Analysis of Superelevation and Side Friction Factor on Horizontal Curve

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Abstract - *Everyday, millions of people use roads for travel. A significant amount of travel happens on highways or interstates. On large volume roadways such as interstates, where speeds are high, problems can occur at locations where there are sharp horizontal curves. At locations such as these the various factors of incline, pavement slope, and friction fully tax the driver's ability to control the vehicle. To make these locations safer study of superelevation and associated curvature criteria is needed. However, superelevation and side friction factor are less studied because they are hard to observe or measures. From recorded data we can conclude the safer speed for the motorists and criteria to design higher speed freeways. For study superelevation and side friction factor various horizontal curves are selected of State Highway 41 (SH 41) which is from Ahmedabad to Palanpur.*

Key words: Superelevation, side friction factor, safer speed.

1. INTRODUCTION

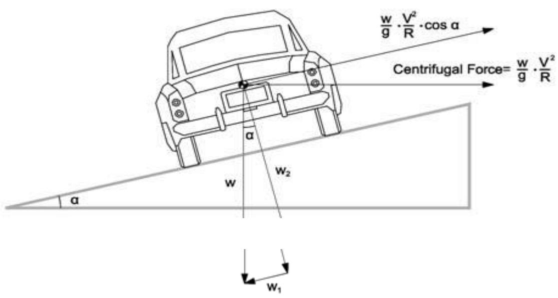
Geometric design policy in the United States (U.S.) is set by the 'American Association of State Highway and Transportation Officials' (AASHTO). A Policy on Geometric Design of Highways and Streets, herein referred to as the Green Book. The physics of uniform circular motion were used to develop horizontal curve design, where a vehicle is assumed to operate as a point mass. As a vehicle travels a horizontal curve, it undergoes centripetal acceleration equal to the square of the vehicle speed divided by the radius of the curved path. This acceleration is balanced by a combination of superelevation and the friction between the road surface and tires of the vehicle.

Horizontal curves designed in accordance with Green Book criteria have been generally shown to provide substantial margins of safety with respect to vehicle skidding and rollover, for both passenger cars and trucks (Harwood et al., 1989; Harwood and Mason, 1994; Harwood et al., 2003). Previous research, however, has considered 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, as has tire design, pavement design, and friction measurement methods.

Two recent research studies were completed that afforded the opportunity to collect asphalt pavement surface friction data on two-lane and multi-lane rural highways in the eastern U.S. These studies also included provisions to collect passenger car and truck operating speed data at the locations where friction measurements were recorded.

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 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 (1). 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 (1). And this relation is called the Mass Point formula in highway design.



$w_1 = w \cdot \sin\alpha$ (Force caused by Superelevation)

$w_2 = w \cdot \cos\alpha \rightarrow f \cdot w \cdot \cos\alpha$ (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

1.2 Objectives of study

- To check the appropriateness of applying current horizontal curve design theory for highway
- To measure speed levels at very flat curves

- Determination of actual side friction levels in existing freeways to make a comparison with theoretical values
- Model formulation for identifying side friction for different situations.

2. BACKGROUND AND LITERATURE REVIEW

Large number of studies have been reported on focusing to identifying the means to improve the safety of road user on horizontal curve. Differently from tangent sections, horizontal curve design theory involves how to deal with centrifugal force generated by fast moving vehicles on the curve. Also, the size of the centrifugal force increases with shorter curves. Therefore, for the safety and comfort of driving motorists, the current design method sets the minimum curve radii for a practical range of highway design speed and requires engineers to apply larger radius than the minimum (8). In the minimum radius calculation, design variables including vehicle operating speed, superelevation, and side friction factor are considered, but among them side friction factor is prevailing. In fact, there are many research findings available for understanding side friction and its characteristics in curve design. For example, Meyer (1949), Barnett (HRB 1936), Moyer & Berry (HRB 1940), and Stonex and Noble (HRB 1940) have published their research findings on side friction values and vehicle speeds made mostly in the US. However, these studies were made in early days of highway design theory development, and it is critical that these research findings, which were based on design speed of 120 km/h at the highest, are not directly applicable to SMART highway design. For instance, J. Emmerson (1969) has calculated actual side friction factors observed at six horizontal curve sites based on passenger car speed data, and found that at the curve radius range of 196-350 m the average value of side friction factors indicated 0.11 with more than 80 % passenger cars having less than 0.15. In contrast, in the case of curve radius range of 70-330 ft, side friction factors were observed to be 0.27 and 0.22 with more than 90 % passenger cars having greater than 0.15. This indicates that observed side friction factors can be different from theoretical values (2). McLean also supported this argument with his finding that motorists experienced higher side friction on curves (7). In summary, it is not desirable to apply the current highway design standards to SMART highway design, and this research has done a review of horizontal alignment design theory and discussed the expected variations of design variables associated with increasing design speed in SMART highway.

Interestingly, there recently was an initial stage research for establishing highway design standards to be used in higher design speed freeways in the US, and its conclusion included the side friction levels of 0.08-0.04 at the increased freeway speed (3). The authors reviewed this research report and found that they simply utilized the existing relationship between side friction factor and design speed (3). A different approach for measuring side friction factors was adopted in Europe. In Switzerland, 300 sites were selected and a relationship expressing their pavement conditions and side friction force at different speed levels were developed. And based on the relationship two side friction factor equations, one for the longitudinal direction and another for the side direction, were published (8). McLean in Australia asserted based on his empirical analysis that the side friction values specified in AASHTO design guideline were too low. Then he proposed to increase the current side friction values ranging 0.11-0.19 to 0.08-0.35 (7).

Meanwhile a group of researchers in Germany including R. Lamm (1999) investigated several European country cases and proposed a new relationship for finding relevant side friction factors in highway curve design as shown in Eqn. (2).

$$F_R = 0.27 - 2.19\times10^{-3}\, V_d + 5.79\times10^{-6}\, (V_d)^2$$

Where, f_R : Side Friction Factor

V_d : Design Speed (km/h)

And the research made an assumption that the model relating side friction factors and design speed would be a logarithmic function. Applying SPSS to the international side friction factors, Eqn. (3) was obtained.

$$F_R = 0.49 - 0.08 \times \ln(V_d)$$

Where, F_R : Side friction factor for this research

V_d : Design speed (km/h)

As a vehicle comers, it is accelerated toward the center of the curve. According to Newton's Second Law, this acceleration must produce a force that is directed toward the center of the curve. This unbalanced force results in side thrust, which must be countered by the component of the vehicle's weight acting along the surface of the roadway, or by side friction between the tires and the pavement, or by some combination of the two. This is indicated by the following equation, commonly called the point-mass equation:

$$f_s + e = V^2/(127\, R)$$

where

f_s = side friction factor,

e = superelevation rate (m/m),

V =speed (km/hr), and

R = radius (m).

J. F. Morrall et. al. 2013 was conducted to determine the amount of side friction demanded and provided for a range of roadway curvatures, vehicle speeds and types, and pavement surface conditions. A ball bank indicator and a commercial accelerometer (the GAnalyst) were used to measure ball bank readings and corresponding lateral accelerations on the test curves. The friction supply levels measured in the field indicate that friction varies between rural two-lane and multi-lane highways. The research indicate that Passenger cars are more likely to skid before rolling over on horizontal curves, while large trucks are more likely to rollover on horizontal curve before skidding on low-speed roads.

Eric Donnell et. al. 2011 In this model, a maximum side friction factor is used, in combination with the selected design speed and maximum rate of superelevation, to determine the minimum radius of curve for an alignment. paper provides an analysis of the margin of safety that exists in horizontal curve design policy. This analysis considers various vehicle types, pavement surface types, and operating speed distributions. Comparisons between friction supply, demand, and design side friction factors are made in this paper. It was found that drivers travel at speeds that nearly approximate AASHTO maximum side friction factors on rural highways with high design speeds (i.e., greater than 45 mph). At lower design speeds, however, the observed friction demand of drivers in the present study often exceeded the AASHTO maximum side friction factors used in horizontal curve design. It was found that the observed friction demand, which were based on speeds collected on dry pavement conditions, was generally at least 0.05 below mean friction supply curves.

The friction data were collected using a combination of a portable dynamic friction tester (DF Tester) and circular texture meter (CT meter).

The test method produces pavement surface friction properties as a function of speed.

ASTM E1960-07 (ASTM 2011) recommends the following standard practice to calculate IFI of a pavement surface:

$S_p = 14.2 + 89.7MPD$

$$F_{60} = 0.081 + 0.732DFT_{20}\exp\left(-\frac{40}{S_p}\right)$$

$$F_s = F_{60} \times \exp\left[\frac{60 - S}{S_p}\right]$$

Where,

S_p = speed constant of wet pavement friction

MPD = mean profile depth (mm)

F_{60} = calibrated wet friction at 60 km/h

DFT_{20} = DFT number at 20 km/h per ASTM E1911

F_s = friction at another slip speed S

G. Kanellaidis et. al. 1991 United States and German guidelines relevant methods of calculating superelevation in highway curves are presented and compared in this paper. The main differences between these two methods are related to design and operating speed concepts and their use to calculate superelevation for curve radii exceeding the absolute minimum. Some modifications to the current AASHTO superelevation design approaches are proposed, based on the relationship between the degree of curve and actual operating speeds, to harmonize highway superelevation design with drivers actual speed behavior, which could enhance highway safety. The use of design speed to determine individual geometric elements like superelevation rates should be revaluated and possibly replaced by operating-speed parameters.

Ali Abdi Kordani et. al. 2014 This research has been conducted to discover the correlation between side friction factor (demand) and longitudinal grade which is located in horizontal curves in three-dimensional simulation model. They present a series of models in order to assess these factors based on design speed, longitudinal grade, and vehicle type (Sedan, SUV, and Truck). The research involves (1) conducting a series of multi-body simulation tests using CarSim and TruckSim, (2) multiplex regression analysis to acquire relations between variables, and (3) recommending models for the side friction factor. Based on the results, side friction factors (demand) are bigger than downgrades for all vehicle types when cornering. Another important result is the significant differences of side friction factors for passenger cars in compared to heavy vehicles.

Faisal Awadallah et. al. 2005 The 2001 AASHTO publication A Policy on Geometric Design of Highways and Streets (Green Book) discusses five different methods for the distribution of side friction and superelevation rates for curves with radii greater than the minimum and recommends one of the methods for rural high-speed roads design. This study provides a theoretical analysis for selection of superelevation rates based on a set value of speed beyond the design speed (or speed limit) at which drivers start feeling lateral acceleration. This study is an attempt to simplify the complexities of this topic and provides a more consistent and clear design method.

$$e = \frac{\left[\frac{V + V_x}{3.6}\right]^2}{gR} - f_s$$

Where,

e=superelevation rate in decimal form,

V=design speed (kmph),

Vx=speed increment above design speed before drivers feel lateral acceleration (kmph),

g=gravitational constant (9.81 m/ s^2),

R=curve radius (m) and

fs=design side friction factor.

3. SELECTION OF LOCATION

The study location should be in such a way that it should represent the real 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

- Paved sections with paved shoulders,
- No changes in lane or shoulder widths,
- Gentle sideslopes 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 so on.

3.2 Based on above criteria the following locations were selected

1) Adalaj chokdi clover leaf
2) Five different horizontal curve of different radius should be selected on Ahmedabad to Palanpur Highway (SH 41).

4. DATA COLLECTION PROCEDURE

To measure the amount of side friction demanded by traffic and supplied by pavement, tests were conducted on rural two-lane highway curves. Curvatures ranged from 120 to 1000 m, whereas maximum superelevation rates ranged from 2 to 8 percent. Because all sites are located on relatively flat terrain, most of the available friction is available for cornering.

A wide range of test vehicles, typical of those found on rural two-lane highways in Gujarat, was used for this project. These test vehicles included , a sedan and a tandem-axle gravel truck. All vehicles were tested unloaded, with the fuel tank approximately half full, and tire pressures equal to those recommended by the tire manufacturer.

A Smart Prtoctor and a commercial accelerometer (the GAnalyst) were used to measure superlevation and corresponding lateral accelerations on the test curves. Since the G-Analyst can be calibrated for a vehicle's roll and pitch angles, the side friction factor in the plane of the roadway can be measured. A radar speedometer was used to collect traffic speed data at the test sites, and to substantiate the calculated test vehicle speeds. As test vehicles traversed a curve at constant speed (ranging from 60 to 120 km/hr), a passenger took ball bank readings and placed flags in the G-Analyst's memory at predetermined sections of the roadway.

5. SUMMARY

A significant amount of travel happens on highways or interstates. On large volume roadways such as interstates, where speeds are high, and problems can occur at locations where there are sharp horizontal curves. At locations such as these the various factors of incline, pavement slope, and friction fully tax the driver's ability to control the vehicle. To make these locations safer study of superelevation and associated curvature criteria is needed. However, superelevation and side friction factor are less studied because they are hard to observe or measures. From recorded data we can conclude the safer speed for the motorists and criteria to design higher speed freeways. For study superelevation and side friction factor various horizontal curves are selected of State Highway 41 (SH 41) which is from Ahmedabad to Palanpur.

The findings of a research project that was conducted to determine the amount of side friction demanded and provided for a range of roadway curvatures and vehicle speeds A three-axis accelerometer was installed in test vehicles of Sweden car.. Lateral accelerations readings was taken as the vehicles traversed test curves at constant speeds. Speeds were increased in increments of 10 km/hr until impending side skid conditions were reached.

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