THE FRICTIONAL REQUIREMENTS OF PASSING VEHICLES

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

•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 fast degradation in the frictional capability of the pavement.

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).

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 also they may 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.

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.

Sponsored by Committee on Surface Properties-Vehicle Interaction.

Study Sites

Two study sites having passing zone lengths of 1,360 and 2,680 ft were selected within a 20-mile radius of College Station, Texas. 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 there were no major access points close to the study sites, traffic flow was fairly consistent. The average daily traffic (ADT) was 1,500 vehicles for site A and 3,600 vehicles for site B. The posted speed on both highways is 70 mph. Speed distributions at the sites were very similar to the statewide distributions found by the Texas Highway Department in 1968, which showed the average 85th percentile speed to be 70 mph and the average 15th percentile speed to be 54 mph. When only the speed characteristics are considered the passing maneuvers observed at the study sites should be indicative of those expected on similar facilities.

Immediately before each site, passing was restricted by a double yellow barrier stripe. No-passing zone lengths were 1,770 ft for site A and 3,000 for site B.

Passing zones at both sites began on the downgrade of a crest, extended through a sag vertical curve, and terminated 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 Texas-6, has 13-ft lanes and 8-ft shoulders. Site A, located 20 miles northeast of College Station on Texas-21, has 12-ft lanes and a short 8-ft shoulder on one side of the site. The rights-of-way at both locations received normal maintanance by the Texas Highway Department, were clear of all large vegetation, and were mowed throughout the study area.

Equipment

Three major elements composed 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 have presumed the impeding vehicle to be a highway patrol vehicle because it was white and displayed the official State of Texas-exempt license plates. Therefore, 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 ½-ton pickup was used as the observation vehicle. So that test subjects would be unaware that their maneuvers were being photographed, the camera and operator were concealed. Because 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 in. above the cab roof line. The box contained a small front window over the driver's side of the cab through which the subject's passing maneuver was photographed. Because 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. Because the window was 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 1.

An Arriflex 16-mm camera was used to photograph the passing maneuvers. Power was supplied by an 8-V battery to a governor-controlled motor to produce a constant

24-frames/sec film advance. Black and white Plus-X reversal film (Kodak ASA 50) on 400-ft 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 2.

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, 2-ft lengths of 6-in. wide temporary traffic line pavement markings were placed perpendicular to, and centered on, the centerline at 40-ft intervals throughout the site. The 2-ft markers gave a length calibration that was always pictured on the film frame where lateral placement measurements were taken. The 40-ft interval gave a longitudinal reference system for speed and radius calculations.

Sample Size

The study was concerned primarily with high-speed passing maneuvers. 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 2,000 subjects were photographed to achieve the desired number of completed passing maneuvers. Because 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 1 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 3 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 had there been 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.

FILM ANALYSIS

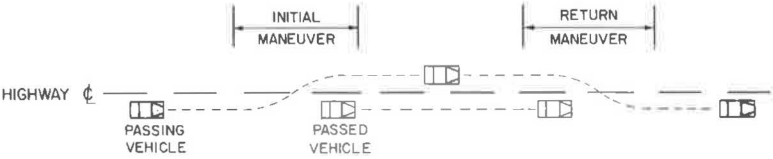
The film was analyzed with a Vanguard motion analyzer. This device is a portable film reader for measuring displacements on photographic projections. It consists of a

Figure 1. Photographic observation vehicle.

Figure 2. Study camera and mounting.

Figure 3. Relative vehicle positions during test.

Figure 4. General path of passing vehicle.



projection head, projection case, and measurement screen.

The 16-mm projection head permits forward and reverse motion of film on 400-ft reels. A variable-speed mechanism moves the image across the projection screen at from 0 to 30 frames/sec. 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 cross-hair system that measures displacement in 0.001-in. 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 2-ft marker 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, we always used the left edge of the left-rear tire as the lateral vehicle position reference. Lateral placement at each reference marker was measured from the frame where the left-rear tire was nearest the marker. After recording calibration readings on the left and right edge of the reference marker, we recorded the position reading of the left-rear tire. These readings, along with the 2-ft known length, gave the data necessary for calculating the actual lateral placement.

MATHEMATICAL ANALYSIS

The Vanguard data were used in a computer program to calculate vehicle speed, left-rear tire lateral placement, vehicle path radius, and lateral g acceleration (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 4.

Vehicle Speed

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

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

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-frames/sec film speed used, this yields an acceptable maximum error of the speed estimate, ranging from about 4 percent at 50 mph to 7 percent at 80 mph.

Vehicle Path 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 being the calibration marker under consideration. Because 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 5 shows the three basic geometric configurations of three successive tire positions. Points A, B, and C represent left-rear tire positions spaced at 40-ft 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, and 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 5 as follows:

Case	Value of θ
I	$\alpha + \beta$
II	$180 + \beta - \alpha$
III	$180 + \alpha - \beta$

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 (a) lateral discrepancy in placing the calibration marker, (b) length discrepancy of the calibration marker, (c) sampling error due to taking lateral placement readings up to one-half frame away from the calibration marker, (d) equipment error, and (e) human error in reading and recording lateral placement measurements.

Estimating the distribution of error values for lateral placement estimates was not possible. Because 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.

Error sensitivity was checked by assuming that the maximum error ranged between 0.05 and 0.10 ft. For this analysis, the lateral placement of the two outside points was assumed to be equal, and the center lateral placement varied an increment of d_x greater. Thus, in reference to Figure 5, the increments $|d_A - d_B|$ and $|d_B - d_C|$ are equivalent to d_x. Figure 6 shows the maximum percentage of error of the radius estimate for various lateral placement differentials and their corresponding radii.

Lateral Acceleration

The lateral g acceleration (friction demand, f) at the tire-pavement interface was estimated at each calibration marker for each sample by using the centripetal force equation, $f = (V^2/15R) - e$. The superelevation, e, in this case, 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/sec) and the analysis interval (80 ft) 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 g acceleration data for each passing vehicle sampled. As mentioned previously, these variables were computed throughout both the initial pull-out maneuver and the return maneuver. The point of maximum lateral g acceleration was selected to represent the critical point for each maneuver.

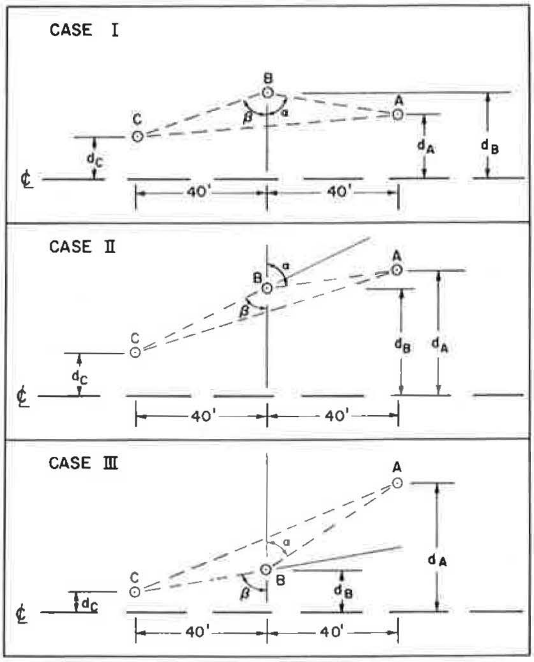


Figure 5. Geometric descriptions of vehicle radius calculations.

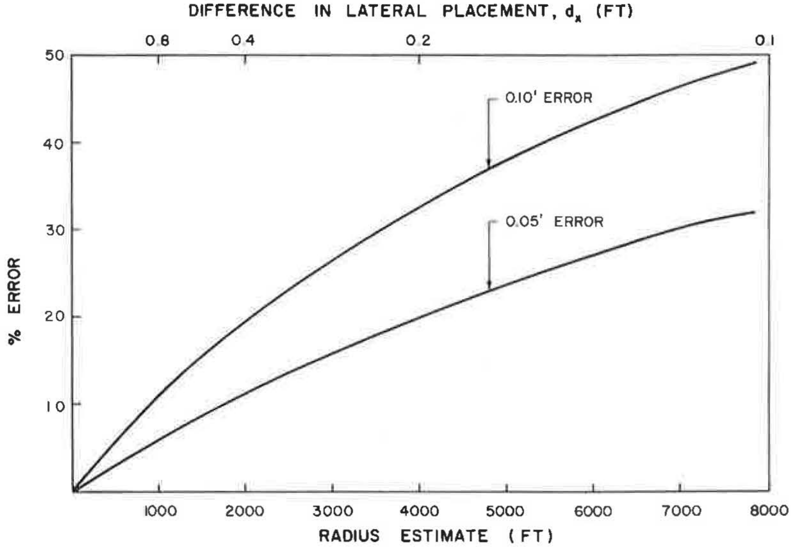


Figure 6. Error sensitivity of estimated radius.

Table 1. Sample data.

Sample No.	Impeding Vehicle Speed	Data and Point of Maximum f			Sample No.	Impeding Vehicle Speed	Data and Point of Maximum f		
		Speed	Radius	f			Speed	Radius	f
Site A—Initial Maneuver					Site B—Initial Maneuver				
40	55	60	963	0.245	64	60	73	1,143	0.308
58	65	82	2,553	0.175	30	65	77	1,461	0.271
20	55	73	3,378	0.104	92	55	55	1,023	0.194
10	50	65	6,218	0.046	116	65	77	3,600	0.110
16	50	55	5,306	0.037	41	60	65	8,685	0.033
Site A—Return Maneuver					Site B—Return Maneuver				
84	50	65	792	0.361	70	60	82	1,177	0.379
19	55	82	1,879	0.238	80	50	60	916	0.258
67	50	73	2,346	0.150	68	50	69	1,566	0.202
64	50	62	2,358	0.110	34	60	94	5,503	0.106
37	55	73	7,150	0.049	30	65	82	11,750	0.038

This point, for most of the samples, coincided with either the point of minimum path radius or the point of maximum speed or both. Sample data, showing the ranges in vehicle speed, radius, and lateral acceleration, are given in Table 1.

Vehicle Speed

Figure 7 shows the distribution of vehicle speeds for the impeding speed, the speed at maximum lateral g acceleration during the initial maneuver, and the speed at maximum lateral g acceleration during the return maneuver. In general, the speed at the critical point of the initial maneuver is about 10 to 12 mph higher than the impeding speed, and the speed at the critical point of the return maneuver is 17 to 21 mph higher than the impeding speed. Also of interest is the fact that only about 12 percent 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 g acceleration) could be expected at any speed within the speed range studied.

Table 2 gives the radius values for the critical end of these distributions. It is important to compare the values in Table 2 with the error sensitivity curve of Figure 6. By doing this, we note that the radius values of Table 2 have a reasonably low error sensitivity.

The values for site B in Table 2 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 larger 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

If the critical side friction requirement is to be determined, a percentile level is needed to ensure that very few vehicles will approach instability. The 10 percent level appears to be a relatively good choice. Using this level would say that only 10 percent of the vehicles would have lower vehicle path radii. To obtain the critical values, we averaged the values for sites A and B. 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 1,470 ft for the initial maneuver and 1,640 ft for the return maneuver. By using these two values in the centripetal force equation, $f = (V^2/15R) - e$, one can plot the critical relationship between lateral g acceleration and speed for the initial and return maneuvers, as shown in Figures 9 and 10 respectively. It is noted that a negative e was used in computing these two curves inasmuch as most critical vehicle paths were adverse to the pavement cross slope (Fig. 4).

Forward Acceleration

Although no precise measurements of instantaneous vehicle acceleration were possible, some general observations are appropriate. The data indicate 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 from 1 to 3 ft/sec^2 for the initial maneuver. Inasmuch as these are averages over fairly long intervals (200 to 500 ft), instantaneous accelerations could be considerably higher.

Figure 7. Speed distributions for various portions of the passing maneuver at both sites.

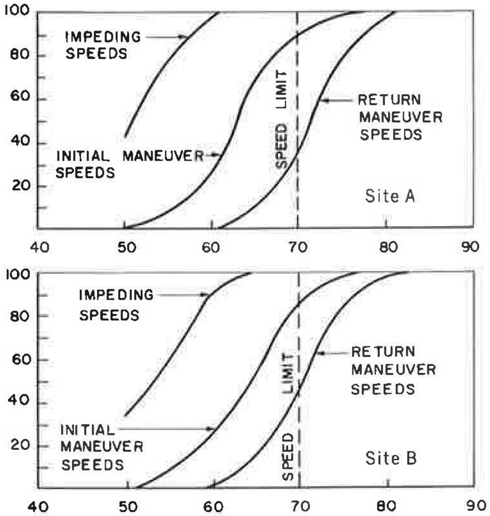


Table 2. Distribution of vehicle path radii.

Percentage of Vehicles Having a Smaller Radius	Radius of Path (ft)			
	Site A		Site B	
	Initial Maneuver	Return Maneuver	Initial Maneuver	Return Maneuver
5	1,500	1,380	1,130	1,320
10	1,650	1,700	1,290	1,580
15	2,010	1,910	1,430	1,770

Figure 8. Total friction requirement for the initial maneuver.

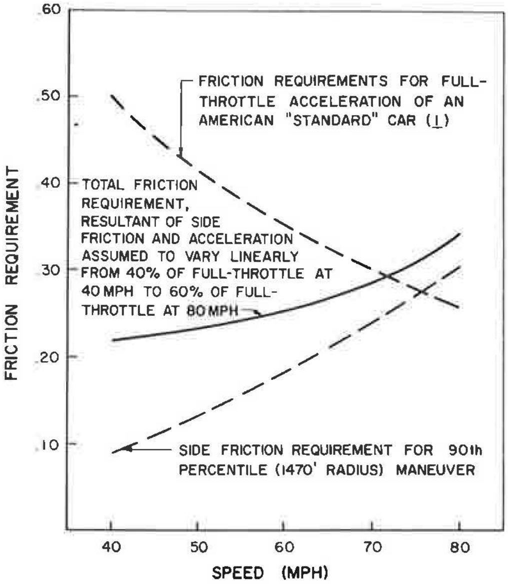
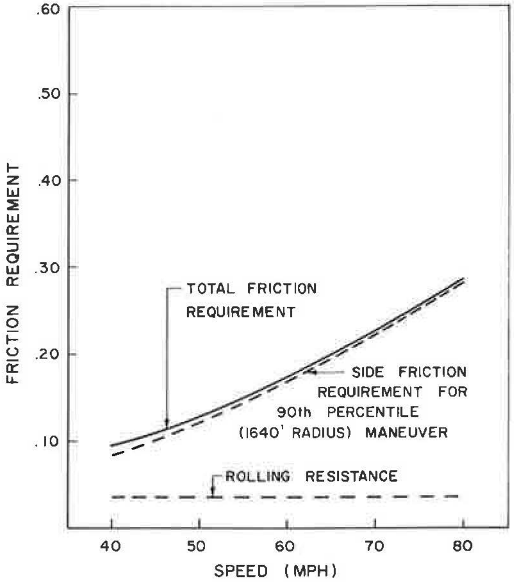


Figure 9. Total friction requirement for the return maneuver.



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. The friction demand of an American "hot" car accelerating at full throttle is considerably greater and of compact cars somewhat less.

To arrive at a reasonable estimate of the total friction demand we assumed the forward acceleration of the passing vehicle during the initial maneuver to vary linearly between 40 percent of full throttle at 40 mph and 60 percent of full throttle at 80 mph. For a 4,000-lb vehicle, this corresponds to an acceleration of 6.4 ft/sec^2 at 40 mph and an acceleration of 5.0 ft/sec^2 at 80 mph. The total friction demand estimate for the initial maneuver is shown on Figure 8. 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 9. Comparing the total friction demand curves of Figures 8 and 9 reveals 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 (nonemergency) 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 10 shows a percentile distribution of skid numbers in one state and will be used for illustration. Also plotted in Figure 10 is the suggested frictional requirement (assuming SN = 100f). The percentage of pavements that satisfy the frictional requirement at various speeds is as follows:

Speed (mph)	Percentage of Pavements
80	42
70	60
60	75
50	85
40	93

As was found in the analysis of field data, only about 12 percent 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 3 compares the effect of using the suggested frictional requirements for various programs in the state depicted in Figure 10. Two assumptions were applied to derive Table 3. First, the statewide speed limit is 70 mph, and, second, the pavements that were improved by not satisfying the minimum skid resistance requirement have the same percentile distribution of skid numbers as the unimproved pavements.

Table 3 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 10. 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.

Figure 10. Percentile distribution of relation between skid number and speed for 500 pavements.

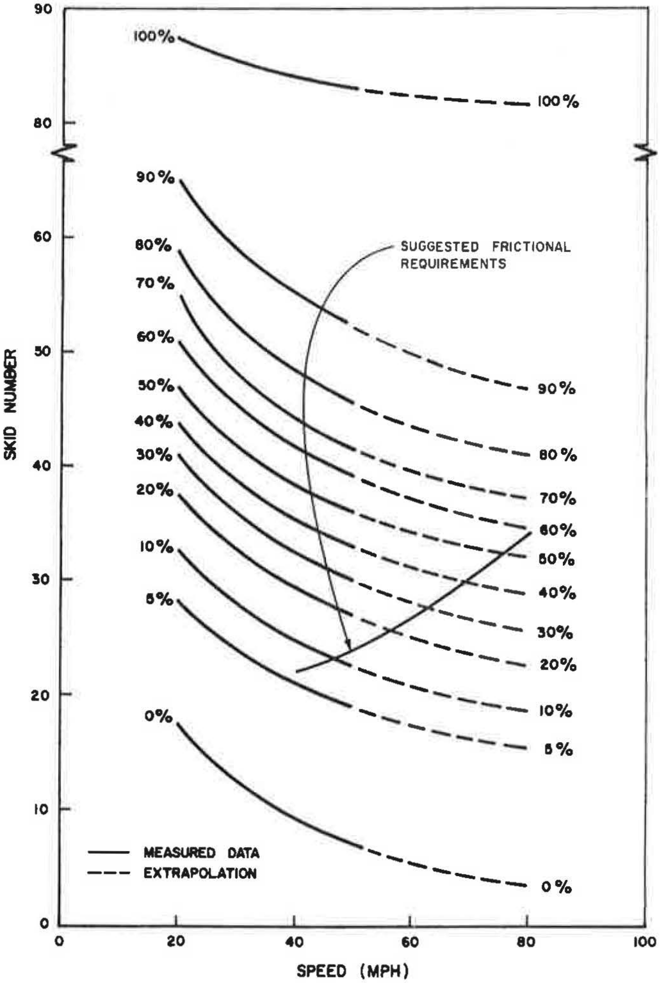


Table 3. Percentage of pavements on roads with posted wet-weather speed limits having minimum skid resistance requirements.

Wet-Weather Speed Limit	Minimum Skid Number Requirement at 40 mph				
	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
Below 70[a]	40	37	33	25	0

[a] Percentage of pavements with wet-weather speed limit below the 70-mph statewide limit.

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

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2. Weaver, G. D., and Glennon J. C. Passing Performance Measurements Related to Sight Distance Design. Texas Transportation Institute, Res. Rept. 134-6, June 1971.