Design Friction Factors of Different Countries Versus Actual Pavement Friction Inventories

RUEDIGER LAMM, ELIAS M. CHOUEIRI, PREM B. GOYAL, AND THEODOR MAILAENDER

A fundamental scale is presented for evaluating appropriate levels of tangential and side friction factors with respect to design speed for new designs, redesigns, and rehabilitation strategies. The friction data used were obtained from the geometric highway design guidelines of the United States and several Western European countries, and from actual pavement friction inventories in New York State and in the Federal Republic of Germany (FRG). From the friction data of the countries in this study, relationships were developed between tangential or side friction factors and speed. The curves resulting from these relationships were then compared with percentile level distribution curves obtained from the actual pavement friction inventories. Analyses indicated that (a) the friction factors produced by the overall regression curves coincided with those obtained from the 90th-percentile level distribution curve of New York State, and with those derived from the 80th-percentile level distribution curve of the FRG; and (b) the friction factors derived from the 95th-percentile level distribution curve of New York State coincided with the friction factors derived from the 95th-percentile level distribution curve of the FRG. On the basis of these results, recommendations are provided for highway design for minimum stopping sight distances and minimum radii of curve. It is estimated that in applying the proposed friction factors for design, redesign, and rehabilitation strategies 95 percent of wet pavements will be covered in the United States and Europe. The recommendations provided should not be regarded as a final solution, but perhaps an international discussion of a larger dynamic safety supply for driving may be useful in reducing accidents on 2-lane rural highways. Because there are often inadequate safety factors in tire-road friction, friction demand often exceeds friction supply, causing more accidents than necessary.

An international review of existing design guidelines (*1–7*) has shown that European countries directly or indirectly address three design issues in their guidelines much more explicitly than United States agencies to gain safety advantages. For example, German, Swedish, and Swiss designers are provided with geometric design criteria that direct them toward

1. Achieving consistency in horizontal alignment,
2. Harmonizing design speed and operating speed on wet pavements, and
3. Providing adequate dynamic safety of driving.

R. Lamm, Institute of Highway and Railroad Engineering, University of Karlsruhe, D–7500 Karlsruhe 1, Kaiserstrasse 12, Federal Republic of Germany. E. M. Choueiri, North Country Community College, Sarnac Lake, Route 1, Box 12, Potsdam, N.Y. 13676. P. B. Goyal, 10 Hunter Lane, Elmsford, N.Y. 10523. T. Mailaender, Mailaender Ingenieur Consult, D–7500 Karlsruhe 1, Mathystrasse 13, Federal Republic of Germany.

Criteria 1 and 2 were the subject of several reports, publications, and presentations by the authors. For example, for the National Science Foundation (*8*), for the New York State Governor's Traffic Safety Committee (*9, 10*), for the Transportation Research Board (*11–14*), for the Ohio Transportation Engineering Conference (*15–18*), for the International Road Federation (*1, 19*), for the Swedish Road and Traffic Research Institute (*20*), for the International Road and Traffic Conference in Berlin (*21*), and for the German research community (*22*). 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, operating speeds, and accident rates; (d) recommendations for achieving good and fair design practices, as well as recommendations for detecting poor designs, provided (*9–11, 19*) on the basis of changes in degrees of curve and operating speeds between successive design elements.

For example, Figure 1 shows the relationships between degree of curve and operating speeds and accident rates for individual lane widths, derived from the analysis of data of 322 two-lane rural highway sections in New York State. The research has 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 so long as visibility is not appreciably affected by heavy rain (*23*).

This paper is primarily concerned with the geometric design Criterion 3, providing adequate dynamic safety of driving.

Recent skid research investigations by Mason and Peterson (*24*) have indicated that sufficient friction supply is to be regarded as an important safety issue. Brinkman (*25*) found that resurfacing alone did not have a significant effect on the mean skid number. He indicated that skid resistance should be regarded as a main safety issue when resurfacing roadways. Glennon et al. (*26*) indicated that the probability that a highway curve may become a frequent accident site increases with decreasing pavement skid resistance.

The primary objective of this study is to develop an objective scale for relating skid resistance—described by coefficient of friction, skid number, or friction number—to speed. In order to achieve this goal, a comparative analysis of tangential and side friction factors in the highway design guidelines of the United States and four Western European

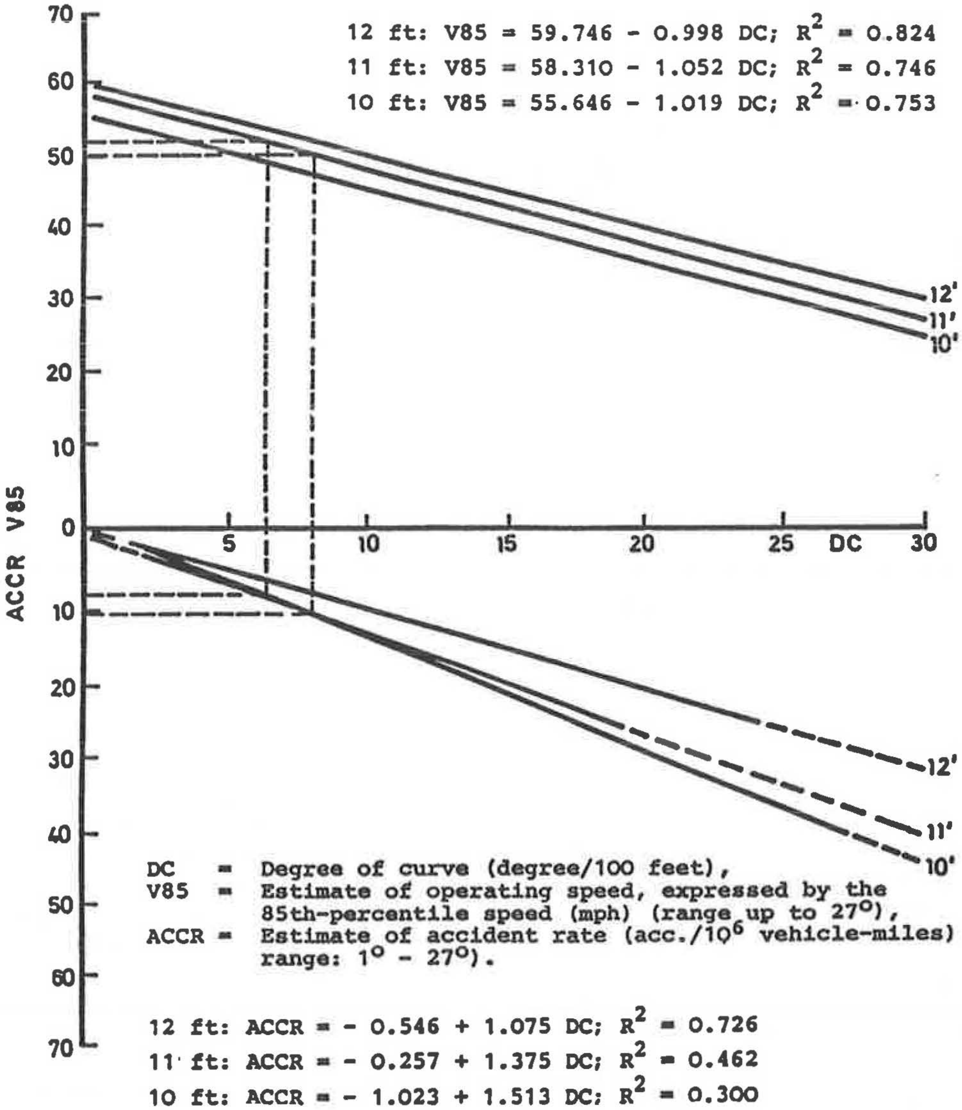

FIGURE 1 Nomogram for evaluating operating speeds and accident rates as related to degree of curve for individual lane widths (*10, 12*).

countries was carried out to determine the type of relationships that exist between friction factors and design speed, and consequently the development of overall relationships between friction and design speed. These overall relationships will then be compared to actual pavement friction inventories in the United States and in the Federal Republic of Germany (FRG), to determine the percentage of wet pavements that could be covered by such relationships.

COMPARATIVE ANALYSES OF FRICTION FACTORS IN DIFFERENT COUNTRIES

How the issue of friction, and equally important the issue of speed in relation to geometric design, are being applied in the United States and several European countries will be subject for discussion later in this section.

Because of the lower coefficients of friction on wet pavements as compared with dry, the wet condition governs in determining stopping sight distances and radii of curve, as revealed in the studied design guidelines. Furthermore, the countries in this study assume that the coefficients of friction used for design criteria should represent not only wet pavements in good condition but also surfaces approaching the end of their useful lives. The values should encompass nearly all significant pavement surface types and the likely field conditions, as it is expressed, for example, in AASHTO 1984 (*7*).

Contacts with responsible transportation agencies in the countries under study revealed that friction data measurements are conducted using an apparatus similar to that of ASTM E 274 (*27*). The apparatus normally consists of the following:

1. An automotive vehicle with one or more test wheels incorporated into it or forming part of a suitable trailer towed by a vehicle.

2. A transducer, instrumentation, water supply, and a proper dispensing system and actuation controls for the brake of the test wheel. The test wheel is equipped with a standard test tire, which is different in different countries.

3. The test apparatus is brought to a desired test speed. The test speeds are different in different countries as they are different in different states of the United States. For example, in the FRG a road section is tested at speeds of 25, 37.5, and 50 mph (40, 60, and 80 km/hr). For evaluating skid resistance, the standard procedure is to compare the measured values with recommended values (*28*): 0.42 for V = 25 mph, 0.33 for V = 37.5 mph, and 0.26 for V = 50 mph. These recommended values represent the skid resistance values that can be reached on 90 percent of road surfaces in the FRG. Similar recommendations exist in several other European countries.

4. Water is delivered ahead of the test tire and the braking system is actuated to lock the test tire. For the test, a water-film thickness of 1 mm is widely used (*29*).

5. The resulting friction force acting between the test tire and the pavement surface, and the speed of the test vehicle are recorded with the proper instrumentation. The skid resistance of the paved surface is determined from the resulting force torque record and reported as the coefficient of friction, the skid number, or the friction number. These values are determined from the force required to slide the locked tire at a stated speed, divided by the effective wheel load. The wheel load depends on the weight of the test trailers used in the different countries.

Because of some variations in testing procedures, the friction data used in this study may be biased. But, the fact remains that the basic method used to measure skid resistance is, to a certain extent, comparable between the countries.

With the exception of the FRG (*2*) and Switzerland (*3, 30, 31*), the rest of the countries in this study do not clearly show how the design friction factors used in their guidelines are obtained from the measured skid resistance values. Despite this lack, the authors still attempted to determine how the friction data used in the guidelines of the subject countries would compare to percentile level distribution curves developed from actual pavement friction inventories in the United States and in the FRG.

Such a comparison should be allowed from a research standpoint because in reality there exist differences in every research field, e.g., medicine and engineering, in testing, as well as in reporting procedures. In performing comparative analyses of data in different countries, there always exists the possibility that the data may be biased.

TANGENTIAL FRICTION FACTOR

The data in Table 1 represent the maximum allowable tangential friction factors for wet pavements with respect to the design speed applied in the highway design guidelines of the United States (USA), Federal Republic of Germany (FRG), France (F), Sweden (S), and Switzerland (CH).

Figure 2 shows an overview of the maximum allowable tangential friction factors of the studied European guidelines and for highway design in the United States with respect to design speed. Note that, with the exception of France, all relationships in Figure 2 are quadratic. The European countries in this study were considered typical European countries by Hayward et al. (*1*). In Figure 2, all speeds have been converted to miles per hour for comparison purposes.

TABLE 1 MAXIMUM ALLOWABLE TANGENTIAL FRICTION FACTORS FOR DIFFERENT DESIGN SPEEDS IN DIFFERENT COUNTRIES (*34*)

Design Speed (mph)	Tangential Friction Factor (f_T) - rounded				
	USA	FRG	F	S	CH
19				.46	
20	.40	.43			.54
25	.38	.39	.37	.44	.50
30	.35	.36			.45
31				.41	
35	.34	.32			.40
38			.37	.39	
40	.32	.29			.37
44				.36	
45	.31	.27			.35
50	.30	.24	.33	.34	.32
55	.30	.22			.30
60	.29	.20			.29
63			.30		
65	.29	.18			.27
70	.28	.17			.26
75		.16	.27		.25

Figure 2 shows that (a) as design speeds increase, friction factors decrease; (b) the friction-speed curves for Switzerland and FRG are nearly parallel, with the friction values of Switzerland higher by about 0.1; (c) the tangential friction values of Sweden are limited because of a maximum design speed of 50 mph on 2-lane rural roads in this country; (d) the American values intersect the German curve at a design speed of about 30 mph and the Swiss curve at a design speed of about 60 mph.

In comparison to the other countries, the United States has the lowest differences in friction values (see Table 1). For example, between design speeds of 30 and 70 mph the difference in the American tangential friction values is 0.07 (0.35 to 0.28), whereas for Germany and Switzerland the difference is 0.19. In the higher, more critical design speed ranges, for example, between 55 and 70 mph, the difference in the American values is only 0.02, whereas for Germany the difference is 0.05, and for Switzerland, 0.04. These small differences in the American friction values, or these low speed gradients of tangential friction, clearly contradict the worldwide research experience that shows that friction values should substantially decrease with increasing speeds (see Figure 2). If this experience is not met, critical driving maneuvers may occur, specially when operating speed exceeds design speed by considerable amounts under wet pavement conditions (*9–11, 19*).

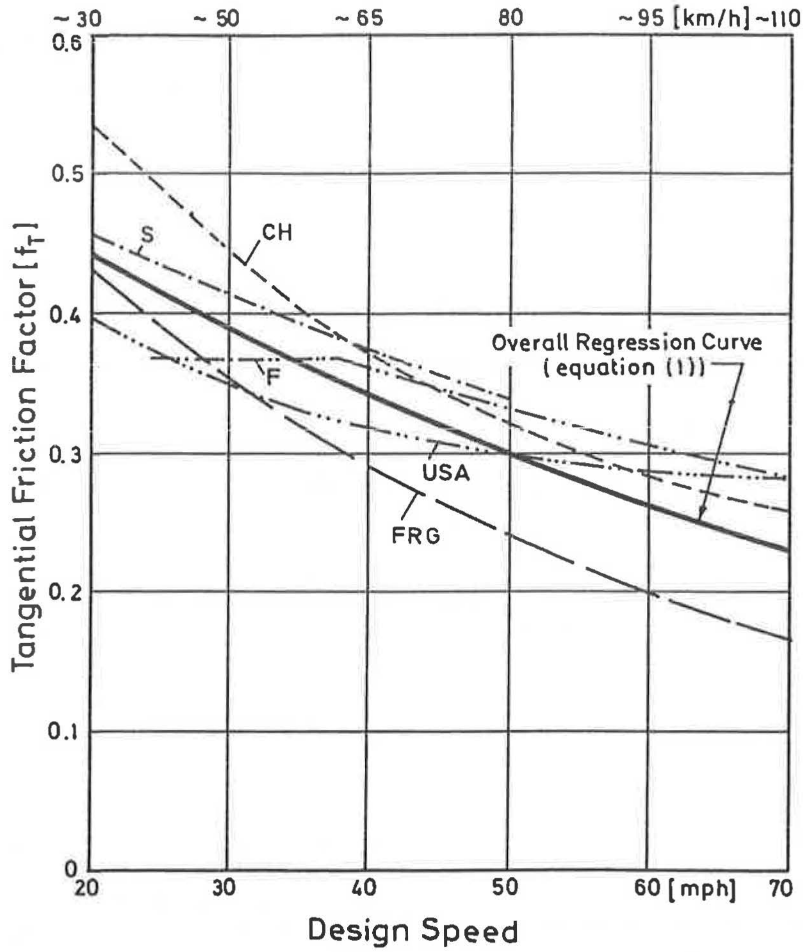

FIGURE 2 Relationships between maximum allowable tangential friction factor and design speed for different countries, along with the overall regression curve.

On the basis of the data of the five studied countries, the following overall regression equation was developed relating tangential friction factor f_T and design speed V_d:

$$f_T = 0.591 - 7.81*10^{-3}V_d + 3.9*10^{-5}(V_d)^2 \quad (1)$$

$R^2 = 0.731$

SEE = 0.044

where

f_T = tangential friction factor,
V_d = design speed (mph),
R^2 = coefficient of determination, and
SEE = standard error of estimate.

The high value of R^2 and low value of SEE of Equation 1 indicate that the relationship between tangential friction and design speed is a strong one.

Figure 2 shows the calculated values of the tangential friction factor (Equation 1) as a solid line superimposed on the curves of the countries in this study. This figure indicates that (a) the Swiss and Swedish tangential friction values are higher than the tangential friction values of the overall regression curve; (b) for design speeds greater than 35 mph, the French values are higher; (c) the FRG values are lower; and (d) the U.S. tangential friction values intersect the overall regression curve at a design speed of about 50 mph. For design speeds greater than 60 mph, the French and U.S. tangential friction values are higher than the tangential friction values of the other countries.

SIDE FRICTION FACTOR

The data presented in Table 2 give the maximum allowable side friction factors for wet pavements with respect to the design speed applied in the highway design guidelines of the same five countries.

Figure 3 shows an overview of the maximum allowable side friction factors of the European guidelines and for highway design in the United States with respect to design speed. Note that, with the exception of the United States, all relationships in Figure 3 are quadratic. In Figure 3, all speeds have been converted to miles per hour for comparison purposes.

On the basis of the data of the five countries in Table 2, the following overall regression equation was developed relating side friction factor f_R and design speed V_d:

$$f_R = 0.269 - 3.53*10^{-3}V_d + 1.5*10^{-5}(V_d)^2 \quad (2)$$

$R^2 = 0.799$

SEE = 0.018

TABLE 2 MAXIMUM ALLOWABLE SIDE FRICTION FACTORS FOR DIFFERENT DESIGN SPEEDS IN DIFFERENT COUNTRIES (*34*)

Design Speed (mph)	Side Friction Factor (f_R) - rounded				
	USA	FRG	F	S	CH
19				.210	
20	.170	.200			
25	.165	.180	.250	.190	.220
30	.160	.170			.200
31				.170	
35	.155	.150			.180
38			.160	.160	
40	.150	.130			.160
44				.150	
45	.145	.120			.150
50	.140	.110	.130	.140	.140
55	.130	.100			.130
60	.120	.090			.130
63			.110		
65	.110	.080			.120
70	.100	.075			.110
75		.070	.100		.110

where

f_R = side friction factor, and
V_d = design speed (mph).

The high value of R^2 and the low value of SEE for Equation 2 indicate that the relationship between side friction and design speed is a strong one.

Figure 3 shows the calculated values of the side friction factor from Equation 2 as a solid line superimposed on the curves for the countries in this study. For speeds greater than 40 mph, this figure indicates that the U.S. side friction values are slightly higher than the values of the overall regression curve and the friction values of the European countries in this study, with the exception of Switzerland.

ADDITIONAL INFORMATION FOR DESIGN PURPOSES

In the guidelines of the United States and Europe, maximum allowable tangential friction factors are used to calculate minimum stopping sight distances, whereas side friction factors are used to calculate minimum radii of curve (*1–7*).

For calculating minimum stopping sight distances, the United States uses a perception-reaction time of 2.5 sec, whereas the European countries use 2.0 sec. Both values were found to be adequate in recent papers presented at the 68th Annual Meeting of the TRB, January 1989. Taoka (*32*), for instance, concluded the following: "It appears that the AASHTO design value of 2.5 seconds may correspond to the response time of the 95th-percentile driver. The stopping sight distance design driver assumption is satisfactory at the present time." In contrast, Wilson et al. (*33*) came to the following conclusion: "The current design standard for perception and reaction time is 2.5 seconds. This value compares with the study

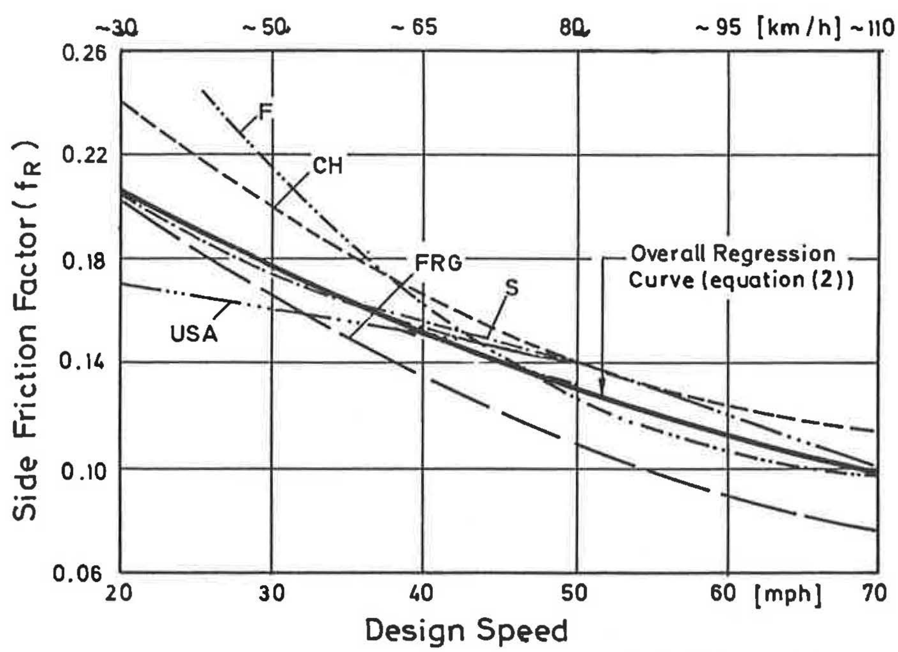

FIGURE 3 Relationships between maximum allowable side friction factor and design speed for different countries, along with the overall regression curve.

findings at the 99th-percentile of 1.60 seconds indicating that the current design standards are conservative."

The maximum superelevation rates used in the different countries for calculating minimum radii of curve can be seen in the following table. The applied superelevation rates range from 5.5 percent in Sweden to 8 percent in the United States.

Country	Perception-Reaction Time (sec)	Superelevation Rate (%)	Superelevation Rate Qualification
United States	2.5	8	Maximum under snow and ice conditions
Federal Republic of Germany	2.0	7 8	Desirable Exception
Switzerland	2.0	7	Unqualified
Great Britain	N/A	5 7	Desirable Absolute
France	2.0	5 7	Desirable Absolute
Sweden	2.0	5.5	Maximum

COMPARATIVE ANALYSES OF THE OVERALL REGRESSION CURVE VERSUS ACTUAL PAVEMENT FRICTION INVENTORIES

In addition to the data in this paper, other studies (*34–38*) were used to determine how the overall regression curve (Equation 1) developed from the data of the countries in this study compares to actual pavement friction inventories. The investigations were based on one friction inventory from New York State (NYS), developed by Goyal (*34*) (see Figure 4), and one inventory from the FRG developed by Wehner and Schulze (e.g., *37, 38*) (see Figure 5). Equations that correspond to the curves in Figures 4 and 5 are given in Table 3, in which V is given in units of miles per hour. The friction values produced by the percentile level distribution curves in Figures 4 and 5 are representative of 60 to 95 percent of wet pavements in the investigated state or country.

The relationships in Figure 4 indicate that the overall regression curve (Equation 1) clearly coincides with the 90th-percentile level distribution curve of NYS. That means that 90 percent of wet pavements could be covered by using the overall regression curve as a driving dynamic basis for design purposes. Figure 5 shows that the overall regression curve could cover about 80 percent or more of wet pavements in the FRG.

Figure 6 shows the results more clearly. This figure shows that the 95th-percentile level distribution curve for NYS nearly coincides with the 95th-percentile level distribution curve for FRG. Furthermore, this figure suggests that AASHTO maximum allowable tangential friction factors (*7*) represent (a) up to a design speed of about 50 mph, 90 percent or more of wet pavements in NYS; (b) up to a design speed of about 60 mph, 80 percent of wet pavements in NYS; and (c) up to a design speed of about 70 mph, only about 65 percent of wet pavements in NYS.

For design speeds greater than 50 mph, AASHTO allows higher tangential friction factors, as compared to the tangential friction factors of the overall regression curve of Equation 1 developed from the data of the countries in this study.

Related to the 95th-percentile level distribution curve for NYS and FRG, these statements would already be true for design speeds greater than 30 mph. The tangential friction factors applied in the German geometric design standards are based on the 95th-percentile level distribution curve for wet pavements, and have been in use in the FRG since 1973 (*39*).

RECOMMENDATIONS FOR HIGHWAY DESIGN

In order not to be too conservative, it is recommended that at least the tangential friction factors produced by the overall regression curve (Equation 1) shall be used for highway design. However, in order to secure the condition that friction supply should most of the time exceed friction demand (*2,35,40*), it may be more appropriate for new design, redesign, and rehabilitation strategies to apply tangential friction factors that correspond to the 95th-percentile level distribution curves developed from actual pavement friction inventories in NYS and FRG.

TANGENTIAL FRICTION FACTOR AND STOPPING SIGHT DISTANCE

The minimum stopping sight distance is defined in most of the geometric design standards studied as follows:

> The minimum stopping sight distance (SSD) is the sum of two distances: (a) the distance traversed by a vehicle from the instant the driver sights an object for which a stop is necessary to the instant the brakes are applied (perception-reaction time), and (b) the distance required to stop the vehicle after the brake application begins (braking distance). The former is primarily a function of speed and perception-reaction time, the latter a function of speed and frictional resistance between the pavement surface and tires.

SSD on level roadway, therefore, may be computed by the formula

$$SSD_{min} = 1.47V_d t + (V_d)^2/30f_{T\max} \quad (3)$$

where

SSD_{min} = minimum stopping sight distance (ft);
V_d = design speed (mph);
$f_{T\max}$ = maximum allowable tangential friction factor; and
t = perception-reaction time (sec).

In using a 2.0-sec perception-reaction time as generally recommended in Europe, or 2.5 sec currently in use in the United States, Equation 3 then becomes

$$SSD_{min} = 2.94V_d + (V_d)^2/30f_{T\max} \quad (4a)$$

or

$$SSD_{min} = 3.67V_d + (V_d)^2/30f_{T\max} \quad (4b)$$

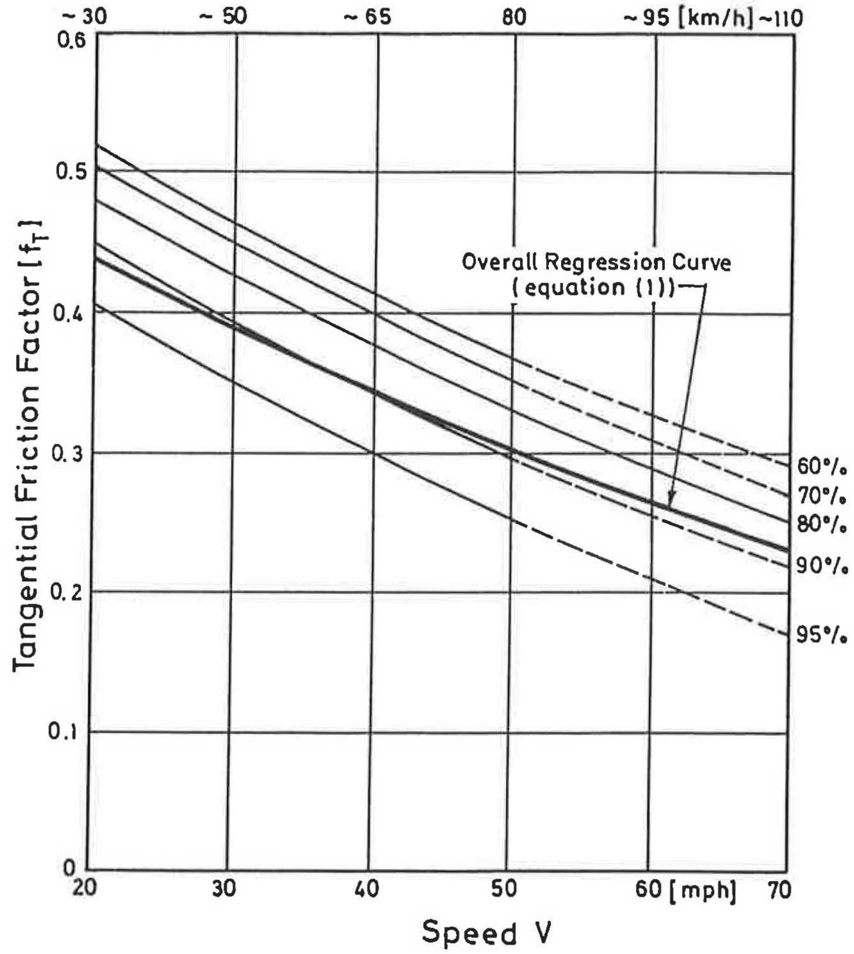

FIGURE 4 Percentile distribution curves for the relationship between tangential friction factor and speed for 93 wet pavements in NYS (*34*).

The data in Table 4 present the computed SSD values from Equations 4a and 4b by using the tangential friction factors produced by the overall regression curve (Equation 1), by the 95th-percentile level distribution curves of NYS and FRG, and by perception-reaction times of 2.0 and 2.5 sec, respectively. For comparative reasons, AASHTO maximum allowable tangential friction factors and ranges of stopping sight distances (*7*) are also presented in Table 4.

Data in Table 4 indicate that (a) for design speeds greater than 55 mph, AASHTO tangential friction factors are higher than the tangential friction factors produced by the overall regression curve (0.30 > 0.28); (b) for design speeds greater than 35 mph, AASHTO tangential friction factors are higher than the tangential friction factors produced by the 95th-percentile level distribution curves (0.34 > 0.32); and (c) between design speeds of 50 and 70 mph, the difference in the recommended tangential friction factors is between 0.06 (0.30 to 0.24) and 0.08 (0.25 to 0.17), whereas the difference in AASHTO tangential friction factors is only 0.02 (0.30 to 0.28).

For the perception-reaction time of 2.5 sec currently in use by AASHTO, note that (a) the computed stopping sight distances, based on the overall regression curve (Equation 1), exceed the upper limit ranges of AASHTO at speeds of 55 mph (560 ft > 550 ft); whereas (b) the computed stopping sight distances, based on the 95th-percentile level distribution curves, exceed the upper limit ranges of AASHTO values already at speeds of 45 mph (410 ft > 400 ft).

Table 4 was developed only to present, in comparison to AASHTO, the significant differences that exist between the computed stopping sight distances from Equation 3 by using different perception-reaction times and by including different tangential friction factors according to the overall regression curve and the 95th-percentile level distribution curves of NYS and FRG. The computed stopping sight distances in Columns 3, 4, 6, and 7 of Table 4 will have to be modified additionally when taking into consideration the effect of air resistance, as has been done, for example, in the FRG (*2, 35, 40*), and in the *Swedish Standard Specifications for Geometric Design* (*4*). Consequently, different minimum stopping sight distances could result from the application of different models, different perception-reaction times, and different tangential friction factors.

These findings clearly indicate that AASHTO officials, in collaboration with the TRB Committee on Geometric Design (A2A02), should consider the following steps, for example,

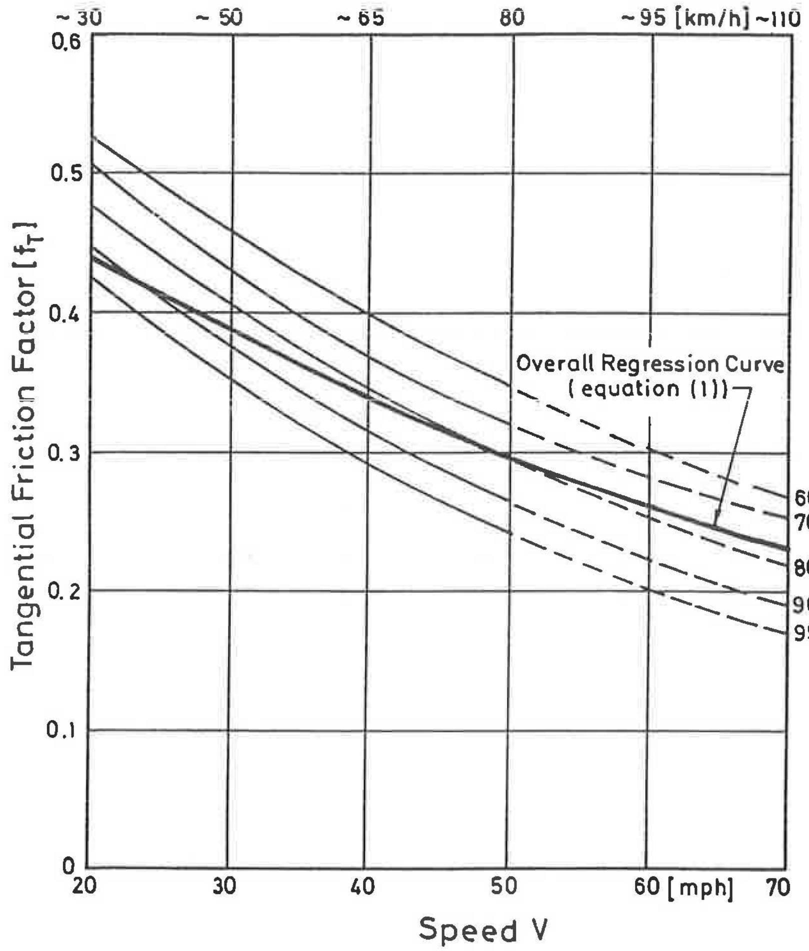

FIGURE 5 Percentile distribution curves for the relationship between tangential friction factor and speed for 600 wet pavements in FRG.

TABLE 3 REGRESSION EQUATIONS FOR TANGENTIAL FRICTION FACTOR VERSUS SPEED FOR PERCENTILE DISTRIBUTION CURVES CORRESPONDING TO FIGURES 4 AND 5 (*34*)

Percentile Level	New York State
60 %	$f_T = 0.6411-6.4143 \cdot 10^{-3}\ V+2.00 \cdot 10^{-5}V^2$
70 %	$f_T = 0.6231-6.4143 \cdot 10^{-3}\ V+2.00 \cdot 10^{-5}V^2$
80 %	$f_T = 0.6040-6.4143 \cdot 10^{-3}\ V+2.00 \cdot 10^{-5}V^2$
90 %	$f_T = 0.5684-6.4143 \cdot 10^{-3}\ V+2.00 \cdot 10^{-5}V^2$
95 %	$f_T = 0.5244-6.4143 \cdot 10^{-3}\ V+2.00 \cdot 10^{-5}V^2$

Percentile Level	Federal Republic of Germany
60 %	$f_T = 0.7063-9.7043 \cdot 10^{-3}\ V+5.1006 \cdot 10^{-5}V^2$
70 %	$f_T = 0.6813-9.7043 \cdot 10^{-3}\ V+5.1006 \cdot 10^{-5}V^2$
80 %	$f_T = 0.6563-9.7043 \cdot 10^{-3}\ V+5.1006 \cdot 10^{-5}V^2$
90 %	$f_T = 0.6263-9.7043 \cdot 10^{-3}\ V+5.1006 \cdot 10^{-5}V^2$
95 %	$f_T = 0.6013-9.7043 \cdot 10^{-3}\ V+5.1006 \cdot 10^{-5}V^2$

in any future plans for achieving well-founded and reliable stopping sight distances:

1. Selection of a model including or not including air resistance. (A model that includes air resistance is recommended.)
2. Selection of perception-reaction time. (A perception-reaction time of 2.0 sec is sufficient.)
3. Selection of reliable maximum allowable tangential friction factors. [At least the values computed from Equation 1 (see Column 2 of Table 4), but preferably the values produced by the 95th-percentile level distribution curves (see Column 5 of Table 4), are recommended.]

SIDE FRICTION FACTOR AND MINIMUM RADIUS OF CURVE

In the *German Design Guidelines* (*2*), the maximum allowable side friction factors are defined as 46 percent of the maximum allowable tangential friction factors for rural highways. In the *Swiss Design Norms* (*3, 30, 31*) and in the *Swedish Specifications* (*4*), the maximum allowable side friction factors are defined as 44 percent of the maximum allowable tangential friction values for rural highways. All three guidelines indicate

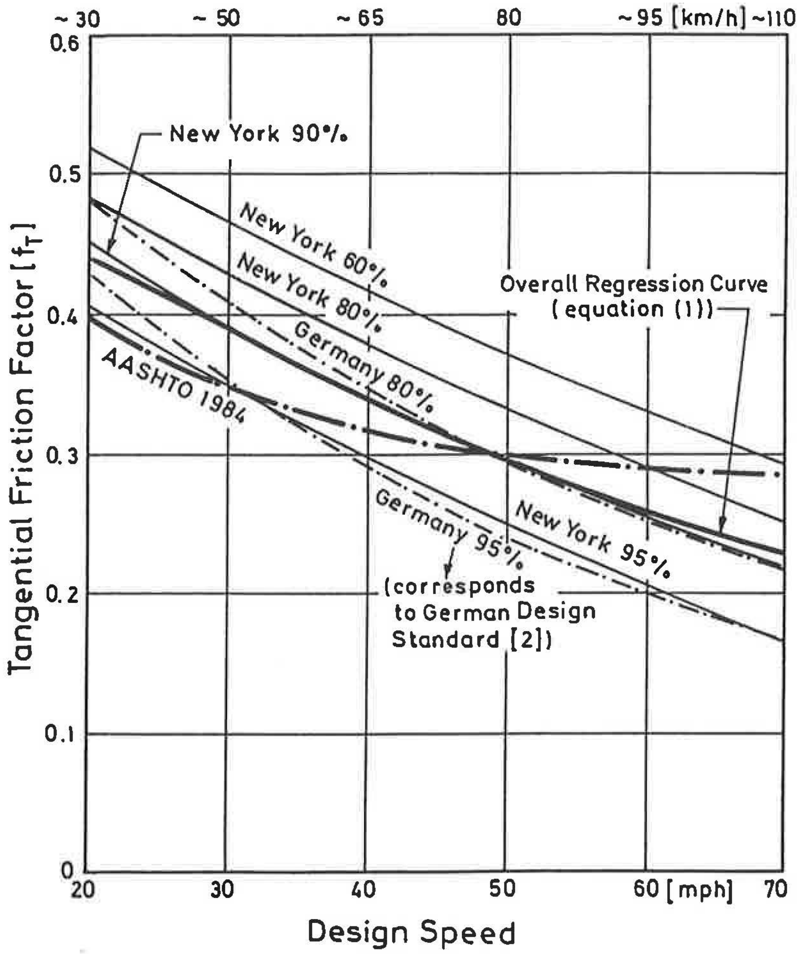

FIGURE 6 Relationships between maximum allowable tangential friction factors and design speed for AASHTO 1984, FRG (80th and 95th percentiles) and NYS (60th, 80th, 90th, and 95th percentiles) along with the overall regression curve.

TABLE 4 RECOMMENDED MAXIMUM ALLOWABLE TANGENTIAL FRICTION FACTORS AND COMPUTED STOPPING SIGHT DISTANCES VERSUS DESIGN SPEEDS

Design Speed (mph)	Stopping Sight Distances based on the Overall Regression Curve (equation (1))			Stopping Sight Distances based on the 95th-Percentile Level Curves of New York State and FRG			Stopping Sight Distances AASHTO 1984	
V_d	f_{Tmax}*	SSD (ft) t = 2,0 s	SSD (ft) t = 2,5 s	f_{Tmax}*	SSD (ft) t = 2,0 s	SSD (ft) t = 2,5 s	f_{Tmax}	SSD (ft) t = 2,5 s
1	2	3	4	5	6	7	8	9
30	.39	165	185	.35	175	195	.35	200-200
35	.37	215	240	.32	230	255	.34	225-250
40	.34	275	305	.30	295	325	.32	275-325
45	.32	345	375	.28	375	410	.31	325-400
50	.30	425	465	.25	475	510	.30	400-475
55	.28	520	560	.23	595	635	.30	450-550
60	.26	635	675	.21	745	785	.29	525-650
65	.25	760	805	.19	925	970	.29	550-725
70	.24	900	950	.17	1145	1200	.28	625-850

*Rounded Values

that by using these percentages of side friction there is still between 80 and 90 percent available for friction in the tangential direction when driving through curves (*35,40*). By this procedure, considerable dynamic safety reserves are still available in the tangential direction in spite of using the maximum allowable side friction factors.

In this study, the maximum allowable side friction factor is defined as 45 percent of the maximum allowable tangential friction factor. This should guarantee that there will be about 90 percent of friction available in the tangential direction for acceleration, deceleration, braking, or evasive maneuvers when driving through curves (*34,35*).

Thus, the equation for the maximum allowable side friction factor for rural highways is

$$f_{R\max} = 0.45*f_{T\max} \qquad (5)$$

Consequently, the equation for the maximum allowable side friction factor for NYS at the 90th-percentile level is (see Table 3):

$$f_{R\max} = 0.2558 - 2.886*10^{-3}V + 0.90*10^{-5}V^2 \qquad (6)$$

and the equation for the maximum allowable side friction factor for NYS at the 95th-percentile level is (see Table 3):

$$f_{R\max} = 0.2360 - 2.886*10^{-3}V + 0.90*10^{-5}V^2 \qquad (7)$$

Equations 6 and 7 are schematically shown in Figure 7. In addition, this figure includes the overall regression curve (Equation 2) between side friction and design speed, based on the data of the five countries in this study, as well as the maximum allowable side friction factors of *AASHTO 1984* (*7*).

Figure 7 indicates that (a) the side friction factors produced by the 90th-percentile level distribution curve of NYS clearly coincide with the friction factors produced by the overall regression curve (Equation 2); (b) the side friction factors produced by the 95th-percentile level distribution curve of NYS clearly coincide again with the side friction factors produced by the 95th-percentile level distribution curve of the FRG; and (c) AASHTO side friction factors intersect the overall regression curve at a design speed of about 40 mph.

A reliable estimate of curve radius may be obtained from the standard centripetal force equation (*7*):

$$R_{\min} = (V_d)^2/[15(e + f_{R\max})] \qquad (8)$$

where

$R_{\min}$ = minimum radius of curve (ft);
V_d = design speed (mph);
$f_{R\max}$ = maximum allowable side friction factor; and
e = maximum superelevation rate (ft/ft).

Because Equation 8 is commonly applied in the geometric design guidelines of the countries in this study, recommendations for minimum radii of curve will be easier to make here. The difficulties encountered with the assumptions used to calculate minimum stopping sight distances do not apply here.

To conform with the findings of the countries in this study, typical superelevation rates of 0.05 and 0.07 were selected. Maximum allowable side friction factors and computed minimum radii of curve with respect to design speed are presented in Table 5. The values in this table are again based on the side friction factors produced by the overall regression curve (Equation 2) and by the 95th-percentile level distribution curves of NYS and FRG. For comparative reasons, AASHTO minimum radii of curve are also shown with respect to design speed in the table.

Table 5 indicates that, for design speeds between 50 and 70 mph and superelevation rates of 0.05 and 0.07, AASHTO

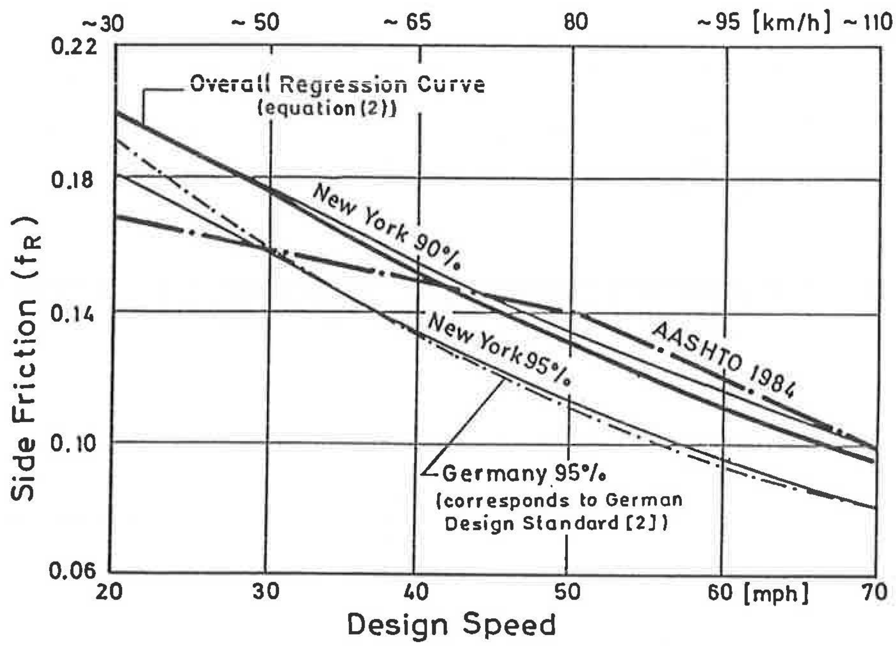

FIGURE 7 Relationships between maximum allowable side friction factors and design speed for AASHTO 1984, FRG (95th percentile), and NYS (90th and 95th percentile), along with the overall regression curve.

TABLE 5 RECOMMENDED MAXIMUM ALLOWABLE SIDE FRICTION FACTORS AND RECOMMENDED MINIMUM RADII OF CURVE VERSUS DESIGN SPEEDS

Design Speed	Superelevation Rate	The least Recommended Minimum Radii of Curve Overall Regression Curve (equation (2))		Recommended Minimum Radii of Curve 95th-Percentile Level Curve of New York State and FRG		Minimum Radii AASHTO 1984	
V_d (mph)	e	f_{Rmax}*	R_{min} (ft)	f_{Rmax}*	R_{min} (ft)	f_{Rmax}	R_{min} (ft)
1	2	3	4	5	6	7	8
30	.05	.18	265	.16	290	.16	286
40	.05	.15	530	.13	575	.15	533
50	.05	.13	925	.11	1015	.14	877
60	.05	.11	1490	.10	1650	.12	1412
65	.05	.105	1840	.09	2065	.11	1760
70	.05	.10	2245	.08	2550	.10	2178
30	.07	.18	245	.16	265	.16	261
40	.07	.15	480	.13	520	.15	485
50	.07	.13	835	.11	905	.14	794
60	.07	.11	1325	.10	1450	.12	1263
65	.07	.105	1630	.09	1800	.11	1564
70	.07	.10	1975	.08	2205	.10	1922

* Rounded Values

minimum radii of curve are 2 to 6 percent lower than those corresponding to the side friction factors produced by the overall regression curve (Equation 2), and about 13 percent lower than those corresponding to the side friction values produced by the 95th-percentile level distribution curves.

It is recommended that at least the side friction factors produced by the overall regression curve (Equation 2) should be regarded in highway design. However, for safety reasons it may be more appropriate to relate minimum radii of curve to the side friction factors produced by the 95th-percentile level distribution curves of NYS and FRG to cover 95 percent of wet pavements, as has been already done in several Western European countries.

CONCLUSIONS

It is difficult to decide where the critical margins for tangential and side friction factors and, derived from them, for minimum stopping sight distances and radii of curve shall be assigned. This is a crucial consideration for engineers concerned with both cost and safety. But 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 higher design speed classes. Therefore, it is recommended for new designs, redesigns, and rehabilitation strategies to relate minimum stopping sight distances and minimum radii of curve to the proposed tangential and side friction factors that cover 95 percent of wet pavements in this study.

The recommendations provided in this paper should not be regarded as a final solution, but perhaps an international discussion of a larger dynamic safety supply for driving may be useful in reducing accidents on two-lane rural highways. Because there are often inadequate safety factors in tire-road friction, friction demand often exceeds friction supply, causing more accidents than necessary.

One of the most important tasks in modern highway design requires that responsible national and international agencies develop reliable inventories of friction data. If the recommendations about the design criteria mentioned in the introduction are regarded—(a) achieving consistency in horizontal alignment, (b) harmonizing design speed and operating speed on wet pavements, and (c) providing adequate dynamic safety of driving—decisive safety advantages may be expected in future geometric highway design of two-lane rural roads.

REFERENCES

1. J. Hayward, R. Lamm, and A. Lyng. *Survey of Current Geometric and Pavement Design Practices in Europe: Geometric Design.* International Road Federation, Washington, D.C., July 1985.
2. Geometric Design Standards. In *Guidelines for the Design of Roads.* RAS-L-1, German Road and Transportation Research Association, Committee 2.3, 1984.
3. Swiss Association of Road Specialists (VSS), Swiss Norm SN 640080a. *Highway Design, Fundamentals, Speed as a Design Element.* 1981.
4. National Swedish Road Administration. *Standard Specifications for Geometric Design of Rural Roads.* Borlenge, Sweden, 1982.
5. Ministere de l'Equipement et du Logement. *Instruction sur les Conditions Techniques D'Amenagement des Routes Nationales.* Paris, 1975.

6. Department of Transport. *Highway Link Design, Geometric Alignment Standards*. Departmental Standard TD9/81, London, 1981.
7. *A Policy on Geometric Design of Highways and Streets*. AASHTO, Washington, D.C., 1984.
8. R. Lamm and E. M. Choueiri. *A Design Procedure to Determine Critical Dissimilarities in Horizontal Alignment and Enhance Traffic Safety by Appropriate Low-Cost or High-Cost Projects*. Final Report for the National Science Foundation, Washington, D.C., March 1987.
9. E. M. Choueiri and R. Lamm. Operating Speeds and Accident Rates on Two-Lane Rural Highway Curved Sections—Investigations about Consistency and Inconsistency in Horizontal Alignment. Part I of *Rural Roads Speed Inconsistencies Design Methods*, State University of New York Research Foundation, Albany, N.Y., July 1987.
10. R. Lamm, E. M. Choueiri, and A. Paluri. A Design Method to Determine Critical Operating Speed Inconsistencies on Two-Lane Rural Roads in the State of New York. Part II of *Rural Roads Speed Inconsistencies Design Methods*, State University of New York Research Foundation, Albany, N.Y., Oct. 1987.
11. R. Lamm, E. M. Choueiri, J. C. Hayward, and A. Paluri. Possible Design Procedure to Promote Design Consistency in Highway Geometric Design on Two-Lane Rural Roads. In *Transportation Research Record 1195*, TRB, National Research Council, Washington, D.C., 1988.
12. R. Lamm, E. M. Choueiri, and J. C. Hayward. Tangent as an Independent Design Element. In *Transportation Research Record 1195*, TRB, National Research Council, Washington, D.C., 1988.
13. R. Lamm, J. C. Hayward, and J. G. Cargin. Comparison of Different Procedures for Evaluating Speed Consistency. In *Transportation Research Record 1100*, TRB, National Research Council, Washington, D.C., 1986, pp. 10–20.
14. R. Lamm and E. M. Choueiri. Recommendations for Evaluating Horizontal Design Consistency Based on Investigations in the State of New York. In *Transportation Research Record 1122*, TRB, National Research Council, Washington, D.C., 1987, pp. 68–78.
15. R. Lamm. New Developments in Highway Design with Special Consideration of Traffic Safety. *Proc., 36th Annual Ohio Transportation Engineering Conference*, Department of Civil Engineering, Ohio State University, Columbus, 1982, pp. 107–119.
16. R. Lamm and J. G. Cargin. Identifying Operating Speed Inconsistencies on Two-Lane Rural Roads. *Proc., 39th Annual Ohio Transportation Engineering Conference*, Department of Civil Engineering, Ohio State University, Columbus, 1985, pp. 13–22.
17. R. Lamm and E. M. Choueiri. Relationship Between Design, Driving Behavior and Accident Risk on Curves. *Proc., 40th Annual Ohio Transportation Engineering Conference*, Department of Civil Engineering, Ohio State University, Columbus, 1986, pp. 87–100.
18. R. Lamm and E. M. Choueiri. The Impact of Traffic Warning Devices on Operating Speeds and Accident Rates on Two-Lane Rural Highway Curves. *Proc., 41st Annual Ohio Transportation Engineering Conference*, Department of Civil Engineering, Ohio State University, Columbus, 1987, pp. 171–192.
19. R. Lamm, E. M. Choueiri, T. Mailaender, and A. Paluri. A Logical Approach to Geometric Design Consistency of Two-Lane Rural Roads in the U.S.A. *Proc., 11th IRF (International Road Federation) World Meeting*, Vol. II, Seoul, Korea, April 16–21, 1989, pp. 8–11.
20. R. Lamm, E. M. Choueiri, and T. Mailaender. Accident Rates on Curves as Influenced by Highway Design Elements—An International Review and an In-Depth Study. *Proc., Road Safety in Europe*, Gothenburg, Sweden, VTIrapport 344A, Swedish Road and Traffic Research Institute, Linkoeping, Sweden, 1989, pp. 33–54.
21. R. Lamm and E. M. Choueiri. Investigations about Driver Behavior and Accident Experiences at Curved Sites (Including Black Spots) of Two-Lane Rural Highways in the U.S.A. *Proc., Roads and Traffic 2000*, Vol. 4/2, Traffic Engineering and Safety, Berlin, Federal Republic of Germany, Sept. 6–9, 1988, pp. 153–158.
22. R. Lamm, T. Mailaender, and E. M. Choueiri. New Ideas for the Design of Two-Lane Rural Roads in the U.S.A. *International Technical Journal: Road and Construction*, Federal Republic of Germany, Vol. 5, pp. 18–25, May 1989, and Vol. 6, pp. 13–18, June 1989.
23. R. Lamm, E. M. Choueiri, and T. Mailaender. Comparison of Operating Speeds on Dry and Wet Pavements of Two-Lane Rural Highways. In *Transportation Research Record*, TRB, National Research Council, Washington, D.C., 1990 (forthcoming).
24. J. M. Mason and H. C. Peterson. Survey of States' R-R-R Practices and Safety Considerations. In *Transportation Research Record 960*, TRB, National Research Council, Washington, D.C., 1984.
25. C. P. Brinkman. Safety Studies Related to RRR Projects. *Transportation Journal of ASCE*, Vol. 108, July 1983.
26. J. C. Glennon, T. R. Neuman, and J. R. Leisch. Safety and Operational Considerations for Design of Rural Highway Curves. Final Report, Aug. 1983.
27. H. W. Kummer and W. E. Meyer. *NCHRP Report 37: Tentative Skid-Resistance Requirements for Main Rural Highways*. HRB, National Research Council, Washington, D.C., 1967.
28. R. Lamm and H. E. Herring. The Side-Friction Factor in Relation to Speed. *Technical Journal: Road and Autobahn*, Vol. 11, Federal Republic of Germany, Nov. 1970, pp. 435–443.
29. R. Lamm, A. Taubmann, and J. Zoellmer. Comprehensive Study on the Term 'Critical Water' Film Thickness. *Technical Journal: Research Road Construction and Traffic Technique*, Vol. 436, Minister of Transportation, Federal Republic of Germany, 1985.
30. Swiss Association of Road Specialists (VSS). *Sight Distances*. Swiss Norm SNV640090, 1974.
31. Swiss Association of Road Specialists (VSS). *Superelevation Rate in Tangents and Circular Curves*. Swiss Norm SNV640123, 1969.
32. G. T. Taoka. An Analytical Model for Driver Response. In *Transportation Research Record 1213*, TRB, National Research Council, Washington, D.C., 1989, pp. 1–3.
33. F. R. Wilson, J. A. Sinclair, and B. G. Bisson. Evaluation of Driver/Vehicle Accident Reaction Times. Paper Presented at the Transportation Research Board 68th Annual Meeting, TRB, National Research Council, Washington, D.C., Jan. 1989.
34. P. B. Goyal. *Friction Factors for Highway Design Regarding Driving Dynamic Safety Concerns in the State of New York*. Master's thesis, Clarkson University, Potsdam, N.Y., Dec. 1987.
35. R. Lamm. Driving Dynamic Considerations: A Comparison of German and American Friction Coefficients for Highway Design. In *Transportation Research Record 960*, TRB, National Research Council, Washington, D.C., 1984.
36. N. J. Rowan, D. L. Woods, V. G. Stover, D. A. Anderson, and J. H. Dozier. *Safety Design and Operational Practices for Streets and Highways*. Texas Transportation Institute, Texas A&M University, College Station, 1980.
37. Wehner. Results of Skid-Resistance Measurements and Traffic Safety. *Road and Autobahn*, Vol. 8, 1965.
38. K. H. Schulze and L. Beckmann. Friction Properties of Pavements at Different Speeds, ASTM Special Technical Publication, No. 326, Philadelphia, Pa., Dec. 1962.
39. Geometric Design Standards. In *Guidelines for the Design of Rural Roads*. RAL-L-1, German Road and Transportation Research Association, Committee 2.3, 1973.
40. R. Lamm. *Driving Dynamics and Road Characteristics—A Contribution for Highway Design under Special Consideration of Operating Speeds*. Publications of the Institute of Highway and Railroad Engineering, University of Karlsruhe, Vol. 11, Karlsruhe, Federal Republic of Germany, 1973.

Publication of this paper sponsored by Committee on Surface Properties–Vehicle Interaction.