TIRE-PAVEMENT FRICTION: A VITAL DESIGN OBJECTIVE

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This paper presents the argument that tire-pavement friction should be considered during the design of a new highway facility. The concept of balanced friction design for safety is presented, and is based on the precept that different maneuvers require different levels of available friction and that different highway geometrics produce the need for different maneuvers. Presented in support of these arguments are the most pertinent results of various research and development studies. The information and examples should be useful not only in designing new highways but also in making decisions concerning the correction of deficiencies in existing highways.

•THE REDUCTION of the losses due to skid-initiated, wet-weather accidents is a goal that has been set by highway officials. Working toward this goal has generated a tremendous amount of research on specific aspects of the problem, but use of this information to evaluate the causative factors has been limited.

The purpose of tire-pavement friction is to allow the driver of the vehicle to perform those maneuvers that he can reasonably expect to accomplish; maneuvers range from the normal driving realm to an emergency avoidance maneuver. When the driver cannot perform an attempted maneuver, whether it be because the tire-pavement interface cannot accept the imposed loads, the capabilities of the vehicle are exceeded, or driver's skills are poor, the result is likely to be an accident. In trying to accommodate all factors that enter into wet-weather accidents, Hankins, Gregory, and Berger (1) prepared a skidding-accident systems model that included 40 separate variables; a simplified representation is shown in Figure 1. Even though complex, this model includes only those most obvious influencing factors, which constitute only a small part of the problem.

Since the 1930s when Moyer (2, 3, 4) conducted a comprehensive study of the requirements of motor vehicles for tire-pavement friction, writers on this subject have been making recommendations for those levels of friction they judged to be appropriate for a range of highway geometrics and conditions. For example, Kummer and Meyer (5) recommended a coefficient of friction of 0.37 for a mean traffic speed of 50 mph and 0.41 for a mean traffic speed of 60 mph. These are not radically different from those made by Moyer in 1932 but were developed from extensive information that was not available to Moyer.

The concept of maintaining certain values of friction over an entire roadway network is an important contribution and undoubtedly has led to much improvement in highway safety. Today, however, we should be prepared to design pavement surfaces to resist the specific horizontal shear loads that are imposed on them, these loads being a function of the maneuvers that can be reasonably expected. This design concept is analogous to designing a beam for the loads that are imposed on it. This same concept, in a generalized way, has been used to derive the levels of friction that were previously mentioned, but it has been done in a research environment and limited to normal maneuvers rather than in the highway design environment where design for friction can interact appropriately with geometric design decisions. The reason for this is partly the seeming complexity of the problem and partly the preoccupation of highway engineers with the vertical wheel loads a pavement must resist under traffic. In many

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early designs pavement friction was something that just happened when a roadway was built. Sometimes it was good, sometimes it was bad, but the concept of actually designing for friction is comparatively new to most highway engineers.

Engineers have accepted the simple concept of a single friction value to satisfy all parts of a highway system and have neglected a more permanent solution to the problem and the potential long-term gains it would bring. Experience and data now available make it possible to design tire-pavement friction to accommodate most maneuvers that drivers will attempt.

BALANCED FRICTION DESIGN FOR SAFETY

The thesis is this: A single skid number is not appropriate for all roads and all positions on any given road. We would not think of designing a building by using the same beam cross section for each span and every load condition. An engineer is taught to design a beam to resist the shear and moment that it must resist, i.e., those internal reactions directly related to the geometry of the beam and the loads that are imposed. Similarly, as shown in Figure 2, a pavement surface should be designed to resist anticipated tractive loads.

This means that available tire-pavement friction must be set at some level above the demand for tire-pavement friction (essentially a function of roadway geometrics), just as yield point is above the working stress, as shown in Figure 3. Figure 4 shows another illustration of the design concept of a balanced friction design for safety. The numbers on the abscissa relate to the numbers on the plan view at the top of the figure. The curves show the demand for friction by a certain percentage of drivers. For example, the 98 percent curve means 98 percent of the drivers do not exceed this friction demand. The supply level is the amount of friction that is available. Any demand above this level could not be accommodated, and skidding would result. The main point is that we should put our costly high-friction surfaces at the locations where demand is greatest.

The equations needed to design pavement friction are presented in several reports (5, 6). The engineering approach to using them is, in most cases, to determine the appropriate input data in terms of speed, stopping distance, cornering radius, and acceleration or deceleration and, thus, to determine the demand for friction. These same equations are suggested for a similar application in the recent report by Weaver, Hankins, and Ivey (7). In that report the available friction is determined empirically and used to determine the safe driving speed, the reverse operation of the friction design process. The equations are presented in detail in the next section of this paper. Empirical determinations of the demand for friction to be available soon from an NCHRP project for certain types of curves and intersections will be a valuable supplement to the information now available for use in the design equations.

The equations presented here are far from perfect, and their application requires something no computer program has succeeded in duplicating—considerable engineering judgment. Aside from the basic design equations and the necessary input data for their use, the other item needed to apply the balanced friction design concept is a consistent way of measuring tire-pavement friction.

A new federally coordinated program for highway safety, initiated by the Federal Highway Administration, seeks to encourage new studies where gaps exist in the present work and undertakes the closure of other gaps by direct administrative contracts. The federally coordinated program for the reduction of wet-weather accidents has undertaken, among other things, the elimination of the large differences among skid number values acquired by different ASTM E 274 skid test units. These differences have been so great that we have been operating during past years under an act not unlike the Mann Act (8): that is, it has been illegal to transport a skid number across state lines for engineering purposes.

To repeal this act, the FHWA is committed to providing a network of inventory skid measurement systems and guide specifications for inventory equipment and field-testing procedures. The National Bureau of Standards will provide the national reference skid measurement system. There will be 3 field test and evaluation centers at Texas A&M

Figure 1. Driver-vehicle-roadway-environment interaction.

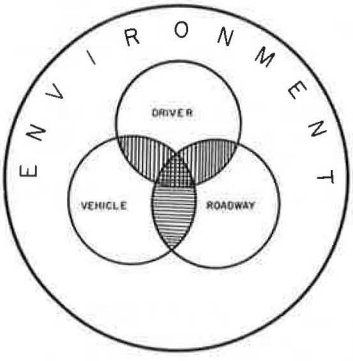


Figure 2. Beam design analogy.

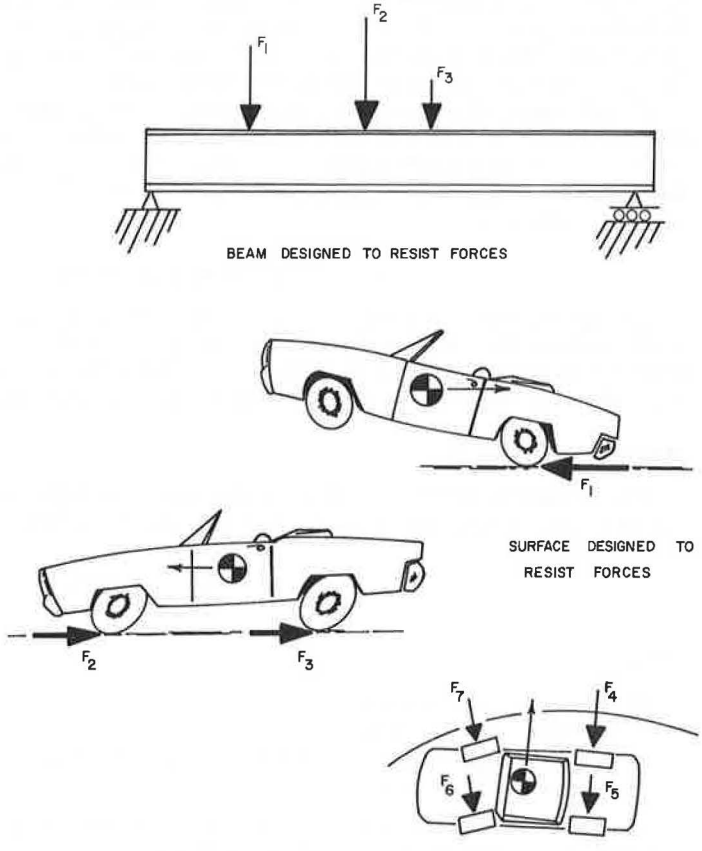
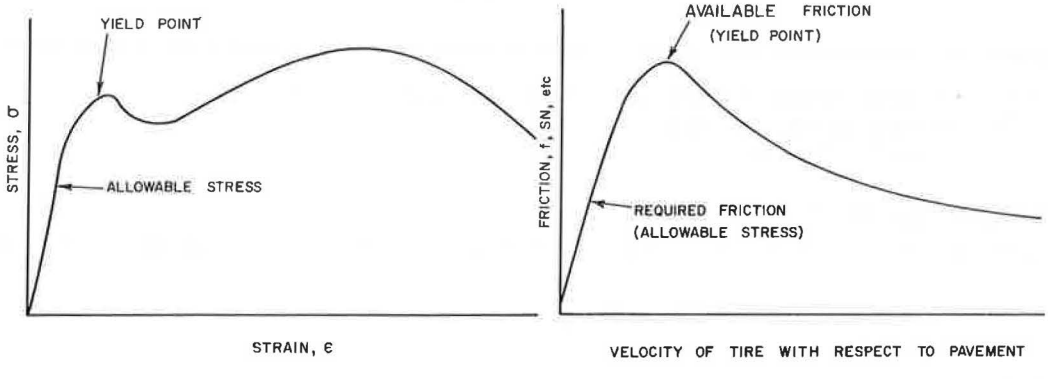


Figure 3. Yield point analogy.



University, at the Ford Proving Grounds (Yucca, Arizona), and at Ohio State University. At each of these centers, there will be an area reference skid measurement system that will be calibrated at the appropriate center and correlated with the center area reference system at designated intervals. When all inventory systems have been related to the NBS in this way, it will then be possible to relate skid number values taken in one state to those observed in any other state.

At this time, there will be a great temptation for governmental agencies to specify certain values of skid numbers on highways. Reasonable decisions must be made concerning the value of tire-pavement friction needed at specific points on highways; or, better still, a balanced friction design policy should be established based on appropriate design equations.

DESIGN EQUATIONS

Design equations are presented as concisely as possible; previously published information is incorporated by the use of appropriate references. Friction numbers are used for continuity with skid numbers. The numbers are the required values of friction multiplied by 100, just as skid numbers are observed values of friction multiplied by 100.

Stopping Maneuvers

The AASHO code (9) provides an acceptable relation between stopping distance and the demand for friction as shown by the following equation:

$$d = \frac{V^2}{30\,f} + 1.47\,Vt$$

where

d = stopping distance, ft;
V = vehicle speed, mph;
f = coefficient of friction between tires and roadway; and
t = perception-reaction time, sec.

Rearranging Eq. 3 and using a 2.5-sec perception-reaction time currently recommended by AASHO (9) relate the demand friction for stopping maneuvers to speed by

$$FN_d = \frac{V^2}{0.3(d - 3.67V)}$$

where

FN_d = demand friction number for stopping within the available distance;
V = vehicle speed, mph; and
d = available distance, ft.

Cornering Maneuvers

The equation used by AASHO in the development of standards for horizontal curves is

$$e + f = \frac{V^2}{15R}$$

where

e = superelevation rate, ft/ft;
f = coefficient of friction;
V = vehicle speed, mph; and
R = curve radius, ft.

This equation was found to give a reasonable estimate of the available friction in a dynamically stable cornering maneuver in a recent study (10) conducted for AASHO.

Rewriting the equation for consistent comparison to values of skid number yields

$$FN_c = \frac{6.67V^2}{R} - 100e$$

where $FN_c = 100(f)$, the demand for lateral friction during cornering.

The friction demand determined from this equation is only appropriate provided the vehicle smoothly traverses the path of the highway curve. Therefore, it should only be used for curves having spiraled transitions or at points significantly removed from abrupt transitions. It there is no transition from tangent to curves with a curvature of 2 deg or greater, the equation developed by Glennon and Weaver (11) should be used:

$$FN_c = \frac{V^2}{0.786R + 40.3} - 100e$$

Combination Maneuvers

Many maneuvers involve some combination of cornering and braking or accelerating. A common way to determine the total friction demand is the vector sum of the demand for the individual changes in speed or direction (5).

If the maneuver is a combination of cornering and braking as might be found in traversing a freeway exit ramp, individual values of FN_c, the friction demand for cornering, and FN_d, the friction demand for decelerating, may be calculated. The total friction demand, FN_t, is found by

$$FN_t = \sqrt{FN_c^2 + FN_d^2}$$

From observations of traffic, Glennon (12) derived the following expression for cornering in the nonconstrained passing maneuver:

$$FN_p = \frac{V^2}{220} + 2$$

This equation was based on a number of other assumptions as described in Weaver's report (13). If the forward acceleration is assumed to vary linearly from 40 to 60 percent, full throttle at 40 and 80 mph respectively, the FN_a needed in accelerating can be found from

$$f(W/2) = \frac{W}{g} a$$

$$FN_a = 2 \frac{a}{g} (100)$$

The appropriate acceleration, a, at 40 percent full throttle was reported by Kummer and Meyer (5) as 6.4 ft/sec^2. The acceleration at 60 percent was 5.0 ft/sec^2. From the vector sum of these 2 effects, the resultant demand for friction was found. The same procedure can be used in any maneuver where estimates of the degree of cornering and braking or accelerating can be supplied.

AVAILABLE FRICTION

Any moving object possesses kinetic energy proportional to the square of its velocity. Dissipation of this energy is required to stop the body. Energy of the wheeled vehicle (neglecting wind resistance and changes in elevation) is dissipated between the tire and

the pavement and in the braking system by the creation of a friction force opposing the direction of motion of the vehicle. After wheel lockup, the total friction force available to oppose the motion of the vehicle must be generated at the tire-pavement interface.

There are many causes of pavement slipperiness. In general it is due to (a) the presence of water or other friction-reducing materials in the tire-pavement contact area and (b) high traffic volumes that, through pavement wear and aggregate polish, drastically reduce the friction of pavement surfaces. Many parameters affect the interactions at the tire-pavement interface. Considered to have major effects are (a) mode of operation, i.e., rolling, slipping, or sliding; (b) pavement-surface characteristics, mainly macroscopic and microscopic roughness and drainage capability, (c) water-film thickness at the interface, (d) tire-tread depth and elastic and damping properties of the tire rubber, and (e) vehicle speed.

Numerous research studies have indicated that almost all pavement surfaces exhibit adequate friction for normal stopping and cornering maneuvers when dry and clean. When wet, however, this is no longer the case. A knowledge of the relative effects of water-film thickness and the water escape mechanism at the tire-pavement interface are therefore of paramount importance.

Relevant Surface Factors

Attempts have been made to characterize properties affecting friction of pavement-surface types by using qualitative terms such as surface macrotexture; aggregate size, shape, microtexture, and mineralogy; and the drainage characteristic of the total surface. Although the relative magnitude of the influence of these characteristics is open to debate, it is generally agreed that they largely determine the ultimate friction properties of surfaces. It is the authors' opinion that the influence of all these characteristics is primarily due to the effect they have on the way water can escape from the tire-pavement interface.

The importance of the type and magnitude of surface texture on the friction properties of pavement surfaces has been studied by several researchers (5, 17, 18, 19, 20). Pavement surface texture refers to the distribution and the geometric configuration of the individual surface aggregates. There is not sufficient agreement among the various researchers to adopt a standard nomenclature for discussing textural parameters. However, general practice today favors the use of the terms macroscopic texture (macrotexture), which refers to the large-scale texture caused by the size and shape of the surface aggregate, and microscopic texture (microtexture), which refers to the fine-scaled roughness contributed by individual small asperities on the individual aggregate particles.

Macrotexture and microtexture respectively provide for gross surface drainage and subsequent puncturing of the water film. Another factor that acts in combination with macrotexture and microtexture is the internal drainage of the pavement surface course itself. Goodwin (19), Hutchinson et al. (20), and Gallaway (21), among others, have postulated that high-void-content surfaces, porous pavements, or vesicular aggregates provide internal escape paths for water under a tire and thus lessen hydrodynamic pressure buildup. This would result in better tire-gripping capability and lessen the need of macrotexture to provide initial, gross drainage. Research directed toward measuring dynamic drainage capabilities of pavement surfaces is in the experimental stage (22).

With respect to the size of the coarse aggregate, the majority opinion seems to be that finer mixes are superior to those that are coarser, at least in bituminous construction (22, 23). However, the advantages of fine mixes are not always apparent, and some investigators have suggested that particle size has actually little or no effect on frictional characteristics (24, 25).

The shape of the aggregate particles is a significant factor in skid-resistance considerations. The individual particles should be angular and sharp in order to give a gritty, sandpaperlike texture (26, 27, 28). Skid-resistance measurements have been found to be about 25 percent higher for bituminous mixes containing angular aggregates than for those containing rounded aggregates (29). The importance of the aggregate shape has also been borne out by laboratory experiments (30, 31, 32).

Wear and polishing under traffic result in skid-resistance variations across the width of the road (32); these may lead to directional control instability during braking regardless of the minimum value of friction. It has been shown analytically (33) that, for a coefficient of friction of 0.40 along one wheelpath and 0.60 along the other, a 3,000-lb vehicle will turn about 17 deg in a locked-wheel stop from 40 mph. This problem is further accentuated on multilane highways where the driving lane is normally more slippery than the passing lane (35, 36).

Because the nature of the wear is directly related to the resistance of the surface aggregate to polishing, wear can actually be desirable on road surfaces. Differential wear, due to variation in hardness of the aggregate constituents or matrix or both (26, 34), greatly contributes to the retention of the rough texture. Particle-by-particle wear, during which aggregate particles are dislodged from the surface before they get excessively polished, continuously rejuvenates the surface (28, 35). In addition, particle-by-particle wear does not just ensure prolonged skid resistance but distributes the energy of stopping to the brakes, tires, and road surface and, therefore, provides instantaneously higher skid resistance.

Test Pavements and Equipment

In a study (37) to test the skid resistance of a number of typical highway surfaces under simulated rainfall, variables included rainfall intensity, pavement macrotexture, tire tread design, tread depth, tire pressure, and vehicle speed. In other tests (38), to evaluate the effectiveness, as measured by skid resistance, of different finishes on a portland cement concrete pavement, variables included rainfall intensity (water depth), tire tread type, tire tread depth, tire pressure, surface finish, and vehicle speed.

A brief description of the experimental and field surfaces is given in Tables 1 and 2 respectively. Major equipment used in the study is shown in Figure 5 and consisted of water tank truck, rainfall simulator, and skid test system.

The framework of the rain simulator is composed of 4-in. wide by 1-in. deep channel iron. A 4-in. diameter pipe serves as the manifold, and 2-in. diameter pipes are used as feeder lines for the shrub-head nozzles. Eight 20-ft long sections of the rain simulator wet an area approximately 210 ft long by 30 ft wide.

A 4,000-gal water truck equipped with a high pressure pump was used to supply water to the system. Desired water depths were measured at various distances along the drainage path. Rainfall intensities were deduced from the amount of water caught in metal cans during a 12-min interval. The number and type of nozzles and header water pressure that were used to produce different rainfall intensities are given in Table 3.

The friction measurements reported were obtained with the Texas Highway Department research skid trailer system, which conforms substantially to ASTM standards (E 274-65T). ASTM standard 14-in. tires (E 249-66) were used and inflated to 24 and 32 psi. The friction force is measured with a strain-gauge instrumented drag link. Figure 5 shows the system under test conditions. Friction measurements were taken at 20, 40, and 60 mph with E-17 tires of 3 tread depths: full tread, half tread, and smooth. Three commercial tires were also tested at 2 pressures and 3 tread depths.

Skid measurements were made by using the trailer's internal watering system; measurements were also made under simulated rain at a minimum of 3 rainfall intensities (6 or more water depths). Reported data represent an average of at least 4 skid test measurements for each variable in the study.

The portland cement concrete field surfaces (Table 2) were tested on a restricted scale because they were formed on a new section of a 4-lane divided highway east of College Station. A summary of the data taken on these surfaces as well as those surfaces previously described in Table 1 is presented and discussed in the following paragraphs.

Test Results

The field sections of PCC were finished by natural bristle brush, plastic bristle broom, metal tines, and a combination burlap drag followed by metal tines. Seven test

Figure 4. Balanced friction design for safety.

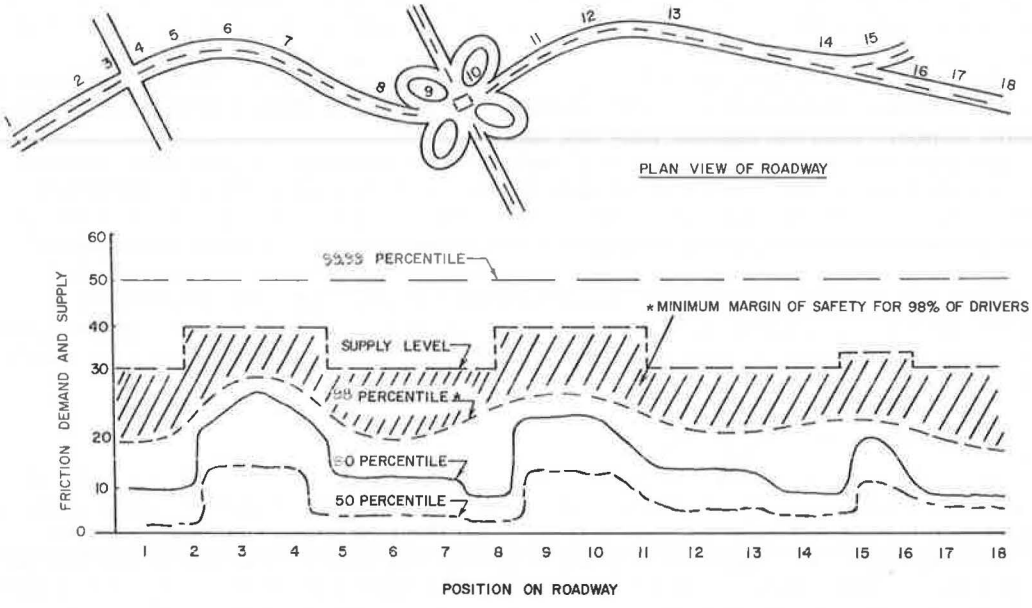


Table 1. Experimental test surfaces.

Test Pad	Surface Type	Aggregate Weight (percent)	Aggregate Type	Max Size (in.)	THD Specification	Construction Date	Preparation Prior to Test	Avg Texture Depth[a] (in.)
1	Portland cement concrete (transverse drag)[b]	67	Rounded siliceous gravel	1½	Existing runway surface	1953	Cleaned with water and power broom	0.039
		33	Siliceous gravel					
2	Clay-filled tar emulsion (Jennite), flushed seal	None	None	None	Type E[c]	1968	Scrubbed with water and rubber float	0.005
3	Hot-mix asphalt concrete (terrazzo finish)	35	Coarse crushed limestone	½	Type D	1968	Ground with terrazzo machine and polished with water, fly ash, and rubber float	0.014
		30	Medium crushed limestone					
		25	Fine crushed limestone					
		10	Field sand					
4	Hot-mix asphalt concrete	60	Coarse crushed siliceous gravel	¼	Type F	1968	Polished with water, fly ash, and rubber float	0.029
		20	Fine crushed siliceous gravel					
		20	Field sand					
5	Hot-mix asphalt concrete	30	Coarse rounded siliceous gravel	⅝	Grade C	1968	Polished with water, fly ash, and rubber float	0.024
		25	Fine rounded siliceous gravel					
		35	Crushed limestone fines					
		10	Field sand					
6	Surface treatment (chip seal)	100	Rounded siliceous gravel	½	Grade 4	1970	None	0.119
7	Surface treatment (chip seal)	100	Lightweight aggregate (fired clay)	½	Grade 4	1970	None	0.148
8	Hot-mix asphalt concrete	40	Lightweight aggregate (fired clay)	½		1970	Scrubbed with water and broom and polished with water, fine sand, and rubber float	0.022
		40	Lignite boiler slag aggregate					
		20	Siliceous field sand					

[a]Obtained by impression method.
[b]With respect to direction of vehicular travel.
[c]A 3/16 in. maximum size type E mix composed of slag and limestone screenings used as base for seal.

sections, each 800 ft long, were constructed with initial texture depths, measured by the putty impression method, ranging from 0.039 in. for the burlap drag finish to 0.094 in. for the longitudinal tines finish.

These 7 test sections were constructed in October and November 1971. After construction they were tested for skid resistance by using the Texas Highway Department ASTM trailer at speeds of 20, 40, and 60 mph.

Prior to opening the highway to traffic (June 1972), the rain simulator (Fig. 5) was moved to the project and skid-resistance measurements were taken under simulated rainfall conditions. These data together with data of the skid trailer and the internal watering system were acquired by using the tires previously described.

The skid trailer friction data for the field and experimental test surfaces were analyzed by using a computerized multiple regression program to obtain the best fit of the data. Equations relating the effects of speed, water depth, texture, tire type, tire tread depth, and tire pressure to skid number (SN) were developed, and the equations developed for a selected portion of the research are presented. The data indicate a 10 to 15 percent increase in the SN value for the full-tread ASTM tire over the 3 commercial tires used in the study. This difference, shown in Figure 6, was not shown when a larger sample of commercial tires was under different setting conditions (39).

Figure 7 shows regression lines for a selected commercial tire tested for skid number as a function of speed on experimental test pads with tire pressure, tread depth, and water depth held constant. For comparison purposes, the broken lines show ASTM values of SN as a function of vehicle speed where the various surfaces were wet only by water from an internal watering system of a locked-wheel skid trailer. Although data are given only for pads 2 and 6, they are representative of general findings that show that ASTM skid numbers are significantly higher than locked-wheel friction values determined on naturally wet (rain-slick) surfaces.

Figure 8 shows data developed on the PCC field surfaces given in Table 2. Finish F2 (transverse tines) yields significantly higher SN values than the other finishes used.

A tentative relation defining available friction as a function of the major parameters was developed by Hankins from a portion of the study presented here. This relationship is

$$SN = 0.7483(FM)^{1.03081}\left(\frac{40}{Vel}\right)^{0.34903}$$

when

$$FM = [0.938 + (0.00675 \times Vel - 0.9)(Tread - 2.33)]\,(SN_{40})$$
$$\{29 + [(Vel - 36.4)(75 - 135\ Tread) - 3{,}600]\,(Text)\}(WD)$$

where

Vel = vehicle speed, mph;
SN_{40} = basic friction value, ASTM skid number at 40 mph;
Tread = tire tread depth, value 1 for smooth and value 2 for full-treaded tires;
Text = pavement surface texture, in.; and
WD = water depth on pavement surface, in.

Gallaway (40) had already developed the following equation to determine water depth:

$$WD = \left[3.38 \times 10^{-3}\left(\frac{1}{T}\right)^{-0.11}(L)^{0.43}(I)^{0.59}\left(\frac{1}{S}\right)^{0.42}\right] - T$$

where

WD = water depth above top of texture, in.;
T = average texture depth, in.;
L = drainage path length, ft;
I = rainfall intensity, in./hr; and
S = cross-slope, ft/ft.

Table 2. Portland cement concrete finishes of field surfaces.

Finish			Avg Texture Depth[a] (in.)
Number	Description	Direction	
F6	Burlap drag (control section)	Longitudinal	0.039
F7	Natural fiber brush	Transverse	0.042
F3	Plastic bristle broom	Longitudinal	0.046
F1	Plastic bristle broom	Transverse	0.064
F2	Steel tines	Transverse	0.070
F5	Burlap drag plus steel tines	Longitudinal	0.086
F4	Steel tines	Longitudinal	0.094

[a]Determined by putty impression test.

Table 3. Rain simulation.

Number of Nozzles	Manifold Water Pressure (lb/in.^{2})	Approximate Rainfall (in./hr)
128	30	6
64	30	3
32	20	1½

Figure 5. Equipment used for surface wetting and friction testing.

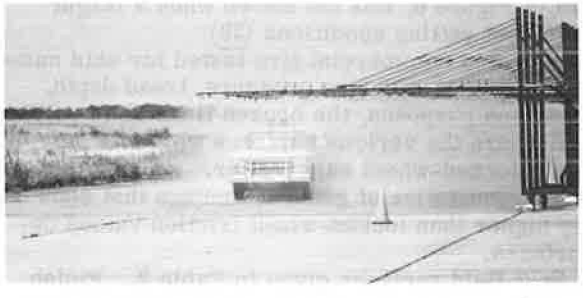


Figure 6. Skid number versus speed on experimental surfaces.

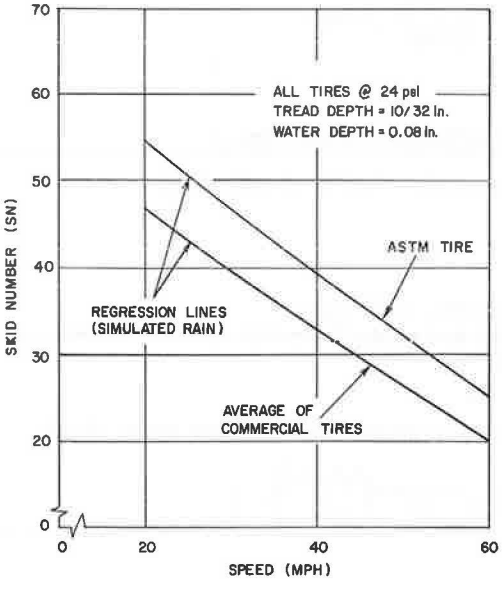


Figure 7. Skid number versus speed for selected tire on experimental surfaces.

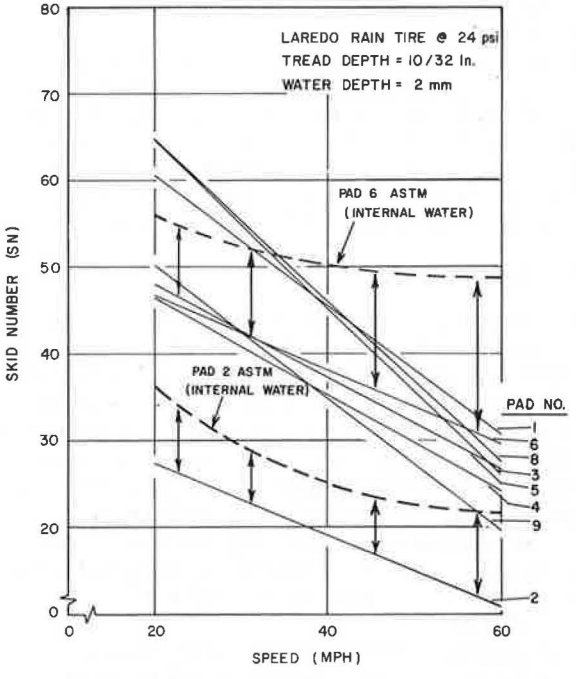
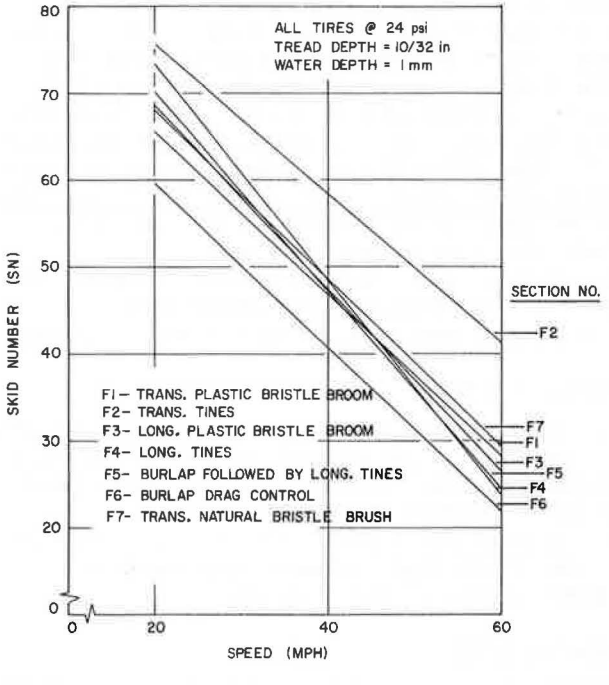


Figure 8. Skid number versus speed on PCC field surfaces.



Nomographs for the solution of these equations have been developed by Hankins and are presented in a current report (7). These relations give reasonable approximations for the available friction of a pavement under given rainfall conditions when the value of SN_{40} has been determined in accordance with ASTM E 274-70.

Concerning the way in which the equation fit the data used in its development (data from 5 Texas A&M Research Annex test pads), Hankins (7) states: "The correlation coefficient was 92 with a standard error of estimate of 1.2 skid numbers indicating that the predicted available friction could vary from the measured available friction by ±2.4 skid numbers with a 95 percent confidence level." The authors think that these relations can be productively used to predict available friction from values of SN_{40} until such time that a better relation, based on more comprehensive data, is derived.

SUMMARY

The initiation of design procedures for pavement friction would not invalidate the current AASHO procedures that are addressed most appropriately to common geometric situations. They will allow a more objective evaluation of any given geometric layout in the geometric design stage and allow the prediction of the amount of friction needed. The need for an unusually high friction would probably indicate the need for a geometric layout change, a change obviously more desirable during design than after construction is completed. The AASHO policy has assumed the availability of certain levels of friction, and its assumptions are conservative with respect to the demands of the basic driving maneuvers considered. The major difference in the new approach is that different maneuvers, including those needed in some emergency situations, would also be considered. For these less common maneuvers, we should also consider allowing some margin of safety in terms of available friction.

The implementation of this concept of designing pavement friction will fulfill the highway engineer's obligation to drivers until such time that research and experience indicate that changes and refinements in the basic equations should be made.

The use of these procedures, however, will not result in the elimination of wet-weather accidents, but will result in a significant reduction. The effect of rainfall on visibility (41) is probably one of the most influential factors in the number of wet-weather accidents. Wilson (42) found that, regardless of the speed posted, the average driver will not drive below 38 to 40 mph in a free-flowing traffic condition with visibility limited to 100 to 200 ft and that the distance allowed between vehicles is not decreased at low traffic volumes. It could be concluded that the average driver is in the habit of driving unsafely during low visibility conditions. Moreover, our present social view is that driving is considered to be a right rather than a privilege, and drivers are licensed who are not prepared for normal driving situations, much less emergency conditions. Therefore, drivers will continue to have more accidents in the exceptional environment, i.e., wet weather, than they have under normal conditions.

Although this situation will continue to detract from the effectiveness and safety of highways, it should not deter efforts to design and construct appropriate surfaces to meet the demand, in both normal and emergency conditions, for tire-pavement friction.

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