International Journal of Research in Advent Technology, Vol.7, No.3, March 2019
E-ISSN: 2321-9637
Available online at www.ijrat.org

ESTIMATING LATERAL FRICTION FACTOR CONSIDERING VEHICLE SPEED, ACCELERATION, SUPERELEVATION AND RADIUS OF CURVATURE OF RURAL HIGHWAY

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Abstract-On rural highways, drivers are able to move at their desired speed because of less interruption of other vehicles. As per the World Road Statistics (2008) report of international Road federation, in India, nearly two third of road accident are found to take place on rural highways and various studies shows that more than 50% of fatal accident crashes in rural highway takes place at sharp horizontal curves. At these locations, the various factors like pavement type, super elevation and friction factor plays an important role to control the vehicle. To make these locations safer, the study of associated curvature criteria is needed. As per AASTHO guidelines along with the speed, radius of curve and super elevation, lateral friction factor is a governing parameter for the design of horizontal curves. However, it is seen that lateral friction factor is less studied because it is difficult to measure at field. For study of super elevation and lateral friction factor, three horizontal curves of varying radius of State Highway No.12 (from Sinnar to Ghoti in Nashik district of Maharashtra state) are selected. The study is carried out for determining the amount of lateral friction required and provided at field for a given curvatures and vehicle speeds, A three-axis accelerometer are installed in test vehicles of Light Commercial vehicle (LCV). The vehicle selected for testing purpose is Mahindra Bolero Pick-up. It is expected the outcome of the study that anticipated later friction factor control the various design parameters.

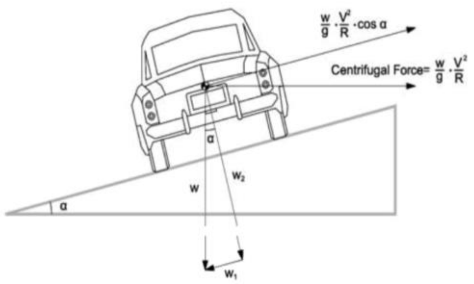
Key words: Super elevation, lateral friction factor and speed of vehicles

1. INTRODUCTION

A good design of highway geometry necessitates proper coordination of straight and curved sections, so that drivers will not be surprised by a change in the alignment. In other words, any improper design of geometry leads to unnecessary speed changes. Evaluating the consistency of geometric design is one of the promising strategies for improving the rural highway safety as sections that lack design consistency experience high collision occurrences. Among all Highway geometric elements, curves are most important for consistency and safety of drivers. Horizontal curves designed in accordance with Green Book (AASTHO, 2011) criteria have been generally shown to provide substantial margins of safety with respect to vehicle skidding and rollover, for both passenger cars and trucks. From many literatures, it is observed, friction data measured in the 1930’s and 1940’s, which were used to develop limiting values of friction used in horizontal curve design policy. since then, the vehicle fleet has changed considerably like in tyre design, pavement design, and friction measurement methods (AASTHO, 2011). discuss five different methods for the distribution of side friction and Superelevation rates for curves with radius greater than the minimum and recommended one of the methods for rural high-speed road design, which is most commonly used in practice. The side friction factors used in the green book are design side friction factors that assume safe driving conditions for minimum allowable radius, design speed and maximum Superelevation rates. The side friction factors used in green book have been based on research conducted mostly in 1930 and 1940s. The research was based on limiting the lateral acceleration to a comfort limit for drivers. Skid failure occurs when the lateral acceleration causes a vehicle to skid outward and away from the curve overcoming the force of friction and weight component parallel to a Superelevation section, if it exists. Peak side friction supply is provided by the tyre pavement interface and should theoretically equal to the peak static coefficient of friction since the direction of skid is not along the direction of motion thus highest coefficient of friction provided is just before the start of skid motion of a vehicle.

1.1 Mass Point Formula

When a vehicle moves in a circular path, it is forced radially outward by centrifugal force. To counterbalance the force and stay moving in the circular



$$w_1 = w \cdot \sin\alpha \text{ (Force caused by Superelevation)}$$
$$w_2 = w \cdot \cos\alpha \rightarrow f \cdot w \cdot \cos\alpha \text{ (Side Friction)}$$
$$\frac{w}{g} \cdot \frac{V^2}{R} \cdot \cos\alpha \le f \cdot w \cdot \cos\alpha + w \cdot \sin\alpha$$
$$\frac{V^2}{g \cdot R} \le f + e \quad (e = \tan\alpha)$$

Figure 1 Centrifugal force in horizontal curve path, the friction force that is developed by vehicle weight and friction factor between tires and pavement must be greater than the centrifugal force. In highway geometric design practice, engineers use superelevation for a long time to supplement the friction force and facilitate smoother vehicle travel in a curve. In the design of highway curves, there exists the relation between design speed and curvature and also the joint relations with superelevation and side friction. This relation is called the Mass Point formula in highway design.

1.2 Objectives of Study

Followings are the prime objectives of the present study:

- To study the important factors on which lateral friction coefficient is dependent(f).
- To establish relation between the independent factors and lateral friction factor.
- To find out the value of lateral friction at existing condition on a horizontal curve of a rural Highway.
- To compare observed value with codal provisions values suggested by IRC and AASTHO.

2. LITERATURE REVIEW

This section mainly concentrates on the literature regarding lateral friction factor. Various attempts have been made to find important factors and their relation with friction factor & some other methods to finding the friction factor value. Various research is to be studied before finalizing the actual work to be done on field. Various literature that have been studied are discussed here.

Shauna Hallmark (2017) studied overcomes all the hurdles through the use of naturalistic driving data, providing insights on how drivers navigate and react to curves on rural two-lane highways. Nearly 10,000 vehicle traces were collected from 202 drivers on 219 horizontal curves as a part of this study. All driving traces were collected on rural two-lane highways with prevailing posted speed limits of 45 mph or 55 mph, as well as a diverse range of curve advisory speeds. Regression models were estimated via generalized estimating equations to discern those factors affecting mean speeds on curves. A log-linear relationship was found between curve radius and mean vehicle speed, with speeds relatively stable on radii of 900–1000 ft. or more, decreasing more rapidly as radii decreased below this range. Drivers were found to reduce speeds when curve advisories were present, but the magnitude of these reductions was much less than suggested by the advisory signs. This study involved the extraction of a total of 9906 driving traces from 202 unique drivers on 219 rural two-lane curves from the SHRP2 NDS dataset. Each driving trace was defined as an instance where a vehicle travels through an individual curve location.

Jaisang CHOI (2016) studied to check the applicability of conventional highway design theories to proposed SMART highway in South Korea. The higher speed use for the highway design considered as 130 Kmph, which was higher as compare to present higher design speed of 120 kmph. The main aim of research was to check for safety against the increased speed for both motorists and other vehicles on horizontal curves. The check was done by comparing supplied friction values against the required values. Other objective of this research was to measure speed levels at very flat curves and calculate actual lateral friction levels in existing freeways to make a comparison with theoretical values. For the study, 3 horizontal curves were selected with curve radius greater than 2 KM and vertical grades of -3% to +3%. The speed survey was made by spot speed measurement and licence plate technique. Using the field study information and mass-point formula, available side friction level experienced by drivers is obtain. This research paper determined that with 0% superelevation driver discomfort would occur when driver faster than 152 Kmph, with proper superelevation design driver discomfort starts occur only when driving faster than 160 Kmph. Another outcome of the study was determining suitable design levels of the side friction factor. First, does the vehicle fail to have a proper side friction level and actually slide on the curve and another was, do motorists feel intolerable levels of discomfort due to centrifugal force while driving the curve. It summarizes that the second criteria are best suitable for determining level of side friction factor.

K. Musey (2016) involved a comprehensive review of crash data to identify the correlation between pavement skid number, roadway curvature degree, crash rate, and crash severity. The dataset showed that greater injury occurred on higher degrees of curvature, and lower skid numbers correlated to a higher percent of wet road crashes. Also, around a skid number of 55, an increase in skid number no longer resulted in decreased crash rates. The goal of this research was to use these correlations to develop Crash Modification

Factor that would integrate pavement friction and horizontal curvature, to enhance the accuracy of the current Highway Safety annual performance function. This research aimed to evaluate whether friction factor actually had an influence on crash incidents and determine if increasing this value on horizontal curved roadways will be improved safety. The results of this research were relevant because they had observed capacity to contribute to the existing crash prediction manual, the Highway Safety Manual (HSM). Although the HSM provides a method to quantify changes in crash frequency as a function of several characteristics such as cross-sectional features and geometric alignment, it does not currently take pavement characteristics such as friction factor and skid number into account. As a result, this research was practical, and had the potential to greatly enhance the study of sustainable roadway safety levels.

Amirarsalan Mehrara Molan (2015) studied the relation between side friction factor and longitudinal grade for horizontal curve was investigated in three dimensions. New models for estimating side friction factors for different vehicle types were presented. The study was analysed in three sections. A series of simulation test were done using the CarSim and TruckSim multi-body simulation software packages. After simulation, multiplex regression analysis and presentation of recommended formulas for the side friction factor was done. Main assumption considered was two different driving behaviours are considered in the simulation process in one, the driver negotiates the curve at constant speed; in the other, the driver brakes while passing downgrades. The side friction factor increases as the downgrade increases, which means that more side friction demand was produced on steep downgrades compared with a flat grade and mild downgrades. Thus, the margin of safety decreases on steep downgrades. Generally, from the perspective of skidding, at high speeds the situation was most critical for the sedan car, although at low speed (40 km/h) it was the truck that was most at risk of skidding. The effect of braking on side friction factors was found to be significant. Another important finding in the study about braking was the presence of large fluctuations in side friction factors throughout the duration of braking hence, braking was an important issue for the safety of vehicles, especially passenger cars. According to the analysis and the recommended models of the side friction factors, road designers should use different side friction factors based on the sort of vehicles (passenger cars or heavy vehicles) and based on the longitudinal grade. The results and recommendation models of this study can be used in the geometric design phase by highway engineers to design safer roads.

Faisal Awadullah (2015) studied to simplify the complexities of superelevation and friction, which were important for consistent and clearer design methods. The side friction from equation obtained from Mass-point formula, was the side friction demand needed to balance the centrifugal force for a given vehicle and design speed. Paper quotes that side friction demand could be greater than side friction supply which indicates that such design speed, maximum superelevation rate were impossible. Researcher also said that side friction supply for roll failure was not a function of pavement or tire condition. A moment was generated about outer wheels due to centrifugal force act at centre which causing rolling action of vehicle. It was concluded from the study that AASTHO design standards provide for high safety factors before lateral acceleration may be detected for the curves with radii greater than minimum radius for a specific superelevation rate based on AASTHO recommendations. Most of the researches for obtaining these factors is very old and needs to be updated considering skid and roll failures for the critical contemporary vehicles designs. Also, the present pavement design practices, human factors and research technologies and methodologies thought to provide more accurate and much needed results.

Laura Garach Morcillo (2014) studied consistency based on operating speed was calculated in two-lane rural highways of the province of Granada, in Spain. Three consistency measures were calculated for 506 homogeneous road sections. The study area, which represents the area bounded by the speed profile and average speed of a road segment, the standard deviation of the operating speed in each design element along the road segment and the consistency model, which was based on the previous measures introduced. Some discrepancies had been found in the results obtained. The complete study was carried out in sequential manner. All road was divided into individual horizontal curve. After that the individual curve segment were subdivided into homogeneous road segments. A constant curve speed was adopted. Given the importance of using speed prediction models calibrated according to local conditions, was adjusted for horizontal curves in two-way rural highways in Spain. The model thus made it possible to obtain the V85 in terms of the radius of the curve.

Said M T Easa (2003) presented a model for determining the distribution of superelevation that maximize highway design consistency, which was based on safety margin. It was also suggested that for horizontal curves the safety margin might be defined as the difference between the critical and real lateral acceleration, friction or speed. The writer also suggests, among the 5 methods suggested by AASTHO for horizontal curve design, 5th method is superior than another four methods. This paper developed a linear optimization model to find the distribution of ‘e’, where such model optimizes an objective function subject to linear constraints. The proposed model not just only overcomes the difficulty of finding the best 'e' values using trial and error method, but also guarantees the optimum solution. Assumption made for highway design consistency is it is desirable to minimize the variance of the safety margin since the variance is nonlinear in the decision variables, if it is not possible to include it directly in the objective function.

2.2 Important findings

Literature reveals that study about various methods done across the globe for determining lateral friction factor. Various simulations have been done for checking the demand It can be noted that very less studies have been done to estimate lateral friction factor, which may be helpful to planners and researchers for designing roads. The important findings from literature review has been enlisted below

- The parameters which are to be selected for estimating *f* should be selected precisely.
- Most of the literature are focusing on factors like roadway characteristics
- The common thing in most of literature is selection of best method among all methods given by AASTHO 2011 regarding superelevation, lateral friction and radius of curvature.
- Along With the present knowledge of various factors the evolution occurred in vehicular characteristics is also important parameter for finding *f*.
- Data collected should be precise. (Rabari, 2018)

3. SELECTION OF LOCATION

The study location should be in such a way that it should represent the actual conditions of the negotiating the horizontal curve. In acquire data from those sorts of locations certain criteria has to be followed for selection.

3.1 *Site selection was based on the following factors*

- Horizontal curves of varying radius of curvature on a same stretch. (Panchal, 2019)
- Paved sections with paved shoulders,
- There are no changes in lane or shoulder widths,
- Gentle side slopes and removal of roadside hazards and other physical features that may create a dangerous environment
- Grades less than 5 percent,
- Location away from the zone of influence of intersections, towns, and urban areas. (Awdallah, 2014)

3.2 *Based on above criteria the following locations were selected*

- The selected stretch is part of Maharashtra state highway No. 12. It is named as Ghorwad ghat section.
- Selected stretch is part of Ghoti- Sinnar State highway.
- It is located in village Ghorwad, Taluka Sinnar of Nashik District.

Figure 2 Study area location using google maps

4. DATA COLLECTION PROCEDURE

For measuring the side friction, comprehensive survey is essential, since various parameters have to be observed simultaneously, the accelerometer (Google application) was adopted for collecting the lateral acceleration data. Measurement of width of highway pavement and rise of outer edge with respect to inner edge reading was taken using Laser light. Radius of curve is measured with the help of Google Earth Pro software. To calculate lateral force absolute value of product of lateral acceleration and weight of test vehicle was done. For calculation of normal force gravitational weight of test vehicle is taken. Side Friction Factor (SFF) is the ratio of lateral force to the normal force. Road inventory data is shown in Table 1.

Table 1: Road inventory Data

CURVE 1

Sr No	Description	At start of Curve	At mid of Curve	At end of Curve
1	Radius (m)	111.67		
2	Carriage way (m)	7.35	7.60	6.90
3	Rise in outer edge	0	0.41	0
4	Shoulder width up	0.75	1.20	1.50
5	Shoulder width down	1.20	0.60	0.45
CURVE 2				
1	Radius (m)	172.10		
2	Carriage way (m)	7.00	6.90	7.05
3	Rise in outer edge	0	0.25	0
4	Shoulder width up	0.75	1.20	1.50
5	Shoulder width down	1.10	0.80	0.60
CURVE 3				
1	Radius (m)	60.36		
2	Carriage way (m)	6.90	7.05	6.85
3	Rise in outer edge	0	0.41	0
4	Shoulder width up	1.1	1.20	1.05
5	Shoulder width down	1.15	0.90	0.75

For the measurement of lateral acceleration, a simple gyroscope is used. It provides Acceleration of vehicle in all directions i.e., in X, Y and Z directions. For calculation purpose magnitude of acceleration in Y direction is considered. Gyroscope also provides the graph of Acceleration Vs Time. Trials were carried out in two phases. First trail was carried out on 18th December 2018 in night time and second trail was carried out on 11th Feb 2019 in day time. For trails a test vehicle (Mahindra Pickup Bolero) is selected. Data is collected on three different speeds of 40,50 and 60 Kmph. A sample graph of acceleration data is shown in Fig. 3 and Fig. no. 4.

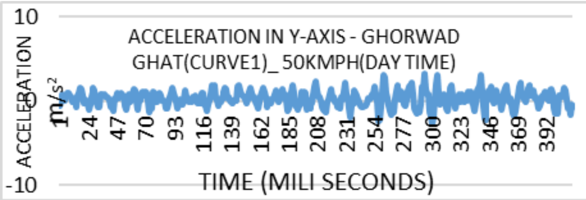


Figure 3 Sample graph of Time Vs Acceleration

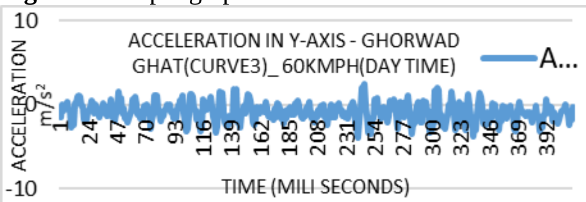


Figure 4 Sample graph of Time Vs Acceleration

5. DATA ANALYSIS

After getting relevant data, lateral friction factor is calculated by using following formulas,
Lateral force is calculated as,

$$\text{Lateral Force (KN)} = \frac{\text{Wt. of Vehicle X Accl in Y dir}}{1000}$$

Where Weight of vehicle is in Kg and Acceleration is in m/s^2 unit.

Normal force can be said as gravitational weight of test vehicle in normal direction and it is calculated as below in kilo-newton.

$$\text{Normal Force (KN)} = \frac{\text{Weight of Vehicle X 9.81}}{1000}$$

Lateral friction factor is a ratio of Lateral Force to normal force, mathematically can be written as, (Easa, 2011)

$$\text{LFF} = \frac{\text{Lateral Force}}{\text{Normal Force}}$$

Weight of test vehicle is 2310 kg. The observed Lateral friction factors (LFF) during day time and night time are shown in Table 2.

Table 2: Observed LFF

Speed (Kmph)	***'f' At Curve 1***	***'f' At Curve 2***	***'f' At Curve 3***
During Day Time			
40.00	0.06	0.043	0.086
50.00	0.12	0.079	0.09
60.00	0.14	0.134	0.160
During Night Time			
40.00	0.059	0.042	0.084
50.00	0.119	0.078	0.089
60.00	0.130	0.131	0.157

For the calculation of lateral friction factor(f) and super elevation, IRC method is used. IRC method suggest to use mass point formula for calculations of 'e', 'f' and 'r' mass point formula is given as,

$$e + f = \frac{V^2}{g\,R}$$

Where,

e = superelevation rate
f = lateral friction factor
V= speed of vehicle m/sec
R= Radius of curvature in meter (m)
g = acceleration due to gravity, 9.81 m/sec^2

Table 3 shows Lateral Friction Factor (LFF) using IRC method

Table 3: LFF by IRC method

Speed (Kmph)	***f At Curve 1***	***f At Curve 2***	***f At Curve 3***
40	0.054	0.030	0.106
50	0.117	0.068	0.224
60	0.194	0.114	0.360

Observed 'f' value is compared with 'f' value obtained by IRC method. It is shown in Table no. 4

Table 4: Comparison of Observed value with IRC Value

Curve No.	Speed (Kmph)	Observed 'f' value	'f' value using IRC method	% Diff
1	40	0.06	0.054	90
	50	0.12	0.117	97
	60	0.14	0.194	129
2	40	0.043	0.030	69
	50	0.079	0.068	86
	60	0.134	0.114	85
3	40.	0.086	0.106	123
	50	0.09	0.224	248
	60	0.160	0.360	225

It is observed from Table 4 that observed 'f' is higher than the suggested by IRC at certain location and lower at certain location on the curve. (IRC 73, 1990)

5 SUMMARY

Various attempts have been made to find important factors and their relation with friction factor & also some other methods to finding the factors on which lateral friction factor is depend. A methodology is prepared to systematically carried out the entire procedure to calculate side friction coefficient. The main component in the entire process is to select a vehicle, which will be use as a testing vehicle to take various testing activities. For this carrying out classified count survey at study area location is done. Followings are the major conclusion of present study.

1. From obtained LFF, it is observed that if radius is more, lesser will be demand of friction, also friction demand increases as speed of vehicle increases.
2. It is also observed that IRC suggested maximum 'f' value as 0.15 for any condition but from results, it is observed that the 'f' value varies as per variation of speed.
3. The observed difference of LFF at curve no 1 in the range from 129% to 97%, at curve no. 2 in the range from 69% to 86% and at curve no. 3 in the range from 123% to 243%.
4. It is concluded from analysis that assessment of LFF is required to know at regular interval for improving the geometric design of road at curve.

ACKNOWLEDGMENT

I would like to thank to my Guide Prof. (Dr.) N. G. Raval, and Prof. H. K. Dave, Professor, Civil Department (Transportation Engineering) G. E. C. Modasa, for their moral support, constant unceasing encouragement, critical evaluation, suggestion, constant untiring guidance and affection during the entire span of my post-graduation study.

I would also like to thank Prof. Dipika Gupta for their perpetual support and guidance during my post-graduation study.

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