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Evaluation of Vehicle Speed with Impact of Vehicular Driver Behaviour at Horizontal Curves

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ABSTRACT: Vehicular driver behaviour is an important factor for vehicular speed and safety at horizontal curves, few studies have attempted to understand this aspect. In this regard, the objective of the present study is to evaluate the vehicular speed characteristics with the effect of driver behaviour at horizontal curves. The study uses real traffic environments where vehicle speed, driver behaviour (lane change or not) and number of vehicles in the opposite lane (approaching vehicles in the opposite lane) data were recorded by video graphic technique. A total of four horizontal curves with different radiuses on two-lane undivided two-way roadways have been studied. Further, the curve characteristics (radius, length of curve, etc.) data were collected from a preliminary survey. The data was analyzed with a multiple linear regression model by considering vehicle speed as the dependent variable and radius of curve, driver lane change behaviour, number of vehicles in the opposite lane, type of vehicle, and shoulder width as independent variables. The study discovered that driver lane change behavior, number of vehicles in the opposite lane, vehicle type in the opposite lane, and shoulder width all have significant effects on vehicle speed characteristics at horizontal curves, in addition to the radius of the curve. These findings are useful for the design of horizontal alignment and evaluating countermeasures for vehicular driver safety at horizontal curves.

KEYWORDS: Vehicle speed; Horizontal curve; Driver behaviour; Undivided roadway; edge drops

1. INTRODUCTION

Road accidents are one of the major concerns in developing countries like India, and two-lane undivided rural highways are major contributors to these road accidents. In recent days, it has been reported that many road accidents are associated with inconsistent horizontal alignment and abrupt driver behaviour at horizontal curves (Bhatnagar, 1994). The horizontal curves have a significant effect on vehicular driver behaviour and safety, particularly on two-lane undivided rural highways (Johnston, 1982). Research reports in India show that 77% of road accidents are due to inconsistent driver behaviour, and it is also reported that out of the total road accidents, 5% of fatal accidents have occurred at curves (RAI, 2016). Global research reports also indicate that traffic crash rates are higher on horizontal curve sections as compared to other road sections (NHTSA, 2008). Further, the American Association of State Highway and Transportation Officials reported that over 42 percent of crashes occur as a result of driver lane change behaviour at horizontal curves, with rural areas accounting for 50 percent of these crashes (AASHTO, 2008). Researchers also stated that many fatal crashes are associated with horizontal curves (Torbic et al., 2004). Studies have noted that road crashes are higher (viz., 1.5 to 4 times) on horizontal curves as compared to tangent sections, even with similar traffic flow on both the sections (Glennon et al., 1985).

Generally, vehicular drivers maneuver along the horizontal curves by changing their vehicular speed to control the steering and centrifugal forces acting on their vehicle. However, a driver's perceived speed while moving along a curve depends on several factors, such as sight distance, terrain conditions, surrounding environmental conditions, and the gradient of the road. A design engineer needs to consider these factors while designing a horizontal alignment or during the crash rectification process at potentially dangerous horizontal curves. The evaluation of horizontal curves is an important process in safety studies and traffic control measures to control crashes. Research studies have stated that an abrupt change in horizontal alignment leads to inconsistency in operating speed, which increases the risk of crashes on rural roads (Ruediger et al., 1988). Research studies found that the inconsistency in horizontal alignment leads to possible lane change behaviour as well as a failure to control vehicle speed at horizontal curves, which further contributes to crashes (Staplin et al., 2001). In general, at a horizontal curve, the vehicle will have a tendency to move in an outward direction due to the centrifugal force acting on it. In such circumstances, if a vehicular driver exceeds the design speed, then the vehicular driver is unable to control the vehicle and the vehicle may leave the outer path of the roadway. On undivided roadways, it may also cause obstruction and increase the risk of collision with vehicles travelling in the opposite direction.

The vehicular driver's behaviour mainly depends on several factors, such as motive of travel, attitude, and familiarity with the road section. Usually, vehicular drivers experience lane departure while maneuvering along the horizontal curve, which results in their abrupt behaviour which indicates that sudden changes in lane or speed while maneuvering along the horizontal curve. In developing countries like India, with mixed traffic conditions on two-lane undivided roadways, drivers will exhibit behaviour such as speed changes and inconsistent lane discipline (Asaithambi et al., 2016). Most of the time, vehicular drivers will occupy the full lane width (viz., it means that the vehicle along the length of the wheelbase occupies the right most corner to left most part of the curve) or vehicle might approach to the opposite lanes of vehicular movement while negotiating the horizontal curve. However, if vehicles are in the opposite lane, in the absence of a median on two-lane undivided roadways, the vehicular drivers have to move towards the edge of the carriageway, which becomes dangerous in the absence of a shoulder and edge drops. Therefore, this study attempts to understand the driver behaviour with effects of factors such as curves as well as roadway characteristics, edge drops, while negotiating the horizontal curve. The organization of this research paper is as follows: Section 1 provides an overview of the importance of speed studies at horizontal curves; Section 2 provides background information on speed studies at horizontal curves. In section 3, an overview of the site characteristics of selected horizontal curves and the data collection process is presented. Section 4 presents the speed model analysis and discussion. The conclusions are summarized in Section 5.

2. LITERATURE REVIEW

In general, the geometric design of a highway includes the systematic arrangement of highway features such as horizontal alignment, vertical alignment, cross-section, and other physical features that significantly affect highway operation and driver safety (Zheng, 1997). In a recent research study, it was shown that age and driver experience are significant contributing factors in high runoff crashes (Choudhari and Maji, 2019). Geometric design necessitates the establishment of fundamental design controls (e.g., gradient, traffic volume) as well as the selection of design speed. These design parameters depend on several variables, including vehicle speed, deceleration, and acceleration of the vehicle, as well as driver reaction time. Highway design consistency requires good design of highway geometry, which demands proper synchronization of straight and curved sections so that drivers are not surprised by changes in the alignment, which causes an increase in driver work load. In other words, any improper design of geometry leads to unnecessary speed changes, which impacts road safety. Hence, consistency in the geometric design process is one of the major contributing factors to drivers' work load, driver reaction time, and driver safety. Design consistency has been defined as the degree to which the road is designed in a consistent manner to help drivers avoid sudden changes in driving behaviour that impact their safety (Al-Masaeid, 1995). It means that the shape of a road doesn't make it hard for cars to drive on it, and it also makes it safe and steady to drive on.

Some studies have performed motorized vehicle safety evaluations at horizontal curves and have reported a correlation between crash rate and inconsistent horizontal alignment (Polus and Mattar-Habib, 2004). Other studies have considered the operating speed, which is termed as the 85th percentile speed under free flow conditions, in order to evaluate the design consistency of the horizontal curve (Cafiso et al., 2010; Haynes et al., 2008). Generally, the operating speed is significantly affected by highway geometric parameters, including curve radius, grade, length of curve, and roadway environment. In another research study, the evaluation of design consistency was carried out considering factors such as driver speed at curve and tangent, and the difference in speed at curve and the tangent is usually used to evaluate design consistency (Lamm et al., 1992). Researchers have shown that the radius of the curve and degree of curvature has a significant effect on operating speed at horizontal alignment (Kanellaidis et al., 1990; Sil et al., 2019). It has also been shown that the operational speed is influenced by the curvature change rate and other roadway characteristics (Perco, 2008). Studies have analysed the acceleration as well as deceleration rates on two-lane rural highways during day and night, and the results concluded that drivers decelerate at a lower rate while approaching a large radius horizontal curve. Furthermore, the increase in the length of the horizontal curve leads to an increase in vehicle speed, and larger departure tangents are helpful to achieve the full desired speed (Hu and Donnell, 2010). Studies related to speed distribution on low-volume roads have concluded that higher radii yield higher operating speeds (Praticò and Giunta, 2011). Extensive research carried on operation speed models considering the curve characteristics has observed the importance of acceleration as well as deceleration in vehicle speed and driver behaviour on operating speed (Fitzpatrick et al., 2003).

Another study discovered that the most influential parameters in safe operating speed at horizontal curves were the driver's behavior, such as deceleration at the midpoint of the curve and acceleration while exiting the curve (Russo et al., 2015).Also, researchers have concluded that the sharper horizontal curves need to have their side friction values revised due to the demand of driver behaviour which includes speed as well as lateral acceleration while negotiating sharper horizontal curves (Said et al., 2009). Driving behaviour has a significant impact in crashes at horizontal curves, and studies using driving simulators have investigated driving behaviour at horizontal curves. The results concluded that reducing vehicular speeds based on the optical circles is an effective tool to improve the driving behaviour of attentive nature to reduce crashes at horizontal curves (Awan et al., 2019). Moreover, recent studies have explored driver behaviour at horizontal curves using the Naturalistic Driving Study (NDS) and the results concluded that the importance of speed behaviour as well as driver comfortable thresholds while traversing horizontal curves needs to be considered to maintain design consistency (Dhahir and Hassan, 2018). Whereas, in another NDS research, has shown that the driver's familiarity with the curves and the results identified that driver familiarity has a significant role in choosing higher vehicle speeds along the curves (Pratt et al., 2019). Further, in some of the studies, familiarity and unfamiliarity were considered accident factors (Intini et al., 2019).

Researchers have modelled driver speed profiles along two-lane rural highways with GPS based data and the results concluded that vertical grade has a significant influence on driver speed profiles (Cafiso and Cerni, 2012). It has been stated that the longitudinal slope and length of an element along the curve are the main contributing factors in the operating speed model for two-lane rural roads (Praticòa and Giunta, 2012). Other studies found that the radius of the curve is one of the main contributing factors in speed prediction at the middle of the curve section (Tarris et al., 1996). Researchers have also analysed the effect of traffic volume on vehicle speed along with geometric parameters and the results concluded that an increase in traffic volume has a negative impact on the average running speed of the vehicle (Polus et al., 1984). Studies have also looked at the importance of sight distance in operational speed evaluation at horizontal curves, and it has been concluded that sight distance is needed for safe and comfortable operation (Gattis and Duncan, 1995). Another study found that sight distance has a significant impact on the design consistency of horizontal curves, and it has been reported that drivers require adequate time to react in order to control their driving performance and ensure safe driving behaviour (Krammes and Glascock, 1992). Existing studies have mainly explored the design consistency along the horizontal curves. Also, some of the studies have analyzed the driving behaviour and safety while negotiating horizontal curves. Recent research studies have used the NDS based data to study the driver's behaviour along the horizontal curves. However, the driving phenomenon is a complex process while drivers are negotiating horizontal curves, and there are several factors associated with the driver's behaviour. Most of the existing studies have considered the driving behaviour at the center of the curve, and a few studies have explored different sections along the curve. In this context, the present study has explored the driver speed change behaviour at the point of curvature, the center of the curve, and the point of tangency of the two lane undivided roadway sections.

3. METHODOLOGY

Data has been collected at 4 different horizontal curves on two-lane undivided roadways. Two curves were selected in non-built-up area and other two were selected in built-up area and these selected curves are representative of the horizontal curves of the local road network. The study sites, illustrated in Figure 1, are located on National Highway NH-165 near Akividu and Bhimavaram, Andhra Pradesh state, India. The selected site does not have any edge lane marking and the selected sites have centre line marking. The selected horizontal curves on 2-lane rural highway have sufficient straight tangent approach sections on both sides of curve and there are no reverse curves. It is also observed that the posted speed limit on selected sites was 30 kmph. Also, the horizontal curves were selected based on various characteristics which include varied curve radii, length, shoulder type, sufficient vehicular flow and high expected fatal crash location. The selected horizontal curves have traffic consisting of different class of vehicles including higher number of motorcycles, public buses and heavy vehicles and different driver behavioural characteristics. This study is limited to 2-lane horizontal curves on national rural highways.

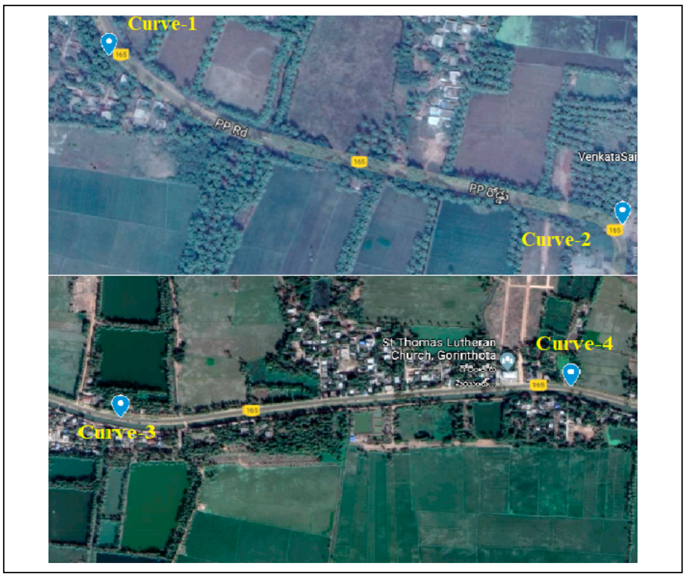

Figure 1. Selected horizontal curve locations at built-up and non-built-up areas.

3.1 Geometric data

The geometric data was collected by using basic survey instruments for each curve which includes curve radius, length of curve, degree of curvature, intersection angle using Total Station, super-elevation using Auto Level, width of carriageway and shoulder are measured using normal tape.

3.2 Data collection

The data were collected from the selected locations in the month of January 2018 during 9:00 AM to 11:00 AM and 3:00 to 5:00 PM (data collection was strictly done before 5PM due to lack of lighting during night time) during normal weather conditions. The cameras were placed at three different locations including point on the curve, center of the curve and point of tangent at suitable raised location to collect the data. The following data were collected from the selected horizontal curves: Point of Curvature (PC), Centre of Curve (CC) and Point of Tangent (PT), driver lane change behaviour, number of opposing vehicles, and type of vehicle etc. The dependent variable has been selected as vehicle speed at different positions on horizontal curve and has been associated with roadway, curve and traffic characteristics as well as vehicle type. The vehicle speed data was extracted by using AVS video editor software in the laboratory from video graphic survey conducted at the site. The speed extraction process is validated with known vehicle runs at the selected locations and comparing the known test vehicle speed data with video graphic data. All these collected variables have been summarized in Table 1. A total of 2100 speed data points were collected from the three different positions viz., PC, CC and PT on the curves. The collected data were processed carefully in lab and the jammed data were eliminated and final data is arrived as 1860 speed data points. Out of the total data, 50% of data is observed with two-wheelers, 20% data with auto-rickshaw (three-wheelers), 20% data with cars and 10% of data with heavy vehicles including bus as well as trucks. The vehicle type in the opposite lane, speed data and number of vehicles at PC, CC and PT were collected in the direction of travel. Figure 2 depicts the characteristics of a typical horizontal curve.

3.3 Data extraction

The vehicle maneuvering with driving behaviour for data extraction process is shown in Figure 2. There are many factors identified which significantly effects the vehicle speed while maneuvering along the horizontal alignment. The curve characteristics (viz., curve radius, length of curve) were collected from the preliminary survey. The driving behaviour data includes number of opposing vehicles, driver lane change behaviour, and opposing vehicle lane change behaviour were collected from captured video. The captured video data was extracted by running in AVS video editor software with step by step forward process.

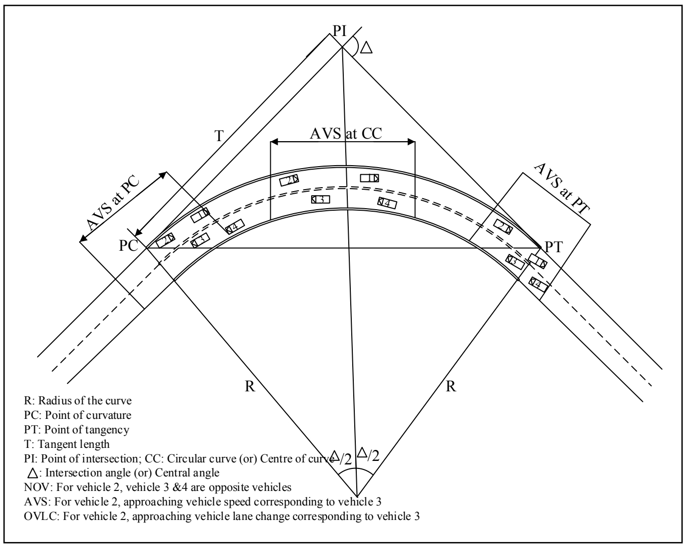

Figure 2. Horizontal curve characteristics

3.4 Roadway data

Roadway and shoulder width: The width of the carriageway and shoulder were measured in meter at selected curve locations at three different positions of curve includes point of curvature, center of the curve and point of tangency. Edge drop: The edge drops were identified from the preliminary survey at three different sections of curve portion and it is coded as yes or no condition.

Type of variable	Unit/Code	Minimum	Maximum	Standard deviation
Curve Characteristics				
Curve Radius (CR)	m	89	350	120.96
Length of Curve (LOC)	m	110	280	92.56
Degree of Curvature (DOC)	degree	2	26	11.12
Intersection Angle (IA)	degree	6	38	13.98
Roadway Characteristics				
Roadway Width (RW)	m	6.8	7.5	0.32
Shoulder Width (SW)	m	0.8	1.8	0.45
Edge Drop (ED)	Yes=1 or No=0	0	1	0.5
Super Elevation (SE)	Percentage	2	5	3.24
Vehicle Characteristics				
Vehicle Speed at Point of Curvature (PC)	Kmph	22	52	13.28
Vehicle Speed at Centre of Curve (CC)	Kmph	15	48	14.33
Vehicle Speed at Point of Tangent (PT)	Kmph	24	64	12.27
Vehicle Speed (AVS) in the opposite lane in Kmph	Two-wheeler	24	64	14.44
	Auto-rickshaw	18	42	15.88
	Car	20	52	17.54
	Truck/Bus	15	40	16.66
Vehicle type in the opposite lane (AVT)	Two-wheeler=2 Auto-rickshaw=3 Car=4; Truck/Bus=5	2	5	1.14
Number of Opposing Vehicles (NOV)	Number	2	6	2.44
Driver Behaviour				
Driver Lane Change Behaviour (DLCB)	Yes=1 or No=0	0	1	0.34
Opposing Vehicle Lane Change Behaviour (OVLCB)	Yes=1 or No=0	0	1	0.46

Table 1. The collected variables at the horizontal curves.

3.5 Driving behaviour and vehicle data

Vehicle type and speed in the opposite lane: From Figure 2, if the vehicle 2 is moving along the horizontal curve and the opposing vehicle type and speed is noted i.e., vehicle 3 and its speed. Number of opposing vehicles: If vehicle 2 is negotiating along the horizontal curve and number of opposing vehicle faced by vehicle 2 is noted at three different positions (viz., PC, CC, and PT) of curve. Driver lane changing: While vehicle 2 is negotiating along the curve whether he/she will change their driving lane or not. Opposing vehicle lane change: While vehicle 2 is negotiating along the curve whether opposing vehicle driver (viz., vehicle 3) ill change his/her driving lane or not.

3.6 Model formulation

In this study, the individual vehicle speed and combined data of speed for different types of vehicles have been modelled at three different section of the horizontal curve (viz., PC, CC, PT) by employing the multiple linear regression (MLR) model. The MLR model has been selected in order to identify the effect of linear combination of selected variables on vehicle speed. To model this, independent variables were considered as curve, vehicle and roadway characteristics as well as driver behaviour characteristics. Based on the preliminary analysis super elevation is not considered for combined model development because it may be attributed to the fact that super-elevation does not have significant effect on two-wheeler' speed and in the present study the two-wheelers' vehicle composition is higher. In the MLR model, the vehicle speed at different sections has been considered as a dependent variable and other collected variables have been selected as independent variables. The MLR model is generally useful to understand the change in vehicle speed while negotiating the horizontal curve (Misaghi and Hassan, 2005). The vehicle speed may vary based on different characteristics while a vehicle is negotiating a curve and linear model will indicate how the vehicle speed is varying with curve, vehicle and roadway characteristics. The MLR model need to satisfy the assumptions of dependent variable follows the normal distribution and the error terms of the calibrated model also follows normal distribution. The MLR model is most common technique used in order to build correlation between independent variables to dependent variable and the general MLR model form is given in equation 1.

$$V = \beta_0 + \beta_1{}^*X_1 + \beta_2{}^*X_2 + \beta_3 {}^* X_3 + .. + \beta_n {}^* X_n \quad (1)$$

where: V = The vehicle speed (viz., for two-wheeler, car, heavy vehicle, etc.); X_{i-n}= explanatory variables; β_{i-n}= are estimated parameters from the model; β_0= y-intercept of regression line.

3.7 Preliminary Analysis

The correlation analysis was carried out between selected independent variables (viz., curve, roadway and driver characteristics) and vehicle speed of individual as well as combined data of different vehicle types at three locations (viz., PC, CC, PT). From the correlation analysis results, it is found that the two-wheeler vehicle speed does not show good correlation with intersection angle (r= 0.06, p>0.05), presence of edge drop (r= -0.08, p>0.05), number of opposing vehicles, viz., while two-wheeler is maneuvering, number of vehicles from the opposite direction at that instant of time (r= -0.09, p>0.05), and it shows strong correlation with driver lane change behaviour (r= 0.394, p<0.01), where r value represents correlation coefficient and p value is the level of significance.

The car vehicle speed does not show any correlation with intersection angle (r= 0.01, p>0.05), super-elevation (r= -0.04, p>0.05), and it shows strong correlation with driver lane change behaviour (r= 0.212, p<0.01), number of opposing vehicles (r= -0.146, p<0.05) and presence of edge drop (r= -0.239, p<0.01). The heavy vehicle (bus/truck) speed has been observed to have good correlation with presence of edge drop (r= -0.214, p<0.01), shoulder width (r= 0.232, p<0.01), number of approaching vehicles from opposite direction (r= -0.212, p<0.01), type of vehicle (r= -0.124, p<0.01) and radius of the curve (r= 0.323, p<0.01). All these reported correlations are corresponding to the center of curve section. Subsequently, Analysis of Variance (ANOVA) is carried in order to identify whether the collected speed data has significant difference at the center of curve section as compared to the point of tangent as well as point of curvature. The results indicated that there is significant difference between vehicle speed of car, auto-rickshaw and heavy vehicles at center of curve as compared to the tangent section (F=24.742, p<0.001, F=12.564, p<0.001, F=32.124, p<0.001, respectively for car, auto-rickshaw and heavy vehicles) where F is the statistic of ANOVA and p is the level of significance. The two-wheeler vehicle speed did not indicate much difference at center of curve section as compared to the tangent section (F=3.124, p<0.005). Further, it is also observed that there is significant difference in vehicle speed of car, auto-rickshaw, heavy vehicles while entering and leaving of point of curvature and point of tangency (F=14.522, p<0.001, F=4.248, p<0.05, F=18.118, p<0.001).

3.8 Development of Model

The model was developed for individual vehicle speed and combined data of all vehicles speed at different sections of horizontal curve. From the collected 2100 vehicle speed data points, the data was processed and disturbed data or outliers were removed and the remaining data points (1860) were used for modelling. The vehicle speed was considered as the dependent variable and the remaining variables are considered as independent variables. For model calibration 1302 samples were considered (70% of data) and remaining data samples (558) were used for model validation purpose. The model validation was performed with Root Mean Square Error (RMSE) method which represents the difference between observed as well as predicted values.

4. MODEL RESULTS

From the MLR model, ANOVA test results of combined vehicle data shows that the vehicle speed model is significantly affected by 4 out of the 12 independent variables at point of curvature section, 7 out of the 12 independent variables at center of curve section, 5 out of the 12 independent variables at point of tangency and the overall significance from the ANOVA test of the calibrated model was F(4, 1297) = 29.444, p < .000 at point of curvature, F(7, 1852) = 35.289, p < .000 at center of curve, and F(5, 1296) = 29.998, p < .000 at point of point of tangency. Generally, the F-statistic represents the significant difference in mean values of the compared groups. Also, it is confirmed that the error terms are normally distributed from the normality plot of the Q-Q plots while calibrating the models in SPSS software.

Further, the variable selection was considered based on stepwise regression analysis and there are several variables such as degree of curvature (t = 1.444, p = 0.082), intersection angle (t = 0.398, p = 0.722), shoulder width (t = 0.877, p = 0.268), vehicle speed in the opposite lane (t = -0.588,

Variables	Estimated coefficient (β)	Standard error	t-Statistic	p-value	Model R-Square	RMSE of Model Calibration	RMSE of Model Validation
Vehicle Speed Model at Point of Curvature Section							
Constant	32.866	0.181	15.834	0.000*			
Edge drop	-0.756	0.055	-13.745	0.000			
AVT	-1.188	0.146	-8.137	0.000	0.458	12.668	14.588
NOV	-0.238	0.052	-4.577	0.000			
DLCB	1.954	0.155	12.232	0.000			
Vehicle Speed Model at Circular curve or Centre of Curve Section							
Constant	3.746	0.298	12.574	0.000*			
Curve radius	0.028	0.009	3.111	0 .011*			
Length of curve	0.263	0.094	2.798	0.028			
Edge drop	-1.338	0.092	-14.543	-0.000	0.655	8.544	11.245
AVT	-2.877	1.464	-1.965	0.051**			
NOV	-2.554	1.044	-2.446	0.029			
DLCB	0.257	0.046	5.587	0.000			
OVLCB	-1.223	0.605	-2.021	0.033			
Vehicle Speed Model at Point of Tangency Section							
Constant	45.221	1.186	4.402	0.000*			
AVS	-0.098	1.038	-2.021	0 .031*			
AVT	-4.163	2.067	-2.014	0.041	0.535	14.586	15.244
DLCB	0.708	0.272	2.603	0.008			
NOV	-0.554	0.168	-3.297	0.002			
OVLCB	-0.743	0.111	-6.693	0.000			

NOTE:AVT: Vehicle Type in the opposite lane; NOV: Number of Opposing Vehicles; DLCB: Driver Lane Change Behaviour; OVLCB: Opposing Vehicle Lane Change Behaviour; AVS: Vehicle Speed in the opposite lane; RMSE: Root Mean Square Error. *Variables are significant at 99% confidence interval; **Variables are significant at 95% confidence interval.

Table 2. Vehicle speed model results at different sections of curve.

p = 0.614), and shoulder width (t = 0.541, p = 0.578) which were excluded from the vehicle speed model at center of curve section, as they were not showing significance on vehicle speed at center of curve at 95% confidence level. The descriptive statistics of the vehicle speed model is summarized with t-values, p-values, R-square values, calibrated and validated RMSE in Table 2. A total 45.8% of the variance is explained by 4 independent variables at point of curvature (R-square = .458, Adjusted R-square = .457), 65.5% of the variance is explained by 7 independent variables at centre of curve (R-square = .655, Adjusted R-square = .653), and 53.5% of the variance is explained by 5 independent variables at point of tangency (R-square = .535, Adjusted R-square = .534), as given in Table 2.

The individual vehicle speed models for different vehicles types at different sections of a horizontal curve have been developed. For this purpose, stepwise regression model is considered and 70% data (viz., 651 numbers of two-wheelers, car as well as auto-rickshaw are 260 numbers each and heavy vehicles are 131 numbers) has been used for calibration and remaining data (viz., two-wheelers are 279 numbers, car as well as auto-rickshaw are 111 numbers each and heavy vehicles are 57 numbers) for model validation. The model results are summarized in Table 3.

5. DISCUSSION

5.1 Effect of curve characteristics on vehicle speed

For the combined vehicle speed data three different models were developed and individual vehicle speed models were also developed at three different locations of horizontal curve (viz., PC, CC and PT). From the combined vehicle speed model results, the curve characteristics have significant effect on vehicle speed at center of curve only and at other sections (viz., PC and PT) it does not show any effect on vehicle speed. From the combined data model results, the curve characteristics including radius and length of curve have positive impact on vehicle speed, which indicates that with increase in radius as well as length of curve, driver is able to attain desired speed at curve portion. However, the existing research studies shown that deflection angle of circular curve have significant effect on vehicle operational speed (Shallam and Ahmed, 2014; Castro et al., 2011). From the individual vehicle speed model, all speed of all vehicle types are affected by curve radius at centre of curve and results also indicate increase in vehicle speed with increase in radius (see in Table 3). Further, heavy vehicle model results at center of curve shows that there is consistency in heavy vehicle speed with increase in length of horizontal curve (see in Table 3). Further it is observed that there is a negative impact with super elevation on heavy vehicle speed at point of curvature as well as center of curve.

5.2 Effect of roadway characteristics on vehicle speed

From the combined data of vehicle speed model results it is observed that the edge drop has significant effect on vehicle speed at point of curvature as well as center of curve. While the vehicle is negotiating along the curve there is a decrease in vehicle speed due to edge drops (viz., 1.33% at center of curve and 0.75% at point of tangency). The presence of edge drops is important for heavy vehicles as due to off-tracking of wheel base length the vehicle had more discomfort in the presence of edge drops. However, the combined results did not show any effect of edge drop at point of tangent. Perhaps it is due to the fact that at selected locations there is sufficient shoulder width at point of tangency. The existing research studies shows that the shoulder width has significant effect on vehicle operating speed but the present combined data model results do not yield any specific conclusions (Castro et al., 2011).

In the present study, the individual model results show that heavy vehicle speed has positive impact with adequate shoulder width at point of curvature. It indicates that there is no reduction heavy vehicle speed while there is proper shoulder width being maintained. Moreover, the two-wheeler and heavy vehicle speed have been observed to reduce by 1.12 % and 0.57 % at center of curve while these vehicles are moving in presence of edge drops. There is an increase in heavy vehicle speed while moving from center of curve to point of tangency in presence of sufficient shoulder width. Existing

Vehicle Type	Model form	Model R-Square
Vehicle Speed Model at Point of Curvature Section		
Two-wheeler	33.699-3.131*AVT-2.228*NOV+3.167*DLCB-2.284*OVLCB	0.442
Autorickshaw	29.674-1.609*AVT-2.069*NOV+2.59*DLCB	0.286
Car	44.131-0.481*AVS-2.99*NOV+2.48*DLCB	0.489
Heavy vehicle (Bus/Truck)	18.322+0.376*SW-0.324SE-0.121*AVT-0.567*NOV-0.44*OVLCB	0.264
Vehicle Speed Model at Circular curve or Centre of Curve Section		
Two-wheeler	17.548+0.108*CR-1.125*ED-0.178*AVT+2.441*DLCB-0.733*OVLCB	0.411
Autorickshaw	18.568+0.092*CR-1.112*AVT+0.324*DLCB-0.066*OVLCB	0.355
Car	13.624+0.213*CR-0.526*AVT-0.224*AVS+1.246*DLCB-0.122*OVLCB	0.518
Heavy vehicle (Bus/Truck)	6.124+0.072*CR+0.022*LOC-0.578*ED-0.01*SE-0.021*AVS-0.315 *NOV-0.033*OVLCB	0.322
Vehicle Speed Model at Point of Tangency Section		
Two-wheeler	35.221-0.025*AVS-0.403*NOV-0.842*OVLCB	0.335
Autorickshaw	19.522-0.014*AVT-0.064*NOV+0.121*DLCB	0.216
Car	24.166-0.122*AVS+0.325*DLCB-0.788*NOV	0.482
Heavy vehicle (Bus/Truck)	13.807+1.142*SW-0.526*NOV+0.02*DLCB-0.114*OVLCB	0.328

NOTE:AVT: Vehicle Type in the opposite lane; NOV: Number of Opposing Vehicles; DLCB: Driver Lane Change Behaviour; OVLCB: Opposing Vehicle Lane Change Behaviour; AVS: Vehicle Speed in the opposite lane; SW:Shoulder Width; SE:Super Elevation;CR: Curve Radius; ED: Edge Drop; LOC: Length Of Curve.

All Variables are significant at 95% confidence interval.

** Indicates that multiplication between explanatory variables and estimated parameters from the model.*

Table 3. Individual vehicle speed model results at different sections of curve.

research studies also pointed that there is no significant relation between roadway geometry at tangent section for vehicle operating speed (Misaghi and Hassan, 2005).

5.3 Effect of driver characteristics on vehicle speed

Results from the combined model analysis suggests that there is a statistically significant linear positive relationship between driver lane change behaviour and vehicle speed at 99% level of confidence (p-value < 0.01) at three locations of the curve (viz., PC, CC and PT). For instance, there is an increase in vehicle speed by 1.95%, 0.25% and 0.70 with driver lane change behaviour at point of curvature, center of curve and point of tangent, respectively (refer Table 2). Research studies have shown that the driver lane change behaviour is observed more at center of curve with large radius and it has significant impact on safety issues at horizontal alignment (Othman et al., 2013; Nalo et al., 2020). The vehicular driver, particularly heavy vehicles, may not have opportunity to change the lane at center of curve and hence there is negligible effect on heavy vehicle speed at center of curve. However, the driver lane change behaviour is observed for two-wheelers at the center of curve, and owing to higher percentage of two-wheelers in combined data, it has significant effect with combined data also at center of curve. Further, if opposite vehicles exhibit lane change behaviour, a significant reduction in vehicle speed is observed (1.22% and 0.74% at center of curve and point of tangent, respectively). This can be attributed to the fact that opposite vehicle lane change behaviour obstructs the on-coming vehicle speed and results in either stoppage or slowing down of vehicle. Existing research studies show that three types of driving behaviour while they negotiate horizontal curves include aggressive, moderate, and cautious driving; this driving behaviour has a significant impact on road crashes (Rosas-López et al., 2021). Also, self-reported qualitative research shows that distraction during driving is one of the important factors while a driver is negotiating along horizontal and vertical curves (Termidi et al., 2021).

The individual vehicle speed models show that all vehicle types (viz., two-wheeler, auto-rickshaw and car) with driver lane change behaviour have positive linear relationship with their vehicle speed at all sections of the curve (refer Table 3). However, the heavy vehicle drivers do not have chance of changing their lane at center of curve section as compared with other vehicle types. It is also observed from the field data that the vehicular drivers (particularly two-wheeler drivers) usually practice change in lane under mixed traffic conditions. The opposite vehicle lane change behaviour has significant negative effect on vehicle speed of all the vehicle types at center of curve. It is observed that there is a reduction in vehicle speed by 0.73%, 0.06%, 0.12%, 0.03% for two wheeler, auto-rickshaw, car and heavy vehicles, respectively, due to opposite vehicle lane change behaviour at center of curve (refer Table 3). Moreover, opposite vehicle lane change behaviour is observed to be higher at point of curvature as well as point of tangency resulting in higher reduction in vehicle speed of two-wheelers (2.28%) and heavy vehicles (0.44%) at point of curvature and a reduction in vehicle speed by 0.84% and 0.11% for two-wheelers and heavy vehicles, respectively, at point of tangent.

5.4 Effect of vehicle characteristics on vehicle speed

The combined model results showed that vehicle types in the opposite lane as well as number of opposite vehicles have significant negative impact on vehicle speed at three different sections of horizontal curve (refer Table 2). When the vehicle type in the opposite lane is heavy vehicle, then a reduction in vehicle speed is observed from model results. Further, more number of opposite vehicles results in reduction in vehicle speed by 0.238%, 2.254% and 0.554% at point of curve, center of curve and point of tangent, respectively. Moreover, the increase in vehicle speed in the opposite lane has negative impact on vehicle speed at point of tangent. From the model results it is observed that the composition of vehicles has significant impact on vehicle speed at horizontal alignment. It is hence suggested that the design speed evaluation needs to consider the composition of vehicles while designing the horizontal alignment.

From the individual vehicle type model results, vehicle speed in the opposite lane and numbers of opposite vehicles have significant negative effect on two-wheeler, auto-rickshaw and heavy vehicles' speed at point of curvature (refer Table 3). The vehicle speed of car is significantly affected by the vehicle speed in the opposite lane and number of opposite vehicles at point of curvature. While a vehicle is entering the horizontal curve, if the vehicle in opposite direction is with higher speed or number of opposite vehicles is higher, this has negative impact on the on-coming vehicle speed. At the center of curve, two-wheelers, auto-rickshaw and cars experience negative impact on their speed when the vehicle types in the opposite lane are heavy vehicles/car or the vehicle speed in the opposite lane is higher. The reason behind this response could be due to the fact that at center of curve portion, two-wheelers from the opposite direction usually move with normal speed without much lane change behaviour, and hence do not show any effect on speed of heavy vehicles, however their change in speed has effect on on-coming heavy vehicle speed. It may be due to overtaking maneuver of two-wheelers at center of curvature at higher speed. However, the present study did not encounter the overtaking behaviour of vehicle at horizontal alignment. Hence, further study is required to make specific conclusions about it. It is also identified that vehicle speed in the opposite lane has negative impact on two-wheeler as well as car vehicle speed and number of opposite vehicles have negative impact on speed of two-wheeler, auto-rickshaw and heavy vehicles at point of tangent. Moreover, at point of tangent section, more number of vehicles are willing to leave with higher speed and such platoon of vehicle has been observed to have significant effect on vehicle speed.

6. CONCLUSIONS

This study presents an experimental investigation of the vehicle speed considering the effect of driver behaviour on horizontal curves of two-lane rural highways under mixed traffic conditions. The effect of curve, roadway and vehicle type on vehicle speed has also been considered in this study. For this purpose, four horizontal curves were selected along the rural highway and driver behaviour as well as vehicle characteristics were collected from the video survey and curve as well as roadway characteristics were collected from the preliminary survey. A total 1860 vehicle speed data points were collected and 70% data was used for modelling and 30% data was used for validation of the models. The modelling has been carried with multiple linear regression with combined vehicle data as well as individual vehicle speed at three different locations of horizontal curve.

From the combined vehicle speed model results it has been concluded that change in lane by vehicle driver significantly increases their speed and such lane change behaviour may critical safety issue at horizontal alignment. It has also been concluded that there is a decrease in vehicle speed with increase in number of opposite vehicles and heavy vehicle type has been observed to have more impact of on-coming vehicle speed. The curve characteristics including radius as well as length of curve were noted to affect the vehicle speed at center of curve portion only. Further, it has also been concluded that edge drops significantly reduces the vehicle speed, especially for heavy vehicles, while vehicles are negotiating the horizontal curve. It is also concluded that there is a decrease in vehicle speed with increase in vehicle speed in the opposite lane as well as opposite vehicle lane change behaviour at point of tangency. From the individual vehicle speed model, it is concluded there is increase in vehicle speed with increase in curve radius for all types of vehicle and there is decrease in vehicle speed with opposite vehicle lane change behaviour as well as increase in number of opposite vehicles at center of curve. The results indicate that length of curve as well as super elevation have significant effect on heavy vehicle speed and it can be concluded that the composition of vehicles has to be considered while designing horizontal alignment. Also, the increase in size of vehicle type in the opposite lane has been observed to substantially reduce the speed of two-wheelers, auto-rickshaw and heavy vehicles at point of curvature. From the model results it can be concluded that the driver lane change behaviour along the horizontal curve may increase their vehicle speed but it may be critical from safety perspective. The study results also concluded that maintaining proper shoulder width helps in maintaining consistency in vehicle speed while vehicle is negotiating along the curve and it is particularly important for heavy vehicles.

The present study results are limited to two-lane two-way rural highway and data is collected at only four horizontal curves during day time conditions. Further, studies are required in order to quantify the effect of driver overtaking behaviour, acceleration as well as deceleration effects at the horizontal curve with mix traffic behaviour. Moreover, with special lighting, the presented models can be validated for traffic during evening and night hours. Apart from these limitations, the analytical results provided insight into the effect of driver behaviour and roadway characteristics on vehicle speed at horizontal curves. The model presented in the study would be useful to predict vehicle speed at horizontal curve with characteristics of mixed traffic, insufficient shoulder width, with edge drops and driver lane change behaviour. The model presented in the study considering various characteristics would provide useful inputs to improve the horizontal alignment particularly at curves, and improve driver behaviour at horizontal curves. Further, these results can be linked with driver safety evaluation and would be useful for planning countermeasures for improving safety at horizontal curves.

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