FRICTIONAL REQUIREMENTS FOR HIGH-SPEED PASSING MANEUVERS

by

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Research Report 134-7

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FOREWORD

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 seventh 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"

Research Report 134-5, "The Relation of Vehicle Paths to Highway Curve Design"

Research Report 134-6, "Passing Performance Measurements Related to Sight Distance Design"

DISCLAIMER

The opinions, findings, and conclusions expressed or implied in this report are those of the authors and not necessarily those of the Texas Highway Department or the Federal Highway Administration.

ABSTRACT

This research determined the tire-pavement friction demands of vehicles performing high-speed passing maneuvers. These frictional demands were found by photographing and analyzing passing maneuvers performed under actual highway conditions. Critical frictional requirements are proposed for application to skidding accident prevention programs that incorporate minimum skid resistance levels and wet weather speed limits.

SUMMARY

Of all the normal (non-emergency) maneuvers performed on our two-lane rural highways, passing probably accounts for the highest frequency of critical tire-pavement friction demands. Not only are passing maneuvers performed at relatively high speeds, but they may also involve critical combinations of lateral and forward acceleration. In addition, the path of the passing vehicle is generally adverse (negative superelevation) to the pavement cross-slope.

This research was conducted to determine the frictional requirements of vehicles performing high-speed passing maneuvers. Identification of critical friction requirements would provide a basis for determining minimum skid resistance requirements and also ascertain the need and basis for wet weather speed limits.

VEHICLE PATHS

A movie camera mounted in an observation box on the bed of a pickup truck was used to photograph the paths of passing vehicles at two study sites. Passing situations were staged with an impeding vehicle traveling at a predetermined speed.

The observation vehicle would move in behind a subject vehicle about two miles upstream from the study site. As these two vehicles approached, the impeding vehicle stationed on the shoulder near the beginning of the no-passing zone, would move out and impede the subject vehicle. Filming was initiated as the three vehicles reached the study site.

Approximately 2000 subjects were tested. Of this number, about 300 completed passing maneuvers were photographed. Impeding speeds were 50, 55, 60 and 65 mph.

Each study site was marked with two-foot stripes at 40-foot intervals along the centerline. This reference system allowed the determination of the lateral placement and speed of the passing vehicle at 40-foot intervals, by analyzing the movie film on a Vanguard Motion Analyzer. From the lateral placement data, an instantaneous path radius was estimated at each point by calculating the radius of the circular curve through three successive lateral placement points. Since a circular curve is the minimum curved path through three points, the radius so calculated was a conservative estimate of the smallest instantaneous path radius over the interval.

The point where vehicle speed and radius gave maximum lateral friction demand $(\frac{V^2}{15R} - e)$ was taken for both the initial pull-out maneuver and the return maneuver of each passing vehicle. Plotting the relationship between vehicle speed and radius for these points indicated no correlation between the two variables for either portion of the passing maneuver. Therefore, it was surmised that the measured distribution of vehicle path radii could be expected at any speed within the speed range studied.

LATERAL FRICTION DEMAND

To determine the critical lateral friction demand, a percentile level is needed to assure that very few vehicles will approach instability. The 10% level appears to be a reasonable choice. Using this level would say that 10% of passing vehicles would have lower vehicle path radii than the critical value. The 10th percentile radius values found from the data were 1470 feet for the initial maneuver and 1640 feet for the return maneuver.

Using these values in the centripedal force equation, $f = \frac{V^2}{15R} - e$, the relationship between critical lateral friction demand and speed was plotted for both maneuvers. An e value of -0.02 was used in the computations since most vehicle paths were adverse to the pavement cross-slope.

FORWARD ACCELERATION

Although no precise measurements of instantaneous forward acceleration were possible, the data indicated that vehicles were almost always accelerating during the initial maneuver and coasting during the return maneuver. Cursory examination of the data indicated an average acceleration range of 1-3 ft/sec^2 for the initial maneuver. As these are averages over fairly long intervals, instantaneous accelerations could be considerably higher.

CRITICAL FRICTION DEMAND

The total friction demand is a vector sum of forward and lateral accelerations. Kummer and Meyer (1) reported a relationship between forward friction demand and speed for full-throttle acceleration of an American "standard" automobile. To arrive at a reasonable estimate of the critical friction demand, the instantaneous forward acceleration of the passing vehicle was assumed to vary linearly from 40% of full throttle at 40 mph to 60% of full throttle at 80 mph. For a 4000 pound vehicle, this corresponds to a 6.4 ft/sec^2 acceleration at 40 mph and a 5.0 ft/sec^2 acceleration at 80 mph. For the return maneuver, the only forward friction component is 0.035 contributed by rolling resistance.

By taking the vector sum of the lateral friction demand and the estimated forward friction demand, a critical relation between total friction demand and speed was plotted for both the initial and return maneuvers. Comparing the two plots, it was found that the initial maneuver creates the critical friction demand. The relationship between critical friction demand and speed is shown in Figure S-1.

As was found in the analysis of the field data, only about 12% of the passing vehicles exceeded the posted speed limit at the critical point of the initial maneuver. Therefore, the critical speed may be equated with the speed limit for determining minimum skid resistance levels and wet weather speed limits.

IMPLEMENTATION

The frictional requirements shown in Figure S-1 have an immediate application to skidding accident programs that incorporate minimum skid resistance levels and wet weather speed limits. Although specific program recommendations cannot be offered, the report (Application of Results) discusses the effects of the proposed frictional requirements for various program parameters in one state that has specific percentile relationships of skid number versus speed. To apply the frictional requirements to an individual section of pavement, of course, requires a skid number versus speed plot for that pavement.

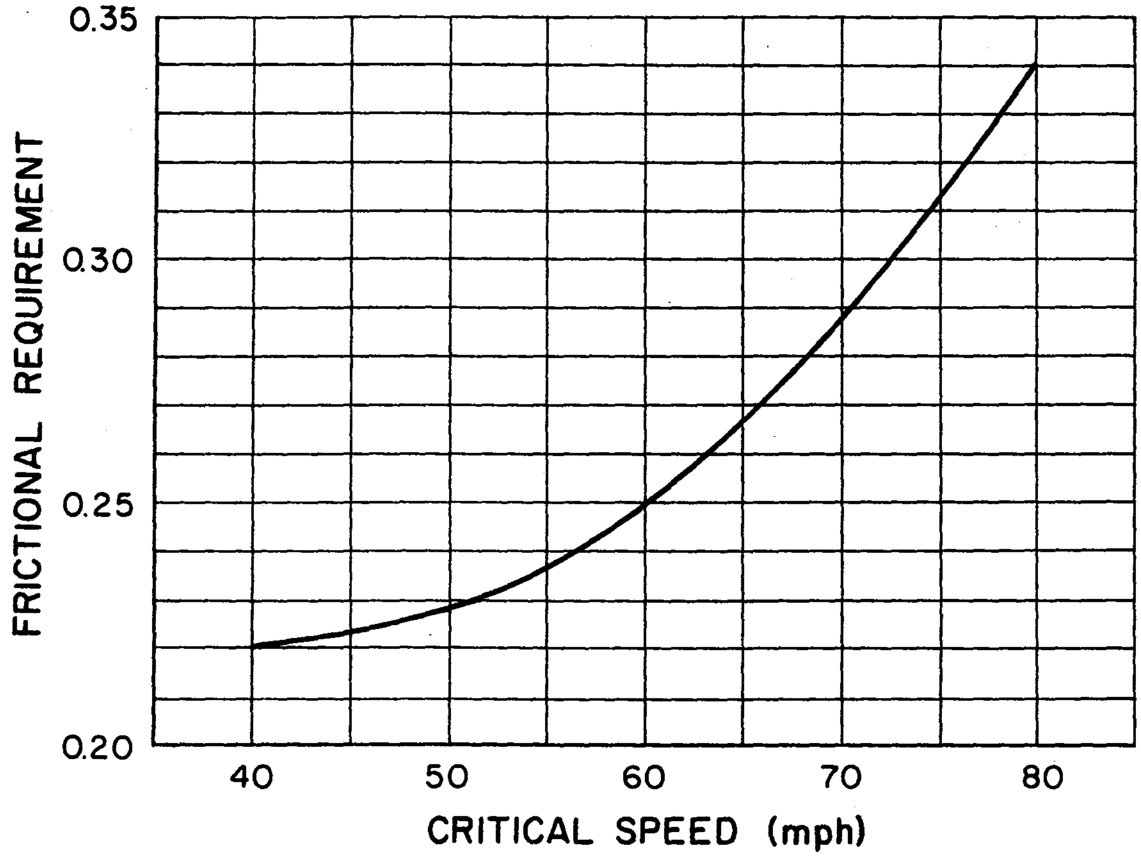

Figure S-1 - Proposed Frictional Requirements

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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 has increased 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).

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*Denotes number in List of References

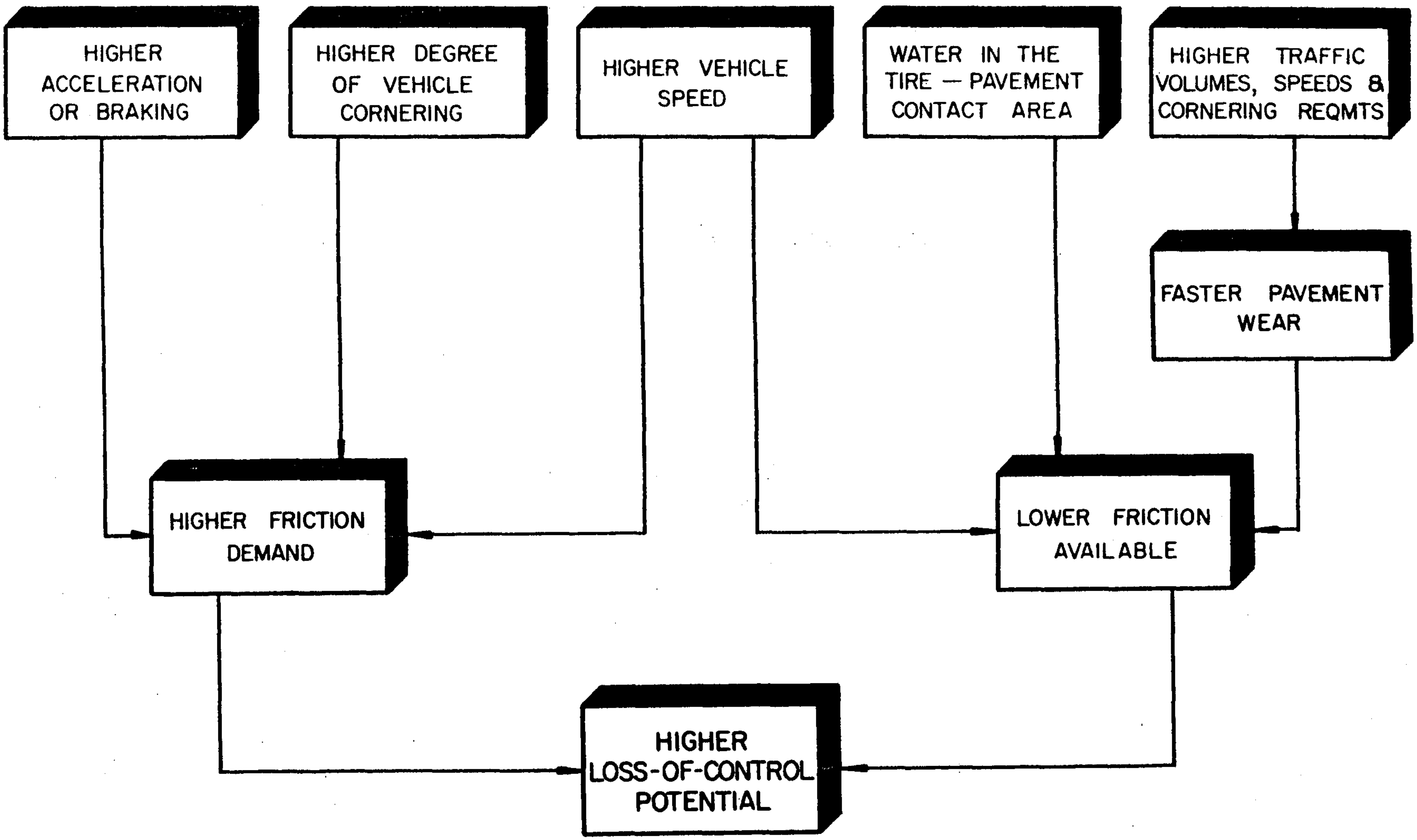


Figure 1. Circumstances Leading to Higher Loss of Control Potential.

Passing maneuvers probably account for the highest frequency of critical tire-pavement friction demands encountered on our rural two-lane highways. Not only are passing maneuvers performed at relatively high speeds, but they may also involve critical combinations of cornering and forward acceleration. In addition, passing vehicle path maneuvers are generally performed adverse (negative superelevation) to the pavement cross-slope.

This research study was conducted to determine the frictional demands of vehicles performing high-speed passing maneuvers. Identification of critical friction requirements should provide a basis for determining minimum skid resistance requirements and also ascertain the need and basis for wet weather speed limits.

The data for this research study was collected in conjunction with another study (2), which had as its purpose the measurement of time-distance requirements of high-speed passing maneuvers as a basis for passing sight distance design standards. Measurements were taken at three passing sites. The research study reported here, however, used data from only two sites because of time and monetary constraints on data reduction and analysis.

FIELD MEASUREMENTS

The general procedure involved the use of an impeding vehicle and an observation vehicle equipped with a 16-mm movie camera. Sample vehicles approaching the study sites through a striped no-passing zone were impeded at selected speeds by the impeding vehicle. The observation vehicle followed immediately behind the sample vehicle. Upon entering the passing zone, the impeding vehicle maintained a constant speed while the sample vehicle's passing maneuver was filmed from the observation vehicle.

Included in this section are descriptions of the study sites, the equipment used, and the procedures used.

STUDY SITES

Two study sites having passing zone lengths of 1360 and 2680 feet were selected within a 20-mile radius of College Station, Texas. Geometric details of the study sites are shown in Figures 2 and 3.

The study sites were selected to be free of external distractions that might alter the driver's normal operating procedure. That is, the driver was not subjected to drastic changes in environment or highway geometry; nor were there any intersections, railroad crossings, narrow bridges or other such unique features. Each site was preceded by several miles of relatively unrestricted geometry. Drivers approaching each site, therefore, were accustomed to relatively unrestricted passing opportunities and, with minor exceptions, to free-flowing traffic conditions.

Because of no major access points close to the study sites, traffic

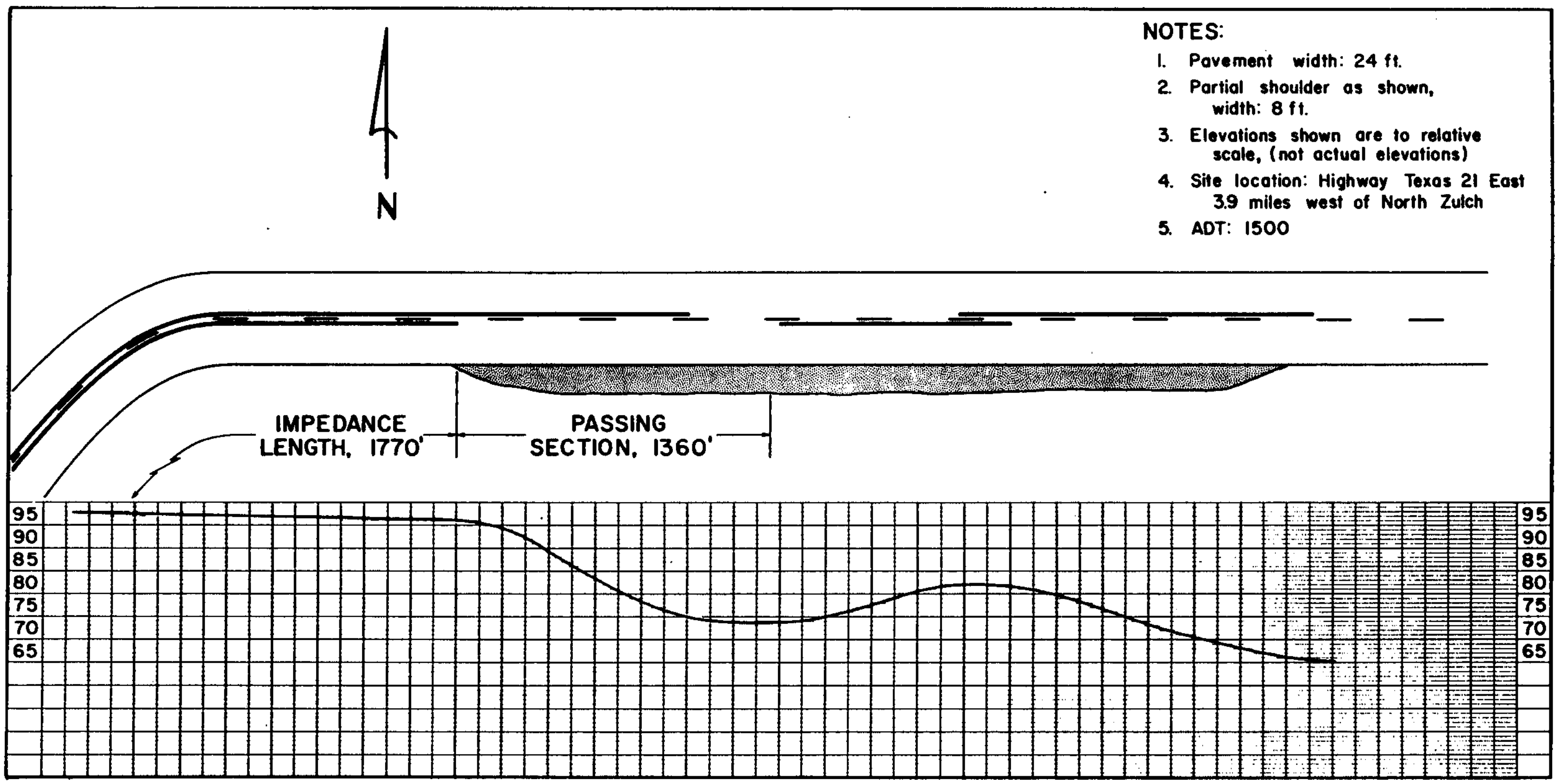


Figure 2 Geometrics of study Site A

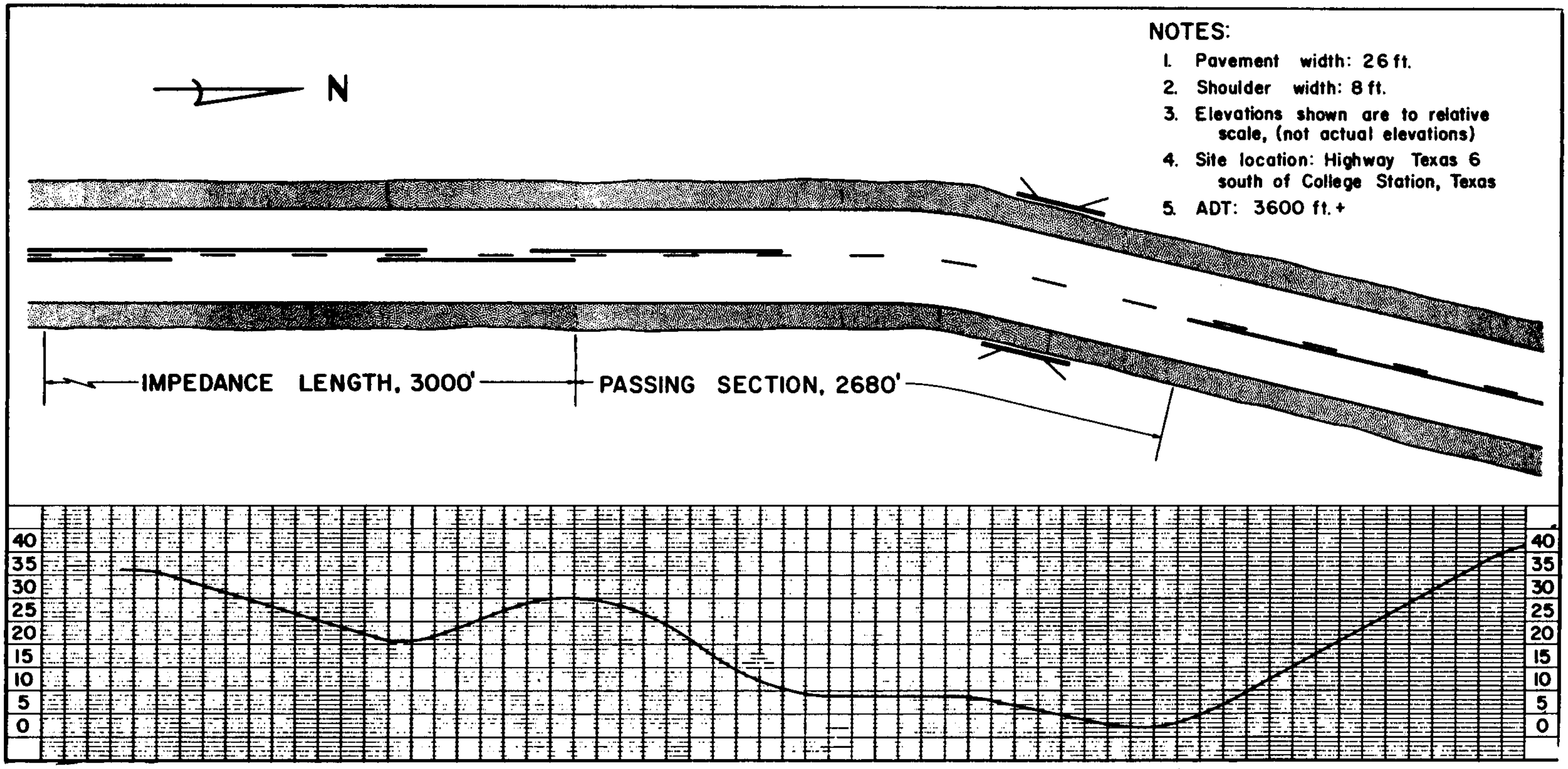


Figure 3 Geometrics of study Site B

flow was fairly consistent. The average daily traffic (ADT) was 1500 vehicles for Site A and 3600 vehicles for Site B.

The posted speed on both highways is 70 mph. Speed distribution studies conducted at the sites are shown in Figures 4 and 5. These distributions are closely similar to the statewide distributions conducted by the Texas Highway Department in 1968, which showed the average 85th percentile speed as 70 mph and the average 15th percentile speed as 54 mph. Considering only the speed characteristics, the passing maneuvers observed at the study sites should be indicative of those expected on similar facilities.

Prior to each site, passing was restricted by a double-yellow barrier stripe. No-passing zone lengths were 1770 feet for Site A and 3000 feet for Site B.

Both passing zones began on the downgrade of a crest, extended through a sag vertical curve, and terminate on the upward grade of a crest. The approaches to the sites differed; whereas, the sight distance prior to Site A was restricted by a horizontal curve, the sight distance prior to Site B was restricted by a crest vertical curve.

Site B, located 12 miles south of College Station on State Highway 6, has 13-foot lanes and 8-foot shoulders. Site A, located 20 miles northeast of College Station on State Highway 21, has 12-foot lanes and a short 8-foot shoulder on one side of the site. The right-of-way at both locations received normal maintenance from the Texas Highway Department, was clear of all large vegetation, and was mown throughout the study area.

Figures 6 and 7 show details of the study sites and present views

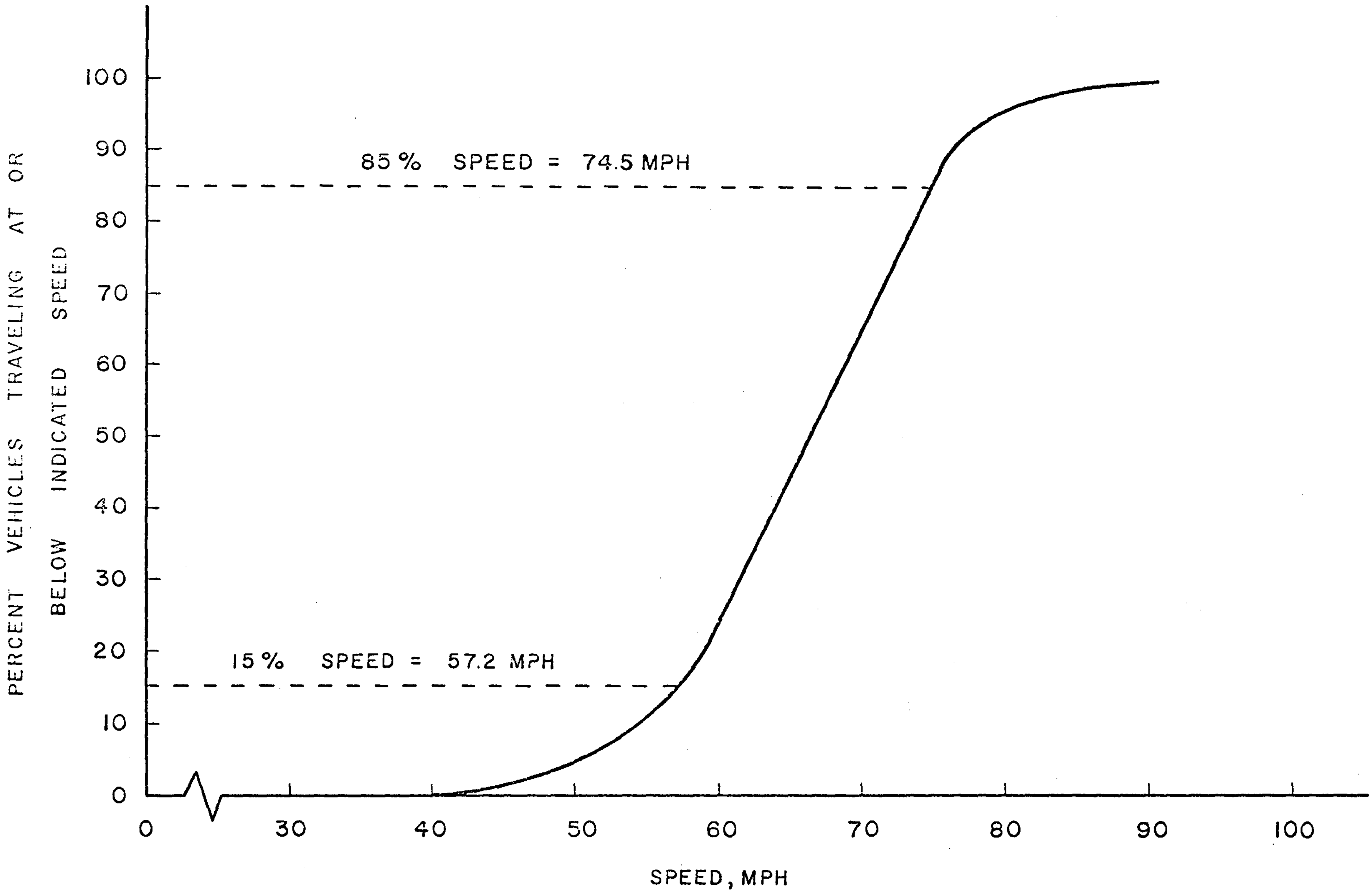


Figure 4 - Cumulative distribution of operating speed, Site A

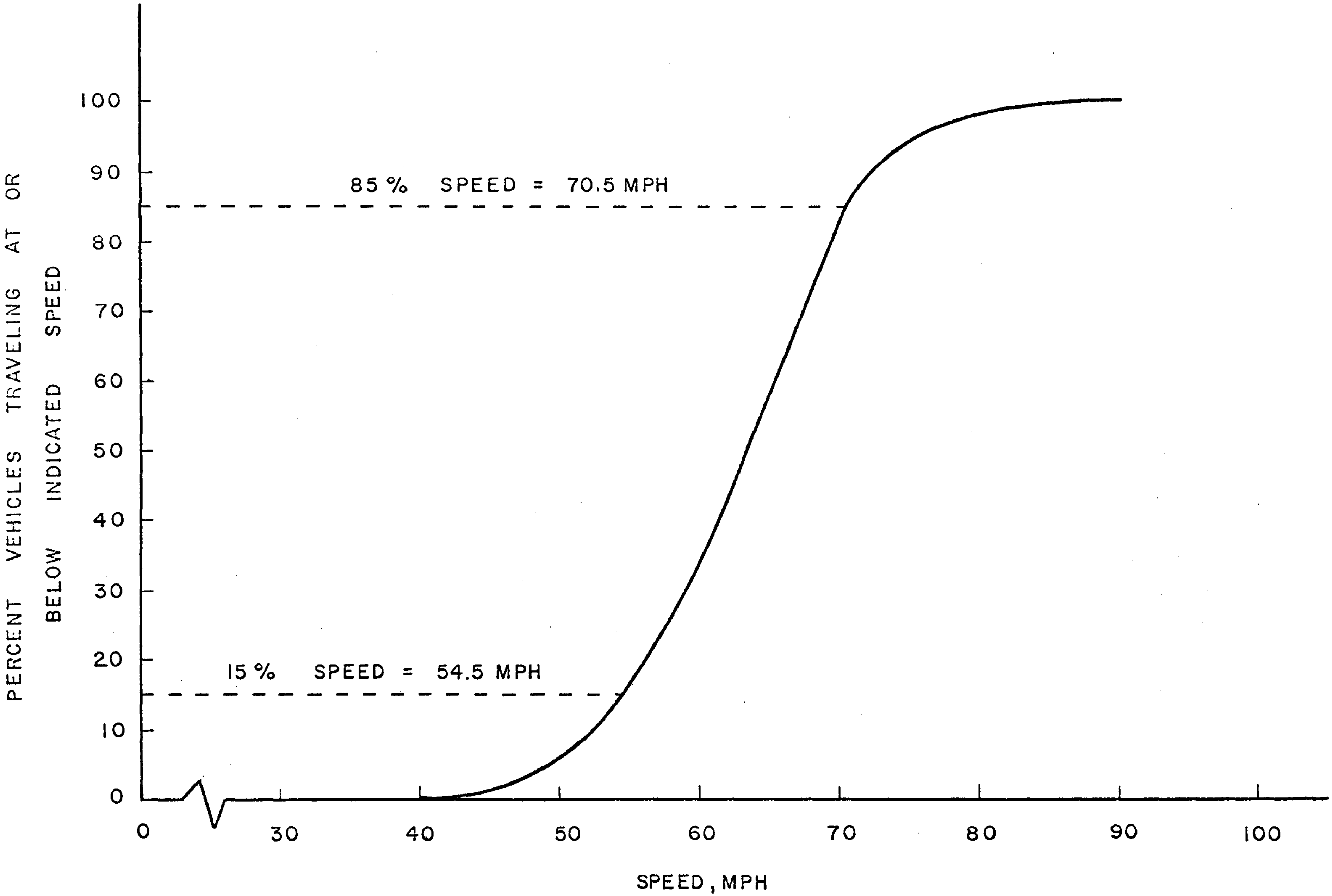


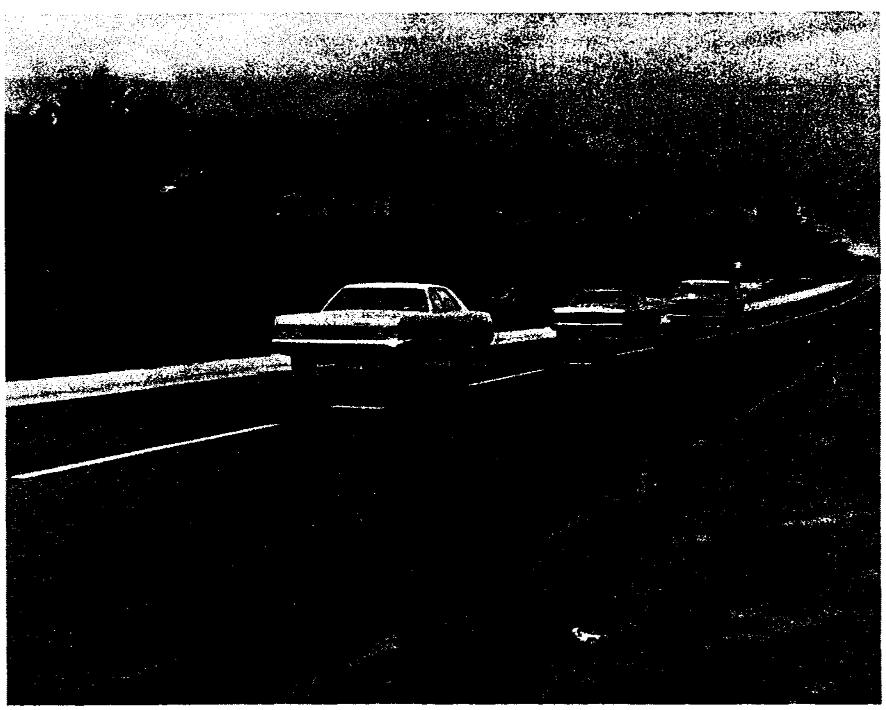
Figure 5 - Cumulative distribution of operating speed, Site B

(a) Driver's view when approaching horizontal curve prior to Site A

(b) Driver's view of roadway just before passing zone at Site A

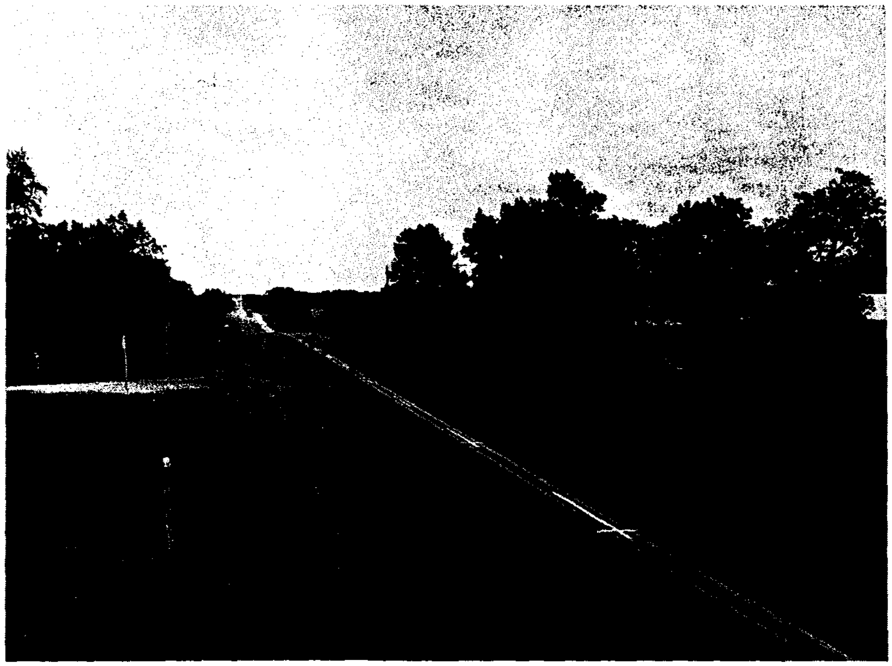
Figure 6

(c) Driver's view of Site A passing zone as seen at beginning of zone



(d) Impeding vehicle, subject vehicle, and observation vehicle in test condition, Site A

Figure 6



(e) Panoramic view of Site A viewed in the study direction

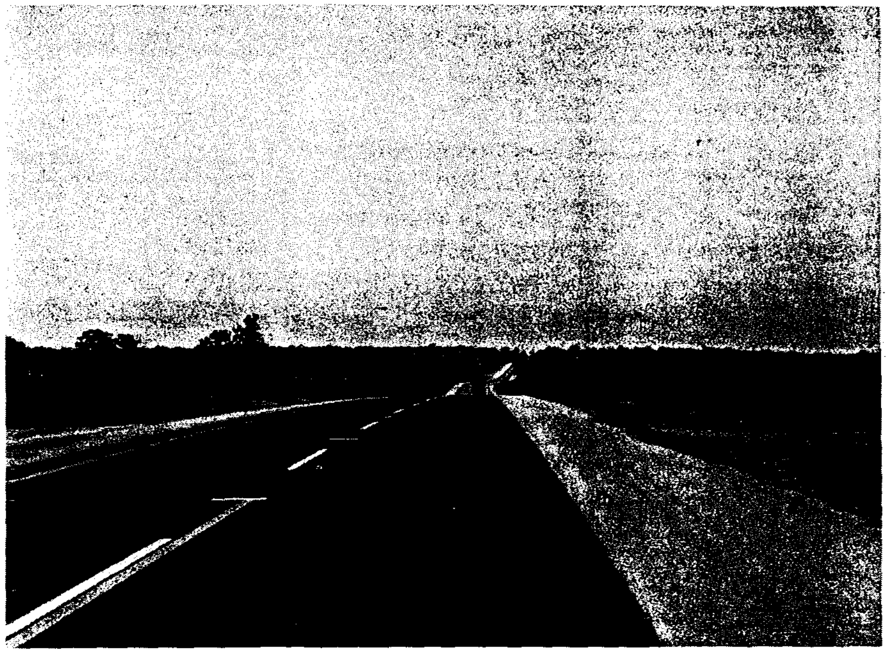
(f) Panoramic view of Site A viewed from terminal end toward the beginning of the passing zone

Figure 6

(a) View from crest vertical curve prior to Site B, looking through impeding zone

(b) View from crest through short passing zone toward Site B

Figure 7



(c) Driver's view of Site B as seen from the beginning of the zone

(d) Driver's view of terminal end of Site B as seen from a point about half way through the zone

Figure 7

of the roadway as seen by the driver.

EQUIPMENT

Three major elements comprised the test equipment; an impeding vehicle, an observation vehicle, and a 16-mm camera.

A 1969 Plymouth sedan was used to impede subjects through the study sites. During the first several days, it became apparent that drivers were hesitant to pass the impedance vehicle, even when there was ample passing distance. It was suggested that drivers might presume the impeding vehicle to be a highway patrol vehicle because it was white and displayed the official State of Texas exempt license plates. All identifying Texas Transportation Institute door legends were masked, and conventional license plates were substituted during data collection periods. To an overtaking driver, the impeding vehicle then appeared to be simply another passenger car.

A 1970 Ford 1/2-ton pickup was used as the observation vehicle. So that test subjects were unaware that their maneuvers were being photographed, the camera and operator were concealed. Since normal operating characteristics could be altered by the obvious presence of photographic equipment, a box resembling a handmade tool shed was placed in the pickup bed immediately behind the cab, extending 24 inches above the cab roofline. The box contained a small front window over the driver's side of the cab through which the subject's passing maneuver was photographed. Since the subject's attention was directed toward the impeding vehicle and the available passing distance, and also, because the small photographing window was above the line of sight through his rear vision mirror, it is doubtful that drivers were aware of the camera. With the window being the only opening, and because light was reflected from the glass, the interior of the box appeared dark and unoccupied. The observation vehicle is shown in Figure 8.

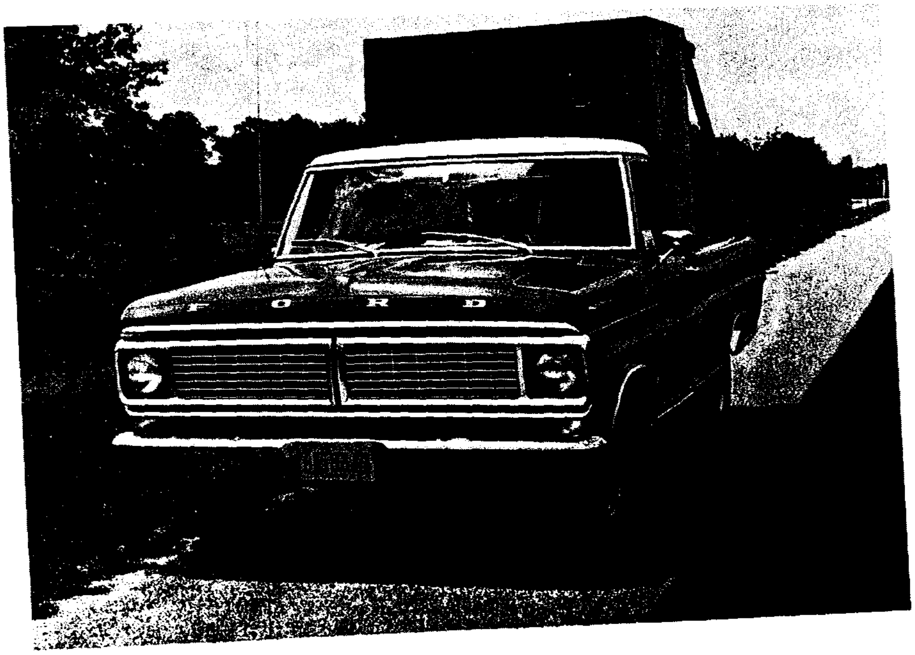
An Arriflex 16-mm movie camera was used to photograph the passing maneuvers. Power was supplied by an 8-volt battery to a governor controlled motor to produce a constant 24 frame-per-second film advance. Black and white Plus-X reversal film (Kodak, ASA 50) on 400-foot rolls was used. Subject vehicles were photographed with a zoom lens (17.5-mm to 70-mm) so that the camera operator could maintain full field of view under varying distance requirements. The camera, mounted on a "ball-head" rigid base mount attached to a shelf, is shown in Figure 9.

CALIBRATION MARKS

The plan was to measure the lateral placement of the subject vehicle's left-rear tire at intervals throughout the passing maneuver, using the highway centerline as a geometric base reference. Therefore, two-foot lengths of six-inch wide temporary traffic line pavement markings were placed perpendicular to, and centered on, the centerline at 40-foot intervals throughout the site. The two-foot markers gave a length calibration that was always pictured on the film frame where lateral placement measurements were taken. The 40-foot interval gave a longitudinal reference system for speed and radius calculations.

SAMPLE SIZE

The study was concerned primarily with high-speed passing maneuvers.



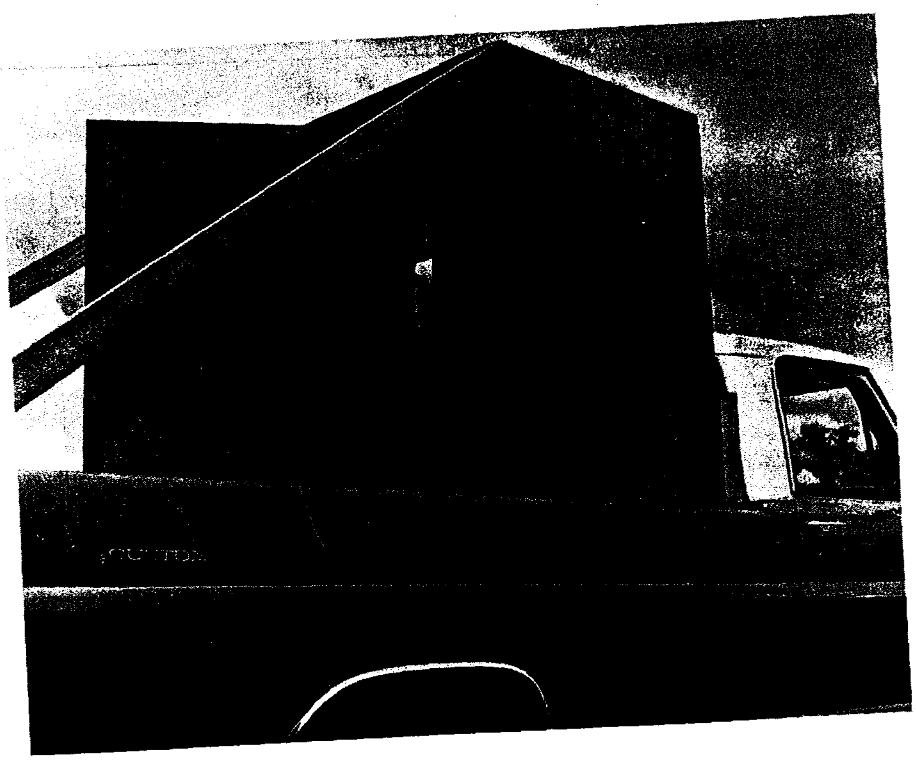


Figure 8 - Observation Vehicle

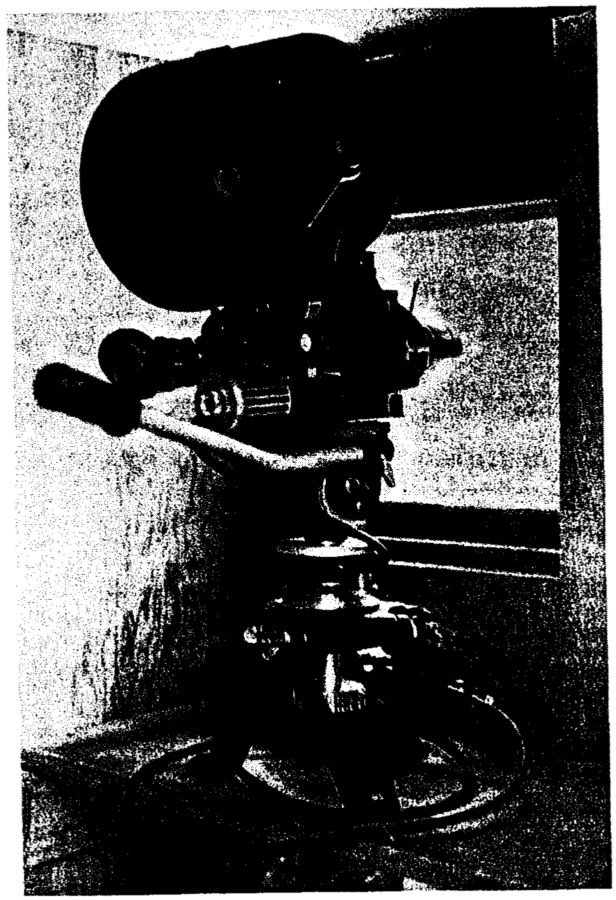


Figure 9 - Study Camera and Mounting

Approximately 300 completed passing maneuvers were photographed during the field study. The sample consisted of about 45 maneuvers at each site for impeding speeds of 50, 55, and 60 mph. In addition, about 35 maneuvers were photographed at a 65 mph impeding speed at Site B. Of this sample, 164 maneuvers were on film of high enough quality to permit precision measurement. Several filmed maneuvers were discarded because of poor field of view or because shadows prohibited film measurements.

The number of tests had no statistical basis, but was set by the time and monetary constraints for data collection and film analysis. In excess of 2000 subjects were photographed to achieve the desired number of completed passing maneuvers. Since approaching traffic was not stopped during the field studies, many potential passing opportunities were negated. Filming was initiated before the point where passing sight distance unfolded, and hence, the presence of opposing traffic near the zone could not be determined in advance.

STUDY PROCEDURE

After each photographic sample was taken, the two test vehicles returned to their starting stations upstream from the passing site. The observation vehicle was parked on the shoulder about one mile upstream from the impeding zone, and the impeding vehicle was parked on the shoulder near the beginning of the impeding zone.

The next subject selected was the first high-speed (generally greater than 55 mph) vehicle that had enough clear distance to the rear to permit the observation vehicle to safely move in behind. The impeding driver was notified by radio that a subject had been selected and was approaching at a specific speed. The impeding driver then moved from the shoulder to the traveled lane and accelerated to the predetermined impeding speed.

The subject driver was forced to follow the impeding vehicle through the no-passing zone (or illegally cross the double-yellow stripe). During this time, the observation vehicle caught and trailed the two vehicles through the remainder of the impeding zone. Figure 10 shows the relative positions of the three vehicles during a test.

Filming was initiated at the first calibration mark, and was continued throughout the passing zone, or until it was obvious that the subject had declined the passing opportunity. The impeding vehicle maintained constant speed throughout the passing zone.

Opposing traffic was not stopped during the study. Many more passing maneuvers would have been performed if there was no opposing traffic in the passing zone, but it was believed that the presence of opposing traffic was a variable with which a passing driver must contend, and to remove this would introduce bias.

Figure 10 - Relative Vehicle Positions During Test

FILM ANALYSIS

The film was analyzed with a Vanguard Motion Analyzer, pictured in Figure 11. 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

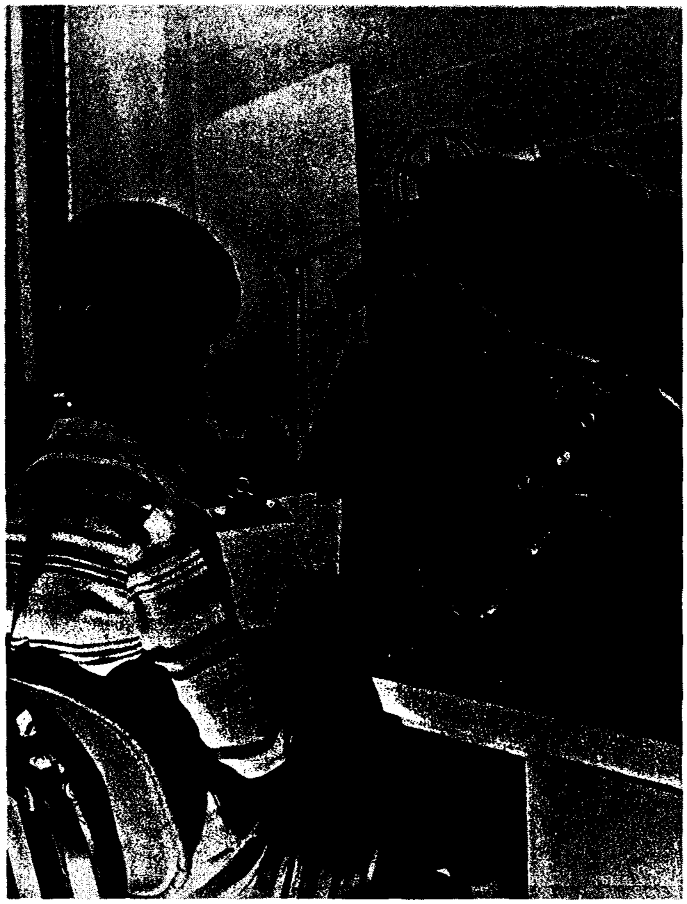
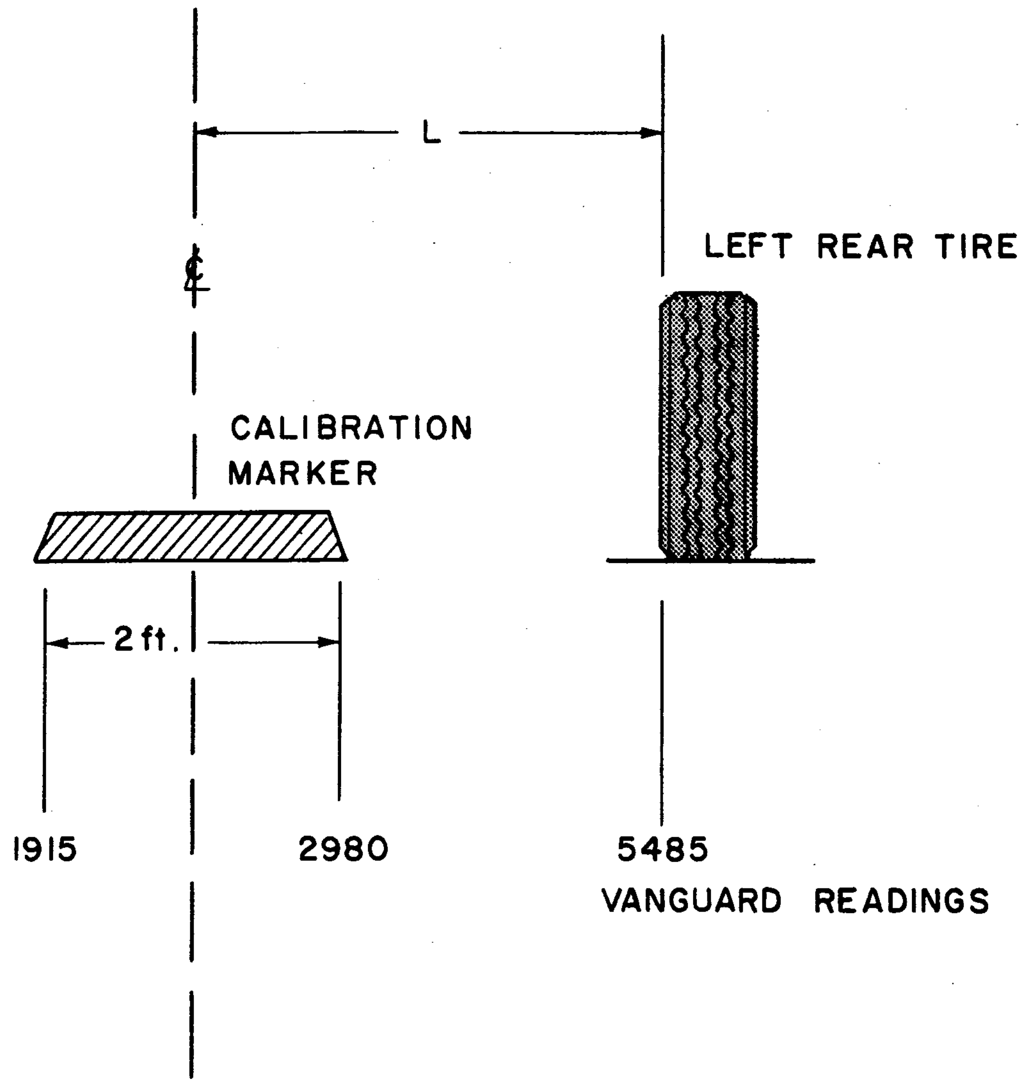


Figure 11 - Vanguard Motion Analyzer

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 12.



$$\text{CALIBRATION} = \frac{2}{2980 - 1915} = \frac{1}{532} \ \frac{\text{FT}}{\text{UNIT}}$$

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

Figure 12 - 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 within the initial pull-out maneuver and the return maneuver. The general path of the passing vehicle is shown in Figure 13.

VEHICLE SPEED

The estimate of vehicle speed at each calibration marker was obtained as the average speed over the 80 foot interval centered on the marker. The speed estimate, V, was calculated using the following equation:

$$V = \frac{\text{film speed x analysis interval}}{\text{elapsed frames}}$$

Because the frame count estimate was to the nearest integer, the greatest frame count error for the analysis interval was one frame. For the 24 frame/second film speed used, this yields an acceptable maximum error of the speed estimate, ranging from about 4% at 50 mph to 7% at 80 mph.

VEHICLE RADIUS

The computer program calculated the lateral placement of the left edge of the left-rear tire at each calibration marker. The instantaneous vehicle path radius was then estimated by computing the radius of the circular arc through three successive tire positions; the center position

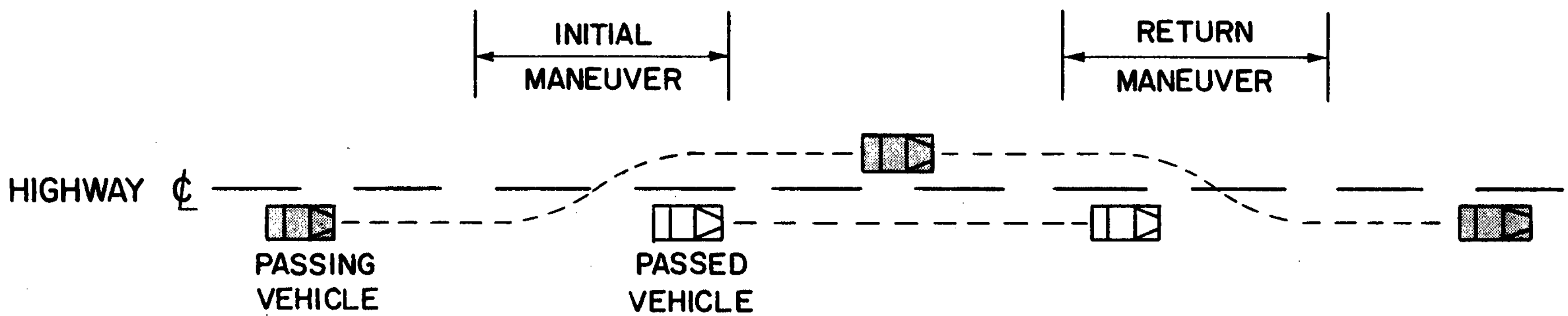


Figure 13 - General Path of Passing Vehicle

being the calibration marker under consideration. Since a circular arc is the minimum path through three points, the radius so calculated is a conservative estimate of the smallest instantaneous radius for the interval.

Figure 14 shows the three basic geometric configurations of three successive tire positions. Points A, B, and C represent left-rear tire positions spaced at the 40-foot intervals, and d_A, d_B, and d_C are the respective lateral placements. From the law of sines, the radius of the vehicle path is the radius of the circle that circumscribes triangle ABC,

$$R_v = \frac{AC}{2 \sin \theta}$$

where θ is the angle ABC.

The length AC is determined by the law of cosines,

$$AC = \sqrt{(AB)^2 + (BC)^2 - 2(AB)(BC) \cos \theta}$$

The values for α, β, AB, BC are calculated as follows:

$$\alpha = \tan^{-1} 40/|d_A - d_B|$$

$$\beta = \tan^{-1} 40/|d_B - d_C|$$

$$AB = 40/\sin \alpha$$

$$BC = 40/\sin \beta$$

The angle θ varies for the three cases shown in Figure 14, as follows:

Case I	$\theta = \alpha + \beta$
Case II	$\theta = 180 + \beta - \alpha$
Case III	$\theta = 180 + \alpha - \beta$

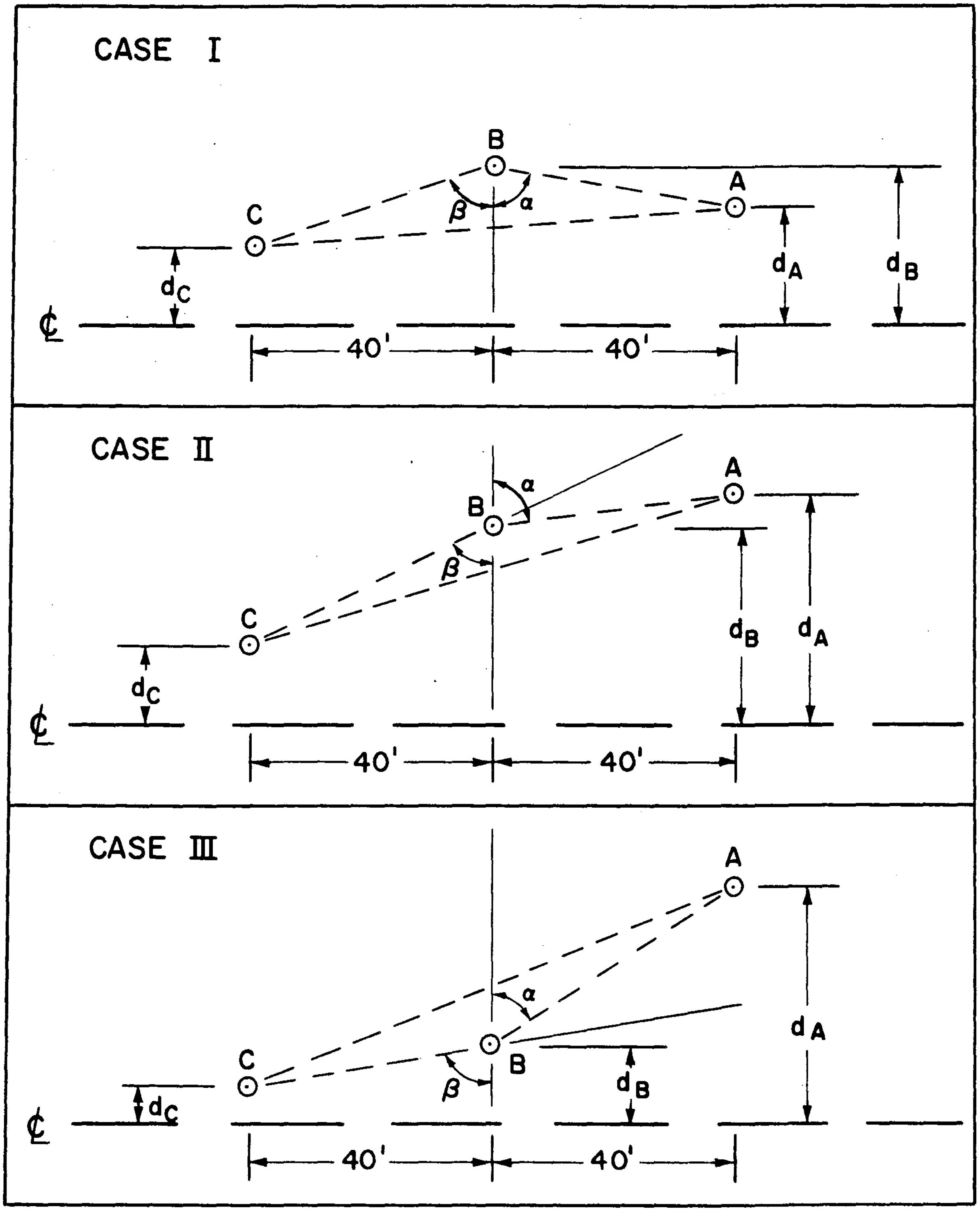


Figure 14 - Geometric Descriptions of Vehicle Radius Calculations

The accuracy of the radius estimate is an important aspect of this analysis. 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 calibration marker, (2) length discrepancy of the calibration marker, (3) sampling error due to taking lateral placement readings up to one half-frame away from the calibration marker, (4) equipment error, and (5) 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 cancellation normally would be expected. In addition, all error sources would not be expected to reach maximum in the same direction at the same time.

To check the error sensitivity, the maximum error was assumed to range between 0.05 and 0.10 feet. For this analysis, the lateral placement of the two outside points were assumed to be equal and the center lateral placement varied an increment of d_x greater. Thus, referring to Figure 14, the increments $|d_A - d_B|$ and $|d_B - d_C|$ are equivalent to d_x. Figure 15, shows the maximum percent error of the radius estimate for various lateral placement differentials, and their corresponding radii.

LATERAL ACCELERATION

The lateral friction demand (f) at the tire-pavement interface was estimated at each calibration marker for each sample by using the centripetal force equation, $f = \frac{V^2}{15R} - e$. The superelevation, e, in this case,

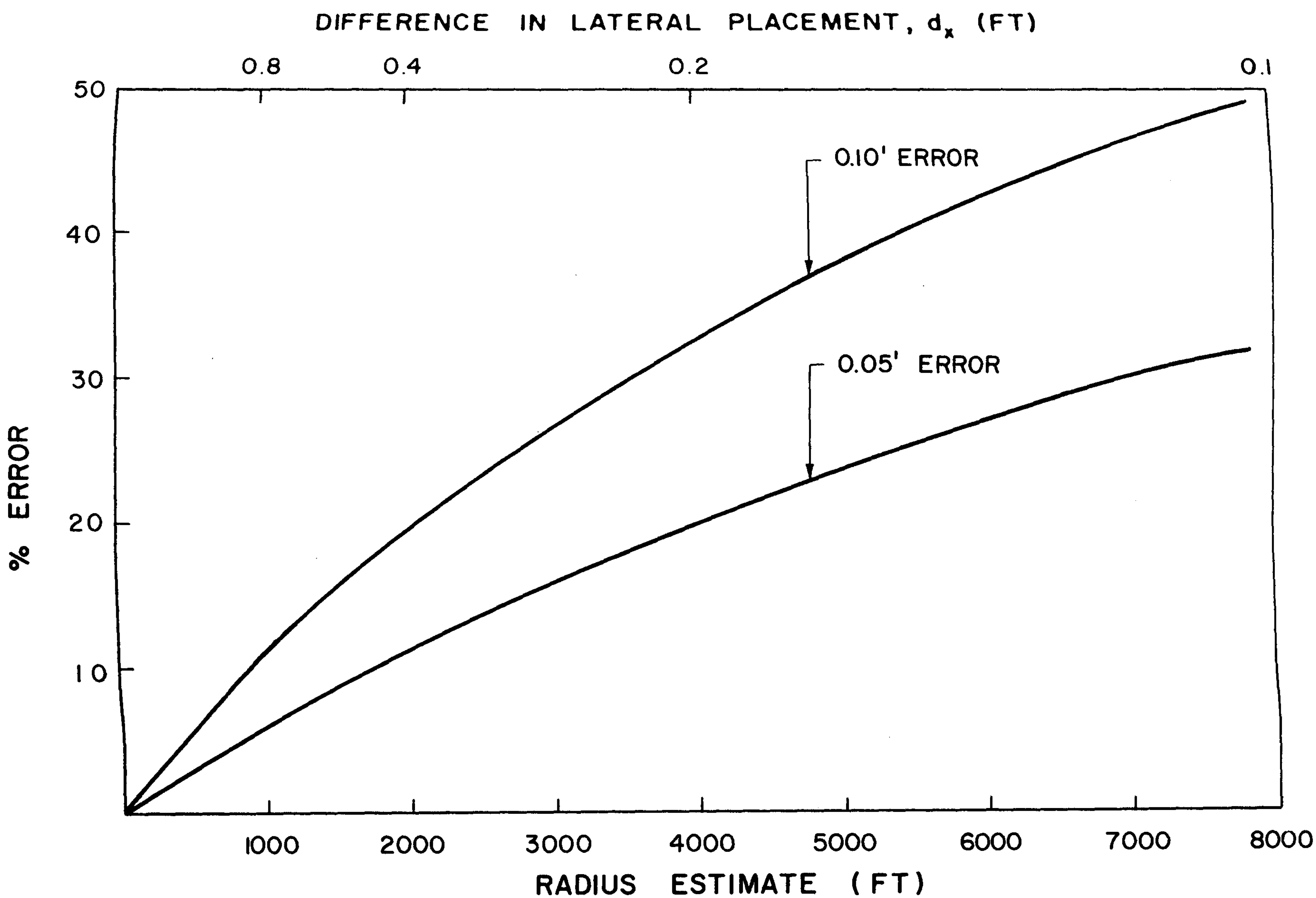


Figure 15 - Error Sensitivity of Estimated Radius

corresponds to the pavement cross-slope, which was assumed equal to 0.02. The computer program was designed to monitor the direction of the vehicle path estimate and determine whether e was positive or negative for that path.

FORWARD ACCELERATION

Unfortunately, the film speed (24 frames/second) and the analysis interval (80 feet) did not permit reasonable estimates of instantaneous forward acceleration and its corresponding friction demand. To obtain reasonable estimates required a much shorter analysis interval and a considerably greater film speed. Neither was feasible for this study.

RESULTS

The result of the computer application was the printing of several sets of lateral placement, speed, instantaneous radius, and lateral friction demand for each passing vehicle sampled. As mentioned previously, these variables were computed throughout both the initial pull-out maneuver and the return maneuver. To represent the critical point for each maneuver, the point of maximum lateral friction demand was selected. This point, for most of the samples, coincided with either the point of minimum path radius or the point of maximum speed, or both. Tables A-1 through A-4, in the Appendix, give a summary of data for each sample.

VEHICLE SPEED

Figures 16 and 17 show the distribution of vehicle speeds for the impeding speed, the speed at maximum lateral friction demand during the initial maneuver, and the speed at maximum lateral friction demand during the return maneuver. In general, the speed at the critical point of the initial maneuver is about 10-12 mph higher than the impeding speed, and the speed at the critical point of the return maneuver is 17-21 mph higher than the impeding speed. Also of interest, only about 12% of the samples exceeded the speed limit at the critical point of the initial maneuver.

VEHICLE RADIUS

Plotting scatter diagrams of speed versus vehicle path radius for the two basic maneuvers showed that there was no relationship between the two parameters. This lack of correlation indicated that the distribution of vehicle path radii (at maximum lateral friction demand)

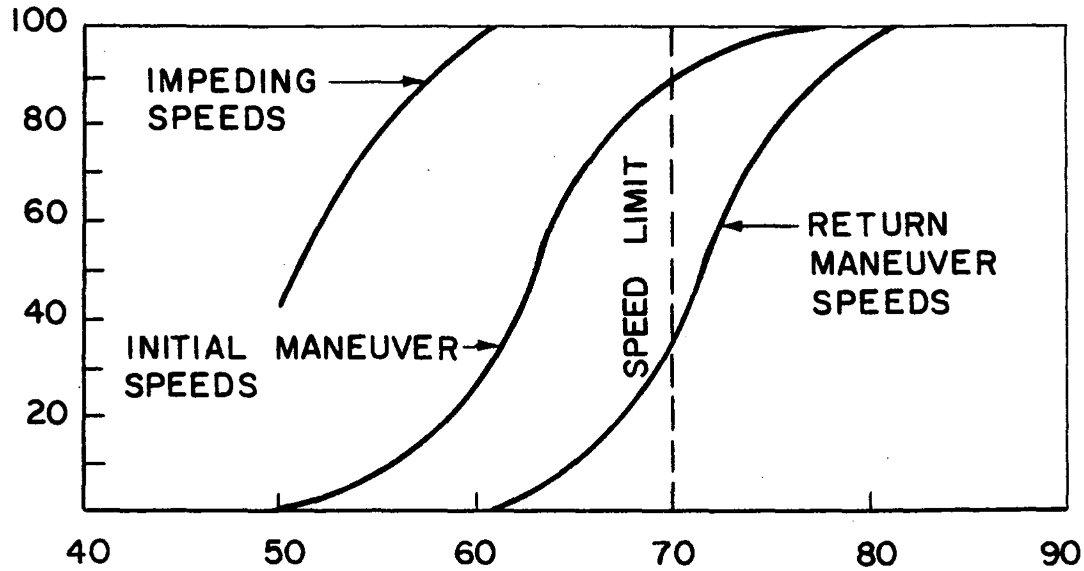


Figure 16 - Speed Distributions for Various Portions of the Passing Maneuver at Site A

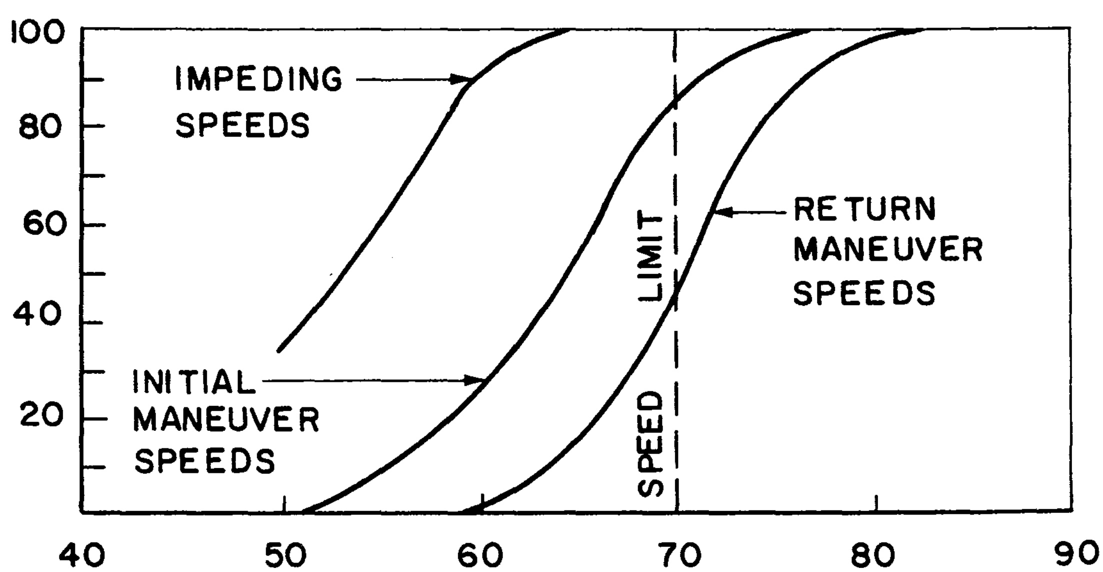


Figure 17 - Speed Distributions for Various Portions of the Passing Maneuver at Site B

could be expected at any speed within the speed range studied.

Table 1 lists the radius values for the critical end of these distributions. It is important to compare the values of Table 1 with the error sensitivity curve of Figure 15. By doing this, it is noted that the radius values of Table 1 have a reasonably low error sensitivity.

The values for Site B in Table 1 are consistently lower than the values for Site A. This may be due to the presence of the horizontal curve at Site B, although very few initial or return maneuvers coincided with the horizontal curve. Actually, the few maneuvers that did coincide with the horizontal curve were deleted because of the large extra effort required to program the transition and curve parameters. Perhaps, however, the horizontal curve had some influence by encouraging drivers to begin or end maneuvers outside the limits of curve to avoid the extra vehicle control problems associated with the curve.

LATERAL ACCELERATION

To determine the critical side friction requirement, a percentile level is needed to assure that very few vehicles will approach instability. The 10% level appears to be a relatively good choice. Using this level would say that only 10% of the vehicles would have lower vehicle path radii. To obtain the critical values, the values for Sites A and B were averaged. Actually the difference between these two values was not too large and may be simply a sampling variation. The critical vehicle path radii, therefore, are 1470 feet for the initial maneuver and 1640 feet for the return maneuver. Using these two values in the centripedal force equation, $f = \frac{V^2}{15R} - e$, the critical relationship between

TABLE 1

DISTRIBUTION OF VEHICLE PATH RADII

Percent of Vehicles Having a Smaller Radius	Radius of Path Maneuver (ft.)			
	Site A Initial Maneuver	Site B Initial Maneuver	Site A Return Maneuver	Site B Return Maneuver
5%	1500	1130	1380	1320
10%	1650	1290	1700	1580
15%	2010	1430	1910	1770

lateral friction demand and speed can be plotted for the initial and return maneuver as shown on Figures 18 and 19, respectively. It is noted that a negative e was used in computing these two curves since most critical vehicle paths were adverse to the pavement cross-slope (as illustrated in Figure 13).

FORWARD ACCELERATION

Although no precise measurements of instantaneous vehicle acceleration were possible, some general observations are appropriate. The data indicates that vehicles were almost always accelerating during the initial maneuver and coasting (constant speed) during the return maneuver. Cursory examination of the data indicates an average acceleration range of about 1-3 ft/sec^2 for the initial maneuver. As these are averages over fairly long intervals (200-500 feet), instantaneous accelerations could be considerably higher.

CRITICAL FRICTION DEMAND

Kummer and Meyer (1) state that the total friction demand, f_T, is a resultant of lateral, f_l, and forward, f_f, accelerations, such that $f_T = \sqrt{f_l^2 + f_f^2}$. They also report the forward friction demand of a standard American vehicle accelerating at full throttle, shown in Figure 18. The friction demand of an American "hot" car accelerating at full throttle is considerably greater, and for compact cars somewhat less.

To arrive at a reasonable estimate of the total friction demand, the forward acceleration of the passing vehicle during the initial maneuver was assumed to vary linearly between 40% of full throttle at 40 mph and 60% of full throttle at 80 mph. For a 4000 pound vehicle, this corresponds to a 6.4 ft/sec^2 acceleration at 40 mph and a 5.0 ft/sec^2 acceleration

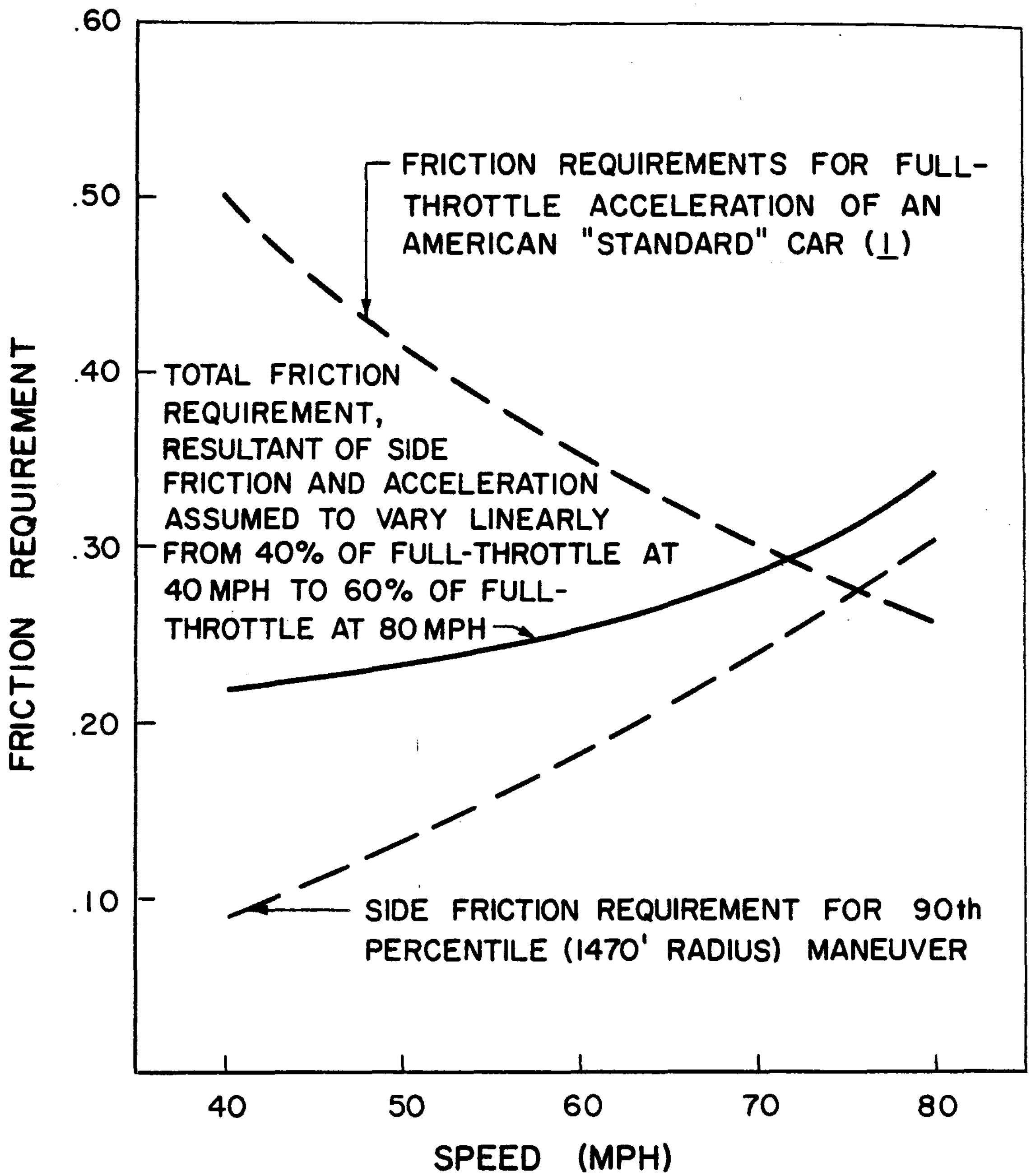


Figure 18 - Total Friction Requirement for the Initial Maneuver

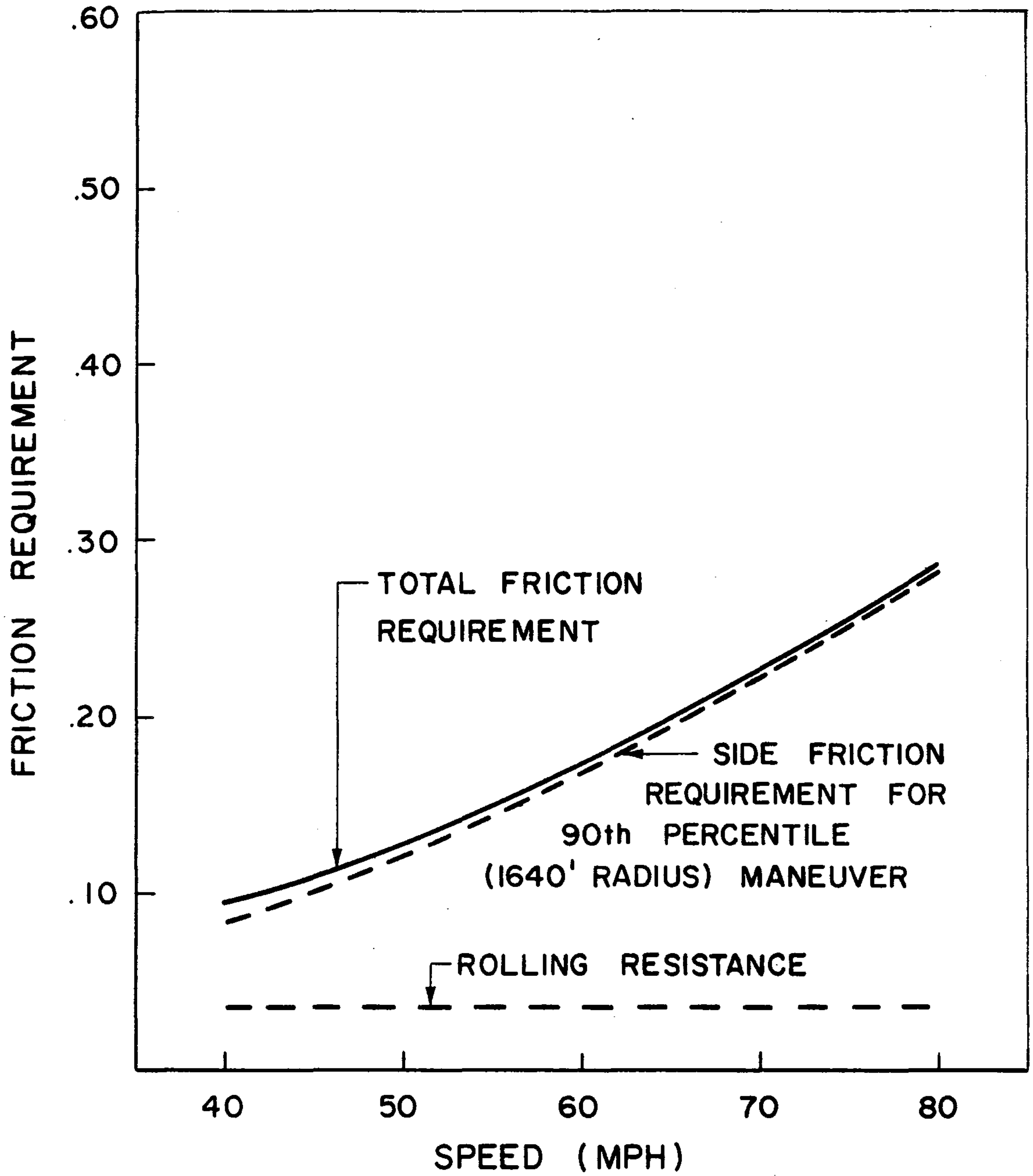


Figure 19 - Total Friction Requirement for the Return Maneuver

at 80 mph. The total friction demand estimate for the initial maneuver is shown on Figure 18. For the return maneuver, the only friction component in the forward direction is 0.035 contributed by rolling resistance. The total friction demand estimate for the return maneuver is shown on Figure 19. Comparing the total friction demand curves of Figures 18 and 19, it is evident that the initial maneuver creates the critical friction demand, varying from 0.22 at 40 mph to 0.34 at 80 mph.

APPLICATION OF RESULTS

Of all the normal (non-emergency) maneuvers performed on our rural two-lane highways, passing probably accounts for the highest frequency of critical tire-pavement friction demands. If there is to be a reasonably low loss-of-control frequency for passing maneuvers (and other maneuvers) during wet weather, then the critical friction demand level must be met. The frictional requirements developed in the previous section, therefore, have an application to a skidding accident prevention program that incorporates minimum skid resistance levels and wet weather speed limits.

Although specific program recommendations cannot be offered, it is important to look at the potential effect of the suggested frictional requirements. Figure 20, a percentile distribution of skid numbers in one state, will be used for illustration (3). Also plotted on Figure 20 is the suggested frictional requirement (assuming SN = 100f). The percentage of pavements that satisfy the frictional requirement at various speeds is as follows:

Speed	% of Pavements
80 mph	42%
70	60
60	75
50	85
40	93

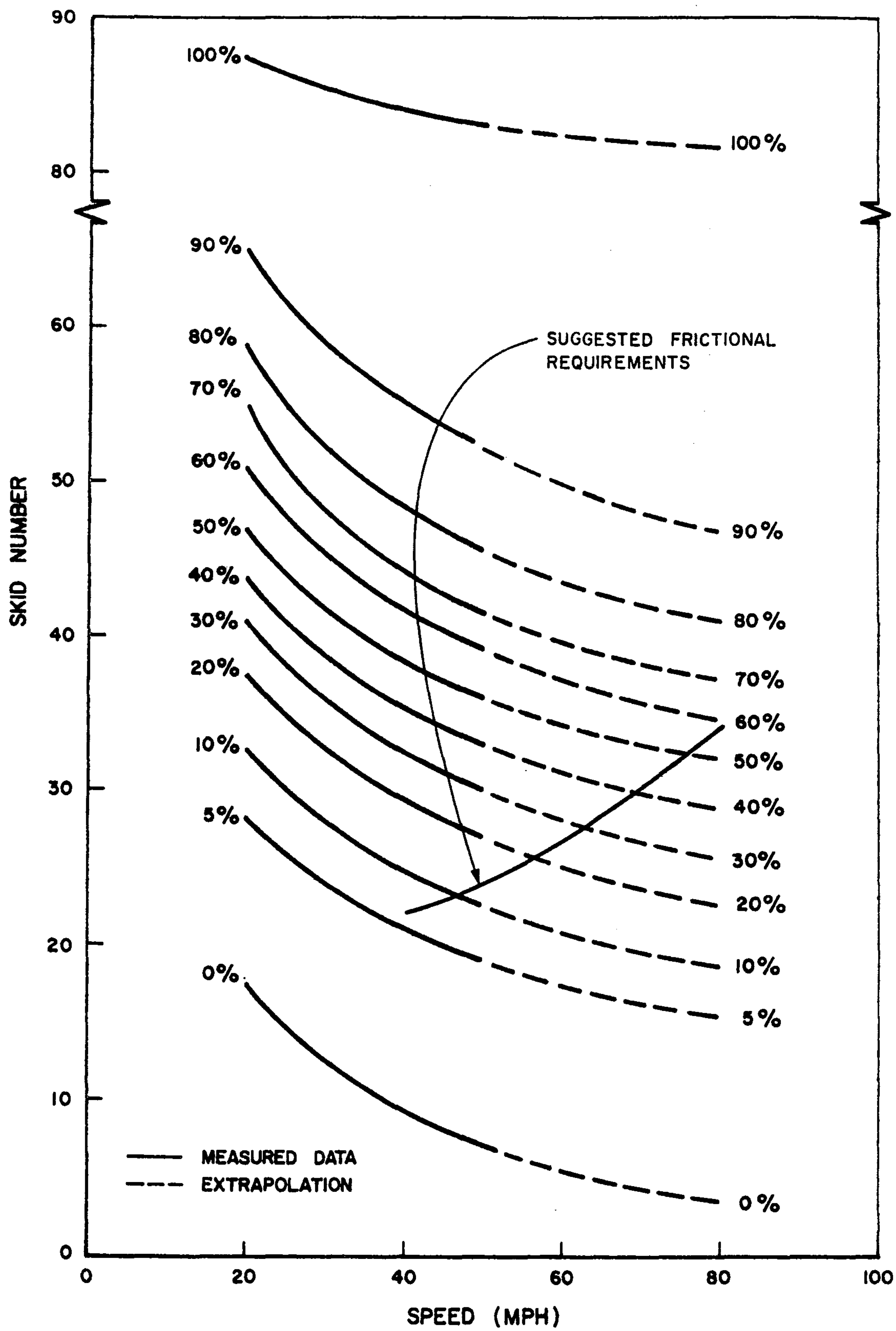


Figure 20 - Percentile Distribution of Relation Between Skid Number and Speed for 500 Pavements in One State (3)

As was found in the analysis of field data, only about 12% of the passing vehicles exceeded the posted speed limit at the critical point in the passing maneuver. Therefore, the critical speed may be equated with the speed limit for determining minimum skid resistance levels and wet weather speed limits.

Table 2 compares the effect of using the suggested frictional requirements for various programs in the state depicted in Figure 20. Two assumptions were applied to derive Table 2; first, the statewide speed limit is 70 mph and, second, the pavements improved because of not satisfying the minimum skid resistance requirement have the same percentile distribution of skid numbers as the unimproved pavements.

Table 2 shows the advantage of having a minimum skid resistance requirement. It is probably undesirable (and maybe ineffective) to have wet weather speed zones below 50 mph on highways normally signed for 70 mph. This would suggest an absolute minimum skid number of about 27 at 40 mph for the state depicted in Figure 20. If wet weather speed limits were not desirable or feasible, then this state should have a minimum skid number requirement of 35 at 40 mph.

The above discussion illustrates program considerations. Of course, to apply the frictional requirements to an individual section of pavement necessitate a skid number versus speed plot for that pavement.

TABLE 2

PERCENT OF PAVEMENTS HAVING CERTAIN WET WEATHER
SPEED LIMITS FOR VARIOUS MINIMUM SKID RESISTANCE REQUIREMENTS

	Minimum Skid Number - Requirement @ 40 mph				
Wet Weather Speed Limit	None	20	25	30	35
40	9%	4%	--	--	--
45	4	5	4%	--	--
50	5	6	6	--	--
55	7	6	8	7%	--
60	7	8	8	9	--
65	8	8	8	9	--
70	60	63	67	75	100%
% of Pavements with Wet Weather Speed Limit Below the 70 mph State-wide Limit	40%	37%	33%	25%	0%

LIST OF REFERENCES

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

2. Weaver, Graeme D., and Glennon, John C., "Passing Performance Measurements Related to Sight Distance Design," Texas Transportation Institute, Research Report No. 134-6, June 1971.

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

APPENDIX

TABLE A-1

DATA FOR INITIAL MANEUVER AT SITE A

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
1	50	60	2423	.097
2	50	55	3554	.056
3	50	62	2799	.093
4	50	62	2675	.097
5	50	60	1539	.153
6	50	62	3980	.065
7	50	62	4427	.059
8	50	50	3701	.046
9	50	52	2480	.074
10	50	65	6218	.046
11	50	60	3119	.076
12	50	65	3408	.084
13	50	62	3893	.067
14	50	60	4130	.057
15	50	57	5010	.043
16	50	55	5306	.037
17	50	60	4133	.057
18	50	62	3315	.078
19	55	65	4613	.062
20	55	73	3378	.104
21	55	62	2315	.112

TABLE A-1 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
22	55	65	2137	.134
26	55	69	3572	.089
27	55	62	2354	.110
28	55	62	5390	.048
29	55	69	2498	.127
30	55	62	6216	.042
32	55	65	2701	.106
33	60	69	3409	.093
34	55	60	2837	.083
35	55	65	3225	.089
37	55	60	4894	.048
38	55	73	2170	.162
39	55	62	3504	.074
40	55	60	963	.245
42	55	65	3041	.094
43	55	73	3751	.094
44	55	65	3337	.086
46	60	73	2569	.137
47	55	69	1636	.193
51	55	69	1770	.179
52	60	69	2172	.146
53	60	65	2640	.108
54	60	73	4627	.076

TABLE A-1 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
55	60	77	2465	.160
56	55	65	2413	.118
57	60	82	3791	.118
58	65	82	2553	.175
60	50	65	1703	.168
61	60	69	2441	.130
62	60	77	2806	.141
63	50	62	3769	.069
64	50	55	2065	.096
65	50	65	3579	.080
66	55	62	6039	.043
67	50	60	4103	.058
68	60	73	6061	.058
69	50	69	1523	.208
70	50	55	2863	.069
72	60	73	3976	.089
73	55	60	1619	.146
74	55	62	1465	.177
75	60	62	4452	.058
77	50	65	2647	.108
78	60	73	2636	.134
79	50	62	1674	.155
80	50	65	2684	.106

TABLE A-1 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
81	60	69	3008	.105
82	60	62	2562	.101
83	50	52	2388	.077
84	50	62	2119	.122
85	60	65	3557	.080
86	60	60	1493	.158
91	50	73	2014	.175

TABLE A-2

DATA FOR INITIAL MANEUVER AT SITE B

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
1	55	73	3757	.094
2	55	62	3371	.077
3	60	73	4652	.076
4	55	69	3288	.096
5	55	57	2386	.091
6	55	65	1962	.146
7	55	77	4073	.097
9	55	62	2625	.099
10	55	65	2695	.106
11	60	73	4011	.088
12	65	69	1792	.177
13	55	60	2952	.080
14	60	69	5062	.063
15	55	65	3351	.085
16	60	69	5193	.061
17	55	57	5701	.038
18	55	69	2302	.137
19	55	57	2817	.077
20	65	69	1505	.210
21	55	57	3414	.063

TABLE A-2 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
23	55	65	4460	.064
25	55	65	3335	.086
26	65	73	2286	.154
27	65	73	1316	.268
28	60	62	3478	.074
29	60	73	5471	.068
30	65	77	1461	.271
31	60	73	4641	.076
32	55	65	5333	.054
33	60	73	3272	.108
34	60	69	4230	.075
35	60	69	2704	.117
37	55	69	2858	.111
38	60	73	3805	.093
39	60	73	3545	.099
40	55	69	1379	.230
41	60	65	8685	.033
42	50	57	2294	.094
43	50	57	1096	.197
44	50	62	1750	.148
45	50	65	5138	.056
46	50	62	4151	.062

TABLE A-2 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
47	50	57	1615	.134
48	50	62	5113	.051
49	50	60	1109	.213
50	50	69	1875	.169
51	55	65	6984	.041
52	50	52	1492	.123
53	60	69	2601	.122
54	50	62	3125	.070
55	60	73	1207	.292
56	60	65	2654	.108
57	60	69	1615	.196
58	60	65	1294	.221
60	50	65	2265	.126
61	50	57	1026	.210
62	60	77	4070	.097
63	50	65	4002	.071
64	60	73	1143	.308
66	50	65	2987	.096
67	60	69	2120	.149
68	50	65	3787	.075
69	60	65	2388	.120
70	60	73	2750	.128

TABLE A-2 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f: Speed	Radius	f
71	60	73	3426	.103
72	60	65	2164	.132
73	50	55	2054	.097
74	60	62	3610	.072
75	60	65	2853	.100
77	50	60	3299	.072
78	50	62	1402	.185
79	50	65	2388	.120
80	50	55	1455	.136
81	50	55	1205	.165
82	50	55	1683	.118
84	50	55	1225	.162
85	50	62	5536	.047
86	50	62	2021	.128
87	50	60	2249	.105
88	50	65	2933	.097
89	50	62	1564	.166
90	50	65	4091	.070
91	55	65	2944	.097
92	55	55	1023	.194
93	55	65	2692	.106
94	55	65	1290	.221
98	60	73	4342	.081

TABLE A-2 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
115	65	77	3600	.110
116	65	77	2283	.173
123	65	69	3477	.091

TABLE A-3

DATA FOR RETURN MANEUVER AT SITE A

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
1	50	69	2401	.132
2	50	77	2789	.142
3	50	73	2445	.144
4	50	73	3927	.090
7	50	69	3792	.083
8	50	73	4479	.079
9	50	69	2082	.152
10	50	82	3637	.123
11	50	73	3816	.092
13	50	65	4173	.068
14	50	69	3044	.104
15	50	73	2292	.154
16	50	73	3778	.093
17	50	73	3167	.111
18	50	69	5416	.058
19	55	82	1879	.238
20	55	73	2321	.152
21	55	82	3252	.137
22	55	77	2480	.159
26	55	73	3089	.114
27	55	77	3730	.106
28	55	77	4792	.082

TABLE A-3 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
32	55	77	1918	.226
33	60	77	3750	.135
34	55	77	2140	.155
37	55	73	7150	.049
38	55	69	2454	.129
39	55	73	3427	.103
40	55	69	1400	.226
42	55	69	1735	.182
44	55	73	1379	.256
46	60	77	3448	.115
47	55	65	1378	.207
51	55	73	4818	.073
52	60	77	2223	.178
53	60	77	3805	.104
54	60	77	1932	.205
55	60	77	2073	.191
56	55	73	1955	.180
57	60	82	1999	.223
58	65	82	2938	.152
60	50	69	2312	.137
61	60	77	2078	.190
62	60	77	2133	.185
63	50	69	2825	.112

TABLE A-3 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
64	50	62	2358	.110
65	50	65	2151	.133
66	55	73	5152	.068
67	50	73	2346	.150
68	60	82	3650	.122
69	50	73	3342	.105
70	50	73	2941	.120
72	60	82	2059	.192
73	55	69	3511	.090
74	55	73	1663	.212
75	60	73	2453	.144
77	50	69	1697	.186
78	60	82	2860	.156
79	50	65	2730	.105
80	50	73	3248	.109
81	60	77	7234	.055
82	60	77	2320	.170
83	50	65	2019	.141
84	50	65	792	.361
85	60	77	1398	.283
91	50	69	1712	.185

TABLE A-4

DATA FOR RETURN NAMEUVER AT SITE B

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
1	55	77	3965	.100
2	55	69	2820	.112
3	60	77	4821	.082
4	55	65	6549	.044
5	55	69	2871	.110
6	55	65	2744	.104
9	55	73	3103	.114
10	55	65	1494	.191
11	50	77	2813	.141
12	65	73	2867	.123
13	55	69	2507	.126
14	60	77	5321	.074
15	55	77	7741	.051
16	60	69	2493	.127
17	55	65	4157	.069
18	55	69	2011	.157
19	55	73	4502	.078
20	65	73	2812	.125
21	55	69	7748	.041
23	55	69	3261	.097
25	55	69	2309	.137
26	65	77	2452	.161

TABLE A-4 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f Speed	Radius	f
27	65	73	2536	.139
28	60	73	3038	.116
30	65	82	1,1750	.038
31	60	73	5878	.060
33	60	73	3876	.091
34	60	94	5503	.106
35	60	77	2500	.158
37	55	77	3683	.107
38	60	77	2852	.139
39	60	77	2638	.150
40	55	73	3333	.106
41	60	77	3755	.105
42	50	73	5603	.063
43	50	69	1293	.245
44	50	65	2785	.103
45	50	69	1753	.180
47	50	82	4863	.092
49	50	69	2075	.153
50	50	73	5833	.060
51	55	69	1844	.172
52	50	69	2748	.115
53	60	77	3028	.131

TABLE A-4 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
54	50	69	1324	.239
57	60	73	1779	.198
58	60	77	5087	.078
61	50	69	1756	.180
63	50	73	4640	.076
64	60	77	5688	.070
66	50	73	3304	.107
67	60	77	3610	.110
68	50	69	1566	.202
69	60	73	2147	.164
70	60	82	1177	.379
71	60	77	2748	.144
72	60	69	2491	.127
73	50	60	1904	.124
74	60	73	3033	.116
75	60	73	4510	.078
77	50	62	1585	.163
78	50	73	3840	.092
79	50	69	1370	.231
80	50	60	916	.258
81	50	69	3186	.099
82	50	65	1958	.146
84	50	73	3974	.089

TABLE A-4 CONT.

Sample No.	Impeding Vehicle Speed	Data for Point of Maximum f		
		Speed	Radius	f
86	50	77	3695	.107
87	50	65	3654	.078
88	50	65	3154	.091
90	50	69	1683	.188
91	55	73	2031	.174
92	55	65	5449	.052
93	55	69	3778	.084
94	55	77	3253	.122
98	60	77	2264	.175
123	65	77	3064	.129