizontal curve radius. This increase is clearly observed in case of heavy vehicles rather than light vehicles. The resulting models are useful in optimizing geometric design on two-lane two-way highways from the capacity point of view in the preliminary design stage.

Keywords: Passenger car unit, passenger car equivalent, capacity, two-lane two-way rural highways

1. Introduction

Capacity is a key concept in design, analysis and operation of highway facilities. Estimation of roadway capacity is an important issue for determining the traffic demand for roadways when these facilities are designed. When estimating capacity, each vehicle type in the traffic stream is considerably different because of occupying different spaces on the roads and moving at variable speeds with different acceleration and deceleration capabilities. This traffic stream is called a heterogeneous traffic and speed differential between different vehicle types is quite substantial. Thus, studying the interaction between moving vehicles under such traffic conditions is complex, and there is a need for a uniform way to measure this traffic composition and thus roadway capacity in terms of a common standard vehicle. For this reason, the concept of passenger car unit (*PCU*) or passenger car equivalent (*PCE*) was developed and is universally adopted to convert different vehicle types into a standard passenger car.

PCU concept was introduced for the first time in the Highway Capacity Manual (HCM 1965) to consider the effect of trucks and buses in the traffic composition. In the HCM (2000) the *PCU* was defined as “the number of passenger cars displaced by a single heavy vehicle of a particular type under specified roadway, traffic, and control conditions”, which means converting all types of vehicle such as buses, trucks, cars, bicycles, etc. into a *PCU*. This conversion will lead to an estimated homogeneous traffic so that it can be used in studying roads density, capacity and other significant characteristics.

There are many factors affecting *PCU* values including vehicle type and vehicle characteristics. There are many types of vehicles such as trucks, buses, mini-buses, cars, etc. These types differ in length, width, acceleration and deceleration capabilities, engine power, weight and number of axes. In addition, roadway characteristics affect *PCU* in terms of location (rural or urban), traffic flow regulations (one-way, two-way, divided), number of lanes, element type (i.e. tangent or curved element), lane width, shoulder width, pavement surface condition, longitudinal grades, and horizontal alignment characteristics.

The main objective of this paper is to study the effect of different geometric features of tangent and curved elements on passenger car unit (*PCU*) values which obviously affect the resulting roadway capacity. The presented factors affecting *PCU* values in this study were chosen according to the available geometry and traffic data.

The paper is organized in five Sections. Section 2 briefly overviews the *PCU* estimation methods followed by background studies in this area. Section 3 describes the objective of the paper and data collection process. Section 4 provides data analysis and results, it includes *PCU* estimation method and the resulting models that present the influence of carriageway width and horizontal curve radius on *PCU* values. Finally, Section 5 summarizes the main findings for this paper.

2. Background

HCM 2000 provides values for PCU which can be used for different types of roadway facilities such as freeways, multi-lane highways, and two-lane two-way highways. However, these are static values and do not consider all dynamic factors which affect PCU values. Therefore, efforts have been performed to reach to PCU values that better reflect the road conditions. Several studies used field data and others used traffic simulation techniques (Aggarwal 2008). These methods include headway method (Greenshields *et al*. 1947), delay method (McShane & Roess 1990), speed method (Van Aerde & Yagar 1984), travel time method (Keller & Saklas 1984), vehicle-hours method(Sumner & Shapiro 1984), density method (used by HCM 2000), and the speed-area method proposed by Chandra & Sikdar (2000) .The speed-area method suggested that the *PCU* value for different vehicles in mixed traffic conditions is directly proportional to the speed ratio and inversely proportional to the space occupancy ratio with respect to the standard design vehicle as given by the following equation:

$$PCU_i = \frac{v_c / v_i}{A_c / A_i} \tag{1}$$

Where: *PCUi* = passenger car unit value of the i^{th} vehicle; *Vc* and *Vi* = the mean speed for passenger cars and type *i* vehicles respectively; and *Ac* = the projected area of the passenger car and type *i* vehicles respectively on the road (length × width).

Out of various available methods, the speed-area method proved most suitable for mixed traffic conditions because of the following advantages:

- It is a commonly used method as well as the availability of the required data (Chandra & Sikdar 2000).
- It gives dynamic values for the PCUs and these values change with change of speed and projected rectangular area of the vehicle.
- It takes into account the effect of vehicles mean speed of each vehicle category in calculating *PCU* values and thus, in calculating capacity. This implies that roadway capacity was fully the result of speed changes (Talaat & Hashim 2011)

Several research was undertaken for studying the influence of roadway geometric features on *PCU* values. Chandra & Kumar (2003) collected data from two-lane two-way highways in Northern and Eastern India for studying the effect of lane width on the capacity of two-lane roads under mixed traffic conditions. A video camera was used to collect the data for about 4 to 5 hours on a typical weekday. The data was collected at different straight sections with carriageway width varying from 5.5 to 8.8 m. The data was analyzed and *PCU* values were estimated using the speed-area method which was proposed by Chandra & Sikdar (2000). It was concluded that the *PCU* for a vehicle type increases linearly with the increase of carriageway width.

Sachdeva (2004) studied the effect of pavement width and shoulder condition on *PCU* values for single-lane, two-lane and four-lane roads. He classified the shoulders into four categories namely excellent, good, average and poor shoulder. Regarding carriageway width, the study concluded that the *PCU* values increases with increasing lane width. Regarding shoulder condition, it was observed that *PCU* value of a vehicle type increases with increasing quality of shoulder. For example, the *PCU* value of a bus is 5.40 if the shoulder has an excellent condition and 5.26 if it has a poor condition. A better shoulder provides extra pavement width for the use of traffic and gives more freedom for vehicles movement. Thus a better shoulder can effectively increase the width of the *carriageway* used by traffic and, therefore, results in higher *PCU* value for different vehicles due to more speed differential between a passenger car and a bus or any type of heavy vehicle.

Leong (1968) measured speeds and capacity at 31 straight sections for two-lane two-way rural highways in New South Wales. The selected sections had varied lane and shoulder widths. The study concluded that as pavement and shoulder widths increase, speed also increases. Farouki & Nixon (1976) carried out field investigations on suburban roads in Belfast. They studied the effect of the carriageway width on speeds of cars under free-flow conditions. It was found that the mean free speed increased linearly with carriageway width within the range of 5.2 to11.3 m.

Hossain & Iqbal (1999) collected data from two-lane two-way national highways of Bangladesh to study speed characteristics. A linear regression analysis was made to explain the effect of pavement and shoulder width on free flow speed. The results showed that the free flow speed of vehicles increased by 7.25 to 10.29 km/h for a pavement width ranging from 5.8 to 7.5m. In addition, it was found that the increase of the free flow speed for cars is more than that of the free speed for heavy vehicles resulting in higher *PCU* value for heavy vehicles.

Yagar &Aerde (1983) collected data at 35 different locations in Ontario, Canada to study the effect of geometric and environmental factors on the speeds for two-lane rural highways. They concluded that speed reduces exponentially with the increase of lane width ranging from 3.3 to 3.8m. It was found that the operating speed at a given section decreases by 5.7 km/h for each meter reduction in the width.

3. Data collection process

The scope of this paper focuses on studying the influence of roadway geometric features on *PCU* values which has a direct effect on roadway capacity. Cairo-Aswan Agricultural Road was selected to achieve the objectives. The road is a two-lane two-way rural road and it is classified as Class I highway according to HCM (2000) classification. Data was collected from six sites. Each site was composed of two elements; a tangent and a succeeding curve. The sites were located on relatively level terrain to minimize the effect of the longitudinal gradient on the results. The radii of the studied curves ranged between 115 m to 790 m. Data collected were geometric characteristics data and traffic data. Geometric characteristics included the carriageway width and shoulder width for tangent elements and carriageway width, shoulder width and horizontal curve radius for curved elements. Table 1 summarizes the geometric characteristics for the sites under study.

The study road had a mixed traffic which were grouped into six categories; motorcycles (MC); passenger car (PC); Minibuses (MB); light ground vehicles (LGV); single unit trucks and heavy ground vehicles (HGV); and all types of buses (Bus). The average dimensions of each vehicle category were measured either by actual field measurements or from the data available on manufacturer websites. Table 2 summarizes the geometric characteristics for each vehicle category.

Vehicle volumes and speeds were also collected at the midpoint of tangents and curves for both directions. The data was collected for 5 hours in both directions during normal, clear weather conditions with dry pavement, and during working hours on weekdays. For speed measurement, the space mean speed was calculated using the average time taken to traverse a longitudinal section of 75 m for each vehicle type on the tangent sections and curved sections. For more details about data collection process refer to Shalkamy et al. (2015)

Table 1. Geometric Characteristics for the Study Sites

Site No.	Tangent element			Curved element			
	Carriageway width (m)	Shoulder width (m)		Carriageway width (m)	Shoulder width (m)		Radius(m)
		going direction	coming direction		going direction	coming direction	
1	8.06	1.50	1.58	8.20	1.55	1.44	308
2	7.10	1.10	1.43	7.45	1.25	1.52	115
3	7.50	1.38	1.16	7.80	1.50	1.22	170
4	8.38	1.22	1.35	8.80	1.40	1.30	492
5	8.90	1.42	1.25	9.17	1.60	1.38	790
6	8.64	1.40	1.60	8.70	1.45	1.65	670

Table 2. Vehicle Categories and their Average Dimensions (Shalkamy et al. 2015)

Vehicle category	Vehicles included	Average dimensions(m)		Projected rectangular area on ground(m^2)
		Length	Width	
MC	Motorcycle	1.90	0.75	1.425
PC	All passenger car types	4.40	1.60	7.04
MB	Minibuses	5.00	1.80	9.00
LGV	light trucks	6 .00	2.20	13.20
HGV	Single unit trucks, construction equipment, trailer truck	13.80	2.50	34.50
Bus	Buses	11.20	2.50	28.00

4. Data analysis and results

4.1 Estimation of PCU Values

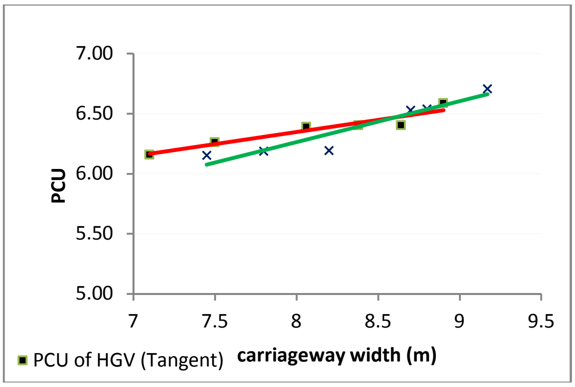
PCU values were estimated using the speed-area method in Equation (1) by Chandra [9]. The resulting *PCU* values for different vehicle categories varied from 0.18 to 0.21, 1.21 to 1.29, 2.10 to 2.52, 6.15 to 6.71, and 4.29 to 4.79 for MC, MB, LGV, HGV, and Bus respectively. Table 3 shows the calculated *PCU* values for the six vehicle categories at the study sites. These resulting *PCU* values agree with recent studies (Talaat and Hashim 2011).

Table 3. Passenger Car Unit (*PCU*) Values for Study Sites.

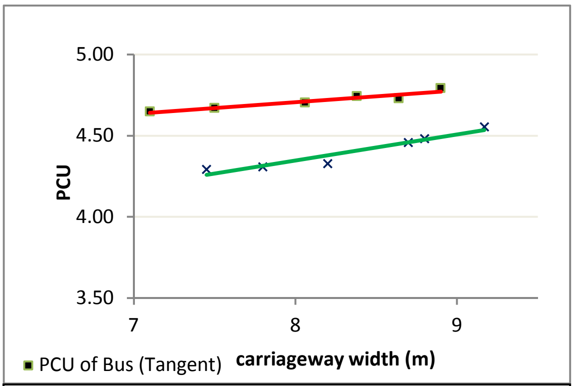
Site No.	Element Type	MC	Microbus	LGV	HGV	Bus
Site No.1	Tangent	0.21	1.25	2.19	6.39	4.70
	Curve	0.19	1.25	2.21	6.19	4.33
Site No.2	Tangent	0.20	1.21	2.10	6.16	4.65
	Curve	0.18	1.23	2.20	6.15	4.29
Site No.3	Tangent	0.21	1.23	2.14	6.26	4.67
	Curve	0.18	1.24	2.21	6.19	4.31
Site No.4	Tangent	0.18	1.25	2.30	6.40	4.74
	Curve	0.19	1.24	2.42	6.54	4.48
Site No.5	Tangent	0.19	1.29	2.36	6.59	4.79
	Curve	0.20	1.27	2.52	6.71	4.55
Site No.6	Tangent	0.20	1.25	2.25	6.40	4.73
	Curve	0.19	1.25	2.33	6.53	4.46

4.2 Influence of carriageway width on PCU Values

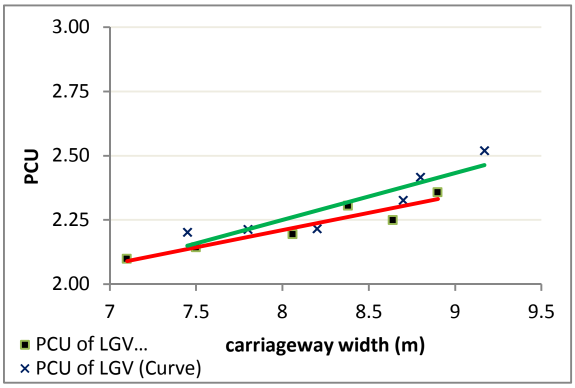
Regression and statistical analyses were conducted using the calculated *PC U* values to model the influence of carriageway width of tangent and curved elements on *PCU* values. Figure 1 summarizes the relation between the carriageway width and the *PCU* values for each vehicle type on tangent and curved sections. The figures show that the *PCU* value for each vehicle category increased linearly with increase of carriageway width on tangents. On horizontal curves, it was found that the relation between *PCU* values and the radius was also linear but with different trends. Most models were significant with high regression coefficients. The explanation of these relationships is that the vehicles travel with more freedom and higher speeds on wider roads. Equation (1) depicts that *PCU* value is directly proportional to (Vc/Vi) where, (Vc) and (Vi) are the mean speed for passenger car and vehicle of type (i) respectively. However, the increase in speed is not uniform for all vehicle categories due to vehicle size and acceleration capability. The standard vehicle (passenger car) has a smaller size than heavy vehicle which is reflected on its speed. Therefore, the speed differential between a passenger car and other types of vehicles increases, thus increasing the term (Vc/Vi), resulting in an increase in *PCU* values, as the case with heavy vehicles. For light vehicles (Microbus and MC), the speed differential between a passenger car and these light vehicles increased slightly or remained constant. Therefore, the *PCU* values slightly increased or remained constant with the increase of carriageway width. In addition, because of the small size of MC with respect to the lane width, the increase in lane width (or carriageway width) was not a significant factor that increased PCU, thus reflecting on the modest value of R^2.As for the shoulder width, it was nearly the same for all study sites and mostly were unpaved or with bad surface condition. Therefore, there was no significant effect on *PCU* values.



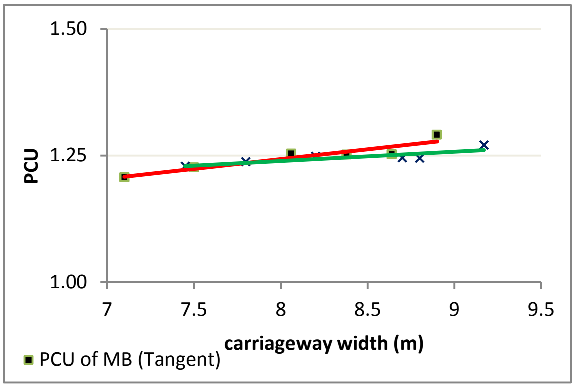
$PCU_{Tangent} = 0.201\ CWT + 4.74$, R^2=0.87
PCU_{Curve}= 0.345 CWC+ 3.51, R^2=0.87



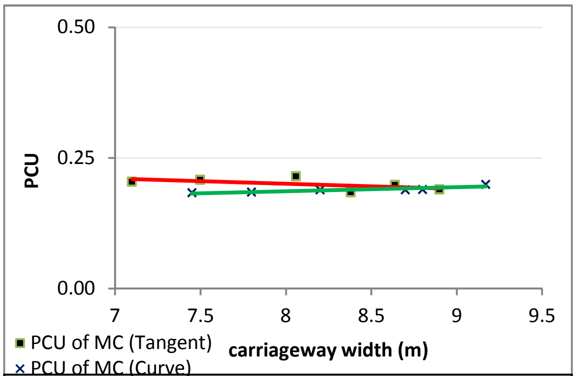
$PCU_{Tangent} = 0.071\ CWT + 4.14$, R^2=0.90
$PCU_{Curve} = PCU = 0.159\ CWC + 3.08$, R^2=0.92



$PCU_{Tangent} = 0.135\ CWT + 1.13$, R^2=0.86
PCU_{Curve}= 0.186 CWC + 0.76, R^2=0.80



$PCU_{Tangent} = 0.035\ CWT + 0.96$, R^2=0.80
$PCU_{Curve} = 0.017\ CWC + 1.08$, R^2=0.54



$PCU_{Tangent} = -0.008\ CWT + 0.27$, R^2=0.06
$PCU_{Curve} = 0.011CWC + 0.10$, R^2=0.82

CWT = Carriageway width of tangent element
CWC = Carriageway width of curved element

Figure 1. Effect of Carriageway Width on PCU Values for Tangents and Horizontal Curves

4.3 Modelling PCU on Horizontal Curves

The previous section proved that there was a difference in *PCU* values depending on whether the vehicle was driving on a tangent or curved section. Therefore, further regression analysis was performed to find the effect of horizontal curvature on the *PCU* values. The regression analysis was performed using the software IBM SPSS ®.

Table 4 shows the results of the regression analysis for the different vehicle types. All models have moderate to high coefficient of determination and low root mean squares. In addition, each statistic had a high t-statistic with p-values less than 0.0001 indicating the significant contribution of the variables to the models. Figure 2 presents the relation between the *PCU* values and the horizontal radius of the tested curves. The figure shows that the *PCU* values increase with increase of radius. This could be attributed to vehicles travelling with more freedom and higher speeds on the horizontal curves with larger radii values. The increase in *PCU* values is clear in case of heavy vehicles. For light vehicles, it increased slightly or remained constant. The explanation of this relations is that the passenger car has a smaller size than the heavy vehicle which is reflected on its speed. Therefore, the speed differential between a passenger car and other types of vehicles increases, thus increasing the term (*Vc/Vi*), resulting in an increase in *PCU* values for heavy vehicles. More specifically, for passenger cars, the speed reduction in case of sharp curves was greater than the speed reduction in case of smooth curves. Therefore, the speed of the passenger cars in case of smooth curves was greater than the speed of the passenger car in case of sharp curves. For heavy vehicle, the speed reduction was not much different between smooth curves and sharp curves because the speeds of heavy vehicles are already low. Thus the term (*Vc/Vi*) in case of smooth curves is higher than the term (*Vc/Vi*) in case of sharp curves resulting in an increase in *PCU* values. For light vehicles (Microbus and MC), the speed differential between a passenger car and these light vehicles increased slightly or remained constant, resulting in a slight or no increase in *PCU* values, implying that the effect of increase of radius is more on heavy vehicles than light vehicles.

A further step was taken to investigate the combined impact of carriageway width and the presence of horizontal curve. Table 5 below shows the results of the analysis. The models show that several types of vehicles are affected more by the curvature of the road rather than the carriageway width for speed reduction. This is obvious for the HGVs and MB. Other types of vehicles were affected by both the horizontal curve radius and carriageway width as for the BUS and LGV. Finally, the MC was only affected by the carriageway width. This is logic, since the MC has a small size with respect to the lane width, and the speed reduction on horizontal curves was not significantly different between sharp and smooth curves. Therefore, the curve radius was not a significant factor affecting on the *PCU*.

The models have a logical explanation for the influence of carriageway width and horizontal curve radius on *PCU* values. The positive sign means that as the horizontal curve radius and carriageway width increase, the *PCU* values increases. In addition, it is clear that the increase of horizontal curve radius and carriageway width is more significant for heavy vehicles rather than light vehicles.

Table 4. The Resulting Models between *PCU* Values and Horizontal Curve Radius

Vehicle	Variable	Stand. Coefficients	T-Ratio $> \pm 1.96$	Significance <0.05
(1) HGV	$PCU = 6.032 + 0.000832\ R$			
	Constant	6.032	96.376	.000
	R	0.000832	6.539	.003
	$R^2 = 0.914$ Adjusted $R^2 = 0.893$ Std. Error of the Estimate= 0.07766 Sig. F Change = 0.003			
(2) Bus	$PCU = 4.244 + 0.000376\ R$			
	Constant	4.244	150.863	.000
	R	0.000376	6.575	.003
	$R^2 = 0.915$ Adjusted $R^2 = 0.894$ Std. Error of the Estimate= 0.03490 Sig. F Change = 0.003			
(3) LGV	$PCU = 2.132 + 0.000430R$			
	Constant	2.132	37.776	.000
	R	0.000430	3.748	.020
	$R^2 = 0.778$ Adjusted $R^2 = 0.723$ Std. Error of the Estimate= 0.07004 Sig. F Change = 0.020			
(4) MB	$PCU = 1.229 + 0.000041\ R$			
	1.229	1.229	176.166	.000
	0.000041	0.000041	2.908	.044
	$R^2 = 0.679$ Adjusted $R^2 = 0.599$ Std. Error of the Estimate= 0.00866 Sig. F Change = 0.044			
(5) MC	$PCU = 0.177754 + 0.000025\ R$			
	Constant	0.177754	61.410	.000
	R	0.000025	4.239	.013
	$R^2 = 0.818$ Adjusted $R^2 = 0.772$ Std. Error of the Estimate= 0.00359 Sig. F Change = 0.013			

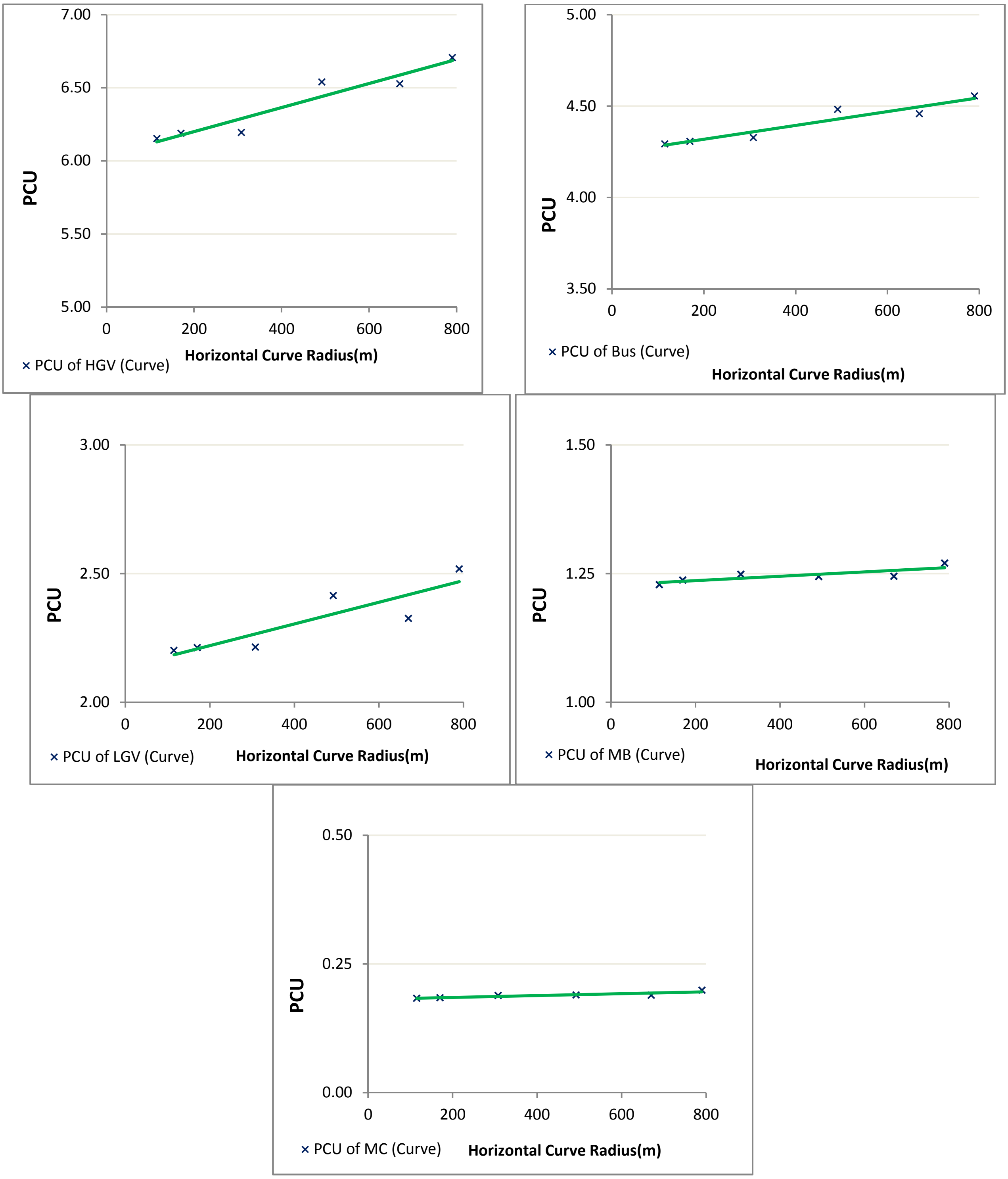


Figure 2. The Influence of Horizontal Curve Radius on *PCU* Values at Curved Elements

Table 5. The Resulting Multivariate Models between *PCU* Values and Horizontal Curve Radius and Carriageway Width

Vehicle	Variable	Stand. Coefficients	T-Ratio > ± 1.96	Significance <0.05
(1) HGV	$PCU = 6.032 – 0.000832\ R$			
	Constant	6.032	96.376	.000
	R	0.000832	6.539	.003
	$R^2 = 0.914$ Adjusted $R^2 = 0.893$ Std. Error of the Estimate= 0.07766 Sig. F Change = 0.003			
(2) Bus	$PCU = 2.4215 + 0.2325\ CWC + 1842.603\ 1/R^2$			
	Constant	2.4215	12.548	0.001
	CWC	0.2325	10.587	0.002
	$1/R^2$	1842.603	3.763	0.033
	$R^2 = 0.98$ Adjusted $R^2 = 0.98$ Std. Error of the Estimate= 0.01461 Sig. F Change = 0.001			
(3) LGV	$PCU = -1.5145 + 0.4325\ CWC + 0.0328\ R/1750$			
	Constant	-1.5145	-6.037	0.009
	CWC	0.4325	15.781	0.001
	R /1750	0.0328	9.450	0.003
	$R^2 = 0.99$ Adjusted $R^2 = 0.99$ Std. Error of the Estimate= 0.01250 Sig. F Change = 0.000			
(4) MB	$PCU = 1.229 + 0.000041\ R$			
	Constant	1.229	176.166	.000
	R	0.000041	2.908	.044
	$R^2 = 0.679$ Adjusted $R^2 = 0.599$ Std. Error of the Estimate= 0.00866 Sig. F Change = 0.044			
(5) MC	$PCU = 0.099276 + 0.010661 CWC$			
	Constant	0.099276	5.409	0.006
	CWC	0.010661	4.865	0.008
	$R^2 = 0.85$ Adjusted $R^2 = 0.82$ Std. Error of the Estimate= 0.00320 Sig. F Change = 0.008			

5. Conclusions

The main objective of this paper was to study the influence of different geometric features of tangent and curved elements on passenger car unit (*PCU*) values. This is important for the estimation of capacity for planning and design of highway facilities. Estimation of capacity in case of mixed traffic condition is by converting all different vehicle categories into a standard type of vehicle (*PCU*).

The results show that the *PCU* values for different vehicle categories increase linearly with increasing of carriageway width and horizontal curve radius. The explanation of this relationship is that the vehicles travel with more freedom and higher speeds on wider roads and on the horizontal curves which has larger radii values. This relationship was clearly observed in case of heavy vehicles. For light vehicles, the *PCU* values slightly increased or remain constant with the increase of carriageway width due to the slight increase of the speed differential between a car and light vehicles. In addition, light vehicles had a small size with respect to the lane width, and therefore the increase in lane width (or carriageway width) was not an important factor that increases *PCU*. Studying the *PCU* values and other factors which affect roadway capacity is significant to be considered in the design stage. It is useful for optimizing geometric design on two-lane two-way highways from the capacity point of view to provide a consistent and flowing highway at a suitable level of service.

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