HIGHWAY CURVE DESIGN FOR SAFE VEHICLE OPERATIONS

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Current design practice for horizontal curves assumes that vehicles follow the path of the highway curve with geometric exactness. The adequacy of this assumption was examined by conducting photographic field studies of vehicle maneuvers on highway curves. Results indicate that most vehicle paths, regardless of speed, exceed the degree of highway curve at some point on the curve. For example, on a 3-deg highway curve, 10 percent of the vehicles can be expected to exceed 4.3 deg. A new design approach is proposed. This approach is dependent on selecting an appropriate vehicle path percentile relation, a reasonable safety margin to account for unexplained variables that may either raise the lateral friction demand or lower the available skid resistance, and a minimum skid resistance versus speed relation that the highway department will provide on all pavements.

•SLIPPERY pavements have existed for many years; but the causes of slipperiness, its measurement, and its effect on traffic safety were not of great concern before 1950. Although reliable data on skidding accidents are hard to find, those in existence suggest that the skidding-accident rate has increased to proportions that may no longer be ignored. This trend may be due to improved accident reporting but also undoubtedly reflects increased vehicle speeds and traffic volumes (1).

More rapid accelerations, higher travel speeds, and faster decelerations made possible by modern highway and vehicle design have raised the frictional demands on the tire-pavement interface. Larger forces are required to keep the vehicle on its intended path. On the other hand, when pavements are wet the frictional capability of the tire-pavement interface decreases with increasing speed. In addition, higher traffic volumes and speeds promote a faster degradation in the frictional capability of the pavement.

From the technological standpoint, the slipperiness problem appears amenable to solutions that either reduce the frictional demand (improved geometric design and reduced speed limits for wet conditions) or increase the frictional capability (improved pavement surface design, tire design, and vehicle inspection procedures). This research study was concerned with the adequacy of geometric design standards for horizontal curves.

A previous report (2) indicated that current standards (3) for minimum horizontal curve design may not give an adequate factor of safety for modern highway operations. Evaluation of the state of the art revealed several uncertain features of the design basis. The adequacy of the following 4 assumptions was questioned:

1. Vehicles follow the path of a highway curve with geometric exactness;
2. The point-mass equation, $e + f = V^2/15R$, defines the impending skid condition;
3. Lateral skid resistance can be measured with a locked-wheel skid trailer; and
4. Levels of lateral acceleration that produce impending driver discomfort can be used for design values to ensure an adequate factor of safety against lateral skidding.

The goal of this current research was to perform field studies, simulation studies, and controlled experiments to test assumptions 1, 2, and 3. With objective data from that research, the adequacy of assumption 4 would then be evaluated.

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The simulation studies and controlled experiments to test assumptions 2 and 3 were done on another project conducted at the Texas Transportation Institute (4). The major emphasis of the research reported here, therefore, was to empirically relate vehicle paths to highway curve paths to test assumption 1. Then, by evaluating the data generated by the 2 research studies, revised curve design standards could be proposed, if appropriate.

FIELD PROCEDURES

The general procedure was to record vehicle paths on movie film by using a camera housed in a following vehicle. That observation vehicle, stationed beside the highway about 1 mile upstream from a highway curve site, was driven onto the highway behind a subject vehicle as it passed. The observation vehicle was then accelerated to close the position headway so that the subject vehicle was within 60 to 100 ft as it approached the curve site. The vehicle path was filmed continuously from about 150 ft upstream to 150 ft downstream of the highway curve.

Study Sites

Five highway curve sites, ranging in curvature from 2 to 7 deg, were selected within a 30-mile radius of College Station, Texas. All curve sites were in rural areas and had essentially level vertical curvature. None of the curve sites had spiral transitions; that is, they were all joined by tangent alignment at both ends of the circular curve. Superelevation rates ranged from 0.04 to 0.08.

Equipment

A 1970 Ford half-ton pickup truck was used as the observation vehicle. So that subject drivers would be unaware of being photographed, the camera and operator were concealed in a box mounted on the truck bed. The box, resembling a tool shed, was directly behind the truck cab, standing 24 in. above the cab roofline. The observation vehicle is shown in Figure 1.

Subject vehicles were photographed through a small window over the left side of the cab. It is doubtful that subject drivers were aware of being photographed because the window was the only opening; therefore, the box appeared dark and unoccupied.

An Arriflex 16-mm camera was used to photograph curve maneuvers. Power was supplied by an 8-volt battery through a governor-controlled motor to produce a constant 24 frame/sec film advance. The film was black and white Plus-X reversal (Kodak, ASA 50) on 400-ft reels.

Subject vehicles were photographed with a zoom lens (17.5 to 70.0 mm) so that the cameraman could maintain field of view and, at the same time, obtain the largest possible view of the left-rear tire of the vehicle. The camera was mounted on a ball-head rigid base attached to a shelf. The camera and mounting configuration are shown in Figure 2.

Geometric Reference Marks

The plan was to measure the lateral placement of the subject vehicle's left-rear tire at intervals along the highway curve by using the geometric centerline of the highway curve as a base reference. Two-foot lengths of 6-in. wide temporary traffic line pavement markings were placed perpendicular to, and centered on, the centerline at 20-ft intervals throughout each study site. The 2-ft markers gave a length calibration that was always pictured on the film frame where lateral placement measurements were taken. The 20-ft interval gave a reference system for speed and radius calculations.

Sampling Procedures

About 100 vehicles were sampled for each curve site. This number has no statistical basis but was set by time and monetary constraints for data collection and film analysis. About half of the samples were taken for each direction of traffic at each curve site. Samples were limited to passenger cars and pickup trucks.

After each photographic sample was taken, the observation vehicle returned to its roadside position at the starting station, about 1 mile upstream from the curve site. The next sample was the first free-flowing vehicle that passed the starting station and had enough clear distance to the rear to allow the observation vehicle to move in behind. This procedure allowed for an essentially random selection of sample speeds.

FILM ANALYSIS

The film was analyzed with a Vanguard motion analyzer. That device is a portable film reader for measuring displacements on photographic projections. It consists of a projection head, projection case, and measurement screen.

The 16-mm projection head permits forward and reverse motion of film on 400-ft reels. A variable-speed mechanism moves the image across the projection screen from 0 to 30 frames/sec. A counter on the projection head displays frame numbers. If the camera speed is known, then, by noting elapsed frames, displacement over time (speed) can be calculated.

The measurement screen has an X-Y cross-hair system that measures displacement in 0.001-in. increments on the projected image. Rotation of the measurement screen permits angular alignment of the cross hairs with the projected image. Two counters display the numerical positions of the movable cross hairs. Conversion of image measurements to real measurements requires a calibration mark of known length in the plane of the photographed object. In other words, the 2-ft markers used at the highway curve sites were measured in machine units on the film image to give a calibration for converting image length to real length.

In the analysis of the curve maneuver samples, the lateral vehicle position reference was always the left edge of the left-rear tire. Lateral placement at each reference marker was measured from the frame where the left-rear tire was nearest the marker. After calibration readings on the left and right edge of the reference marker were recorded, the position reading of the left-rear tire was recorded. These readings, along with the 2-ft known length, gave the data necessary for calculating the actual lateral placement.

MATHEMATICAL ANALYSIS

The Vanguard data were used in a computer program to calculate vehicle speed, left-rear tire lateral placement, vehicle path radius, and lateral friction demand f. Those estimates were calculated for each sample at each reference marker.

Vehicle Speed

The estimate of vehicle speed at each reference marker was obtained as the average speed over a distance interval. Selection of the interval was dependent on the error sensitivity from 2 sources. The smaller the interval was, the smaller was the error due to sudden speed changes and the greater was the error due to integer frame-count estimates (number of frames elapsed as the vehicle traveled the 20 ft between successive markers). Because the samples did not exhibit large speed changes over short intervals, the accuracy of the instantaneous speed was most sensitive to the frame-count estimate.

Because the frame-count estimate was to the nearest integer, the greatest frame-count error at a point was ½ frame. For an analysis length, the greatest error in frame-count difference was 1 frame (½ frame at each end). Figure 3 shows the sensitivity of the speed estimate to frame-count differences for several analysis intervals. To reasonably diminish this error source, we set the speed estimate analysis interval at 160 ft. Therefore, the speed estimate at each reference marker was the average speed over the 160-ft interval centered on that marker.

Vehicle Radius

The computer program calculated the lateral placement of the left edge of the left-rear tire at each reference marker. The instantaneous vehicle path radius was then

Figure 1. Observation vehicle.

Figure 2. Camera and mounting.

Figure 3. Sensitivity of speed estimate to frame count.

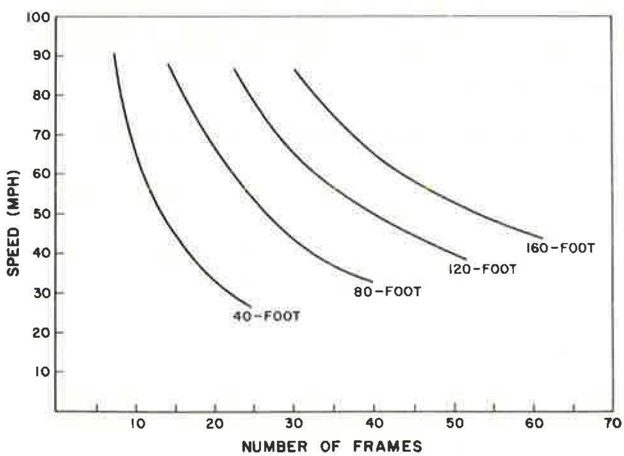


Figure 4. Geometric description of vehicle radius calculation.

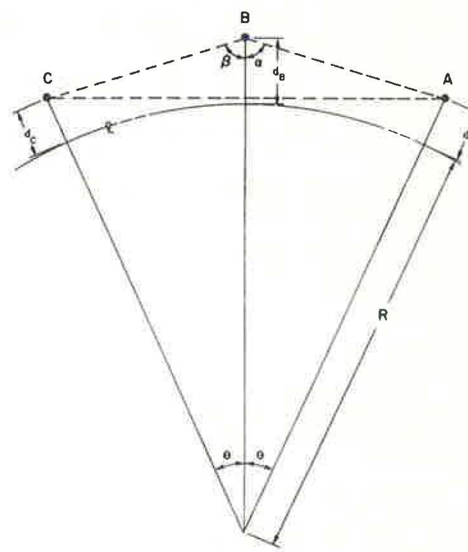
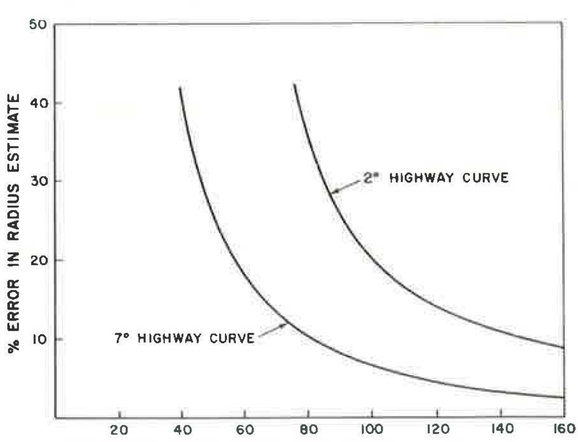


Figure 5. Error sensitivity of vehicle radius estimate.



estimated by computing the radius of the circular curve through 3 successive tire positions, the center position being at the reference marker under consideration. Inasmuch as a circular arc is the minimum curved path through 3 points, the radius so calculated is a conservative estimate of the smallest instantaneous radius over the interval.

Figure 4 shows the geometric description of the vehicle radius calculation. Points A, B, and C represent left-rear positions at equal intervals along the highway curve. The estimated vehicle path radius R_v is the radius of the circular arc that circumscribes triangle ABC. The following calculations were performed to obtain that radius.

From the law of cosines, lines AB, BC, and AC are (in ft)

$$\overline{AB} = \sqrt{(R + d_A)^2 + (R + d_B)^2 - 2(R + d_A)(R + d_B) \cos \theta}$$

$$\overline{BC} = \sqrt{(R + d_B)^2 + (R + d_C)^2 - 2(R + d_B)(R + d_C) \cos \theta}$$

$$\overline{AC} = \sqrt{(R + d_A)^2 + (R + d_C)^2 - 2(R + d_A)(R + d_C) \cos 2\theta}$$

where

d_A, d_B, and d_C = lateral displacements from the centerline at points A, B, and C, ft;
R = radius of the highway curve, ft; and
θ = central angle subtended by arc length of half the analysis interval.

From the law of sines,

$$\alpha = \sin^{-1} [(R + d_A)(\sin \theta)/\overline{AB}]$$

$$\beta = \sin^{-1} [(R + d_C)(\sin \theta)/\overline{BC}]$$

The radius of the vehicle path R_v that circumscribes triangle ABC is then calculated by

$$R_v = \overline{AC}/2 \sin(\alpha + \beta)$$

As with the speed estimate, it is necessary to look at the error sensitivity of the radius estimate for various analysis intervals. Any error in the radius estimate would, of course, come from an error in the lateral placement estimate. Although study control was exerted, small errors were possible from several sources, including (a) lateral discrepancy in placing the reference marker, (b) length discrepancy of the reference marker, (c) film parallax, (d) sampling error due to taking lateral placement readings up to ½ frame away from the reference marker, (e) equipment error, and (f) human error in reading and recording lateral placement measurements.

Estimating the distribution of error values for lateral placement estimates was not possible. All the error sources could be either positive or negative, and some error cancelation normally would be expected. In addition, all error sources would not be expected to reach maximum in the same direction at the same time.

An error of 0.10 ft in the lateral placement estimate was assumed to check the error sensitivity of the radius estimate for various analysis intervals. For this analysis, the correct path was assumed to be the path of the highway curve. Therefore, the error has the effect of changing the middle ordinate M of the circular arc. The middle ordinate M of the correct circular arc and the middle ordinate M_e of the circular arc in error are as follows (in ft):

$$M = C/2 \tan DC/400$$

$$M_e = M + 0.10 = C/2 \tan D_eC/400$$

where

C = chord length (approximately by arc length over short intervals) of both curves, ft;
D = deg of correct path; and
D_e = deg of path in error.

If d is the absolute error in curve degree, then

$$d = D_e - D$$

Solving for D and D_e in the first 2 equations, we obtain

$$d = 400/C \{\tan^{-1}[2(M + 0.10)/C]\} - 400/C[\tan^{-1}(2M/C)]$$

or

$$d = 400/C (\tan^{-1} \tfrac{1}{5}C)$$

if E is the percentage of error of the vehicle path degree estimate (and likewise the percentage of error of the radius estimate), then

$$E = 100 \{[400/C (\tan^{-1} \tfrac{1}{5}C)]/D\}$$

Figure 5 shows the percentage of error of the radius estimate for an absolute lateral placement error of 0.10 ft. The percentage of error is plotted against the length of analysis interval for the range in highway curves studied. The figure shows that the error sensitivity is greatly reduced as the analysis interval is increased.

For calculating instantaneous radius estimates, the analysis interval was set at 160 ft; a greater interval would increase the chance of grossly overestimating the smallest instantaneous radius by diluting the true path deviations at the 20-ft intervals.

Lateral Friction Demand

The lateral friction demand at the tire-pavement interface was estimated at each reference marker for each sample by using the centripetal force equation, $f = V^2/15R - e$. The results of full-scale vehicle skidding tests (4) on several pavements indicated that this equation is a reasonably good predictive tool.

RESULTS

The result of the computer application was the printing of 50 to 80 data sets of lateral placement, speed, instantaneous radius, and lateral friction demand for each vehicle sampled. The critical point of each sample was represented by selecting the point of maximum friction demand. This point, for a great number of samples, coincided with either the point of maximum speed or the point of minimum path radius or both. Sample data, showing the ranges in speed, vehicle radius, and lateral friction demand, are given in Table 1 for each study site.

When the design equation $e + f = V^2/15R$ (in which R is the vehicle path radius) was used, the highway curve radius we assumed to be equal to the vehicle path radius. The study data showed that this assumption is invalid. The problem for design then is to write the equation not in terms of vehicle path radius but in terms of highway curve radius. Thus, a representative form of the vehicle path radius in terms of the highway curve radius is called for.

The original research plan was to generate for each highway curve a relation between vehicle path radius and vehicle speed at the point of maximum lateral friction demand. With this information, an acceptable highway curve radius could be designed for any combination of design speed V, design lateral friction demand f, and superelevation rate e.

Plotting scatter diagrams of speed versus radius did not indicate any relation between the 2 parameters. This fact was verified by conducting a simple linear regression analysis on the data. For the 5 highway curves studied, the vehicle speed explained no more

Table 1. Speed, vehicle radius, and lateral friction demand.

Site and Curve	Sample	Left or Right	Initial Speed	Maximum Speed	Minimum Radius	Data at Point of Maximum f: Quarter of Curve	Speed	Radius	f
1, 7 deg	105	L	61	69	732	4	67	769	0.356
	22	L	60	60	647	1	56	647	0.285
	84	L	60	61	806	2	58	811	0.243
	11	R	47	51	690	4	51	700	0.201
	104	R	45	45	587	1	43	587	0.159
	91	R	42	42	718	1	41	735	0.102
3, 5 deg	37	L	75	75	909	1	75	909	0.340
	30	L	65	69	996	1	69	1,087	0.271
	58	R	64	67	973	1	67	1,113	0.240
	53	L	56	57	780	4	55	780	0.184
	25	R	56	56	995	1	55	1,205	0.135
	49	L	42	43	1,000	1	43	1,044	0.098
2, 4 deg	101	R	77	77	1,003	4	75	1,042	0.295
	105	R	65	65	913	4	65	913	0.228
	89	L	54	61	750	3	56	787	0.188
	5	L	57	58	967	1	58	967	0.158
	79	L	58	64	1,267	4	64	1,354	0.126
	37	R	41	41	1,239	4	40	1,239	0.002
5, 2.5 deg	75	L	73	75	1,582	3	75	1,582	0.186
	18	R	69	69	1,022	4	61	1,022	0.182
	7	R	69	71	1,662	2	69	1,662	0.130
	43	L	67	69	1,834	3	67	1,834	0.114
	97	L	62	64	1,974	4	64	2,045	0.083
	98	R	46	49	1,499	4	48	1,499	0.041
4, 2 deg	99	R	73	75	1,694	3	75	1,715	0.177
	92	R	69	69	2,084	4	69	2,084	0.132
	52	R	67	67	1,865	3	65	1,865	0.113
	24	R	60	60	1,495	1	57	1,495	0.084
	73	L	64	64	2,117	3	62	2,365	0:080
	40	L	44	44	1,536	4	38	1,536	0.032

Figure 6. Percentile distribution of vehicle path radius versus highway radius.

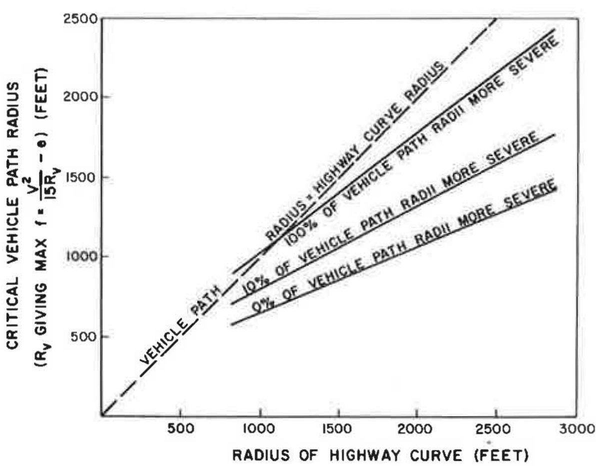
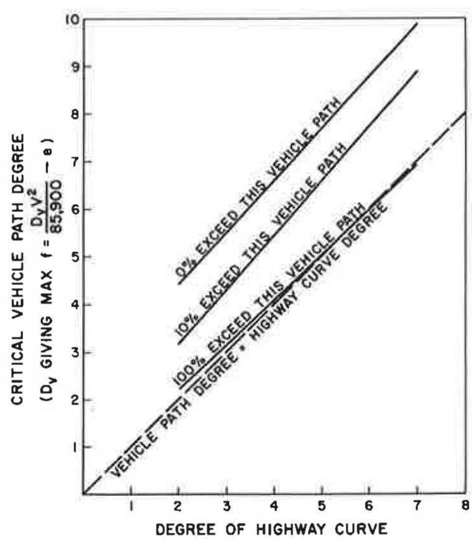


Figure 7. Percentile distribution of vehicle path degree versus highway curve degree.



than 11.4 percent ($r^2 = 0.114$) of the variation in the vehicle path radius, and in fact, for 3 of the study sites, explained than 4.7 percent.

Actually, the lack of correlation between vehicle radius and speed simplified the analysis, because it indicated that the distribution of vehicle path radii (at maximum lateral friction demand) found for each site could be expected at any speed within the speed range studied. Therefore, percentiles of vehicle path radius could be plotted for each highway curve radius.

Figure 6 shows simple linear regression fits for different percentiles of vehicle path radius versus highway curve radius. Figure 7 shows a similar relation in terms of degrees of curve. For these 2 graphs, the equations of the lines and their goodness of fit are given in Table 2. What these relations show, for example, is that, on a 3-deg highway curve, 10 percent of the vehicles will exceed a 4.3-deg path maneuver.

To arrive at the design relation for highway curve radius, a percentile level is needed that ensures that very few vehicles will approach instability. The 10 percent level appears to be a reasonable choice. Using this level for design would say that only 10 percent of the vehicles traveling at design speed will exceed a given vehicle path radius. This level would change the design equation, in terms of highway curve radius R, to read

$$e + f = V^2/7.86R + 4{,}030$$

or

$$e + f = (D + 0.9)\ V^2/76{,}100$$

It is interesting to analyze these equations to see what percentage of vehicles might exceed the design f. For example, if we design a curve for 60 mph with 0.06 superelevation and a design f = 0.13, what percentage of vehicles will exceed the design f? For the given design parameters, using the modified design equations gives R = 1,890 ft and D = 3.1 deg. Using the equations given in Table 2, it can be found that design f will be exceeded by 0 percent of the vehicles at 53 mph, 10 percent at 60 mph, 50 percent at 64 mph, and 100 percent at 70 mph.

DESIGN APPLICATION

With the developments of the previous section we now have the more explicit design equation:

$$e + f = V^2/7.86R + 4{,}030$$

But the questions of what skid resistance level to design for and what factor of safety to use have not yet been resolved.

Lateral Skid Resistance

The results of full-scale vehicle skidding tests (4) indicate that skid numbers measured with an ASTM locked-wheel skid trailer give good estimates of lateral skid resistance for speeds up to 40 mph. With trailer speeds above 40 mph, measured skid numbers are biased slightly upward, because of inherent difficulties with the trailer's watering system. Water is sprayed, ejected, or splashed on the pavement directly in advance of the test wheel, just before and during lockup. At higher speeds, the watering system does not adequately wet the pavement because of the small time difference between when water contacts the pavement and when the tire is skidded over the wetted segment.

Standard skid trailer tests compared with tests made with an external watering source, for a speed range of 20 mph to 60 mph, revealed that measurements at speeds above 40 mph gave lower skid resistance values for the external watering tests. In addition, using the skid number versus speed relation for external watering in the centripetal force equation more closely predicted the results of full-scale spin-out tests conducted on the project. The results are inconclusive, however, because only 2 pavements were used.

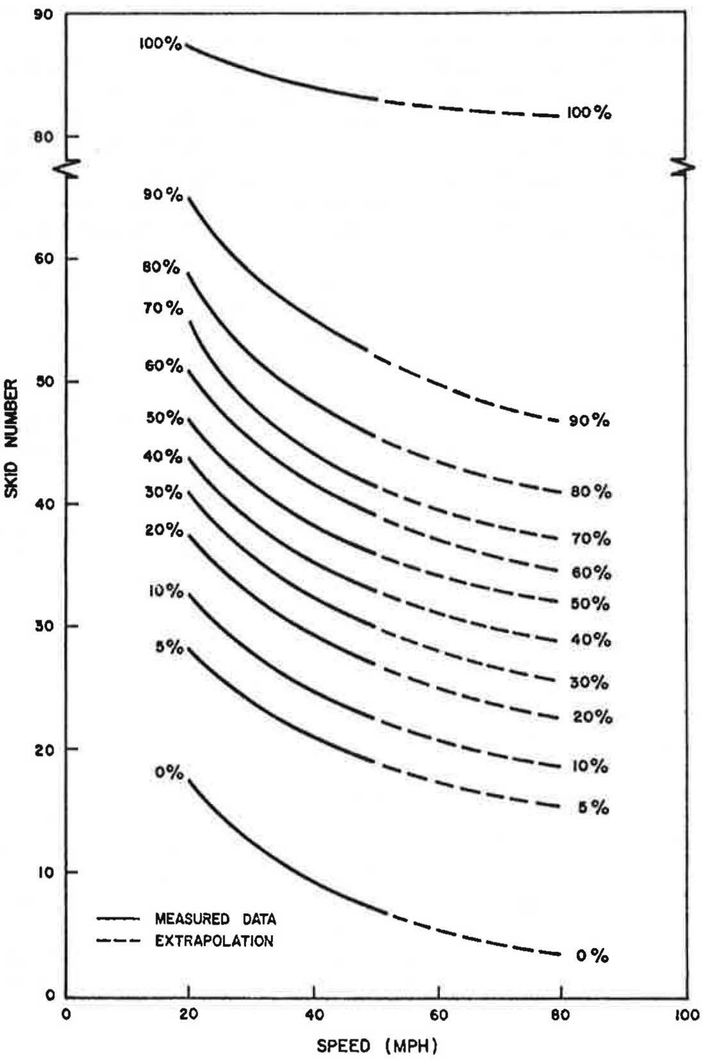
Table 2. Percentiles of vehicle path versus highway curve path.

Vehicle Path Degree Greater Than D_v (percent)	Vehicle Path Radii Lower Than R_v (percent)	Equation	Goodness of Linear Fit (r^2)
0		$D_v = 2.427 + 1.057\ D$	0.930
5		$D_v = 0.984 + 1.165\ D$	0.985
10		$D_v = 1.014 + 1.128\ D$	0.984
15		$D_v = 0.894 + 1.124\ D$	0.983
50		$D_v = 0.796 + 1.030\ D$	0.991
100		$D_v = 0.474 + 0.919\ D$	0.986
	0	$R_v = 225.1 + 0.416\ R$	0.990
	5	$R_v = 266.0 + 0.510\ R$	0.953
	10	$R_v = 268.0 + 0.524\ R$	0.951
	15	$R_v = 271.1 + 0.538\ R$	0.956
	50	$R_v = 267.5 + 0.611\ R$	0.971
	100	$R_v = 276.7 + 0.751\ R$	0.987

Table 3. Hypothetical solution of proposed design equation where e = 0.06 and M_s = 0.10.

SN_{40}	Design Speed (mph)	Design Radius (ft)	Design Value (deg)
35	50	640	9.0
	60	1,270	4.5
	70	2,080	2.8
	80	3,000	1.9
25	40	560	10.2
	50	1,400	4.1
	60	2,500	2.3
	70	3,900	1.5
	80	5,700	1.0

Figure 8. Percentile distribution of skid number versus speed relation for 500 pavements in 1 state.



Other research (5) using 15 pavement surfaces showed similar comparisons of the skid number versus speed relation for internal and external watering tests. The measured differences, however, were not too substantial, amounting to an average of 0.04 at 60 mph. That difference varies between pavements; therefore, it is difficult to predict. Perhaps the difference can best be accounted for in the design process by providing an adequate safety margin between predicted friction demand and measured skid number.

Spiral Transitions

Although no specific research was done to study spiral transitions for highway curves (all sites had tangent to circular curve transitions), the data do indicate that spiral transitions may be desirable. The data clearly revealed that many drivers have trouble transitioning their vehicle path from tangent to circular curve and from circular curve to tangent. This fact is shown by the majority of samples that had their highest lateral friction demand in either the first quarter or the last quarter of the highway curve.

Superelevation

A previous report (2) has shown that the higher the superelevation is the greater the problem is of driving through the area of superelevation runoff for unspiraled highway curves that curve to the left. As the vehicle approaches the curve, it is presented first with an area where the cross slope is less than 0.01. Because of this slight cross slope, the pavement does not drain well; thus, a high potential hydroplaning section is created. The vehicle no sooner gets through this first problem area when it is presented with a second problem area. In the second area, the driver may experience some steering difficulty because, while still on the tangent section, the superelevated cross slope requires him to steer opposite the direction of the approaching curve. When the vehicle gets to the point of tangency, the driver must reverse his steering to follow the highway curve. In this third problem area, if he attempts to precisely steer the highway curve path, the lateral friction demand will exceed (at design speed) the design values because this area lacks full superelevation.

At design speed, for most current highway curve designs, the vehicle proceeds through this "compound dilemma area" in about 3 sec. It is questionable that the driver can adequately react to those demands on his perception in the time required. A partial solution to this problem is to keep the maximum allowable superelevation to a minimum. This practice will reduce the severity and length of the superelevation runoff area.

The other problem with superelevation, previously mentioned, is that full superelevation is not available near the beginning and the end of the highway curve. Depending on the design practice for superelevation runoff (which varies from state to state), the superelevation at the tangent-to-curve points may be from 50 percent to 80 percent of full superelevation. Because the data from this study show that most drivers have steering trouble at the beginning and end of the curve, the design equation should reflect this reduced superelevation.

Safety Margin

Current design practice (3) uses the criterion that the design f should correspond to "that point at which side force causes the driver to recognize a feeling of discomfort and act instinctively to avoid higher speed." Based on several studies of this phenomenon, design values ranging linearly from 0.16 at 30 mph to 0.11 at 80 mph are used. These values are assumed (3) to give an adequate factor of safety against lateral skidding.

Actually, these design f values have no objective relation to available skid resistance. In addition, they give smaller factors of safety as design speed is increased. Required is a more realistic relation between the design f and available skid resistance.

Many variables, as their magnitudes increase, lead to a higher loss-of-control potential for the cornering vehicle. Some of these variables are vehicle speed, driver steering judgment, faulty vehicle dynamics, microvertical curvature (pavement bumps and dips), vehicle acceleration and braking, steering reversal rate, water depth, tire temperature, tire wear, and wind gusts. On wet pavements, vehicle speed is the most significant variable, not only because the lateral friction demand increases with the square of the speed but also because skid resistance decreases with speed. These 2 phenomena, of course, are already accounted for in the design procedure. Also, with the design equation modified to account for statistical values of vehicle path, the effects of driver steering judgment and faulty vehicle dynamics are probably taken care of. Therefore, factors of safety are only needed to give some margin of error for the remaining variables.

Because these other variables have not been explicity evaluated, it is difficult to determine representative factors of safety. It seems clear, however, because vehicle paths are now explicit in the design equation, that lower factors of safety can be used. In addition, there may be a low probability of the other variables causing a considerably greater lateral friction demand than already accounted for in the modified design equation.

Because skid resistance varies by pavement, a safety margin is a better tool than a factor of safety. A constant safety margin also has the advantage of giving a higher factor of safety as design speed is increased. Although there are no supporting data, a safety margin in the range of 0.08 to 0.12 should reasonably allow for the unaccounted variables, including the deviation between actual and measured skid numbers.

Design Equation

With all the considerations previously discussed, it is possible to modify the design equation into a comprehensive tool. The original equation is

$$e + f = V^2/15R_v$$

If the derived expression for the tenth percentile R_v in terms of the highway curve radius R is substituted, the following equation results:

$$e + f = V^2/7.86R + 4{,}030$$

If the reduced superelevation at the beginning and end of the curve is approximated by 0.7e, and if f is expressed by the skid number SN_v, divided by 100, minus a safety margin M_s, the following equation results:

$$0.7e + SN_v/100 - M_s = V^2/7.86R + 4{,}030$$

or

$$R = -514 + V^2/[5.48e + 7.86\ (0.01\ SN_v - M_s)]$$

It is not possible, of course, to use this equation for design unless, first, a safety margin is selected and, second, a "typical" skid resistance versus speed relation is selected. The latter makes it difficult to give specific recommendations for design standards. Essentially, the selection of a skid resistance versus speed relation depends on what minimum level of skid resistance the highway department provides.

Hypothetical Design Use

Although specific design standards cannot be recommended, the sensitivity of the suggested design equation to minimum skid resistance levels is important. Figure 8, a percentile distribution of skid numbers in one state, will be used for illustration. The 2 curves having skid numbers of 35 and 25 at 40 mph will be used as hypothetical minimum skid resistance requirements. The value of 35 has been widely recommended.

A safety margin of 0.10 and a design e of 0.06 will yield solutions to the design equation for the various skid resistance levels as given in Table 3. The design values below 2 deg are somewhat questionable because of the limits of the field data. It can be shown, though, that a 2-deg curve will not satisfy the selected safety margin for these higher design speeds.

REFERENCES

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