National Cooperative Highway Research Program

RESEARCH RESULTS DIGEST

DIGEST 50 - NOVEMBER 1973

Determining Pavement Skid Resistance Requirements at Intersections and Braking Sites

An NCHRP staff digest of the essential findings from the final report on NCHRP Project 1-12, "The Determination of Pavement Friction Coefficients Required for Driving Tasks," by E. Farber, M. Janoff, and staff researchers, The Franklin Institute Research Laboratories, Philadelphia, Pennsylvania.

THE PROBLEM AND ITS SOLUTION

A crucial question in the highway safety problem area is the level of skid resistance that should be available on highway pavements to provide for safe operation of motor vehicles. Dry pavements usually are quite adequate in this regard but the skid resistance of wet pavements, which is one of the critical factors of traffic safety, is often of questionable adequacy for traffic conditions. The construction and maintenance of all pavements with wet skid resistance properties comparable to those of dry pavements would not result in best use of available materials and funds in most cases because of the extremely high cost in relation to possible benefits. Realistic skid resistance requirements should be dictated by actual traffic needs at the particular site. Thus, the objective of Project 1-12 was to provide highway departments with methods for determining pavement skid resistance requirements for any given set of roadway and traffic conditions.

Because wet-pavement skidding accidents occur most frequently at intersections and curves, the study concentrated on these types of sites. The research was successful in that procedures were developed and their feasibility for determining skid resistance requirements for intersections and other braking site types was demonstrated in the field. However, considerably more extensive field evaluations are necessary to verify the ability of the procedures to determine the relative hazardous nature of various intersection sites and to identify hazardous locations before they become high accident sites. Because the need is critical, the research agency

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also developed a simplified version of the procedures that highway agencies should field test. The limited study on cornering has shown that not enough is presently known about the relationship between lateral accelerations and pavement skid resistance to permit establishment of skid resistance requirements for highway curves by the procedures. This relationship is made particularly complex by the rather extreme, and yet undetermined, influence of the vehicle tires.

FINDINGS

A pavement can be considered deficient in skid resistance only in relation to the demand of traffic on it. Skidding will occur on a dry pavement of high skid resistance if a sufficiently violent maneuver (such as braking to a stop from 60 mph in 100 ft, or negotiating a 200-ft-radius curve at 60 mph) is attempted. Such demands can arise in an emergency or as a result of extremely poor driving, but the resulting skidding cannot be blamed on the pavement. It is only when skidding occurs as a consequence of maneuvers that are within the range of normal demand (accelerations, braking, and cornering by a majority of drivers under normal traffic conditions) or intermediate demand (last-minute braking or steering corrections caused by inattention, misjudgment, or unusual incidents) that the pavement skid resistance should be considered inadequate. Neither can skidding under normal braking and cornering on a wet pavement with adequate skid resistance be attributed to the pavement if the vehicle is deficient in such respects as bald tires, improper brake adjustment, faulty steering components, poor suspension, etc.

The FIRL procedure for determination of skid resistance requirements at a given highway site involves the following steps:

1. Measurement of the accelerations (g forces) developed by automobiles as they pass through the site and assumption that these are a reasonable representation of demand on the tire-pavement interface.
2. Conduct of skid studies, using representative vehicles, tires, and pavement surfaces, to develop empirical relationships between maximum accelerations at skidding speeds and locked-wheel skid resistance measurements of the pavement surfaces.
3. Determination of pavement skid resistance values that will accommodate the representative demand levels by combining the information from steps 1 and 2.

The system developed for measurement of longitudinal acceleration at intersections is based on the use of a series of Tapeswitch* event detectors to determine the time-position signature of a vehicle over some known distance, from which acceleration values can be computed. At prescribed intervals for a distance of about 400 ft in advance of the stop point, series of 16 sections of Tapeswitch were accurately placed on the pavement, and data were collected and processed by electronic equipment. A study was conducted to determine the accuracy of the acceleration values computed from the time-position data by driving an instrumented vehicle over an installed Tapeswitch system and comparing the computed values with data from the accelerometer installed on the vehicle. Over a range of 0.03g to 0.48g, the computed values were within 0.02g of the measured values. Studies were conducted to evaluate the influence of the Tapeswitch installation on driver behavior and the relationship between data collected on wet vs dry pavements. Although the results were based on limited data, it was concluded that the influence of these factors is of no practical significance, particularly in view of the accuracy of various other parts of the over-all procedure. Consequently, most data collected at the 12 intersection sites were from dry pavements with the full 16-section system. Regarding the wet vs dry pavement data collection, an important consideration is that many drivers attempting to brake at or near peak demand on a wet pavement are likely to skid; thus, the highest deceleration values measured would be the maximum permitted by the wet pavement rather than the actual driver demand.

Longitudinal Acceleration Measurements

Data were collected for an average of 350 vehicles at each of the 12 intersection sites, all located in eastern Pennsylvania and New Jersey, and longitudinal accelerations were computed for various distances from the stopline. As an example of the data collected, Figure 1 is a plot of the 90th, 95th, 99th, and 100th percentile longitudinal accelerations for one intersection site. Figure 2 is a plot of the measured speed patterns associated with each of the accelerations of Figure 1.

Skid Studies

Controlled skid studies to determine the relationships between longitudinal acceleration and pavement skid resistance requirements were conducted by FIRL personnel at the Texas Transportation Institute using seven skid pads of varying surface characteristics. Two instrumented automobiles, a 1970 Plymouth Fury and a 1971 Ford Mustang, were used for the skid tests. Three sets of tires (conventional bias ply, belted bias ply, and radial) were used on the Plymouth and belted bias ply only were used on the Ford. All tires were relatively new. For the purpose of developing correlations, the skid resistance of each test pad was measured as skid numbers (SN) at 20, 40, and 60 mph using a locked-wheel skid tester in general conformance with ASTM Method E-274.

Skid Resistance Requirements

It is apparent from analysis of the braking data that complex interactions exist between pavement surface characteristics, speeds, tires, and vehicles. No tire-vehicle combination produced the highest longitudinal acceleration for all surfaces and all speeds. However, a maximum deceleration (negative longitudinal acceleration) vs skid number plot (Fig. 3) was developed in which each point is the worst case from among the four tire-vehicle combinations at each of the speeds for each of the seven skid pads used for the correlation. Each point represents the average of six skid tests. This plot was used to convert the measured accelerations to skid resistance requirements. Figure 4 shows the conversion of measured acceleration to required skid resistance for a particular intersection site: Table 1 lists the skid resistance requirements for the 12 intersection sites studied during the project as determined by the FIRL procedure. Figure 5 shows that the skid resistance requirements for the 12 intersections follow a rather consistent pattern when the 100th value is not considered. These data show a considerable spread of SN_{40} values, indicating a rather wide range of skid resistance requirements for the sites studied. By listing the 12 sites in numerical order on the basis of the 99th percentile computed skid resistance requirements (Table 2), it is noted that the procedure could be useful in determining whether a particular site is in a category requiring normal, intermediate, or high skid resistance to safely accomodate wet-pavement braking maneuvers of a vast majority of the drivers using the site.

Due to current variability in pavement skid resistance measurement and the considerable influence of the vehicle-tire combination, which is not at present controlled by any type of standard, this project's rather sophisticated procedure for measuring longitudinal accelerations and computing skid resistance requirements is not likely to be realistic for individual site studies. Consequently, the report describes a simplified Intersection Demand Model (IDM) for estimating skid resistance requirements on the basis of limited data collected at the site. The simplified ap-

* Tapeswitch is a trade name for a pressure-sensitive electrical strip switch that can be placed on the pavement as a vehicle detector in the same manner as a pneumatic tube.

proach is based on the apparent normality of the distribution of observed deceleration values at the various distance intervals from the stop line for the 12 sites studied.

The required data for estimating skid resistance requirements at an intersection site using the IDM are:

V_{225} = the speed of each vehicle at a point 225 ft from the stopline;
TC_H = the hourly traffic count in the lane under study; and
SP = An estimate of the distance, in feet, between the stopline and the actual stop point for each vehicle.

Vehicle speeds can be measured by placing two Tapeswitches in the traffic lane, evenly bracketing the 225-ft distance from the stop point with a 30-ft separation between the detectors. A 0.01-sec-interval timer connected to the detectors will provide sufficient accuracy. The stop point can be estimated with sufficient accuracy (within 10 ft) by selecting a series of landmarks (trees, poles, etc.) which, from a fixed vantage point, are in line-of-sight with the 30-ft distance intervals in the instrumented traffic lane. Reasonable estimates of skid resistance requirements can be made on the basis of a sample size of 200 vehicles.

The average deceleration ($\bar{a}$) of each vehicle is computed as:

$$\bar{a} = \frac{V_{225}^2}{30\ (225-SP)}$$

and the following statistical representations provide input for operation of the IDM:

$\bar{\bar{a}}$ = mean average deceleration, in g's;
$\overline{TC_H}$ = mean hourly traffic count in lane under study;
S_{V225} = standard deviation of the speed at 225 ft from the stopline;
$S_{\bar{a}}$ = standard deviation of $\bar{a}$, in g's; and
$\bar{V}_{225}$ = mean speed at 225 ft from stopline, in mph.

To determine the estimated skid resistance requirement for a given site, it is necessary to compute the demand at each of several points in the intersection approach. It is recommended that this be computed at distances (d) of 20, 40, 80, 120, 160, and 320 ft from the stopline to determine the shape of the demand curve and locate its peak or controlling value. The procedures for determining the estimated 99th percentile skid resistance requirement at a given distance (d) from the stopline are as follows:

1. Compute the mean deceleration ($\bar{g}_d$) at various points between 385 ft and the stopline and the standard deviation (S_{g_d}) of the deceleration at the various points using the following equations:

$$\bar{g}_d = \frac{1}{1000}\ (1036\ \bar{\bar{a}} + 0.041\ \overline{TC}_H - 0.372d + 21)$$

$$S_{g_d} = \frac{1}{1000}\ (83.1 + 146/d - 1.02\ \sqrt{d} + 6.16\ S_{V225} + 404S_{\bar{a}} + 9.06)$$

2. Compute the 99th percentile deceleration for the various distances from the stopline as follows:

$$g_{99P} = \bar{g}_d + 1.96\ S_{g_d} + 0.07$$

3. Compute the 99th percentile speed for the various distances from the stopline as follows:

$$V99_d = 95.88\ \bar{\bar{a}} + 1.896\ \sqrt{d} - 5.063$$

4. Enter Table 3 with the computed values for g_{99P} and $V99_d$ to find the required skid resistance (SN_{40}) for the various distances from the stopline.

By using appropriate data from the 12 intersection sites studies, the skid resistance requirements estimated by IDM were compared with the requirements determined by the more sophisticated procedure using data from the 16-section Tapeswitch system. Table 4 gives the estimated skid resistance requirements using the IDM; these are generally greater, and hence more conservative, than those computed from the more extensive data. For the 99th percentile demand, the estimated skid numbers (SN_{40}) are greater than the values based on the measured accelerations and speeds in nine of the twelve and, on the average, the estimated values were 2 skid numbers higher than those determined by the more sophisticated procedure. Thus, the value yielded by the model for a particular site incorporates a factor for possible errors of underestimation.

APPLICATIONS

The findings of this study and other research indicate that the required pavement skid resistance to accomodate automobile braking can be determined quite accurately by empirical relationship between the longitudinal acceleration and locked-wheel skid measurements when the same tire is used on the vehicle and the tester. However, such factors as braking demand (negative longitudinal acceleration), speed, and tire characteristics influence the pavement skid resistance requirement of a particular site and are extremely variable and complex in their interactions. From analysis of limited data (an average of 350 vehicles at each of 12 intersection sites), it appears that (a) a strong general relationship exists between pavement skid resistance and locked-wheel braking deceleration, even though the actual relationship varies with the particular vehicle-tire-pavement combination; (b) accelerations and speeds of vehicles braking at intersections are normally distributed and exhibit stable standard deviations; and (c) there is some relationship between average approach speed and skid resistance requirements (Fig. 6).

The findings of this study add substantially to the general body of knowledge in this important problem area and, further, offer several prospects for practical application by highway agencies.

Intersection and other braking sites can be studied, using either the full Tapeswitch system or the simplified procedure, to determine (a) the relative skid resistance requirements, such as high, intermediate, or normal; (b) the probable cause of accident involvement, such as unusually high demand or low skid resistance; and (c) the influence of such modifications as signing and traffic marking on skid resistance requirements.

When it is not feasible to use either the Tapeswitch system or the Intersection Demand Model to determine pavement skid resistance requirements, the information in Table 5 can provide general guidelines for minimum requirements. It must be recognized that these guidelines are very tentative because they are based on extremely limited field data (12 intersections in the eastern Pennsylvania and New Jersey area). They cannot be applied universally but should be evaluated and modified by further field studies. They are based on the generally increasing demand with traffic speed, an SN_{40}-value of 40 as a desirable minimum for any condition, and the recognition that an SN_{40}-value of 55 accommodates substantially all of the 99th percentile demand of the 12 sites studied. It is emphasized that these tentative skid resistance requirements apply only to the short distance (the L point to the stop point) at intersection sites where braking is a frequent maneuver and the required skid resistance under wet-pavement conditions is higher than on mainline sections of roadway. The traffic speed is defined as the 85th percentile speed of freely moving traffic at a sufficient distance from the intersection so that traffic speeds are not influenced by the intersection. The recommended minimum distance from the intersection at which traffic speed measurements are to be made are 1,200, 800, and 500 ft, respectively, for fast, intermediate, and slow traffic.

Although the procedures developed during this project are based on limited data collected in one locality, they have undergone limited field evaluation and represent the best available approach for estimating skid resistance requirements at braking sites at the present time. Pilot implementation of the procedures is encouraged so that potential users will have firsthand knowledge of their ability to identify both potential high-accident sites and the relative need for wet-pavement skid resistance.

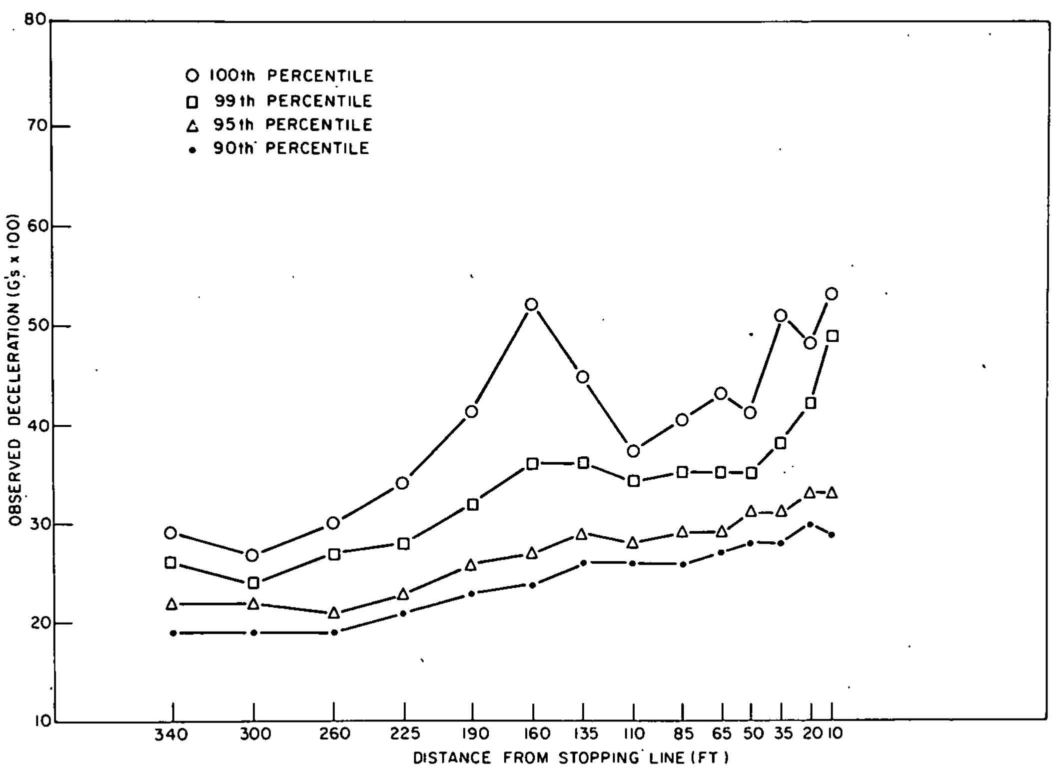

Figure 1. Observed deceleration vs distance from stopline, Intersection Site 8.

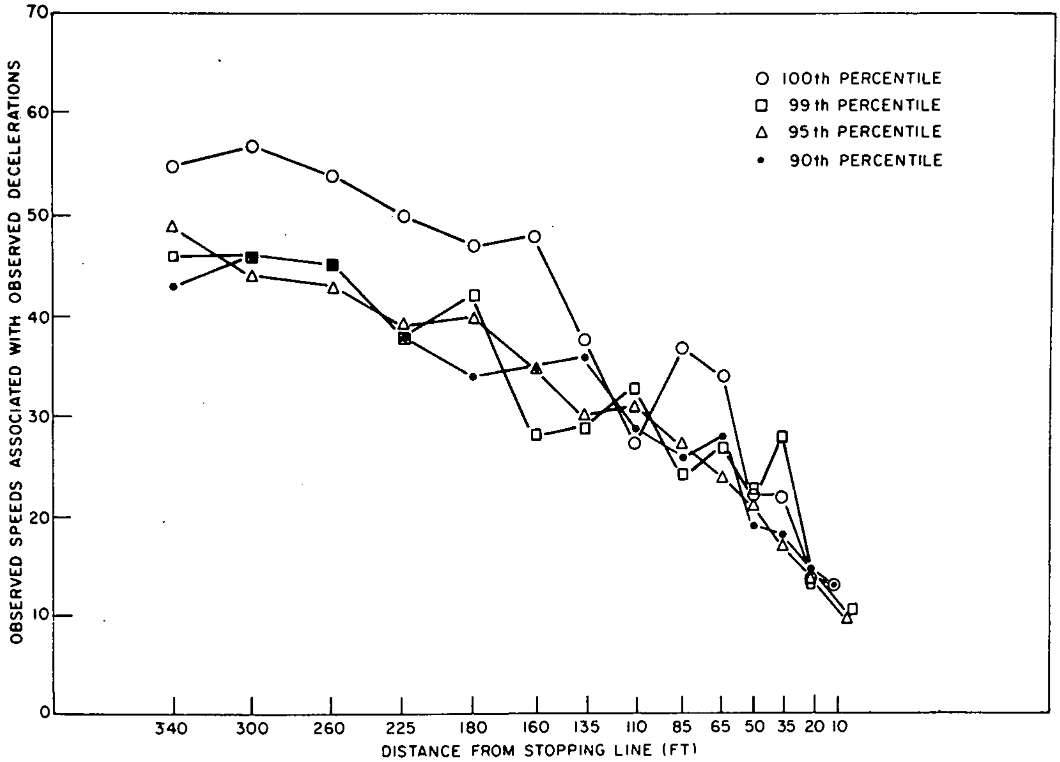

Figure 2. Observed speeds associated with decelerations vs distance from stopline, Intersection Site 8.

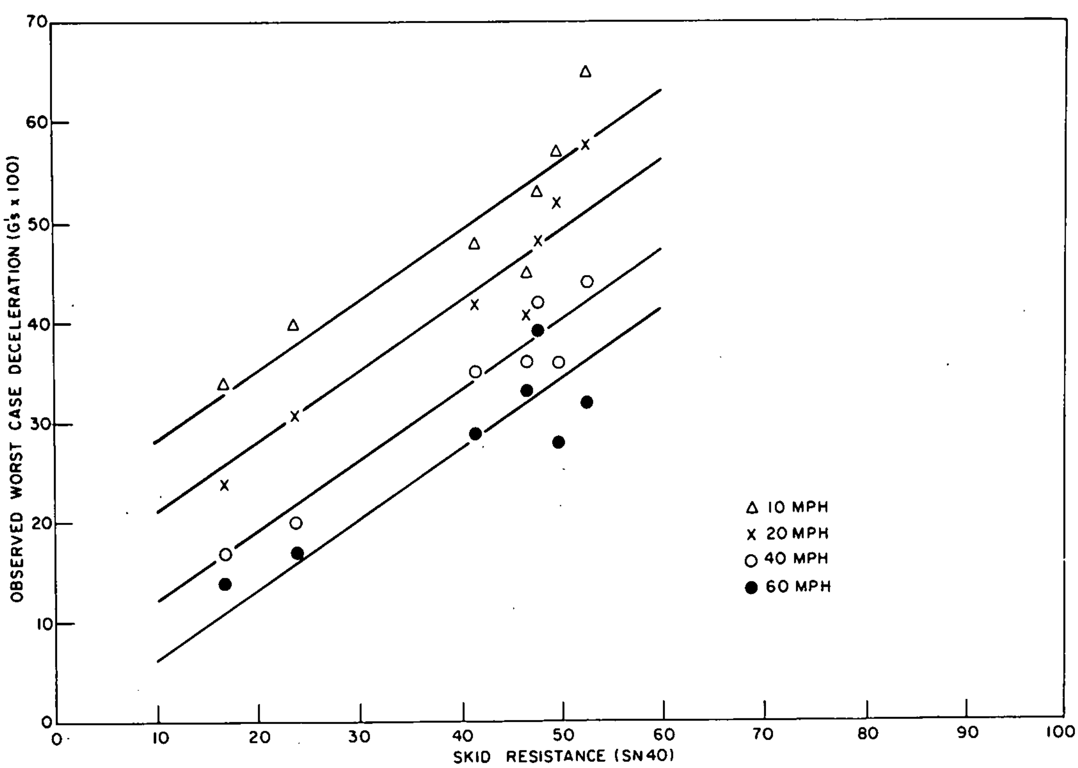

Figure 3. Observed worst case deceleration for selected speeds vs skid numbers (SN_{40}), Texas Transportation Institute skid pads.

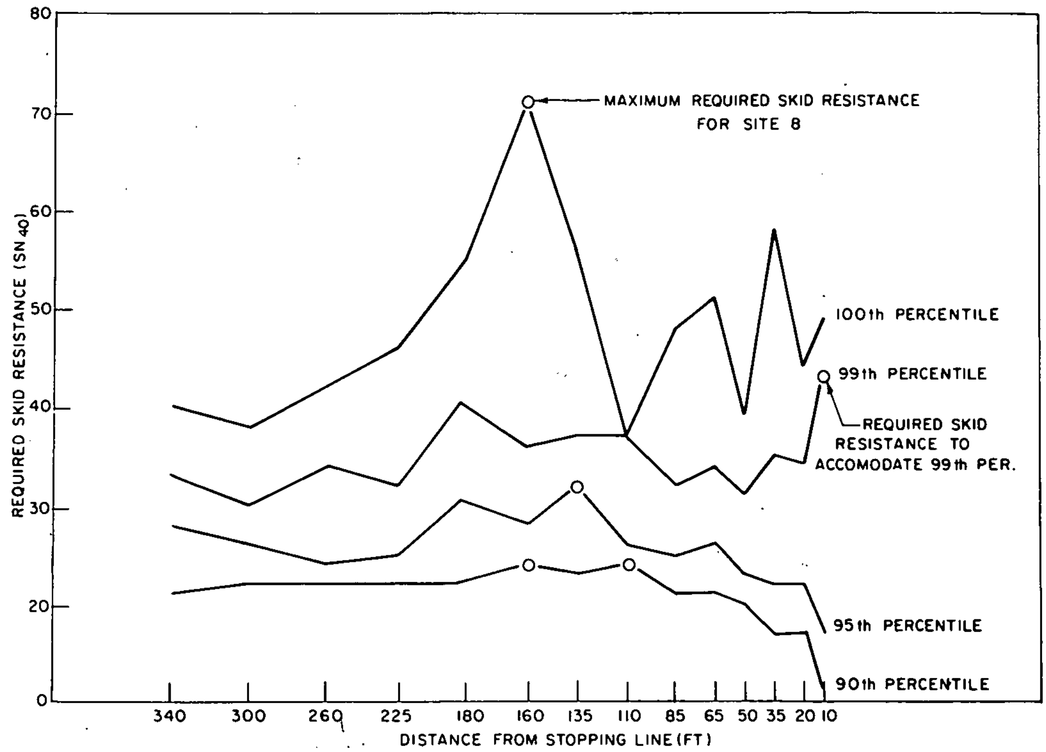

Figure 4. Required skid resistance predicted from observed decelerations and their associated speeds vs distance from stopline, Intersection Site 8.

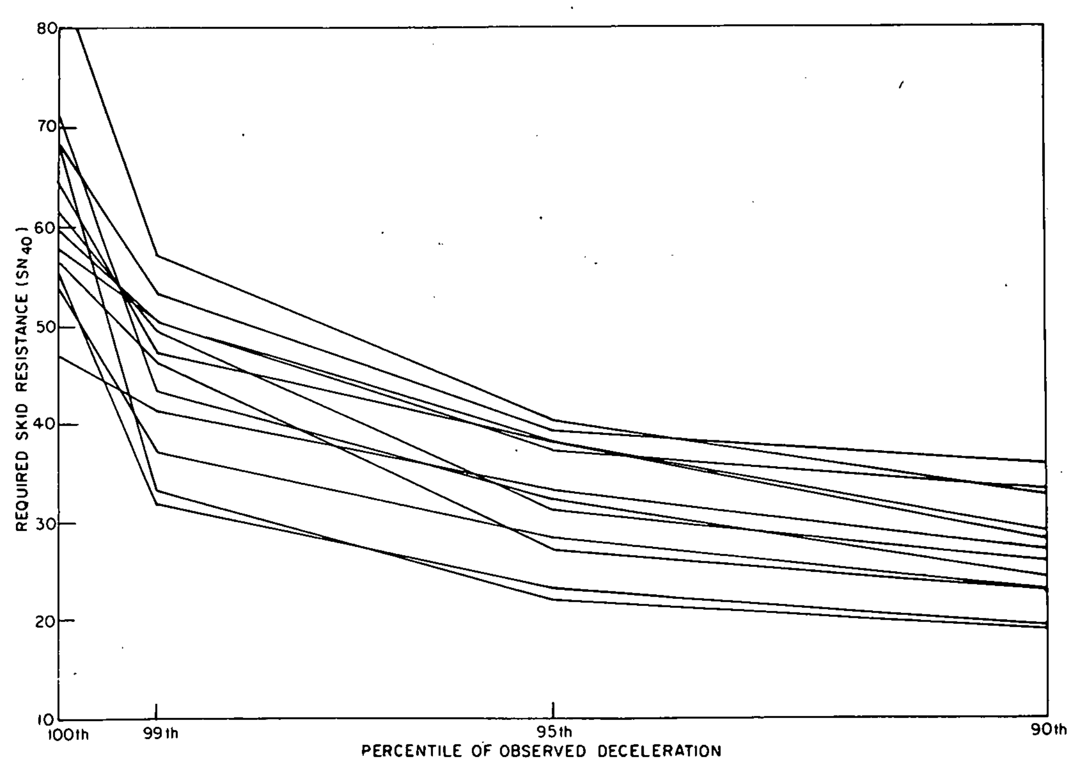

Figure 5. Maximum required skid resistance vs percentile of observed deceleration, 12 intersection sites.

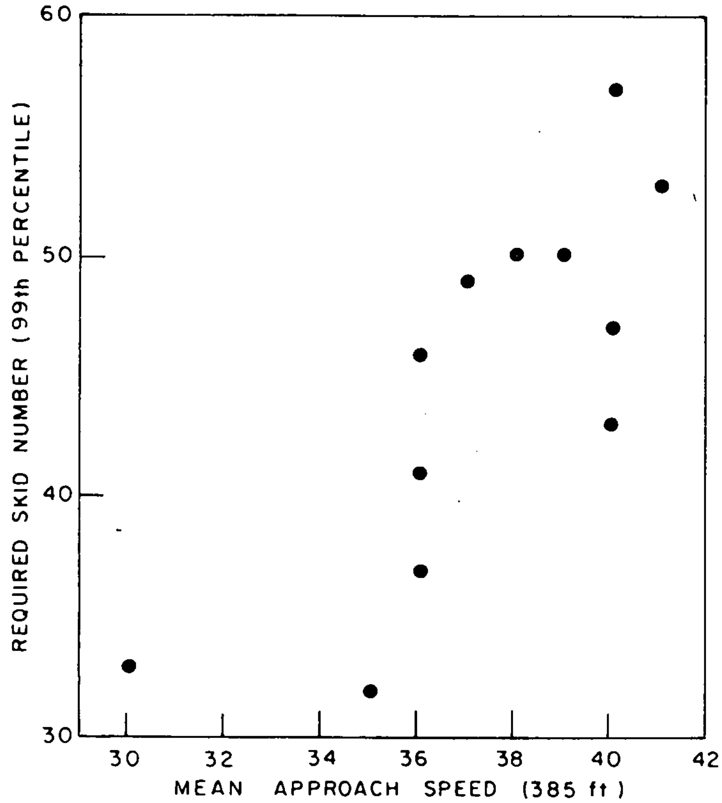

Figure 6. Required 99th percentile skid number vs initial speed at 385 ft.

TABLE 1
MAXIMUM SKID NUMBER (SN_{40}) REQUIRED TO ACCOMMODATE pth PERCENTILE DECELERATION

Site Number	100 Percentile	99 Percentile	95 Percentile	90 Percentile
1	47	41	33	27
2	56	46	27	23
3	64	47	38	29
4	54	37	28	23
5	59	50	39	28
6	68	33	22	19
7	57	50	37	33
8	71	43	32	24
9	68	53	39	36
10	61	49	31	26
11	84	57	40	32
12	55	32	23	19

* Computed using observed deceleration values and observed associated speeds.

TABLE 2
MAXIMUM SKID NUMBERS (SN_{40}) REQUIRED TO ACCOMMODATE 99th PERCENTILE DECELERATION

Site Number	Required Skid Number	Skid Resistance Requirements Category
11	57	High
9	53	
7	50	
5	50	
10	49	Intermediate
3	47	
2	46	
8	43	
1	41	
4	37	Low
6	33	
12	32	

TABLE 4

MAXIMUM SKID NUMBERS (SN_{40}) REQUIRED TO ACCOMODATE 99TH PERCENTILE DECELERATION

Site No.	SN_{40} Computed from Detailed Acceleration and Speed Data	SN_{40} Estimated by Intersection Demand Model	ΔSN_{40}
1	41	46	5
2	46	44	-2
3	47	51	4
4	37	40	3
5	50	47	-3
6	33	35	2
7	50	52	2
8	43	46	3
9	53	56	3
10	49	45	-4
11	57	58	1
12	32	39	7

TABLE 3
SN_{40} REQUIRED TO ACCOMMODATE VARIOUS COMBINATIONS OF SPEED AND ACCELERATION

Braking Decel. (g's)	Speed (mph)						
	10	15	20	30	40	50	60
.60	56.5						
.58	53.0	58.2					
.56	50.0	55.0	60.1				
.54	47.4	52.3	57.5				
.52	44.0	49.0	54.5				
.50	41.4	46.1	51.3	58.0			
.48	37.8	43.0	48.5	55.0			
.46	35.0	40.0	45.2	52.3	58.6		
.44	32.4	37.0	42.5	49.3	56.0		
.42	28.5	34.0	39.5	46.5	52.5	57.5	
.40	26.0	31.0	36.5	43.0	50.0	54.9	59.3
.38	22.7	27.6	33.5	40.1	47.0	52.0	56.5
.36	20.0	25.0	30.4	37.5	43.9	48.8	53.5
.34	17.0	22.0	27.5	34.5	41.0	46.0	50.8
.32	13.8	18.9	24.8	32.3	38.0	42.9	47.5
.30	11.0	15.8	21.9	28.0	35.2	40.0	44.3
.28		12.5	18.5	25.5	32.5	37.0	41.5
.26		9.9	16.0	22.5	29.5	34.0	38.5
.24			12.6	19.5	26.5	31.5	36.0
.22			10.0	17.0	23.8	28.5	32.5
.20				13.6	21.0	25.3	30.0

Table 5

TENTATIVE GENERAL MINIMUM SKID RESISTANCE REQUIREMENTS AT INTERSECTIONS

Design or Traffic Speed (mph)	L Point * (ft)	Minimum Skid Resistance (SN_{40})
Below 40	330	40
40-50	415	45
Above 55	480	55

* The L point is the distance from the stop point at which skid resistance requirements apply.

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