Side Friction Demand Versus Side Friction Assumed for Curve Design on Two-Lane Rural Highways

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With the objective of exploring whether AASHTO's existing *Policy on Geometric Design of Highways and Streets* provides adequate dynamic safety of driving for new designs, redesigns, and rehabilitation strategies at curved sites, side friction factors on curved sections of two-lane rural highways were investigated. The study was based on geometric design, operating speed, and accident data for 197 curved roadway sections in New York State. To achieve this objective, a comparative analysis of side friction demand versus side friction assumed was carried out. With respect to the independent variable degree of curve, it was determined that (a) friction increases as degree of curve increases; (b) side friction assumed is higher than side friction demand on curves up to about 6.5 degrees; (c) for curves greater than 6.5 degrees, side friction demand is higher than side friction assumed; and (d) the gap between friction assumed and demand increases with increasing degree of curve. With respect to the independent variable operating speed, it was determined that (a) friction decreases as operating speed increases; (b) side friction assumed is lower than side friction demand up to operating speeds of 50 mph; (c) the gap between side friction assumed and demand increases with decreasing operating speeds; and (d) for operating speeds greater than 50 mph, side friction assumed is higher than side friction demand. With respect to the independent variable accident rate, it was determined that (a) side friction demand begins to exceed side friction assumed when the accident rate is about six or seven accidents per million vehicle-miles and (b) the gap between side friction assumed and demand increases with increasing accident rates. In general, analyses indicated that, especially in the lower design speed classes, which are combined with higher maximum allowable degree of curve classes, there exists the possibility that (a) friction demand exceeds friction assumed and (b) a high accident risk results, because at lower design speed levels the danger exists that design speeds and operating speeds are not well balanced. Thus, it is apparent that driving dynamic safety aspects have an important impact on geometric design, operating speed, and accident experience on curved roadway sections of two-lane rural highways.

One of the main safety goals in developing recommendations for the design of rural highways is the enhancement of traffic safety by increasing friction supply wherever possible.

A study of accidents on curved roadway sections in New York State (*1*) determined that

1. More than 70 percent of accidents on curves were fatal or injury accidents;
2. About 50 percent of accidents on curves were the result of wet or icy road conditions even though vehicle mileage driven under these conditions is far lower than that on dry pavements; and
3. About 65 percent of accidents on curves were single-vehicle accidents, mostly run-off-the-road accidents.

In summary, the study (*1*) concluded that a high risk of fatal or injury accidents does exist on curves, especially on wet or icy road surfaces and at night, with an accident type represented mainly by run-off-the-road accidents.

In this connection, the safety considerations of most countries are centered on improving highway geometric characteristics, not on improving skid resistance (tangential and side friction factors), although sufficient friction supply had been reported to be an important safety issue (*2*).

Several research investigations have indicated that skid resistance (friction) should be a main safety consideration in designing, redesigning, or resurfacing roadways (*3,4*). For instance, Brinkman (*3*) found that resurfacing alone did not have a significant effect on the mean skid number. He indicated that skid resistance should be a main safety issue. Glennon et al. (*4*) argued that accident studies indicate that pavement skid resistance is a safety consideration. They indicated that the probability of a highway curve becoming an accident black spot increases with decreasing pavement skid resistance. This finding supports the recommendation that the AASHTO policy should more clearly delineate the need for providing adequate friction between tire and roadway surface, for example, as on highway curves.

The upward trend of vehicle speeds and traffic densities will undoubtedly continue throughout this decade, and the skidding problem will become more serious, potentially becoming a major limitation to safe high-speed travel, especially on wet two-lane rural highways (*5*).

The objective of this research was to explore whether AASHTO's 1984 *Policy on Geometric Design of Highways and Streets* (*6*), provides adequate dynamic safety of driving for new designs, redesigns, and rehabilitation strategies at curved sites.

REVIEW

Research studies conducted during the past two decades have shown that highway geometric designs should address three design issues in order to gain direct or indirect safety advan-

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tages. These issues are (1) achieving consistency in horizontal alignment; (2) harmonizing design speed and operating speed, especially on wet pavements; and (3) providing adequate dynamic safety of driving (*7–14*).

Criteria 1 and 2 have been the subject of several reports, publications, and presentations (*1,15–23*). These investigations included (a) processes for evaluating horizontal design consistency and inconsistency, (b) processes for evaluating design speed and operating speed differences, (c) relationships between geometric design parameters and operating speeds and/or accident rates, and (d) recommendations for achieving good and fair design practices, as well as recommendations for detecting poor designs (see Table 1).

For example, Figure 1 shows the relationships between degree of curve and operating speeds, as well as between degree of curve and accidents rates for individual lane widths, as derived from the analysis of data on 322 two-lane rural highway sections in New York State (*15*). The studies demonstrated that (a) the most successful parameter in explaining much of the variability in operating speeds and accident rates was degree of curve, and (b) the relationship between degree of curve and operating speed is valid for both dry and wet pavements, as long as visibility is not appreciably affected by heavy rain (*24*).

Criterion 3 was the subject of a comparative analysis of tangential and side friction factors in the highway design

TABLE 1 RECOMMENDED RANGES FOR GOOD, FAIR, AND POOR DESIGN PRACTICES BETWEEN SUCCESSIVE DESIGN ELEMENTS (*15,16,20,22*)

CONSISTENCY CRITERIA

CASE 1 (GOOD DESIGN):
Range of change in degree of curve: $\Delta DC \leq 5^{\circ}$.
Range of change in operating speed: $\Delta V85 \leq 6$ mph (10km/h).
For these road sections, consistency in horizontal alignment exists between successive design elements, and the horizontal alignment does not create inconsistencies in vehicle operating speeds.

CASE 2 (FAIR DESIGN):
Range of change in degree of curve: $5^{\circ} < \Delta DC \leq 10^{\circ}$.
Range of change in operating speed: 6 mph $< \Delta V85 \leq 12$ mph (20 km/h).
These road sections may represent at least minor inconsistencies in geometric design between successive design elements. Normally, they would warrant traffic warning devices, but no redesigns.

CASE 3 (POOR DESIGN):
Range of change in degree of curve: $\Delta DC > 10^{\circ}$.
Range of change in operating speed: $\Delta V85 > 12$ mph (20km/h).
These road sections have strong inconsistencies horizontal geometric design between successive design elements combined with those breaks in the speed profile that may lead to critical driving maneuvers. Normally redesigns are recommended.

DESIGN SPEED CRITERIA

CASE 1 (GOOD DESIGN):

$V85 - V_d{}^* \leq 6$ mph (10 km/h).
No adaptions or corrections are necessary.

CASE 2 (FAIR DESIGN):

6 mph $< V85 - V_d \leq 12$ mph (20 km/h).
Superelevation rates and stopping sight distances must be related to V85 to ensure that friction assumed will accomodate to friction demand.

CASE 3 (POOR DESIGN):

$V85 - V_d > 12$ mph (20 km/h).
Normally redesigns are recommended.

$^*V_d$ = Design Speed

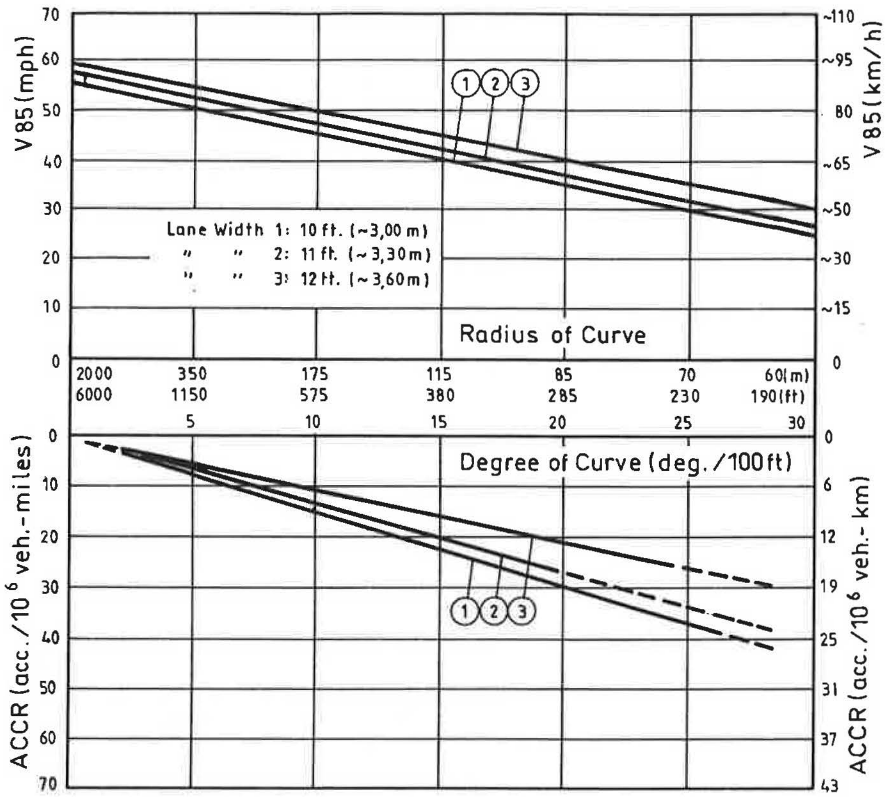

FIGURE 1 Nomogram for evaluating operating speeds and accident rates as related to degree of curve (radius of curve) for individual lane widths.

guidelines of four Western European countries—Federal Republic of Germany, France, Sweden, and Switzerland—and the United States, which (a) determined the type of the relationships that exist between friction factors and design speed and (b) developed overall relationships between friction factors and design speed. The resulting overall relationships were then compared to actual pavement friction inventories in New York State and the Federal Republic of Germany (*25,26*). Analyses indicated that the friction factors derived from the New York 95th-percentile level distribution curve (that is, 95 percent of wet pavements could be covered by using the 95th-percentile level distribution curve as a driving dynamic basis for design purposes) coincided with the friction factors derived from the German 95th-percentile level distribution curve (see Figure 2). Based on these results, recommendations were provided for minimum stopping sight distances and minimum radii of curve (*26*). It is estimated that by applying the proposed tangential and side friction factors, 95 percent of wet pavements will be covered in the United States and Europe. In this respect, Figure 2 shows the maximum allowable side friction factors versus design speed for AASHTO (*6*), AASHO (*27*), and the German Design Standard (*12*) and the overall relationship recommended by Lamm et al. (*26*). This figure clearly indicates that AASHO/AASHTO values exceed the recommended values already at design speeds $V_d \geq 30$ mph.

In contrast to the design friction factors of AASHO/AASHTO (*6,27*), using lower maximum allowable friction factors will certainly lead to a higher driving dynamic safety supply and could reduce the number and severity of accidents. It will also support maintenance personnel by easing the problems of maintaining high tangential and side friction factors for lower design speed classes where operating speeds often exceed design speeds decisively. Therefore, new designs, redesigns, and rehabilitation strategies are recommended to relate minimum stopping sight distances and minimum radii of curve to the proposed tangential and side friction factors, which cover 95 percent of wet pavements (see Figure 2) (*26*).

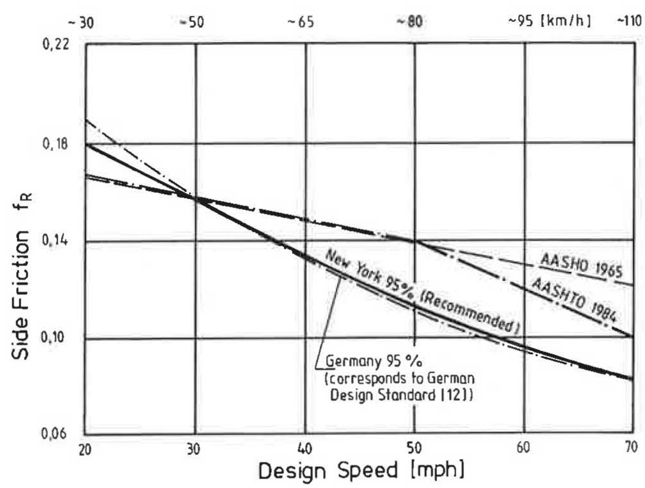

FIGURE 2 Maximum allowable side friction factors versus design speed for AASHTO 1984 (*6*), AASHO 1965 (*27*), Germany, and recommended relationships (*26*).

It may be concluded that by regarding all three design issues, mainly in relation to speed, a safer highway geometric design could be expected.

To prove that these statements are of great importance in enhancing traffic safety, the primary objective of this study was to determine to what extent friction assumed for curve design (*6,27*) corresponds to friction demand on existing curved sections of two-lane rural highways. In particular, regression analysis was used to obtain a quantitative estimate of the effect on the side friction factor produced by the following independent variables: degree of curve, 85th-percentile speed, and accident rate.

DRIVING DYNAMIC BASICS

With wide variation in vehicle speeds on curves, there usually is an unbalanced force whether or not the curve is superelevated. This force results in tire side thrust, which is counterbalanced by friction between tire and surface. The counterforce of friction is developed by distortion of the contact path area of the tire (*6,27*).

The coefficient of side friction (f_R) is the friction force divided by the weight perpendicular to the pavement and is expressed as the following simplified curve formula:

$$f_R = (V^2/15R) - e \qquad (1)$$

where

V = constant speed in curve (mph),
R = radius of curve (ft),
e = superelevation rate (ft/ft), and
f_R = side friction factor.

This coefficient has been called *lateral ratio*, *cornering ratio*, *unbalanced centrifugal ratio*, *friction factor*, and *side friction factor*. Because of its widespread use, the last term is used here. The upper limit of this factor is that at which the tire is skidding, or at the point of impending skid. Because highway curves are designed to avoid skidding conditions with a margin of safety, the f_R-values should be substantially less than the coefficient of friction of impending skid (*6,27*).

However, this simplified curve formula is based on the assumption that the vehicle is considered a rigid body and that the dynamic forces are imagined acting in the center of gravity (*6,9,12*). In this assumption, the vehicle is idealized as a point of mass. However, it is easy to realize that such an explanation will not be able to determine the actual forces acting on each wheel of the vehicle and the strains of the resulting friction. Therefore, to overcome previous driving dynamic deficiencies and to enhance traffic safety, new principles for tangential and side friction factors were developed for the highway design guidelines of the Federal Republic of Germany (*12*) and were proposed for the United States in (*26*). The goal was to reduce the driving dynamic safety risk that may be caused by selecting improper design elements and sequences in horizontal and vertical alignments.

The side friction factor at which side skidding is imminent depends on a number of factors, most important of which are the speed of the vehicle, the type and condition of the roadway surface, and the type and condition of the tires (*25*).

The minimum safe radius (R_{min}) can be calculated directly from the following formula:

$$R_{min} = V^2/[15(e + f_{R_{max}})] \qquad (2)$$

where $f_{R_{max}}$ is the maximum allowable side friction factor.

On the basis of this formula, a safer minimum radius could be determined by introducing the recommended maximum allowable side friction factors of Figure 2 (*26*) than by applying the AASHO/AASHTO values for design speed classes $V_d \geq$ 30 mph.

The degree of curve of a given circular curve is the angle (or number of degrees) subtended at the center by a 100-ft arc (*6*). It is defined as degrees per 100 ft. Many countries consider radius of curve an important design parameter, but U.S. highway geometric design is mainly related to the design parameter *degree of curve* (DC) (*6*). The relationship between degree of curve and radius of curve is given by DC = 5,729.6/R. The simplified curve formula (Equation 1) then becomes

$$DC_{max} = 85{,}660(e + f_{R_{max}})/V^2 \qquad (3)$$

where DC_{max} is the maximum degree of curve (degree/100 ft).

DATA COLLECTION AND REDUCTION

The data collection process for this investigation was broken down into four steps. The first step was the selection of road sections that were appropriate for the study. The second step was the collection of as much field data about the road sections as possible. The third step was the measurement of operating free speeds at each section. The fourth step was the collection of accident data for each section.

The sites selected for this research investigation were on two-lane rural highways in New York State. A total of 197 curved roadway sections, with degrees of curve ranging from 1 degree to 23 degrees, was selected from a data base of 322 roadway sections (*15,28,29*). The grades were level or nearly so at the curved sites and for a considerable distance before and after. Site selection was limited to sections with the following features:

1. Removed from the influence of intersections;
2. No physical features adjacent to or in the course of the roadway, such as narrow bridges, that may create abnormal hazards;
3. Delineated and with paved shoulders;
4. No changes in pavement or shoulder widths;
5. Protected by guardrails when the height of the embankment exceeded 5 ft;
6. Grades less than or equal to 5 percent; and
7. Average annual daily traffic (AADT) between 400 and 5,000 vehicles per day (vpd).

The design data for the curves under study were collected in the field and from the regional offices of the New York State Department of Transportation (NYSDOT). Degree of curve and superelevation rate, two of the most important geometric design parameters considered in the study, were collected in the field and later checked against the latest design plans of NYSDOT.

The basic method used for speed data collection involved the measurement of the time required for a vehicle to traverse a measured course laid out in the center of the curved site. The length of the course for this study was 150 ft. The measurement of time over the measured distance involved the use of transverse pavement markings placed at each end of the course and an observer who started and stopped an electronic stop watch as a vehicle passed the markings. The observer was placed at least 15 ft from the pavement edge of the road to ensure that his presence would not influence the speeds of passing vehicles, but not too far away to minimize the cosine effect. By applying this procedure, satisfactory speed data, which were occasionally substantiated by the use of radar devices, were obtained for both directions of travel. About 120 to 140 passenger cars under free-flow conditions were sampled at each site for both directions of traffic (*1,15,28,29*).

To ensure that the speeds measured in this study represented the free speeds desired by the driver under a set of road conditions and were not affected by other traffic on the road, only the speeds of isolated vehicles (time gap of about 6 sec) or those heading a platoon of vehicles were measured in this study. Speed measurements were made during daytime hours, on weekdays, under dry pavement conditions.

After the data were collected, they were displayed in frequency distribution spot speed tables. The data from the spot speed tables were then used to obtain the operating speed, expressed as the 85th-percentile speeds (mph) (speed below which 85 percent of the vehicles travel). The observed operating speeds were shown to be valid for both dry and wet pavements, as long as visibility was not appreciably affected by heavy rain (*24*).

For each of the curved sites under study, accident data from January 1983 to December 1985 were obtained for all vehicle types from the New York State Accident Surveillance System (SASS) accident description file.

Because the amount of accident data (569 accidents) was not large enough to allow disaggregation into several categories, only the total number of accidents was analyzed. To assess the quality of the road, the accident rate was defined as the number of accidents per 1 million vehicle-mi. The accident rate for each of the investigated road sections was calculated from the following formula:

$$\text{ACCR} = [(\text{no. acc.} \times 10^6)/(365 \times \text{no. years} \times \text{LC} \times \text{AADT})]$$

where

ACCR = number of accidents per 1 million vehicle-mi,
no. acc. = number of accidents in the curved section related to all vehicle types,
no. years = number of years investigated (i.e., 3 years),
LC = length of curve or curved section (mi), and
AADT = average annual daily traffic (vpd, both directions).

The average curve length for 90 percent of the curves investigated was 1,230 ft. For the remaining 10 percent, the average curve length was 410 ft. For these curved sections, a length of 0.1 mile (528 ft) was used in the ACCR equation to calculate the accident rate. The 0.1-mi length was considered an appropriate value to use (a) because the New York SASS accident description file is based on a reference marker system of 0.1 mi and (b) to account for those accidents that may have occurred directly before and beyond short curves.

In general, nearly two-thirds of the accidents were fatal or injury accidents, attributed mostly to run-off-the-road accidents.

Other publications include detailed discussions of the data collection and reduction process (*1,15,28,29*). Table 2 shows a typical example of geometric design, speed, accident, and side friction data for some of the roadway sections under study.

SIDE FRICTION ASSUMED AND SIDE FRICTION DEMAND

The maximum allowable side friction factors ($f_{R_{max}}$) assumed for curve design by AASHTO are given in Table III-6 of the 1984 *Policy on Geometric Design of Highways and Streets* (*6*). This table reveals that

1. There is a one-to-one relationship between side friction factor (f_R) and design speed (V_d) ranging from 20 to 70 mph.
2. The assumed values of the side friction factors are held constant for superelevation rates ranging from 4 to 10 percent.
3. The assumed value of the side friction factor at a certain curved section in the field can be determined by the method of linear interpolation by simply knowing degree of curve and superelevation rate of that section, in case the design speed is not known.

For this investigation, Table III-6 (*6*) was extended to include superelevation rates between 2 and 12 percent, using increments of 0.5 percent to account for the actual superelevation rates collected in the field or obtained from NYSDOT for the 197 curved roadway sections under study. Table 3 shows a typical example of this extension for superelevation rates between 6.5 and 7.5 percent.

For the majority of the investigated curved roadway sections, design speed was not known, but degree of curve and superelevation rate were known from field observations (see Table 2). Therefore, on the basis of degree of curve and superelevation rate from Table 3, and in accordance with item 3, the assumed side friction factor (f_R) for curve design was determined for each of the curved sites under study by the method of linear interpolation. The resulting interpolated values are also given in Table 2.

It is well known that the design speed for a curved section often does not reflect the actual driving behavior. For example, at low and intermediate design speed levels, the portion of relatively flat alignments interspersed between the controlling portions of the highway tends to produce increases in operating speeds that may substantially exceed the design speeds on which the original designs of the road sections were based (*8*). This could lead to a higher side friction demand as compared with the side friction assumed for curve design.

On the basis of observed operating speeds, expressed by the 85th-percentile speeds, the actual side friction demand in this study was calculated for each curve site directly from the following formula:

$$f_{RD} = [(V85)^2 \times (\text{DC})/85{,}660] - e \tag{4}$$

TABLE 2 EXAMPLES OF COLLECTED GEOMETRIC DESIGN, SPEED, ACCIDENT, AND SIDE FRICTION DATA FOR INVESTIGATED CURVED SECTIONS

Section Number	Degree of Curve	Accident Rate (ACCR)	Superelevation Rate (e)	Assumed Side Friction Factor (f_R)	85th-Percentile Speed	Side Friction Demand (f_{RD})
3-5	16.1	18.6	0.065	0.155	43.3	0.287
3-9	7.8	9.6	0.065	0.145	48.0	0.145
3-11	2.5	2.9	0.030	0.100	57.6	0.067
3-15	1.8	0.0	0.025	0.100	59.3	0.049
3-19	1.0	0.0	0.020	0.100	58.0	0.019
11-1	3.50	0.7	0.050	0.110	56.5	0.080
11-3	20.00	25.7	0.065	0.160	39.3	0.296
11-5	2.30	2.3	0.030	0.100	59.0	0.063
11-7	1.40	0.0	0.020	0.100	59.8	0.038
19-1	11.00	18.8	0.075	0.150	46.9	0.207
20A-1	6.00	3.6	0.050	0.140	51.4	0.135
20A-3	22.40	24.3	0.050	0.160	33.7	0.247
28-3	3.20	5.3	0.035	0.120	57.3	0.088
28-7	19.00	23.0	0.095	0.155	41.0	0.278
30-1	21.60	19.6	0.085	0.160	36.9	0.258
31-1	5.30	6.1	0.060	0.130	52.9	0.113
31-3	4.20	6.8	0.050	0.120	55.5	0.101
31-5	4.20	4.1	0.035	0.130	55.0	0.113
37-1	4.20	2.6	0.050	0.120	57.2	0.110
37-3	4.60	2.0	0.040	0.130	54.7	0.121
58-1	3.00	0.0	0.040	0.110	58.0	0.078
68-3	4.50	4.8	0.060	0.120	57.9	0.116
86-1	6.80	6.3	0.065	0.140	51.0	0.141
96A-1	6.80	4.2	0.065	0.140	56.6	0.189
104-1	5.80	3.5	0.060	0.130	52.9	0.129
104-5	3.00	1.2	0.035	0.110	53.4	0.065

where f_{RD} equals side friction demand, and $V85$ equals 85th-percentile speed (mph).

In this manner, the side friction demand was calculated for each of the curved roadway sections under study.

RELATIONSHIPS BETWEEN VARIABLES

Regression analysis was used to obtain quantitative estimates of the effects produced by the independent variables—degree of curve, 85th-percentile speed, and accident rate—on side friction assumed and side friction demand. The following stipulations were used to terminate the regression process and to determine the final regression equation:

1. The selected equation must have a multiple regression coefficient R^2 that is significant at the 0.05 level.
2. Each of the independent variables included in the regression equation must have a regression coefficient that is significantly different from 0 at the 0.05 level.

The selected regression equation had to fulfill both stipulations.

The results of the regression analyses are discussed in the following order:

1. Relationship between side friction assumed/demand and degree of curve.
2. Relationship between side friction assumed/demand and operating speed.
3. Relationship between side friction assumed/demand and accident rate.

Relationship Between Side Friction Assumed/Demand and Degree of Curve

The relationships of side friction assumed/demand and degree of curve are quantified by the following regression models:

$$f_R = 0.092 + 8.104 * 10^{-3}\ \mathrm{DC} - 2.3 * 10^{-4}\ (\mathrm{DC})^2$$

$$R^2 = 0.887 \qquad \mathrm{SEE} = 0.006 \tag{5}$$

where

f_R = side friction assumed for curve design,
R^2 = coefficient of determination, and
SEE = standard error of the estimate.

This small standard error (0.006) and large R^2-value (0.887) suggest that the relationship represented by Equation 5 is a strong one.

$$f_{RD} = 0.014 + 2.248 * 10^{-2}\ \mathrm{DC} - 5.7 * 10^{-4}\ (\mathrm{DC})^2$$

$$R^2 = 0.864 \qquad \mathrm{SEE} = 0.021 \tag{6}$$

Again, the large coefficient of determination (0.864) and the small standard error (0.021) suggest that the relationship represented by Equation 6 is also strong.

Equations 5 and 6 are shown schematically in Figure 3, in which the side friction assumed is higher than the side friction demand on curves up to about 6.5 degrees. For degrees of

TABLE 3 EXAMPLES OF EXTENSION OF TABLE III-6 OF AASHTO 1984 (*6*) FOR SUPERELEVATION RATES BETWEEN 6.5 AND 7.5 PERCENT

DESIGN SPEED	MAXIMUM SUPER ELEVATION	ASSUMED SIDE FRICTION	TOTAL	MAXIMUM DEGREE OF CURVE
V_d (mph)	e	f_R	$[e+f_R]$	DC °
20	0.065	0.170	0.235	50.325
25	0.065	0.165	0.230	31.523
30	0.065	0.160	0.225	21.415
35	0.065	0.155	0.220	15.384
40	0.065	0.150	0.215	11.511
45	0.065	0.145	0.210	8.883
50	0.065	0.140	0.205	7.024
55	0.065	0.130	0.195	5.522
60	0.065	0.120	0.185	4.402
65	0.065	0.110	0.175	3.548
70	0.065	0.100	0.165	2.884
75	0.065	0.100	0.165	2.513
20	0.070	0.170	0.240	51.396
25	0.070	0.165	0.235	32.208
30	0.070	0.160	0.230	21.891
35	0.070	0.155	0.225	15.733
40	0.070	0.150	0.220	11.778
45	0.070	0.145	0.215	9.095
50	0.070	0.140	0.210	7.195
55	0.070	0.130	0.200	5.663
60	0.070	0.120	0.190	4.521
65	0.070	0.110	0.180	3.649
70	0.070	0.100	0.170	2.972
75	0.070	0.100	0.170	2.589
20	0.075	0.170	0.245	52.467
25	0.075	0.165	0.240	32.893
30	0.075	0.160	0.235	22.367
35	0.075	0.155	0.230	16.083
40	0.075	0.150	0.225	12.046
45	0.075	0.145	0.220	9.306
50	0.075	0.140	0.215	7.367
55	0.075	0.130	0.205	5.805
60	0.075	0.120	0.195	4.640
65	0.075	0.110	0.185	3.751
70	0.075	0.100	0.175	3.059
75	0.075	0.100	0.175	2.665

curve greater than 6.5, Figure 3 reveals that (a) the side friction demand is higher than the side friction assumed and (b) the gap between friction assumed and demand increases with increasing degree of curve. That means that, from a driving dynamic safety point of view, beginning with the point where the two curves intersect, the probability of critical driving maneuvers increases with increasing degree of curve. On the basis of the recommendations for good, fair, and poor design practices (see Table 1), it is clear that the point of intersection at 6.5 degrees, as related to degree of curve, falls into the range of fair design practices, for example, in a sequence from a tangent to a curve. In the case of good design practices ($\Delta DC \leq 5$ degrees) side friction assumed exceeds side friction demand, whereas the case of poor design practices ($\Delta DC > 10$ degrees) side friction demand exceeds side friction assumed.

Thus, it may be concluded that for higher degree of curve classes, the side friction values assumed for design by AASHO (*27*) and AASHTO (*6*) appear to be rather inadequate for their adaptation to actual curve designs as observed in the field. Therefore, these values should be further evaluated, with particular reference to operating speeds. The consequences of this will be discussed later in the section that discusses the relationship between side friction assumed/demand and accident rate.

Relationship Between Side Friction Assumed/Demand and Operating Speed

The relationships of side friction assumed/demand and operating speed are quantified by the following regression models:

$$f_R = 0.082 + 4.692 * 10^{-3}\, V85 - 7.0 * 10^{-5}\, (V85)^2$$

$$R^2 = 0.742 \qquad (7)$$

$$\text{SEE} = 0.009$$

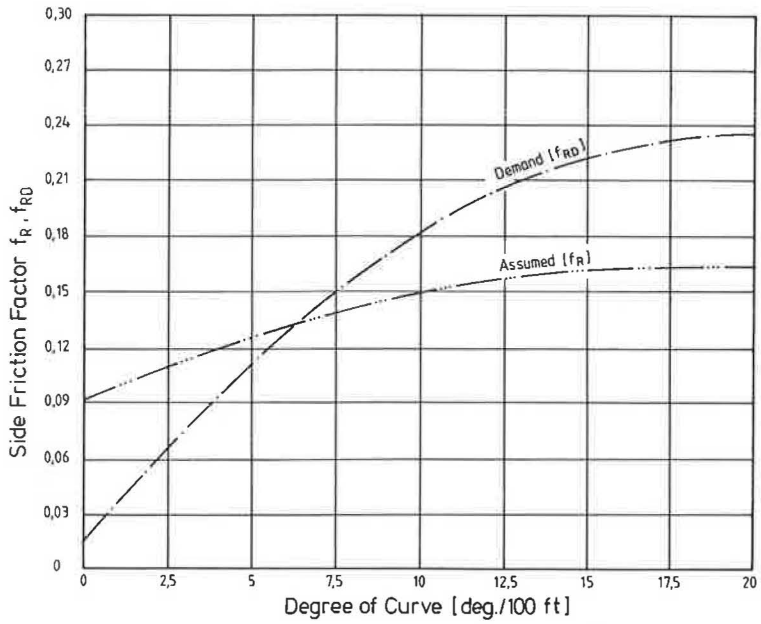

FIGURE 3 Relationship between side friction assumed/demand and degree of curve.

This small standard error (0.009) and large R^2-value (0.742) suggest that the relationship represented by Equation 7 is a strong one.

$$f_{RD} = 0.253 + 2.330 * 10^{-3}\ V85 - 9.0 * 10^{-5}\ (V85)^2$$

$$R^2 = 0.557 \qquad \qquad (8)$$
$$\text{SEE} = 0.038$$

The moderately large coefficient of determination (0.557) and small standard error (0.038) suggest that the relationship represented by Equation 8 is a moderate one.

Equations 7 and 8 are shown schematically in Figure 4, which reveals that (a) side friction assumed/demand decrease as operating speed increases and (b) the point of intersection corresponds to an operating speed of about 50 mph. This finding is not surprising because for higher design speed classes (for example $V_d \geq 60$ mph), degrees of curve ≤ 5 degrees are normally suggested by AASHTO (*6*) and AASHO (*27*) for geometric highway design. Tuning the horizontal alignment in such a way—whenever the changes in degree of curve (ΔDC) between successive design elements are less than or equal to 5 degrees—generally results in gentle curvilinear horizontal alignments that can be evaluated as good design practices (see Table 1).

Furthermore, operating speeds, which are influenced by the nationwide speed limit of 55 mph on two-lane rural (non-Interstate) roads, often do not reach the design speed levels on which the horizontal alignment is based. Thus, it should not be surprising that beginning at about 50 mph, side friction assumed is definitely higher than side friction demand. From a driving dynamic point of view, safe designs could be expected in these cases.

In contrast, for lower design speed levels, which are mostly combined with higher degrees of curve up to maximum values of about 50 degrees [see Table III-6, AASHTO (*6*)] operating

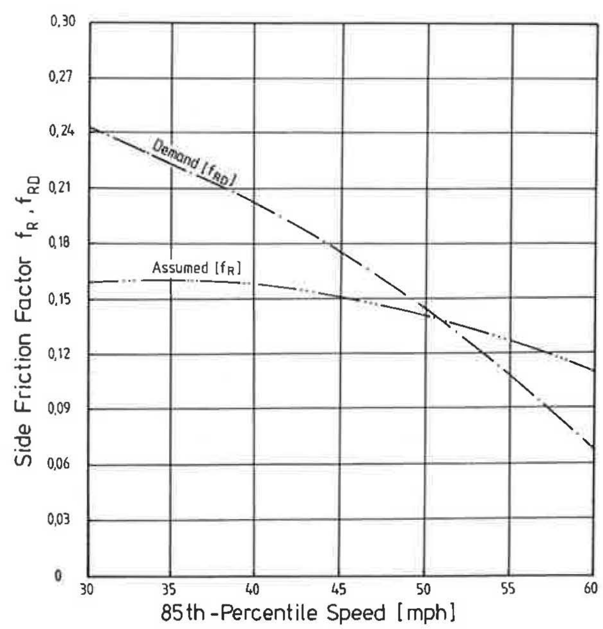

FIGURE 4 Relationship between side friction assumed/demand and operating speed.

speeds often substantially exceed design speeds (*2,4,7–14*). These operating speeds create substantially higher side friction demands than those assumed for highway design (*6,27*) (see Figure 4), at least based on the analysis of data for the 197 curved roadway sections under study.

Relationship Between Side Friction Assumed/Demand and Accident Rate

The relationships of side friction assumed/demand and accident rate are quantified by the following regression models:

$$f_R = 0.121 + 1.860 * 10^{-3}\,\text{ACCR} - 2.0 * 10^{-5}\,(\text{ACCR})^2$$

$$R^2 = 0.406 \qquad \text{SEE} = 0.013 \tag{9}$$

and

$$f_{RD} = 0.097 + 6.041 * 10^{-3}\,\text{ACCR} - 7.0 * 10^{-5}\,(\text{ACCR})^2$$

$$R^2 = 0.401 \qquad \text{SEE} = 0.045 \tag{10}$$

The relatively small coefficients of determination (R^2) of Equations 9 and 10 are not at all surprising because accident research relationships are not simple and direct, but often complex, and changes in frequency of accidents are often the result of many factors other than the driving dynamic aspects, expressed by side friction assumed and side friction demand.

Equations 9 and 10 are shown schematically in Figure 5. Side friction demand begins to exceed side friction assumed when the accident rate is about six or seven accidents per 1 million vehicle-mi. To understand the meaning of this outcome as related to highway geometric design and the accident situation, Table 4 was developed (*15,22,29*). On the basis of these studies, degree of curve was found to be the most successful parameter in explaining the variability in accident rates. As shown in Table 4, the results indicate significant increases (at the 95 percent level of confidence) in the average accident rates among the different degree of curve classes compared. In other words, the results of Table 4 indicate that gentle curvilinear horizontal alignments consisting of tangents or transition curves combined with curves up to 5 degrees showed the lowest average accident risk. These observations agree with the findings of some European guidelines (*12,14*) and the statements of AASHTO (*6*, pp. 248ff.).

For horizontal alignments with changes of curve between 5 and 10 degrees between successive design elements, the mean accident rate in Table 4 is already twice as high as for those between 1 and 5 degrees. For changes between 10 and 15 degrees of curve, the mean accident rate is four times the rate associated with curves between 1 and 5 degrees. For greater changes in degree of curve, the mean accident rate is even higher. This confirms that changes in curve that exceed 10 degrees between successive design elements should be interpreted as poor designs while those in the range between 5 and 10 degrees can still be judged as fair designs.

On the basis of the results of Table 4, and in addition to investigations about geometric design parameters and operating speed changes between successive design elements (*15,16,20,22*), recommendations for good, fair, and poor design practices were developed (see Table 1).

A comparison of the results clearly shows that the point of intersection at which side friction demand begins to exceed side friction assumed in Figure 5 nearly corresponds to the average accident rate for fair design in Table 4. In the range of good design, Figure 5 shows that the side friction assumed is higher than the side friction demand. On the other hand, in the range of poor design, Figure 5 shows that the side friction demand is higher than the side friction assumed. These results clearly support the opinions expressed by several researchers who argue that, in recognition of safety considerations, insufficient dynamic safety of driving has a direct impact on accident rate. Similar results are obvious from Figure 3 and Table 4 with respect to degree of curve.

These results clearly contradict the opinion of many practitioners and researchers who argue that the margin of safety against skidding (especially for passenger cars), that is, the difference between assumed friction and available actual pavement friction, is large enough to provide an adequate dynamic safety of driving. Related to good skid resistant pavements, this margin of safety may reach a factor of 2 for wet

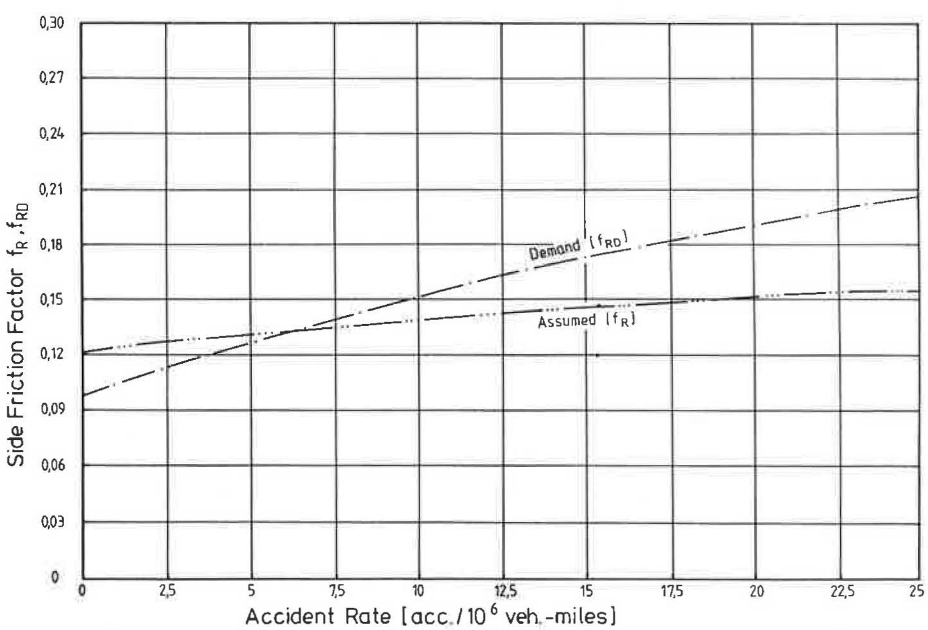

FIGURE 5 Relationship between side friction assumed/demand and accident rate.

TABLE 4 T-TEST RESULTS OF ACCIDENT RATES FOR CHANGES IN DEGREE OF CURVE CLASSES BETWEEN SUCCESSIVE DESIGN ELEMENTS (*15,22,29*)

Degree of Curve Classes (degrees per 100 ft)	Average Acc. Rate (acc./million veh. - miles)	t calc.	t crit.	Significance	Remarks	
tangent 0°	1.87					Consider
		4.00	> 1.96	Yes		
1° - 5°	3.66				----	GD
		7.03	> 1.96	Yes		
> 5° - 10°	8.05				----	FD
		6.06	> 1.99	Yes		
> 10° - 15°	17.55				----	PD
		3.44	> 1.99	Yes		
> 15° - 26.9°	26.41				----	PD

Legend: GD = Good Design; FD = Fair Design; PD = Poor Design.

pavements and a factor of 4 or higher for dry pavements. Related to vehicular and human aspects, there may be another margin of safety against skidding. This additional margin is based on the fact that in nearly all highway design guidelines, assumed friction values are derived from locked-wheel friction measurements. These assumed friction values are lower than the peak friction coefficients that may be reached by experienced drivers, or with the presence of an antilock braking system. However, even those margins of safety do not alter the fact that higher accident risks do exist on poorly designed roadways, which exhibit inconsistencies in horizontal alignment and disharmony between design speeds and operating speeds, as compared to those roadways exhibiting fair designs or even good designs that are based on conditions in the real world.

CONCLUSIONS

The objective of this research was to explore whether the side friction assumed in the policies on geometric design (*6,27*) corresponds to friction demand on existing curved sections of two-lane rural highways. A total of 197 curved roadway sections was selected for the study. For each of the selected roadway sections, geometric design, operating speed, and accident data were collected. Side friction was determined from the available data. Regression analysis was used to obtain a quantitative estimate of the effect on side friction assumed and side friction demand produced by

- Roadway geometry (expressed by degree of curve),
- Operating speed (expressed by the 85th-percentile speed), and
- Accidents (expressed by the accident rate).

The resulting regression equations (see Figures 3 to 5) clearly reveal points of intersection in the relationships between side friction assumed and demand and degree of curve (DC), 85th-percentile speed (*V*85), and accident rate (ACCR). In other words, the figures show that there are ranges for the independent variables (DC, *V*85, ACCR) where side friction demand exceeds side friction assumed and vice versa.

On the basis of prior research (see Tables 1 and 4), this study has shown that, in relation to degree of curve and accident rate, (a) side friction assumed exceeded side friction demand, especially in the range of good design practices and (b) side friction demand exceeded side friction assumed, especially in the range of poor design practices. The points of intersection in Figures 3 and 5 lie somewhere into the range of fair design practices, as related to degree of curve and accident rate.

With respect to side friction, analyses of Figures 3 to 5 indicate that the points of intersection correspond to side friction factors of f_R, $f_{RD} \approx 0.13$. AASHTO Table III-6 (*6*) indicates that this side friction factor corresponds to a design speed between 50 and 60 mph and to a degree of curve between 5 and 7 degrees.

These findings mean that, especially in the lower design speed classes, which are combined with higher maximum allowable degree of curve classes, (a) the danger exists that friction demand exceeds friction assumed (see Figure 3) and (b) a high accident risk results (see Figure 5 and Table 4). These statements are fully supported by the relationships shown in Figure 4, which reveals that side friction demand exceeds side friction assumed for operating speeds $V85 < 50$ mph, where (a) lower design speed levels could be expected and (b) the danger exists that design speeds and operating speeds are not well balanced. Thus, it is apparent that driving dynamic safety aspects have an important impact on geometric design, operating speed, and accident experience on curved roadway sections of two-lane rural highways.

However, previous research (*1,15–24*) demonstrated that adequate dynamic safety of driving is only one safety related criterion in modern geometric highway design. Thus, overall safety improvement, which would, for example, lead to a better harmony between friction assumed and friction demand, would result only through an interaction among the three geometric criteria:

- Achieving consistency in horizontal alignment (Table 1),
- Harmonizing design speed and operating speed (Table 1), and
- Providing adequate dynamic safety of driving (Figure 2).

By regarding only one safety related criterion, for example, adopting the recommended side friction factors of Figure 2 for new geometric design, only a partial success would result.

The relationships provided in this study demonstrated that changes in the AASHTO geometric design policy are warranted in order to fulfill these three geometric criteria. Specific recommendations for those changes have already been discussed and have been provided elsewhere (*16,17,26*). Because the research is primarily based on data collected in New York State, further research in other areas of the United States may be warranted.

In summary, these three safety related issues should be of prime concern to state agencies as they carry out new designs, redesigns, and rehabilitation strategies in order to enhance traffic safety.

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