Experimental Analysis of Effect of Lateral Friction on Horizontal Curve for Highways

Dipika Gupta*[1], Dr. P.J. Gundaliya[2]

*[1] *Ph.D Scholar, Civil Engineering dept. Gujarat Technological University*

[2]*Professor, Civil Engineering Dept. L.D.C.E, Gujarat Technological University*

Abstract: *For the design of horizontal curve, the different factors are calculated. Friction also plays an important role while designing the horizontal curve of the road. The lateral friction which applies to the road as per the fundamental of phyiscs, always taken as constant value in the design process. Here, the finding of the conducted research project is to estimate the lateral friction factor demanded over the lateral friction supply. An experimental approach is conducted to find the value of Lateral Friction on horizontal curve. Study has gone under the different factors which are usually effecting the lateral friction such as, radius of curvature, speed of vehicle, curve inventory data, site condition as downgrade and upgrade, lateral acceleration, trajectory path of vehicle. A sensor based device is developed to identify the direct lateral friction and human behaviour while a vehicle is negotiating the horizontal curve. The data is accounted and comparison were observed between the codal provision and the output of device. Again the data is compared with and simulation software: CARSIM. The result of all the comparison were seen and concluded that the Lateral Friction Factor is inversely proportional to the speed of vehicle. With increase of speed of vehicle, the lateral friction gets reduced. This would result to take a new value of lateral friction by highway designers in real office practice while designing the horizontal curves, that would not take the constant lateral friction as always. Also the horizontal curve should be designed without at driver's risk.*

Keywords: **Horizontal Curve, Lateral friction factor, Lateral Acceleration, Superelevation, Supply Friction, Demand Friction**.

1. INTRODUCTION

Highway plays an important role in the day to day life of road users. The design of pavement requires a proper matching of highway curved and straight portion, in that while driving by the users, they will not get surprised by the abrupt change in the alignment. Generally, the design of pavement is concern majorly by the efficient geometric design. In terms of Geometric need, the pavement should be reliable on the speed, safety and comfort road elements. While designing the highway the design should be safe and efficient both during day light, night light, bad and good weather conditions. In present practice of designing the highway in respect of Horizontal Curves and streets is taken with the assistance of standard code of country. For design of horizontal curve of highway IRC code mentioned a specific value, where in all Highway designer are following the same constant value for all conditions. Majority of highway design in real office practice and in existence is based on the empirical formulas given an IRC. This lead to maintain the mandatory possible results for all type of conditions. Now, for different conditions, the effective factors which effect the design parameters also act as differently for individual ones. So it is very decisive to take steps for critical study for that parameters and to evaluate the existing condition with operative solutions. The major factors for designing horizontal curves is to be in considerations are superelevation and side friction (Lateral Friction) which is to be distributed in such a manner, that person when negotiate a curve they will be free from fear of anxiety. If not designed properly, this will actually lead to an accident risk and loss of life. Many research has been done to evaluate the parameters, some of that are implemented. But in Indian practices we follow the IRC codes for designing, which is to be bone up in depth for different conditions.

2. Recent Research

This presents a summary of major findings in the area of safety aspects. A wide range of issues are addressed related to horizontal alignment design. A proper organized investigation is presented in two components: (a) Horizontal curve radius design and (b) identification of side friction i.e. lateral friction. The first comprises of two design variables: horizontal curve radius and superelevation rate and the second components is to find out the values of lateral friction i.e. side friction factor for the vehicle negotiating horizontal curve. The topic of horizontal curve radius is researched by several researchers. In Green book, the horizontal curve alignment is design issues and specific guidelines are indicated as an hierarchical arrangement of various terms which describes roadway for its design and function [1] not designed with perfection. Minimum curve radius is derived into account the limit value of superelevation. The equation of minimum radius of horizontal curve depends on the superelevation value is presented by AASTHO' A policy on Geometric Design of Highways and streets 2018 [2] as follows in equation (1):

$$R_{min} = \frac{V^2}{127(0.01\, e_{max} + f_{max})} \qquad (1)$$

Rmin =Minimum curve radius(m)

emax= Maximum superelevation

fmax = Maximum allowable side friction factor

V = speed of vehicle

A ball bank indicator is curved identifier generally used to identify the safe speed of horizontal curves. This measures, a combination of lateral acceleration, superelevation and body roll angle in the following relationship [3] in equation (2)

$$BBI = lateral\ acceleration - superelevation + bodyroll \qquad (2)$$

BBI is the reading is the simple relationship of three parameters. In this, if body roll angle is neglected, the radius can be identified with the help of point mass equation [4,12] in equation (3)

$$R = \frac{V^2}{15\,(e+f)} \qquad (3)$$

$R = Radius\ (ft)$

$V = speed\,(mph)$

$e = avg.\, full\ superelevation$

$f - side\ friction\ factor$

According to AASTHO, the basic side friction equation can be given by rearranging terms of point mass formula as in equation 4:

$$f - \frac{V_{DS}^2}{g.R} - (.01.e) \qquad (4)$$

The change in lateral acceleration with respect to the time is stated as jerk and this concept is also referred as second acceleration [5]. This is the value which finds voyage and comfort. It is the change of lateral acceleration generated by the centrifugal force on the horizontal curve with respect to time. The lateral acceleration is balanced by the friction between the tire and pavement when the road is having superelevation with component of gravity [6]. The relationship is given by $a_f = a_r - a_e$, where, a_f = acceleration balanced by friction (or lateral acceleration = gfD), m/s^2, a_r= centripetal acceleration (v^2/R), m/s^2, and a_e= acceleration balanced by superelevation (=ge/100), m/s^2. The side friction factor i.e lateral friction factor is mention as in equation 4. The lateral friction design curves have been revised for the high-speed provisions. This reflects a reassessment of research on vehicle operations on a curve, there represents a marginal restrictive set of values for design [7]. Generally, the relationship between the curves geometry and lateral friction factor were determined and concluded that motorist is demanding more lateral friction on curves sharper than 2 degrees/100m with operating speed lower than 80km/hr [8]. The study indicates that very less no. of research has been taken to identify the step wise procedure in consideration with all factors effecting the lateral friction factor. Here, the findings are to identify the step wise procedure to estimate the lateral friction factor when a vehicle negotiates horizontal curve.

3. Methodology

For this findings, one test vehicle is selected as an SUV an E class sedan, with a young expert driver having certified driving license. The sprung mass of car is 998 kg and it carries two people one with driver and other handling the device to record the data's. The real performance of vehicle was observed for different condition of road geometry with different speed adopted for the study of vehicle behavior at the point of curvature location of horizontal curve. The test vehicle is running at the center of the length of the curve. Different speed was taken as 10,20,30,40,50,60,70,80,90 km/h for SUV passenger car and with different maximum rate of super elevation and radii of horizontal curves were selected as per the site condition. The google earth pro software and auto-level instrument are used to identify the different radii as 365.14, 283.34,566.32,885,142.02 and 372.93. As lateral friction between tire and pavement especially considering the horizontal curve location depends on many factors, such as speed of the vehicle, pavement surface, downgrade profile and upgrade profile. The speed of SUV vehicle decreases significantly on sharp horizontal curves on upgrades and downgrades. The inventory details are shown in table 1, these are the location of Bhavnagar to Ahmedabad route in Gujarat. The site selection [13] was depending on some factors as: 1) The section of horizontal curve should be paved with the paved section.2) Grade should be less than 5%, 3) The cross slope must be having small variation within the horizontal curve, 4) The horizontal curve should be true Circular curve (undistorted), 5) Two- Lane, Two-way State Highway and National Highway sections. For the curves detail, a table-1 is representing the inventory information with no. runs which means that a test vehicle carried that many no. of runs for particular curve and combining all the runs the no. of observations were collected.

Table 1. Curve Inventory Details of the Selected sections of Highway

`	Speed		No. Runs	No. of Observation
	km/h	mps		
Curve : 01	20	5.56	5	6624
Radius=365.14m	30	8.34	4	
Design Speed=80km/h	40	11.12	5	
Superelevation=2.3%	50	13.9	3	
Length=105m	60	16.68	2	
Grade-Downward	70	19.46	2	
	80	22.24	2	
	90	25.02	1	
Curve : 02	20	5.56	5	8256
Radius=283.34m	30	8.34	4	
Design Speed=80km/h	40	11.12	5	
Superelevation=1.2%	50	13.9	3	
Length=105m	60	16.68	2	
Grade-Upward	70	19.46	2	

	80	22.24	2	
	90	25.02	1	
Curve : 03	20	5.56	5	
Radius=566.32m	30	8.34	4	
Design Speed=80km/h	40	11.12	6	
Superelevation=0.4%	50	13.9	4	9792
Length=595.45m	60	16.68	2	
Grade- Upward	70	19.46	3	
	80	22.24	2	
	90	25.02	1	
Curve : 04	20	5.56	5	
Radius=885m	30	8.34	4	
Design Speed=80km/h	40	11.12	6	
Superelevation=0.3%	50	13.9	4	
Length=595.45m	60	16.68	2	9900
Grade- Upward	70	19.46	3	
	80	22.24	2	
	90	25.02	1	
	110	30.58	1	
Curve : 05	20	5.56	5	
Radius=142.02m	30	8.34	4	
Design Speed=80km/h	40	11.12	6	
Superelevation=0%	50	13.9	4	
Length=595.45m	60	16.68	2	7956
Grade- Upward	70	19.46	3	
	80	22.24	2	
	90	25.02	1	
	100	27.8	1	
Curve : 06	20	5.56	5	
Radius=372.93m	30	8.34	4	
Design Speed=80km/h	40	11.12	6	
Superelevation=0.3%	50	13.9	4	8625
Length=595.45m	60	16.68	2	
Grade- Upward	70	19.46	13	
	80	22.24	2	

There are two types of driver behavior is observed that the vehicle will negotiate with constant speed and driver will use brakes in the downgrade surface of pavement. In this case the type of behavior with no braking will give the impulsive results, but this kind of driver behavior is almost impossible on steep downgrades, were in the drivers usually needs to use the brakes for decelerating the vehicle and control the vehicle form lateral movement. As per the earlier research by Harwood [9], the braking reaction time is not effecting the maximum lateral friction factor. The formulation of model is depending upon the point mass concept and the expression for the friction factor [6] are as in equation 5:

$$f = \frac{Fc}{N}\ \frac{e}{100} = tan\alpha \qquad (5)$$

Here, $f = Lateral\ friction\ factor$
$Fc = Tire\ pavement\ friction, force\ acting\ at\ the\ road\ outward\ the\ centre\ of\ rotation$
$N = Normal\ Rection\ from\ the\ road$

A device is developed named: Lateral Friction Factor device, used to determine the lateral i.e. side friction value for the different speed and different factors to be considered in it. Lateral Friction Factor Device is developed by combining all the additional features like accelerometer sensor, gyroscope, high speed MCU with GUI Software for the data display and controlling. The sensor equipped in the system are examine the behavior of the movement of vehicle on the curve. It comes with the basic principal of horizontal curve design that is derived from the application of kinematics equations as shown in equation (5). Centrifugal acceleration is counted as lateral acceleration, which is applied through pavement superelevation and tire pavement friction on vehicle when negotiating a horizontal curve. It is able to find the lateral acceleration in all direction say x-axis, y-axis and z-axis. A TMFT software working with simultaneous principal of device which is equipped with sensors as discussed and shown in figure 1

Figure 1. A Lateral friction factor(LFF) device and Driver Behaviour Analysis(DBA), equipped with sensors and inbuilt software to get the values.

4. Analysis and Results

The data is analyzed by two approach:

1) By the Lateral Friction Factor and Driver Behaviour Analysis Device
2) CARSIM Software

If the car is in normal condition, the vertical component will generate the static coefficient. And if the same car is pushed up to some application of load that it will get shifted is the lateral friction. If we take the ratio of vertical friction to the lateral friction, that ratio will define actual Lateral friction factor. Some lateral force is required by the car to negotiate the curve. In the case of vertical, if the vehicle is not subject to force then the friction coefficient is μs and if it is subjected to lateral force then friction coefficient will be μl. This shows the lateral friction factor. As μs is through constant because it is a function of weight of car and the surface of road and tire. And in majority it is predefined by the manufacture company. Here, the reference is adopted for the static friction of Jones and Childers [10]. They reported the coefficient of friction of about 0.7 for dry roads and 0.4 for wet roads. If the car negotiating the curve with 10 kmph speed the lateral thrust observed in the car is 10KN, likewise if the speed is increasing the centrifugal force will be increasing, so the car if negotiate the curve with the speed of 20kmph the centrifugal force will be 20KN. Now by calculating the lateral coefficient as μ_l-10, μ_l-20- μ_l-30, so we have F_l-10, F_l-20 such as $F_l = m*a_l$.

μ_s = Coefficient of Static Friction

μ_l = Coefficient of Lateral Friction, at 10 kmph speed, 20 kmph speed etc.

F_l = Lateral Force, at 10 kmph speed, 20 kmph speed etc.

So the static friction is considered as the supply friction and demand friction is the value which is coming as per the Friction values that were computed using the equation (5). As discuss previously, to calculate the lateral friction factor, we have to take the ratio of Static coefficient friction and lateral coefficient friction or ratio of Supply friction and Demand friction [11]. The equation in (4) represents the point mass formulation. Side Friction supply is the available friction between the tire and road surface for preventing skidding on horizontal curve [14]. Based on the values getting form the inventory survey, they are formulated in the equation (4). The results shown here in the figure 2:

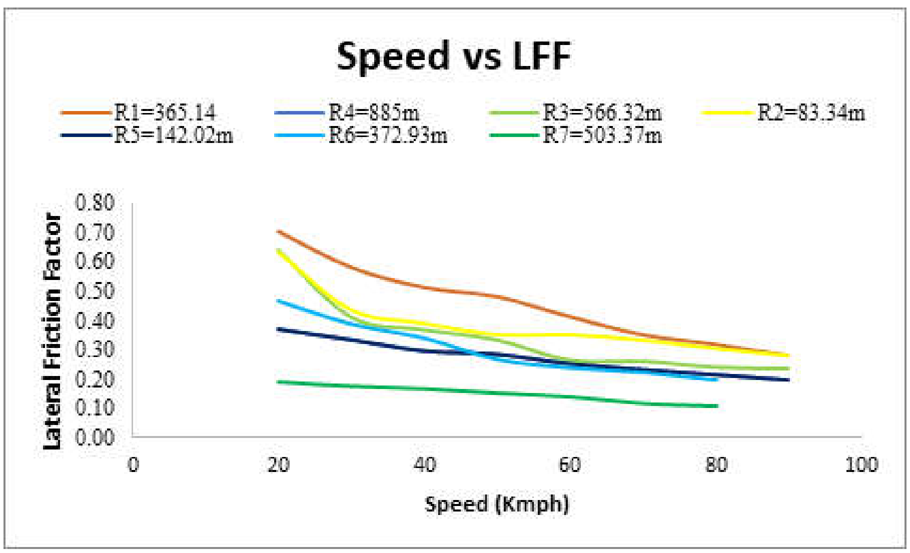

Figure 2. Relationship between Lateral Friction Factor and Vehicle Speed of Different Horizontal Curve

As the graph indicates, for all location of curves with different curve radii, vehicle speed and superelevation. With the increase in vehicle speed there will be decrease in lateral friction factor. Form the data taken, the downgrade and upgrade variations effect the friction values in specific curve portion where a vehicle is about to take the rotational jerk at the point of curvature. In the table 2: the values represent the relationship and variations between the Lateral friction factor and corresponding velocity of vehicle.

Table 2. Lateral friction Factor from LFF Device based on the concept of equation (5).

Vehicle Speed (kmph)	20	30	40	50	60	70	80	90
Lateral Friction Factor	0.49	0.39	0.35	0.33	0.29	0.27	0.25	0.24

Table 3. Lateral friction Factor from CARSIM

Vehicle Speed (kmph)	20	30	40	50	60	70	80	90
Lateral Friction Factor	0.58	0.55	0.50	0.42	0.40	0.35	0.32	0.30

For validating the results, values obtained from the device and software is compared. CarSim is a mechanical simulation tool, which simulates the passenger car and light duty trucks. It is one of the preferred tool for analysing the vehicle dynamics. In figure 3,4, &5 there are some glimpse of the work carried in CARSIM. The obtained data is near about similar to the simulations results. About 10 % of difference is coming in between the both approach which is admissible for the proper validation of the process.

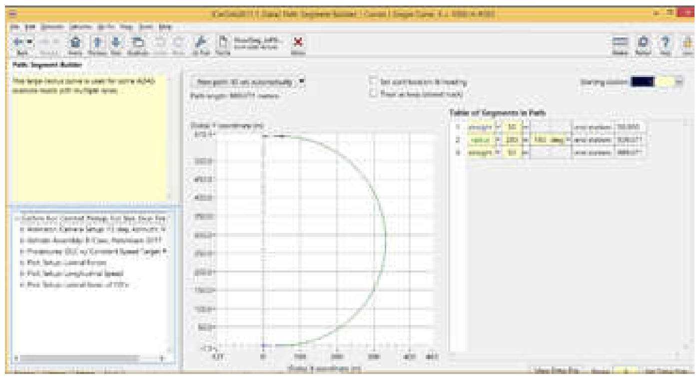

Figure 3. Alignment Creation as per Radius

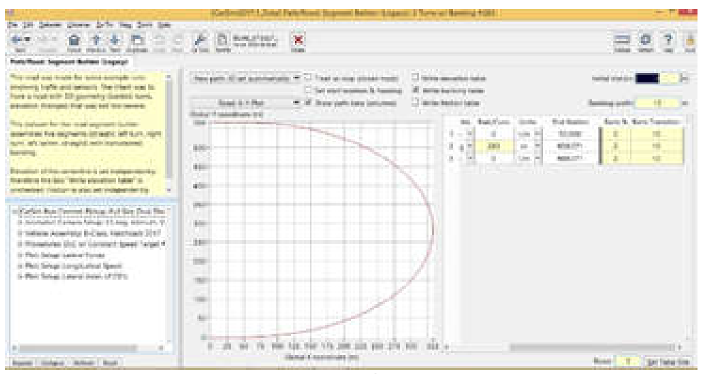

Figure 4. Providing Superelevation Values

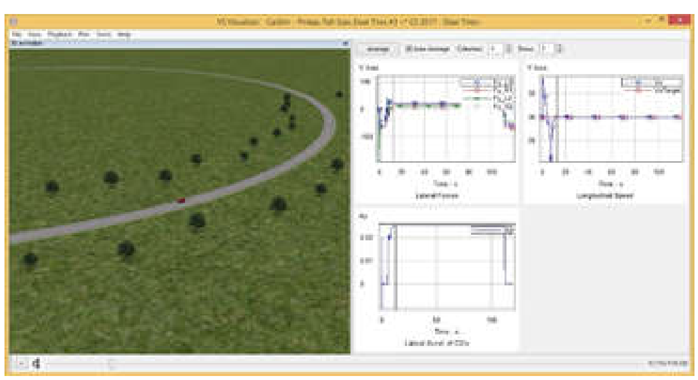

Figure 5. Running the Simulation

However, the regression analysis used as an approach for modelling the relationship between a scalar dependent variable 'Y' and one or more explanatory variables denoted as 'X'. Basically Regression analysis is a set of statistical processes for estimating the relationships among variables. Estimating LF coefficient using regression technique. The models are developed using the data collected from the study area. Total three number of models are developed considering different factors affecting lateral coefficient of friction. Variable Considered for model development are LFF, V, R, al , $\hat{\upsilon}$ and e where LFF is a dependant Variable and V, R, al , $\hat{\upsilon}$ and e are independent variables. The four model is shown in table 3

$V = Speed\ of\ vehicle, m/s$

$R = Radius\ of\ Horizontal\ curve, m$

$a_l = Lateral\ acceleration, m/s^2$

$\hat{\upsilon} = Heart\ beat\ rate, bpm$

$e = Superelevation\ rate$ Author names and affiliations are to be centered beneath the title and printed in Times New Roman 12-point, non-boldface type. (See example below)

Table 3. Lateral Friction Factor Model Development by Regression Method

Variables	Model Equation	R2	*T-OBS	**T-CR	***C-Level
$V, R, a_l, \hat{\upsilon}, e$	$LFF = -0.00025V + 6.1375R + 0.082522a_l + 0.076845e - 7.2922\hat{\upsilon}$	**.83**	**2.0**	**1.02**	**83%**
V, R, a_l, e	$LFF = -0.00024V + 1.59277R + 0.081522a_l + .117425e$	**.84**	**3.336**	**1.999**	**84%**
V, R, a_l	$LFF = -0.00024V - 6.509R + 0.080602a_l$	.85	2.28	1.99	85%

*T-OBS is T Test Observed Value

**T-CR is T Test Critical Value

***C-Level is Confidence Level

Considering all models and their validation it is observed that model 1 gives best result among all regression models. It also gives coefficient of co relation value very nearer. Hence, any model concerning with different factors are to be taken as lateral friction factor value.

5. Conclusion

The value of f_{max} in table 3 are for passenger cars on sealed and unsealed pavement. Here the research has shown the articulated vehicle may negotiate at the value of side friction in the range 0.22. The finding of the research is summaries as follow:

1) Clarifies the basic concept of lateral friction for horizontal curve addressing the factors affecting coefficient of friction.
2) The study also gives clear identification about the unstable variation of acceleration rate with varying speed at horizontal curves having different radius and geometric profile.
3) Among all developed models most positive result giving model is selected. The R2 value indicated relationship profile between observed friction values

with dependent & independent variables, after model validation using "t" test, "t" observed value is greater than "t" critical value which concludes that the model contains 85% confidence level.

4) As far as lateral acceleration is concerned, it's seen that lateral acceleration rate has more effects on coefficient of lateral friction than super-elevation rate.
5) Increasing lateral friction values with speed clearly indicates that friction coefficient is in-directly proportional to the speed of the vehicle and it is inversely proportional to the radius of the horizontal curves, while IRC Code doesn't recommend lateral friction values with this type of variation.
6) As Heartbeat rate count went continuously increasing with the increasing speed, it reflects to the effects of human perception on curves. Even addressing the age factor to the count, the driver of the test vehicle was only 32 year old with a very high Heartbeat rate fluctuation with the speed at the curves. So what could be the physical and psychological situation for the old age drivers while negotiating the curve, ultimately relates to the endangerment of the curve and results in originating blackspots at the curves.
7) It is desirable to develop the device which help to identify the lateral friction values. The lateral friction factor device not only observing the lateral friction value, but with the lateral acceleration in all directions with gyroscope details in three dimensions. The concept assists to develop other instrument DBA (Driver Behaviour Analysis). DBA gives the values as heart beat rate in bpm (heart beats per minute), which also aid to identify the driver -friction behaviour at point of curvature along the horizontal curve.

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