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Original Article

Enhanced Operating Speed Prediction Models for Horizontal Curves on Non-Urban Two-Lane Roads: A Case Study from South India

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Abstract - *The inconsistency in geometric parameters of road alignment significantly influences individual vehicle speeds, contributing to increased crash occurrences. The lack of uniformity and accuracy in existing operating speed models has led to improper selection of geometric parameters, impacting road design consistency and vehicle operating speed. Furthermore, current models are limited to passenger cars and often consider only a narrow set of geometric variables.*

This study addresses the limitations of poor accuracy and uniformity in existing models by including all types of vehicles and incorporating a comprehensive range of geometric variables influencing speed. Traffic data from 261 curves and 261 tangents are used to develop refined speed prediction models. A mixed-effect modelling approach is employed to account for the clustered complexity of the model variables. The proposed mixed-effect models account for the heterogeneous nature of traffic conditions in India. These models demonstrate the ability to compute operating speeds with high accuracy, especially when compared to existing models developed under homogeneous traffic conditions with limited data. By considering a broader range of vehicles and geometric variables, this work aims to contribute to more reliable and applicable operating speed models for diverse traffic scenarios.

Keywords - *Horizontal curves, Operating speed models, Clustering, Speed data, Mixed effect models.*

1. Introduction

Inconsistencies in road alignment contribute to changes in the road environment, impacting road traffic dynamics, driver workload, and driver operating speed [1, 2]. This holds particularly true for horizontal curves. Numerous studies have indicated that horizontal curves on rural two-lane roads are more susceptible to road traffic crashes than other sections. The crash rate on such curves is reported to be 1.5 to 4.0 times higher than on tangents [3]. Horizontal curves are associated with over 25 percent of fatal crashes, with increased vehicle speed leading to a rise in crash severity, especially at speeds exceeding 60 miles/h (96 km/h) [5]. The fatality rate is also higher at very high speeds and lowest at the average speed. In addition to speed, the geometry of the curve plays a crucial role in influencing vehicle speeds. An independent narrow curve poses a higher risk than a sequence of curves with the same radius in an otherwise straight alignment [6].

Geometric elements on a horizontal curve show a positive relationship with vehicle speeds [7, 8]. Numerous studies have focused on horizontal curve geometry for calculating vehicle operating speeds, and the details of these earlier works are discussed in a separate section.

To gain a clearer understanding of vehicle speeds on horizontal curves, the authors conducted preliminary field studies. These studies revealed significant differences in vehicle speed between the tangent-to-horizontal-curve section and the mid-curve section, as evidenced by the coefficient of variation of speeds. Developing speed prediction models can help identify the influence of geometric variables on speeds at tangent and mid-curve sections. Unlike previous works that often considered the role of geometric variables in isolation, this work aims to explore the clustering effect of geometric variables on vehicle operating speeds at horizontal curves on non-urban two-lane roads.

Data from 261 horizontal curve sections and 261 tangent sections are categorized into three clusters based on their geometric characteristics and radius, using the K-means clustering technique. Mixed-effect models are then developed to predict the

85th percentile speed (V85), which represents the upper speed limit. Additional variables, like extra widening and sight distance for mid-curve and shoulder width and carriageway width for the tangent, are included in these models. The models also account for the clustering effect in the data. A sensitivity analysis is performed on the formulated models to analyse the variation in operating speed concerning extra widening, sight distance, and radius.

2. Summary of Previous Literature

Numerous models have been developed to predict operating speeds at horizontal curves, considering various geometric variables such as the degree of horizontal curve, lane width, curve length, shoulder width, superelevation, radius, vertical gradient, posted speed limit, and Average Annual Daily Traffic (AADT). In many studies, the degree of curvature is often identified as the main variable affecting vehicle speed. Some models focused on predicting passenger car speeds, while others included additional variables like superelevation. However, a detailed review by the Transportation Research Board (TRB) identified limitations in existing models. The first limitation was the lack of uniformity and accuracy in different operating speed models, attributed to differences in driver behaviour. This work suggests that radius, a crucial variable, can have a range of values, leading to clusters that provide a better understanding of inaccuracies and lack of uniformity in models. The second limitation highlighted was the development of models only for passenger cars and not for other vehicle types. This work addresses this limitation by considering four main types of vehicles and formulating specific models for each type. The third limitation was that most existing models relied on linear regression techniques. Linear regression models may overestimate or underestimate speed due to variability in the regression function. This study proposes a mixed-effect modelling approach, which reduces the variability associated with ordinary regression. Linear mixed effect models distinguish between within-subject and between-subject variances, providing a more comprehensive analysis. Most research works were conducted for homogeneous traffic conditions, and few studies in India explored the influence of geometric consistency on operating speed. This work aims to bridge this gap by considering various geometric variables and employing a mixed-effect modelling approach for non-urban two-lane roads. A comparison of models developed by other researchers and the proposed model is presented in Table 1, focusing on the number of sites, traffic conditions, modelling approach, variables considered, and R2 value. This comprehensive approach aims to overcome the limitations identified in previous literature and provide more accurate and applicable operating speed models for a diverse range of traffic scenarios. For mid-curve, shoulder width and carriageway width for the tangent are included in these models. The models also account for the clustering effect in the data. A sensitivity analysis is performed on the formulated models to analyse the variation in operating speed concerning extra widening, sight distance, and radius.

Table 1. Comparison of different speed prediction models

Details of Literature Review	Number of Sites	Traffic condition	Modelling approach	Variables considered	R^2 Value
Proposed modelling approach	262 curves and 262 tangents	Heterogenous	Mixed effect	R, SD, EW, C L	0.86
Jacob et al., 2013	152 curves	Heterogenous	Regression	R, C L	0.74
Lamm et al., 1987–1990	261 curves	Homogenous	OLS Regrssion	DC, R, LW, SW, ADT	0.84
Krammes et al., 1995	138 circular curves; 78 approach tangents	Homogenous	Regression	DC, C L, DA	0.8
Islam and Seneviratne, 1994	8 curves	Homogenous	Regression	DC	0.99
Voigt and Krammes, 1996	138 circular curves; 78 approach tangents	Homogenous	Regression	e, C L, DA	0.84
Passetti and Fambro, 1999	51	Homogenous	Regression	1/R	0.68
Fambro et al., 2000	36	Homogenous	Regression	R	0.48
McFadden and Elefteriadou, 2000	21	Homogenous	Regression	R, TL	0.71
Fitzpatrick et al., 2000	176 sites	Homogenous	Regression	1/R	0.76
Polus et al, 2000	162 tangent sections	Homogenous	TWOPAS model	R, TL	0.84
Donnell et al., 2001	13	Homogenous	TWOPAS model	TL, R, G	0.65
Gibreel et al., 2001	38	Homogenous	Regression	R, G, SD, ADT	0.98
Jessen et al., 2001	70	Homogenous	Regression	DA, C L, PS	0.57

Details of Literature Review	Number of Sites	Traffic condition	Modelling approach	Variables considered	R^2 Value
Schurr et al., 2002	40	Homogenous	Regression	DA, C L, PS	0.55
IHSDM, 2003	80	Homogenous	Regression	TL, PS, R	0.5
Adolini-Minnicino and Elefteriadou, 2004	78	Homogenous	TWOPAS model	TL, PS, R	0.8
	85 on tangent/flat				
Figueroa Medina and Tarko, 2005	curves; 14 sharp	Homogenous	OLS-PD estimator	SD, DC, e	0.85
	curves)				
Misaghi and Hassan, 2005	40 sites	Homogenous	OLS regression	R	0.52
Nie and Hassan, 2007	10 curves and approach tangents	Homogenous	Regression	TL, R, DA	0.9
R-Radius, SD- Sight distance, EW-Extra widening, CL- Curve length, DC- Degree of curvature, DA-Degree of angle, e-Super elevation, TL- Tangent length, G-Grade, PS-Posted speed					

The work presented in this paper considers the aforementioned parameters to improve the predictability of operating speed models. Another factor influencing the speed prediction is the accuracy of data collected for model development.

In the present work, a Transportable Infrared Traffic Logger (TIRTL) is used to collect the speed data at 522 locations. This method is seen to provide speed data with an accuracy of ±1% [23] when compared to the manual method of speed data collection used by [8]. The next section details the methodology adopted for the study, along with the data requirements.

3. Study Methodology and Data Requirements

The primary goal of this research is to develop accurate models for predicting operating speeds on horizontal curves for two-lane, non-urban, two-way roads. The study focuses on seven districts in the State of Kerala, India, encompassing the diverse characteristics of non-urban roads. The selected sites include National Highways (NH), State Highways (SH), and Major District Roads (MDR) in each district, offering a comprehensive representation of road types. Geometric and traffic data are collected from 261 curves and 261 tangent sections at these locations.

TIRTL (Traffic Information Recording and Transmission with Laser Technology) is employed to capture various traffic flow characteristics, such as lane, headway, vehicle speed, and wheelbase time sequence. The speed data are recorded at two crucial locations on the horizontal curve: the tangent and mid-curve. These locations are chosen based on previous research findings indicating that the maximum and minimum vehicle speeds occur at the tangent (60 to 80 m from the curvature point) and mid-curve (within 10m on both sides of the mid-curve), respectively [8]. Figure 1 illustrates the measurement locations on a typical horizontal curve. Data collection is carried out on regular working days, excluding days with significant events like religious occasions, festivals, processions, and public holidays. TIRTL is operational from 6 AM to 6 PM, ensuring a 12-hour data collection period. Geometric data for the horizontal curve sites are obtained through the Total Station Survey (TSS).

Parameters such as radius of the Horizontal Curve (R), Superelevation (e), Curve Length (CL), Degree of Curvature (DC), Extra Width (EW), Deflection Angle (DA), Shoulder Width (SW), Carriageway Width (CW), and Approach Tangent Length (ATL) are derived from the TSS data, imported into AutoCAD format. Sight Distance (SD) for the curve is measured using an odometer, tape, and a specially developed staff with a height of 1.2 meters. The combination of detailed geometric and traffic data from diverse road types and locations in Kerala aims to ensure the robustness and applicability of the developed operating speed prediction models.

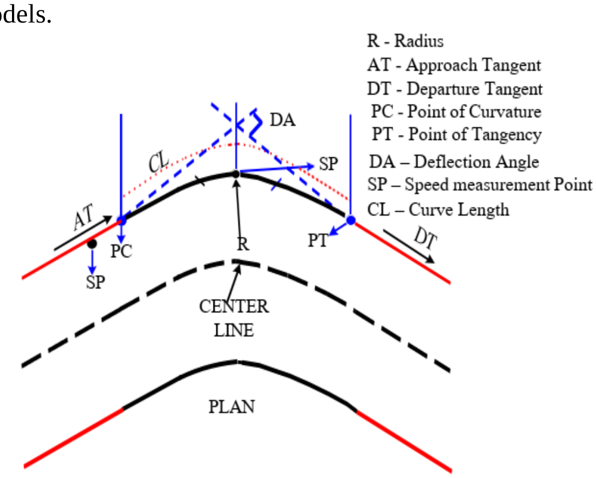


Fig. 1 Speed measurement locations a typical horizontal curve

4. Analysis of Speed Data

The collected speed data is initially categorized based on time headways of 5, 10, 20, 30, 40, 50, 60, and over 120 seconds to determine the threshold headway. Operating speeds are then calculated separately for each vehicle category and each time headway. An analysis of speeds at the tangent and mid-curve reveals that three-wheelers and Small Commercial Vehicles (SCVs) exhibit no significant reduction in speed from the tangent to mid-curve on horizontal curves. In contrast, Two Wheelers (TW), Light Motor Vehicles (LMV), Heavy Commercial Vehicles (HCV), Medium Commercial Vehicles (MCV), and Light Commercial Vehicles (LCV) experience a substantial decrease in speed from tangent to mid-curve. The validation of speed reduction from tangent to mid-curve is further confirmed using the Coefficient of Variation (CV) for speeds across all vehicle categories.

4.1. Effect of Geometric Variables on the Speed of Individual Vehicles

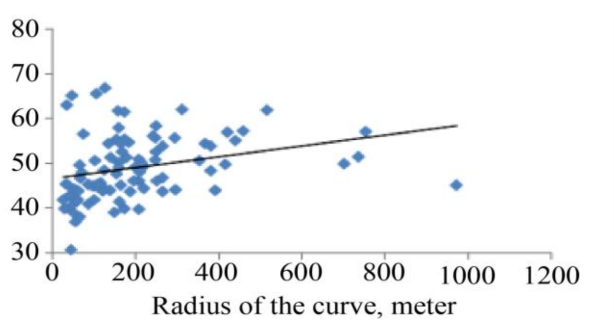
The interaction between design speed and curvature, along with their correlation to superelevation and side friction, is crucial in the design of horizontal curves. The design of horizontal curves requires consideration of the relationship between highway geometry and traffic speed, as these factors significantly impact safety. Variables such as radius, degree of curvature, deflection angle, curve length, sight distance, superelevation, extra widening, shoulder width, and carriageway width are recognized as key factors influencing traffic speeds at horizontal curves.

In this study, a thorough analysis is conducted to establish the relationship between operating speed and geometric variables. This analysis is based on three clusters of geometric variables within the previously mentioned radius clusters. The design speed at various sites is computed using Equation (1), incorporating radius, superelevation, and design speed. This approach allows for a comprehensive exploration of the intricate connections between design speed, curvature, and other geometric variables, providing valuable insights into the design and safety considerations of horizontal curves.

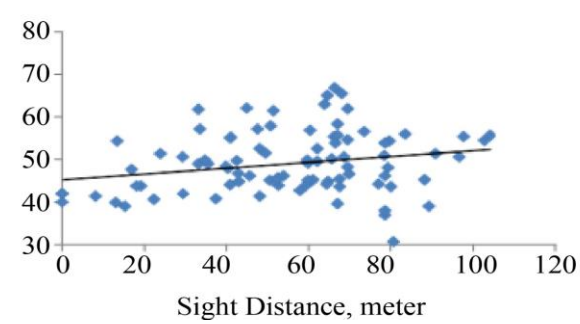
$$e = \frac{V^2}{225R} \quad (1)$$

The relationship between design speed, superelevation, and curve radius is represented by Equation (1), where 'e' is the superelevation, 'V' is the design speed, and 'R' is the radius of the curve. This equation is sourced from the design standard IRC -73, Geometric design standards for rural (non-urban) highways, 1980. According to IRC -73, 1980, the superelevation in this equation assumes that three-fourths of the centrifugal force corresponding to the design speed is balanced by the superelevation, and the rest is counteracted by side friction. While this equation is typically used to determine the superelevation of a curve based on speed and radius, in this study, it is utilized to calculate the design speed using available superelevation and curve radius. For curves with a 0-150 m radius, the considered range of minimum and maximum radii is 18 m and 150 m, respectively. As per [33], sharp horizontal curves necessitate widening of the carriageway for the safe passage of vehicles. Detailed analysis is conducted to understand how the extra widening of the mid-curve influences operating speed on curves of different radii. At sites where the extra width is 0.5 m and below, the speeds of all vehicle categories are below the 50th percentile speed. In Figure 2(e), it is evident that for a radius of 0 to 150 m, a minimum extra width of 0.7 m is required to maintain the desired operating speed of vehicles.

The variation in operating speed concerning geometric variables is illustrated in Figure 2. Figure 2(a) indicates that as the radius increases, the operating speed also increases. Figure 2(d) depicts the relationship between curve length and operating speed, showing lower operating speeds at curves with longer lengths. Carriageway width and shoulder width demonstrate a positive relationship with the operating speed of the vehicle, as seen in Figure 2(c). Sight distance, representing the length of road surface visible to a driver with satisfactory clarity, exhibits a positive relation with operating speed, as observed in the scatter plot shown in Figure 2(b). Extra widening and approach tangent length also demonstrate positive relations with operating speeds for all classes of vehicles, as depicted in Figures 2(e) and 2(f). A similar detailed analysis for the other two radius categories (151-450 and >450) is conducted, and the relationships between variables and operating speed are identified. In subsequent sections, these variables are used to develop operating speed models.



(a)



(b)

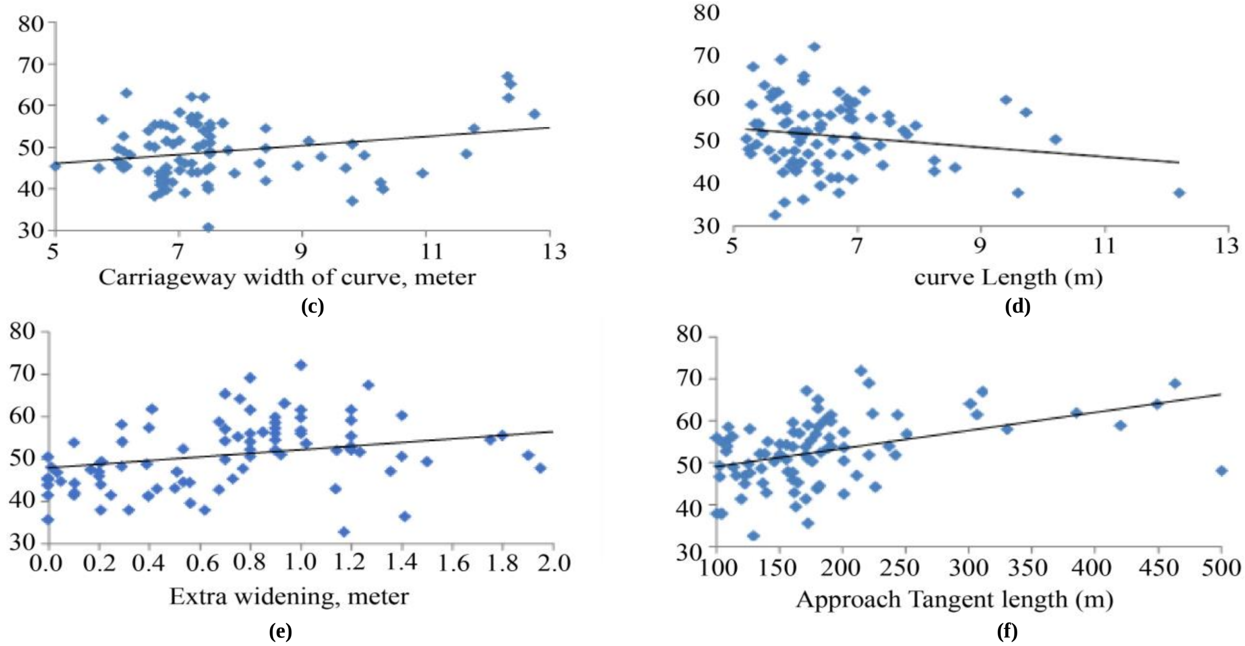


Fig. 2 Variation of the operating speed and geometric variables

5. Operating Speed Models

The initial phase involves a preliminary analysis aimed at defining the trend and pattern within the collected data. Based on the results of this preliminary analysis, the variables influencing operating speed at curves are identified. These identified variables are then used to model and predict operating speed. Specifically, operating speed models for mid-curve and tangent sections are formulated using both multiple linear regression techniques and linear mixed-effect models for different types of vehicles.

5.1. Correlation Analysis

The variables selected for model development are determined through a correlation analysis, considering the interrelationships between different variables. Due to the degrees of curvature and deflection angle dependence on the curve radius, neither of these variables is included in the models. Descriptive statistics of the road geometry variables are presented in Table 2. Although important in gradually changing speed from tangent to mid-curve, transition curves are not considered in this analysis due to their absence at these sites. Correlation analysis is employed to identify the variables influencing operating speeds across various vehicle categories, as detailed in Table 3. Carriageway width at the tangent and mid-curve is observed to have a relatively low correlation with the operating speed of different vehicle categories across all identified radii. For Medium Commercial Vehicle (MCV) and Heavy Commercial Vehicle (HCV), operating speed is found to be highly correlated with extra widening, curve length, sight distance, and carriageway width. However, the impact of carriageway width and shoulder width diminishes significantly, especially with larger curve radii, where road visibility improves. Consequently, heavy vehicles like MCVs and HCVs can maintain their speed from tangent to mid-curve more effortlessly under these conditions. A similar trend is observed for Light Commercial Vehicle (LCV) and Light Motor Vehicle (LMV). This correlation analysis forms the basis for selecting the variables included in the subsequent operating speed models, enabling a more comprehensive understanding of the factors influencing vehicle speed at curves.

Table 2. Summary of statistics of variables

Geometric variable	Minimum	Maximum	Average	Standard Deviation
CW at tangent (m)	5.5	10	7.7	1.32
CW at mid-curve (m)	5.7	11.5	8.1	1.35
SW (m)	0	2.8	1.34	0.71
ATL (m)	100	800	220	131
R (m)	18	1682	235	220
DC (deg)	1	95.3	15.4	13.1
CL (m)	15.4	364	87.4	58.3
DA (deg)	5	238	32.4	23.4
SD (m)	15	310	71.8	40.1
e (%)	0.9	8.4	3.7	2.2
EW (m)	0.0	2.9	1.2	0.9

5.2. Model Development at Mid Curve

All variables exhibit a positive relationship with the operating speed of vehicles, except for curve length. Curve length is particularly significant in the case of Two-Wheeler (TW) and Light Motor Vehicles (LMV) at mid-curve. Conversely, approach tangent length, sight distance, and extra widening are the more influential variables in predicting the operating speed of Medium Commercial Vehicles (MCV) and Heavy Commercial Vehicles (HCV) at mid-curve. Therefore, approach tangent length, carriageway width, and shoulder width are identified as crucial variables for predicting the operating speeds at the tangent section for nearly all vehicle types. A linear mixed-effect model is proposed and explained in the next section to enhance accuracy compared to multiple linear regression models.

5.3. Linear Mixed-Effects Models

A mixed-effect model is a statistical model incorporating fixed and random effects. These models are particularly valuable when dealing with calculations involving related statistical unit clusters. Mixed-effect models are often preferred over traditional approaches due to their ability to handle missing values effectively. As stated by [21], "A linear model with mixed effects is the generalization of a linear model in which data will show correlation and non-constant variability." The general form of a linear mixed-effect model is expressed below in Equation (2).

$$Y = X.\beta + Z.\gamma + \epsilon \quad (2)$$

In the matrix notation, where 'Y' represents the matrix of response vectors, 'X' is the fixed effects coefficient matrix, 'Z' is the random effects coefficients matrix, 'β' is the vector of fixed effects slopes, 'γ' is a random vector with a mean of zero, and 'ϵ' denotes the error variance. Categorical variables utilized in developing the mixed-effects model include road and vehicle types. These encompass three road types (NH, SH, and MDR) and four vehicle classes Two-Wheeler (TW), Light Motor Vehicle (LMV), Medium Commercial Vehicle (MCV), and Heavy Commercial Vehicle (HCV).

According to [34], "Mixed models are mathematical models containing parameters for fixed effects as well as random effects. Because of how the random effects are interpreted, there is always at least one fixed-effect parameter in a random effects model. So any random-effect model is a mixed model." The proposed models employ operating speed as the dependent variable and geometric variables as the explanatory variables. Through scatter plots, correlation matrices, and insights from the literature review, a list of tentative variables to be included in the models is identified. Numerous trials are conducted using the 'R' software, and only the most significant and logical models are presented herein.
As previously mentioned, the mixed model developed without data grouping but with inherent clusters should accurately predict speed. The mixed model developed without clustering is relevant for comparisons with models formulated by other authors in earlier works. The mixed-effect models for all vehicle categories without clustering are developed using the R-platform, and the t-value, R2, AIC, BIC, and log-likelihood are presented in Table 3. Statistical parameters such as Akaike's Information Criterion (AIC), Bayesian Information Criterion (BIC), and log-likelihood values are employed to measure the accuracy of the formulated mixed-effects models. Smaller values of AIC, BIC, and the log-likelihood ratio indicate a better model. The variables with the most significant influence on predicting the operating speed of all vehicle categories at mid-curve in the formulated mixed-effect model are sight distance, extra widening, curve length, and radius.

Table 3. Mixed effect models for operating speed at the curve

Type of vehicle	Variables	Estimate	Standard error	t-value	R^2	AIC	BIC	Log-likelihood
	Constant	57.00	7.59	7.51				
	CL	0.02	0.01	3.54				
TW	1/R	1250.00	304.88	4.10	0.86	401.62	425.33	-192.81
	SD	0.15	0.05	3.24				
	EW	0.07	0.01	5.02				
	Constant	58.00	17.01	3.41				
	CL	0.03	0.01	4.13				
LMV	1/R	984.00	371.32	2.65	0.80	442.00	455.41	-204.00
	SD	0.18	0.05	3.44				
	EW	0.08	0.03	2.94				
	Constant	50.00	8.05	6.21				
	CL	0.02	0.00	4.62				
MCV	1/R	950.00	143.94	6.60	0.88	378.12	389.34	-174.17
	SD	0.19	0.03	6.62				
	EW	0.07	0.01	5.41				
	Constant	52.58	11.07	4.75				
	CL	0.01	0.00	2.99				
HCV	1/R	1000.00	217.39	4.60	0.84	394.16	404.15	-178.87
	SD	0.17	0.06	3.01				
	EW	0.06	0.02	3.58				

The models incorporate four essential parameters derived directly from the curve: curve length, radius, sight distance, and extra widening. The provided models illustrate that the operating speed increases with an increase in radius, sight distance, and extra widening. The most influential variables in the proposed model are radius and sight distance, as evidenced by their higher coefficients in the model. A reduced radius necessitates a larger sight distance to enhance safety and uphold vehicle speed within permissible limits. Decreasing the radius results in sharp curves and limited sight distance on the road, posing an accident risk. Therefore, the sight distance must be sufficiently large, especially at sharp curves. However, in the case of curve length, the speed decreases with an increase in curve length, suggesting that longer curves require more time for vehicles to traverse, making it challenging for drivers to cover the entire curve length for a given radius. The rate of speed increase or decrease varies based on the type of vehicle class. The sensitivity analysis results in Figure 3 indicate a significant increase in operating speed for radius values between 100 and 250 meters, with no significant change beyond 500 meters. These findings align with those reported by [8] and [9]. A thorough validation and comparison of the formulated models are conducted using a dataset collected from Ernakulum district, another major district in Kerala, encompassing data from 8 curves and 8 tangent sections on National Highways and State Highways, as detailed in Table 4. Existing models have predominantly focused on passenger cars. Consequently, a comparison of predicted operating speeds for passenger cars using the proposed model, existing models, and observed speeds is presented in Figure 4(a). The comparative analysis reveals that the predicted speed based on the proposed model closely aligns with the observed speed, exhibiting minimal deviation. In contrast, speeds from other models [18, 35] are overpredicted, potentially due to the homogeneous traffic conditions in countries other than India. The under-predicted speeds could be attributed to errors in speed data collection techniques employed in existing works in India. This study adopts a more reliable automated traffic data collection method using TIRTL. For other vehicle types, the comparison and validation of speeds are based on existing works in India. Figure 4(b) displays a comparative plot between the observed operating speed of HCV with the proposed and existing model.

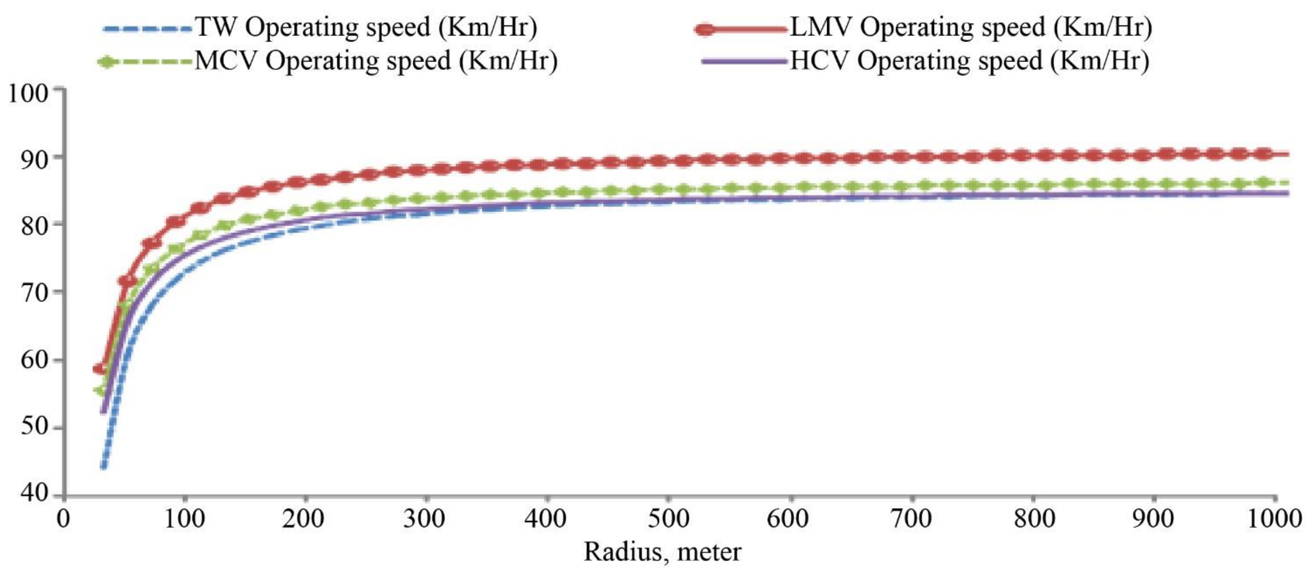


Fig. 3 Sensitivity analysis of the operating speed of vehicles with varying radii

Table 4. Details of the validation data

SW (m)	CW (m)	ATL (m)	CL (m)	EW (m)	R (m)	SD (m)	Observed Operating speed (Km/Hr) LMV Mid curve	LMV Tangent	TW Mid curve	TW Tangent	MCV Mid curve	MCV Tangent	HCV Mid curve	HCV Tangent
0.7	6.5	100.0	67.0	1.4	210.0	68.5	62	65	59	65	61	66	60	62
1.5	7.0	280.0	71.0	1.25	100.0	69.0	55	68	52	70	55	74	54	64
1.0	7.0	175.0	52.8	1.2	115.1	88.0	65	66	58	65	60	65	59	65
2.0	7.5	500.0	95.0	2.0	700.0	129.0	77	79	74	78	72	75	70	73
1.5	7.0	180.0	97.0	2.0	318.0	118.0	70	72	66	68	64	69	68	70
1.2	6.8	350.0	179.9	2.1	284.7	95.10	69	75	65	70	65	70	62	65
2.0	7.0	310.0	71.0	0.8	216.3	104.0	72	73	65	71	67	70	65	68
2.5	7.2	290.0	148.0	0.7	87.2	69.0	53	74	51	70	52	75	52	65

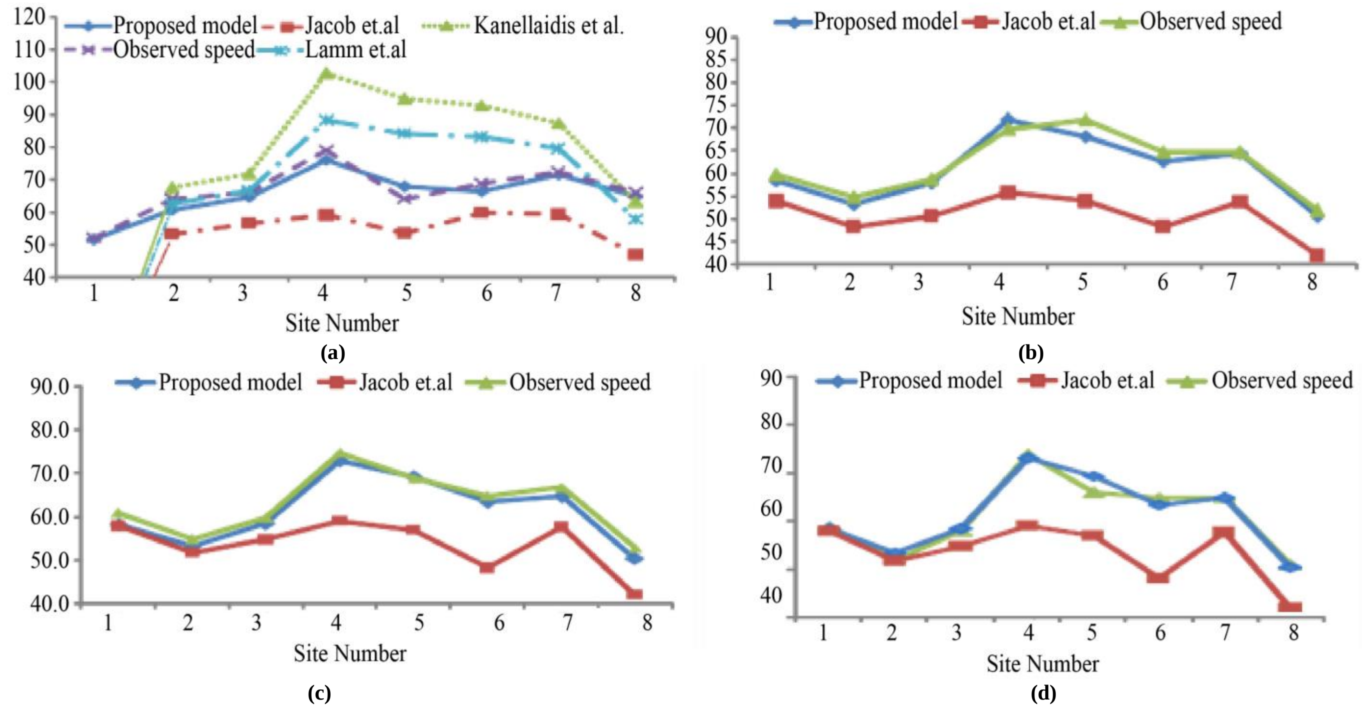


Fig. 4 Validation and comparison of the proposed mixed effect model at the curve (a) LMV, (b) HCV, (c) MCV, and (d) TW.

6. Application of the Proposed Models

The developed operating speed models are valuable in assessing consistency at various sites. To illustrate the process of evaluating consistency, we consider a curve with the following parameters: extra widening = 2m, sight distance = 100m, curve length = 120m, carriageway width = 7m, shoulder width = 2m, and approach tangent length = 280m. Using the proposed model, the estimated difference in operating speed for each class of Vehicles at a Tangent (VT) and mid-curve (V85) is computed as follows: 7 km/h for LMV, 9 km/h for TW, 12 km/h for MCV, and 8 km/h for HCV. These values are derived from the model's predictions. The consistency evaluation criterion, as proposed by [35], is then applied to these estimations, and the results are presented in Table 5. Upon applying Lamm's consistency criterion, the design is deemed good for all categories of vehicles except for MCV, which is considered fairly consistent.

Table 5. Consistency evaluation criterion by [35]

Good	$\|V_T - V_{85}\| \leq 10$ km/h
Fair	10 km/h $< \|V_T - V_{85}\| \leq 20$ km/h
Poor	$\|V_T - V_{85}\| > 20$ km/h

The validation data available (Table 5) are also used to repeat the consistency evaluation of the sites, using the proposed mixed effect model for all categories of vehicles, the details of which are presented in Figure 5. Here, validation data from 8 curves are used to check the consistency of the geometry of the curve and the operating speed. For all sites, except sites 2 and 8, the design consistency is evaluated as good, per [35] consistency criterion.

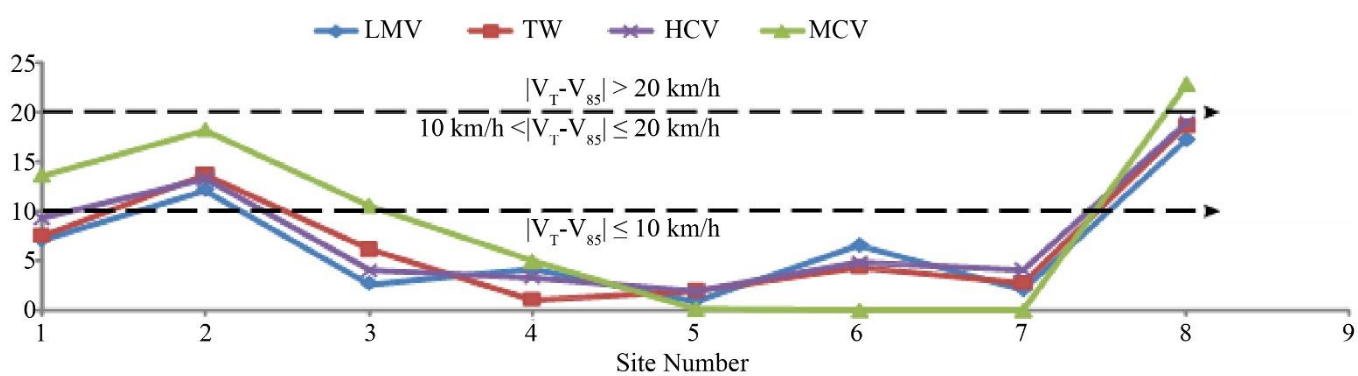


Fig. 5 Consistency evaluation of selected sites

7. Summary and Conclusion

Several studies have addressed operating speed prediction at horizontal curves, but a comprehensive analysis and evaluation conducted by [19] have highlighted limitations in earlier versions of operating speed models. Therefore, the primary focus of this work is to address these limitations. The lack of uniformity in past models may be attributed to data heterogeneity. Utilizing the identified variables, operating speed models are formulated based on a mixed-effect modelling approach. Subsequently, a sensitivity analysis is performed on the mixed-effect model with clustered data to establish the relationship between extra widening, sight distance, and operating speed.

The second limitation reported in the Transportation Research Circular pertains to the lower accuracy of existing models. A comparison between the developed models and existing operating speed models indicates that the mixed-effect models are more accurate. The sensitivity analysis reveals a significant increase in operating speed for all types of vehicles with a radius up to 300m, while for a radius greater than 500m, the increase in operating speed is not very significant. Validation of the developed models confirms that existing models, such as those proposed by [8], are unable to predict speeds at curves and tangents with higher operating speeds (i.e., greater than 70 km/h). The proposed mixed-effect models accurately predict observed speeds at curves. Additionally, it is observed that existing models by [18] and [35] predict operating speeds higher than the observed speed at study sites, possibly due to the heterogeneous traffic conditions in India [36] compared to the homogeneous conditions considered in previous works. Finally, an application of the proposed mixed-effect models for horizontal curves is evaluated and presented using a case study for a curve.

This approach significantly improves the accuracy of predicted operating speed for individual vehicle classes and all vehicle classes. The study also notes that the limited number of data samples considered for modelling contributes to poor uniformity [19] in existing models. To overcome this, data samples from 261 tangent sections and 261 curve sections are considered for formulating the models presented in this work. This results in a model that accounts for all ranges of variation in all relevant geometric parameters. Ultimately, an improved model for operating speed prediction based on the mixed-effect modelling approach is formulated, validated, and presented as part of this work. The developed models are expected to be useful for practitioners, providing specific consistency measures on the geometry of curves.
As a future scope of the study, increasing the number of data samples can be considered. This would compensate for the reduction in samples after data clustering, ensuring that the number of samples in each cluster is a minimum of 100. This is anticipated to enhance the accuracy of the proposed models' predictions.

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