THE RELATIONSHIP OF VEHICLE PATHS TO HIGHWAY CURVE DESIGN

by

John C. Glennon
and
Graeme D. Weaver

Research Report 134-5

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F O R E W O R D

This report is one phase of Research Study No. 2-8-68-134 entitled "An Examination of the Basic Design Criteria as They Relate to Safe Operation on Modern High Speed Highways." Other active phases of this research are; (1) a field study of the passing sight distance requirements of high speed passing drivers, (2) a field study of the degree of path taken in high-speed passing maneuvers, and (3) an evaluation of vehicle paths as a basis for wet weather speed limit values.

This is the fifth project report. Previously prepared reports are;

Research Report 134-1, "The Passing Maneuver as it Relates to Passing Sight Distance Standards"

Research Report 134-2, "Re-Evaluation of Truck Climbing Characteristics for Use in Geometric Design"

Research Report 134-3, "Evaluation of Stopping Sight Distance Design Criteria"

Research Report 134-4, "State-of-the-Art Related to Safety Criteria for Highway Curve Design"

D I S C L A I M E R

ABSTRACT

Current design practice for horizontal curves assumes that vehicles follow the path of the highway curve with geometric exactness. To examine the adequacy of this assumption, photographic field studies were conducted of vehicle maneuvers on highway curves.

Results of the field studies indicate that most vehicle paths, regardless of speed, exceed the degree of highway curve at some point on the curve. For example, on a 3-degree highway curve, 10 percent of the vehicles can be expected to exceed 4.3 degrees.

A new design approach is proposed. This approach is dependent upon selecting: (1) an appropriate vehicle path percentile relation, (2) a reasonable safety margin to account for unexplained variables that may either raise the lateral force demand or lower the available skid resistance, and (3) a minimum skid resistance versus speed relationship that the highway department will provide on all pavements.

SUMMARY

This research was conducted to obtain objective data for evaluating the adequacy of current geometric design standards for highway curves. An earlier study report* indicated that current standards may not provide an adequate factor of safety for modern highway operations.

VEHICLE PATHS

Current design practice assumes that vehicles follow the path of the highway curve with geometric exactness. The major emphasis of this research was to empirically relate vehicle paths to highway curve paths to test this assumption.

A movie camera mounted in an observation box on the bed of a pickup truck was used to photograph the path traveled by sample vehicles. The observation truck would begin following a sample vehicle about one mile upstream from the highway curve site. When the curve site was reached, the vehicle maneuver was filmed from a position headway of 60 to 100 feet.

Five unspiraled highway curves, ranging in curvature from two to seven degrees, were studied. About 100 vehicles were sampled for each site. Each sample was an unimpeded vehicle of randomly selected speed. The speed distribution of sampled vehicles was representative of the overall speed distribution for each site. Each curve site was marked with two-foot stripes at twenty-foot intervals along the centerline.

*Glennon, John C., "State of the Art Related to Safety Criteria for Highway Curve Design," Texas Transportation Institute, Research Report 134-4, November, 1969.

This reference system allowed the determination of the lateral placement and speed of the vehicle at 20-foot intervals by analyzing the movie film on a Vanguard Motion Analyzer. From the lateral placement data, an instantaneous radius at each point was estimated by calculating the radius of the circular curve through three successive lateral placement points. (Actually a 160-foot analysis interval was used to reduce the sensitivity to analysis errors.) Since a circular arc is the minimum curved path through three points, the radius so calculated was a conservative estimate of the smallest instantaneous vehicle path radius over the interval.

To relate critical vehicle path radius to highway curve radius, the point where vehicle speed and radius gave the maximum lateral friction demand $(\frac{V^2}{15R} - e)$ was taken for each sample. Plotting the relationship between vehicle speed and radius for these points indicated no correlation between these two variables for any of the five highway curves. Therefore, it was surmised that the measured distribution of critical vehicle path radii could be expected at any speed on that highway curve. This fact allowed the development of relationships between highway curve radius and various percentiles of critical vehicle path radius. Figure 19 on page 32 of the report shows this relationship for various percentiles. This figure indicates that most vehicles will have a path radius that is less than the highway curve radius at some point on the curve.

Figure 19 has a direct application to design. If a particular percentile of vehicle path can be selected as the critical level, then the design equation can be modified to account for path radii smaller than the highway curve radius. For example, if the 10th percentile is selected as the critical level (only 10 percent of the vehicles would have a more severe path), the appropriate design equation (in which R is the highway curve radius) would be:

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

LATERAL SKID RESISTANCE

Current design practice also assumes that; (1) the centripetal force equation, $e + f = V^2/15R$ (where R is the vehicle path radius and f is the lateral skid resistance available at speed V) predicts the impending skid condition, and (2) the lateral skid resistance can be measured with a standard locked-wheel skid trailer test. These two assumptions were tested on another project at the Texas Transportation Institute.

Full-scale vehicle cornering skid tests were conducted on several surfaces. ASTM skid trailer tests were also run at 20, 40 and 60 mph on these surfaces using the standard internal watering system for one test and an external watering source for another test. Results of these tests indicate that; (1) the centripetal force equation does yield a reasonably good prediction of impending skid, (2) the skid numbers measured with the standard ASTM skid test give good estimates of lateral skid resistance for speeds up to 40 mph, and (3) the standard skid numbers measured at speeds above 40 mph were somewhat high (average of 4 units).

SUPERELEVATION

Because of the need for superelevation runoff, full superelevation is not available near the beginning and end of the highway curve. Depending on design practice for superelevation runoff, the superelevation at the tangent-to-curve points may be from 50 to 80 percent of full superelevation. Because the data from this study show that most vehicles experience their critical path maneuvers near the beginning or end of the curve, the design equation should reflect this reduced superelevation.

IMPLEMENTATION

With all the considerations previously discussed, it is possible to modify the design equation into a comprehensive tool. If the 10th percentile vehicle path radius is stated in terms of highway curve radius, if the reduced superelevation at the beginning and end of the curve is approximated by 0.7 e, and if f is expressed by the skid number, SN_V, divided by 100, minus a safety margin, then the following equation results:

$$R = -514 + \frac{V^2}{5.48\ e + 7.86\ (0.01\ SN_V - M_s)}$$

where R = design radius, in feet

V = design speed, in mph

e = design superelevation, in feet per foot

M_s = safety margin

SN_V = standard skid number at the design speed

It is not possible to use this equation for design unless, first a safety margin is selected and second a "typical" skid resistance versus speed relation is selected. The latter precludes recommending specific minimum design standards. Essentially, the skid resistance versus speed relationship used for design depends on the minimum level of skid resistance provided by the highway department.

A safety margin is required because of several unaccounted variables that may either increase the lateral force demand or decrease available lateral skid resistance. On wet pavements, vehicle speed is the most significant variable, not only because lateral force demand increases with the square of the speed, but also because lateral skid resistance decreases with speed. These two phenomena, of course, are already accounted for in the design procedure. Also, with design equation modified to account for statistical values of vehicle path, the effects of driver steering judgment and faulty vehicle dynamics are probably taken care of. Therefore, factors of safety are only needed to give some margin of error for variables such as vehicle acceleration and braking, excessive water on the pavement, pavement bumps, faulty tires, and wind gusts.

Because these other variables have not been explicitly evaluated, it is difficult to determine representative factors of safety. It seems clear, however, since critical vehicle paths can now be considered in the design equation, that lower factors of safety can be used. In addition, there may be a low probability of the unaccounted variables combining to produce a much more unstable condition than already accounted for by the critical vehicle path and speed.

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

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INTRODUCTION

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

More rapid accelerations, higher travel speeds, and faster decelerations made possible by modern highway and vehicle design have raised the frictional demands on the tire-pavement interface. Larger forces are required to keep the vehicle on its intended path. On the other hand, for wet pavements, the frictional capability of the tire-pavement interface decreases with increasing speed. In addition, higher traffic volumes and speeds promote a faster degradation in the frictional capability of the pavement. Figure 1 shows how these parameters interact to produce a higher loss of control potential.

From the technological standpoint, the slipperiness problem appears amenable to solutions that either reduce the frictional demand (improved geometric design, and lower speed limits for wet conditions) or increase the frictional capability (improved pavement surface design, improved tire design, and improved vehicle inspection procedures). This research

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*Denotes number in List of References

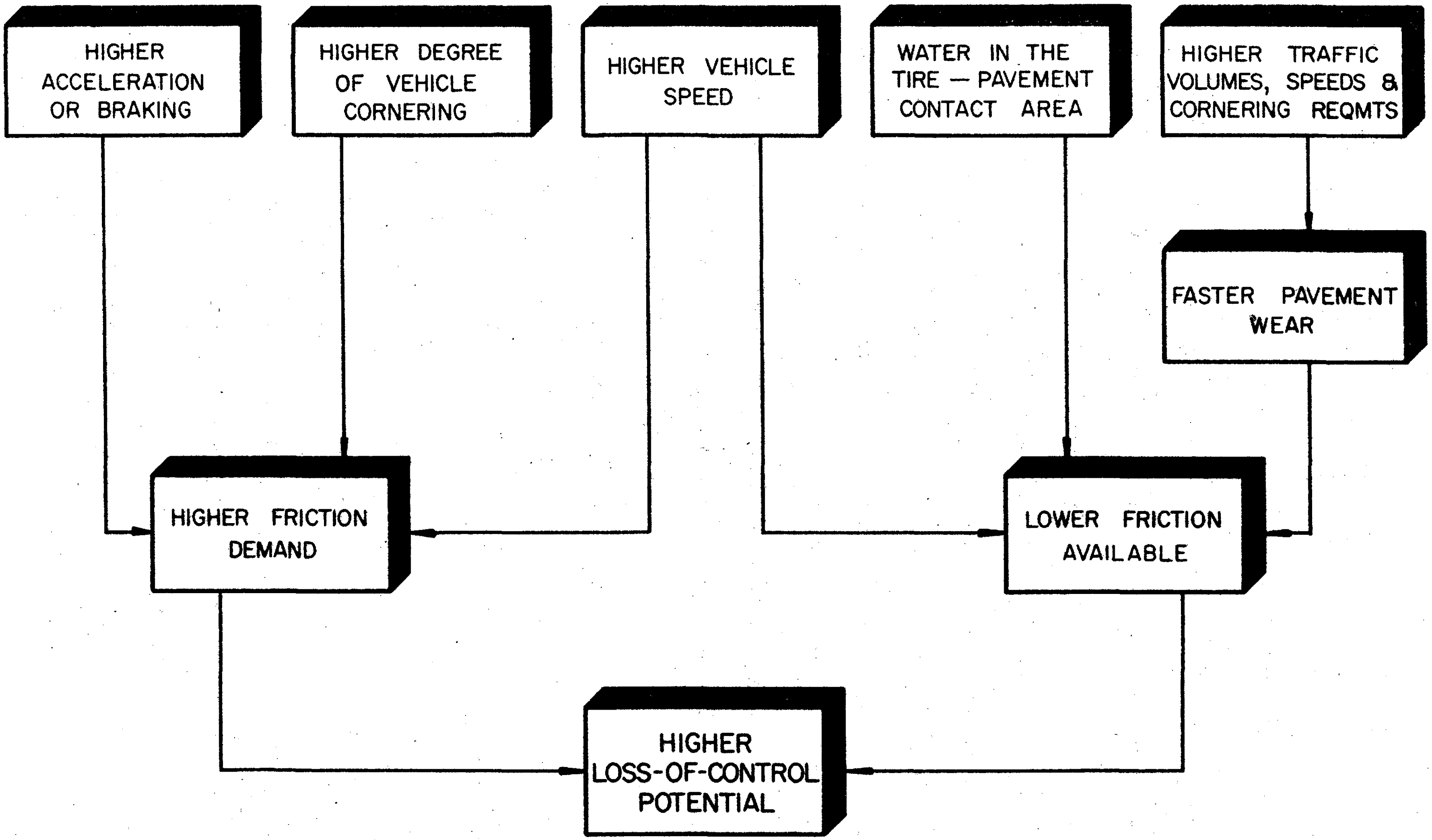


Figure 1. Circumstances Leading to Higher Loss of Control Potential.

study is concerned with the adequacy of geometric design standards for horizontal curves.

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

(1) that vehicles follow the path of a highway curve with geometric exactness,

(2) that the point-mass equation, $e + f = V^2/15R$, defines the impending skid condition,

(3) that lateral skid resistance can be measured with a locked-wheel skid trailer, and

(4) that levels of lateral acceleration that produce impending driver discomfort can be used for design values to insure an adequate factor of safety against lateral skidding.

The goal of this current research was to perform field studies, simulation studies, and controlled experiments to test the first three assumptions listed above. With objective data on the first three assumptions, the adequacy of the fourth assumption can then be evaluated.

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

FIELD PROCEDURES

The general procedure was to record vehicle paths on movie film using a following vehicle to house the camera. This recording vehicle, stationed beside the highway about one mile upstream from a highway curve site, was driven onto the highway behind a subject vehicle as it passed. The recording vehicle was then accelerated to close the position headway so the subject vehicle was within 60 to 100 feet as it approached the curve site. The vehicle path was filmed continuously from about 150 feet upstream to 150 feet downstream of the highway curve.

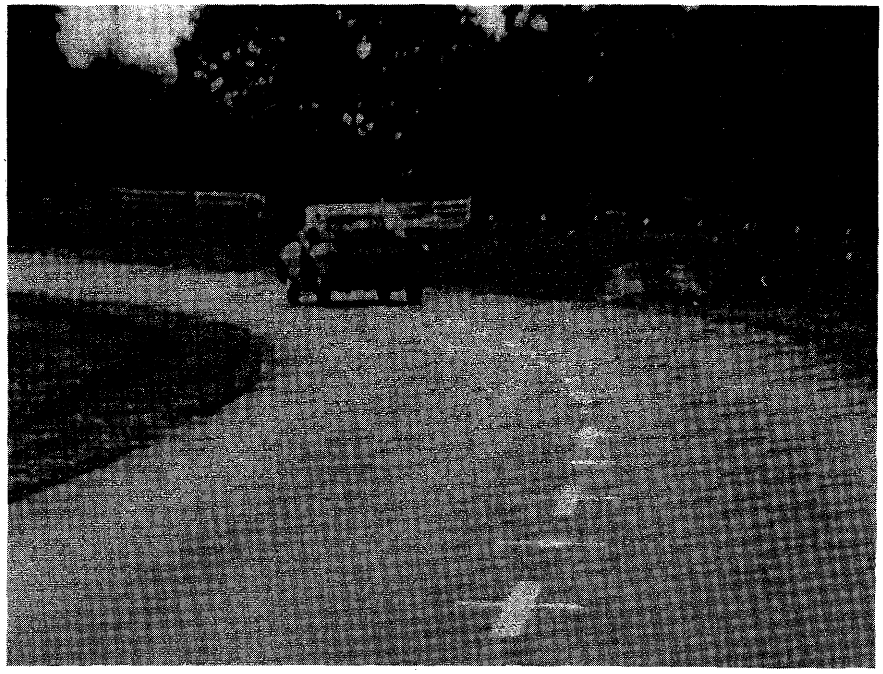
STUDY SITES

Five highway curve sites, ranging in curvature from two to seven degrees, were selected within a 30-mile radius of Texas A&M University. All curve sites were in rural areas and had essentially level vertical curvature. None of the curve sites had spiral transitions; that is, they were all joined by tangent alignment at both ends of the circular curve.

Photographs and descriptive site data are presented for each of the curve sites in Figures 2 through 6.

EQUIPMENT

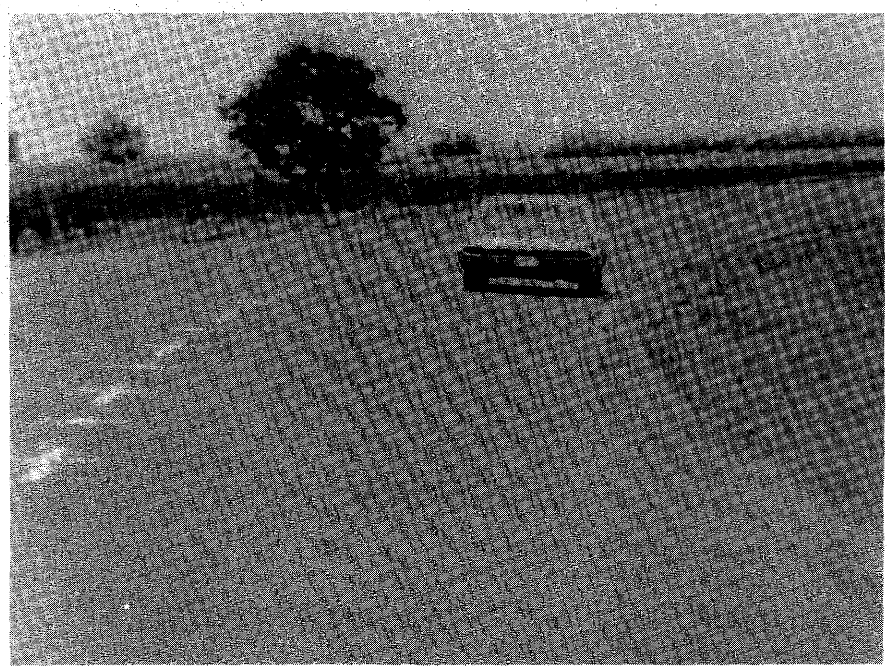
A 1970 Ford half-ton pickup truck was used as the recording vehicle. So subject drivers would be unaware of being photographed, the camera and operator were concealed in a box mounted on the truck bed. The box, resembling a tool shed, was directly behind the truck cab, standing



Location: State Highway 30, 8 miles east of College Station.

Description: 7° curve, 0.4 superelevation, 1,060 feet long, 22-foot pavement, no shoulders, ADT = 850, 45-mph advisory speed, 70-mph speed zone.

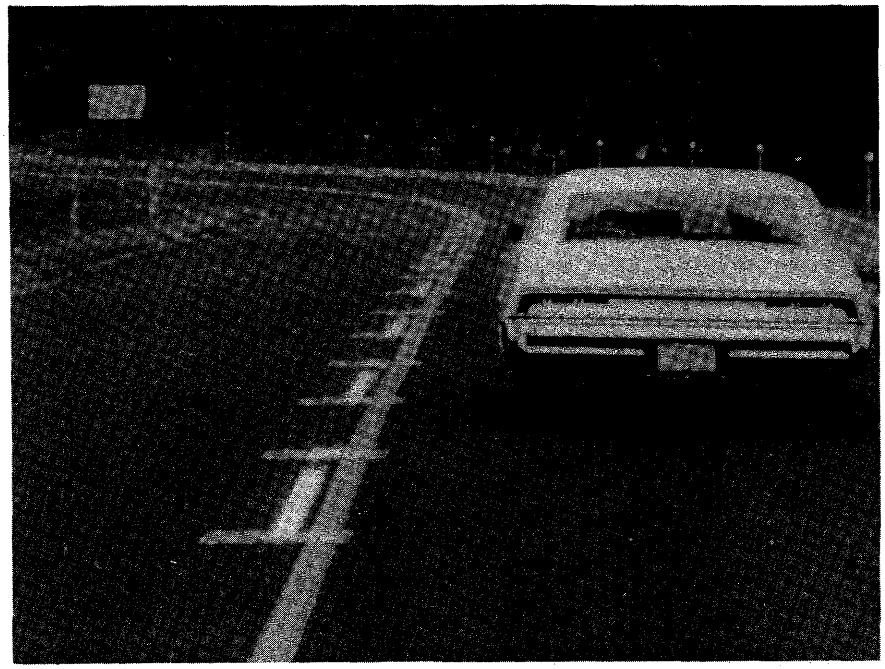
Figure 2 - Curve Site 1



Location: FM Road 60, just west of Brazos River, milepost 16.

Description: 4° curve, .08 superelevation, 900 feet long, 24-foot pavement, no shoulders, ADT = 900, 60-mph speed zone.

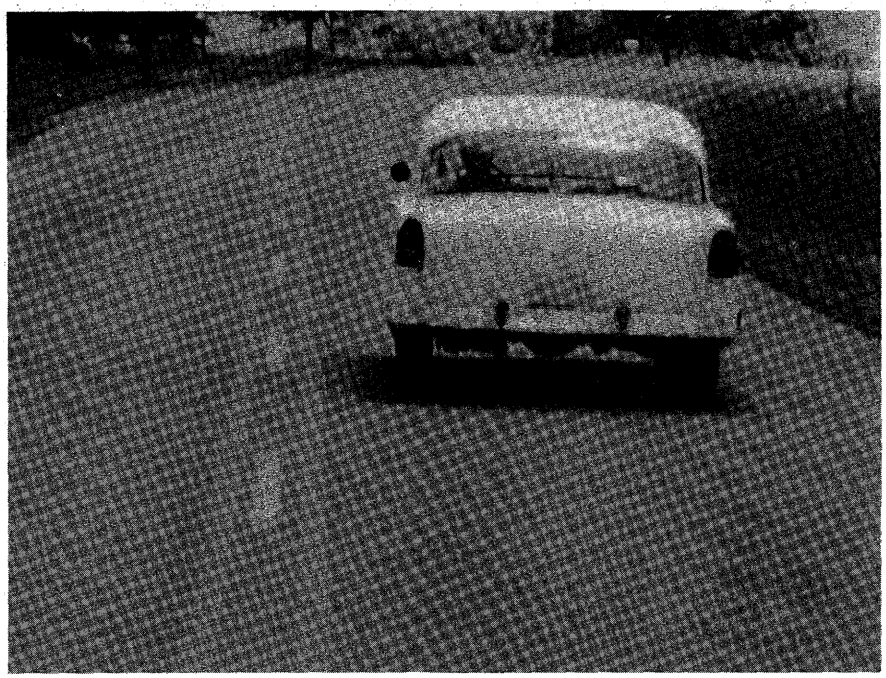
Figure 3 - Curve Site 2



Location: State Highway 21, 2 miles east of North Zulch, milepost 8.

Description: 5° curve, .07 superelevation, 840 feet long, 26-foot pavement, 6-foot earth shoulders, ADT = 1500, 70-mph speed zone.

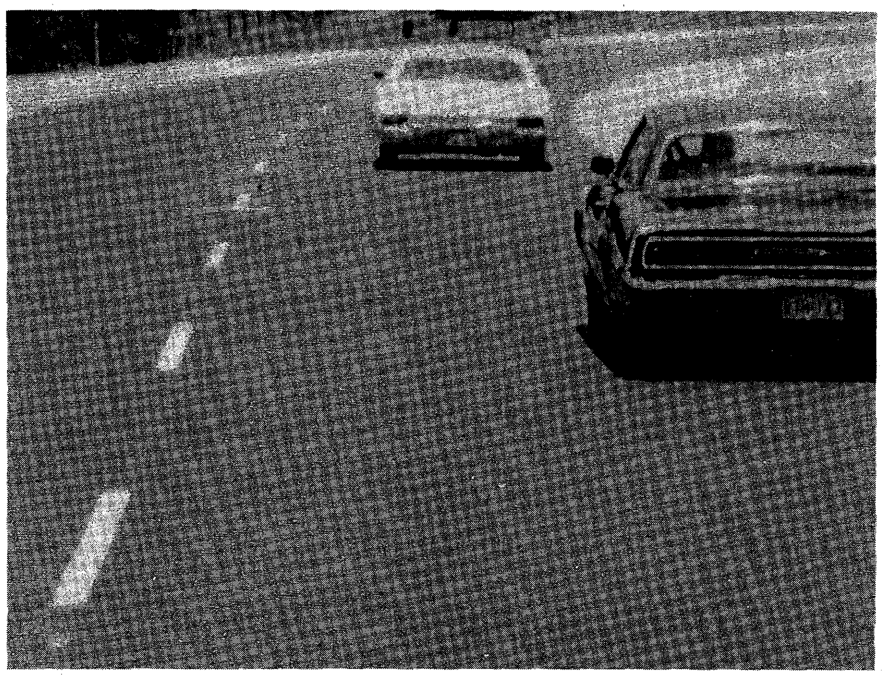
Figure 4 - Curve Site 3



Location: State Highway 21, west of Brazos River, milepost 20.

Description: 2° curve, .06 superelevation, 810 feet long, 24-foot pavement, no shoulders, ADT = 2,000, 70-mph speed zone.

Figure 5 - Curve Site 4



Location: State Highway 36, 4 miles south of Caldwell, milepost 15.

Description: 2.5° curve, .06 superelevation, 1,340 feet long, 24-foot pavement, 8-foot paved shoulders, ADT = 2,000, 70-mph speed zone.

Figure 6 - Curve Site 5

24 inches above the cab roofline. The truck and observation box are shown in Figure 7.

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

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

Subject vehicles were photographed with a zoom lens (17.5-mm to 70.0-mm) so the cameraman could maintain field of view and, at the same time, obtain the largest possible view of the left-rear tire of the vehicle. The camera was mounted on a ball-head rigid base attached to a shelf. The camera and mounting configuration are shown in Figure 8.

GEOMETRIC REFERENCE MARKS

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

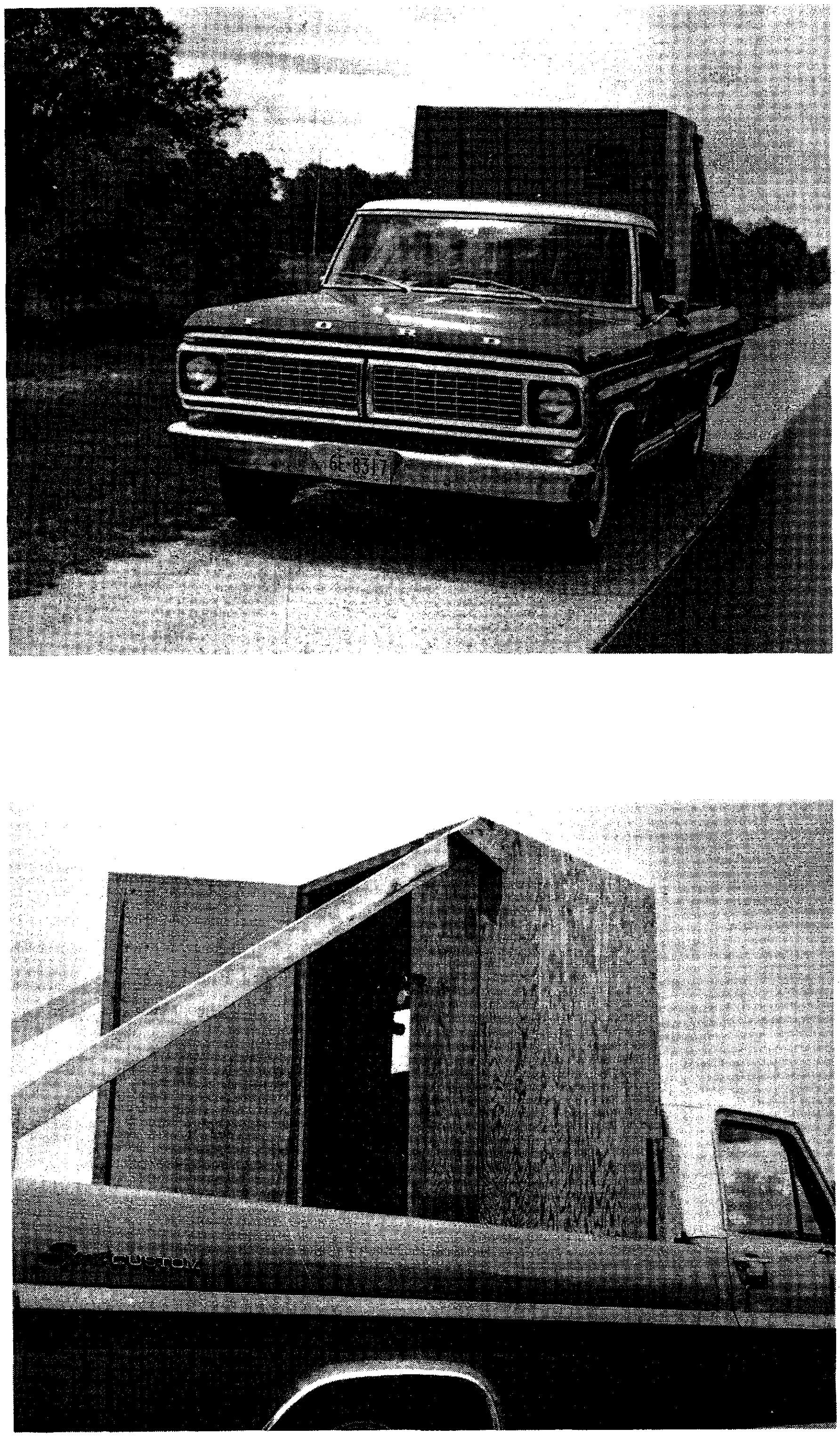


Figure 7 - Recording Vehicle and Observation Box

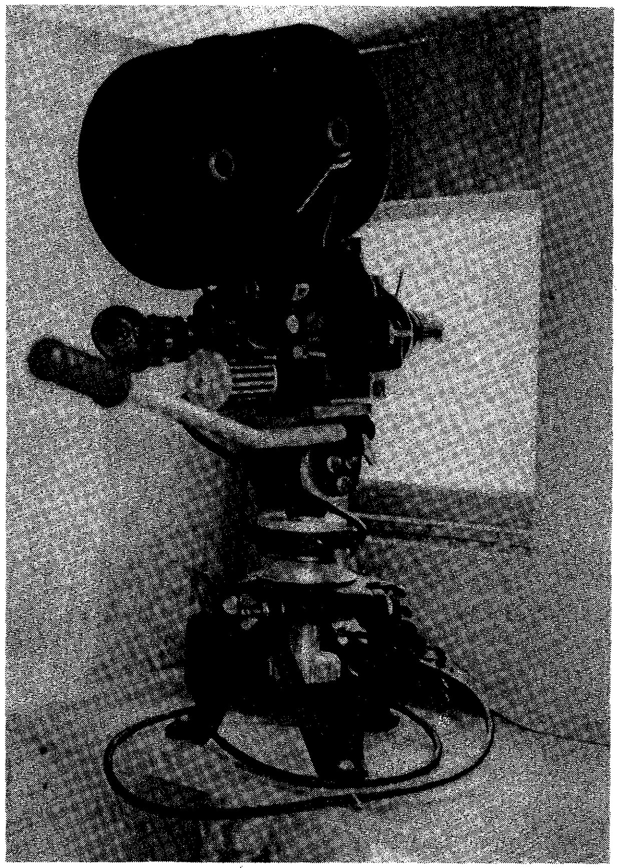


Figure 8 - Study Camera and Mounting

where lateral placement measurements were taken. The 20-foot interval gave a reference system for speed and radius calculations.

SAMPLING PROCEDURES

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

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

A comparison of the overall speed distribution for the site and the speed distribution for the sample population is shown for each curve site in Figures 9 through 13. These distributions represent the spot speed on the tangent alignment just before the curve. The overall speed distributions for the sites were compiled from speed surveys of 200 vehicles in each direction at each site. The sample speed distributions were compiled from the film analysis.

The sample speed distributions are fairly representative of the speed range at each site. Only the extremely high speeds are not

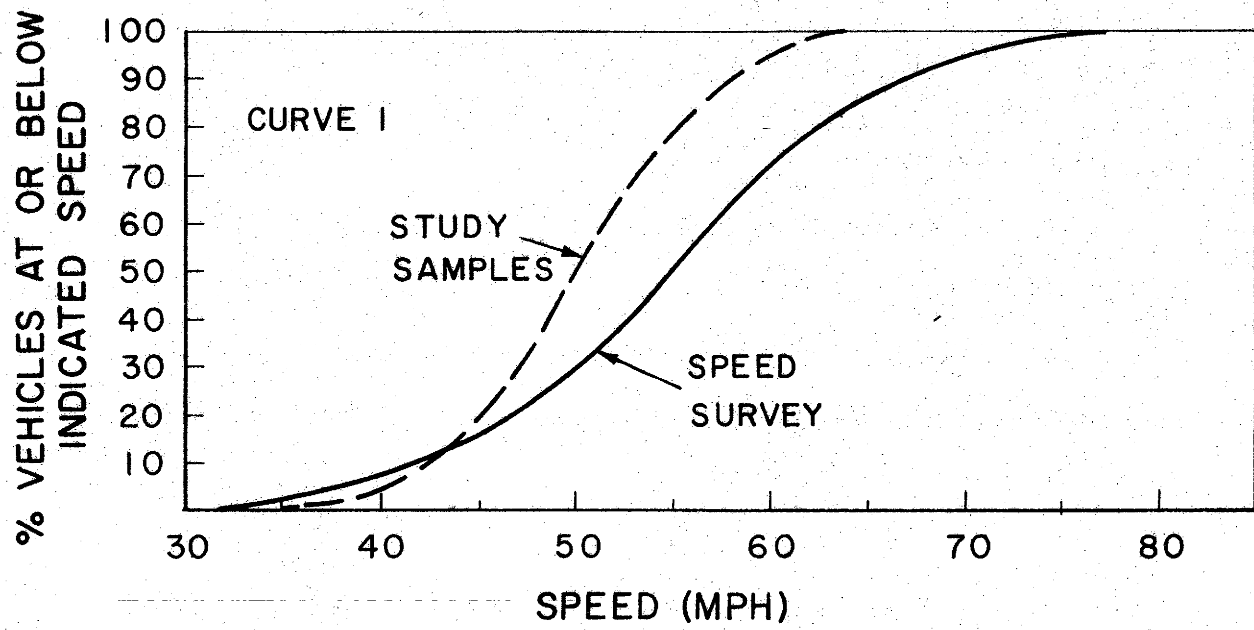


Figure 9 - Curve Site 1 Speed Distribution and Maneuver Sample Speed Distribution

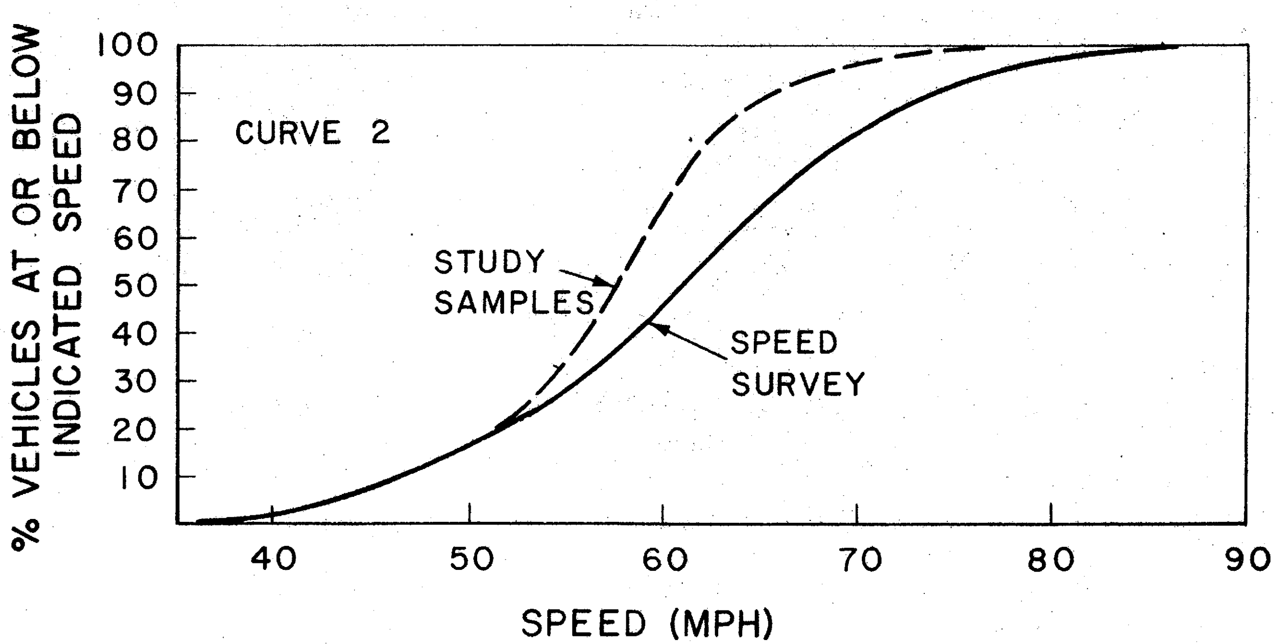


Figure 10 - Curve Site 2 Speed Distribution and Maneuver Sample Speed Distribution

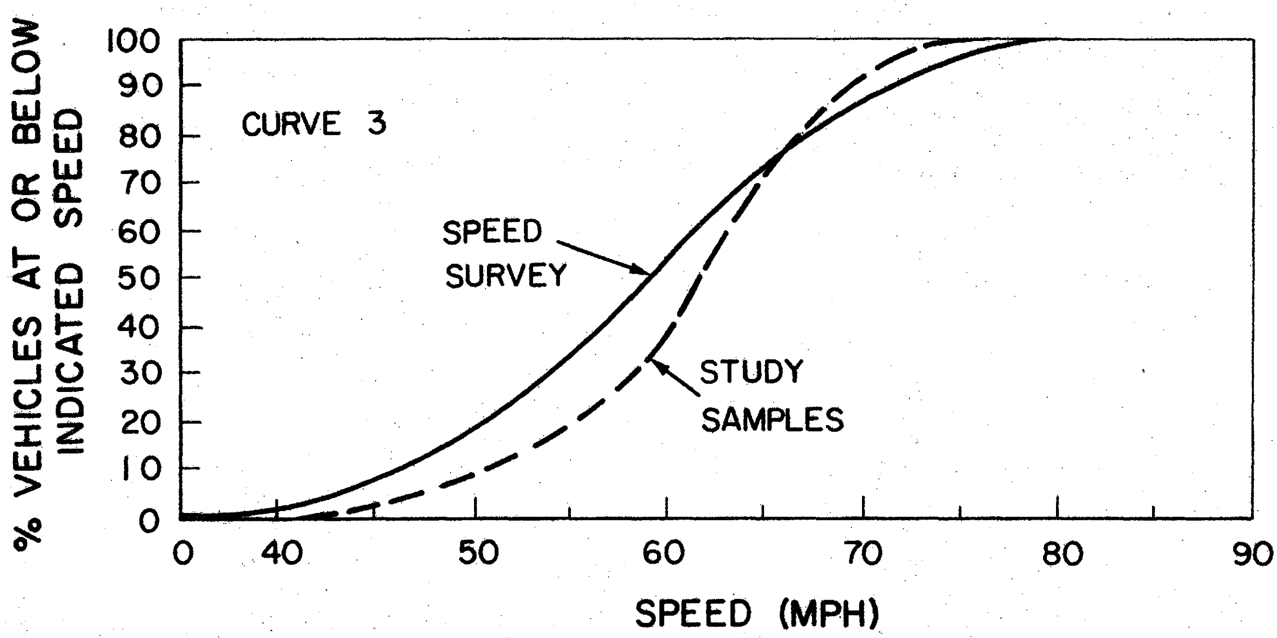


Figure 11 - Curve Site 3 Speed Distribution and Maneuver Sample Speed Distribution

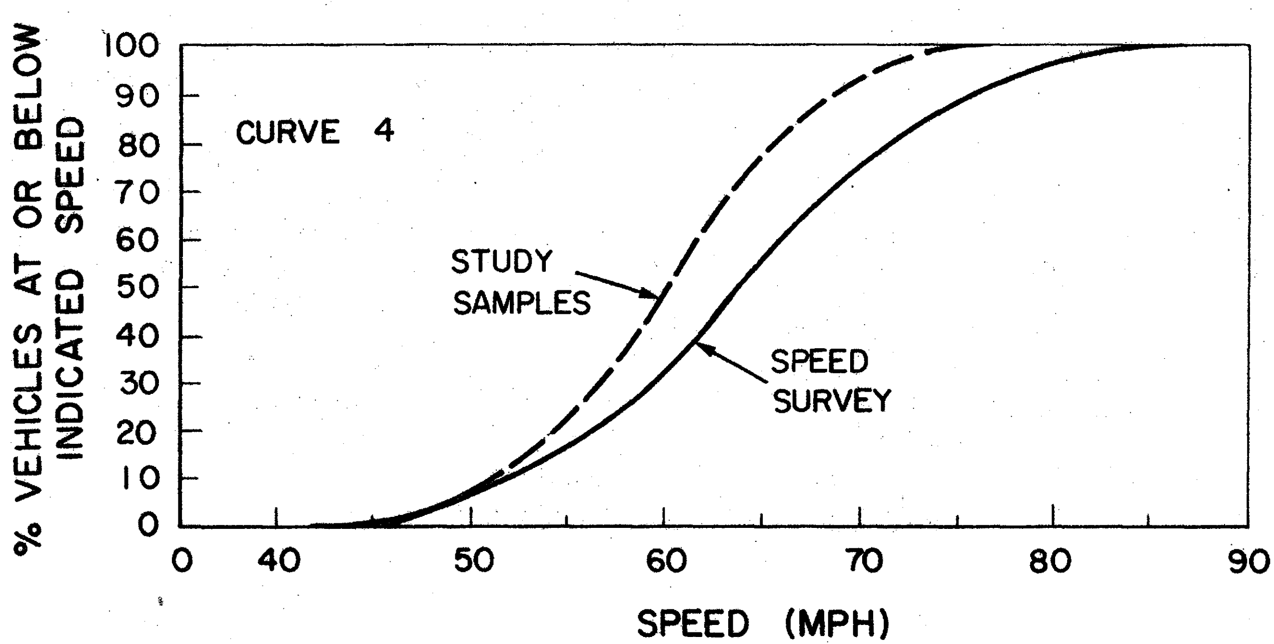


Figure 12 - Curve Site 4 Speed Distribution and Maneuver Sample Speed Distribution

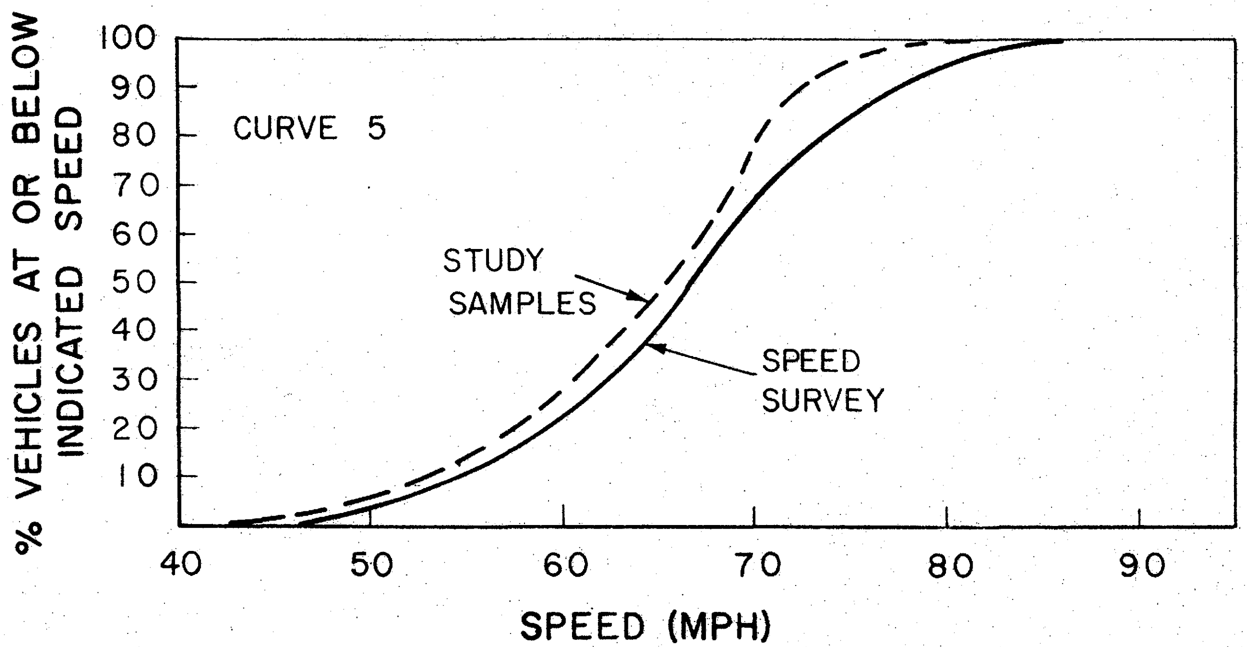


Figure 13 - Curve Site 5 Speed Distribution and Maneuver Sample Speed Distribution

included because high-speed samples were aborted. It was not possible to close the position headway on high-speed subject vehicles without endangering the study personnel.

FILM ANALYSIS

The film was analyzed with a Vanguard Motion Analyzer, pictured in Figure 14. This device is a portable film reader for measuring displacements on photographic projections. It consists of a projection head, projection case, and measurement screen.

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

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

To analyze the vehicle path of the samples, the lateral vehicle position reference was always the left edge of the left-rear tire. Lateral placement at each reference marker was measured from the frame where the left-rear tire was nearest the marker. After recording

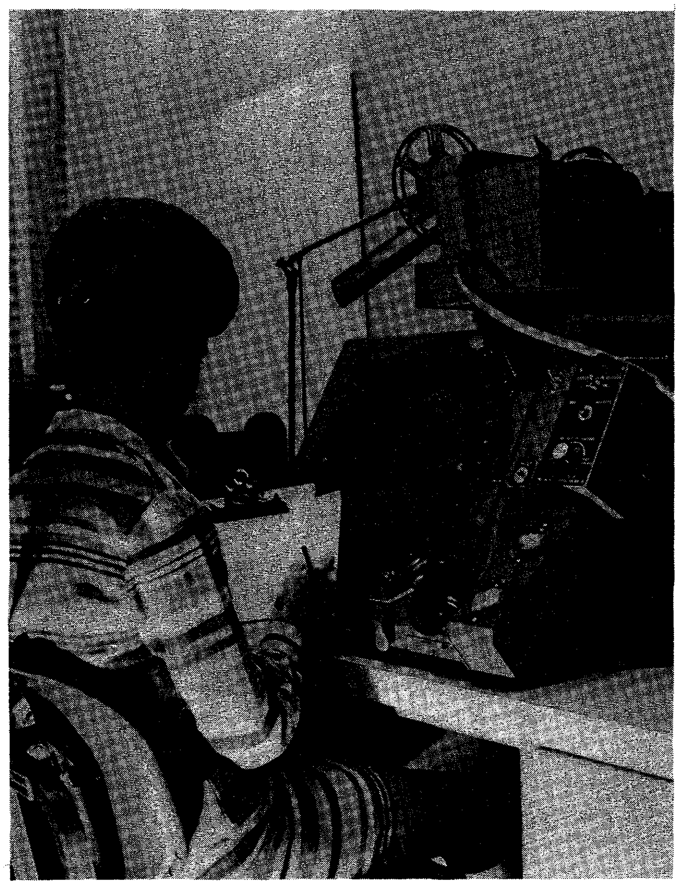
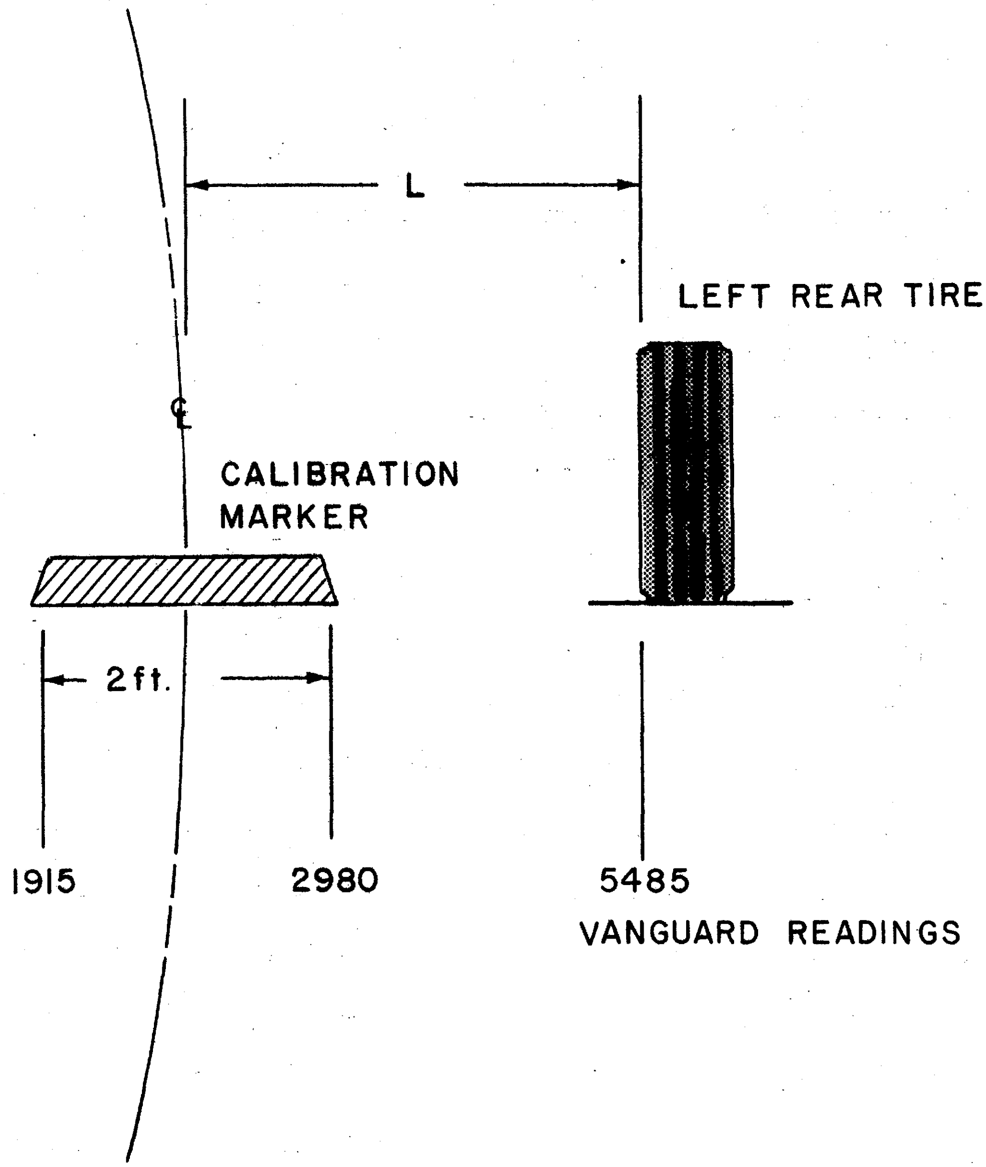


Figure 14 - Vanguard Motion Analyzer

calibration readings on the left and right edge of the reference marker, the position reading of left-rear tire was recorded. These readings, along with the two-foot known length, gave the data necessary for calculating the actual lateral placement. An example of these readings and calculations is shown in Figure 15.



$$\text{CALIBRATION} = \frac{2}{2980-1915} = \frac{1}{532}\ \frac{\text{ft.}}{\text{unit}}$$

$$\text{LATERAL PLACEMENT} : L = \frac{5485-2980}{532} + 1 = 5.71\ \text{ft.}$$

Figure 15 - Example Vanguard Readings and Lateral Placement Calculations

MATHEMATICAL ANALYSIS

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

VEHICLE SPEED

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

Because the frame-count estimate was to the nearest integer, the greatest frame-count error at a point was one-half frame. For an analysis length, the greatest error in frame-count difference was one frame (one-half frame at each end). Figure 16 shows the sensitivity of the speed estimate to frame-count differences for several analysis intervals. To reasonably diminish this error source the speed estimate analysis interval was chosen at 160 feet. Therefore, the speed estimate at each reference marker was the average speed over the 160-foot interval centered on that marker.

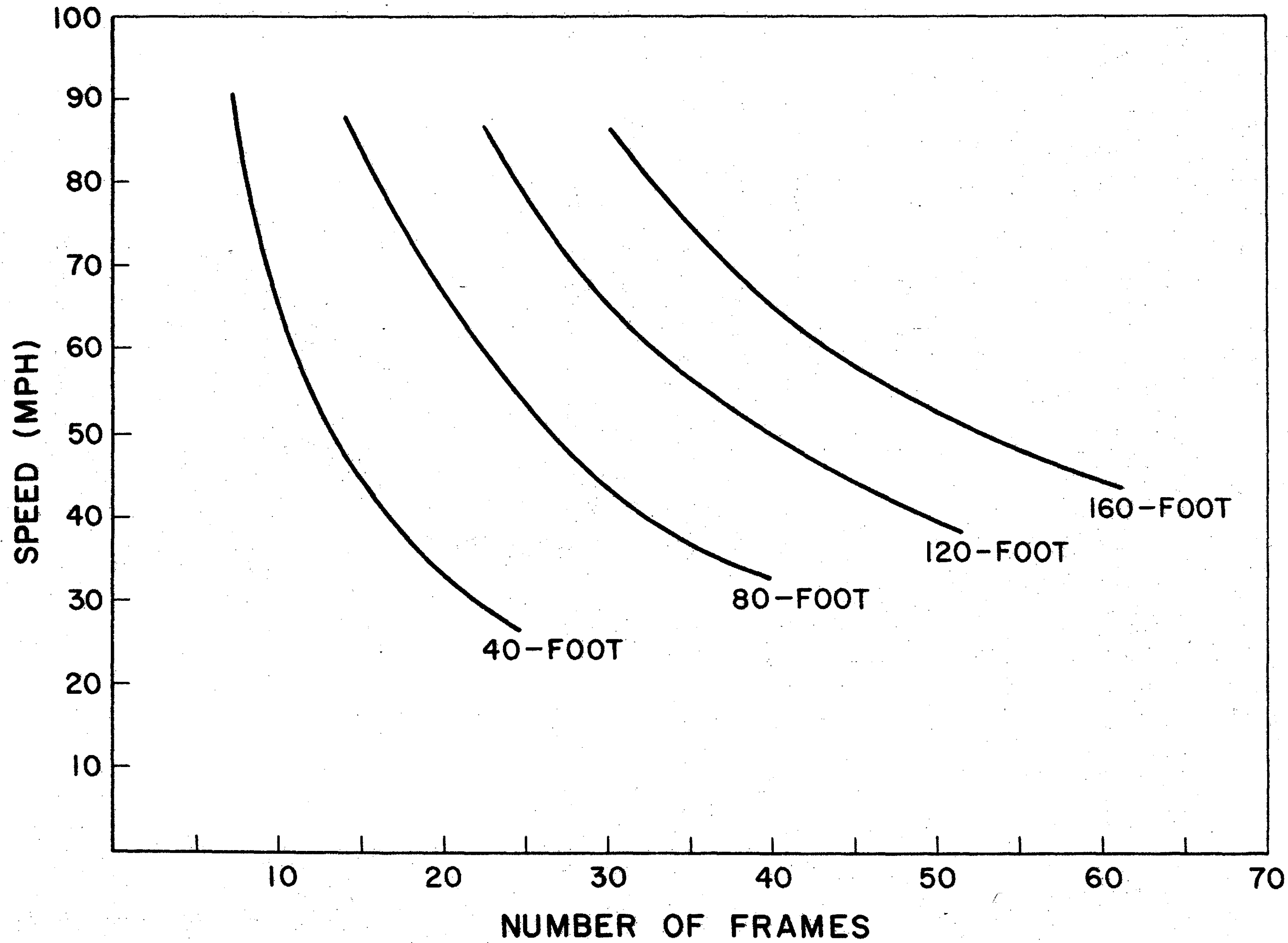


Figure 16 - Sensitivity of the Speed Estimate to Frame Count

VEHICLE RADIUS

The computer program calculated the lateral placement of the left edge of the left-rear tire at each reference marker. The instantaneous vehicle path radius was then estimated by computing the radius of the circular curve through three successive tire positions, the center position being at the reference marker under consideration. Since a circular arc is the minimum curved path through three points, the radius so calculated is a conservative estimate of the smallest instantaneous radius over the interval.

Figure 17 shows the geometric description of the vehicle radius calculation. Points A, B, and C represent left-rear tire positions at equal intervals along the highway curve. The estimated vehicle path radius, R_v, is the radius of the circular arc that circumscribes triangle ABC. The following calculations were performed to obtain this radius:

from the law of cosines, lines AB, BC, and AC are (in feet);

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

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

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

where,

d_A, d_B, and d_C = lateral displacements from the centerline at points A, B, and C, in feet

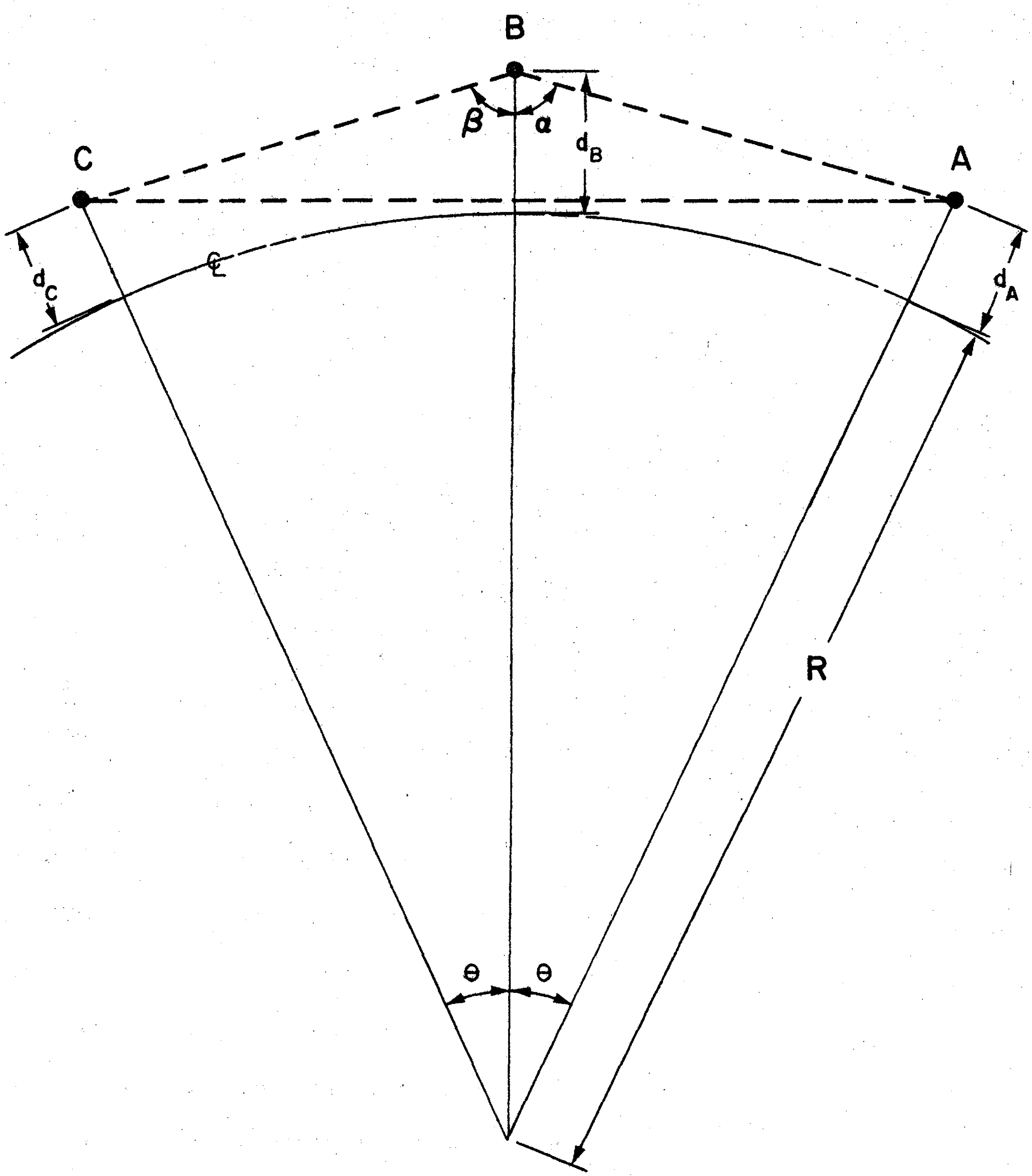


Figure 17 - Geometric Description of Vehicle Radius Calculation

R = radius of the highway curve, in feet

θ = central angle subtended by arc length of one-half the analysis interval

from the law of sines,

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

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

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

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

As with the speed estimate, it is necessary to look at the error sensitivity of the radius estimate for various analysis intervals. Any error in the radius estimate would, of course, come from an error in the lateral placement estimate. Although study control was exerted, small errors were possible from several sources, including: (1) lateral discrepancy in placing the reference marker, (2) length discrepancy of the reference marker, (3) film parallax, (4) sampling error due to taking lateral placement readings up to one-half frame away from the reference marker, (5) equipment error, and (6) human error in reading and recording lateral placement measurements.

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

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

$$M = \frac{C}{2} \tan \frac{DC}{400}$$

$$M_e = M + 0.10 = \frac{C}{2} \tan \frac{D_e C}{400}$$

where,

C = chord length (approximately by arc length over short intervals) of both curves, in feet

D = degree of correct path

D_e = degree of path in error

if "d" is the absolute error in curve degree then,

$$d = D_e - D$$

Solving for D and D_e in the first two equations, the equation for "d" becomes,

$$d = \frac{400}{C} \tan^{-1} \frac{2(M + .10)}{C} - \frac{400}{C} \tan^{-1} \frac{2M}{C}$$

or,

$$d = \frac{400}{C} \tan^{-1} \frac{1}{5C}$$

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

$$E = 100 \frac{\left(\frac{400}{C} \tan^{-1} \frac{1}{5C}\right)}{D}$$

Figure 18 shows the percent error of the radius estimate for an absolute lateral placement error of 0.10 feet. The percent error is plotted against the length of analysis interval for the range in highway curves studied. The figure shows that the error sensitivity is greatly reduced as the analysis interval is increased.

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

LATERAL ACCELERATION

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

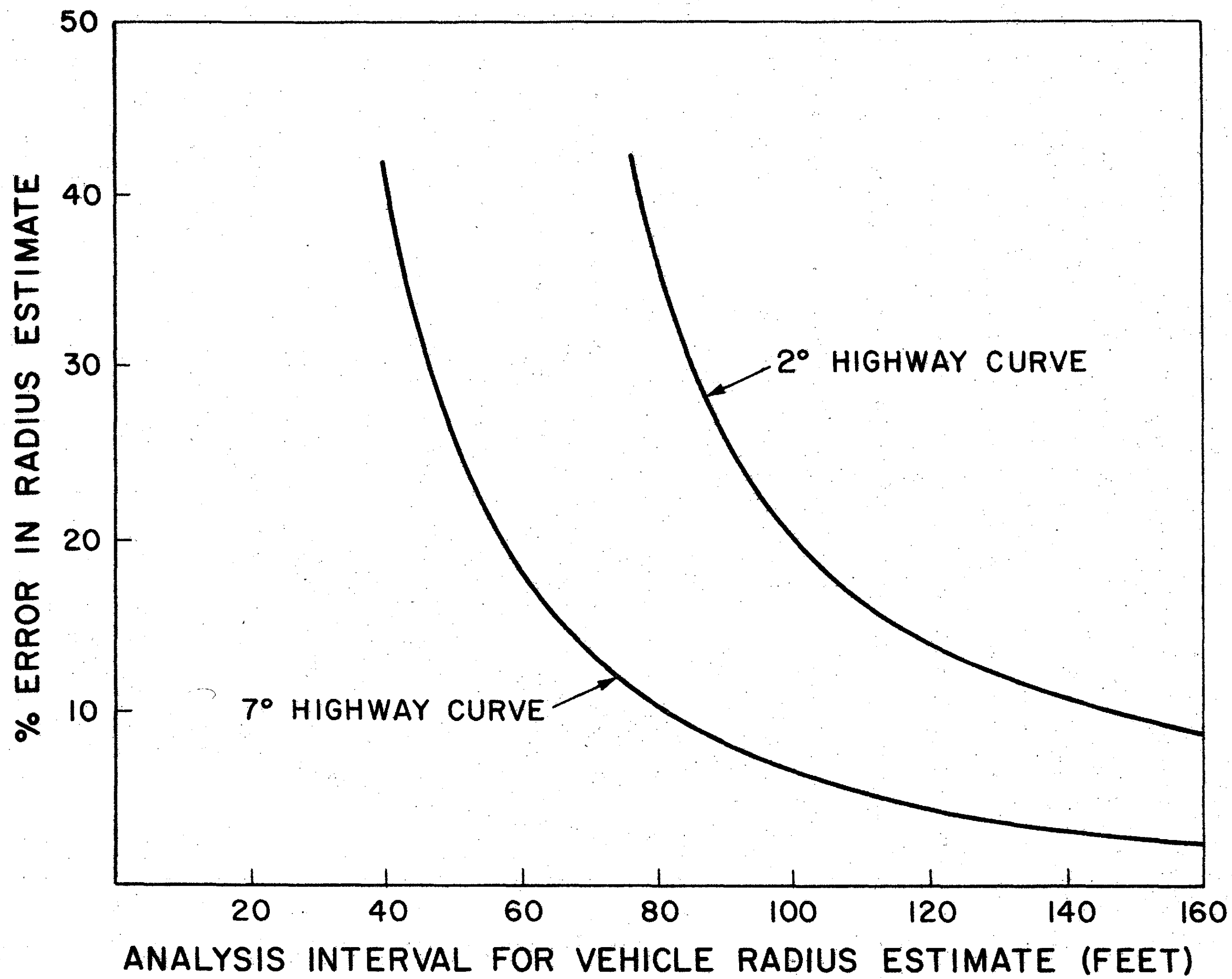


Figure 18 - Error Sensitivity of Vehicle Radius Estimate

ANALYSIS RESULTS

The result of the computer application was the printing of 50 to 80 data sets of lateral placement, speed, instantaneous radius, and lateral friction demand for each vehicle sampled. To represent the critical point of each sample, the point of maximum lateral friction demand was selected. This point, for a great number of samples, coincided with either the point of maximum speed or the point of minimum path radius, or both. Tables A-1 through A-5, in the Appendix A, give a summary of data for each sample. Appendix B shows some sample plots of lateral placement measurements.

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

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

Plotting scatter diagrams of speed versus radius did not indicate any relationship between the two parameters. This fact was verified by conducting simple linear regression analysis on the data. For the five highway curves studies, the vehicle speed never explained more than 11.4% ($r^2 = 0.114$) of the variation in the vehicle path radius; in fact, for three of the study sites, this percentage was below 4.7%.

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

Figure 19 shows simple linear regression fits for different percentiles of vehicle path radius versus highway curve radius. Figure 20 shows a similar relationship in terms of degrees of curve. For these two graphs, the equations of the lines and their goodness of fit are presented in Table 1. What these relationships show, for example, is that on a three-degree highway curve, 10% of the vehicles will exceed a 4.3-degree path maneuver.

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

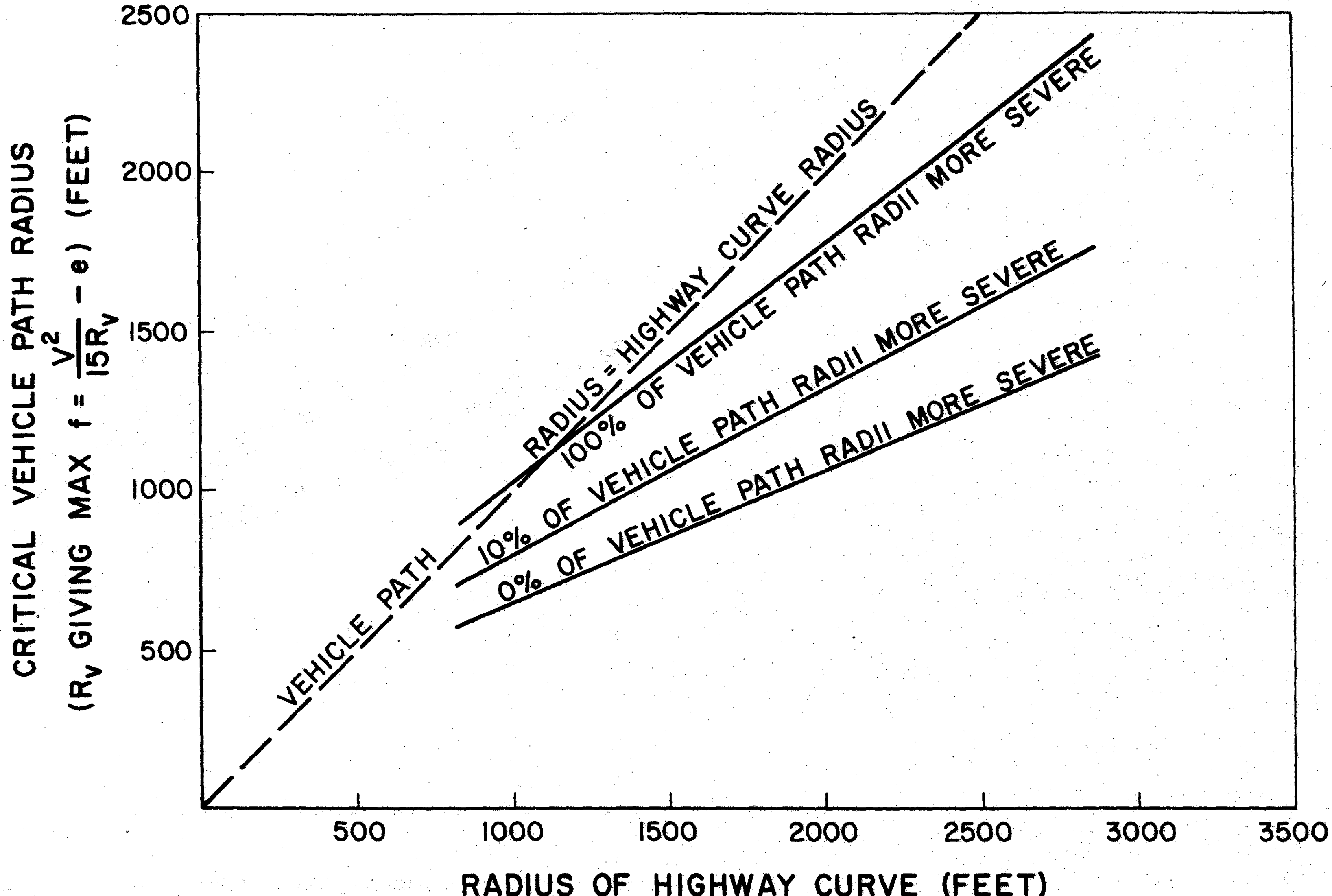


Figure 19 - Percentile Distribution of Vehicle Path Radius Versus Highway Radius

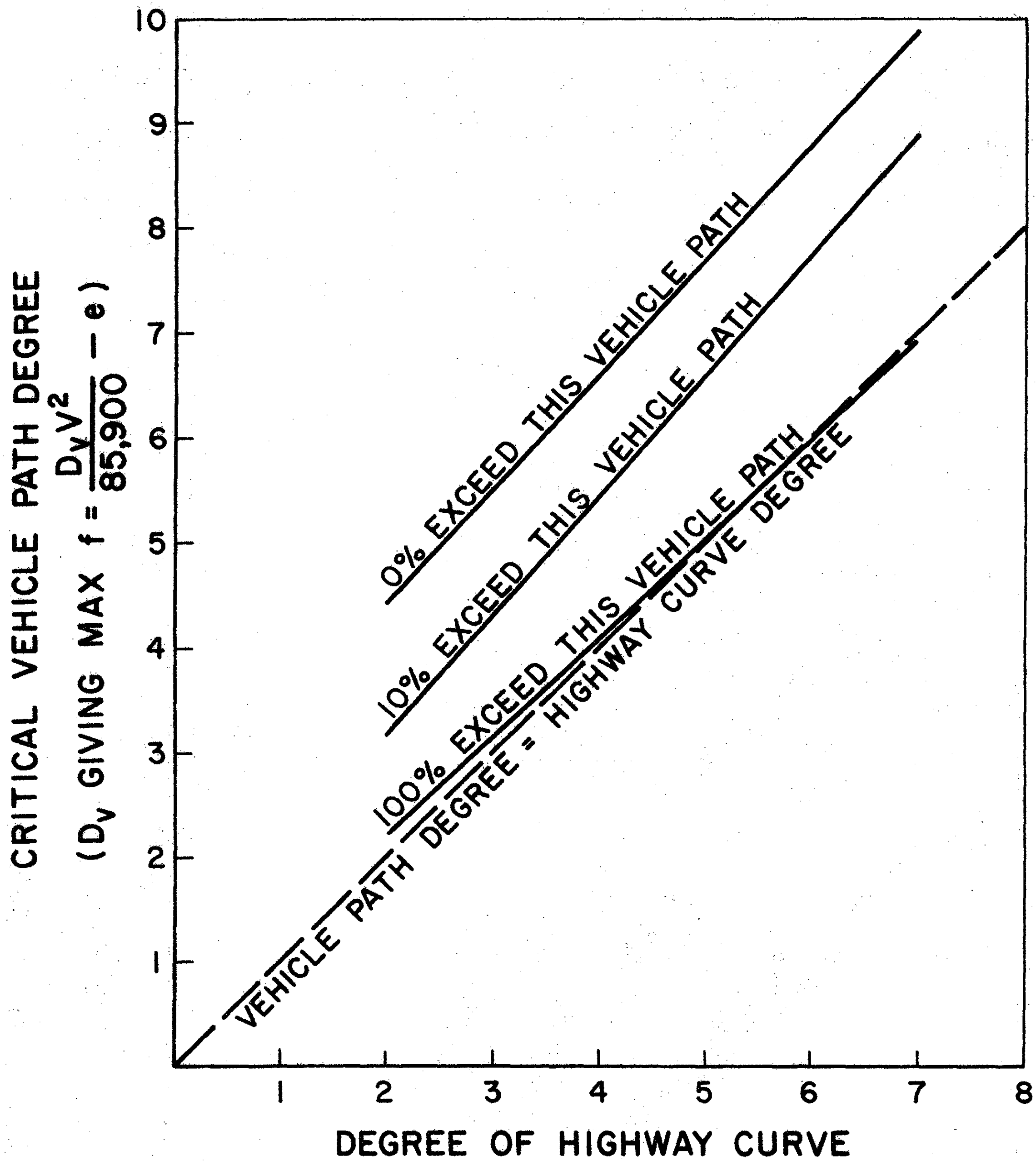


Figure 28 - Percentile Distribution of Vehicle Path Degree Versus Highway Curve Degree

TABLE 1

PERCENTILES OF VEHICLE PATH
VERSUS HIGHWAY CURVE PATH

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

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

or,

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

It is interesting to analyze these equations to see what percent of vehicles might exceed the design f. For example, if we design a curve for 60 mph with .06 superelevation and a design f = 0.13, what percentage of vehicles will exceed the design f? For the given design parameters, using the modified design equations gives R = 1890' and D = 3.1°. Using the equations of Table 1, it can be found that none of the vehicles will exceed the design f at 53 mph, 10% at 60 mph, 50% at 64 mph, and 100% at 70 mph.

DESIGN APPLICATION

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

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

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

LATERAL SKID RESISTANCE

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

By comparing standard skid trailer tests with tests made with an external watering source, for a speed range of 20 mph to 60 mph, it was found that measurements at speeds above 40 mph gave lower skid resistance values for the external watering tests. In addition, using the skid number versus speed relationship for external watering in the centripetal force equation more closely explained the results of full-scale spin-out tests conducted on the project.

Other research (5) using 15 pavement surfaces showed similar comparisons of the skid number versus speed relationship for internal and external watering tests. The measured differences, however, were not too substantial, amounting to an average of 4 units at 60 mph. Since this difference varies between pavements, it is difficult to predict. Perhaps the difference can best be accounted for in the design process by providing an adequate safety margin between predicted friction demand and measured skid number.

SPIRAL TRANSITIONS

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

SUPERELEVATION

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

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

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

SAFETY MARGIN

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

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

Many variables, as their magnitudes increase, lead to a higher loss-of-control potential for the cornering vehicle. Some of these variables are:

1. Vehicle speed
2. Driver steering judgment
3. Faulty vehicle dynamics
4. Micro vertical curvature (pavement bumps and dips)
5. Vehicle acceleration and braking
6. Steering reversal rate
7. Water depth
8. Tire temperature
9. Tire wear
10. Wind gusts

On wet pavements, vehicle speed is the most significant variable, not only because the lateral friction demand increases with the square of the speed, but also because skid resistance decreases with speed. These two phenomena, of course, are already accounted for in the design procedure. Also, with the design equation modified to account for statistical values of vehicle path, the effects of driving steering judgment and faulty vehicle dynamics are probably taken care of. Therefore, factors of safety are only needed to give some margin or error for the remaining variables.

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

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

DESIGN EQUATION

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

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

if the derived expression for the 10th percentile R_V in terms of the highway curve radius, R, is substituted, the following equation results:

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

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

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

or solving for R,

$$R = -514 + \frac{V^2}{5.48e + 7.86\ (0.01\ SN_v - M_s)}$$

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

HYPOTHETICAL DESIGN USE

Although specific design standards cannot be recommended, it is important to look at the sensitivities of the suggested design equation. Figure 20, a percentile distribution of skid number in one state, is used for illustration (6). The two curves having skid numbers of 35 and 25 at 40 mph are used as hypothetical minimum skid resistance requirements. The value of 35 has been widely recommended.

Selecting a safety margin of 0.10 and a design e of 0.06, the solutions of the design equation for these two "typical" pavements are as shown in Table 2. The design values below 2° are somewhat questionable because of the limits of the field data. It can be shown, though, that a 2° curve will not satisfy the selected safety margin for these higher design speeds.

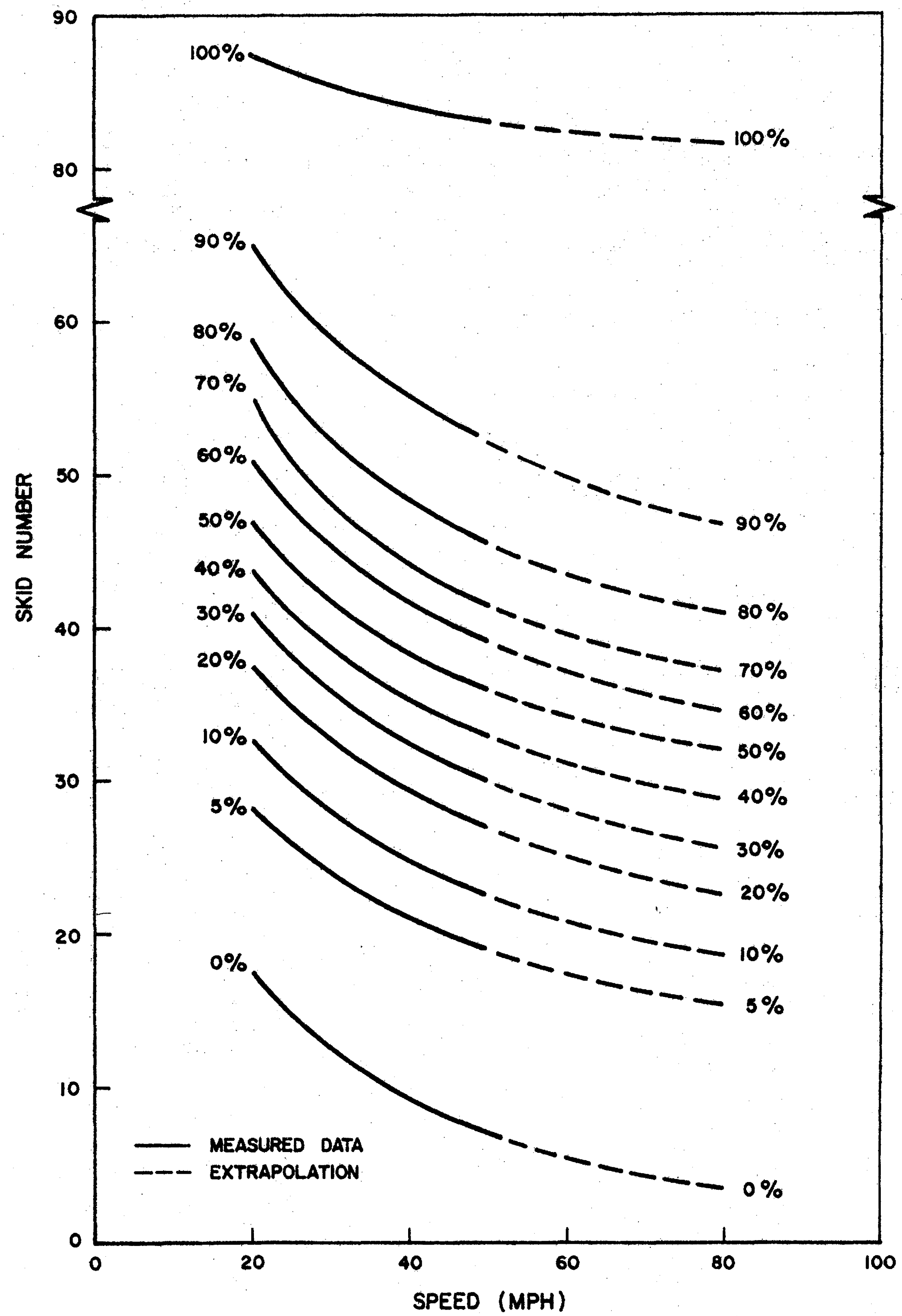


Figure 21 - Percentile Distribution of Skid Numbers Versus Speed for 500 Pavements in One State (5)

Table 2

HYPOTHETICAL SOLUTION OF PROPOSED DESIGN EQUATION
(Using e = 0.06 and M_s = 0.10)

Design Speed	Design Radius (ft.)	Design Degree
SN_{40} = 35 as Typical Pavement		
50	640	9.0°
60	1,270	4.5°
70	2,080	2.8°
80	3,000	1.9°
SN_{40} = 25 as Typical Pavement		
40	560	10.2°
50	1,400	4.1°
60	2,500	2.3°
70	3,900	1.5°
80	5,700	1.0°

LIST OF REFERENCES

1. Kummer, H. W., and Meyer, W. E., Tenative Skid-Resistance Requirements for Main Rural Highways," NCHRP Report 37, 1967.

2. Glennon, John C., "State of the Art Related to Safety Criteria for Highway Curve Design," Texas Transportation Institute, Research Report No. 134-4, November, 1969.

3. American Association of State Highway Officials, <u>A Policy on Geometric Design of Rural Highways - 1965</u>.

4. Ivey, Don L., Ross, Hayes E., Hayes, Gordon G., Young, Ronald D., and Glennon, John C., "Side Friction Factors Used in the Design of Highway Curve," unpublished draft report, March, 1971.

5. Gallaway, Bob M., and Rose, Jerry R., "Highway Friction Measurements with Mu-Meter and Locked Wheel Trailer," Texas Transportation Institute, Research Report No. 138-3, June 1970.

6. Unpublished analysis of data measured in 1964 by a state highway department.

APPENDIX A

SAMPLE DATA FOR EACH MANEUVER

TABLE A-1
DATA FOR CURVE SITE 1 (7° CURVE)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
1	L	46	48	722	1	44	722	.147
2	R	44	44	673	4	43	683	.130
3	L	47	49	739	4	48	767	.169
4	R	48	52	718	4	49	718	.177
5	R	51	53	645	4	53	768	.198
6	L	56	57	688	1	54	688	.253
9	R	52	53	669	4	53	669	.234
10	L	43	45	687	3	44	687	.156
11	R	47	51	690	4	51	700	.201
12	L	53	53	700	1	51	760	.196
13	L	56	56	749	1	52	866	.176
15	L	46	46	751	1	44	783	.127
16	L	52	52	701	1	49	701	.197
17	R	48	48	645	4	48	645	.193
18	L	55	55	714	1	53	757	.216
19	R	53	57	665	4	56	665	.261
20	L	46	46	670	1	44	729	.139
21	L	53	53	679	4	49	679	.205
22	L	60	60	647	1	56	647	.285
23	R	49	50	716	4	48	716	.169
24	L	52	52	717	2	51	763	.195
25	R	48	52	680	4	52	680	.219
26	R	53	53	693	4	51	703	.200
27	L	48	48	750	1	45	750	.146
28	R	57	57	612	4	53	612	.261
29	R	49	50	661	4	48	661	.187
30	L	60	64	710	4	62	768	.302
31	R	40	42	611	4	42	696	.121
32	L	49	50	773	4	50	810	.174

TABLE A-1 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter or Curve	Velocity	Radius	f
33	L	48	48	705	1	46	746	.154
34	R	57	61	730	4	60	730	.273
35	L	61	62	784	1	61	784	.280
36	L	57	57	739	1	55	740	.233
37	R	53	57	681	4	56	712	.240
38	L	48	48	629	2	45	629	.181
39	L	46	46	707	1	45	789	.137
40	L	58	58	713	4	57	732	.260
41	R	57	58	698	4	58	752	.250
42	L	58	58	708	3	55	708	.245
43	R	48	48	652	4	48	672	.183
44	L	56	56	720	1	56	720	.252
45	R	52	52	683	1	48	685	.179
46	L	53	53	698	3	51	698	.217
47	R	57	58	660	4	58	660	.292
48	L	43	43	656	4	40	663	.123
50	L	61	61	721	1	58	749	.266
51	R	57	58	657	4	58	668	.288
53	R	60	61	678	1	57	744	.240
54	L	55	55	725	1	51	736	.204
55	R	53	56	638	4	56	639	.274
56	L	46	46	715	1	44	742	.142
57	R	45	48	700	4	48	736	.163
58	L	61	61	737	1	58	750	.266
59	R	47	48	646	2	47	646	.175
60	L	48	48	730	1	46	768	.148
61	R	46	48	679	4	47	705	.157
63	R	55	55	689	4	53	701	.222
64	L	55	55	720	1	53	746	.220

TABLE A-1 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
65	R	48	48	628	4	42	681	.125
66	L	55	55	712	1	52	779	.200
67	R	51	51	679	4	44	709	.142
68	R	61	61	704	1	58	723	.262
69	L	57	57	658	1	53	688	.242
70	L	50	50	722	3	49	744	.184
71	R	50	50	644	4	47	644	.176
72	L	57	57	699	4	53	736	.223
73	R	55	58	648	4	57	648	.283
74	L	48	48	690	1	46	717	.161
75	R	51	52	693	4	52	696	.213
76	L	48	48	709	1	46	709	.163
77	R	58	58	641	4	52	641	.235
78	L	47	48	638	1	46	638	.186
79	L	58	62	670	4	62	670	.352
80	L	55	55	741	2	52	744	.211
82	L	61	61	701	1	58	731	.274
83	R	48	48	620	4	48	620	.203
84	L	60	61	806	2	58	811	.243
85	R	46	46	662	1	46	684	.156
86	L	50	50	702	1	48	720	.183
87	R	48	48	621	4	48	621	.193
88	L	60	60	705	1	60	705	.300
89	R	53	58	721	4	58	721	.263
90	L	47	48	620	2	46	620	.192
91	R	42	42	718	1	41	735	.102
92	L	51	51	757	1	49	757	.180
93	R	56	57	725	4	57	725	.248
94	L	58	60	695	4	57	696	.275

TABLE A-1 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
95	R	42	42	608	4	42	608	.146
96	L	61	61	732	2	61	732	.303
97	R	40	40	685	1	40	685	.103
98	R	57	57	717	2	51	717	.195
99	L	53	53	677	3	48	677	.196
100	R	53	58	659	4	58	659	.292
101	L	57	57	727	1	53	727	.227
103	L	60	60	724	1	57	750	.253
104	R	45	45	587	1	43	587	.159
105	L	61	69	732	4	67	769	.356
106	R	53	55	668	4	55	668	.247
108	L	45	45	717	1	43	718	.136

TABLE A-2
DATA FOR CURVE SITE 2 (4° CURVE)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
1	R	71	73	1099	3	71	1099	.219
2	L	69	71	1075	1	70	1075	.219
3	R	82	82	1052	3	67	1052	.201
4	L	58	61	1150	1	58	1150	.121
5	L	57	58	967	1	58	967	.158
6	R	49	49	1134	2	49	1134	.058
7	L	57	57	1146	3	57	1153	.112
8	R	51	52	1063	4	50	1063	.074
9	L	64	64	1044	4	62	1050	.184
10	R	77	79	1099	4	79	1126	.288
11	L	45	45	1239	2	44	1239	.031
12	R	65	65	958	4	65	958	.213
13	L	49	50	1166	1	50	1181	.068
14	R	49	49	1080	4	48	1080	.060
15	L	55	55	1045	1	55	1045	.115
16	R	58	58	1086	1	58	1086	.123
17	L	53	53	1181	1	53	1181	.086
18	R	57	57	1063	4	56	1063	.110
19	L	57	58	1115	1	56	1115	.111
20	R	64	64	1092	4	62	1092	.152
21	L	65	69	1067	4	69	1067	.222
22	R	62	64	1009	4	64	1009	.184
23	L	56	58	1128	1	57	1128	.117
24	L	56	57	1135	1	57	1149	.113
25	R	64	65	1241	3	64	1241	.134
26	L	69	71	1235	3	69	1235	.181
27	R	45	46	1217	1	46	1235	.029
28	L	64	65	1020	3	65	1054	.196
29	R	71	71	941	4	64	941	.204

TABLE A-2 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
30	L	61	61	1070	1	60	1078	.144
31	R	57	57	1103	2	53	1191	.075
32	L	65	67	1078	4	65	1078	.190
33	R	65	65	1033	2	62	1171	.136
34	L	61	61	1126	1	52	1166	.082
35	R	60	61	1064	1	61	1064	.147
36	L	61	67	1151	4	65	1151	.173
37	R	41	41	1239	4	40	1239	.002
38	L	57	57	1225	4	56	1225	.094
39	R	64	65	1146	1	65	1179	.157
41	R	57	57	1156	4	52	1156	.073
43	L	57	58	1035	3	58	1055	.139
44	R	62	62	1160	3	62	1160	.138
45	L	56	56	1148	2	53	1148	.091
47	L	64	64	1116	3	64	1116	.169
48	R	60	60	1165	2	58	1165	.109
49	L	71	71	1102	2	69	1102	.212
50	R	71	71	1055	4	69	1077	.209
52	L	62	62	1144	1	62	1145	.151
53	R	65	65	997	1	64	1022	.181
54	L	58	58	979	1	57	979	.146
55	R	55	55	983	2	55	983	.117
56	L	60	61	1150	2	60	1150	.130
57	R	48	48	1127	1	48	1127	.054
58	L	41	53	806	4	52	1080	.094
59	L	62	64	1098	1	64	1132	.165
60	R	60	60	1113	2	58	1169	.108
61	R	62	62	983	4	57	983	.135
62	L	65	65	1023	1	65	1023	.204

TABLE A-2 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
63	R	62	64	1179	3	64	1205	.141
65	R	65	65	1096	4	62	1096	.151
66	L	69	71	1125	1	67	1125	.192
67	R	64	64	1078	1	62	1138	.143
68	L	61	61	1107	3	58	1107	.129
69	R	56	56	1080	4	56	1080	.107
70	L	49	52	1135	4	52	1137	.086
71	R	71	71	971	4	69	970	.041
72	L	39	39	1142	2	39	1142	.012
73	R	69	71	980	4	69	980	.238
74	L	53	56	1172	4	56	1217	.095
75	R	75	77	1034	1	75	1034	.276
76	L	56	59	1129	4	58	1129	.125
77	R	47	47	1085	1	45	1277	.021
78	L	62	64	1044	1	64	1044	.185
79	L	58	64	1267	4	64	1354	.126
80	R	69	75	967	4	71	967	.260
81	R	71	73	1077	4	71	1077	.225
82	L	62	65	993	2	62	993	.186
83	R	67	69	1075	2	67	1182	.169
84	R	64	64	1072	4	62	1072	.156
85	L	48	51	1167	4	51	1234	.067
86	R	51	51	1045	1	50	1045	.077
87	L	52	52		1	52	1202	.077
89	L	54	61	750	3	56	787	.188
90	R	65	67	1044	4	64	1044	.175
91	L	60	61	1146	1	60	1163	.128
92	L	60	61	1116	1	60	1116	.136
93	L	67	69	1156	1	67	1165	.183

TABLE A-2 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
94	R	62	62	1028	4	61	1028	.155
95	L	62	64	980	1	63	980	.202
96	R	50	50	1084	1	49	1084	.065
98	L	57	62	1112	1	57	1112	.119
99	R	42	42	1214	2	41	1214	.007
100	L	64	69	1009	1	64	1009	.194
101	R	77	77	1003	4	75	1042	.295
102	L	62	62	1159	1	62	1162	.148
103	R	55	55	1091	4	51	1091	.076
104	L	61	61	1023	3	60	1023	.156
105	R	65	65	913	4	65	913	.228
106	L	61	62	1655	1	61	1155	.139
107	R	49	51	1048	4	51	1060	.087
108	L	60	61	1206	4	60	1206	.121
109	R	58	61	986	4	60	986	.154
110	L	56	56	1024	1	55	1100	.105
111	L	57	57	1207	1	55	1220	.088
112	R	58	62	1168	3	61	1168	.127

TABLE A-3
DATA FOR CURVE SITE 3 (5^{o} CURVE)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
1	L	50	50	921	1	49	994	.114
2	R	62	62	994	1	62	1064	.213
3	L	67	67	1056	1	64	1056	.207
4	R	64	64	979	4	62	1075	.191
5	L	71	71	938	1	69	1072	.275
6	R	48	49	980	1	48	1143	.107
7	L	52	53	901	4	52	901	.153
8	R	58	59	902	1	57	1087	.169
9	L	71	71	974	4	71	974	.293
10	R	64	65	1018	1	64	1112	.215
11	L	58	58	1062	1	58	1103	.185
12	R	67	67	874	3	61	874	.213
13	L	65	65	988	1	64	1135	.219
14	R	73	73	977	2	71	977	.271
15	L	73	73	934	4	71	934	.297
16	L	61	61	972	1	61	973	.214
17	L	69	69	1023	1	69	1043	.264
18	R	73	75	976	4	69	998	.267
19	L	62	62	983	4	62	983	.213
20	L	71	71	1022	1	69	1080	.233
23	R	65	65	938	4	65	938	.254
24	L	56	56	968	4	55	969	.145
25	R	56	56	995	1	55	1205	.135
26	L	67	67	1012	1	67	1165	.238
27	R	67	67	955	1	65	1043	.244
28	L	65	67	996	3	67	996	.232
29	R	52	52	962	3	52	963	.120
30	L	65	69	996	1	69	1087	.271

TABLE A-3 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
31	L	64	67	982	4	67	982	.266
33	R	73	73	985	1	73	1118	.285
34	R	69	71	998	1	71	1015	.299
35	R	48	48	926	1	47	944	.104
36	R	64	65	957	2	65	996	.217
37	L	75	75	909	1	75	909	.340
39	R	64	64	922	1	61	1081	.196
40	L	61	61	996	1	60	1052	.184
42	R	69	69	978	1	65	978	.232
43	L	58	59	993	1	58	1150	.176
44	R	57	57	988	4	55	988	.141
45	L	53	53	945	4	50	957	.126
46	R	69	71	1003	1	69	1034	.276
47	L	58	65	982	4	65	1102	.209
48	R	64	65	935	4	64	970	.230
49	L	42	43	1000	1	43	1044	.098
50	R	71	71	981	1	71	1109	.271
51	L	60	61	1012	1	60	1093	.196
52	R	69	73	964	4	73	990	.306
53	L	56	57	780	4	55	780	.184
54	R	77	77	1047	1	77	1101	.329
55	L	65	73	1015	4	73	1015	.297
56	R	62	67	957	4	67	1079	.228
57	L	75	77	1030	4	73	1030	.292
58	R	64	67	973	1	67	1113	.240
60	R	57	57	845	3	54	845	.165
61	L	67	69	881	1	69	1046	.283

TABLE A-3 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
63	L	69	69	1029	4	65	1072	.227
64	R	64	64	972	2	60	972	.173
65	L	51	51	1001	1	51	1001	.115
66	R	58	60	952	1	58	1016	.192
68	R	48	50	953	1	50	1008	.118
69	R	61	62	1013	2	61	1013	.174
70	L	60	61	988	1	61	988	.200
71	R	67	67	939	1	67	1065	.252
73	R	52	52	891	1	49	891	.133
75	R	61	61	871	4	60	900	.212
76	L	56	56	984	4	50	1111	.112
77	R	67	71	967	3	69	999	.247
79	R	52	53	1029	1	53	1133	.138
80	L	61	61	953	4	57	953	.177
81	L	64	64	1026	1	62	1105	.214
82	R	71	71	937	4	67	938	.250
83	L	61	65	964	1	64	1027	.215
84	R	65	67	999	1	65	1035	.226
85	L	71	71	948	4	71	1050	.278
86	R	69	69	926	4	69	961	.279
87	L	65	65	986	1	65	994	.227
88	R	64	64	949	1	64	1012	.238
90	R	58	60	886	2	56	906	.158
91	L	71	71	1018	1	67	1091	.255
92	R	64	65	1017	1	65	1174	.213
93	L	65	67	910	1	65	910	.254
95	L	67	67	941	3	65	941	.233
96	R	64	65	966	1	64	1007	.210
97	L	75	75	918	4	69	918	.285

TABLE A-3 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f			
					Quarter of Curve	Velocity	Radius	f
98	R	61	62	915	4	62	937	.206
99	L	69	73	1001	4	73	1062	.292
100	R	73	73	995	1	73	1129	.282
101	L	64	64	966	1	61	1038	.178
102	R	65	65	961	1	64	1062	.226
104	R	53	53	935	1	52	984	.136
105	R	71	73	1011	4	73	1080	.276
106	L	71	73	1024	4	71	1024	.276
107	R	69	71	1018	4	67	1018	.225

TABLE A-4
DATA FOR CURVE SITE 4 (2^{o} CURVE)

					Data At Point of Maximum f			
Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Quarter of Curve	Velocity	Radius	f
1	L	53	57	1843	4	55	1843	.078
3	L	56	56	2192	3	56	2193	.064
4	R	75	77	2004	4	75	2067	.160
5	L	62	62	2123	1	62	2123	.072
7	L	67	71	2030	3	69	2030	.126
8	R	75	84	2123	3	79	2130	.167
9	L	61	61	2150	4	61	2280	.078
10	R	64	64	1917	4	58	1917	.098
11	L	47	48	2067	4	48	2288	.036
12	L	61	64	1988	3	62	2022	.098
13	R	71	73	1930	3	73	1930	.143
14	L	67	69	1896		67	1896	.128
15	R	71	75	1657	3	73	1657	.173
16	L	48	48	2053	3	48	2053	.044
17	R	61	61	1861	3	60	1861	.097
20	R	53	58	1866	4	56	2189	.074
21	L	52	53	1990	4	53	1990	.066
22	R	67	67	1812	3	64	1905	.113
23	L	56	56	1686	4	50	1686	.070
24	R	60	60	1495	1	57	1495	.084
25	L	67	67	1945	4	67	2136	.111
26	R	69	75	2190	4	73	2197	.141
27	L	62	64	1725	4	64	1725	.128
28	R	55	57	2130	4	57	2349	.072
30	R	61	61	2014	4	58	2014	.092
31	L	50	53	1650	4	52	1650	.081
32	L	53	58	1806	4	55	1806	.080
33	R	62	64	1711	3	60	1711	.098

TABLE A-4 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
34	L	67	69	2135	4	69	2190	.114
35	R	62	62	1886	3	60	1886	.085
36	L	62	62	2102	4	62	2250	.085
38	R	69	71	1965	4	71	1965	.150
39	L	67	67	1895	3	65	1895	.121
40	L	44	44	1536	4	38	1536	.032
41	R	73	75	1874	4	75	2109	.157
42	L	64	71	1940	3	67	2006	.128
43	L	53	60	1892	4	56	2081	.069
44	R	56	58	1654	3	56	1654	.085
46	R	69	73	1836	3	71	1836	.142
48	R	62	65	2081	4	65	2081	.117
49	L	69	73	1869	4	71	1869	.149
50	L	67	67	1953	4	64	2093	.100
51	R	61	62	1932	4	61	1951	.107
52	R	67	67	1865	3	65	1865	.113
53	L	57	57	1965	3	55	1965	.071
54	R	60	61	1951	4	60	1978	.099
55	L	65	65	1855	4	65	1855	.124
58	R	67	69	1806	3	67	1806	.126
60	R	69	71	1605	3	69	1605	.157
61	L	60	60	1999	4	58	2057	.080
62	R	67	67	1904	4	66	2046	.120
63	L	61	61	1778	4	56	1868	.081
64	L	65	67	1835	4	65	1835	.126
65	R	62	62	1830	4	62	1830	.122
66	L	65	67	1833	3	67	1834	.134
67	L	64	67	1653	2	65	1653	.114
68	R	64	64	1775	3	64	1775	.113

TABLE A-4 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
69	L	61	62	1804	4	62	2072	.095
70	L	65	65	1874	3	64	2087	.100
71	L	65	67	1758	4	65	1758	.133
73	L	64	64	2117	3	62	2365	.080
74	L	61	61	1954	4	61	2174	.084
75	R	49	49	1550	4	49	1550	.085
76	L	62	65	2022	3	64	2045	.103
77	R	61	65	2040	4	65	2356	.101
78	L	62	64	1741	4	64	1741	.126
82	R	73	73	1662	4	71	1917	.154
83	L	58	58	1711	1	58	1711	.082
84	R	75	78	2220	4	75	2220	.148
85	L	62	62	1759	4	62	1759	.117
86	R	67	67	1770	3	65	1862	.123
87	L	49	50	1832	4	50	1878	.060
88	R	75	75	1785	1	73	1785	.138
89	L	62	62	1641	2	61	1641	.101
90	L	55	57	2225	4	57	2343	.072
91	L	67	67	1984	4	67	1984	.121
92	R	69	69	2084	4	69	2084	.132
93	R	71	71	1851	3	67	1851	.122
96	L	75	75	2046	3	73	2145	.134
98	L	67	67	1821	4	65	1821	.127
99	R	73	75	1694	3	75	1715	.177
100	L	65	71	2000	3	69	2257	.110
101	R	67	71	1679	3	71	1679	.149
102	L	67	67	1948	4	62	1961	.102
103	R	71	73	1858	3	73	1858	.150

TABLE A-4 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
104	L	67	69	1698	4	69	1698	.156
105	R	65	69	2001	4	69	2175	.126
106	L	64	64	1911	4	62	2105	.093
107	R	52	52	2079	4	52	2079	.068
108	L	67	67	1900	4	64	1925	.111
110	L	56	58	1708	4	58	1882	.090
112	R	67	67	1996	4	67	2064	.126
113	R	60	63	1973	4	61	1973	.105

TABLE A-5
DATA FOR CURVE SITE 5 (2.5° CURVE)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
1	L	71	73	1689	1	71	1689	.148
2	R	69	75	1873	4	75	1951	.131
3	L	67	69	1821	4	69	1821	.124
4	L	75	77	1879	2	77	1879	.160
5	R	64	65	1459	1	62	1459	.118
6	L	64	64	1716	3	62	1765	.097
7	R	69	71	1662	2	69	1662	.130
8	L	73	75	1870	4	75	1955	.141
9	R	69	71	1826	4	71	1874	.118
10	L	64	65	1858	3	65	1897	.101
11	L	64	65	1613	3	64	1613	.119
14	R	69	71	1625	4	71	1625	.145
15	L	60	60	1587	3	60	1587	.099
16	R	65	71	1598	1	65	1598	.119
17	L	73	75	1810	3	73	1810	.145
18	R	69	69	1022	4	61	1022	.182
19	L	79	79	1802	1	79	1825	.180
20	R	75	82	1849	3	77	1849	.154
21	L	62	64	1593	3	62	1593	.113
22	R	64	67	1741	4	65	1741	.104
23	L	75	79	1818	3	75	1818	.155
24	R	71	75	1814	2	73	1814	.134
25	L	77	77	1842	2	75	1842	.153
26	R	57	57	1743	4	56	1795	.055
27	R	73	73	1569	4	71	1569	.153
28	L	56	57	1798	3	57	1798	.070
29	R	61	62	1757	1	62	1757	.087
30	L	71	73	1696	4	71	1696	.147
31	R	79	82	1920	4	79	1920	.159

TABLE A-5 (Continued)

Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
32	L	48	51	1628	4	50	1628	.054
33	R	67	69	1745	4	67	1745	.112
34	L	67	67	1894	4	65	1894	.101
35	R	71	73	1617	1	71	1617	.146
36	L	62	65	1685	4	64	1685	.111
37	R	73	75	1729	1	73	1729	.144
38	L	73	75	2000	3	75	2010	.136
39	R	73	73	1703	1	71	1703	.136
40	L	71	71	1757	3	69	1757	.130
41	R	75	75	1700	1	75	1717	.157
42	L	73	75	1910	1	75	1937	.143
43	L	67	69	1834	3	67	1834	.114
44	R	71	75	1742	4	75	1770	.151
45	L	57	57	1819	2	57	1857	.066
46	R	77	77	1698	4	73	1698	.148
47	L	71	71	1798	1	69	1798	.126
48	R	75	75	1820	3	75	1820	.145
49	R	58	64	1776	4	62	1859	.079
50	L	60	60	1617	4	58	1617	.090
51	R	53	57	1607	1	56	1657	.065
52	L	67	71	1957	3	71	2035	.114
53	R	75	79	1831	4	79	1872	.164
54	L	75	77	1768	4	77	1966	.151
55	R	71	73	1808	3	71	1808	.125
56	L	75	75	1638	1	73	1638	.165
57	R	67	73	1913	1	71	1913	.114
58	L	61	61	1663	1	60	1663	.092
59	R	69	71	1696	4	71	1696	.137
60	L	55	58	1772	4	57	1772	.072

TABLE A-5 (Continued)

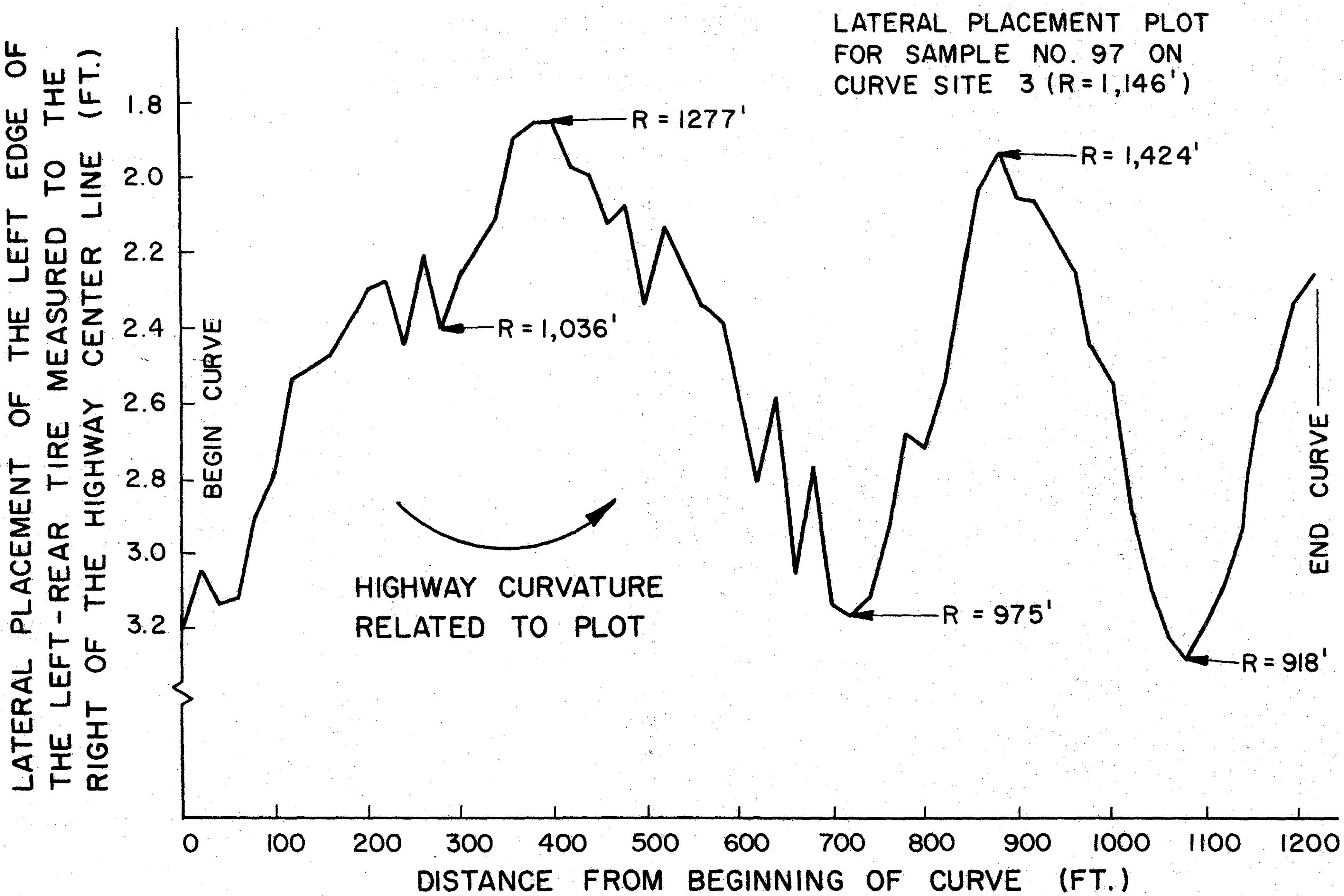
Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
61	L	56	58	1886	2	57	1886	.064
62	R	77	77	1706	2	71	1706	.136
63	R	75	79	1786	2	75	1786	.149
64	L	71	73	1792	4	71	1792	.136
66	L	64	71	1879	3	69	1956	.112
67	R	75	79	1523	3	77	1604	.186
68	L	69	69	1823	1	69	1908	.116
70	L	55	56	1678	2	55	1678	.068
71	R	64	64	1517	4	64	1574	.113
72	R	75	79	1725	4	77	1813	.158
73	L	56	58	1453	3	56	1453	.092
74	R	75	77	1671	2	75	1671	.163
75	L	73	75	1582	3	75	1582	.186
76	R	62	64	1684	1	62	1684	.094
77	L	51	52	1905	1	51	1905	.042
78	R	61	65	1797	3	65	1797	.099
79	L	73	73	1780	1	73	1780	.148
81	L	60	61	1644	2	57	1644	.081
82	L	69	71	1778	3	67	1778	.119
83	R	75	77	1830	3	77	1917	.146
84	L	73	79	1687	3	77	1687	.184
85	R	75	75	1714	4	75	1714	.158
86	L	56	57	1708	1	56	1708	.071
87	R	69	77	1869	1	75	1869	.140
88	R	73	75	1638	1	73	1662	.152
89	R	62	69	1884	2	64	1885	.084
90	L	69	71	1768	1	67	1768	.120
91	L	73	73	1893	1	71	1949	.121
92	R	67	75	1668	4	75	1963	.130

TABLE A-5 (Continued)

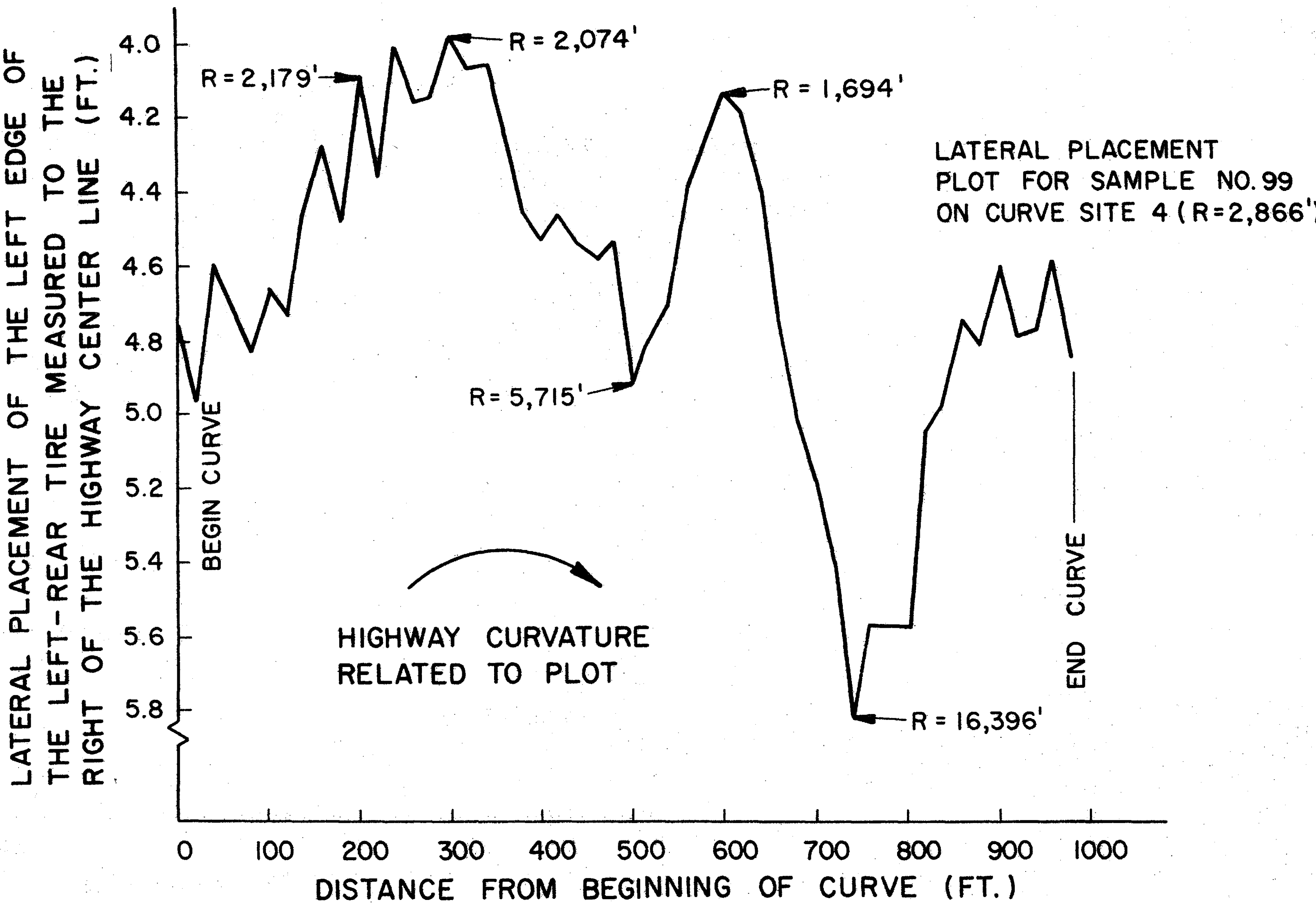
Sample No.	Left or Right	Initial Velocity	Maximum Velocity	Minimum Radius	Data At Point of Maximum f: Quarter of Curve	Velocity	Radius	f
93	L	60	60	1778	3	58	1802	.075
94	R	75	77	1859	2	75	1859	.141
95	L	73	73	1844	4	73	1844	.141
96	R	69	71	1969	3	69	1969	.101
97	L	62	64	1974	4	64	2045	.083
98	R	46	49	1499	4	48	1499	.041
101	L	58	61	1673	4	61	1673	.098
102	L	55	56	1743	2	56	1744	.069
103	R	75	75	1693	1	73	1715	.146

APPENDIX B

EXAMPLE PLOTS OF LATERAL PLACEMENT MEASUREMENTS



LATERAL PLACEMENT PLOT
FOR SAMPLE NO. 97 ON
CURVE SITE 3 (R = 1,146')
LATERAL PLACEMENT OF THE LEFT EDGE OF THE LEFT-REAR TIRE MEASURED TO THE RIGHT OF THE HIGHWAY CENTER LINE (FT.)
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
BEGIN CURVE
END CURVE
R = 1277'
R = 1,424'
R = 1,036'
R = 975'
R = 918'
HIGHWAY CURVATURE
RELATED TO PLOT
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
DISTANCE FROM BEGINNING OF CURVE (FT.)



LATERAL PLACEMENT OF THE LEFT EDGE OF THE LEFT-REAR TIRE MEASURED TO THE RIGHT OF THE HIGHWAY CENTER LINE (FT.)
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
R = 2,179'
R = 2,074'
R = 1,694'
R = 5,715'
R = 16,396'
BEGIN CURVE
END CURVE
LATERAL PLACEMENT PLOT FOR SAMPLE NO. 99 ON CURVE SITE 4 (R=2,866')
HIGHWAY CURVATURE RELATED TO PLOT
0
100
200
300
400
500
600
700
800
900
1000
DISTANCE FROM BEGINNING OF CURVE (FT.)