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Program

RESEARCH RESULTS DIGEST

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Side-Friction Factors in the Design of Highway Curves

An NCHRP staff digest of the essential findings from the final report on NCHRP Project 20-7, Task 4, "Lateral Accelerations and Lateral Tire-Pavement Forces in a Vehicle Traversing Curves Relating to Available Pavement Skid Resistance Measures," by Don L. Ivey, Hayes E. Ross, Gordon G. Hayes, Ronald D. Young, and John C. Glennon, Texas Transportation Institute, Texas A & M University, College Station, Texas. This project was proposed by the AASHTO Standing Committee on Engineering Research.

THE PROBLEM AND ITS SOLUTION

In the design of horizontal curves for highways, practicality requires that significant reliance be placed on the resistance of the pavement surface to lateral slippage of the vehicle. The AASHTO curve design standards, for which the classic point-mass equation is the foundation, account for lateral pavement skid resistance through modification of the equation. These standards, first published in 1941, and again in 1954 and 1965 with only slight revision, have been based mainly on an intuitive understanding of the problem because of the very limited amount of experimental data that has been available. Although significant advances have been made in the acquisition of knowledge regarding pavement skid resistance since the standards were last published in 1965, the question of how much lateral resistance should be available or required has not been answered rigorously to this day. Fortunately, driver discomfort in undergoing the centrifugal force present when rounding curves designed to current standards usually becomes a controlling influence before the lateral skid resistance of the pavement surface is exceeded.

During the past few years, skid-resistance research has been greatly accelerated both in the United States and abroad. Within the National Cooperative Highway Research Program five major studies, including the study that is the basis for this report, have been active. The others are Project 1-12, "Determination of Pavement Friction Coefficients Required for Driving Tasks;" Project 1-12(2), "Locked-Wheel Pavement Skid Tester Correlation and Calibration Techniques;" Project 1-12(3), "Requirements for Wear-Resistant and Skid-Resistant Highway Pavement Surfaces;" and Project 1-14, "Influence of Combined Highway Grade and Horizontal Alignment on Skidding."

The research objective of the project that this digest covers was to provide an evaluation of current AASHTO curve design standards as presented in the AASHTO publication, *A Policy on Geometric Design of Rural Highways*, 1965 edition, and to provide the information necessary to substantiate any proposed changes in these curve design standards. The study relates to one part of a complex system of interaction between driver, vehicle, and pavement, and is restricted primarily to those physical characteristics of the vehicle and the pavement that influence the critical cornering maneuver.

The approach selected to achieve the objective of this study included: (1) use of mathematical simulations of motor vehicles traversing highway curves; (2) evaluation of the mathematical simulations by means of full-scale vehicle tests; and (3) use of the mathematical simulations in parametric studies to evaluate current AASHTO curve design standards. An advanced simulation model, CALSVA, developed at the Cornell Aeronautical Laboratory (now Calspan) by Raymond McHenry, was modified for use in this study. Full-scale tests with two vehicles, a 1964 Ford and a 1971 Pontiac, were used to validate the simulation. The Ford was equipped with new bias-ply tires and the Pontiac with new belted tires. The critical cornering speeds for the two vehicle/tire combinations were established over a wide range of curve radii. The same tires were used on an ASTM Method E-274 locked-wheel tester and on the mobile tire tester of the University of Michigan's Highway Safety Research Institute to determine pavement skid resistance and cornering slip resistance factors for use in the simulation models. Data from current and past research by others in the skid-resistance field also were used in the evaluation process.

A modified point-mass equation, similar to the classic equation upon which current AASHTO design standards are based, was also used in the analysis. The classic equation is

$$e + f = \frac{V^2}{15R} \qquad (1)$$

in which e = rate of pavement superelevation (ft/ft);
f = side friction factor;
V = vehicle speed (mph); and
R = radius of curve (ft).

The modification, which permits consideration of variations in available tire-friction with speed, is

$$V_{cr} = \frac{Q_1 \pm \sqrt{Q_1^2 - 4Q_2}}{2} \qquad (2)$$

in which
V_{cr} = critical vehicle speed (mph);
Q_1 = $15RK_v$;
Q_2 = $15R\,(40K_v - f_{40} - e)$;

K_V = slope of f vs speed line (negative number); and
f_{40} = side friction factor at 40 mph.

The adopted modification became possible when it was found during the tests that a roughly straight-line relationship existed between locked-wheel skid resistance and speed within the range of the parameters tested.

The modified equation was found to produce curves of predicted critical speed that agreed substantially with full-scale test data for the two pavement surfaces, two tire types, and two vehicles used in the study when the side friction factor is considered equivalent to 1/100 x Skid Number (SN) determined with the vehicle tire mounted on the ASTM skid trailer. Although additional data covering different tires and pavements are needed to better interpret the results as they apply to AASHTO curve design procedures, this study provided means of incorporating the friction/speed relationship of tire-pavement interactions, which is referred to as the speed sensitivity coefficient (K_v) in this report, into the evaluation of existing curves and in the design of new curves when the speed sensitivity is other than that assumed in the AASHTO curve design standards. For at least the vehicle, tire, and pavement combinations investigated, the pavement skid resistance as measured by an ASTM locked-wheel skid tester is an adequate representation of the relative ability of the pavement to resist lateral skidding.

FINDINGS

The results of this study indicate that the AASHTO geometric design policy will in most cases provide safe, conservative designs for highway curves. When comparing the AASHTO maximum design speeds* to the critical cornering speeds (speeds at which skidding occurs), mathematical simulations using the equation developed herein show that in one state the AASHTO design speed could be achieved without skidding during cornering on approximately 96 percent of the surveyed pavements if these pavements were used on the most critical AASHTO combinations of superelevation, curvature, and speed. It is predicted that this AASHTO maximum design speed could not be achieved safely while traversing curves on the remaining small percentage of these pavements because of their extremely low skid resistance.

In this study the critical cornering speed was derived as a function of vehicle/tire and tire properties. Further studies of available skid resistance are needed nationwide to better interpret the results of this study as they apply to AASHTO curve design procedures.

It is concluded that the AASHTO curve design policy has remained a viable and reasonable recommendation since its initial adoption in 1941. It is believed, however, that the real factors of safety with which the motoring public is confronted should be better understood by those applying the policy to highway design and operation. Emphasis should be placed on the way the factor of safety (defined as the ratio of the maximum speed at which a curve can be traversed divided by the AASHTO maximum design speed) can be expected to deteriorate with low tire-pavement friction values, with poor vehicle cornering characteristics, with erratic driver behavior, and with operating speeds exceeding the AASHTO design speeds.

The specific findings of this study have been classified as "direct" and

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*AASHTO maximum design speed relates to AASHTO-recommended combinations of superelevation, curvature, and speed that fully utilize the friction AASHTO has assumed to be available.

"indirect" for the purpose of distinguishing between those that were derived directly from the data developed during this study, and those that are indicated by mathematical simulation studies using the equations developed herein.

Direct

1. For automobiles equipped with tires similar to those used for the empirical measurement of tire-pavement friction, the mathematical relationships developed in this study provide reasonable estimates of their cornering capabilities within the ranges of the parameters subjected to test (see Figs. 1, 2, 3, and 4).

2. Both Skid Number (SN) and Cornering Slip Number (CSN) were considered as indicators of lateral skid resistance (side friction factor) during cornering. Of these two, SN appears to be the better indicator of the side friction factor for the common understeering vehicle. Differences related to the parameters of study were identifiable only when curve radii exceeded about 800 ft (see Figs. 1, 2, 3, and 4).

3. Although the magnitude of wheel load has some effect on skid resistance, its over-all effect in the computation of critical cornering speeds appears negligible for the vehicles, tires, and pavements investigated in this study (Fig. 5).

Indirect

1. The current work has re-emphasized the importance of the effect of the speed gradient of pavement skid resistance on critical cornering speed (Fig. 5).

2. For conventional sedans, a safety factor of 1.0 (no margin of safety) is encountered when traversing curves at the AASHTO maximum design speed when the Skid Number* is approximately 20. This assumes that the speed sensitivity coefficient** is not greater than -0.002 (Fig. 6). The safety factor deteriorates rapidly with increases in speed sensitivity (compare Figs. 6 and 7).

3. If a Skid Number of 35 exists on a curve, coupled with a speed sensitivity coefficient not greater than -0.002, the safety factors which will be encountered on curves when traveling at the AASHTO maximum design speed will have values over about 1.2 at superelevation rates between -0.02 and +0.12. These safety factors will diminish for vehicles with cornering capabilities significantly poorer than the sedans tested, whether due to deterioration of steering and suspension systems, vehicle geometric and dynamic properties, or worn tires.

4. As a consequence of direct conclusions 1 and 2, modified point-mass equations can be used to approximate critical cornering speeds. A modified version that is essentially the same as the equation AASHTO has used in the past but which accounts for the variation of skid resistance with speed is suitable for this purpose. It is easily solved by hand calculations (see following section).

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*Unless otherwise noted, all Skid Numbers stated in this report are measured at 40 mph.

**The speed sensitivity coefficient (K_V) is a measure of the rate of decrease of Skid Number (SN) with increases in vehicle speed. It is the slope of the SN versus velocity curve divided by 100.

APPLICATION OF FINDINGS

A major finding of this study is that the skid number (SN) as measured with an ASTM locked-wheel skid trailer equipped with highway-type tires is a reasonable indicator of the average lateral pavement skid resistance available to cornering vehicles using the same tires when traversing longer-radius highway curves (over 800-ft radius). It should be emphasized that allowance must be made for variation of SN with vehicle speed. In other words, pavement skid resistance is not a constant, but in general decreases with increased speed. This variation has been accounted for in this work by the speed sensitivity factor, K_v, the slope of the SN vs speed line. The AASHTO curve design procedure contains a side friction factor vs speed line that varies from f = 0.16 to f = 0.12 as the speed varies from 30 to 70 mph. This line has a slope (K_v value) of -0.001/mph.

In general, pavements have SN values considerably above the friction-factor values (multiplied by 100) contained in the AASHTO procedure, and modification of the present policy does not appear to be needed for the majority of cases. In some cases, however, pavements have a speed gradient or sensitivity factor that leads to very low values of available skid resistance at high speeds. If these available skid resistance values measured at high speeds are below the AASHTO side friction factor values used for the design of highway curves, unsafe conditions probably exist.

A procedure using the results of this work that might be applied toward correcting unsafe conditions that could exist on highway curves is illustrated in the following. Two examples, in which only the assumed frictional resistances of the pavements are changed to show how the critical speed can be affected by frictional resistance, are used in the illustration. The unsafe conditions could result from any of several circumstances including:

1. Arbitrary establishment of a posted speed limit above a safe value.
2. Deterioration of skid resistance following posting.
3. Lack of coordination with AASHTO standards at the design stage.

The examples make use of Eq.(2), and assume that skid-trailer tests have been conducted on the surfaces in question to determine SN vs speed values to define f_{40} and K_v for use in solving the equation.

	Example 1	Example 2
$f_{40} = \frac{SN_{40}}{100} =$	0.20	0.35
$K_v =$	-0.004	-0.004
Then $Q_1 =$	$15 \times 1500(-0.004) = -90.0$	$15 \times 1500(-0.004) = -90.0$
$Q_2 =$	$15 \times 1500(40(-0.004)-0.20-0.10) = -10{,}350$	$15 \times 1500(40(-0.004)-0.35-0.10) = -13{,}725$
and $V_{cr} =$	$\frac{-90.0 \pm\sqrt{(-90.0)^2 - 4(-10{,}350)}}{2}$ = 66.3 mph	$\frac{-90.0 \pm\sqrt{(-90.0)^2 - 4(-13{,}725)}}{2}$ = 80.5 mph

It is important to recognize that these computed critical speeds are the speeds at which a vehicle with new tires, negotiating the curve smoothly, could be expected to spin out. To provide for safe operation of vehicles with worn tires and driven with a lesser degree of control, application of a safety factor is necessary. No substantial background is available for the selection of a safety factor, and at present the factor that is chosen must be based on judgment. Some applications of safety factors in the example problems follow:

Example 1

Assumed Safety Factor	Safe Posted Speed Limit
1.25	50 mph
1.5	40 mph
2.0	30 mph

Example 2

Assumed Safety Factor	Safe Posted Speed Limit
1.25	60 mph
1.5	50 mph
2.0	40 mph

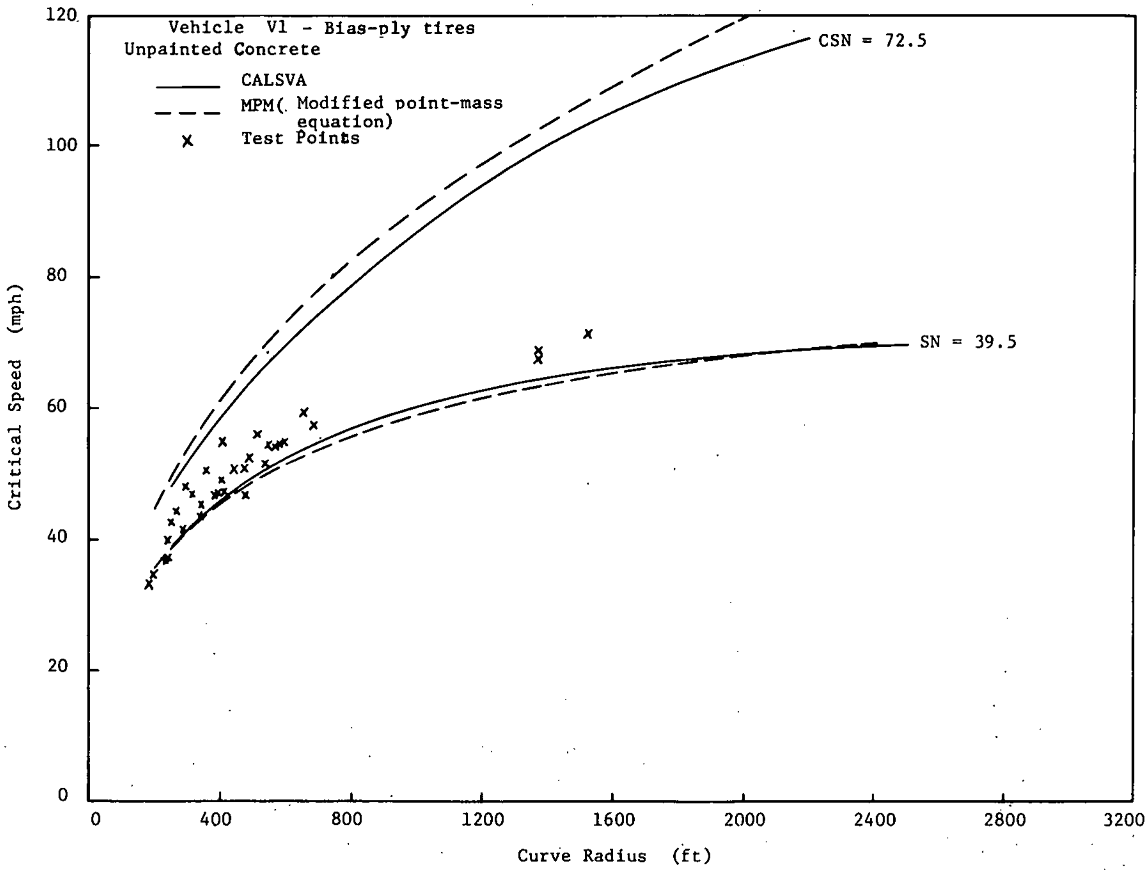

Figure 1. Comparison of theory with tests, vehicle V1, unpainted concrete.

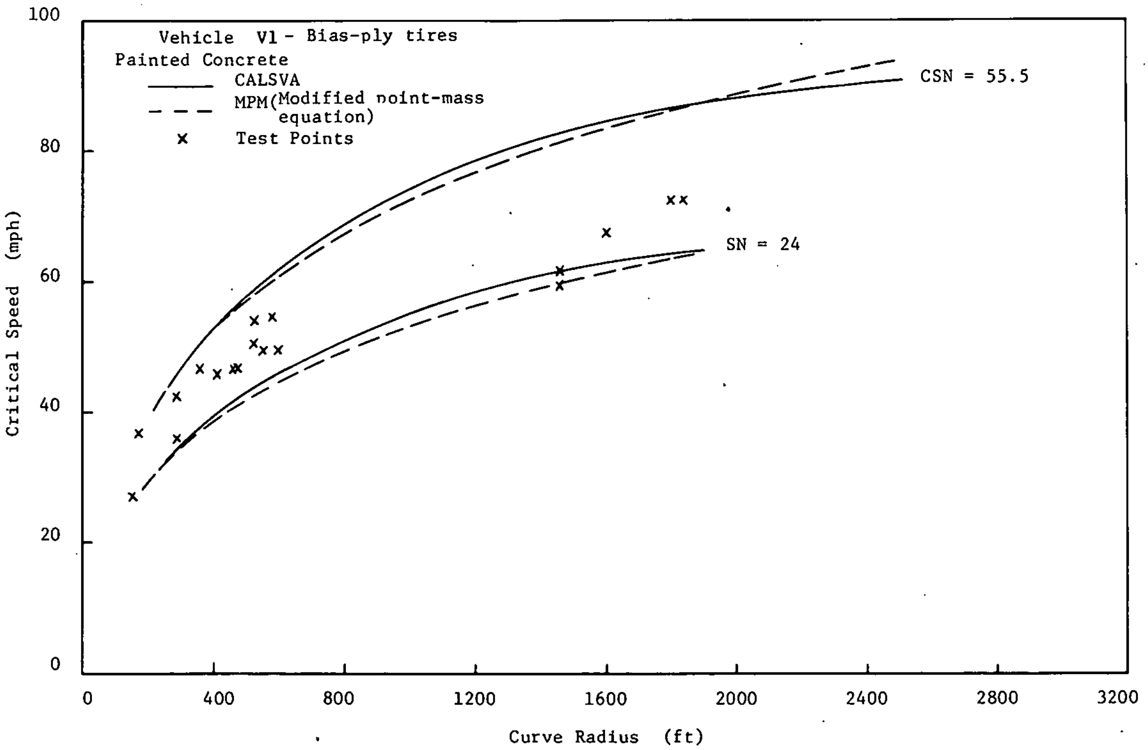

Figure 2. Comparison of theory with tests, vehicle V1, painted concrete.

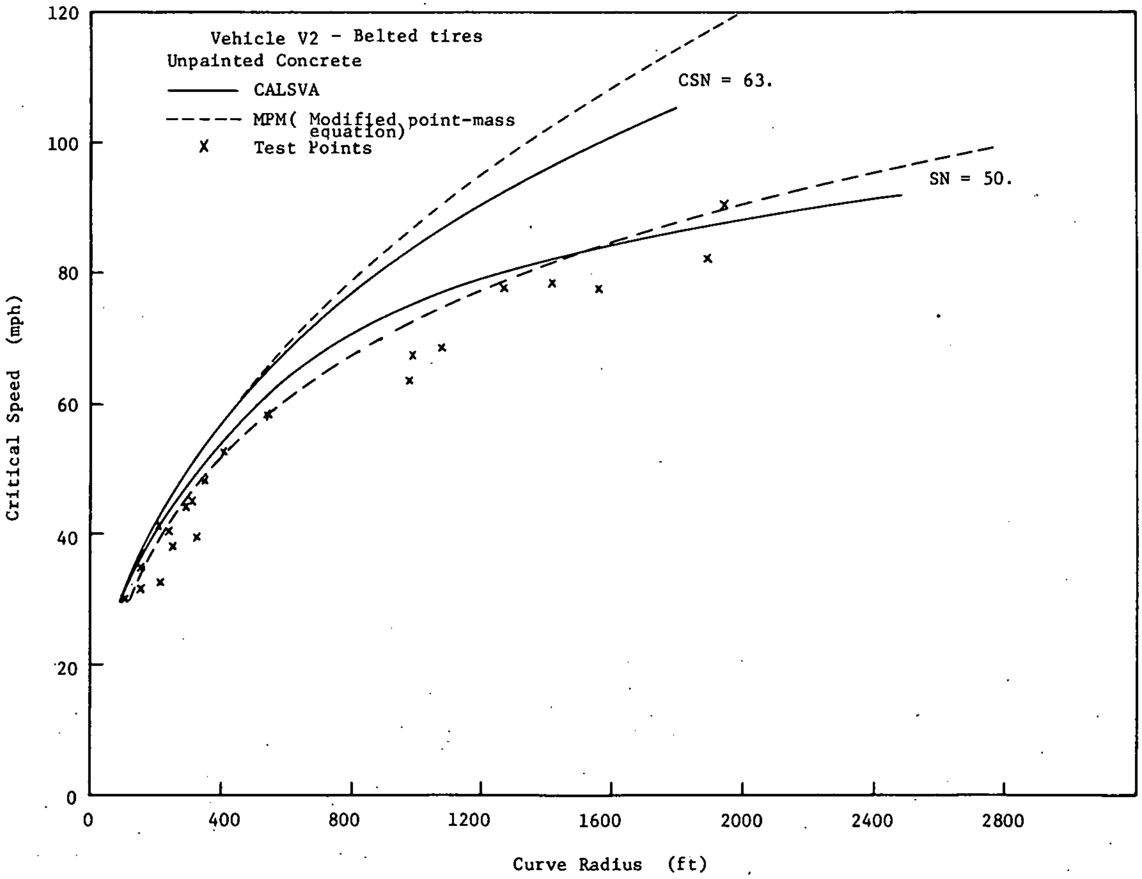

Figure 3. Comparison of theory with tests, vehicle V2, unpainted concrete.

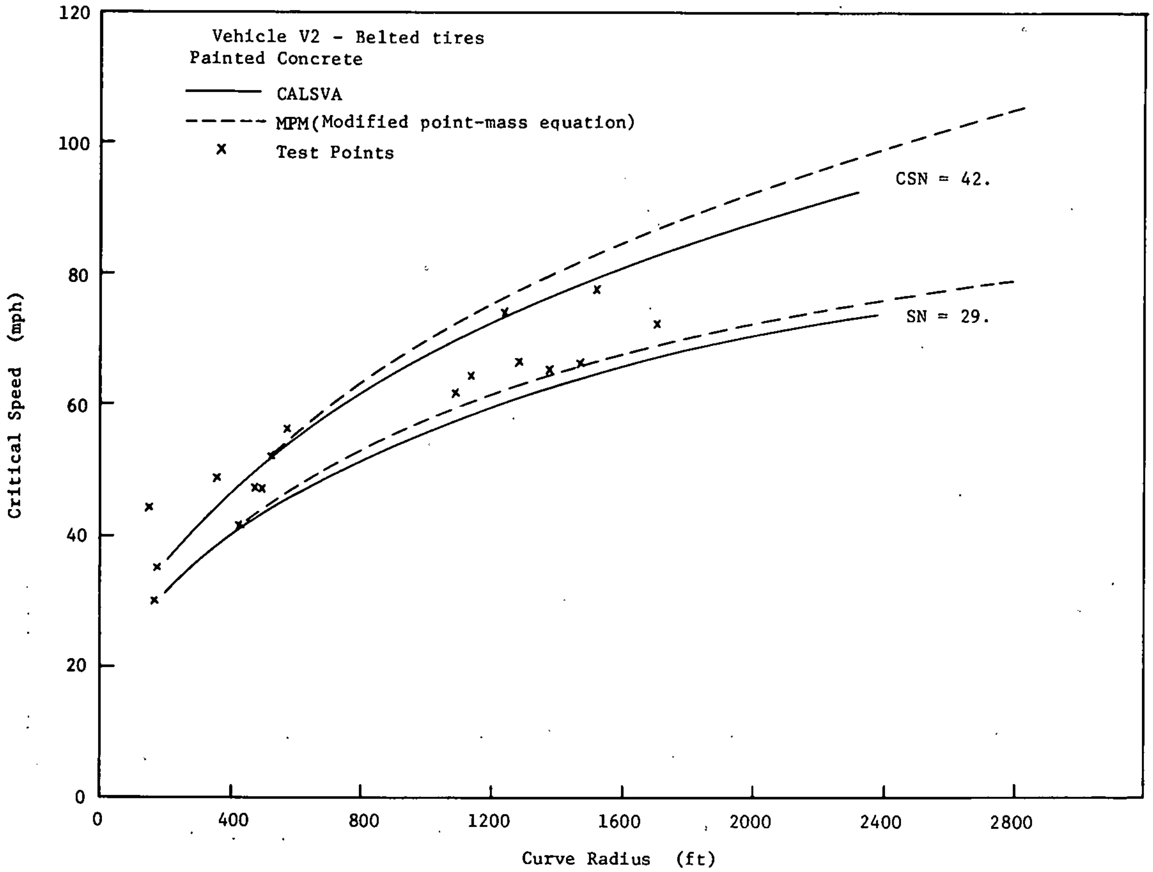

Figure 4. Comparison of theory with tests, vehicle V2, painted concrete.

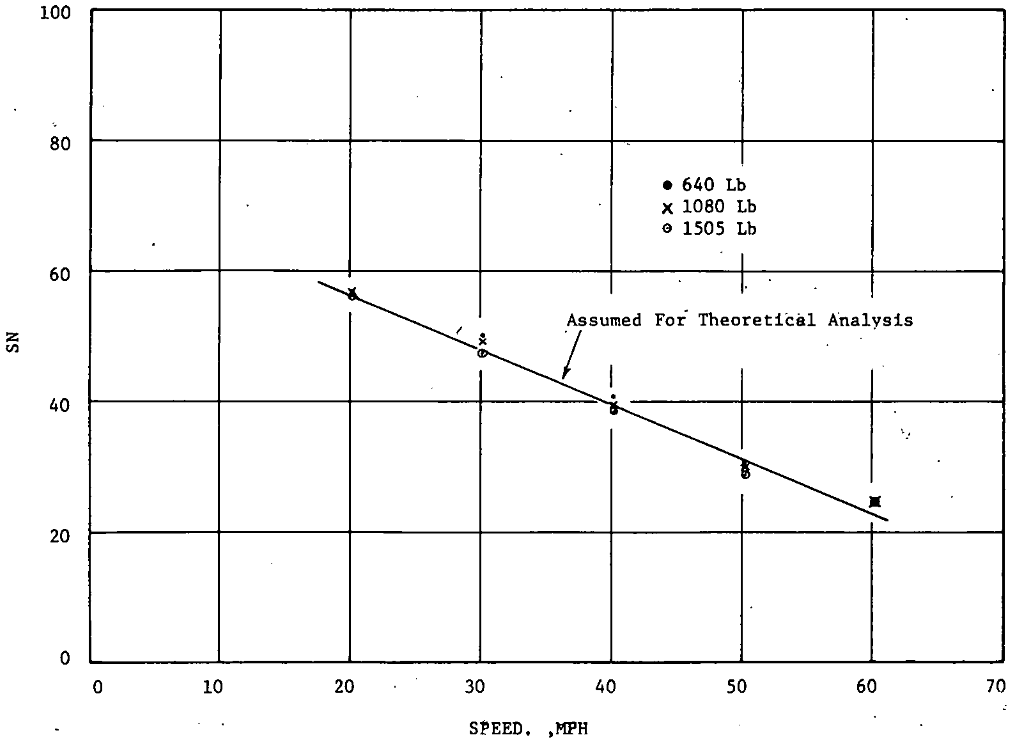

Figure 5. Effect of speed on SN for a skidding Sears Supertread at 3 loads on unpainted concrete.

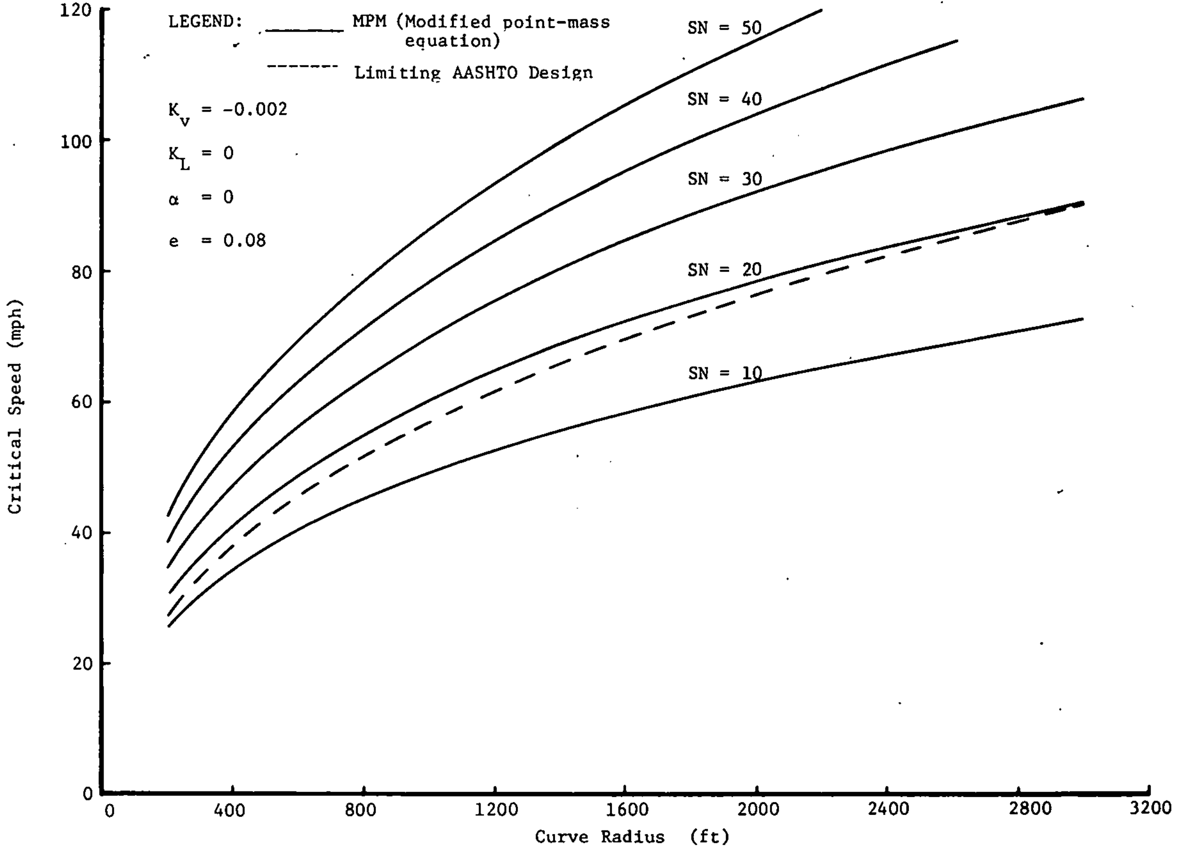

Figure 6. Comparison of limiting AASHTO design to MPM predictions based on various SNs with a speed sensitivity of -0.002 and a superelevation rate of 0.08.

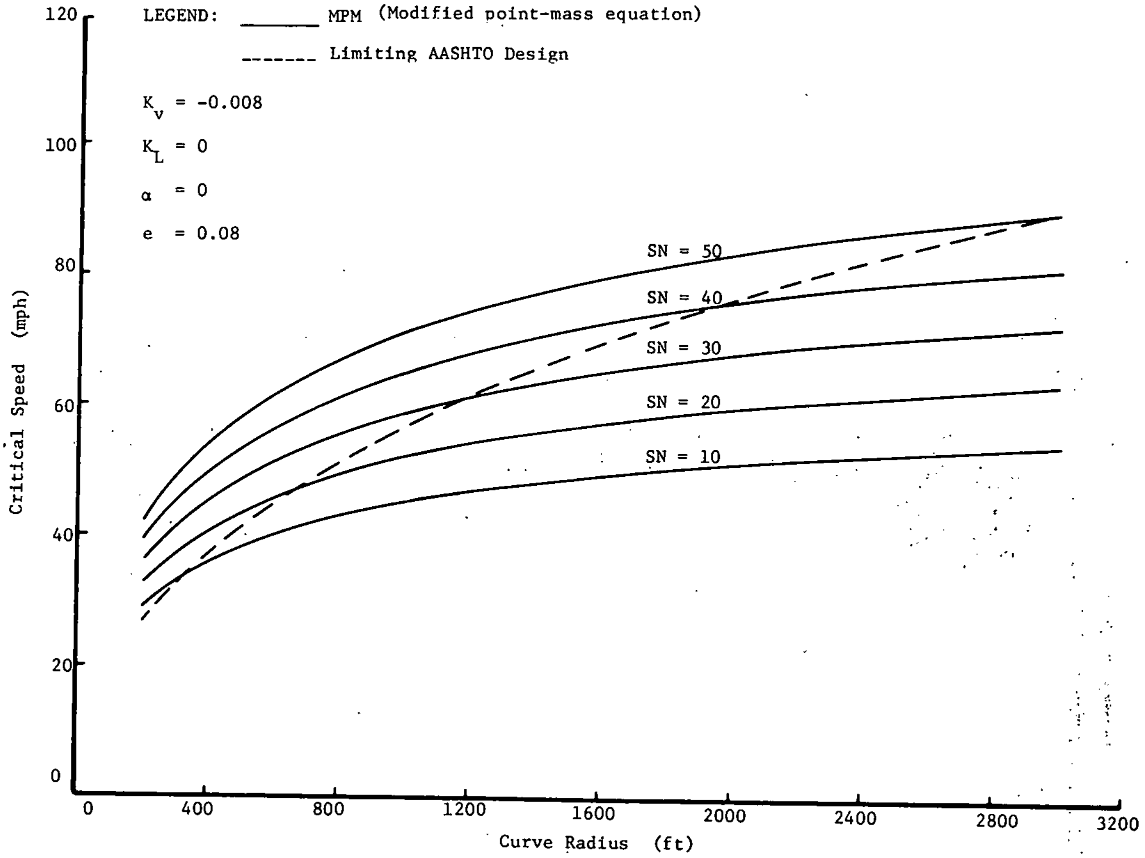

Figure 7. Comparison of limiting AASHTO design to MPM predictions based on various SNs with a speed sensitivity of -0.008 and a superelevation rate of 0.08.

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