Side Friction Demanded and Margins of Safety on Horizontal Curves

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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, vehicle speeds and types, and pavement surface conditions are described. Seven horizontal curves located on rural two-lane highways in Alberta as well as curves at the Calgary Police Service's Driver Training Facility were used as test sites. A three-axis accelerometer and a ball bank indicator were installed in seven test vehicles, including passenger cars, a half-ton pick-up, and a tandem-axle gravel truck. Lateral accelerations and ball bank readings were 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. Ball bank readings are regressed upon lateral accelerations for each vehicle type, and equations predicting the implied value of safe side friction, the safe speed of the curve, and the margin of safety provided by the safe speed are developed. Maximum values of side friction demanded on dry and icy roadways are determined and used to calculate the margin of safety provided at various speeds. It was found that the current design standards are quite conservative and provide a more-than-sufficient margin of safety for motorists.

As a vehicle corners, 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:

$$f_s + e = V^2/(127\ R) \qquad (1)$$

where

f_s = side friction factor,
e = superelevation rate (m/m),
V = speed (km/hr), and
R = radius (m).

If a vehicle demands more side friction than the pavement/tire interface can provide the vehicle will skid off the roadway. AASHTO (*1*) notes that "the upper limit of this factor (f_s) is that at which the tire is skidding or at the point of impending skid." AASHTO (*1*) does not indicate the margin of safety against side-skid that the design factors provide. Although AASHTO notes that the f_s used for highway design should be substantially less than the f_s at impending skid, the agency (*1*) also notes that "in selecting maximum allowable side friction factors for use in design, one criterion is the point at which the centrifugal force is sufficient to cause the driver to experience a feeling of discomfort and cause him to react instinctively to avoid higher speed. The speed on a curve, at which discomfort due to centrifugal force is evident to the driver, can be accepted as a design control for the maximum allowable amount of side friction." AASHTO (*1*) also provides a caution that other factors, such as swerving and increased steering effort, are required and act to control driver speed at conditions of high friction demand. In addition, AASHTO (*1*) notes that when practical, "the maximum factors selected should be conservative for dry pavements and provide a margin of safety for operating on pavements that are wet as well as ice or snow covered." This paper describes 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, vehicle speeds and types, and pavement surface conditions.

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RECENT RESEARCH

Surprisingly little research has been done in the area of side friction and margins of safety since the late 1940s. In fact, very few full-scale road tests have been conducted, and only a small number of these have been conducted on icy pavement surfaces. Instead of conducting full-scale tests, some researchers (*2–4*) used an assumed value of side friction provided to calculate the margin of safety a vehicle has when cornering.

Other researchers have used skid trailers to determine how much side friction a tire can provide (ANSI/ASTM E670-79; *5*). The skid trailer is connected to a tow vehicle so that the longitudinal axis of the trailer is at an angle to the line of motion of the two vehicle. As the tow vehicle moves, the trailer moves forward, with the wheels rolling forward with a side skid motion. Because of the lack of a driving force on the trailer tires, combined with the absence of the vehicle roll that occurs during cornering, skid trailers do not provide a realistic model of a side-skidding vehicle.

Others (*6*) have observed vehicle speeds on curves and used the point-mass equation to calculate the amount of friction demanded. Relationships between curve geometry and friction factor were then established. Lamm et al. (*6*) found that motorists demand more friction on curves sharper than 2 degrees/100 m and at operating speeds lower than 80 km/hr. By observing driver behavior on curves, McLean (*7*) also found that drivers tend to demand more side friction on tighter, highly superelevated curves.

Research into side friction on icy pavement surfaces is extremely sparse. The research that has been conducted on this type of surface typically consisted of driving a vehicle around a circular path with a known radius until the driver felt that impending skid conditions were reached (*8,9*). By recording the time required to drive the vehicle through a number of laps, the point-mass equation was used to determine the side friction factor.

Most researchers note that the friction factors used for design should not use all of a tire's available friction for cornering (*2,3,10*); the tire must be able to provide braking friction as well. By limiting the allowable side friction factor used for design to a certain percentage of the maximum side friction factor, designers can ensure that enough friction remains for other maneuvers.

Because the side friction factor is essentially an acceleration, measured in *g*-units, in the plane of the road, one can use an accelerometer to measure the friction factor directly. This method was used in a research project conducted by the Department of Civil Engineering at the University of Calgary for Alberta Transportation and Utilities (*11*).

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 within the province of Alberta and on the Calgary Police Service's Driver Training Facility. Curvatures ranged from 290 to 3490 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.

Site selection was based on the following factors (*6,11*):

1. Circular curves with no spiral transitions,
2. Paved sections with paved shoulders,
3. No changes in lane or shoulder widths,
4. Gentle sideslopes and removal of roadside hazards and other physical features that may create a dangerous environment,
5. Grades less than 5 percent,
6. Location away from the zone of influence of intersections, towns, and so on, and
7. Relatively low traffic volumes.

A wide range of test vehicles, typical of those found on rural two-lane highways in Alberta, was used for this project. These test vehicles included two late model sports cars, a sports sedan, a compact car, a half-ton pick-up truck, and a tandem-axle gravel truck; a Calgary Police service cruiser was also used for high-speed tests. All vehicles were tested unloaded, with the fuel tank approximately half full, and tire pressures equal to those recommended by the tire manufacturer.

A ball bank indicator and a commercial accelerometer (the G-Analyst) were used to measure ball bank readings and corresponding lateral accelerations on the test curves. During vehicle roll, the ball bank reading is the sum of the centrifugal force angle and the body roll angle, minus the superelevation angle, and therefore provides a measure of the centrifugal force acting on the occupants of a vehicle (*12*). 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.

RELATIONSHIP BETWEEN SPEED AND CURVATURE

Vehicle speeds on horizontal curves are a function of many variables, including site, traffic, and motorist characteristics along with other variable factors (*13*). Because each test site is located on fairly level terrain and has good sight distance, uniform lane and shoulder widths, and design speeds, the effects that these parameters have on operating speeds cannot be determined. Since superelevation is strongly correlated with curvature, it was not considered as an independent variable in any of the regression models. The following criteria were used to determine the most appropriate model:

- The selected regression equation must have a multiple regression coefficient that is significant at the 95 percent level.
- The coefficient estimator for each of the independent variables included in the regression equation must be significantly different from zero at the 95 percent level.

On the basis of field observations on nine curves in Alberta, regression analysis was used to obtain estimates of the effect on operating speed produced by degree of curvature. Linear, multiplicative, exponential, and reciprocal regression models were developed. The model given here was found to best satisfy the given criteria:

$$V_{85} = e^{[4.561 - 0.00586(DC)]} \text{ km/hr} \quad (2)$$

where

V_{85} = 85th-percentile speed (km/hr),
DC = degree of curve (degrees/100 m),
r^2 = coefficient of determination, and
S.E. = standard error of estimate (km/hr).

For this relationship, $r^2 = 0.631$ and S.E. = 0.0326, which suggest that the relationship given here is moderately strong.

SIDE FRICTION FACTORS AND BALL BANK ANGLES

Regression analysis was used to obtain models of the relationship between ball bank angle and side friction factor (determined by using the acceleration data collected with the G-Analyst). Because the ball bank indicator can be accurately read only to the nearest degree, it is possible that small lateral acceleration values may be assigned to ball bank angles that equal zero. Therefore, these regression models were not forced through the origin. Ball bank angles were found to vary linearly with side friction factors. Coefficients of determination between ball bank angle and side friction factor for the highway sites range from 0.976 to 0.645. Some of this variation may be a result of vehicle characteristics because these relationships were determined using data collected for all vehicle types. In general, the correlation coefficients between ball bank angle and side friction factor are lower for flatter curves than for sharper curves. This difference may be because of the small range of ball bank angles developed on these sites. No ball bank readings greater than 6.5 degrees were developed on the flatter curves, whereas ball bank readings greater than 15 degrees were commonly developed on the sharper curves. Therefore, small errors in ball bank readings have a greater effect on the flatter curves than they do on the sharper curves. In addition, because the flat curves are longer than the sharp curves, drivers have more opportunities to make steering inputs on the flatter curves. AASHTO (*1*) defines the safe speed of a curve as that which produces a ball bank angle of ± 10 degrees for speeds greater than 55 km/hr. The relationships developed between ball bank angle and side friction factor were used to determine the amount of side friction that corresponds to the safe speed. Using these "safe side friction" values combined with the radius of curvature and the as-built maximum superelevation rate, the safe speed for each curve was calculated. It was found that, based on AASHTO (*1*) design criteria for horizontal curves, curves flatter than 1000 m provide a very high margin of safety. For the tighter curves, speeds greater than 90 km/hr can be achieved before driver discomfort is noticed. This indicates that the margins of safety provided on these curves by design guidelines (*1*) are lower than those provided on the flatter curves.

Regression models relating ball bank angle and side friction factor on icy pavement surfaces also were developed. Coefficients of determination for ball bank angle and side friction factor for the icy curves range from 0.85 to 0.70—substantially lower than those obtained for dry pavements. The main source of variation is caused by differences in ice temperature and ice surface condition. Because climatic conditions could not be controlled, the data analyzed were collected under temperatures ranging from −20°C to −5°C. Furthermore, the ice surfaces of the 30- and 50-m curves were very smooth, whereas that of the 70-m curve was noticeably rougher. Finally, variation also may have been introduced by repeated wheel loads heating the ice cover.

Safe side friction factors for icy surfaces were determined using the regression equations developed for icy pavement. These values, combined with the point mass curve equation, were then used to calculate safe speeds of 25, 31, and 38 km/hr for the 30-, 50-, and 70-m icy curves, respectively.

SIDE FRICTION FACTORS AND BALL BANK ANGLES FOR TEST VEHICLES

Regression models relating ball bank angles to side friction factors (determined by using the acceleration data collected with the G-Analyst) for each test vehicle were also developed. Because of data limitations and marginal differences in side friction factors between vehicle types, along with the fact that design guidelines (*1*) are based on all classes of vehicles, data for all vehicle types were grouped together. The resulting relationship is shown in Figure 1. The high coefficient of determination and low standard error indicated that the relationship is strong between ball bank angle and side friction factor.

Using Figure 1, safe side friction factors for the inside and outside of a given curve were found to be 0.1588 and 0.1790. These factors are slightly higher than those found by previous researchers (*14–16*).

A similar regression model was developed for the icy curves. The regression model for these curves has a lower coefficient of determination (r^2 = 0.78) than that of the highway curves. This is mainly a result of variations in ice temperature and surface condition. The safe side friction factors for all the vehicles on the icy curves was determined to be 0.187. However, because side skid occurred at ball bank angles of less than 10 degrees, this safe side friction factor is unrealistic. In fact, side skid occurred at substantially lower ball bank angles than those at which discomfort is noticed. Therefore, basing design side friction factors on driver comfort levels in jurisdictions where freezing temperatures routinely occur during the winter months is clearly not a conservative approach to highway design.

PEAK SIDE FRICTION DEMANDED

It is widely known that drivers tend to drive a spiral when traversing a horizontal curve (*17*), which means that side friction demands do not increase instantaneously to their peak value as a vehicle enters a curve. Instead, the amount of side friction demanded varies with the distance along the curve, as Figure 2 shows, and increases with speed. On dry pavement surfaces, it was found that peak side friction demanded can occur anywhere along a curve. On icy pavement surfaces it was found that the amount of side friction demanded increases gradually as a vehicle enters a curve and gradually decreases as the vehicle exits the curve. This suggests that drivers steer a spiral when traversing a curve and may be because, compared with the highway curves, icy curves had very smooth surfaces, thereby negating the effects of surface roughness on lateral acceleration readings. In addition, because these curves are very short compared with the highway curves and because drivers can devote much more of their attention to the driving task, fewer steering inputs are required.

To investigate whether side friction factors given in current design guidelines provide an adequate margin of safety, the peak amount of side friction demanded by all vehicle types under a range of speeds on each test curve was determined. Because the amount of peak side friction demanded (fs_p) varies with the radius of curvature, peak values obtained on the inside and the outside of each highway curve were determined. Linear regression models were found to fit the data points the best and are shown in Table

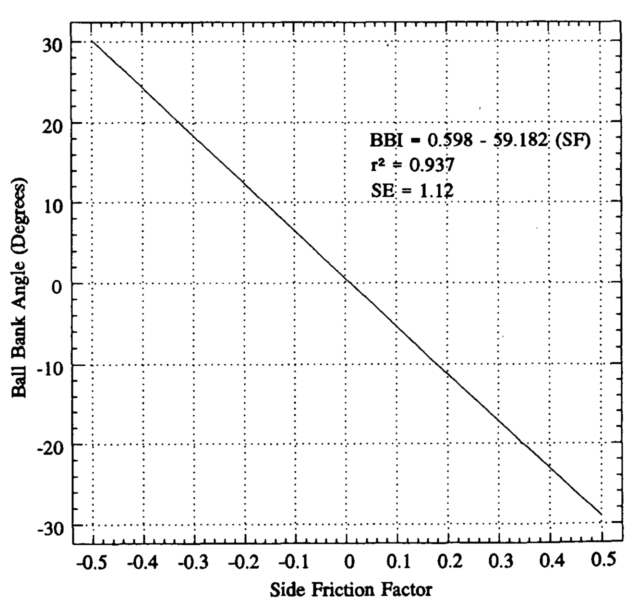

FIGURE 1 Regression of ball bank angle on side friction factor for all vehicles on highway test curves.

1 for the inside and outside of each highway curve as well as for the icy curves.

For the highway curves, Table 1 indicates that the correlation between peak side friction factor and speed decreases as the radius of curvature increases. In fact, the coefficients of determination between speed and peak side friction factor for the 3000- and 3490-m radius curves are so low that no significant relationship exists. This is largely because the peak friction demanded on the flatter curves is small, which means that factors that have minor influences on the peak friction demanded on sharper curves now play a larger role. In addition, because the flatter curves are longer than the sharper curves, there are more opportunities for factors such as steering inputs and pavement surface irregularities to affect the amount of peak friction required.

At speeds between 65 and 90 km/hr, the side friction factors suggested by AASHTO (*1*) for design are exceeded on the 290- and 435-m radius curves. This indicates that more side friction is being used at these speeds than the design guidelines recommend.

The relationships between peak friction demanded and speed for the icy curves along with the side friction factors recommended for design (*1*) are given in Table 1 and also are shown graphically in Figure 3. The moderately low coefficient of determination for the 30-m curve is because only a narrow range of speeds could be investigated. Furthermore, because the air temperature increased from approximately −14°C to slightly below freezing during the time in which these data were collected and because the ice layer had started to melt, the tests had to be discontinued and completed on another day. Therefore, the ice temperature and surface condition introduced variation in the data for which the regression model does not take into account.

As Figure 3 indicates, peak side friction demanded increases with speed and radius of curvature. Figure 3 also shows that more side friction is demanded than design guidelines (*1*) provide for speeds greater than 25, 29, and 34 km/hr for 30-, 50-, and 70-m curves, respectively. Therefore, the margin of safety that the design side friction factors provide appears to be inadequate for icy surfaces.

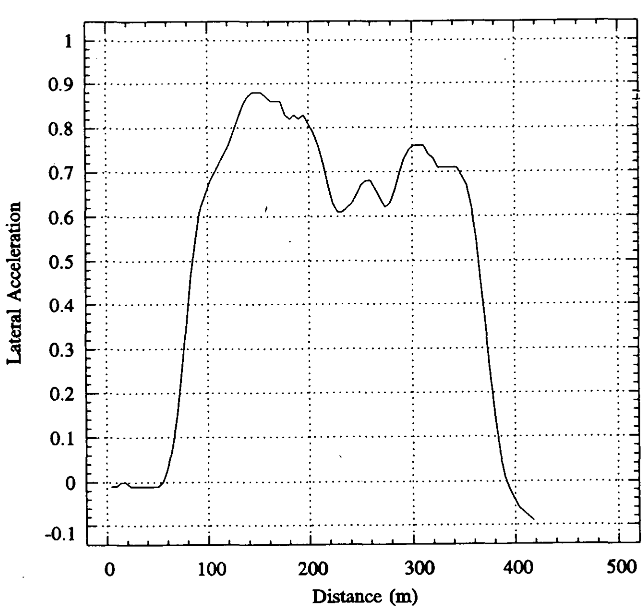

FIGURE 2 Side friction demanded by 1991 Caprice police cruiser on 435-m radius curve.

MARGIN OF SAFETY AGAINST SKIDDING

To estimate the margin of safety a curve provides against skidding, the side friction at impending skid conditions and the peak side friction demanded must be known. Once these values are known, the margin of safety can be defined as

$$MS_{\text{skid}} = f_{s\ \text{skid}} - f_{s\ \text{peak}} \quad (3)$$

where

MS_{skid} = margin of safety against skidding,
$f_{s\ \text{skid}}$ = side friction factor at impending skid condition at a given speed, and
$f_{s\ \text{peak}}$ = peak side friction demanded at a given speed.

Because the side friction at impending skid depends on the pavement surface condition, different margins of safety exist on dry, wet, and icy pavements.

Margin of Safety on Dry Pavements

Because impending skid conditions were reached at two test sites with the higher-powered vehicles only, limited data on side friction factors at impending skid were obtained. However, the data collected suggest that the maximum amount of side friction provided is approximately 0.90. This value agrees well with the findings of other researchers, (*4,17,18*). Using these data, combined with the margin of safety definition given in Equation 3, margins of safety against skidding on dry pavement for each highway site were calculated. These margins of safety, along with those for wet and icy pavements, are shown in Table 2.

Table 2 indicates that on dry pavement the margin of safety decreases with speed and decreases at a faster rate on tighter curves than on flatter curves. For example, the margin of safety provided on the 3500-m radius curve varies from 0.93 to 0.85 for all speeds. This suggests that drivers are using a minimal amount of friction for cornering, which leaves the bulk of the total available friction for changes in deceleration, acceleration, or direction. Therefore, these curves provide a high level of driving dynamic safety on dry pavement. Furthermore, these values indicate that very little superelevation is needed on these types of curves. Because the manner in which margin of safety against skidding was defined does not account for the superelevation provided on a curve, the provision of superelevation will increase the frictional supply of a curve and increase further the margin of safety. By providing superelevation equal to reverse crown, not only would an adequate margin of safety on dry pavements be provided, but construction costs would also decrease.

For the 290- and 435-m radius curves, the margin of safety decreases with speed at approximately 14 times the rate of the flatter curves. This rapid decrease suggests that there may not be enough friction available for drivers to perform evasive maneuvers under normal operating speeds. In addition, the coefficients of determination between speed and margin of safety of the linear regression models for the flatter curves are low. This indicates that a large portion of the variance in margin of safety cannot be explained by speed for these sites and is mainly the result of the poor relationship between peak side friction demanded and speed that exists for these sites.

Margin of Safety on Wet Pavements

Impending skid tests on wet pavement were not conducted for two reasons. First, there is no standard method for measuring water layer thickness on pavements. Second, the relatively high superelevation rates provided on these curves prohibited a uniform water thickness layer from being formed. Other researchers (*4*) have found that the maximum side friction provided by wet pavements is 0.58 at 30 km/hr, decreasing to 0.41 at 113 km/hr. For this study, side friction factors of 0.54 at 30 km/hr, decreasing to 0.315 at 200 km/hr, were used.

Regression equations to relate margins of safety to speed were developed for each highway site; coefficients of determination ranged from 0.55 to 0.99. These equations were then used to calculate the margin of safety against skidding at various speeds for each site and are given in Table 2.

Once again, sharper curves appear to provide a lower margin of safety against skidding than do flatter curves. In fact, at speeds of 110 km/hr or greater, no margin of safety against skidding exists on the three sharpest curves. For vehicles traveling at the 85th-percentile speeds on these curves, margins of safety range from approximately 0.06 to 0.13. Therefore, sharp curves do not provide a sufficient margin of safety against skidding under wet pavement conditions for vehicles traveling at the normal operating speed of the curve. Moreover, very little friction is available for motorists to perform evasive maneuvers if required. Therefore, the provision of adequate superelevation on these types of curves is critical. In fact, if drivers are surprised on these sites during rainy weather on curves with adequate superelevation, it is possible that they may lose control of their vehicle and skid off the roadway.

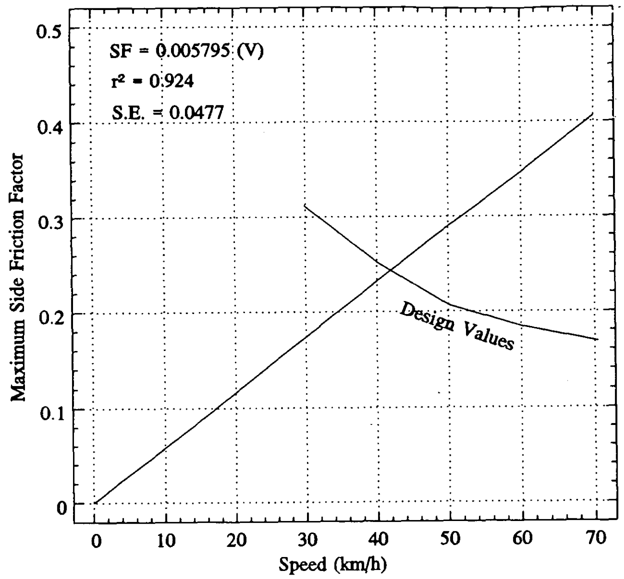

FIGURE 3 Variation of maximum side friction factor on ice with speed.

For the four flatter curves tested, margins of safety against skidding of approximately 0.38 can be expected at the normal operating speeds of vehicles on these highways. These frictional reserve levels appear to be adequate to provide enough braking

TABLE 1 Relationship Between Peak Side Friction, Radius of Curve, and Speed

Radius (m)	Direction of Travel	Regression Equation	R^2 (%)	S.E.
30*	Inside	fs_p = -0.0629 + 0.0926(V)	62.12	0.0420
50*	Inside	fs_p = -0.143 + 0.0106(V)	88.73	0.0217
70*	Inside	fs_p = -0.906 + 0.0073(V)	82.32	0.0295
290	Inside	fs_p = -0.385 + 0.00683(V)	96.94	0.0421
	Outside	fs_p = 0.451 - 0.00670(V)	91.55	0.0405
435	Inside	fs_p = -0.405 + 0.00745(V)	97.98	0.0382
	Outside	fs_p = 0.337 - 0.00645(V)	96.34	0.0233
580	Inside	fs_p = -0.391 + 0.00570(V)	93.42	0.0490
	Outside	fs_p = 0.322 - 0.00466(V)	92.92	0.0254
1164	Inside	fs_p = -0.158 + 0.00220(V)	79.79	0.0200
	Outside	fs_p = 0.188 - 0.00218(V)	83.2	0.0200
1164	Inside	fs_p = -0.184 + 0.00253(V)	84.17	0.0208
	Outside	fs_p = 0.235 - 0.00260(V)	77.24	0.0265
3000	Inside	fs_p = 0.000606(V)	22.74	0.0248
3490	Inside	fs_p = 0.000458(V)	13.1	0.0226
	Outside	fs_p = -0.000360(V)	32.7	0.0103

* icy curves

TABLE 2 Margin of Safety Against Skidding on Dry, Wet, and Icy Pavement

Speed (km/h)	Pavement Condition	Margin of Safety for Different Degrees of Curve								
		DC= 191	DC= 115	DC= 82	DC= 20	DC= 13	DC= 10	DC= 5	DC = 2*	DC = 1.6*
30	Dry	-	-	-	1.08	1.08	1.12	0.99	0.88	0.89
	Wet	-	-	-	0.72	0.72	0.76	0.63	0.52	0.53
	Icy	-0.08	-0.12	-0.16	-	-	-	-	-	-
40	Dry	-	-	-	1.01	1.01	1.06	0.97	0.88	0.88
	Wet	-	-	-	0.62	0.61	0.67	0.58	0.48	0.49
	Icy	0.02	0.01	-0.05	-	-	-	-	-	-
60	Dry	-	-	-	0.88	0.86	0.95	0.93	0.86	0.87
	Wet	-	-	-	0.41	0.39	0.48	0.46	0.40	0.41
80	Dry	-	-	-	0.74	0.71	0.84	0.88	0.85	0.86
	Wet	-	-	-	0.24	0.21	0.34	0.38	0.35	0.36
100	Dry	-	-	-	0.60	0.56	0.72	0.84	0.84	0.85
	Wet	-	-	-	0.08	0.04	0.20	0.31	0.31	0.33
150	Dry	-	-	-	0.26	0.19	0.44	0.73	0.81	0.83
	Wet	-	-	-	-0.29	-0.37	-0.12	0.17	0.26	0.28
200	Dry	-	-	-	-.08	-0.19	0.15	0.62	0.78	0.81
	Wet	-	-	-	-0.67	-0.77	-0.43	0.03	0.19	0.22

* r^2 of regression model is less than 0.45.
- no data available

friction for drivers to stop safely, even if superelevation rates equal to reverse crown are provided on these types of curves.

It was also evident that the margin of safety decreases at a higher rate with speed on wet pavements than on dry pavements. In addition, wet pavements provide a margin of safety of approximately 0.50 less than dry pavements for any given speed and radius of curvature. This significant reduction in available side friction clearly indicates that water on pavement dramatically decreases the margin of safety against skidding.

Margin of Safety on Icy Pavements

Lateral acceleration and speed data at impending skid conditions were collected on icy pavement surfaces. These data were then used to develop regression models relating side friction factors to speed, as given in Table 2. A linear regression model was found to best fit the data points and is shown in Figure 3. Figure 3 is based on over 130 lateral acceleration and speed readings; the speeds ranged from approximately 20 to 50 km/hr. The moderate correlation coefficient indicates that the relationship between margin of safety and speed is moderately strong.

Knowing the maximum friction provided at impending skid, along with the design side friction factors, the margin of safety against skidding provided by the design factors can be defined as

$$MS_{\text{design}} = f_{s\ \text{skid}} - f_{s\ \text{design}} \quad (4)$$

where $f_{s\ \text{design}}$ is the side friction factor assumed for design.

A negative margin of safety, as presented in Table 2, means that design guidelines are using more side friction than the tire-pavement interface can provide. Therefore, a negative margin of safety is clearly undesirable. Because design friction factors are not specified for speeds less than 30 km/hr (*1,19*), a side friction factor of 0.31 was assumed for a design speed of 29 km/hr. This approach is conservative because side friction factors increase with decreasing speed.

Table 2 indicates that the margin of safety against skidding on the icy curves increases with increasing radius and speed. This increase is because substantially higher side friction factors are assumed for lower speeds than for slightly higher speeds. Because the side friction provided at impending skid conditions varies marginally with speed, the large change in design friction factors with speed causes the margin of safety to increase with speed. Therefore, lower design side friction factors for speeds of less than 40 km/hr would increase the margin of safety for curves with low design speeds.

It was found that the side friction factors suggested by design guidelines (*1,19*) do not provide any margin of safety against skidding for speeds less than 37 to 44 km/hr for radii of 30 and 70 m, respectively. In addition, only a small margin of safety exists for speeds greater than 48 km/hr. This margin of safety does not appear to be adequate to accommodate emergency braking or other evasive maneuvers. Therefore, it appears that the side friction factors suggested by design guidelines do not provide adequate margins of safety for vehicles traveling on icy pavements, especially on curves with lower design standards.

SUMMARY

The findings of this research project can be summarized as follows:

1. Ball bank angles of ±10 degrees yield side friction factors of 0.16 to 0.17 for the test vehicles used; these values correspond well to those suggested for design (*1*). In addition, safe side friction factors appear to be relatively constant across the vehicle types investigated, which suggests that most drivers will experience the same level of comfort on horizontal curves regardless of the type of vehicle they are driving. Basing horizontal curve guidelines on ball bank angles may not be a conservative approach to highway design, because skid may occur at low speeds before discomfort is perceived, especially on icy pavement surfaces, or in vehicles with high centers of gravity. Under these circumstances, motorists do not have any warning that they are approaching the limit of stability. Therefore, basing design side friction factors on the amount of friction demanded and supplied would seem to be a more conservative approach to horizontal curve design.

2. Because drivers tend to steer a spiral when entering and exiting a horizontal curve, the amount of side friction drivers demand is not constant. However, models can be created to predict peak friction demands as a function of vehicle speed for different curvatures on dry and icy pavement surfaces. These relationships provide a more accurate representation of actual driving behavior and could be used instead of the point mass equation to estimate the frictional demands drivers place on horizontal curves.

3. Curvatures flatter than 500 m provide high levels of driving dynamic safety on both dry and wet pavements. Motorists would be able to brake safely from the operating speed on these types of curves without exceeding the frictional supply. For curves with radii greater than 1000 m, the margins of safety are so high that these curves could be constructed with maximum superelevation equal to reverse or normal crown and would still provide frictional reserve levels large enough to allow vehicles traveling at normal operating speeds to brake safely without skidding. This suggests that the minimum radii for maximum superelevation equal to normal crown used for design (*1*) are very conservative. Decreasing the maximum superelevation rate on these types of curves would provide the following benefits:

–Minimize the operational problems associated with intersections on curves.

–Decrease the probability of vehicles with high centers of gravity overturning.

–Decrease the probability of a slow-moving vehicle sliding toward the center of an ice-covered curve. In fact, by using the point-mass equation, it can be determined that a vehicle traveling slower than 15 km/hr on a curve with a maximum superelevation rate of 8 percent and a radius of curvature greater than 300 m will slide down the superelevation, toward the center of the curve. As noted previously (*20*), Alberta Transportation and Utilities' most recent design standards have decreased the maximum superelevation rate from 8 to 6 percent.

4. The margin of safety against skidding decreases with increasing curvature and speed. On dry pavements, the margin of safety that exists on curves sharper than 500 m appears to provide adequate frictional reserve levels to allow vehicles traveling at normal highway operating speeds to brake safely. On wet pavement, these curves provide no margin of safety for operating speeds of 110 km/hr or greater. Because it is not uncommon for Alberta drivers to travel at these speeds, these types of curves appear to be underdesigned.

5. The margins of safety provided by design guidelines appear to provide adequate margins of safety against skidding. The problem appears to lie with the speeds at which vehicles in Alberta are operated. By tuning design speeds with operating speeds, the amount of side friction supplied would increase, whereas frictional demands would remain relatively constant. The overall effect would be an increase in the margin of safety provided on sharp curves, along with fewer overdesigned flat curves.

6. The side friction provided by icy pavements at impending skid conditions shows slight but significant variation with speed. The side friction factors used for low-speed urban design appear to be too high for speeds less than 40 km/hr and do not provide any margin of safety against skidding on icy pavements. Therefore comfort levels may not result in conservative curve designs in regions where icy pavement conditions routinely occur. Therefore, lower friction factors than those recommended by current design guidelines (*1,19*) should be considered. Because basing guidelines solely on icy pavement conditions is not economical and the consequences of an accident at such low speeds are minimal, the side friction factors should be a compromise between wet pavement conditions and icy pavement conditions.

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REFERENCES

1. *A Policy on Geometric Design of Rural Roads*. AASHTO, Washington, D.C., 1990.
2. Dunlap, D. F., P. S. Fancher, R. E. Scott, C. C. MacAdam, and L. Segel. *NCHRP Report 184: Influence of Combined Highway Grade and Horizontal Alignment on Skidding*. HRB, National Research Council, Washington, D.C., 1978.
3. Zuk, W. Instability Analysis of A Vehicle Negotiating a Curve with Downgrade Superelevation. In *Highway Research Record 390*, HRB, National Research Council, Washington, D.C., 1972, pp. 40–44.
4. Harwood, D. W., J. M. Mason, W. D. Glauz, B. T. Kulakowski, and K. Fitzpatrick. *Truck Characteristics for use in Highway Design and Operation*. Final Report, Project 8932-S. Midwest Research Institute, Kansas City, Mo., 1989.
5. Salt, G. F. Research on Skid-Resistance at the Transport and Road Research Laboratory (1927–1977). In *Transportation Research Record 622*, TRB, National Research Council, Washington, D.C., 1976, pp. 26–38.
6. Lamm, R., E. M. Choueiri, and T. Mailaender. Side Friction Demand Versus Side Friction Assumed for Curve Design on Two-Lane Rural Highways. In *Transportation Research Record 1303*, TRB, National Research Council, Washington, D.C., 1991, pp. 11–21.
7. McLean, J. R. Driver Behaviour on Curves—A Review. *Proc., Australian Road Research Board*, Vol. 7, Part 5, 1974, pp. 129–143.
8. Paustian, R. G. Tractive Resistance as Related to Roadway Surfaces and Motor Vehicle Operation. *Iowa State College of Agriculture and Mechanic Arts Official Publication*, Vol. 33, No. 9, 1934, pp. 87–108.
9. Whitehurst, E. A. *STP 456: The Cornering Capacity of Studded Tires, in Highway Skid Resistance*. American Society for Testing and Materials, 1969, pp. 144–153.
10. Lamm, R., E. M. Choueiri, and T. Mailaender. Accident Rates on Curves as Influenced by Highway Design Elements—An International Review and In-Depth Study. *Proc., Road Safety in Europe*, Gothenburg, Sweden, VTI Rapport 344A, Swedish Road and Traffic Research Institute, Linköping, Sweden, 1989, pp. 33–54.

11. Morrall, J. F. and R. J. Talarico. *Side Friction Factors for Horizontal Curve Design*. Department of Civil Engineering, University of Calgary, Alberta, Canada, 1993.
12. Merritt, D. R. Safe Speeds on Curves: A Historical Perspective of the Ball Bank Indicator. *ITE Journal*, Sept. 1988, pp. 15–19.
13. Oppenlander, J. C. *Special Report 89: Variables Influencing Spot Speed Characteristics*. HRB, National Research Council, Washington, D.C., 1966.
14. Barnett, J. Safe Side Friction Factors and Superelevation Design. *Proc., Highway Research Board*, Vol. 16, 1936, pp. 69–80.
15. Moyer, R. A. and D. S. Berry. Marking Highway Curves with Safe Speed Indicators. *Proc., 20th Annual Meeting of the Highway Research Board*, Washington, D.C., 1940, pp. 399–428.
16. Stonex, K. A. and C. M. Noble. Curve Design and Tests on the Pennsylvania Turnpike, *Proc., Annual Meeting of the Highway Research Board*, Vol. 20, 1940, pp. 419–451.
17. Harwood, D. W. and J. M. Mason. Horizontal Curve Design for Passenger Cars and Trucks. Presented at 72nd Annual Meeting of the Transportation Research Board, Washington, D.C., 1993.
18. Gegenbach, W. *Das Verhalten von Kraft-Fahrzeugreifen auf trockener und nasser Fahrbahn*. Dissertation, Institute for Transport Studies, University of Karlsruhe, Germany, 1967.
19. *Manual of Geometric Design Standards for Canadian Roads*. Transportation Association of Canada, Ottawa, Ontario, 1986.
20. Kenny, W. *Superelevation Policy for Rural Roads in Alberta*. Alberta Transportation and Utilities, Canada, 1990.

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