Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

9th International Conference on Civil and Architecture Engineering
ICCAE-9-2012

Effect of Horizontal Alignment Characteristics on Capacity Loss at Rural Two-Lane Roads

Talaat Abdel-Wahed[a], and Ibrahim Hashim[b]

ABSTRACT

The primary objective of this paper is to explore the impact of horizontal alignment characteristics on capacity and capacity loss at two successive elements, tangent and succeeding horizontal curve. The horizontal alignment characteristics include lane width, shoulder width, carriageway width, forward visibility, number of side access points, curve radius, curve length, tangent length, deflection angle and superelevation. Traffic volumes, speeds and densities are used to estimate capacity by extrapolating free-flow observations. Vehicle speeds and flows on the two successive elements were recorded for each five-minute intervals during the survey period, enabling the capacities of the two elements to be estimated and capacity loss determined.
The effect of different types of vehicle within the traffic stream is normally accommodated for by converting vehicles into passenger car units (PCU) using PCU values.
Correlation and regression analyses are used to investigate the relationships between horizontal alignment characteristics and capacity and capacity loss. Several models are introduced to indicate these relationships and the best one was chosen for each case (i.e. capacity at tangents, capacity at curves and capacity loss between the two successive elements).

Keywords:

capacity loss, traffic stream, Correlation, regression analyses, horizontal alignment, capacity at tangents, capacity at curves.

1. Introduction

Estimation and knowledge of roadway capacity are essential in the planning, design and operation of transportation facilities. Capacity is greatly influenced by roadway, traffic and driver conditions. It is defined in the HCM 2000 as "the maximum hourly rate at which persons or vehicles can be reasonably expected to traverse a point or a uniform segment of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions" (TRB,2000)[1]. Roadway conditions may contain all of the geometric parameters describing the roadway including the type of facility, lane width, shoulder width, lateral clearance, and horizontal and vertical

[a]Civil Engineering Department, Sohag University, Egypt
[b]Civil Engineering Department, Minoufiya University, Egypt

alignments. Horizontal alignment, especially horizontal curve characteristics, can have a substantial impact on traffic flow. For example, on sharp curves, vehicles may reduce their speed or increase the longitudinal gaps consequently the flow is reduced. Horizontal alignment is composed of either straight elements (tangents) or curved elements. Each of these elements has its own geometric characteristics that influence the maximum traffic flows that can be achieved. Therefore, capacity flows may be differed from one element to another. Roadway capacity loss for two successive elements is the negative difference in road capacity between these two elements. This study supposes that the capacity value is affected by highway geometry , as indicated in Figure 1, when road element changes from tangent to curve. Although, the impact of highway geometry on capacity was studied by many researchers, it seems that no research has been done to investigate the impact of horizontal alignment characteristics on capacity loss. The present study was undertaken to quantify the impact of horizontal alignment characteristics on capacity and capacity loss using traffic and geometry data from rural two-lane roads in Minoufiya Governorate, Egypt. The results of this research should help highway and traffic engineers, and researchers to deal with capacity analysis more accurately.

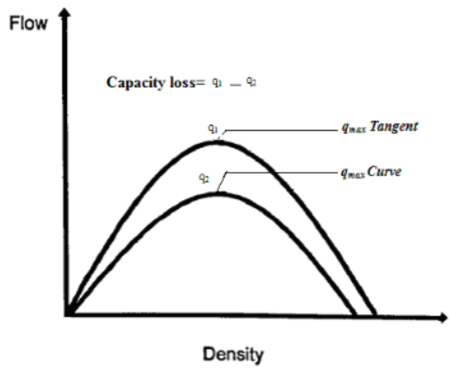

Figure 1: Influence of road geometry on flow-density relationship (Modify the Drawing_add word LOSS)

2. Background Studies

Previous studies on the impact of roadway characteristics on capacity and capacity loss were reviewed. Examples of these studies are presented in this section.

Polus et al. (1991)[2] investigated the traffic flow and capacity characteristics on two-lane highways. Several models were developed for the relationships between flow parameters. The relationships varied from one road to another and were dependent on the characteristics of each site. They concluded that the capacity value is sensitive to the geometric characteristics of each site.

Nakamura (1994)[3] has discussed the concept of highway capacity in Japan. He has suggested adjustment factors (YL) for lane width (WL) less than 3.25 m as YL=0.24WL+0.22

Gibreel et al. (1999)[4] studied the relationship between geometric design consistency and highway capacity based on a three-dimensional analysis, considering combinations of vertical and horizontal curves. They have compared the actual service flow rate as determined based on the observed traffic flow data, and the theoretical flow rate as calculated based on highway capacity analysis. The results show that the actual service flow rate is always smaller than the theoretical one with ratio ranging from 0.74 to 0.98. Gibreel et al. argued that the difference is due the geometric design inconsistencies. Therefore, a new adjustment f actor called the consistency factor is developed to account for the difference.

Chandra and Kumar (2003)[5] investigated the impact of lane width on capacity in India. They found that the capacity in PCU/h of two -lane road increases with total width (W) of the carriageway and the relationship between the two follows a second degree curve as: $C = -2184 - 22.6W^2 + 857.4W$. The relationship can provide a capacity estimate for two-lane roads with a carriageway width ranging from 5.5 to 8.8 m.

Yang and Zhang (2005)[6] investigated the impact of the number of lanes on highway capacity using field traffic flow data from Beijing. The findings showed that average capacity per lane decreases with increasing number of lanes on uninterrupted highway segments. Thus, the marginal decrease rate of average capacity per lane with increasing number of lanes is around 6.7%.

Ben-Edigbe and Ferguson (2005)[7] investigated the impact of road condition, pavement distress, on capacity and capacity loss at two -way roads in Nigeria. A capacity estimation method based on extrapolation from a fundamental diagram representing the relationship between traffic flow and density was used. Capacities were estimated for without distress and with distress road sections. It was found that capacities on without distress and with distress sections differed significantly. Also, Chandra (2004)[8] studied the effect of road roughness on capacity of two -lane roads in India. The study found that the FFS of a vehicle decreases with the roughness of the road surface. The effect of roughness is more apparent on the speed of passenger cars than of heavy vehicles. The speed–volume relationships drawn at different sections of two-lane rural roads indicate that the capacity decreases with an i ncrease in the road roughness.

Chin et al. (2002)[9] investigated the impact of temporary events on capacity loss. Temporary capacity losses due to work zones, crashes, breakdowns, adverse weather, and sub-optimal signal timing resulted in an estimated 2.3 billion vehicle-hours of delay on U.S. freeways and principal arterials in 1999. Assuming an average vehicle occupancy of 1.6 persons, this translates into 3.7 billion person-hours of delay.

Kim and Elefteriadou (2010)[10] Developed a new microscopic si mulation model called TWOSIM for the estimation of capacity for two -way two-lane highway (TWTLHW) under a variety of prevailing traffic and geometric conditions. These include percentage of traffic per direction, presence of a passing zone, a horizontal curve, a driveway, an upgrade, and heavy vehicles. The results showed that the capacity was found to vary by the average free flow speed. Some other results found that capacity decreased by 12–26% as a function of the turning curb radius and percentage of turning flow when there was a driveway. Capacity decreased by 3–17% as a function of curb radius when there was a horizontal curve. With an increasing proportion of trucks (10– 20%), when there was a driveway, capacity decreased by 10– 23%, when there was a horizontal curve it decreased by 3–36%, when there was an upgrade section it decreased by 11–40%.

3. Data Collection and Preparation

The paper used road sites from intercity rural two-lane roads, in Minoufiya Governorate, Egypt, with a speed limit of 60 km/h. Each site is consisted of one horizontal curve and the adjoining tangent. A total number of 12 horizontal curves with various geometric characteristics (i.e. curve radius, length) were chosen for this study. The curve radii for the chosen curves were ranged from 100 to 586m. All of the chosen curves were connected with relatively long tangents, ranged from 180 to 904m. Also, all of the chosen sites are located on relatively level terrain to minimize or avoid the effect of the longitudinal gradient. All geometry data was estimated using automatic and manual field surveys. Sight distance (forward visibility) was measured in the field manually according to the method presented by Hashim (2006)[11]. The road geometry characteristics that estimate in the fil ed include pavement width, lane width, shoulder width, sight distance (forward visibility), number of side access points, curve radius, curve length, deflection angle, superelevation, and tangent length. Tables 1 and 2 show the characteristics of the selected sites as well as their limits for tangent and curve elements.

Table 1. Geometric characteristics of the selected sites (tangent elements)

Site No	Pavement Width (PW), m	Right Shoulder Width (RSW), m	Left Shoulder Width (LSW), m	Tangent Length (TL), m	Forward Visibility (FV), m	No. of Side Accesses (SA)
1	6.96	1.80	1.90	768	360	4
2	5.60	1.22	1.34	260	286	2
3	7.00	1.80	2.00	904	396	9
4	6.80	1.70	1.70	822	382	7
5	6.70	1.10	1.30	779	367	7
6	6.20	1.30	1.30	579	180	8
7	6.46	1.50	1.30	488	196	6
8	6.90	1.30	1.10	180	204	1
9	6.00	1.30	1.20	523	198	7
10	6.50	1.30	1.40	565	202	7
11	6.00	1.20	1.50	679	320	3
12	6.20	1.60	1.30	495	199	6
Summary statistics						
Avg.	6.44	1.43	1.45	586.83	274.17	5.58
Max.	7	1.8	2.1	904	396	9
Min.	5.6	1.1	1.1	180	180	1
SD	0.45	0.24	0.30	219.36	85.95	2.50

Table 2. Geometric characteristics of the selected sites (Curve elements)

Site No.	Pavement Width (PW), m	Right Shoulder Width (RSW), m	Left Shoulder Width (LSW), m	Forward Visibility (FV), m	Curve Radius (R), m	Curve Length (L), m	Deflection angle (Δ),°	Superelevation (e), %
1	7.00	2.14	1.10	235	228	198	50	3.3

2	6.00	1.21	1.39	491	148	136	53	3.6
3	7.00	1.70	2.20	241	586	296	29	2.79
4	6.80	1.90	1.90	185	402	181	26	1.01
5	6.82	1.55	1.62	265	370	178	28	1.95
6	6.40	1.60	1.50	173	100	46	55	2.6
7	7.00	1.60	1.70	167	146	87	34	2.75
8	6.90	1.50	1.20	185	128	97	43	.41
9	6.40	1.60	1.50	170	157	127	46	3.0
10	6.50	1.50	1.20	244	164	137	48	1.27
11	6.60	1.4	1.60	153	298	219	42	1.78
12	6.20	1.96	1.33	209	120	62	53	2.2
Summary statistics								
Avg.	6.64	1.64	1.52	226.50	237.25	147.00	42.25	2.22
Max.	7	2.14	2.2	491	586	296	55	3.6
Min.	6	1.21	1.1	153	100	46	26	0.41
SD	0.34	0.26	0.31	90.84	148.56	71.51	10.50	0.97

Roadside automatic traffic counters were used to conduct the traffic surveys. The survey placed two automatic traffic counters for at least 7 hours at the12 sites. The configuration of the counter positions is presented in Figure 2. Based on this configuration, the traffic characteristics were surveyed at the midpoint of the tangent (A) preceding the curve, and midpoint of curve (B). This configuration could help in studying the impact of horizontal alignment characteristics on flow and other traffic stream characteristics. Collection of traffic data was carried out in working days during the daylight hours. During data collection periods, the weather was clear and the pavement was dry.

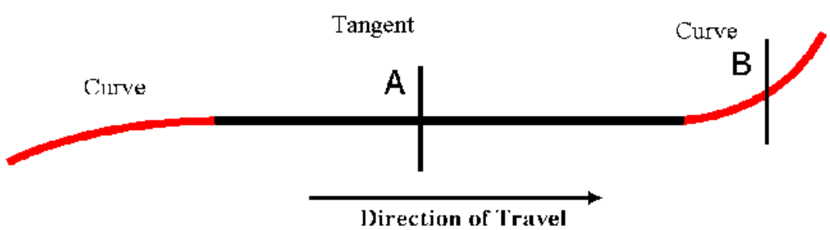

Figure 2. Position of automatic traffic counters for study sites

Data set at each direction of travel on each site was divided into 5-minutes intervals. In each interval, vehicle counts were multiplied by twelve to convert them into flow rates. The average travel speed was equal to the output mean speed. The density can be calculated from the following equation:

Density (K) = Flow Rate (q) / Average Travel Speed (ATS)

Description of field traffic data including data collecting duration, vehicular counts, percentage of heavy vehicles and buses, and directional split ratio is provided in Table 3.

Table 3: Field traffic data for study sites

Site No.	Duration of data collection (hours)	Traffic counts in both directions (vehicles)	Percentage of heavy vehicles and buses (%)	Directional split ratio (%)
1	8.25	3085	5.6	51
2	8.25	1534	4.1	52
3	8.10	1954	7.2	50
4	8.10	4891	3.6	54
5	8.10	3214	5.3	51
6	8.00	2584	4.2	56
7	8.00	5313	2.8	55
8	7.33	1558	3.8	52
9	7.35	968	6.2	53
10	8.25	799	5.1	55
11	9.45	960	5.5	53
12	8.00	2363	3.6	52

Figure 3 presents an example of the main relationships of traffic flow paramete rs at one of the study sites for one direction for both elements (tangent and curve); other sites show relatively similar patterns. The figure shows the three relationships (Average travel speed (ATS)–Density), (Flow Rate–ATS) and (Flow Rate–Density). The relationships show that the traffic stream is in un -congested state, as these roads usually carry relatively low traffic volumes (Hashim, 2011)[12]. From these relationships, it is clear that the variation of ATS with traffic volume and density is relatively low. However, the variation of density with traffic volume is much clearer. The relationships also show the impact of horizontal alignment/element type (i.e. tangent, horizontal curve) on traffic flow parameters.

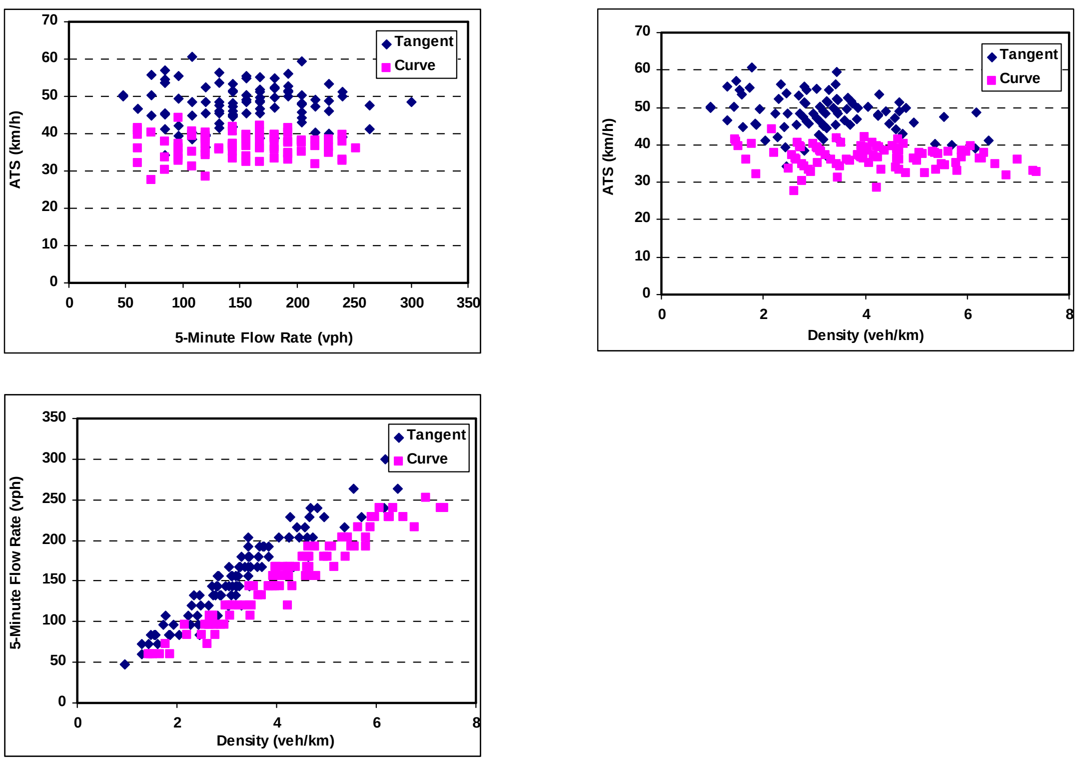

Figure 3. Traffic stream relationships for one study site, at one direction of travel

4. Capacity Estimation Methodology

Capacity estimation methodology can be divided into two categories: the direct empirical methods, based on observed traffic flow characteristics; and indirect empirical methods, based on guidelines and simulation models (Minderhoud et al., 1997)[13]. The direct methods include estimation with headways, estimation with traffic volumes and speeds, and estimation with traffic volumes, speeds and densities. In this paper, the direct-empirical methods based on the observed volumes, speeds and densities was used. In the direct methods, capacity is measured directly from the traffic data if a road section forms a bottleneck or estimated by extrapolating free-flow observations. Harwood et al. (1999)[14]. developed the HCM 2000 methodology for two-lane, two-way highways. They indicated that capacity conditions are difficult to observe because there are very few two-lane two-way highways operating over capacity. In this paper, the critical density can be extrapolated mathematically until the maximum of the q-k function is reached.

The flow-density relationship has been shown by Van Arem et al. (1994)[15] and Minderhoud et al. (1998)[16]. to have a quadratic function, where density (k) is used as the control parameter and flow (q) the objective function, as shown in the following equation: $q = -\beta_0 + \beta_1 k - \beta_2 k^2$.

The capacity theory underlying the relationship dictates that concavity in the flow density curve must be present for validity. To satisfy the concavity requirement of the flow-density curve, the coefficients signs must return a negative sign or zero for coefficients β_2 and β_0 and a positive sign for β_1, as in the above equation. In theory, where the flow-density relationship has been used to compute roadway capacity, the critical density is reached, when flow becomes maximum, at the summit point.

As the main subject is estimating the capacity change due to road geometry, the choice of precise value of critical density is fundamental to the outcome of this study. By maximizing flow critical density, the capacity can be computed.

Traffic capacity can be calculated by the way of quadratic function and the point of the extrapolated curve represents the capacity. This point is a function of critical density and determined by differentiating flow with respect to density.

The effect of different types of vehicles within a traffic stream is considered by converting vehicles into passenger car units (PCU). Several methods are available in the literature to calculate the PCU values. The methods may include headway ratio, speed parameters and actual delay. Speed and vehicles area on the road is another method for calculating PCU. Krammes and Crowley (1986)[17] indicated that the variables used to define the LOS should be used to estimate the PCU values also. The LOS of a highway segment is defined in terms of operating speed (TRB, 2000)[1]. For that reason, speed is considered a key variable to determine the relative effect of individual vehicles on the traffic stream in terms of the PCU. Chandra and Sikdar (2000)[18] stated that, the projected rectangular area of each vehicle is considered also another prime variable to determine the PCU. The physical size of a vehicle indicates the pavement occupancy which is crucial in traffic operation. Therefore, the PCU of a vehicle type can be given according to Chandra and Kumar [5] by the following equation:

$$\mathrm{PCU_i} = \frac{V_c / V_i}{A_c / A_i}$$

where:

V_c and V_i = mean speeds for cars and type i vehicles, respectively; and
A_c and A_i = their projected rectangular areas (length × width) on the road.

In this paper, the PCU values were estimated based on the previous equation at each site for each element separately (i.e. tangent, curve) as this could reflect the effects of road geometry on roadway capacity. The results of the PCU values for the four vehicle categories (motorcycles (MC), Light good Vehicles (LGV), Heavy Good Vehicles (HGV) and Buses (BUS)) vary from 0.22 to 0.30, 1.4 to 1.79, 3.9 to 6.0, and 3.0 to 4.0, for each category respectively.

5. Data Results

5.1 Estimation of Capacity and Capacity Loss

The analysis is based on observations of one-direction of traffic flow (from tangent to curve), as indicated in Figure 2. The steps to determine the capacity loss between tangent and succeeding horizontal curve elements at one of the study sites are presented, as follows:

Step 1: Using tangent and curve data, traffic volumes for each 5-minute interval for each vehicle class were converted to 5-minute flow rates in (vph), after applying the PCU values. Densities were calculated in (veh/km) using the following relation:

$$\textit{Density } (k) = \textit{Flow } (q) \,/\, \textit{Average Travel Speed (ATS)}$$

Step 2: The quadratic relationships between flow and density were calibrated and the model coefficients for both tangent and curve were determined as:

$$q_{tangent} = -ß_o + ß_1\, k - ß_2\, k^2 = -16.90 + 75.02\, k - 1.18\, k^2$$

$$q_{curve} = -ß_o + ß_1\, k - ß_2\, k^2 = -11.34 + 79.83\, k - 1.66\, k^2$$

The models coefficients have the signs that satisfy the concavity requirements; also they were significantly different from zero at the 95% confidence level as the t-test statistics greater than (±1.96). Also the resulting coefficients of determinations (R^2) are 0.94 and 0.90 for tangent and curve respectively.

Step 3: By differentiating q with respect to K; for a maximum value of flow (q): $\partial q/\partial K = 0$, the critical densities for both straight and curve were determined as :

$$K_{critical\ (tangent)} = 75.02 / (2 \times 1.18) = 30.70 \text{ PCU/km}$$

$$K_{critical\ (curve)} = 79.83 / (2 \times 1.66) = 24.05 \text{ PCU/km}$$

Step 4: The computed critical densities were substituted into the quadratic equations in step 2 to determine the maximum flow per road elements as follows : $q_{max\ (tangent)}$ = 1172 PCU/h; and $q_{max\ (curve)}$ = 948 PCU/h. Therefore the capacity loss at this site = 1172- 948 = 224 PCU/h and consequently the percentage of Loss = 224/ 1172= 19.1 %.

These steps were applied to all sites for both tangents and curves. The resulting models, in the majority of the cases, have the expected signs and the coefficients of determinations (R^2) are in general greater than 0.85. Table 4 summarizes the capacity values for both curve and tangent elements and the percentage of capacity loss in each site.

Table 4. Capacity values and percentage of capacity loss in each site.

Site no.	Capacity at tangent elements (PCU/h)	Capacity at curve elements (PCU/h)	Capacity Loss (%)

1	1172	948	19.1
2	N. A	N. A	-
3	1199	1150	4.1
4	1130	1007	10.9
5	1044	919	12.0
6	940	611	35.0
7	983	736	25.1
8	N. A	N. A	-
9	893	622	30.3
10	994	732	26.4
11	N.A	N.A	-
12	953	634	33.5

N.A. refereeing to sites with model coefficients have not the signs that satisfy the concavity requirements. Therefore, these sites were removed from the analysis.

Looking to results presented in Table 4 indicates that capacity values at all sites didn't reach the HCM 2000 value (1700 PCU/h for one direction under ideal condition). This could be due to several reasons, as follows:

- All roads are classified as class II, according to the HCM 2000, which serves shorter trips;
- All roads have posted low speed limit of 60 km/h. Polus et al. (2000)[19] stated that speed limit can explain more than 50 percent of the variability in operating speed;
- The site characteristics are relatively far from the ideal conditions;
- The nature of study roads (agriculture roads), with restricted circumstances from the two directions (i.e. trees), may affect the forward visibility and therefore the capacity values; and
- Capacity depends on roadway, traffic and driver behaviour conditions. Therefore, the values obtained could reflect the conditions for road, traffic and driver characteristics of the area under study.

Based on the results in Table 4, it can be noticed that the percentage of capacity loss was mainly depending on the radius of horizontal curve (see also Tables XX). However, this was verified statistically using the appropriate statistical analysis, as in Section 5.3.

5.2 Impact of Road Geometry on Capacity

To investigate the relationship between horizontal alignment characteristics and capacity values for the two elements (tangent and curve), correlation and regression analyses were used.

Tangent Elements

Correlation coefficients between horizontal alignment characteristics and capacity values for tangent elements, using data presented in Tables 1 and 4 , are shown in Table 5.

Table 5: Correlation coefficients between capacity and tangent characteristics

Tangent Characteristics	LW**	RSW	CW***	TL	SA	FV
Capacity	0.98*	0.70*	0.97*	0.90*	-0.10	0.90*

*Correlation is significant at the 0.05 level (2-tailed).
**Lane Width (LW) = Pavement Width (PW)/2
***Carriageway Width = LW+RSW+LSW

All tangent characteristics showed directly proportional and significant relationships with capacity except number of side access points that showed inversely proportional correlation, as expected.

A linear regression analysis was conducted to produce several models between tangent characteristics (independent variables) and capacity (dependent variable). Details of the best regression models found are shown in Table 6.

Table 6: Results of the best regression models between capacity and tangent elements

Model #	Variable (s)	Constant	LW	RSW	CW	T_L	FV	R^2 F(p-value)
1	Coefficient	-914.83	596.45					0.95
	t (p-value)	-5.2(0.001)	11.1(0.000)					124.12(0.00)
2	Coefficient	628.78				0.616		0.81
	t (p-value)	8.2(0.0)				5.4(0.001)		29.58(0.001)
3	Coefficient	752.34					1.02	0.82
	t (p-value)	14.1(0.00)					5.56(0.001)	30.93(0.001)
4	Coefficient	-809.67	520.90	95.18				0.98
	t (p-value)	-6.7(0.001)	12.2(0.00)	3.2(0.02)				146.44(0.00)
5	Coefficient	456.22		165.17		0.50		0.93
	t (p-value)	6.1(0.001)		3.16(0.02)		6.1(0.001)		38.78(0.00)
6	Coefficient	571.0		156.04			0.84	0.92
	t (p-value)	7.5(0.00)		2.8(0.03)			5.7(0.001)	34.1(0.001)
7	Coefficient	-19.13			94.86	0.23		0.99
	t (p-value)	-0.3(0.81)			8.8(0.00)	4.2(0.006)		213.8(0.00)
8	Coefficient	-437.49	363.63	105.89		0.19		0.998
	t (p-value)	-7.3(0.001)	15.1(0.000)	11.4(0.000)		7.8(0.001)		1079.8(0.00)
9	Coefficient	-457.06	387.50	101.71			0.27	0.992
	t (p-value)	-2.9(0.035)	6.6(0.001)	4.7(0.005)			2.6(0.046)	196.9(0.000)

Based on Table 6, the best single variable model found was as follows:

$$Capacity = -914.83 + 596.45(LW).$$

The resulting coefficient of determinations (R2) of 0.95 is considered good which reflects a high goodness-of-fit of the model. It is also found significant at the 95% confidence level as the significance of F static < 0.001. Also, the coefficient of independent parameter LW (lane width) was significantly different from zero at the 95% confidence level as the t-value equals 11.0. The model has a logical explanation for the effect of lane width on capacity. The positive sign means that as the lane width increases, the capacity increases. In other words, drivers tend to increase their speeds as lane width increases. Thus, capacity also increases.

The best multivariate model found for predicting capacity was as follows:

$$Capacity = -437.49 + 363.63(LW) + 105.89(RSW) + 0.19(T_L)$$

The resulting coefficient of determinations (R2) and the significance of F statistic equaled 0.998 and < 0.001 respectively, which reflects a high goodness-of-fit of the model and the significance of model for use in predication. The coefficient of independent variables LW (lane width), RSW (right shoulder width) and TL (tangent length) were significantly different from zero at the 95% confidence level as the t-value equals 15.1, 11.4 and 7.8, respectively. The model has a logical explanation for the effect of independent variables on capacity. The positive signs mean that as lane width, right shoulder width and tangent length increase, capacity increases. The result of best multivariate model was presented in Figure 4. This figure can be used easily to estimate the tangent directional capacity given the lane width, the shoulder width and the tangent width. For example, if the lane width equals 2.6m, shoulder width equals, 1.5m and tangent length equals 900m, and then the capacity at tangent will equal 838PCU/h.

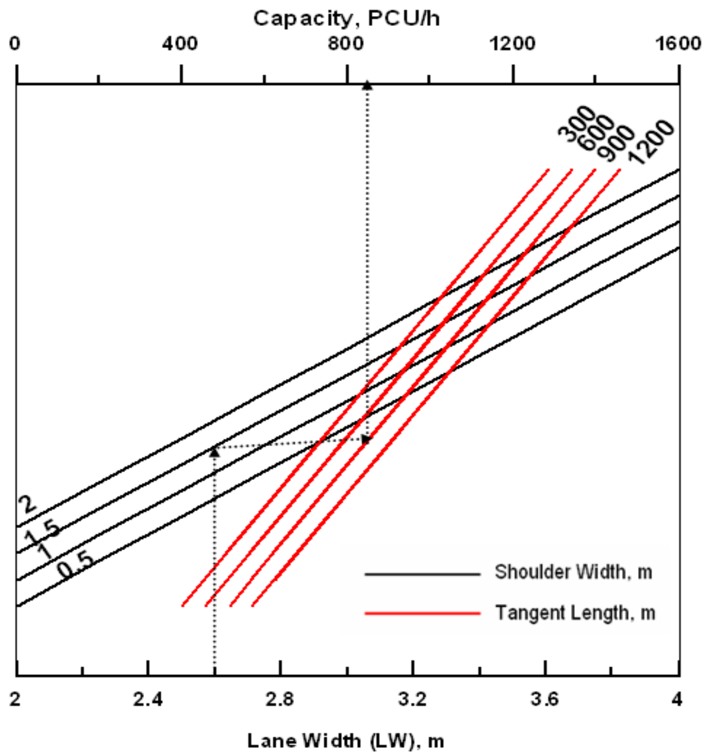

Figure 4. Determination of capacity at tangent elements

There are other models that can be used in predicting capacity as indicated in Table 6. These models are presented in this table to use the suitable one according to the available data.

Curve Elements

Correlation coefficients between curve characteristics and capacity values are shown in Table 7.

Table 7: Correlation coefficient between capacity curve characteristics

Variables	LW	RSW	CW	R	**L_{PT}	L	FV	Δ	e_{max}

Capacity	**0.73***	0.55	**0.87***	**0.93***	**0.81***	**0.71***	0.59	-0.65	-0.11

**Correlation is significant at the 0.05 level (2-tailed).*
*** L_{PT} = length of preceding tangent*

Based on Table 7, all horizontal alignment characteristics showed highly significant correlations with capacity except right shoulder width, forward visibility, deflection angle and superelevation. Deflection angle and superelevation showed inversely proportional with capacity. The remaining horizontal alignment characteristics for curve element showed directly proportional with capacity.

Linear regression analysis was conducted to produce several models between horizontal alignment characteristics of curve elements and capacity values. Details of the best single and multiple regression analysis of the models are shown in Table 8.

Table 8: Results of the best regression models between capacity and curve characteristics

Model #	Variable (s)	Constant	LW	CW	R	L_{PT}	L	R^2 F(p-value)
1	Coefficient	-1520.65	693.18					0.53
	t (p-value)	-1.8(0.11)	2.8(0.027)					7.8(0.027)
2	Coefficient	-1760.95		257.23				0.75
	t (p-value)	-3.2(0.016)		4.6(0.002)				21.4(0.002)
3	Coefficient	540.17			1.1			0.87
	t (p-value)	11.3(0.0)			6.8(0.00)			46.2(0.00)
4	Coefficient	142.2				1.01		0.65
	t (p-value)	0.7(0.49)				3.6(0.009)		12.9(0.009)
5	Coefficient	555.99					1.69	0.50
	t (p-value)	5.0(0.001)					2.7(0.033)	7.0(0.033)
6	Coefficient	-603.82	354.44		0.89			0.98
	t (p-value)	-2.7(0.035)	5.2(0.002)		10.6(0.00)			121.3(0.00)
7	Coefficient	-580.91		120.58	0.75			0.94
	t (p-value)	-1.6(0.17)		3.0(0.024)	4.7(0.003)			53.9(0.00)

The best single variable model found was as follows:

$$Capacity = 540.17 + 1.1(R)$$

The resulting coefficient of determinations (R2) of 0.87 is considered good. It is also found significant at the 95% confidence level as the significance of F statistic < 0.001.

The coefficient of independent parameter R (curve radius) was significantly different from zero at the 95% confidence level as the t-value equals 6.8. The t-value showed the relative importance of variables in model, as the greater the t-value, the greater the contribution of the variables to the model. The model has a logical explanation for the effect of curve radius on capacity. The positive sign means that as the curve radius increases, the capacity increases. In other words, drivers tend to increase their speeds as curve radius increases. Thus, capacity also increases.

The best multivariate model found for predicting capacity was as follows:

$$Capacity = -603.82 + 354.44(LW) + 0.89(R)$$

The resulting coefficient of determinations (R2) is 0.98 which is greater than that of the single variable model, and it was found significant at 95% confidence level as the significance of the F statistic < 0.001. The coefficients of the independent variables are LW (lane width) and R (curve radius). It can be noticed from Table 8 that the hypothesis that each of the coefficients is equal to zero can be rejected at the 95% confidence level as the t-value is greater than ±1.96. The model has a logical explanation for the effect of the independent variables (lane width and curve radius) on predicting capacity. The positive sign of the independent variable (lane width) means that as lane width increase, the capacity increases, as expected. The positive sign of the independent variable (curve radius) means that as curve radius increases, capacity increases.

The results of best multivariate model are summarized in Figure 5. This figure can be used easily to estimate the capacity at curve elements. Example of using this figure is presented in black arrows. For example, if the lane width equals 3.1m and curve radius equals 500m, the capacity at curve elements will equal 940 PCU/h.

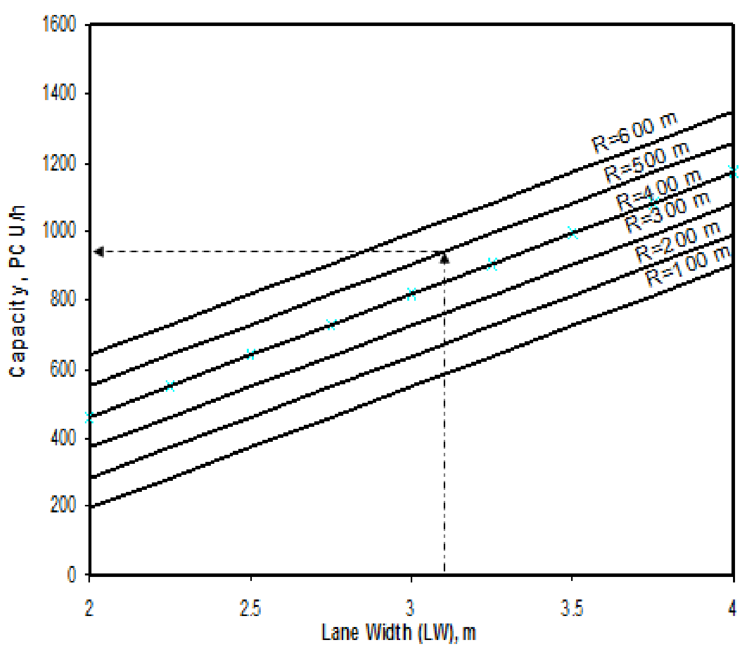

Figure 5. Determination of capacity at curve elements

There are other models that can be used in predicting capacity as indicated in Table 8. These models are presented in this table to use the suitable one according to the available data.

5.3 Impact of Road Geometry on Capacity Loss

For the impact of horizontal alignment characteristics on capacity loss between two successive elements, tangent and succeeding horizontal curve, data in Tables 1, 2 and 4 were used to investigate the relationships between them. The horizontal alignment characteristics in Table 9 include difference in lane width, difference in right shoulder width, carriageway width at curve element, curve length, preceding tangent length, curve radius, forward visibility at curve elements and superelevation, as well as capacity loss.

Correlation analysis was used to investigate the correlation coefficients between capacity loss and all variables. The results are presented in Table 9.

Table 9: Correlation coefficient between percent of capacity loss and horizontal alignment characteristics

	Δ_{LW}	Δ_{RSW}	CW_{curve}	L	T_{PT}	R	FV	e_{max}
Capacity loss	0.21	0.43	**-0.80***	-0.66	**-0.76***	**-0.96***	-0.63	0.18

**Correlation is significant at the 0.05 level (2-tailed).*
where:
$\Delta_{LW} = LW_{curve} - LW_{tangent.}$
$\Delta_{RSW} = RSW_{curve} - RSW_{tangent.}$

The most important observations that can be discerned from Table 9 are:

Curve radius, carriageway width and preceding tangent length showed highest and most significant correlations with percentage of capacity loss, respectively. However, difference in lane width, difference in right shoulder width, curve length, forward visibility and superelevation showed lowest correlations.

Carriageway width, curve radius and preceding tangent length showed inversely proportional with percentage of capacity loss. It means that as preceding tangent length, curve radius and carriageway width increase, capacity loss decreases.

Difference in lane width and difference in right shoulder width showed directly proportional with percentage of capacity loss. This is illogical explanation for the effect of increasing width of lane and shoulder on capacity loss. This may need more data for reexamination.

To quantify the impact of horizontal alignment characteristics on capacity loss, linear regression was used to produce several models that indicate the relationship between capacity loss (dependent variable) and horizontal alignment characteristics (independent variables). Table 10 shows the best regression models for the highest correlation variables.

Table 10: Results of the best regression models between capacity loss and horizontal curve design elements

	Model #	Variables	Constant	CW_{curve}	R	T_{PT}	R^2 F(p-value)
%Capacity Loss	1	Coefficient	155.26	-13.31			0.64
		t (p-value)	4.1(0.005)	-3.5(0.009)			12.5(0.009)
	2	Coefficient	37.81		-0.0633		0.91
		t (p-value)	17.6(0.00)		-8.7(0.00)		76.2(0.00)
	3	Coefficient	57.70			-0.0535	0.58
		t (p-value)	4.9(0.002)			-3.1(0.017)	9.7(0.017)

The best model found was as follows:

$$\%CapacityLoss = 37.81 - 0.0633(R)$$

where:

R= curve radius (m)

The resulting coefficient of determinations (R^2) of 0.92 is considered good which reflects a high goodness-of-fit of the model. It was also found significant at the 95% confidence level as the significance of F statistics < 0.001.

The coefficient of independent parameter (curve radius) was significantly different from zero at the 95% confidence level as the t-value equals -8.70. The model has a logical explanation for the effect of curve radius on capacity loss. The negative sign means that as curve radius decreases, capacity loss increases. In other words, drivers tend to increase their speeds as curve radius increases. Thus, capacity loss decreases. Other single models that can be used for predicting percentage of capacity loss are presented in Table 10.

The results of the best model are summarized in Figure 6. This figure can be used easily to estimate the percentage of capacity loss between two successive elements based on curve radius. Example of using this figure is presented in black arrows. For example, if the curve radius equals 350m, the percentage of capacity loss will equal 15.6%.

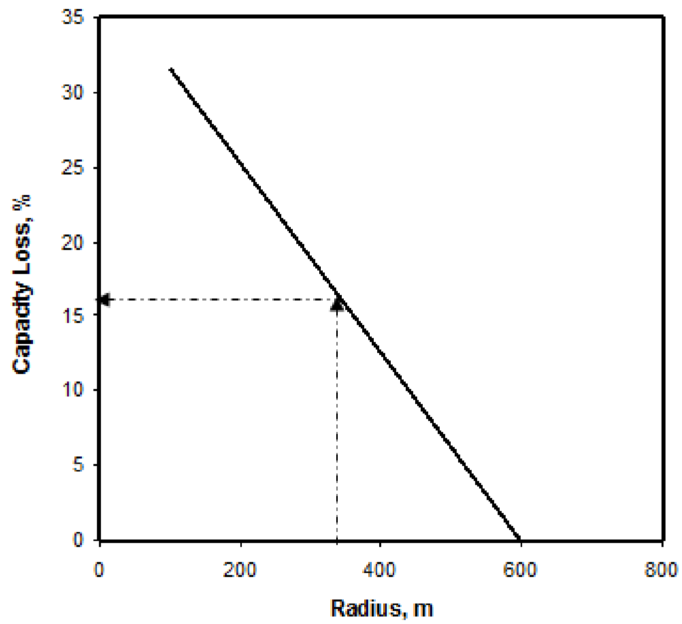

Figure 6. Determination of percentage capacity loss (%)

6. Conclusions

The main goal is to study the impact of horizontal alignment characteristics on capacity and capacity loss on Egyptian roads. This objective can be done by determining capacity loss at two successive elements (i.e. tangent and curve). Road capacity loss for two sections on a road is the negative difference in road capacity between these elements. Hypothetically, it can be suggested that there is a relationship between highway geometry and capacity loss, where capacity loss is the objective function and road geometry is the control parameter. To that effect the study was carried out at 12 selected sites which each site composed of tangent and successive curve. The density was a resultant of average speed and 5- minute flow rate in passenger car units (PCU). The speed- area method is considered the best method to calculate the passenger car units for study sites. The results show that, the PCU values for four categories (motorcycles (MC), Light good Vehicles (LGV), Heavy Good Vehicles (HGV) and Buses (BUS)) vary from 0.20 to 0.30, 1.42 to 1.91, 3.93 to 6.42, and 3.17 to 3.77, respectively.

To estimate capacity, the direct-empirical methods based on the observed volumes, speeds and densities, and relying on the fundamental relationships between these parameters by extrapolating free-flow observations was used. It is noticed that, capacity value at all sites didn't reach to the HCM 2000 value (1700 pc/h for one direction under ideal condition). This may be due to the following reasons:

To calculate capacity loss from real observations, relationships between 5-minute flow rate in passenger car units and density were drawn for study sites. The percentage of capacity loss in the two directions ("to curve and from curve") at the same site was not quite equal. This may be due to the different road characteristics drivers face upstream of horizontal curves compared to those in the other direction (Hashim, 2006).

Graphical and statistical analyses were carried out to investigate the relationships between horizontal alignment characteristics and capacity at two successive elements (tangent, succeeding curve) as well as capacity loss. The investigations were reached the following conclusions and results:

- Correlations were found between horizontal alignment characteristics (lane width, right shoulder width, carriageway width, tangent length and forward visibility) and capacity value at tangent element. However, number of access points was found to have weak correlations with capacity value.
- Regression analysis was used to produce the best relationship between horizontal alignment characteristics (independent variables) and capacity (dependent variable). Single-variable models and multivariate models were developed. Several models were suggested such as:

Although the second model was found the best one, various models were introduced to fit the available site data.

The resulting coefficients of determinations (R^2) of the suggested models reflect a high goodness-of-fit of the models. They are also found significant at the 95% confidence level as the significance of F statistics < 0.001.

- For curve element, correlations were found between horizontal alignment characteristics (lane width, carriageway width, curve radius, curve length and proceeding tangent length) and capacity value. Meanwhile, right shoulder width, forward visibility, deflection angle and superelevation were found to have weak correlations with capacity value.
- Regression analysis was used to produce the best relationship between horizontal alignment characteristics (independent variable) and capacity (dependent variable). Single variable models and multivariate models were developed. Several models were suggested such as the following:

$$Capacity = 540.17 + 1.1(R) \qquad (R^2 = 0.87)$$

$$Capacity = -580.91 + 120.58(CW) + 0.75(R) \qquad (R^2 = 0.94)$$

$$Capacity = -603.82 + 354.44(LW) + 0.89(R) \qquad (R^2 = 0.98)$$

Although the last model was found to be the best one, all models perhaps could be presented for further aid for practitioners.

The coefficients of independent parameters are significantly different from zero at the 95% confidence level as t-test value greater than ±1.96. Also, the resulting coefficients of determinations (R^2) of the suggested models reflect a high goodness-of-fit of the model. They are also found significant at the 95% confidence level as the significance of F statistics < 0.001.

- Correlations were found between horizontal alignment characteristics (curve radius, carriageway width and preceding tangent length) and capacity loss at two elements: tangent and succeeding horizontal curve. On the contrary, change in pavement width, change in right shoulder width, curve length, forward visibility and Superelevation were found to have weak correlations with capacity loss.
- To produce the best relationship between the highest correlation characteristics (independent variables) and capacity loss (dependent variable), regression analysis was used. The best single-variable model found was as follow:

$$\%CapacityLoss = 37.81 - 0.0633(R) \qquad (R^2 = 0.91)$$

The above model has a logical explanation for the effect of the independent variable (curve radius) on predicting capacity loss (dependent variable). The model is found significant at the 95% confidence level as the significance of F statistics < 0.001. Also, the coefficient of curve radius was significantly different from zero at the 95% confidence level as the t-value equals 9.40.

- Finally, the best capacity models at tangent element and succeeding horizontal curve element were evaluated with real observations. The capacity loss between two successive elements was obtained. Also, the suggested capacity loss model was evaluated with real observation. The comparison showed agreement with real observation.

The recommendations for practitioners are as follows:

1) There are a set of proposed figures that can be used easily to estimate the capacity at tangent or at curve as well as the capacity loss between two successive elements.
2) To improve the performance measures on rural two-lane highways:
   a) Road characteristics should be close to the ideal characteristics (i.e. lane width =3.75m, shoulder width = 1.8m, ….etc.).
   b) Number of side access points and driveways should be reduced.
   c) There shouldn't be any trucks in the traffic stream to reduce the percentage of follower vehicles. Private lane should be allowed to heavy vehicles and trucks.
3) The capacity of two-lane, two-way highways was found to be a function of tangent length and curve radius. Compared with the single directional capacity (1,700 pc/h) in the HCM 2000, this study found lower capacity values. To reach this values:
   a. Tangent length should not be less than 1700 m (for straight part); and
   b. The curve radius should not be less than 1000m (for curve part) with lane width of 3.75m. If lane width increases, curve radius will decrease.
4) To reduce the capacity loss between two successive elements (tangent and succeeding horizontal curve), a curve radius of 600 m is a threshold value of the horizontal which seems to be a critical value from the traffic performance point of view

References

1) Transportation Research Board (TRB). Highway Capacity Manual (HCM). 4th edition. TRB, National Research Council, Washington, D.C., 2000.
2) Polus, A., Craus, J., and Livneh M. (1991). "Flow and Capacity Characteristics on Two-Lane Rural Highways." Transportation Research Record, Transportation Research Board, National Research Council, Washington, D.C., 1320, 128-134.
3) Nakamura, M. (1994). "Research and Application of Highway Capacity in Japan." 2nd International Symposium on Highway Capacity, Sydney, Australia, 103–112.
4) Gibreel, G., El-Dimeery, I.A., Hassan, Y. and Easa, S.M. (1999). "Impact of Highway Consistency on Capacity Utilization of Two-Lane Rural Highways." Canadian Journal of Civil Engineering, 26(6), 789-798.
5) Chandra, S., and Kumar, U. (2003). "Effect of Lane Width on Capacity under Mixed Traffic Conditions in India." Journal of Transportation Engineering, ASCE, 129(2), 155-160.
6) Yang, X., and Zhang, N. (2005). "The Marginal Decrease of Lane Capacity with the Number of Lanes on Highway." Proceedings of the Eastern Asia Society for Transportation Studies, Vol. 5, 739 - 749.

7) Ben-Edigbe, J. and Ferguson, N. (2005) "Extent of Capacity Loss Resulting from Pavement Distress." Proceedings of the Institution of Civil Engineers: Transport, 158 (TR1), 27-32.
8) Chandra, S. (2004)." Effect of Road Roughness on Capacity of Two-Lane Roads." Journal of Transportation Engineering, ASCE,130(3), 360-364.
9) Chin, S. M., Franzese, O., Greene, D. L., Hwang, H. L., and Gibson, R. C. (2002). "Temporary Losses of Highway Capacity and Impacts on Performance." U.S. Department of Energy (DOE) Information Bridge, 04-209, (Website: http://www.osti.gov/bridge).
10) Kim, J., and Elefteriadou, L. (2010). "Estimation of Capacity of Two-Lane Two-Way Highways Using Simulation Model." Journal of Transportation Engineering, ASCE, 136(1), 61-66.
11) Hashim, I. H. (2006). "Safety and the Consistency of Geometry and Speed on Rural Single Carriageways." PhD Thesis, School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, United Kingdom.
12) Hashim, I. H. (2011). "Analysis of Speed Characteristics for Rural Two-Lane Roads: A Field Study from Minoufiya Governorate, Egypt." Ain Shams Eng. J. doi:10.1016/j.asej.2011.05.005.
13) Minderhoud, M., Botma, H., and Bovy, P. (1997). "Assessment of Roadway Capacity Estimation Methods." Transportation Research Record Transportation Research Board, National Research Council, Washington, D.C., 1572, 59-67.
14) Harwood, D., May, AD., Anderson, I., Leiman, L., and Archilla, R. (1999). "Capacity and Quality of Service of Two-Lane Highways." Midwest Research Institute, Final Report, NCHRP Project 3-55(3).
15) Van Arem, B., Van Der Vlist, M. J, De Ruiter, J. C., Muste, M., and Smulders, S. A. (1994). "Design of the Procedures for Current Capacity Estimation and Travel Time and Congestion Monitoring." DRIVE-11 Project V2044, Commission of the European Communities, (CEC).
16) Minderhoud, M., Botma, H., and Bovy, P. (1998). "Roadway Capacity Using the Product-Limit Approach." 77th Annual Meeting of the Transportation Research Board, Washington D.C.
17) Krammes, R. A., and Crowley, K. W. (1986). ‘‘Passenger Car Equivalents for Trucks on Level Freeway Segments." Transportation Research Record Transportation Research Board, National Research Council, Washington, D.C., 1091,10-16.
18) Chandra, S., and Sikdar, P. K. (2000). "Factors Affecting PCU in Mixed Traffic on Urban Roads." Road and Transport Research, ARRB, Australia, Vol. 9, No. 3, 40-50.
19) Polus, A., Fitzpatrick, k., and Fambro, D. (2000)."Predicting Operating Speeds on Tangent Sections of Two-Lane Rural Highways." Transportation Research Record Transportation Research Board, National Research Council, Washington, D.C., 1737, 50-57.