JOURNAL OF TRANSPORTATION
SYSTEMS ENGINEERING AND INFORMATION TECHNOLOGY
Volume 12, Issue 5, October 2012
Online English edition of the Chinese language journal

**Cite this article as:** J Transpn Sys Eng & IT, 2012, 12(5), 65−75.

RESEARCH PAPER

# Effect of Highway Geometric Characteristics on Capacity Loss

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**Abstract:** The estimation of roadway capacity is essential in the planning, designing, and operation of highway facilities. This paper aims at assessing the influence of highway geometric characteristics on capacity at tangents and horizontal curves as well as on capacity loss at the change from tangent to curve. Traffic and geometry data obtained from twelve rural, two-lane road sites in Minoufiya Governorate, Egypt, were used. Each site consists of a tangent element and the succeeding horizontal curve. Vehicle flows and speeds were collected at each element in the study sites. A capacity estimation method that was based on extrapolation from a fundamental diagram which represented the relationship between traffic flow and density was used. The effect of different vehicle types was accommodated for by converting them into equivalent passenger car units. Regression analysis was used to investigate the relationships between geometric characteristics and capacity. The best regression models for each case (i.e. capacity at tangents, capacity at curves, and capacity loss between the two elements) were introduced. For tangents, the significant independent variables are lane width, shoulder width, and tangent length. In the case of curves, the significant variables are curve radius and lane width. The best model that exhibits the relationship between capacity loss and geometry characteristics includes only curve radius, which functions as an independent variable. The models are very useful and can be used to deal with capacity analysis as well as for the evaluation of rural, two-lane roads, especially for the area under study.

**Key Words:** highway transportation; capacity; highway geometry; horizontal curve; flow-density relationship; regression analysis

## 1 Introduction

The estimation and knowledge of roadway capacity are essential in the planning, designing, 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”[1]. Roadway conditions may consist of various geometric parameters that describe roadways, such as the type of facility, lane width, shoulder width, and horizontal and vertical alignments. Horizontal alignment, especially horizontal curve characteristics, can have a substantial impact on traffic flow. For example, on sharp curves, vehicles may either 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 which can be achieved. Therefore, capacity flows may vary from one element to another. Roadway capacity loss for two successive elements is the negative difference in road capacity between both these elements. This study supposes that the capacity value is affected by highway geometry, as indicated in Fig. 1, when the 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, especially curve radius, on capacity loss. The present study was undertaken to estimate the impact of highway geometry, with specific reference to horizontal alignment characteristics, on capacity and capacity loss using

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Received date: Oct 28, 2011; Revised date: Jan 31, 2012; Accepted date: Mar 9, 2012
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DOI: 10.1016/S1570-6672(11)60223-7

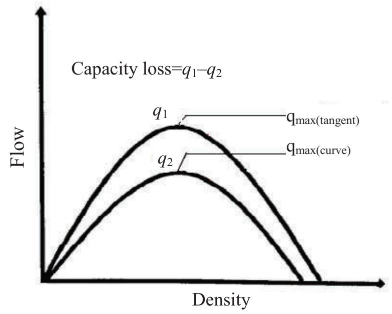

Fig. 1 Influence of road geometry on flow-density relationship

traffic and geometry data from rural, two-lane roads in Minoufiya Governorate, Egypt. The results of this research should help highway and traffic engineers as well as researchers to deal with capacity analysis in a more accurate manner.

## 2 Background studies

In this section, previous studies that dealt with the impact of roadway characteristics on capacity and capacity loss were reviewed. Polus *et al.*[2] investigated the impact of traffic flow and capacity characteristics on two-lane highways. Several models were developed for studying 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[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 being $YL=0.24WL+0.22$.

Gibreel *et al.*[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 a ratio ranging from 0.74 to 0.98. Gibreel *et al.*[4] argued that the difference is due the inconsistencies in geometric design. Therefore, a new adjustment factor called the consistency factor is developed to account for the difference.

Chandra and Kumar[5] investigated the impact of lane width on capacity using data from ten sections of two-lane roads in India. They found that the capacity ($C$) in PCU/h of two-lane roads increases with total width ($W$) of the carriageway, and the relationship between the two follows a second-degree curve, such as $C=-2184-226W^2+8574W$. 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[6] investigated the impact of the number of lanes on highway capacity using field traffic flow data obtained from Beijing. The findings showed that average capacity per lane decreases by increasing the number of lanes on uninterrupted highway segments. Thus, the marginal decrease rate of average capacity per lane by increasing the number of lanes is around 6.7%.

Ben-Edigbe and Ferguson[7] investigated the impact of road condition, pavement distress, on capacity and capacity loss at two-way roads based on observations from eight sites in Nigeria. A capacity estimation method that was based on extrapolation from a fundamental diagram which represented 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. In addition, Chandra[8] studied the effect of road roughness on the capacity of two-lane roads in India using eight road sections. The study found that the free flow speed of a vehicle decreases with the roughness of the road surface. The effect of roughness is more apparent in the speed of passenger cars than in heavy vehicles. The speed–volume relationships drawn at different sections of two-lane rural roads indicate that the capacity decreases with an increase in the road roughness.

Chin *et al.*[9] investigated the impact of temporary events on capacity loss. In 1999, 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. Assuming an average vehicle occupancy of 1.6 people, this translates into 3.7 billion person hours of delay.

Kim and Elefteriadou[10] developed a new microscopic simulation model called TWOSIM that was used for the estimation of capacity for a two-way, two-lane highway (TWTLHW) under a variety of prevailing traffic and geometric conditions. Kim and Elefteriadou concluded that the capacity for TLTWHW using field data has not been frequently observed, because there are a very limited number of sites operating at capacity. The simulation results showed that the capacity was found to vary according to the average free flow speed. Some other results were found, such as capacity decreasing by 12%–26% as a function of the turning curb radius and the percentage of turning flow when there was a driveway. A summary of reviewed studies is in Table 1.

## 3 Data collection and preparation

### 3.1 Site selection

This paper used twelve road sites with various geometric characteristics from intercity, rural, two-lane roads, in Minoufiya Governorate, Egypt, with a speed limit of 60 km/h. Each site consisted of one tangent (straight section) and the succeeding horizontal curve. All the chosen sites are located on relatively level terrain to minimize or avoid the effect of the longitudinal gradient.

Table 1 Summary of purposes and main findings of previous studies

| Study | Purpose | Main findings |
|---|---|---|
| Polus *et al.*[2] | Develop relationships between flow parameters | The capacity value is sensitive to the geometric characteristics of the site |
| Nakamura[3] | Discuss the concept of highway capacity in Japan | An equation that calculates adjustment factors for lane widths was suggested |
| Gibreel *et al.*[4] | Impact of geometric design consistency on highway capacity | A new adjustment factor called the consistency factor is developed |
| Chandra and Kumar[5] | Impact of lane width on capacity | The relationship between capacity and lane width follows a second-degree curve |
| Yang and Zhang[6] | Impact of number of lanes on highway capacity | Average capacity per lane decreases by increasing the number of lanes |
| Ben-Edigbe and Ferguson[7] | Impact of pavement distress on capacity and capacity loss | Capacities on without distress and with distress sections differed significantly |
| Chandra[8] | The effect of road roughness on capacity | Capacity decreases with an increase in the road roughness |
| Chin *et al.*[9] | Impact of temporary events on capacity loss | Temporary capacity losses cause billions of person hours of delay |
| Kim and Elefteriadou[10] | Estimation of capacity for two-way, two-lane highway | Simulation results show that capacity was found to vary according to traffic and geometric characteristics |

Table 2 Statistics of geometric characteristics for tangent elements

| Tangent Characteristics | Max. | Min. | Avg. | SD |
|---|---|---|---|---|
| Lane width (LW), m | 3.5 | 2.80 | 3.23 | 0.23 |
| Shoulder width, averaged from both directions (SW), m | 1.9 | 1.2 | 1.44 | 0.25 |
| Tangent length (TL), m | 904 | 180 | 586.83 | 219.36 |

Table 3 Statistics of geometric characteristics for curve elements

| Curve characteristics | Max. | Min. | Avg. | SD |
|---|---|---|---|---|
| Lane width (LW), m | 3.65 | 3 | 3.33 | 0.19 |
| Shoulder width, averaged from both directions (SW), m | 1.95 | 1.30 | 1.58 | 0.20 |
| Curve radius (R), m | 586 | 100 | 237.25 | 148.56 |

### 3.2 Highway geometry estimation

All geometry data were estimated using automatic and manual field surveys. The road geometry characteristics that were estimated in the field include lane width, shoulder width, tangent length, and curve radius. Tables 2 and 3 depict the summary statistics of the geometric characteristics for tangent and curve elements.

### 3.3 Traffic surveys

Traffic data were obtained on working days during the daylight hours with clear weather and dry pavements. Roadside automatic traffic counters were used to conduct the traffic surveys for at least 7 hours at the 12 sites. The configuration of the counter positions is presented in Fig. 2. Based on this configuration, the traffic data were collected at the midpoint of the tangent (point A) preceding the curve, and at the midpoint of the curve (point B). The collected traffic data include time of vehicle arrival, vehicle class, and vehicle speed.

### 3.4 Preliminary analysis of traffic surveys

Since this study considers the traffic flow in the direction from tangent to curve (from A to B), the data set at this direction of travel, at each point (A and B) for each site, was divided into 5-min intervals. In each interval, vehicle counts were multiplied by 12 to convert them into flow rates (veh/h). The traffic survey durations and maximum flow rates during the survey durations for each element at each site are provided in Table 4.

The average travel speed of all vehicles at each 5-min interval was calculated in (km/h). Subsequently, the density (veh/km) can be calculated from the following equation:

$$\text{Density } (K) = \textit{Flow rate } (q) / \textit{Average travel speed } (ATS)$$

Then, the flow rate-density relationship can be drawn. Fig. 3 presents an example of the relationship between flow rate and density at one of the study sites for both elements (tangent and curve), for the direction from point A to point B; other sites show relatively similar patterns. The relationship shows that the traffic stream is in an uncongested state, as these roads usually carry relatively low traffic volumes[11]. This also agrees with the conclusion proposed by Kim and Elefteriadou[10] that the capacity for two-lane roads using field data has not been frequently observed. The relationships also show the impact of horizontal alignment/element type (tangent, horizontal curve) on traffic flow parameters.

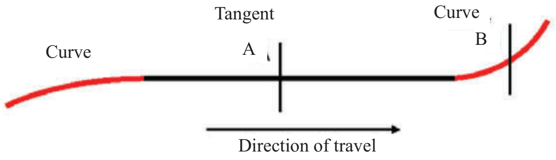

Fig. 2 Position of automatic traffic counters for study sites

Table 4 Data collection durations and maximum flow rates at survey sites

| Site No. | Duration of data collection (h) | Max. 5-min. flow rate (vph) | |
|---|---|---|---|
| | | Tangents | Curves |
| 1 | 8.25 | 420 | 336 |
| 2 | 8.25 | 240 | 216 |
| 3 | 8.10 | 300 | 252 |
| 4 | 8.10 | 576 | 324 |
| 5 | 8.10 | 384 | 324 |
| 6 | 8.00 | 420 | 324 |
| 7 | 8.00 | 804 | 600 |
| 8 | 7.33 | 216 | 204 |
| 9 | 7.35 | 132 | 120 |
| 10 | 8.25 | 168 | 156 |
| 11 | 9.45 | 168 | 156 |
| 12 | 8.00 | 300 | 252 |

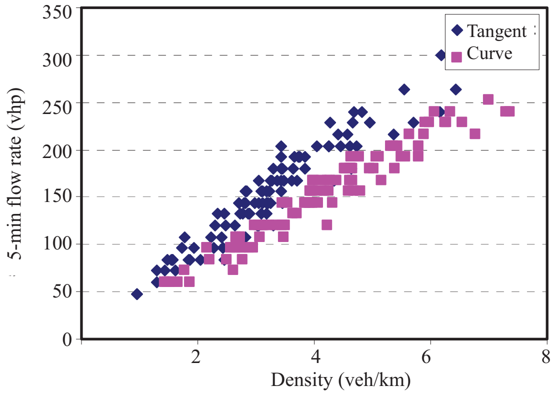

Fig. 3 Flow rate and density relationship for one study site, at one direction of travel

## 4 Capacity and passenger car unit estimation Methodologies

Roadway capacity is a very important factor that is used in highway planning, designing, and evaluation of operational performance[12,13]. 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[14]. In this paper, the direct-empirical method that was based on the observed volumes, speeds, and densities was used. In this method, capacity is either measured directly from the traffic data, if a road section forms a bottleneck, or estimated by extrapolating uncongested flow observations. Harwood *et al.*[15], who developed the HCM 2000 methodology, for two-lane, two-way highways indicated that capacity conditions are difficult to observe, because there are very few two-lane, two-way highways operating over capacity. Since this is the situation in this paper, as can be observed in Table 4 and Fig. 3, the critical density can be extrapolated mathematically until the maximum of the flow-density relationship is reached.

The flow-density relationship has been depicted by van Arem *et al.*[16] and Minderhoud *et al.*[17] as having a quadratic form. In this form, density ($k$) is used as the control parameter and flow rate ($q$) is used as 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 should be present for validity. To satisfy the concavity requirement of the flow-density curve, the coefficients signs should return a negative sign or zero for coefficients $\beta_2$ and $\beta_0$ and a positive sign for $\beta_1$, as in the equation cited earlier[7]. In theory, where the flow-density relationship has been used to compute roadway capacity, the critical density is reached, when the flow becomes maximum, at the summit point. In this paper, 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 is determined by differentiating the flow with regard to density. It is worth mentioning that this method was applied earlier by Ben-Edigbe and Ferguson, in a different application[7].

The effect of different types of vehicles within a traffic stream is considered by converting the vehicles into passenger car units (PCU). Several methods are available in the literature for calculating the PCU values. The methods may include headway ratio, speed parameters, and actual delay. Speed and vehicles area on the road is another method that is used for calculating PCU[5,18]. Krammes and Crowley[19] indicated that the variables used to define the level of service (LOS) should be used to estimate the PCU values as well. The LOS of a highway segment is defined in terms of operating speed[1]. Accordingly, speed is considered a key variable that is used for determining the relative effect of different types of vehicles on the traffic stream. Chandra and Sikdar[18] stated that the projected rectangular area of each vehicle is also considered another prime variable for determining the PCU. The physical size of a vehicle indicates the pavement occupancy, which is crucial in traffic operation. Therefore, according to Chandra and Kumar[5], the PCU of a vehicle type can be calculated by the following equation:

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

where $V_c$ and $V_i$ are mean speeds for cars and type $i$ vehicles, respectively; $A_c$ and $A_i$ are 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 (tangent and 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 Analysis and 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 Fig. 2. The steps that determine the capacity loss between the tangent and the succeeding horizontal curve elements at one of the study sites are presented as follows:

Step 1: Using tangent and curve traffic data, vehicle counts for each 5-min interval for each vehicle class were converted to 5-min flow rates ($q$) in (PCU/h), after applying the PCU values. The average travel speed of all vehicle classes in each 5-min interval was calculated in (km/h). Then, densities were calculated in (veh/km) using the following relation:

$$Density\ (k) = Flow\ (q\ /Average\ travel\ speed\ (ATS)$$

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

$$q_{\text{tangent}}=-\beta_o+\beta_1 k-\beta_2 k^2=-16.90+75.02k-1.18k^2$$
$$q_{\text{curve}}=-\beta_o+\beta_1 k-\beta_2 k^2=-11.34+79.83k-1.66k^2$$

The model coefficients have the signs that satisfy the concavity requirements; they were also significantly different from zero at the 95% confidence level. In addition, the resulting coefficients of determinations ($R^2$) are 0.94 and 0.90 for tangent and curve, respectively.

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

$$K\ \text{critical (tangent)}=75.02/(2\times1.18)=30.70\ \text{PCU/km}$$
$$K_{\text{critical (curve)}}=79.83/(2\times1.66)=24.05\ \text{PCU/km}$$

Step 4: The computed critical densities were substituted in the quadratic equations in step 2 to determine the maximum flow per road element as follows: $q_{\max(\text{tangent})}$=1,172 PCU/h; $q_{\max(\text{curve})}$=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 5 summarizes the capacity values for both curve and tangent elements and the percentage of capacity loss at each site.

The results presented in Table 5 indicate that capacity values at all sites did not reach the HCM 2000 value (1700 PCU/h for one direction under ideal conditions). This could be due to several reasons, as follows: (i) All roads are classified as class II, according to the HCM 2000, which serves shorter trips; (ii) All roads have posted a low speed limit of 60 km/h. Polus *et al*.[20] stated that speed limit can explain more than 50% of the variability in operating speed; (iii) The site characteristics are relatively far from the ideal conditions; (iv) 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; (v) Capacity depends on roadway, traffic, and driver behavior conditions. Therefore, the obtained values could reflect the conditions for road, traffic, and driver characteristics of the area under study.

## 5.2 Impact of road geometry on capacity

To investigate the relationship between highway geometric characteristics and capacity values for the two elements (tangent and curve), regression analysis was used. Regression analysis was conducted to produce several models that explained the relationship between tangent/curve characteristics (independent variables) and capacity (dependent variable). Two types of regression analysis were used. The first used a single independent variable as the predictor, whereas the second used multivariate analysis. The criteria used to assess the predictive accuracy of the models were as follows:

(i) The coefficient of determination $R^2$ should be as high as possible and also significant at the 95% confidence level. (ii) Each of the independent variables should have regression coefficients that are significantly different from zero, and whose signs should logically explain the effect of these variables on capacity speed.

With applying these criteria, the best single variable and the best multivariate models were selected.

(1) Tangent elements

Details of the best single and multivariate regression models that explain the relationship between capacity and tangent characteristics are provided in Tables 6 and 7.

Table 5 Capacity values and percentage of capacity loss at each site

| Site No. | Capacity at tangent elements (PCU/h) | Capacity at curve elements (PCU/h) | Capacity loss (%) |
|---|---|---|---|
| 1 | 1,172 | 948 | 19.1 |
| 2 | N.A. | N.A. | - |
| 3 | 1,199 | 1,150 | 4.1 |
| 4 | 1,130 | 1,007 | 10.9 |
| 5 | 1,044 | 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. referring to sites with model coefficients do not have the signs that satisfy the concavity requirements. Therefore, these sites were removed from the analysis.

Table 6 Results of the best single variable model for capacity on tangents

| Variable | Coefficient | $T$ | Significance | $R^2$ | Significance of $F$ statistic |
|---|---|---|---|---|---|
| Constant | –882.30 | –4.824 | 0.002 | 0.940 | <0.001 |
| $LW$ | 585.69 | 10.492 | <0.001 | | |

Table 7 Results of the best multivariate model for capacity on tangents

| Variable | Coefficient | $T$ | Significance | $R^2$ | Significance of $F$ statistic |
|---|---|---|---|---|---|
| Constant | –295.53 | –7.66 | 0.001 | 0.999 | <0.001 |
| $LW$ | 313.10 | 20.22 | <0.001 | | |
| $SW$ | 129.11 | 17.23 | <0.001 | | |
| $TL$ | 0.17 | 11.36 | <0.001 | | |

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

$$Capacity = -882.30 + 585.695\left(LW\right)$$

The resulting coefficient of determinations ($R^2$) of 0.94 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 statistic<0.001. In addition, the coefficient of the independent parameter LW (lane width) was significantly different from zero at the 95% confidence level, as the t value equals 10.50. 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 also increases. In other words, drivers tend to increase their speeds as lane width increases; thus, capacity also increases.

Based on Table 7, the best multivariate developed model for predicting capacity was as follows:

$$Capacity = -295.53 + 313.10\left(LW\right) + 129.11\left(SW\right) + 0.17\left(T_L\right)$$

The resulting coefficient of determinations (R2) and the significance of $F$ statistic equaled 0.999 and<0.001, respectively, which reflects a high goodness of fit of the model and the significance of the model for the use in predication. The coefficient of independent variables $LW$ (lane width), $SW$ (shoulder width), and $TL$ (tangent length) were significantly different from zero at the 95% confidence level, as the t values equal 20.22, 17.23, and 11.36, respectively. The model has a logical explanation for the effect of independent variables on capacity. The positive signs mean that as lane width, shoulder width, and tangent length increase, capacity also increases.

(2) Curve elements

Details of the best single and multivariate regression models for curves are provided in Tables 8 and 9.

The best single variable model was as follows:

$$Capacity = 540.17 + 1.1\left(R\right)$$

The resulting coefficient of determinations ($R^2$) of 0.87 is considered good. It is also found to be significant at the 95% confidence level, as the significance of $F$ statistic < 0.001. The coefficient of the independent parameter $R$ (curve radius) was significantly different from zero at the 95% confidence level, as the t value equals 6.8. 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 also increases. In other words, drivers tend to increase their speeds as curve radius increases; thus, capacity also increases.

The best multivariate model for predicting capacity was as:

$$Capacity = -718.1 + 0.89\left(R\right) + 391.1\left(LW\right)$$

The resulting coefficient of determinations ($R^2$) is 0.97, which is greater than that of the single variable model, and it was found to be significant at a 95% confidence level, as the significance of the $F$ statistic<0.001. The coefficients of the independent variables are $R$ (curve radius) and $LW$ (lane width). The hypothesis that each of the coefficients is equal to zero can be rejected at the 95% confidence level, as the $t$ values are greater than ±1.96. The $t$ values showed the relative importance of variables in the 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 the independent variables (curve radius and lane width) on predicting capacity. The positive signs of the independent variables (curve radius and lane width) mean that as curve radius or tangent length increases, capacity also increases, as expected.

## 5.3 Impact of road geometry on capacity loss

Linear regression was used to produce the best model that indicates the relationship between the percentage of capacity loss and highway geometric characteristics. The examined geometric characteristics include difference in lane width between the tangent and the curve at the same site, difference in shoulder width, tangent length, and curve radius. The best model found was as follows:

$$\%\ Capacity\ Loss = 37.81 - 0.0633\left(R\right)$$

Details of the regression analysis for this model are provided in Table 10.

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 to be significant at the 95% confidence level, as the significance of F statistics<0.001. The coefficient of the independent parameter (curve radius, $R$) was significantly different from zero at the 95% confidence level, as the $t$ value equals –8.74. 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 also increases. In other words, drivers tend to increase their speeds as curve radius increases. Thus, capacity loss decreases.

Table 8 Results of the best single variable model for capacity on curves

| Variable | Coefficient | $T$ | Significance | $R^2$ | Significance of $F$ statistic |
|---|---|---|---|---|---|
| Constant | 540.17 | 11.24 | <0.001 | 0.87 | <0.001 |
| $R$ | 1.1 | 6.79 | <0.001 | | |

Table 9 Results of the best multivariate model for capacity on curves

| Variable | Coefficient | $T$ | Significance | $R^2$ | Significance of F statistic |
|---|---|---|---|---|---|
| Constant | –718.1 | –2.32 | 0.059 | 0.97 | <0.001 |
| $R$ | 0.89 | 8.84 | <0.001 | | |
| $LW$ | 391.1 | 4.08 | 0.006 | | |

Table 10 Results of the best regression model that explains the relationship between capacity loss and geometric characteristics

| Variable | Coefficient | $T$ | Significance | $R^2$ | Significance of $F$ statistic |
|---|---|---|---|---|---|
| Constant | 37.81 | 17.61 | <0.001 | 0.92 | <0.001 |
| $R$ | –0.0633 | –8.74 | <0.001 | | |

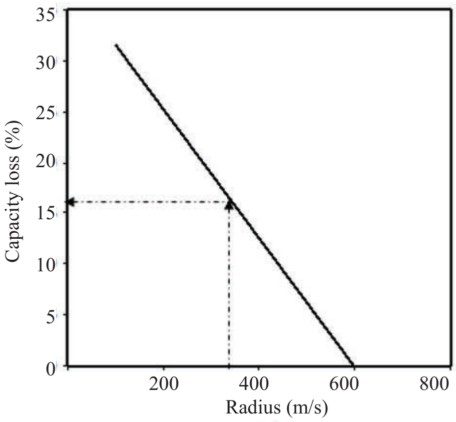

Fig. 4 Determination of percentage of capacity loss (%)

The results of this model are summarized in Fig. 4. This figure can be easily used to estimate the percentage of capacity loss between two successive elements based on curve radius. For example, if the curve radius equals 350 m, then the percentage of capacity loss will equal 15.7%. Based on this figure, also, a curve radius of 600 m seems to be the threshold value for diminishing the capacity loss between two successive elements (the tangent and the succeeding horizontal curve).

## 6 Conclusions

The primary objective of this paper is to explore the influence of highway geometric characteristics on capacity and capacity loss. Traffic and geometry data were collected from twelve rural, two-lane, two-way road sites in Minoufiya Governorate, Egypt. Each site consisted of one tangent and the adjoining horizontal curve. To estimate the capacity of both tangents and curves, one of 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. A few general points related to the results of this paper may be summarized as follows.

The capacity values at all sites did not reach the HCM 2000 value (1700 pc/h for one direction under ideal condition), as the geometric characteristics of the roads under study are relatively far from the ideal characteristics. In addition, capacity depends on roadway, traffic and driver behavior conditions. Therefore, the obtained values could reflect the conditions for roads, traffic, and drivers of the area under study.

Different regression models were developed to study the relationship between capacity values and geometric characteristics for tangents and curves. These models are very useful and can be used to deal with capacity analysis and the evaluation of rural, two-lane roads.

For the best multivariate relationship between capacity and tangent characteristics, the significant independent variables are lane width, shoulder width, and tangent length, displaying positive signs. The model has a logical explanation for the effect of independent variables on capacity. The positive signs mean that as lane width, shoulder width, and tangent length increase, capacity also increases.

In the case of curves, the significant independent variables are lane width and curve radius, displaying positive signs. The model has a logical explanation for the effect of the independent variables on predicting capacity. The positive signs mean that as lane width and curve radius increase, the capacity also increases, as expected.

The best model that indicates the relationship between capacity loss percentage and horizontal alignment characteristics includes only the curve radius, with a negative sign, which functions as an independent variable. The negative sign means that as curve radius decreases capacity loss, between tangent and succeeding curve increases. In other words, drivers tend to increase their speeds as curve radius increases. Consequently, capacity loss decreases. Based on this model, it was found that a 600-m curve radius seems to be the threshold value for diminishing the capacity loss between the tangent and the succeeding curve.

The results presented in this paper are based on observations of directional traffic flow in uncongested conditions. Other investigations are recommended while taking into account other traffic conditions (i.e., congested state).

Finally, the case study is based on observations from 12 sites at selected roads in Minoufiya Governorate, Egypt. Therefore, the results relating traffic capacity and capacity loss to geometric characteristics are preliminary, even though the hypothesis that geometric characteristics have a significant effect on traffic capacity and capacity loss remains valid. In addition, such results are applicable to the data range used. Care should be exercised in interpreting any results using data characteristics out of this range. It is recommended to extend this research using comprehensive field data obtained from various regions and governorates in Egypt.

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