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Effect of Curve Length on Operating Speed on Horizontal Curve of Multilane Divided Rural Roadway

Sarmad S. Al-Sayyaf
sarmad.22enp17@student.uomosul.edu.iq

Ayman A. Abdulmawjoud
aymanmawjoud@uomosul.edu.iq

Civil Engineering Department, College of Engineering, University of Mosul, Mosul, Iraq

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ABSTRACT

This study deals with evaluating and developing speed predictive models of vehicles on horizontal curves for multilane rural highways. A total of 37 sites were identified, and data were collected through field surveys in sections of Northern Iraq. Speed data were collected using a radar speed gun, while the curve length was measured using appropriate surveying equipment. The models were developed using Minitab 21 software and the simple linear regression method. Two predictive models were developed to estimate the speeds of passenger cars and heavy vehicles at the midpoint of the curve. The developed models indicate a positive correlation between vehicle speed and curve length. The coefficient for passenger cars (0.207) is nearly twice that of heavy vehicles, suggesting a more significant impact of curve length on the operating speeds of passenger cars compared to heavy vehicles. The authors suggested studying the effect of other factors on operating speed. In addition, they proposed developing models for each type of vehicle for different types of roadways.

Keywords:

Curve length; Horizontal curve; Multilane rural roadway; Operating speed; Predictive models.

https://rengj.uomosul.edu.iq/
Email: alrafidain_engjournal3@uomosul.edu.iq

1. INTRODUCTION

Horizontal curves are regarded as crucial geometric elements of highways, presenting significant safety challenges [1]. There has been extensive research on the topic since it was discovered that horizontal curves significantly affect vehicle speeds. High-quality geometric design ensures an appropriate level of mobility and access to land uses for both drivers and pedestrians, all while upholding a strong emphasis on safety. Prioritizing the safety of individuals and goods moving along the roadway should be a fundamental consideration in any road design [2]. The operating speed ($V85^{th}$), which is the 85th percentile of the speed distribution selected by drivers in free-flow scenarios, free from environmental restrictions, is the basis for the most popular techniques for evaluating geometric design consistency [3].

Operating speed reflects the speed drivers select based on their perception of the road, while design speed is a criterion used by engineers to determine roadway characteristics. Given the potential disparity between these two values, further research is needed to identify the variables influencing drivers' operating speed decisions. A major drawback of the design speed approach is that it is often based on the most restrictive geometric feature in the roadway section [4]. Curve length and other geometric features had an impact on the 85th percentile speed for passenger cars. Models based on tangent length, curve length, and deflection angle were created[5]. Sil, S. Nama, A. Maji, and A. K. Maurya showed throughout the validation phase that these models can forecast operating speeds with above 90% accuracy.

2. OBJECTIVES

The main objective of this study is to evaluate and determine the effect of horizontal curve length on the operating speed of passenger cars and heavy vehicles on rural multilane highways. Additionally, it aims to develop a predictive model with operating speed as the dependent variable and the horizontal curve element (length of curve) as the independent variable.

3. LIMITS OF STUDY

The study was limited to the following points:

1. All free-flowing vehicles have been included in the study, except for ambulances, fire brigade, tractors and motorbikes.
2. The study defines a free-flowing vehicle as one that maintains a headway of at least 5 seconds[6].
3. Vehicles that braked, turned, or exhibited any unusual issues that ultimately reduced their speed were not considered in the study.

4. LITERATURE REVIEW

Ottesen & Krammes (2000) have shown that the operational speeds of rural two-lane roads' inner and outer lanes did not differ significantly. Using information gathered on free-flow speeds at rural two-lane horizontal bends in Indiana, two models were created to predict the free-flow rates during transitional zones[7]. In recent studies, researchers have formulated predictive models to estimate operating speeds on four-lane divided highways. The majority of research in this area has adopted the 85th percentile of free-flow speeds as a key metric to define operating speed[8],[9]. The multi-linear regression analysis was conducted using stepwise entry and backward elimination methodologies. The resulting model incorporated deflection angle, curve length, and preceding tangent length as explanatory variables. The researcher developed distinct models for passenger cars and heavy commercial vehicles, as shown in Equations (1) and (2). Also, the validation procedures demonstrated that the proposed models exhibit robust predictive performance, achieving over 90% accuracy in estimating operating speeds. Sensitivity analysis revealed curve length to be the most influential parameter in forecasting the 85th percentile speed at the curve center. The explanatory variables integrated into the models effectively captured speed variations at horizontal curve centers, aligning with drivers' perceptual evaluations of roadway geometry[5].

$$V_{85\_PC} = 56.36 - 0.27\Delta + 0.11CL + 0.06PTL \quad (1)$$

$$V_{85\_HCV} = 41.30 - 0.14\Delta + 0.07CL + 0.06PTL \quad (2)$$

Where: Δ: deflection angle; CL:Curve length and PTL: Preceding tangent length.

Avijit Maji, Gourab Sil ,and Ayush Tyagi (2018) developed statistical models to predict the 85th and 98th percentile speeds of light and heavy commercial vehicles on four-lane divided horizontal curves in rural highways using a stepwise multiple linear regression approach. The study's principal findings revealed that commercial vehicle speeds at midcurve depended on their preceding-section speeds and geometric characteristics. In contrast, passenger car speeds correlated with curve length and deflection angle[10].

5. METHODOLOGY

The sites were selected in northern Iraq because the topography naturally features many horizontal curve segments. In contrast, other terrains are primarily mountainous or flat, with almost no such curves. High-resolution aerial photography and Geographic Information System (GIS) software were used to carefully select appropriate survey sites before conducting field surveys. The practical aspect of this research involves several steps. First, identify locations that meet specific criteria. Second, data collection, which is divided into two parts:

1. Collecting spot speed data.
2. Collecting geometric design data, particularly the length of the horizontal curve.

There are several criteria considered in selecting locations, as shown in Table 1, while Table 2 explains the sites' distribution.

Table 1: Selection Criteria for Sites.

Type Area	Rural
No. of Lanes	No Restrictions
Functional Class	Multilane
Type of Facility	2-way
Type of Median	Divided
Type of Terrain	No Restrictions
Radius	No Restrictions
Grade	Up or down
Speed Design	No Restrictions
Speed Limitation	No Restrictions

Table 2: Details of Sites Distribution in the region of study area

no. of sections	coordinate (from - to)	name of road
15	44.14°E 36.31°N - 44.19°E36.37°N	Erbil-Shaqlawa
9	44.20°E 36.38°N - 44.23°E36.39°N	Erbil-Shaqlawa
2	44.75°E 35.51°N - 44.86°E35.56°N	Sulamania-Kirkuk
4	45.15°E 35.58°N - 45.20°E35.59°N	Sulamania-Kirkuk
4	43.10°E 36.42°N - 43.05°E36.49°N	Mosul - Duhok
1	42.97°E 36.71°N - 42.92°E36.75°N	Mosul - Duhok
6	43.13°E 36.90°N - 43.16°E36.95°N	Sirsink - Amadea
4	43.21°E 36.99°N - 43.22°E37.00°N	Sirsink - Amadea
1	42.67°E 36.96°N - 42.64°E36.98°N	Duhok - Zakho

Figure 1 illustrates the steps and mechanism for achieving the desired results.

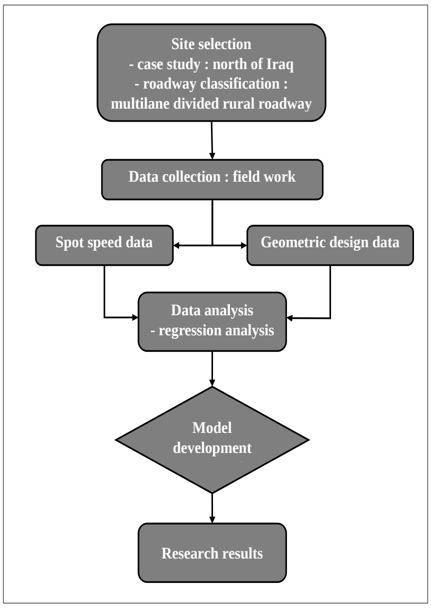

Fig. 1 Research Process Flowchart.

5.1 DATA COLLECTION

After identifying the study sites, which covered a large region of northern Iraq that included the governorates of Nineveh, Erbil, Dohuk, and Sulaymaniyah, the research moved on to a thorough field survey. Thirty-seven sites have been chosen, and data collection was conducted throughout the day between November 2023 and March 2024 in an environment conducive to the best possible road surface quality. The two main focuses of the field study were collecting the geometric design feature, i.e., the length of the roadway curve, and collecting vehicles' spot speed data. Table 2 presents the spatial distribution details of the sites across the governorates of northern Iraq.

5.2 GEOMETRIC DATA COLLECTION

Using appropriate surveying equipment, the length of the horizontal curve is measured. Figure 2 illustrates the measurement process.

Fig. 2 Horizontal Curve Elements.

Table 3 shows the length of the curve for each location.

Table 3: Details of the Field Collected of curve length for all sites.

Site	LC (m)	Site	LC (m)
S1	123.5	S20	84
S2	35.95	S21	62
S3	42.24	S22	95
S4	31.27	S23	85
S5	36.48	S24	63
S6	52.8	S25	44
S7	47.97	S26	68
S8	33.17	S27	72
S9	35.97	S28	57
S10	41.72	S29	44
S11	27.4	S30	123
S12	110	S31	254
S13	63	S32	257
S14	235	S33	164
S15	319.4	S34	149
S16	264.3	S35	154
S17	298	S36	184
S18	258.5	S37	302
S19	258.3		

5.3 SPOT SPEED DATA COLLECTION

Approximately 5,920 spot speed data points were collected for passenger cars and heavy vehicles. Speed readings were collected only during daytime hours, off-peak times, and in good weather conditions between November 2023 and March 2024. Vehicle types were determined by direct observation, and speed-collecting staff were entrusted with recording and confirming all pertinent site information. A minimum time of five seconds between successive vehicles was required to guarantee the measurement of free-flow speeds [11]. Furthermore, Bushnell's Radar Speed Gun was used to collect speed data, as seen in Figure 3. While speed observations were taken at the midpoint of the horizontal curve, as shown in Figure 4.

Fig. 3 Typical Radar Speed Gun.

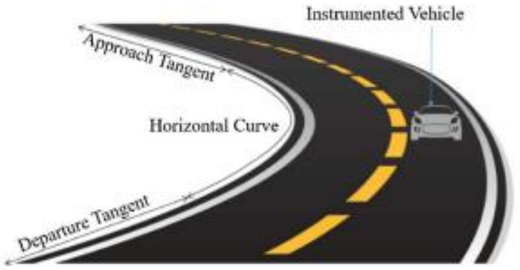

Fig.4 Location of Spot Speed Measurement [12].

5.4 Sample Size

The margin of error related to the data gathering techniques is taken into consideration when calculating the sample size. The necessary sample size is calculated using the following formula [13].

$$n = \left(\frac{SD\times Z}{E}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, n**:** is the smallest size of the sample, Z**:** is the Z-score that corresponds to the required degree of confidence (usually found in statistical tables for a certain level of confidence, such as 1.96 for 95%, SD**:** is the parameter's standard deviation on the measurement, E**:** The acceptable variance in determining the average speed, which depends on the measuring technique employed, is represented by the error. As per the manufacturer's requirements, the error margin of a speed measuring instrument usually falls within a range of ±1.609 km/h.

The speed percentile was determined after conducting a statistical analysis, and the cumulative frequency was applied to the number of observations gathered at each site. The speed at which 85% of vehicles recorded at the location are represented by the 85th percentile, indicating that 85% of vehicles move at speeds equal to or lower than this number. This percentile is an essential measure of the road's true operating speed in the specified circumstances. Table 4 shows the operating speeds (85^{th} percentile curve speed) for passenger cars and heavy vehicles at each location.

Table 4: Operating Speed Data for Passenger Cars and Heavy Vehicles at the Mid-Point of the Curve.

	PCs	HVs		PCs	HVs
Site	**$V85^{th}_{MC}$**	**$V85^{th}_{MC}$**	**Site**	**$V85^{th}_{MC}$**	**$V85^{th}_{MC}$**
S1	38.94	32.05	S20	38.13	31.94
S2	41.93	27.57	S21	34.93	29.9
S3	33.28	29.1	S22	45.34	29.05
S4	35.95	30.04	S23	45.54	28.69
S5	30.81	27.97	S24	45.49	29.54
S6	36.88	29.92	S25	36.13	29.46
S7	32.93	29.1	S26	31.1	29.93
S8	41.16	31.4	S27	34.9	25.85
S9	35.88	26.45	S28	48.9	26.43
S10	37.9	30.64	S29	44.23	30.72
S11	32.71	29.16	S30	59.23	39.77
S12	41.57	29.8	S31	65.88	44.2
S13	42.57	28.95	S32	58.49	45.15
S14	89.49	59.6	S33	62.65	40.1
S15	82.94	70.9	S34	60.63	35.2
S16	63.68	34.37	S35	68.9	33.94
S17	92.28	50.8	S36	65.88	33.58
S18	90.27	63.52	S37	75.23	43.05
S19	77.85	52.94			

Where, PCs: passenger cars; HVs: heavy vehicles; $V85^{th}_{MC}$: 85th percentile curve speed at the mid of curve (km/h).

5.5 OPERATING SPEED PREDICTION MODEL DEVELOPMENT

Simple linear regression was frequently used to create operational speed prediction models. However, this study uses a stepwise linear regression technique to simulate the operating speeds of passenger cars and heavy vehicles on horizontal curves of multilane rural highways. Therefore, the Shapiro-Wilk test was used for this study [14]. For this, a 95% confidence interval Shapiro-Wilk test was performed [15]. According to the test findings, all sites had p-values greater than 0.05%. As a result, all sites' speed data are regularly distributed and may be utilized to build a regression analysis speed prediction model.

6. RESULTS AND DISCUSSIONS

6.1 NORMALITY EXAMINATION

Following the speed data gathering, there were between 80 and 100 observations at each measurement point along the curve. The Shapiro-Wilk test (Ryan-Joiner test) was also used to evaluate the normality of these speed samples. The findings supported the appropriateness of each measurement location for further data analysis by confirming that all datasets had a normal distribution. Figure 5 shows the probability plot for site No. 20

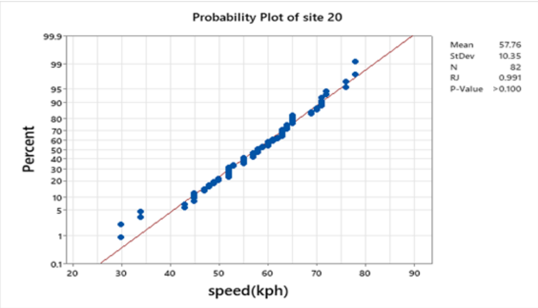

Fig. 5 Normality Test for Site 20 (Similar to the Shapiro-Wilk test).

6.2 CORRELATION TEST

Several methods were used in the preliminary investigation to find possible relationships between the 85th percentile operating speed and various combinations of geometric design features. Using criteria like graphical analysis, correlation matrices, and other diagnostic tools. Pearson's correlation (parametric), which gauges the linear relationship between two variables, was used to evaluate the correlation coefficients between the dependent and independent variables. Table 5 shows the correlation between passenger cars and heavy vehicles with curve length.

Table 5: Pearson Correlation Matrix between V85th Percentile Speed and Independent Variables for Passenger Cars and Heavy Vehicles.

Variables	**V85thMC-PCs**	**LC**
LC	**0.916**	**1**
V85thMC-HVs	**-**	**0.854**

Where:V85thMC-PCs: operating speed for passenger cars in the mid curve(km/h); V85thMC-HVs: operating speed for heavy vehicles in the mid curve(km/h); LC: curve length(m).

- Strong positive correlations indicate that the dependent variables (i.e., V85thMC-PCs and V85thMC-HVs) and the independent variable, i.e., curve length, vary in the same direction, with correlation indices of 0.92 and 0.85, respectively.

6.3 EQUATIONS FOR PREDICTING SPEED ON HORIZONTAL CURVES

A simple linear regression approach was employed to analyze the relationship between a dependent variable (operating curve speed) and an independent variable (curve length). To validate the model, a t-test was conducted to determine whether the regression coefficient (β) significantly differed from zero, with a p-value threshold of < 0.05 indicating statistical significance. Model diagnostics included calculating R-squared to quantify the proportion of variance explained by the independent variable and performing residual analysis to verify adherence to regression assumptions (e.g., normality, homoscedasticity).

Table 6: Regression Equations for 85th Percentile Curve Speed (a) for Passenger Cars and (b) for Heavy vehicles, respectively.

(a): 85th percentile curve speed for passenger cars

Term	Coef	T-Value	P-Value
Constant	27.26	12.11	0.000
LC	0.2075	13.19	0.000

Ajusted R square = 0.874

(b): 85th percentile curve speed for heavy vehicles

Term	Coef	T-Value	P-Value
Constant	23.05	15.16	0.000
LC	0.1058	9.95	0.000

Ajusted R square = 0.797

The regression models for the 85th percentile curve speed of passenger cars and heavy vehicles reveal both shared characteristics and distinct differences. Both models indicate a positive correlation between the independent variable (LC) and speed, meaning that as LC increases, the speed for both vehicle types also increases. However, passenger cars display a higher baseline speed and are more responsive to changes in LC compared to heavy vehicles. Additionally, we notice that the curve length coefficient is approximately twice for passenger cars compared to heavy vehicles. Additionally, the model for passenger cars has greater explanatory power(R^2), indicating it is more accurate in predicting variations in speed. These results emphasize the necessity of creating speed prediction models for specific vehicle types and suggest that further investigation is needed to uncover other factors that may affect the speed of heavy vehicles. The basic variations in the physical and dynamic properties, as well as the driving behaviors, of passenger cars and heavy vehicles, account for the discrepancy in the curve length coefficient. Curve length affects passenger cars more than heavier trucks, which are limited by physical constraints and careful driving, because passenger cars can react more effectively to changes in road elements.

7. CONCLUSION AND RECOMMENDATION

The authors concluded through this study that there is a direct relationship between the operating speed of passenger cars and heavy vehicles with the curve length, with correlation coefficients of 91.6% and 85.4%, respectively. Additionally, this study developed two models to estimate the operating speed at the midpoint of the curve for both passenger vehicles and heavy vehicles, achieving coefficients of determination of 0.874 and 0.797, respectively. The study also revealed that passenger cars are more affected by the curve length compared to heavy vehicles.

This study serves as a basis for data-driven decision-making and offers insightful information on the relationships between operating speeds for passenger cars and heavy vehicles with curve lengths.

According to these findings, speed prediction models must be customized for certain vehicle types, and more research is required to identify additional variables that can influence heavy vehicle speed. The authors suggest studying or developing predictive models for accidents on these roads and examining the impact of other geometric design elements on operating speeds, both on the curve and its approach.

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