MARKING HIGHWAY CURVES WITH SAFE SPEED INDICATIONS

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SYNOPSIS

The satisfactory experience in Missouri in marking curves with speed signs and the adoption of a similar plan by many other States, prompted the organization of a cooperative investigation between the Committee on Curvature and Speed of the Highway Research Board, the Committee on Speed Regulation of the National Safety Council and the Iowa Engineering Experiment Station to study the factors relating to determination and marking of safe speeds on curves

The first important phase of this investigation involved a questionnaire survey in which the practices in regard to marking speed indications on curves were determined

The majority of the States reported that a ball-bank indicator reading of 10 deg was the most satisfactory indication of safe speed Charts and graphs of driving tests on curves conducted by the research staff of the Iowa Engineering Experiment Station, the General Motors Proving Ground, and by engineers in several States, provide factual data on practically every phase of car operation on curves related to safe speeds, such as variations in ball-bank readings for various makes of cars at various speeds, the body roll angles of cars, the sideways frictional factor, steering angles and steering forces, the effect of surface roughness and road slipperiness, and the visibility on curves at night with sealed beams or common type headlights In general it was found that a ball-bank angle of 10 deg provided an ample margin of safety for all of the above factors except extreme conditions of surface slipperiness, or for snow and ice conditions

The practice in regard to the size, shape, and color of signs was found to vary although a sign approximately one foot square with black numerals and letters on a white background was generally used The State of Illinois uses white numerals and letters on a black background The before and after studies reported by several States indicated that speeds were more nearly uniform on marked curves than on unmarked curves and that there was less congestion of traffic on these curves The accident experience on a 95-mile section in Indiana was particularly noteworthy In 1939 and 1940 there were 10 fewer fatalities, 12 fewer persons injured, 36 fewer accidents on curves, and approximately $9,000,000 less property damage during the twelve month period in which the signs were in operation than in the previous 12 months period The greatest advantage to the motorist provided by speed signs is that they eliminate the surprise element when coming into a low speed curve, especially an isolated curve, where the approach speed may be 50 to 60 m p h and the safe speed on the curve 30 to 35 m p h

In June 1937 the Missouri State Highway Department conducted road tests on Route U S 40 to determine the maximum safe driving speeds on all curves on this route As a result of these tests the approaches to all curves with safe speed indications below 60 m p h were marked with speed signs placed directly below the standard curve signs The experience in Missouri in marking these curves with reflectorized signs proved to be very satisfactory both to the motorists and to the state highway officials from Missouri and from many other states Since that time more than one half of the states have adopted a similar plan on an experimental basis, on their main routes, and in some states on all routes

While engineers in general are fairly well informed in regard to the principles involved in determining safe speeds on curves, a comprehensive analysis of the many factors involved appeared to be a timely and worthwhile undertaking Also, there appeared to be some valid arguments among engineers questioning the ability of a highway department to establish a definite safe speed for a given curve to meet all the conflicting conditions such as differences in the skills of drivers, in the makes, types, and speedometers of cars, and in weather, road surfaces, and driving conditions whether wet or dry, rough or smooth, day or night. Accordingly, a cooperative project was set up during the summer of 1940, between the Committee on Curvature and Speed of the Highway Research Board, the Committee on Speed Regulation of the National Safety Council, and the Highway Research Staff of the Iowa Engineering Experiment Station.

The first important phase of this investigation involved a questionnaire survey in which the practices in regard to marking speed indications on curves were determined through the cooperation of the engineers in charge of traffic control in each of the 48 States. The contributions of these men provided valuable material for this report and the authors hereby desire to express their sincere appreciation for this assistance without which the report in its present form would not have been possible. Many driving tests on curves were conducted by the members of the research staffs of the Iowa Engineering Experiment Station and the General Motors Proving Ground to cover every important phase of operation on curves The charts and graphs obtained from these tests provide the answers to many questions raised in regard to various factors involved when establishing safe speeds on curves

In the early work by the Missouri State Highway Department and according to the reports from the various states, the simplest and most important device used in establishing safe speeds, was the ball type bank and turn indicator used on airplanes. The majority of the States reported that a ball bank indicator reading of 10 degrees was the most satisfactory indication of safe speed on curves. The driving tests, speed studies, and driver polls confirmed these reports. Forms and charts developed by various traffic engineers replying to the questionnaire and by the authors simplify the field operations in determining safe speed using the ball bank indicator In view of the general approval of motorists of curve speed signs, the interest of the state traffic engineers in marking curves as expressed in their replies to the questionnaire, and the simplicity of determining safe speeds, it is anticipated that marking highway curves with safe speed indications will be extended to many states which are not now following this practice. To be of greatest value to the motorist, it is hoped that uniform standards in determining safe speeds and for marking curves will be developed as indicated in this investigation. While this report is concerned mainly with the analysis of factors related to the determinination of safe speeds on curves, the replies to the questionnaires provide information in regard to signs and markings which should be helpful in arriving at a uniform standard for all states.

QUESTIONNAIRE FORM RETURNED BY 48 STATES

The questionnaire form was sent to the engineers in charge of traffic control in each of the 48 states The first response was most encouraging with replies from about two thirds of the States. By means of follow-up letters replies from every State were obtained. This, in itself, is an indication of the interest in this subject. In the questionnaire the information requested included when curves were marked and the extent of marking curves; the method or methods used, such as by means of a ball bank indicator, computations using a formula, trial runs, and speed observations, the position, color, shape, and size of the sign, the legend on the sign and height of letters and numbers, whether the indicated speeds are legal limits or recommended speeds only as an aid to motorists, data on before and after experience such as studies of speeds, driver polls, and accident experience; and in addition information was requested in regard to the use of speed zones and the extent of speed zones on other sections of state highways

The results of the questionnaire survey are summarized in Tables 1 and 2 It is of interest to note that the states in which marking curves on state routes has been adopted form a tier of states through the center of the United States east and west and north and south More curves on route U S 40 and on U S 65 are marked than on any other routes in the United States These routes carry large volumes of through traffic and marking the curves on them is particularly helpful in controlling speed The reports of the States showed that 23 States were not marking curves at all, 2 rarely, 6 occasionally, 12 on some routes and 5 on all routes The curves marked were sharper than 3 deg and in some states only curves sharper than 7 deg or 10 deg were marked. One reason for difference in this practice was the variation in the speed limit which is as low as 45 m p h in some States For this same reason no curves in these States were marked for speeds above 45 m p h whereas in others with no speed limit or a higher limit, all curves were marked for speeds below 60 m p h or 50 m p h depending on the State speed limit

In five States all State routes are marked and the mileage and curves marked runs into the thousands In many of the States, this work is on an experimental basis and only a relatively short mileage on certain routes is marked At least three States are just starting but are planning to mark the entire system In three other States marking curves is a part of speed zoning Several States reported that curves were not marked because cars differ, weather affects results, the ability of drivers to drive on curves differ, road conditions affect results as when wet or dry, rough or smooth, and different speeds are needed at nighttime than in the daytime

The methods used in selecting a safe speed value varied although in the majority of the States trial runs with a ball bank indicator reading of 10 degrees formed the basis for establishing the speed In nine States the usual curve formula was used in which

$$f = 0.067 \frac{V^2}{R} - e \qquad (1)$$

f = the coefficient of friction
V = the speed in m p h
R = the radius of the curve in feet, and
e = the superelevation in feet per foot.

The values of f in formula (1) varied from 0 14 to 0 25 although a value of 0 16 was generally used

In one State the formula reported by Baldwin in *Public Safety*, December, 1934, was used to determine the critical speed

$$S^3 = 466\,R\,(E + 0\ 2) \qquad (2)$$

where

S = the critical speed in m p h
R = the radius of the curve in feet, and
E = the superelevation in feet per foot

This formula gives higher speeds for radii below 800 ft and lower speeds for radii above that than formula (1) if the same values of f is used in formula (1) at all speeds It was stated that this formula gave speeds more representative of the actual driving practices than formula (1) over a wide range of curvature It is the authors' contention that formula (2) is entirely empirical and does not have the flexibility to meet varying conditions which the theoretically correct formula (1) has as will be shown later Also, by

TABLE 1

Questionnaire Survey on Marking Highway Curves with Safe Speed Indications

State	When marked							Extent		Methods in selecting proper speed value						
										Ball bank indicator		Computations		Trial runs	Speed observations	
	Not at all	Rarely	Occasionally	On some routes	On all routes	Degrees (above)	Speed (below)	No of miles	No of curves	Cases used	Reading used	Cases used	"f"		Used	Criteria
										%		%		%	%	%
Ariz				X		4	60	110	31	Yes	8°–14°	100	14– 25	100		90
Ark				X	[1]	3	50	2068	1930	100	10°	3		100	5	85
Calif				X					300	50	10°	Yes	14– 16		50	Ave.
Colo	X[2]															
Ill					X		55	5000[3]	2800	100				100	100	85
Ind				X				95	190	100	10°					
Kans					X	3		[4]		Yes		Yes		100	Yes	80
Ky		X												100		
La			X											100		
Md				X	Planned			430	600	100	10°					
Mich	X[5]															
Minn					X	Part of speed zoning				90	Mercury tube			100	90	85
Miss	X	Planned								Yes	10°					
Mo				X			60	1872		100	10°			100		
Nev				X			60	75	17		10°–20°			100	100	80
N H			X				60	Part of speed zoning						80	10	
N M				X			50	60	25	100	10°			100		
N Y				X			40	1650[6]		Yes						
N C			X			7	45					Yes	16		Yes	[7]
Ohio				X		7	45	300	75	100	10°	80	[8]	100	100	85
Okla			X				50	30	15			100		100	100	85
Pa				X			50	280	356	100	10°					
R I					X			Part of speed zoning by state police								
S C			X					8	15			25	16	100	100	85
S D			X				45	125	48	100	10°				Yes	90
Texas		X				10	45	14	25			25		25	50	85
Utah	X	Planned														
Wash					X		50	3682		(When side thrust becomes apparent)				100		
Wyo				X			60	2500	1250	100	15°					
Total	23	2	6	12	5											

[1] On all paved routes

[2] Do not use because cars differ, weather affects results, and oil mat road change

[3] 13,500 miles to be zoned by 1941—white on black signs

[4] This work has just been started Have on hand 5000 10 by 12 in speed signs to be used

[5] State manual provides different degree signs for different critical speeds

[6] Planning to complete entire system

[7] Speed indications also determined on the basis of accident records

[8] Use formula $S^2 = 466R(E + 0.2)$ See Public Safety, December 1934

Note. States reporting curves not marked are Alabama, Colorado, Connecticut, Delaware, Florida, Georgia, Idaho, Iowa, Maine, Massachusetts, Michigan, Mississippi (planned), Montana, Nebraska, New Jersey, North Dakota, Oregon, Tennessee, Utah (planned), Vermont, Virginia, W Virginia, Wisconsin

TABLE 2

QUESTIONNAIRE SURVEY ON SPEED SIGNS AND SPEED ZONING

State	Speed sign used on curves												Meaning of curve speed sign		Speed zoning		
	Color[1]			Position					Reflectorized		Size	Height of speed number	Legal limit	Recommended value	No of miles	Rural	Remarks
	A	B	C	Above	Below	On curve sign	Separate sign	Other	Yes	No							
											in	in				%	
Ariz			X		X				X		12 x 13	6		X	200	99	[2]
Ark					X				X		12 x 12	6	X		50	75	
Calif		X			X				X		Diamond	9		X	0		
Ill			X		X				X		12 x 18	6		X	City	0	
Ind	X			X					X		13 x 13	5		X	800	30	
Ia															47	05	
Kans	X			X					X		10 x 12	6		X	50	100	[3]
Ky	X				X					X	12 x 12	8		X			
La											Varies			X			
Md					X	Planned			X					X	0		
Mass	X							X	Zoning			12			5	100	
Mich															250	01	
Minn	X			Part of zoning				X		X		8	X		2500	90	
Miss	X			X					X		12 x 10	6		X	9	5	
Mo	X				X				X		13 x 13	5		X	Yes		
Mont															150	100	
Nev					X				X		18 x 18	4		X			
N H	X						X		Some are		18 x 24	9	X		3700	100	
N J															45 m p h zones		
N M		X			X				X		12 x 13	6		X	1000	100	
N Y		X				X			X		36 x 36			X	Yes		
N C		X					X		Seldom			4		X	"Slow to 30 miles"		
Ohio	X				X				X		12 x 16	8		X	40		[4]
Okla	X				X				X		12 x 12	6		X	30	All need law	
Pa	X				X				X		12 x 12	5		X	771	0	
R I					Part of speed zoning by state police										Yes		
S C	X			Part of speed zoning								6	X		40	50	
S D	X				X					X	15 x 15	5		X	0		
Texas							X			X				X	14	100	[5]
Wash		X			X				X[6]		10 x 12	4		X	75	All	
Wyo		X			X				X		14 x 14 Diamond	8		X	250	10	
Total	13	6	2	3	15	1	3	2	17	4			4	21			

[1] Color legend (A) black numbers on white background, (B) black numbers on yellow background, (C) white numbers on black background

[2] Accident experience shows 16 7 percent reduction in zoned areas and 7 8 percent in areas not zoned

[3] Seldom restrict speed to less than 40 m p h

[4] No legal authority in Ohio for establishing speed zones—experimental only

[5] Experimental only

[6] No speed signs for speeds above 35 m p h Amber buttons on curve arrows

Note Replies in regard to speed zoning for the following states were Colorado (some speed zoning but kept to minimum), Connecticut (yes), Delaware (planned), Georgia (just beginning), Maine (occasional rural area zoned, need legal support), North Dakota (yes), Tennessee (yes, small towns, school zones, etc) use of formula (1), the engineer can obtain a better understanding of all the factors which influence the selection of a safe speed on a given curve than if formula (2) is used.

Practically every state reported the use of trial runs in the determination of safe speeds. Of course, the use of the ball bank indicator implies that a driving test was made using a car with a calibrated speedometer. However, in this connection the trial runs are interpreted as consisting of test runs at the particular speed at which the curve is to be posted. This provides a field check on the particular speed recommended as safe for all passenger cars and for all ordinary weather conditions

Speed observations are used by many states as an aid in selecting the proper speed value It should be recognized that marking the curve is likely to affect the speed distribution on the curve The greatest advantage to the motorist provided by speed signs is that they eliminate the surprise element when coming into a low speed curve, especially an isolated one, where the approach speed may be 50 60 m.p.h. and the safe speed on the curve 30 to 35 m.p.h. The driver's judgment in regard to a safe speed is not likely to be so dependable, even on familiar routes, as the safe speed established on the basis of a careful engineering study of each curve. For this reason the speed observations after the curve is marked are of greater value than those observed before marking in determining whether or not the speed selected was the proper one In any case before and after speed studies are very valuable as will be shown later in determining whether or not marking has improved the speed distribution of traffic on the curve by reducing the number of cars driving too fast and too slow for conditions.

The second phase of the questionnaire survey, covered in Table 2, in regard to the position, color, size, and shape of sign, the height of letters and numbers, the meaning of the sign and speed zoning will be discussed in detail in the latter part of the report.

ANALYSIS OF FACTORS INFLUENCING SAFE SPEED ON CURVES

Ball Bank Indicator Angle Observations as a Measure of Centrifugal Force, Superelevation, Speed, and Curvature

To the best of the authors' knowledge, the use of the ball bank indicator to determine safe speeds was first employed by the Missouri State Highway Department in 1937. The ball bank indicator consists of a steel ball in a sealed curved glass tube. The ball is free to roll except for the damping effect of the liquid in the tube The tube is enclosed in a metal case and one model is graduated in 5 deg. divisions up to 20 deg. on each side of zero. In another model the graduations run in 2 deg. divisions from zero to 10 deg. in both directions. The indicator can be mounted on the dash of a passenger car by means of rubber suction cups and is, thus, readily transferred from one car to another. The indicators can be purchased from dealers in airplane accessories at the low price of $3.00 to $5.00 each.

In mounting the indicator, the car should be in a stationary level position with the steel ball at the 0 degree position. Also, all occupants who are to be in the car when the observations are to be made should be in the same position when mounting or checking the instrument as when making the test. This is necessary because changing positions of the passengers or the load in the car may cause the body to tilt to the right or to the left depending upon the transfer of the load from one side to the other and this tilting action or body roll is reflected in a change in the ball bank reading. On a level surface with the car stationary the reading should be 0 degree while on a superelevated curve with the car at rest, the ball bank reading (∞) will be equal to the sum of the superelevation angle (ϕ) plus a small angle (ρ) caused by the tilting of the body on the inclined slope hereafter referred to as the body-roll

On a level surface a definite centrifugal force is developed as the car travels at a given speed on a fixed curved path This force and a small amount of body roll will cause the ball to roll out to a fixed angle position much as a pendulum would if supported at the center of the arc of the glass tube Tests have shown that in the usual range of speeds at which curves are marked, a ball bank angle of 10 deg is a fairly reliable indication of safe speed

The roadway on highway curves is rarely level but is usually superelevated The greatest amount of superelevation is used on the sharper curves and on the inside traffic lane of practically all curves The superelevation provides a horizontal component of the gravity force or weight of the car which opposes centrifugal force The ball bank reading of 10 deg at the maximum safe speed on the given curve is the sum of the centrifugal force angle (θ) plus the body roll angle minus the superelevation angle (ϕ) (Fig 1). At the maximum safe speed

$$\infty = \theta + \rho - \phi \tag{3}$$

During the summer and fall of 1940, driving tests were conducted by the research staff of the Iowa Engineering Experiment Station over a wide range of speeds and degrees of curvature for both right and left turn traffic lanes on roads near Ames The car used was a 1938 sedan The speedometer of the car was carefully calibrated with a stop watch over a measured course one mile in length The ball bank angles were observed on all of these tests and measurements of the average superelevations and radii of curvature were taken on all curves From these measurements the ball bank angle could be computed assuming no body roll according to the following formula

$$\infty = \tan^{-1} \frac{v^2}{g^R} - \phi$$

where

v = speed in feet per second

g = acceleration due to gravity or 32 2 ft per sec ^{2}, and

R = the radius of the curve in feet

Also, $\tan^{-1} \frac{v^2}{g^R} = \theta$, the centrifugal force angle

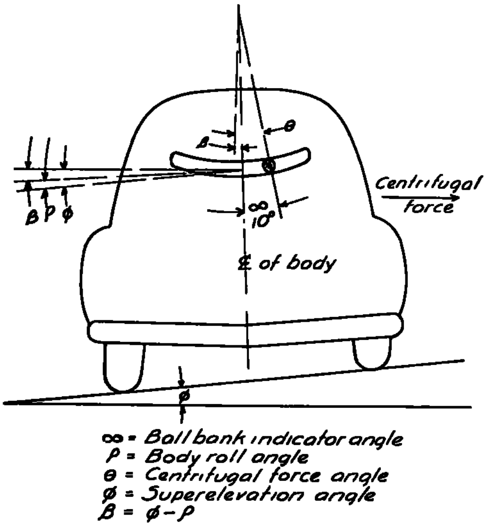

Figure 1. A Car at Maximum Safe Speed on a Superelevated Curve

The results of these tests and the computed values of the ball bank angle are given in Figure 2 It should be noted that at zero ball bank angle of the observed values and computed values are the same At this speed the horizontal component of the gravity force equals the centrifugal force and no friction is required to hold the car on the curved path However, as the speed is increased above this point the observed ball bank angles are greater than the computed angles because friction is required to hold the car on the curve and this causes the body to tilt outward farther as the speed is increased. The difference between the observed angles and the computed angles at the higher speeds represents the body observed ball bank angles, which are now negative, are again greater than the computed angles With the car stationary

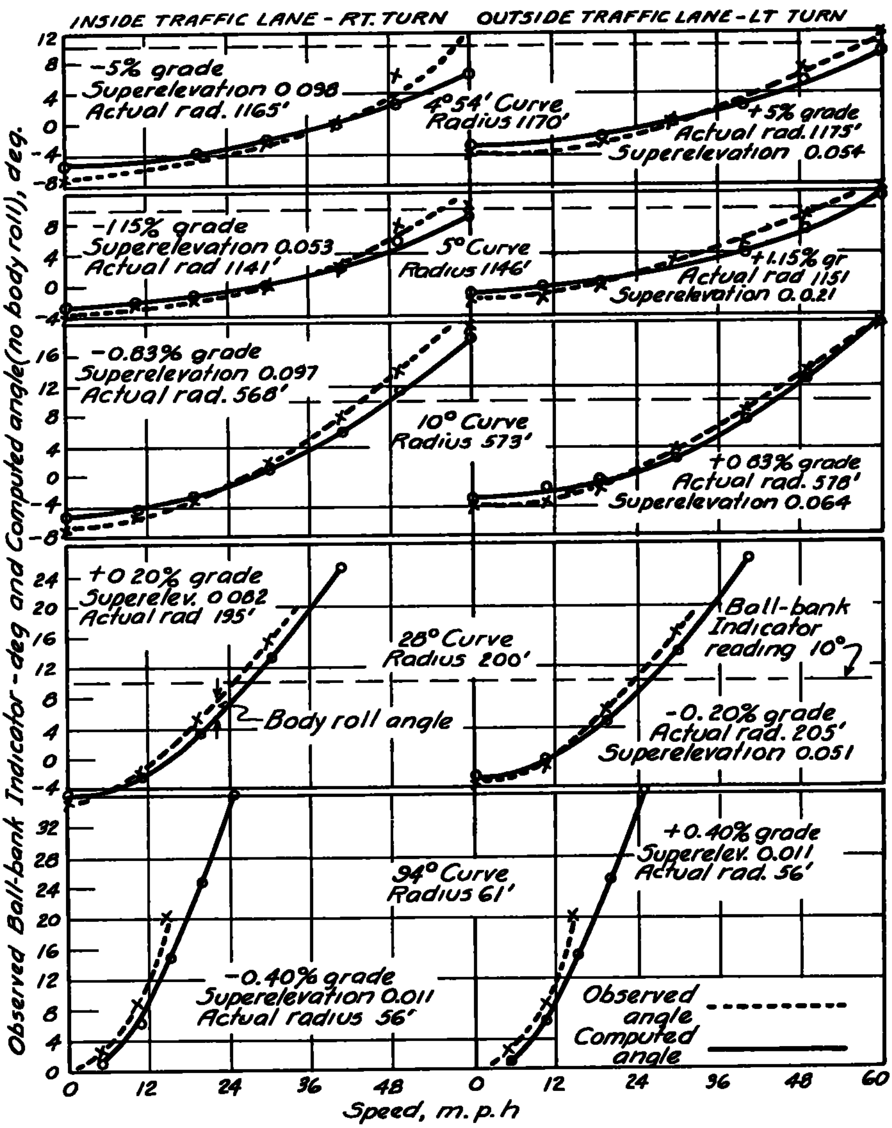

Figure 2. Observed and computed ball-bank indicator readings over a wide range of speeds and degrees of curvature for both right and left turn traffic lanes

roll at these speeds At speeds below the ball bank angle zero, the frictional force required to hold the car on the curve acts in the opposite direction and the observed ball bank angles, which are now negative... on the curve, the observed ball bank angle is the same as the superelevation angle plus the body roll for the given car on that slope.

While most of the driving tests were run on flat grades, one series of tests was run on a 4 deg 54 min -curve on a 5 percent grade The results on this curve were not so consistent as on the other curves possibly because slight differences in superelevation and a somewhat rougher surface caused small differences in the readings The differences in the observed and computed angles on the down grade were slightly greater than on the up grade This means that the body roll was greater going down grade than when going up which is as might be expected This also shows that the 10 deg ball bank angle would have been developed at a lower speed going down than when going up hill if the superelevation in both traffic lanes had been the same Actually the superelevation down grade was almost double that up grade and yet the speed at the 10 deg ball bank reading was the same This, of course, is desirable when establishing safe speeds where grades are involved

In these tests no differences could be observed in the ball bank readings when making left turns as compared to right turns when the tests were made in the same path, conditions under which the superelevation and radius of the curve were the same In fact the difference between the maximum safe speeds in the two traffic lanes was small because the slight increase in the observed angles on the inside lane due to the sharper curve was offset by the greater superelevation for this lane when compared with the outer lane Accurate observations in tests on curves at the General Motors Proving Ground bear out the conclusion that differences between observed values for right and left turns are negligible if the conditions of test are similar

Effect of Body Roll of Car on Safe Speed

In the reports from the States, a criticism voiced by several engineers was that the maximum safe speed based on a 10 degree ball bank reading varied with the year model and make of car, and that new cars could take curves faster than old cars Now, the only variation in ball bank readings due to differences in cars is that due to differences in the body roll of the car if other conditions remain the same It is to be expected that the indicator is mounted properly at zero degrees with the cars stationary on a level surface, that the speedometers of the cars are accurately calibrated, and that the tires are inflated uniformly if a comparison of cars is to be made The best complete data on differences in body roll for all makes of cars over a five-year period of which the authors have any knowledge has been collected by the General Motors Proving Ground in their roadability tests Through the generosity of Mr A J Schamehorn, Director of the Proving Ground, and Mr Merritt Fox, who supervised the tests and compiled the data, the maximum, minimum, and average values of roll angle for 1936, 1937, 1939, and 1940 cars was furnished as a function of the frictional side force (Fig 3)

It should be noted that for a 10 deg ball bank reading the maximum roll angle was 2 deg 25 min and the minimum roll angle was 1 deg 25 min , which means that a maximum difference of only 1 deg in the ball bank reading can be attributed to differences in cars with tires properly inflated It is true that as the speed is increased above the 10 deg value, the body roll increases and the difference between cars increases proportionately However, the maximum safe speed as indicated by a 10 deg ball bank reading is so far below the maximum permissible speed or maximum possible speed that the differences in the year model and makes of cars is not likely to have any effect on the speed selected, if the observers understand the effect of body roll and make due allowance for it in case cars with extreme values are used for the driving tests

Effect of Inaccurate Speedometers

It is true that many speedometers. particularly of popular priced cars after several years of use, are inaccurate but in the calibration of the speedometers of a score or more cars, the authors have found them to be surprisingly accurate in recent years for speeds up to 50 m p.h ;

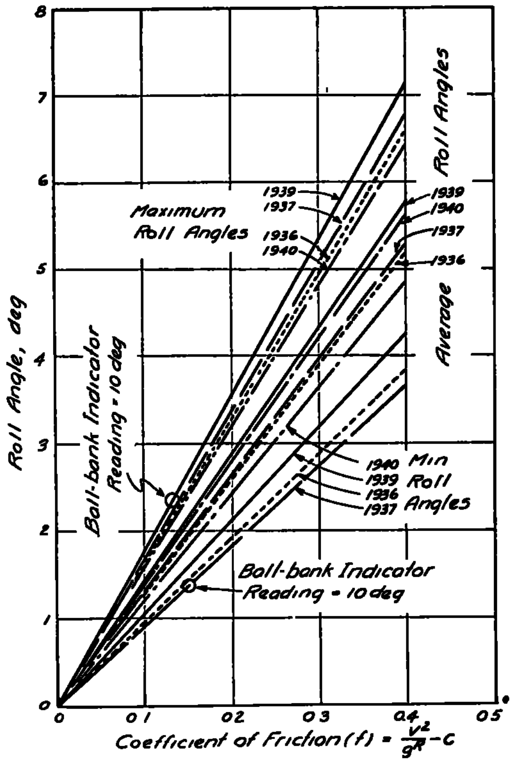

Figure 3. Roll angle of car as function of frictional side force. Average and range of roll angle for 1936, 1937, 1939 and 1940 cars. Test data furnished by General Motors Proving Ground.

the maximum speed which need be considered in marking curves. Generally the extreme error is not over 10 percent and usually the indicated speed is higher than the actual speed Thus, with a 10 percent error the indicated speed would be 44 m p h for an actual speed of 40 m.p.h.

Most drivers know when the speedometer of the car they are driving is in error, especially when the error is greater than 10 percent. With curves marked accurately they will soon decide at what speed in relation to the marked speed they prefer to take the curves, that is, at the marked speed or 5 or 10 miles above or below this speed The most important point which engineers should keep in mind in regard to speedometers is that when establishing safe speeds on curves the trial runs should always be made

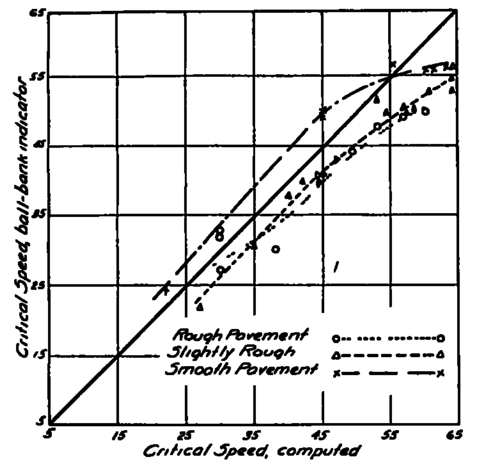

Figure 4. Comparison of critical speeds as determined by formula and by ball-bank indicator on rough, slightly rough and smooth pavements. Illinois Division of Highways.

using cars with accurately calibrated speedometers

Effect of Rough, Slightly Rough, and Smooth Pavements on Safe Speed

The importance of making trial runs at the maximum safe speeds for which a given curve is to be posted is best illustrated when comparing ball bank readings on smooth, slightly rough, and rough pavements using data furnished by the Illinois Division of Highways (Fig. 4). Thus on a smooth pavement the ball bank value of 10 deg was found to establish a safe speed at 39 m p h as compared to a computed speed of 35 m p h On a slightly rough pavement the ball bank indicator established a speed of 38 m p h as compared to a computed speed of 40 m p h , and on a rough pavement the observed safe speed on a given curve was 30 m p h as compared to a computed speed of 38 m p h These results are consistent with the general driving experience on rough surfaces which require reduction in speed when driving close to the critical speed, particularly on curves

With a ball bank reading of 10 deg , a friction factor close to $f = 0\ 15$ is required This means that a friction force equal to about one sixth of the weight of the car must be effective in holding the car on the curve To develop this friction the wheels must be in continual contact with the road surface and if either the front or the rear wheels leave the surface the friction factor at that point reduces to zero temporarily and will cause the car to skid more or less depending on the degree of roughness.

The ball bank readings on rough surfaces are not likely to be consistent at various points on the curve and it is recommended that the average of the lower observed speeds be used rather than the higher speeds in deciding upon the safe speed on these surfaces

Correlating Friction Factor and Ball Bank Readings with Safe Speed

As previously implied, safety on curves is largely dependent upon friction and in establishing the safe speed and understanding of the relationship between friction, the ball bank angles, and speed is desirable. It has generally been accepted by engineers who have conducted curve tests that a speed based on a 10 deg observed ball bank reading provides a safe speed in the usual range for which curves are marked This corresponds to a coefficient of friction of about 0 14 to 0 15 depending upon the body roll of the car The general acceptance of this value is rather surprising because it is after all an arbitrary value at which the driver of a car senses some discomfort and where the hazard of skidding off the curve becomes apparent

As is evident in Figure 5 considerably higher friction values than 0 15 and

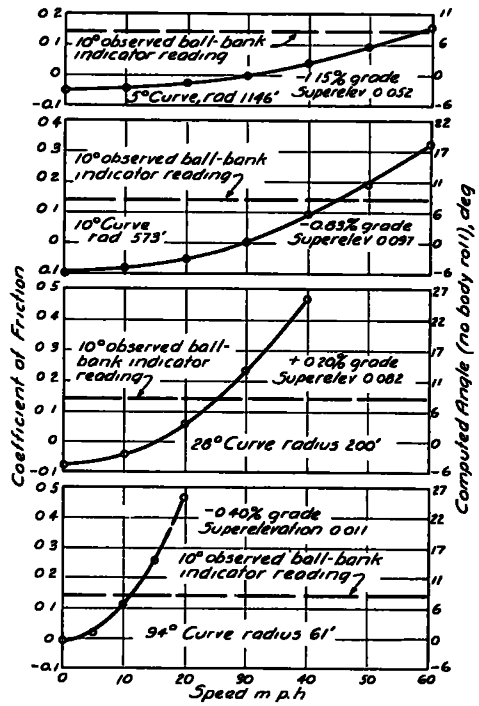

Figure 5. Coefficient of friction and computed ball-bank indicator readings over a wide range of speeds and degrees of curvature.

higher speeds than that for a ball bank reading of 10 deg are possible and, in fact, permissible under certain conditions and on certain curves This is most evident on the sharper ones as the 61-ft and the 200-ft radius curves. On these curves friction values close to 0 5 were developed at speeds almost double the safe speed based on a ball bank reading of 10 deg The ride at these speeds was far from comfortable and the limit of steering control was not far off, in fact, the path of the car was increasingly uncertain as the top speeds on these curves were approached For sharp curves requiring speeds below 30 m.p.h. for a ball bank reading of 10 deg., it would be quite consistent with driving experience to develop a friction coefficient approaching 0 20 at the maximum safe speed or an observed ball bank angle of 12 to 14 deg At these low speeds slight loss of control or variations in the path

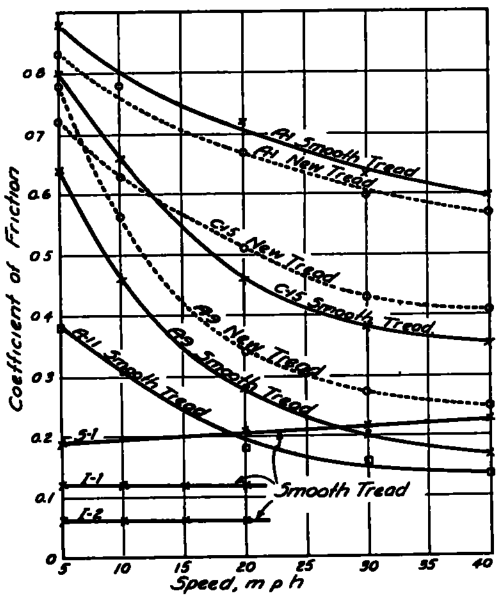

Figure 6. Effect of surface texture and surface condition on coefficient of friction for new and smooth tread tires. All tests conducted on wet surfaces except where noted.

of the car are not serious because in a short distance the error can be corrected but at high speeds this is usually serious because by the time the driver realizes that he is in trouble he may be in an opposing traffic lane or in the ditch For speeds up to 50 or even 60 m p.h , a ball bank angle of 10 deg. has been found to be quite satisfactory but for speeds above 60 m p.h., a lower value should be used. Actually few States are likely to mark curves above 50 m p h and the use of a ball bank angle below 10 degrees is not a problem. Curves requiring speeds of 30 m p h. or less are quite common, and since control is not so difficult at these speeds, ball bank angles of 12 to 14 deg. are recommended, the latter on curves with safe speeds of 20 m.p h. or less

Usually it is implied that the safe speeds apply only when road conditions and driving conditions are favorable, that is, when the surfaces are dry, but when surfaces are wet or covered with snow or ice, it is expected that speeds should be reduced below the posted speed. While it is true that lower friction values are usually developed on wet surfaces than on dry surfaces, and considerably lower on snow- and ice-covered surfaces than on dry surfaces, there is still a large margin of safety on wet surfaces properly constructed and maintained if the low value of $f = 0.15$ at a ball bank reading of 10 deg is used when posting curves on these surfaces.

In Figure 6 the results of skid tests on various surfaces indicate the range of friction values which may be expected for both new tread and smooth tread tires. The asphaltic concrete and similar types with a gritty surface texture or sand paper finish provide a wide margin of safety against skidding for speeds with a ball bank value of 10 deg. The smooth textured belt finished concrete is somewhat lower but still amply safe. The coarser textured broom finished concrete provides higher friction values than the smooth concrete Asphalt or oil mat surfaces glazed with excess asphalt or oil were found to be dangerously slippery at speeds above 20 m.p h. It will be noted that at speeds above 20 m.p h., the friction values on slippery surfaces when wet fall within the range of snow and ice, and that the decrease in coefficient of friction with an increase in speed is greatest on these surfaces It is of interest to note that smooth tread tires provide higher friction values on gritty surfaces than new tread tires while the reverse is true on the smooth slippery surfaces This may be explained by the fact that on the gritty surfaces, the road provides the channels for the water to escape and on the smooth glazed surfaces, the grooves in the tire tread provide the means for water to escape and thus eliminate the lubricating effect of the water

Slippery roads exist because of improper construction and inadequate maintenance Any road can be made skid resistant and kept in that condition A "Slippery Road" sign is a confession of faulty construction or upkeep In most cases the methods to provide skid-resistant surfaces are simple and can be stated in brief terms Generally all that is required is a gritty abrasive surface Bleeding oiled surfaces can be corrected by covering with rock chips or sand rolled into the surface A kerosene cut-back may have to be applied before adding the cover material to provide the necessary binder to hold the aggregate in place after rolling

This analysis shows that drivers can drive safely at the posted speed on properly constructed and maintained surfaces when wet and even when covered with snow free from ice Only on ice-covered surfaces or on slippery wet surfaces are speeds below the posted speed necessary On ice and on snow approaching the ice condition, it is expected that speeds will be reduced on the tangents as well as the curves to a point considerably below the posted speed. Nevertheless, the speed signs provide a definite indication of the sharpness of the curves and will serve as a good guide even when the surface is snowy or icy However, if the surface is slippery when wet, the average motorist is not likely to recognize the slippery condition unless "Slippery Road" signs are used The best solution would be to correct the slippery condition, but if that is not done, the "Slippery When Wet" signs should supplement the speed signs It might be well to follow the practice of the state of Kentucky where the safe speed when wet is posted on the "Slippery When Wet" signs near approaches to curves

Correlating Steering Angles and Steering Forces with Safe Speed

In driving various yearly models and makes of cars, it is generally agreed that there is a difference in the way they handle on curves These differences are most apparent on the sharper curves for which speed restrictions are advisable as recommended in this report They are due to differences in steering angles, steering forces, and in the front and rear wheel slip angles of the various cars as was brought out so effectively in the paper on "Relations between Curvature and Speed" presented by M L Fox at the 17th Annual Meeting of the Highway Research Board In this paper Mr Fox presented data to show the differences between two distinctly different types of cars as far as steering is concerned, one, the understeering type and the other, the oversteering type

The following explanation, based on Mr Fox's paper and the tests and driving experiences of the authors, is offered to indicate certain steering characteristics of cars which should be considered in determining safe speeds on curves When driving a car on a curve at the speed for which a ball bank angle of 10 deg is measured, an average friction force equal to 0 14 of the weight of the car must be developed between the tires and the road to prevent the car from skidding sideways off the road To exert this frictional side force, each pair of tires both front and rear must "slip" at certain definite angles between the path of travel and the longitudinal axis of the wheels These angles are known as slip angles and determine very largely the way the car steers or handles on a curve, that is, whether it is oversteering or understeering.

There are many factors which influence the magnitude of the front and rear slip angles and thus determine whether the car is oversteering or understeering. The average driver, no doubt, assumes that steering is largely a matter of manipulation of the steering wheel although he realizes that the application of the brakes or the use of the throttle on slippery curves has a marked effect on the steering or the path of the car and that at high speed the steering or the path of the car is frequently likely to be unpredictable. Factors besides braking and accelerating which influence the slip angles and the steering of the car are changes in tire pressure front and rear, a shift in load, the size and design of tires, the camber, caster, and front wheel alignment, the type of spring suspension, the use of shock absorbers and stabilizers which are related to the body roll, and other factors of like nature. Only in rare cases will the front and rear slip angles be the same and for this reason oversteering and understeering are the only conditions which are generally recognized in a discussion of the way a car handles on a curve

A clear-cut definition of oversteering and understeering is rather difficult to state, but, in general, a fundamental consideration is that when the rear slip angles are greater than the front slip angles, the car is oversteering and when the reverse is true, making the rear slip angles less than the front, the car is said to be understeering. Thus, when driving on a moderately sharp curve at a critical speed for the given curve with an oversteering car, the slip angles for the rear wheels which are greater than for the front wheels will reach such proportions that either the rear end of the car will skid sideways off the road or the car will go into a flat spin. At high speeds on flat curves it has been found that this extreme condition is not likely to develop according to the results of tests as reported by Stonex and Noble in their paper on "Curve Design and Tests on the Pennsylvania Turnpike" presented at this year's meeting of the Highway Research Board.[1] Instead of skidding or sliding off the road, it was found that the driver of the car was not able to steer it in a true course at high speeds and that the car deviated from this course by increasing amounts as the speed was increased.

In regard to the steering of an extreme understeering car, it has been found that on a moderately sharp curve the slip angles at the front wheels will be greater than at the rear wheels, so that when a certain critical speed is exceeded the front end of the car will slide off the road. Normally when the critical speed is exceeded the understeering car will not go into a spin and is easier to handle on the curve than an oversteering car because it will hold to a fairly fixed course although this course or path is likely to be outside the one the driver intended to take The majority of drivers will use their brakes when the car swerves out of its normal path or goes into a skid. With an understeering car the use of the brakes will generally assist in steering the car into the curve and also will reduce the speed to assist the driver in regaining control The understeering car responds to the normal steering operation in that it requires an increase in the steering angle at the steering wheel as the speed of the car on the curve is increased. In the oversteering car, the reverse is true and only the exceptional skill of the driver can hold the car on a true course above a certain critical speed. The Turnpike tests reported by Stonex and Noble, however, indicated that despite the greater stability of the understeering type car, the first evidence of lack of

[1] See page 429.

control of this type car at high speeds on flat curves was an increase in the devia- there is little difference between an understeering and an oversteering car.

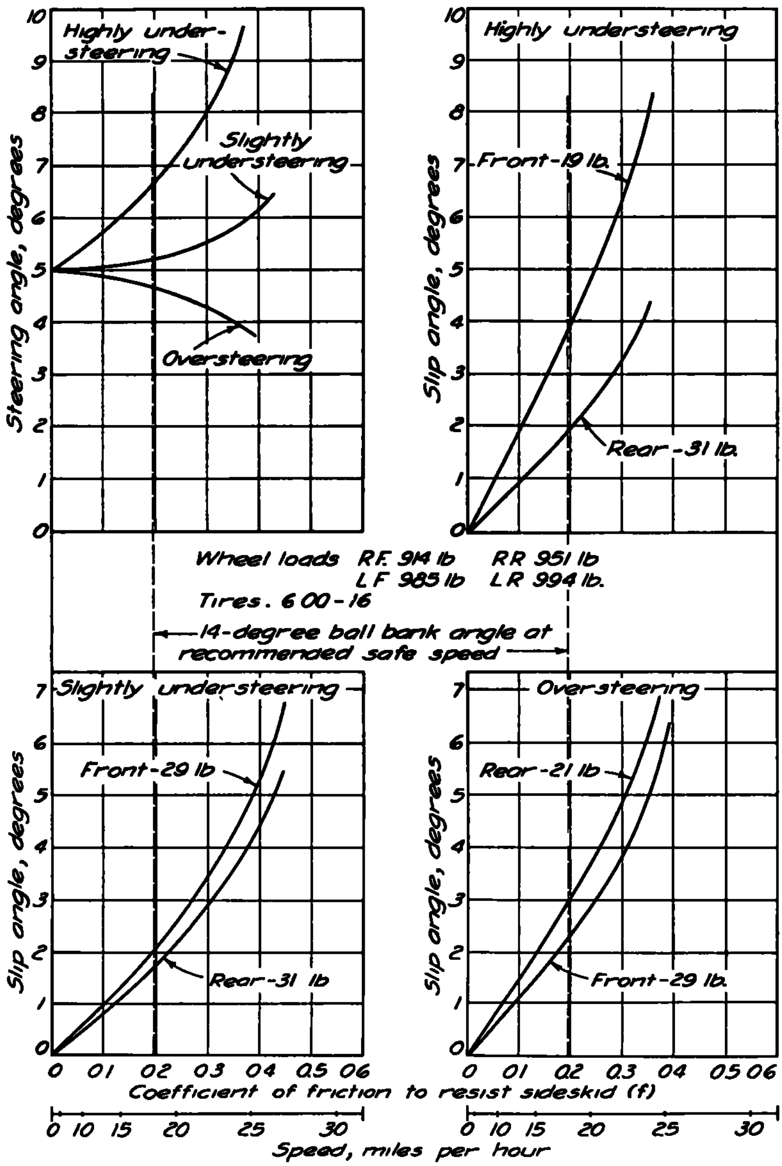

Figure 7. Skid pad roadability test data demonstrating the handling of a car on a 108 ft. radius circle with adjustments in tire pressure only to make the car either highly understeering or oversteering or any condition in between. Data furnished by General Motors Proving Ground. Later published in paper "Car Control Factors and Their Measurement" by K. A. Stonex, S.A.E. Journal, March, 1941.

tion from the path the driver intended to take as the speed was increased above a certain critical value and in this respect

An interesting demonstration is provided in Figure 7 to show that even the same car can be made either strongly oversteering or highly understeering, or any condition in between, by merely making certain adjustments in the front and rear tire pressures These data were furnished by Mr K. A. Stonex of the General Motors Proving Ground[2] and were based on tests on their level concrete skid pad where the car was driven at various uniform speeds on a 108-ft. radius circle It should be noted that the understeering and oversteering characteristics are most evident in the

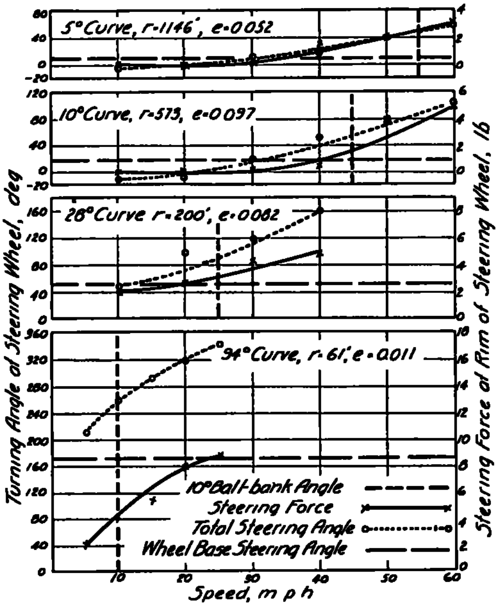

Figure 8. Variations in angles and forces at steering wheel for a wide range in speed on curves near Ames, Iowa.

steering angle curves for the three tire pressure conditions reported With the low pressure of 19 lb. in front and a normal pressure of 31 lb in the rear tires, the car is highly understeering with a marked increase in the steering angles accompanying an increase in speed on this curve. However, when this condition was reversed by using a low pressure of 21 lb. in the rear tires and a normal pressure of 29 lb. in the front tires, the car developed an extreme form of oversteering and for this condition the steering angles were found to be decreasing with an increase in speed. With normal pressures front and rear the car was found to be slightly understeering and the results indicated that this was probably its most stable condition because the front slip angles were only slightly greater than the rear slip angles and it appeared that the highest maximum speed was possible on the given curve under this condition.

Despite the objections to the oversteering car, it should be noted that within the range of speed up to the maximum safe speed recommended for this particular curve based on a ball bank angle of 14 deg., the difference in the steering angles for the extreme under- and oversteering condition is less than 2 deg., an amount so small that the average driver would not notice it. On slippery surfaces larger steering angles and slip angles are required to hold the car on the curve than on highly skid resistant surfaces and for this reason the importance of providing skid-resistant surfaces cannot be overemphasized.

In Figure 8 the variations in the angles and forces at the steering wheel of a 1938 year model car are given over a wide range of speed and curvature. For the 5 deg. and 10 deg. curves the total angle of turn at the steering wheel was less than 60 deg for the maximum safe speed with a ball bank angle of 10 deg. On the 200-ft radius turn it was about 95 deg. and on the 61-ft radius city street corner turn it was 265 deg Turns at the steering wheel less than 90 deg. can readily be made without shifting the position of the hands but if larger angles are required, the hands must generally be shifted and this adds to the uncertainty of steering particularly at high

[2] The data were later published in the March, 1941, S A E *Journal* in a paper "Car Control Factors and Their Measurement," by Kenneth A Stonex.

TABLE 3

Speed Survey at Curves on US Route 40 Both Before and After Erection of Critical Speed Signs—Illinois Division of Highways

Critical speed	No of curves	Before or after	Type of vehicle	No of vehicles	Percentage at speed: Critical speed − 10 m p h	Critical speed − 5 m p h	Critical speed	Critical speed + 5 m p h	Critical speed + 10 m p h
m p h									
25	4	B	Ill Pass	157		8.6	48.0	82.9	95.4
		A	Ill Pass	155		8.4	63.9	81.9	96.8
		B	For Pass	117		4.3	27.4	71.8	90.6
		A	For Pass	154		3.2	55.2	79.9	93.5
		B	Commercial	62		24.2	45.2	85.5	96.8
		A	Commercial	74		9.5	67.6	82.4	92.0
		B	All Veh	336		9.8	39.6	78.3	92.6
		A	All Veh	383		6.5	61.1	81.2	94.5
30	4	B	Ill Pass	145	6.2	13.1	66.9	86.2	97.2
		A	Ill Pass	140	10.7	27.9	72.9	90.7	98.6
		B	For Pass	30	3.3	3.3	53.3	80.0	96.7
		A	For Pass	161	1.2	8.7	55.9	87.0	98.8
		B	Commercial	53	17.0	28.3	92.5	96.2	98.1
		A	Commercial	60	8.3	28.3	81.6	96.7	100.0
		B	All Veh	228	8.3	15.4	71.1	87.7	97.4
		A	All Veh	361	6.1	19.4	66.8	90.0	98.9
45	10	B	Ill Pass	259	40.2	62.2	86.1	94.6	97.7
		A	Ill Pass	217	41.5	75.1	98.2	99.5	100.0
		B	For Pass	138	27.5	59.4	80.4	92.0	95.7
		A	For Pass	284	25.0	60.0	90.1	96.5	98.2
		B	Commercial	102	56.9	73.5	96.1	97.1	100.0
		A	Commercial	140	55.7	90.0	98.6	100.0	
		B	All Veh	499	40.1	63.7	86.6	94.4	97.6
		A	All Veh	641	37.3	69.9	95.0	98.3	99.2
50	11	B	Ill Pass	265	50.9	78.5	88.7	92.5	98.1
		A	Ill Pass	441	60.8	86.8	92.3	95.7	99.5
		B	For Pass	237	47.3	77.2	83.5	89.5	97.9
		A	For Pass	487	40.9	79.9	90.3	94.3	99.8
		B	Commercial	279	74.2	93.9	97.1	98.6	100.0
		A	Commercial	265	86.4	98.1	99.2	100.0	
		B	All Veh	781	58.1	83.6	90.1	93.7	98.7
		A	All Veh	1193	58.3	86.5	93.0	96.1	99.7

speeds On the 61-ft. radius curve the speed with a ball bank angle of 10 deg. was only 10 m.p.h. and thus the large angle presented no difficulty. The forces at the steering wheel for all these curves were small with a minimum of 3 lb. on the 5 deg. curve and slightly more than 4 lb. on the 61-ft. radius curve at the critical speed with a ball bank reading of 10 deg.

Correlating Percentile Speeds with Safe Speeds—Before and After Studies

Before and after studies to determine the effect of safe speed signs on curves were provided by the Ohio Department of Highways (Figure 9) and by the Illinois Division of Highways (Table 3). The South Dakota Highway Commission also provided speed data. In general, the studies indicate that speed signs result in reduction in speeds on the sharp curves requiring low speeds but on flatter curves with speeds above 40 m.p.h. the changes are not so great in the before and after studies.

In 13 of the States speed observations are used to determine the safe speed. The 85 percentile value is most commonly used as the criterion for safe speed although the values used ranged from 50 percent to 90 percent. The Illinois data show that the percentile values are less than 70 percent for curves with critical speeds of 25 and 30 m.p.h. and between 90 and 95 percent for curves with speeds of 45 and 50 m.p.h. This also seems to be borne out by the Ohio data. It would seem logical that the percentile values should be very nearly the same at the critical speed for which the curves are posted. These studies show that at low speeds motorists will exceed the comfortable and "safe" value provided by a ball bank angle of 10 deg. As was shown earlier, at these speeds the margin of safety with a 10 deg. ball bank angle is greater than at the higher speeds. For these reasons a ball bank angle of 12 deg. is recommended for the 25 and 30 m.p.h. speeds and of 14 deg. for speeds of 20 m.p.h. or less.

With these changes there should be closer agreement in the percentile values at the various speeds, especially if the speed comparisons are made after the curves have been posted. There seems

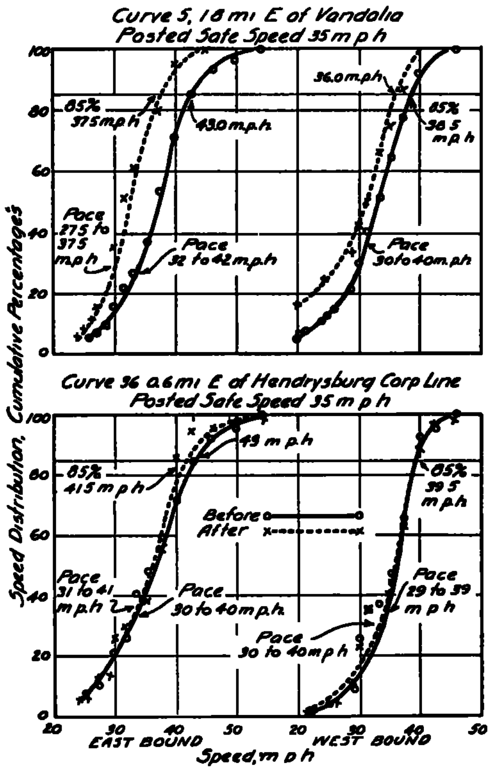

Figure 9. Before and after studies to determine effect of safe speed signs on curves. Ohio Department of Highways.

to be general agreement that speed signs should serve as a guide to motorists and if that is the function of the signs, they should serve to reduce the extremes in the range in speeds, especially the dangerously high speeds. An 85 percentile value for speeds below 35 m.p.h. and a 90 percentile value for speeds above 40 m.p.h should indicate reasonably safe driving and a satisfactory safe speed value.

In this connection, the results of a driver poll conducted by the Illinois Division of Highways with the cooperation of the state police is of special interest Quoting from their report

"The survey was conducted to obtain the reaction of foreign motorists. Two locations were selected At one location east-bound traffic was stopped and at the other west-bound traffic was stopped Foreign cars were stopped at a location which gave assurance that the drivers had operated over a considerable distance on the route. Also, the inquiry was conducted both during the day and night to obtain the reaction of persons operating both in daylight and darkness

"The questions which were asked and the answers given are as follows.

1 Are the signs helpful and do they add to your safety? Yes, 327, No, 4.
2 In general, do you believe the posted speeds too high, too low, all right? Too high, 63, too low, 23, all right, 245.
3. Do you believe the curve signs should be moved farther back from the beginning of the curves to permit greater braking by motor compression? Yes, 94, No, 237.
4 Should signs in advance of sharp curves be farther away from the curve than those in advance of curves of medium or long radius? Yes, 207, No, 291
5 Do you think curves should be marked with speeds higher than 50 miles per hour where such speeds are safe? Yes, 40, No, 291

"Most of the motorists questioned were very emphatic about their approval of the signs, however, several had not noticed the signs and some others had not realized their significance. A truck driver who had driven over this route at regular intervals both before and after the erection of the critical speed signs remarked that since their installation he had noticed fewer cars partially out of control from taking the curves at too high speeds."

Chart to Simplify Field Operations in the Determination of Safe Daytime Speeds

At the recent annual convention of the Institute of Traffic Engineers a paper on "A New Concept of Traffic Sign Reflecterization," was given by Mr R F Riegelmeier in which he presented a chart to simplify the determination of safe speeds on curves The chart applied only to curves with no superelevation and was based on an empirical formula developed by means of road tests with one car only. The method and purpose Riegelmeier had in mind in developing the chart had considerable merit in simplifying field operations when determining safe speeds and with his kind permission the authors have borrowed the general idea he had in mind, developed a formula, and revised the chart to make it applicable generally to all curves and all types of cars (Fig. 10).

The use of this chart as intended by Riegelmeier was to make one trial run on the curve at any given speed and observe the ball bank angle By referring to the chart, a point could be located for the ball bank reading at the given speed. From the curves on the chart, the safe speed for a ball bank reading of 10 deg. could be determined This method eliminated making the many trial runs usually necessary to determine the safe speed. It merited further study for general use Accordingly, formula (11) with the derivation indicated below was developed on the basis of which the new chart was plotted The derivation of the formula is as follows

According to formula (3) referred to earlier in the report,

Ball bank angle = centrifugal force angle − superelevation angle + body roll angle

or $$\infty = \theta - \phi + \rho \qquad (3)$$

The angle due to body roll was found by test to be proportional to the coefficient of friction (f) (see Fig. 3). Thus

$$\text{since } f = \frac{v^2}{g^R} - e \qquad (4)$$

$$\text{then, } \tan^{-1} f = \tan^{-1}\left(\frac{v^2}{g^R} - e\right) \qquad (5)$$

or using a factor K for body roll,

$$\rho = K(\tan^{-1} f) = K \tan^{-1}\left(\frac{v^2}{g^R} - e\right) \qquad (6)$$

$$\text{and } \infty = \theta - \phi + K \tan^{-1}\left(\frac{v^2}{g^R} - e\right) \qquad (7)$$

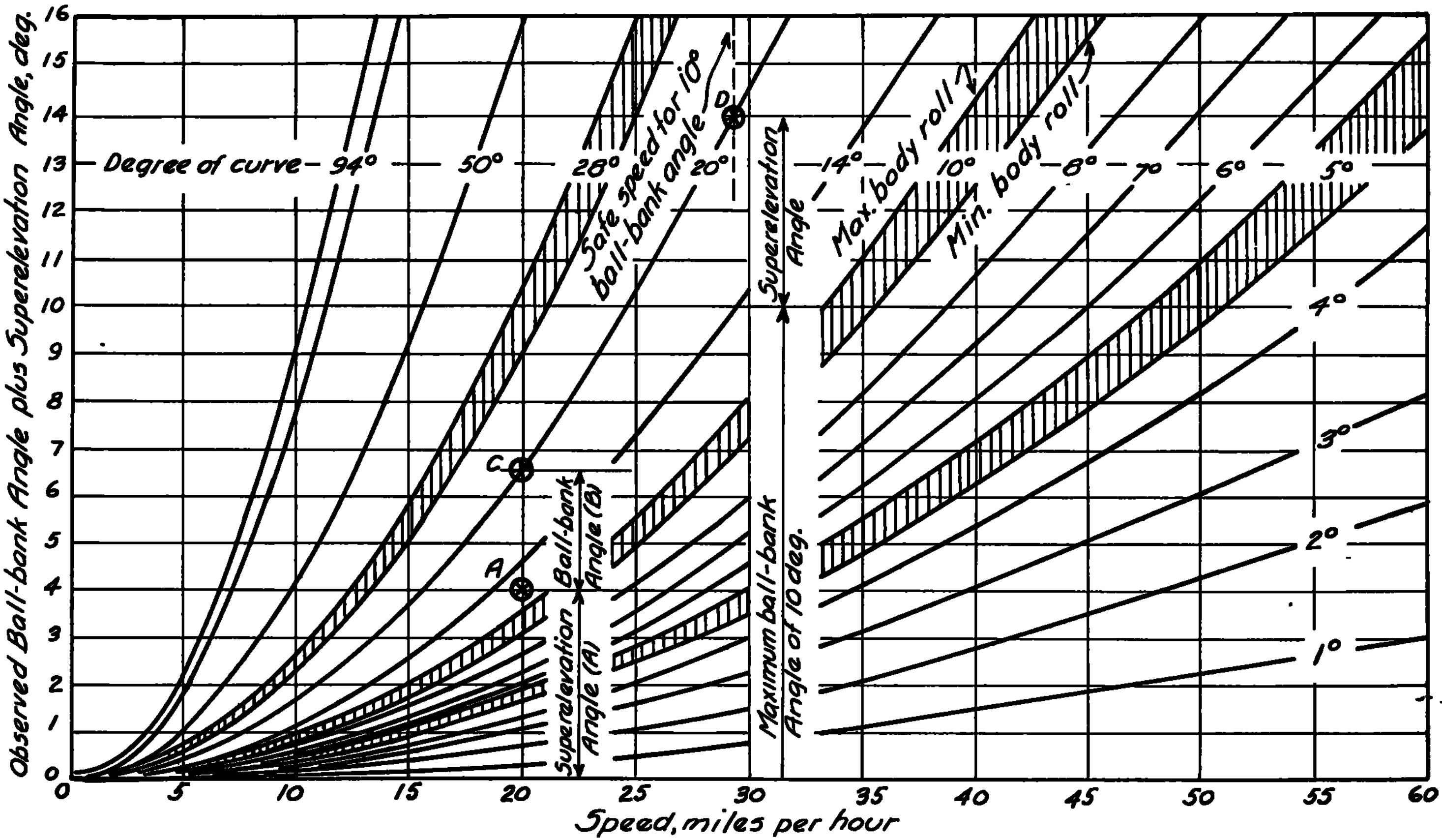

Figure 10. Chart to determine safe speed indications for highway curve signs. Patterned after chart by R. F. Riegelmeier, Traffic Engineer, Pennsylvania Department of Highways

Rule for Safe Speed

Add superelevation angle (A) to ball bank angle (B) observed at any given speed to obtain the total angle (C) Follow curve on which (C) is located to point (D) which is sum of superelevation angle and 10 degree ball bank angle Maximum safe speed for reflectorized sign is the closest speed value for point (D) to the nearest 5 miles per hour

To simplify the application of formula (7) to field operations and permit reading the superelevation direct with the ball bank indicator, formula (7) was revised as follows

For small angles,

$$\tan^{-1} f = \tan^{-1} \frac{v^2}{gR} - \tan^{-1} e \quad (8)$$

$$\text{or } \tan^{-1} f = \tan^{-1} \frac{v^2}{gR} - \phi \quad (9)$$

and

$$\rho = K \tan^{-1} f = K(\tan^{-1} \frac{v^2}{gR}) - K\phi \quad (10)$$

The final formula for the ball bank reading then reduces to

$$\infty = \tan^{-1} \frac{v^2}{gR} - \phi + K(\tan^{-1} \frac{v^2}{gR}) - K\phi \quad (11)$$

The test data in Figure 3 indicate that the maximum, average, and minimum values of K for cars over a five year period are $K_{max} = 0\ 31$, $K_{ave} = 0\ 24$, and $K_{min} = 0\ 16$

These values were used in formula (11) with various values of speed, radius of curvature and superelevation to obtain the curves in the chart (Fig 10)

The rule for determining the safe speed for a ball bank reading of 10 degrees (or for any other reading) is given on the chart. The general procedure, if the superelevation and radius of the curve is not known, would be to stop the car at several points along the curve and read the ball bank angle which for this reading will give the superelevation angle plus the body roll angle with car on this slope (referred to only as the superelevation angle (A) on the chart) The car is then driven at any reasonably safe speed on the curve and the average ball bank angle (B) observed The sum of A and B will locate the point (C) or angle C for the given speed on the chart The observer then can follow the curve on the chart on which C is located to point (D) which is the sum of superelevation angle (A) and 10 deg. ball bank angle (or any other suitable ball bank angle). The maximum safe speed is the closest speed value for point (D) to the nearest 5 m p h although it is preferred to use the lower 5 m p h. value than the higher value Thus, if the point (D) indicated a speed value of 38 m p h , a safe speed of 35 m p h would be preferred for the speed sign instead of a 40 m p h speed For a value of 39 m p h to 43 m p h , the speed selected would be 40 m p h This makes a slight allowance for differences in drivers, cars, and all ordinary road conditions Before accepting this speed as final, a trial run at the proposed safe speed should always be made to make certain that all road conditions and visibility factors are taken into account and that the ball bank reading is close to or at the maximum desired.

It should be noted that the shaded curves show the variations in the ball bank reading at any given speed due to extreme values of body roll The single line curves were computed for a car with average body roll After a few curves have been run, the observers should have little difficulty in finding out if the car used in the driving tests has a small or a large amount of body roll On curves sharper than 10 deg. or for speeds below 40 m p h , the difference in the safe speed due to body roll is indicated as less than 3 m p h

A useful shortcut can be introduced for curves in which the superelevation and radius are known In these cases the safe speed can be read directly from the chart by adding the superelevation angle ($K \tan^{-1} e$) to the ball bank angle of 10 deg (or any other desired angle) and then noting the speed on the chart for this total angle and the degree of curvature for the curve in question Here again it is desirable to make a trial run at the proposed safe speed to check road and driving conditions on the curve. On any given route, the road can be logged and forms prepared to record the curve speed data in a simple form as is shown in Figure 15.

Effect of Headlight Patterns on Safe Night Speeds on Curves

Up to the present time, the safe speeds on curves have generally been the same for nighttime as for daytime driving. The safe speed has largely been determined on the basis of retaining control of the car on the curve. Curve signs and speed signs have been reflectorized because at no time is the surprise element greater than when a driver cruises along at 50 m.p.h. at night and then suddenly without adequate warning hits a 25 m.p.h. curve. The reflectorized speed sign has removed this surprise element at night and, as far as control of the car on the curve is concerned, the driver should have little difficulty at the indicated speed. Night driving, however, presents the special hazard of poor visibility and the question has been raised by some engineers as to whether or not the light patterns which the headlights of cars provide have a wide enough spread and range to provide satisfactory sight distances for various degrees of curvature at the speeds established as safe for driving in the daytime. Information on this subject was very meager and for this reason the authors decided that some study should be given the problem and included in this report.

Fortunately, Dr. A. R. Lauer and his assistants, on the Highway Research Staff of the Iowa Engineering Experiment Station, had developed some excellent equipment to measure the light intensity of headlights The light patterns of the headlights of two makes of cars were measured, one a 1938 car with dual-beam headlights and the other a 1940 car with the newly developed sealed-beam headlights. The measurements were taken on the level dark dirt floor of the College armory with all lights turned off in the building. The light measurements were taken with a cluster of five Weston photoelectric cells with viscor filters which transmit only the light affecting the human eye The cells were mounted on an adjustable arm with the cluster of cells on approximately a 5-in. circle from the center of the cells. The output

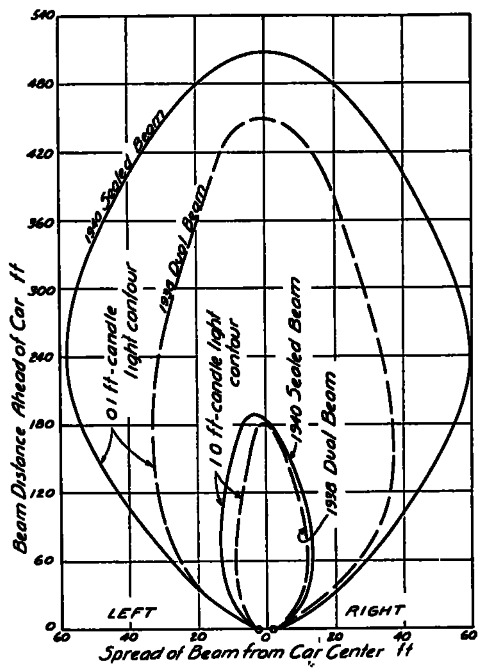

Figure 11. Light patterns for a 1940 car with sealed-beam headlamps and a 1938 car with dual-beam headlamps showing light contours for 1.0 ft.-candle and 0.1 ft.-candle of light.

of the cells was measured with a portable galvanometer. The results of the tests are given in Figure 11 showing the pattern in light contours for 1.0 ft-candle and 0.1 ft.-candle of light The improved illumination and wide spread of the light pattern for the sealed-beam headlights is clearly shown here when compared with the old type headlights. Both headlights were in excellent condition.

In applying the light patterns for the

headlights to determine the safe speed on horizontal curves, the 0 1 ft-candle contour was selected as a reasonable amount of light intensity and was plotted to scale on a two lane roadway with 5, 10, 15, and 25 deg curves (Fig 12) The cars, roadway and light distances are all drawn to the same scale The spacing was measured between the headlights of the car and the point where the speed is safe on the 25 deg curve for all conditions day and night, but with the flatter curves and the higher speeds, the required stopping distances increase rapidly and the light intensity drops off at such a rate that the safe night speed is lower than the safe day speed This difference in night and day speed is more marked if the more conservative perception and reaction time of 3 sec

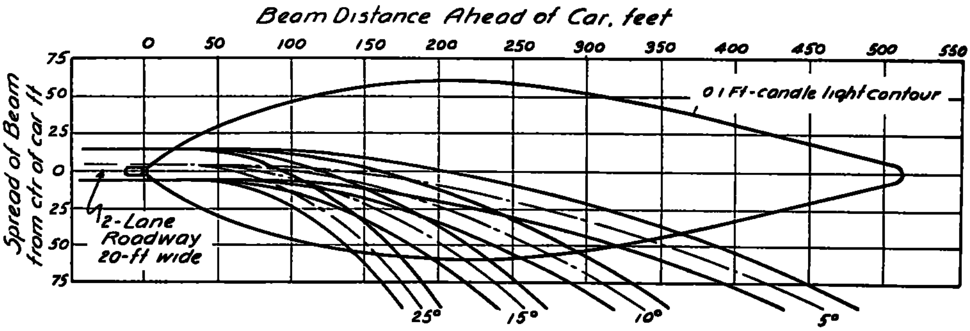

Figure 12. Application of light patterns for sealed-beam headlights in the determination of safe speeds at night on horizontal curves

Degree of curve	Safe day speed for ball-bank angle at 10°	Safe night speed (sealed beam): 3 sec perception and reaction time (friction factor "f" = 0 4)		Safe night speed (sealed beam): 1 sec perception and reaction time (friction factor "f" = 0 4)	
		Stopping distance	Speed	Stopping distance	Speed
	m p h	ft.	m p h	ft	m p h.
5	60	310	40	332	55
10	45	257	35	235	45
15	35	207	30	153	35
25	25	162	25	89	25

car ahead on the given curve was just passing through the 0.1 ft-candle contour of the headlight. This spacing for the sealed-beam headlights was then compared with the corresponding stopping distances required for various speeds on the curve using a 3-sec perception and reaction time and a braking friction factor of $f = 0\ 4$ and also with stopping distances with the same friction factor but a perception and reaction time of 1 sec It will be noted that the 25 m p h is used instead of the 1 sec perception and reaction time value If the latter value of 1 sec is used, the differences between day and night speeds are small for cars with the sealed-beam headlights

The question may be raised as to why the 0 1 ft-candle of light intensity was used instead of a higher or lower value. The reasons are as follows Tests have shown that the 50,000 candle-power sealed-beam headlights provide ample visibility to make a white object visible at a distance of 1,000 to 1,200 ft. directly ahead of the car A gray object can be seen at a distance of about 800 ft. and a black object at 400 ft. The maximum safe night speed on a straight road is a controversial value but for the average car, a speed of 50 m.p h is commonly accepted. With sealed-beam headlights in excellent condition a maximum speed of 60 m p.h is not so commonly accepted but, when compared with ordinary headlight visibility, it can be considered as an acceptable value. The stopping distance at 60 m p.h. with a 3-sec. perception and reaction time is 564 ft and with a 1-sec value is 388 ft. The 0.1 ft -candle contour cut the path of the car straight ahead at 510 ft. and was selected as the degree of illumination required to see with sealed-beam headlights any ordinary hazard encountered straight ahead on the highway at night when traveling at 60 m.p.h and still be able to stop the car within this sight distance. The value selected is entirely arbitrary and further study may indicate the need for revision but it is believed to be in line with the present speed practices of traffic at night.

The above study, limited in scope as it was, indicated that the safe night speeds on curves which are not protected with reflectorized marker posts are practically the same as safe day speeds for curves sharper than 15 deg requiring speeds of 35 m.p h. or less but on curves flatter than 15 deg , a reduction of from 5 to 15 m.p h in the night speed as compared to the day speed is desirable. The reduction of 15 m p h. should apply to the 4- or 5-deg. curves with safe day speeds of 60 m p h.

Marking highways for a lower night speed than the day speed is not a difficult item to handle and has been done effectively by the use of a reflectorized sign in which the painted numbers indicate the day speed and the reflectorized buttons the night speed.

Safe night driving on curves has been greatly improved by the use of reflectorized marker posts which reveal the curve over its entire length. On a level road the reflectors will pick up the light rays from the headlights when the car is still more than one half mile from the curve, thus giving the driver ample warning in regard to the location of the curve and its sharpness, particularly when the reflectorized posts are combined with a reflectorized curve sign and speed sign The Ohio Department of Highways uses road edge delineators spaced at intervals which vary according to the degree of curve. Table 4 shows

TABLE 4

Degree of curve	Spacing	Tangent spacing on transitions to curves			
		First post	Second post	Third post	Fourth post
	ft.	*ft*	*ft*	*ft.*	*ft.*
0° to 2° 44′	200	200	200	200	200
2° 45′ to 3° 29′	160	200	200	200	200
3° 30′ to 4° 44′	120	160	200	200	200
4° 45′ to 7° 14′	80	120	160	200	200
7° 15′ and over	40	80	120	160	200

the recommended spacings for various degrees of curves.

The spacings for the curve listed in Table 4 at the P C. of the curve are continued to the P T. or as near the end of the curve as the regular spacing happens to come. On the sharper curves the spacing is then increased on the tangent transitions until the maximum spacing of 200 ft is reached as recommended in the table. The delineators on the inside of the curve should be placed radially opposite those on the outside of the curve Although placing delineators on both the inside and outside on the curve is preferred, satisfactory results may be obtained by marking the outside of the curve if delineators are used to mark curves only where safe speed indications will be required for speeds below 50 m.p.h.

In general, the driving experience on curves marked with delineators has indicated that the safe night speeds on these curves may be the same as the safe day speed determined by a ball bank indicator reading of 10 deg. on these curves.

The combined use of reflectorized marker posts and reflectorized speed signs on curves with safe speeds of less than 50 m.p.h. is certain to make night driving on these curves safer than if this aid is not provided to guide the motorist.

TYPES OF CURVE SPEED SIGNS AND LOCATION OF SIGNS

The curve speed signs are usually considered as information signs and are combined with the curve sign which is a warning sign. The usual type of curve speed sign is a square or rectangular sign with black numbers and letters on a white background placed directly below the curve sign. In the states of Arizona and Illinois the colors are reversed by providing a black background with white letters which their engineers contend provides a more distinctive and more legible sign for both day and night driving.

The height of the numbers ranges from a minimum of 4 in. to a maximum of 12 in. with a 6-in. height most commonly used. To provide the amount of legibility required to make the speed sign most effective day and night, a minimum height of 6 in. for the numbers is recommended. This requires that the size of the sign be at least 12 by 13 in.

Figure 13 shows the distinctive features of the Illinois speed signs with the white letters on the black background in the daytime and the improved reflectorization this method provides at night.

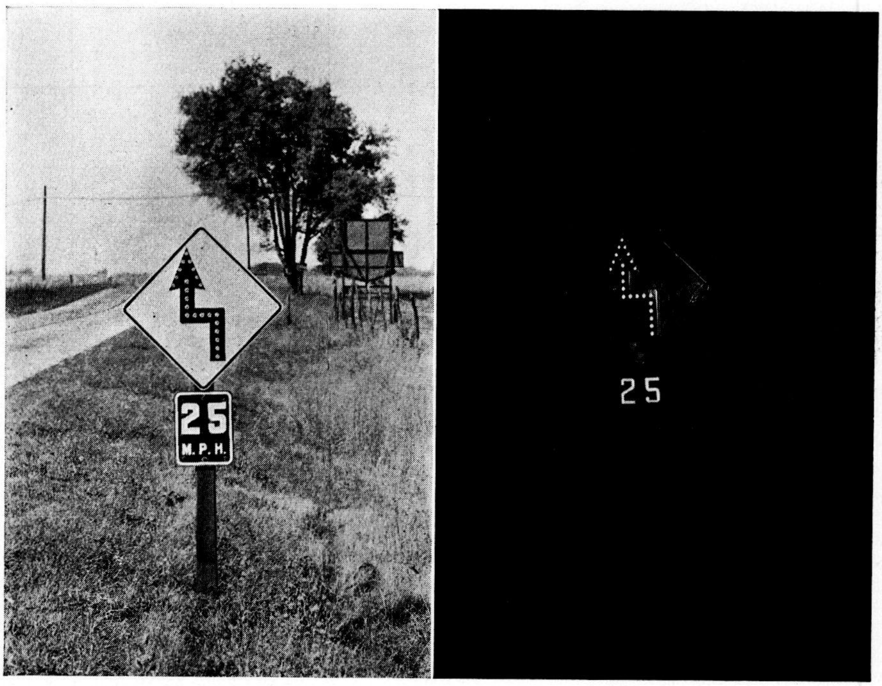

Figure 13. Day and Night View of 25 m.p.h. Reverse Curve Sign in Illinois

The Michigan State Highway Department does not mark curves with safe speed signs but indicates the degree of hazard on the curve by the type of symbol used on the sign (Fig 14). Thus for curves up to 2 deg. no curve sign is used. As the curvature increases the sharpness of the curve in the symbol increases in three stages until the turn symbol is reached. The turn symbol is used on all sharp right-angle turns, a practice common to all States. This method has also been used in Iowa but was abandoned because it was felt that the

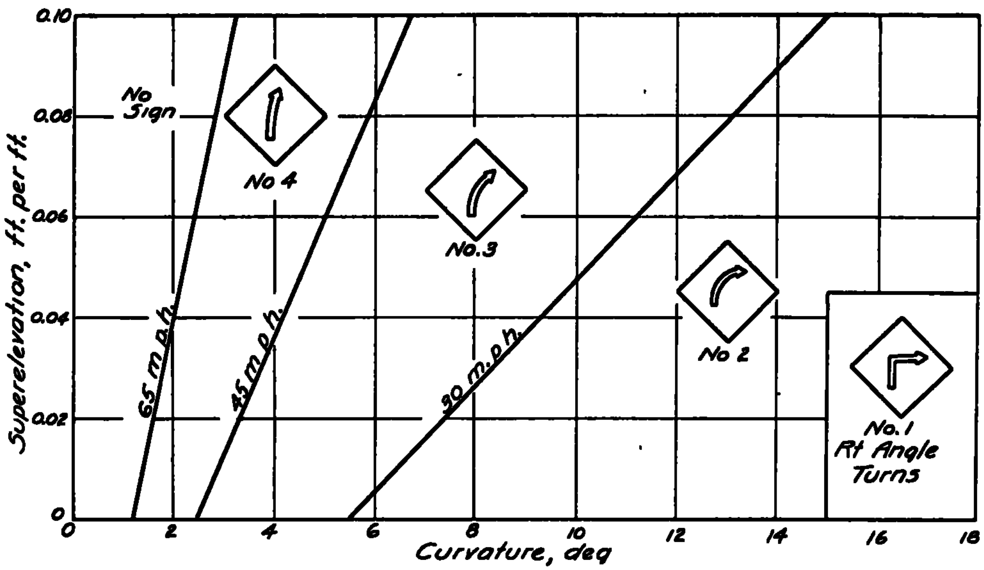

Figure 14. Michigan State Highway Department curve sign application chart showing type of sign used for varying conditions of curvature, superelevation, and speed

motorist could not distinguish between the speed requirements for the flat and intermediate type curve signs. The only sign the motorists seemed to understand in regard to the speed requirements was the turn sign and for this reason only two types of signs are used, the curve sign and the turn sign.

In the paper by Riegelmeier from the Pennsylvania Department of Highways, referred to previously, he proposes that the degree of hazard be indicated by the type of sign used with special attention to reflectorization. His recommendations for curve signs take into account the hazard on the curve in terms of the ball bank reading at 50 m.p.h. and are as follows:

Ball bank indicator angle at 50 m p h	Type of curve sign
0°– 3°	None
3°– 6°	Plain
6°–10°	Luminous paint
10° and higher	Reflector button with safe speed sign

He further recommends that if a particular curve shows a record of three or more serious accidents within a year, the procedure should be to use the next highest type of sign. On curves where the hazard is unusually great, oversize curve signs with large reflecting elements should be the next step to indicate an increase in the hazard where the standard reflectorized speed sign is already in use. Electrically illuminated units offer a further increase in visibility.

MEANING AND VALUE OF CURVE SPEED SIGNS

Legal Limit Versus Recommended Value

Only in four States out of the 25 in which curves are marked, is the speed indicated on the signs used as a legal limit. In all of the other states the speeds are recommended speeds only as an aid to motorists. In two of the four States the marking of curves with safe speeds is a part of a program of speed zoning and the speeds on the signs are required to be considered as legal limits to comply with the speed laws of the state. There was some indication that a number of states not now marking curves have not been doing so because of the legal limitations in regard to speed signs and speed limits. Texas is proposing to meet such a situation by calling the speed signs information signs and informing motorists as frequently as is necessary of the meaning of the speed signs by using a large sign 19 by 48 in. with the following legend. "Signs Show Limits of Reasonable Speed for Average Conditions."

On the basis of all the replies from States in which speed signs on curves have been used, there is every indication of unanimous approval of the general idea of marking curves with speed indications and in no case where it has been used has it been abandoned. Also the motorists are for it and from such accident data as are available, there are indications that accidents and accident costs are definitely reduced where curves are marked. For these reasons, the authors recommend that in states where legal limitations or technicalities hamper the work of the engineer in marking curves, steps be taken to correct this situation either by the proposed Texas plan or by legislation at the earliest possible date.

Value of Speed Signs on Curves in Accident Reduction

Very little accident data are available in which before and after experience is provided to show the value of marking curves with safe speed indications. The Indiana State Highway Commission reported that signs indicating safe speeds on all curves on a 95-mile section of Route 37 between Indianapolis and Paoli were installed in 1939. At the end of the year in which these signs had been in place, the records showed that despite a 15 percent increase in traffic on this 95 mile section, in comparison with the preceding 12-month period, there were 10 fewer fatalities, 12 fewer persons injured, 36 fewer accidents on curves, 33 fewer persons injured on curves, and 7 fewer fatalities on curves with approximately $9,000,000 less property damage. Such a report is encouraging to say the least, and while the reductions indicated may be exceptionally high, there should be little doubt but that marking curves played a large part in the change during the 2-year period.

RECORDS AND FORMS FOR MARKING CURVES

Marking all curves on an entire state highway system with speed signs involves considerable work first in the determination of safe speed values and second in installing the signs. As was indicated in the discussion of the use of the chart in Figure 10, one of the purposes of this report was to present a simple short-cut method for the determination of the safe speed value which the authors believe can be accomplished by the use of this chart. In fairly open country a driver and an observer should be able to log and determine safe speeds on 200 miles of route per day. A form such as is used by the Ohio Department of Highways (Fig. 15) helps to systematize the work and to provide a record which can be kept in a file on a route number basis or by counties In many cases much of the information can be obtained from the construction plans and in such cases stops on the curves will not be necessary and the field work further simplified. Trial runs at the proposed speeds should always be made and this information should be correlated with speed surveys of traffic on representative curves.

this service to the motorists, there seems to be little question but that it is money well spent.

For the most effective use of speed signs special attention should be given to the location of the signs with respect to the beginning of the curve. The location procedure of the Illinois Division of Highways (Table 5) takes into account the elements of changes in speed required and

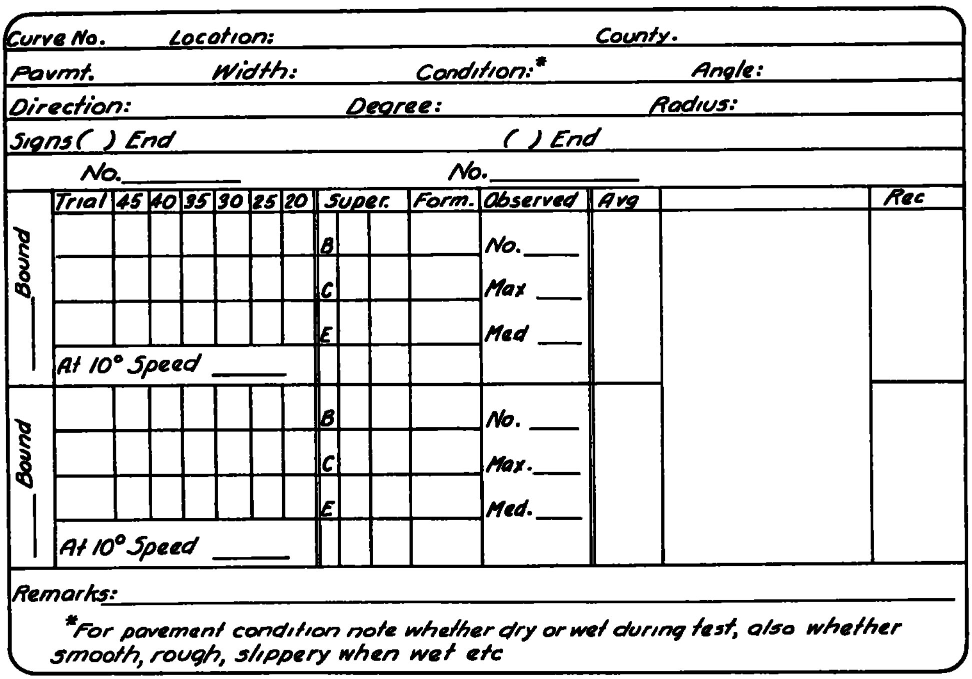
Curve No. Location: County.
Pavmt. Width: Condition:* Angle:
Direction: Degree: Radius:
Signs ( ) End ( ) End
No.____ No.____
Trial 45 40 35 30 25 20 Super. Form. Observed Avg Rec
Bound
B C E
No. Max Med
At 10° Speed
Bound
B C E
No. Max. Med.
At 10° Speed
Remarks:
*For pavement condition note whether dry or wet during test, also whether smooth, rough, slippery when wet etc

Figure 15. Form used by Ohio Department of Highways in Determining safe speed on curves. Printed on a 5-in. by 8-in. card

The installation of the signs is quite an undertaking but it can be so organized as to greatly simplify the work In most states the speed signs are placed on the same post with the existing curve sign. With such a procedure, the installation can be made quickly and easily. In some states new posts will be required. This adds greatly to the cost of installation and should be avoided. Actually when comparing the cost of marking a given curve as compared to the value of

the effect of grade which should be considered in locating signs. The values in this table appear to be reasonable and are recommended for general use.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The following summary statements, conclusions, and recommendations represent the more important findings in this investigation:

1 Since the first curves were marked

with safe speed indications in Missouri in 1937, 25 States have adopted this plan on an experimental basis or as standard practice

2 The ball bank indicator is the simplest and most widely used device to measure safe speeds now in use by the various State highway departments

TABLE 5

LOCATION PROCEDURE ILLINOIS DIVISION OF HIGHWAYS

Critical speed of curve	Critical speed sign	Distance between sign assembly and P C of curve[a]
m p h	*m p h*	*ft*
0–12	10	800
13–17	15	800
18–22	20	800
23–27	25	700
28–32	30	700
33–37	35	600
38–42	40	500
43–47	45	400
48–52	50	400
53–57	50	400
58–62	None	400
Above 62	No speed sign and also no curve sign	

[a] For descending grades exceeding 3 percent this distance should be increased approximately 100 ft

Note Standard curve and turn symbols are used as usual

3 A ball bank angle of 10 deg is the usual value used to establish the safe speed

4 To obtain the driver's respect for the speed on the sign over a wide range of speed, the following ball bank angles to determine the safe speed are recommended 14 deg for speeds below 20 m p h, 12 deg for speeds of 25 and 30 m p h, and 10 deg for speeds of 35 m p h and higher

5 The safe speed can be computed using the standard curve formula with a friction factor of $f = 0.21$ for speeds below 20 m p h, $f = 0.18$ for speeds of 25 and 30 m p h, and $f = 0.15$ for speeds of 35 m p h and higher

6 Trial speed runs at the established safe speed using a car with an accurately calibrated speedometer should be made before the curve is marked

7 The established speed should be verified on certain typical curves by before and after speed studies of both day and night traffic.

8. A percentile value of 85 percent for curves of 30 m p h or less and 90 percent for curves with speeds of 35 m p h indicates a satisfactory speed value

9. The extreme effect of body roll of various year model and makes of cars is only about one degree in the ball bank angle and provides a difference of about 3 m p h in speed

10 The ball bank readings on rough pavements may be 1 deg to 2 deg higher than on smooth pavements, thus indicating approximately a 5 m p h lower safe speed on rough pavements than on smooth pavements

11 The only condition in which the ball bank angle of 10 deg or higher will not indicate the safe daylight speed is when the surfaces are slippery when wet, or ice or snow covered

12 Slippery when wet surfaces should be so marked and lower safe speed values established for this condition than that obtained using the 10 deg ball bank angle speed value.

13 Differences in steering properties of cars present no difficulties if the cars are operated within the safe speed for a ball bank value of 10 deg except on slippery surfaces where lower speeds are required

14 The field tests to determine the safe speed using a ball bank indicator can be greatly simplified by using the chart in Figure 10 developed in this study

15. Safe night speeds for sealed-beam headlights as determined in this investigation were found to be the same as safe day speeds on sharp curves and at speeds below 30 m.p.h. At speeds above 30 m.p.h. the safe night speeds were found to be 5 to 15 m.p.h. lower than the safe day speeds.

16. Black letters 6 in. high on a white background using a sign 12 by 13 in. are used most widely although white letters on a black background provide a more distinctive and more legible sign for both the day and night conditions.

17. The speed sign should preferably be placed directly below the curve sign.

18. The degree of illumination and reflectorization of curve signs and of speed signs may be used as an indication of the extent of the hazard on the curve.

19. The reflectorizing of all speed signs on curves is recommended for safe operation at night when the curve hazard is greatest. The delineation of highway curve for night driving by the use of reflectorized marker posts spaced 50 to 100 ft. apart will permit the use of the same safe speed indications for night as for day driving as far as the curve hazard is concerned.

20. Curve speed signs are an aid to motorists to eliminate the surprise element experienced on sharp curves not adequately marked.

21. Speed marking of curves has the general approval of drivers, particularly for foreign cars, on the basis of driver polls. The safe speeds on curves based on a careful engineering study are more dependable than the speeds based on the quick decision and judgment required of the driver upon entering the curve.

22. Present indications are that curves marked with uniform standard type speed signs will reduce congestion and accidents on curves.

23. The indicated speeds on the signs should preferably be used as recommended speeds only and not as legal speed limits.

24. The speeds should be indicated to the nearest 5 m.p.h. with greater weight given to the lower speed value to allow for slight differences in cars, speedometers, drivers, and road conditions.

25. In a series of connected curves the lowest safe speed of the series is preferred and should be placed at the approach to the first curve. On a winding road, the given section can be zoned and occasional signs placed along the route where the hazard is greatest.