INTERACTION OF VEHICLE AND ROAD SURFACE

Don L. Ivey and Charles J. Keese, Texas Transportation Institute, Texas A&M
    University; and
A. H. Neill, Jr., and Cecil Brenner. Tire Systems Section,
    National Bureau of Standards

•THE origins of skid-initiated accidents cannot be studied effectively without consider-
ing the interaction of the automobile, the highway, and the driver and their relationship
to the total environment. The complexity of the system of interaction shown in Figure
1 is impossible to describe. As in almost all problems that involve a large number of
variables, simplification and synthesis are necessary to avoid confusion. The interac-
tion of driver, vehicle, and roadway has not been successfully synthesized; historically
it has been fragmentized. One group of researchers has considered the driver; private in-
dustry has concentrated on the vehicle; and highway engineers have been concerned
primarily with the roadway. Because vehicle characteristics are susceptible to and
have undergone rapid change compared to roadway conditions, there exists today a
mismatch between many vehicles using the roadways and the roadway system. Be-
cause the capabilities of drivers vary so widely, there is also a mismatch between the
capabilities of many drivers and the functions they are required to perform to drive
safely. Figure 2 shows how a deterioration in any one of the three major factors can
produce such a mismatch (27). Elimination of these mismatches should be a primary
goal of any anti-skid program.

DRIVER REQUIREMENTS

Three distinct maneuvers—acceleration, deceleration, and cornering—and two com-
binations of these, acceleration and deceleration while cornering, are required to drive
a vehicle. The development of friction between the vehicle tires and road surface is
necessary to accomplish these maneuvers. Newton's First Law of Motion is, "Every
body perseveres in its state of rest or of uniform motion in a right line, unless it is
compelled to change that state by forces impressed thereon." The forces developed
by friction between the tire and the road surface are the "impressed" forces that pro-
duce acceleration, deceleration, and cornering.

The classic method of defining driver demand for friction has been to observe driver
behavior in the real driving environment. A number of research projects were con-
ducted between the late 1930s and the mid-1950s, but relatively little work has been
done since that time. Consequently, our present design policies have changed little
since 1954. Because vehicle capabilities and the demand for vehicle high performance
have increased, the codes and policies formulated on the basis of the early research
are still surprisingly adequate; exceptions to this may be stated, but they are relatively
few.

Deceleration

A vehicle's deceleration requirement (in g's) is equal "numerically" to the friction
requirement. Figure 3 shows this numerical equality. The understanding that these
concepts are completely different while numerically equal is important to eliminate
communication problems between those who prefer to talk about friction requirements
and those who best relate to acceleration levels.

An excellent summary of the work that has been done on friction requirements was developed by Farber (1). Wilson (2) reported in 1940 that the maximum average deceleration from 70 mph was approximately 0.7 g. This compares favorably to the maximum deceleration achievable by contemporary vehicles on dry pavement as reported by Tignor (3). This high level of maximum achievable deceleration is in sharp contrast to the actual deceleration demanded by most drivers. Studies performed by Crawford (4) and May (5) report an average friction coefficient demand of the 50th percentile driving group of 0.4 to 0.5 g for decelerations at 50 mph. A more recent study was conducted by Kummer and Meyer (6) using selected drivers both in business-section traffic and in highway traffic. They reported very few brake applications exceeding friction level demands of 0.35. This number represents the peak deceleration, however, and the average values would be substan-

Figure 1. Interaction of driver, vehicle, and roadway.

tially lower than the average values observed by May. A comparison of emergency "locked-wheel" deceleration with controlled deceleration is shown in Figure 4. The controlled deceleration pattern observed by Spurr (7, 8) results in low initial deceleration but a significantly higher value near the end of the stopping period. This is the reverse of the pattern of deceleration we would expect in a locked-wheel stop (Fig. 4).

Most of the recent studies of deceleration have been conducted by using selected drivers of test vehicles and are based on the assumption that a representative cross section of drivers is achieved and that the driver is acting as he would normally. Undoubtedly, economic considerations have played a large part in dictating this approach. The most desirable approach, from a statistical viewpoint, in determining driver behavior is to observe "real" drivers under "real" highway conditions. A project of this sort is now being undertaken at the Franklin Institute (1).

Acceleration

Of the three basic maneuvers, acceleration is the one that has drawn the least attention from highway engineers and researchers. Perhaps this is because almost all
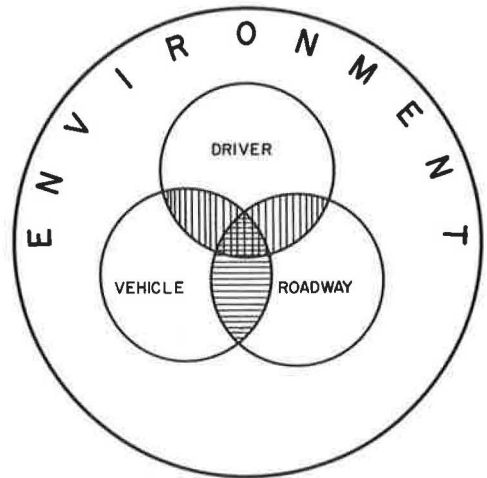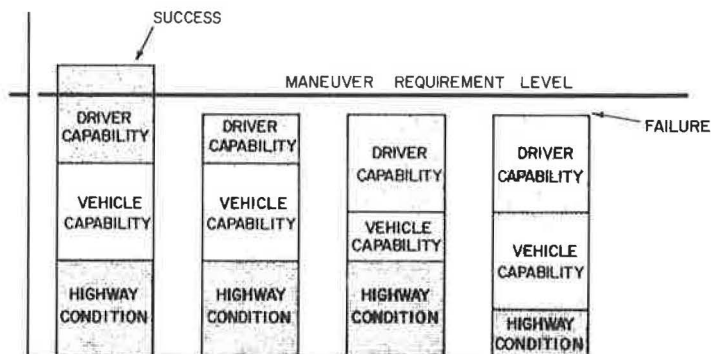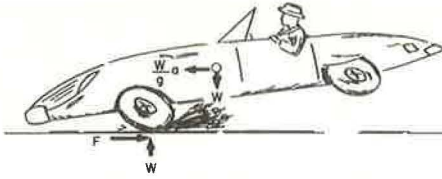

Figure 2. Potential causes of vehicular failure.

$$\mu = \frac{F}{W}$$

$$F = Ma = \frac{W}{g} a$$

$$\frac{F}{W} = \frac{a}{g}$$

μ = COEFFICIENT OF FRICTION

$\frac{a}{g}$ = DECELERATION IN g's

THEREFORE : THE DEVELOPED AVERAGE COEFFICIENT OF
FRICTION IS EQUAL NUMERICALLY TO THE
DECELERATION IN g's. TRUE FOR ACCELERATION,
DECELERATING, AND CORNERING.

Figure 3. Numerical equality of coefficient of friction and deceleration.

emergency maneuvers, with the notable exception of the passing maneuver, do not re-
quire acceleration. Few drivers desire, or try, to achieve the maximum acceleration
level of which their vehicle is capable.

A study of the passing maneuver has been reported by Weaver and Glennon (9). From
the information presented, average accelerations can usually be estimated to be less
than 0.05 g. Therefore, the simple acceleration maneuver does not seem particularly
critical when compared to the higher demand for braking and cornering friction. It
may become critical, however, when combined with the cornering maneuvers necessary
to pass a slower vehicle. Design standards for length of acceleration lanes on free-
ways assume that the vehicle is capable of an average acceleration of 0.2 g, also con-
siderably below the friction potential of most pavements in a wet condition.

Cornering

The classic study of vehicle demand for friction during the cornering maneuver was
conducted by Taragin (10) in 1954. Taragin observed the speed of thousands of vehicles
on rural roads. The horizontal curves included in his study ranged in curvature from
3 to 29 deg (1,910-ft radius to 198-ft radius). He found a high correlation between speed
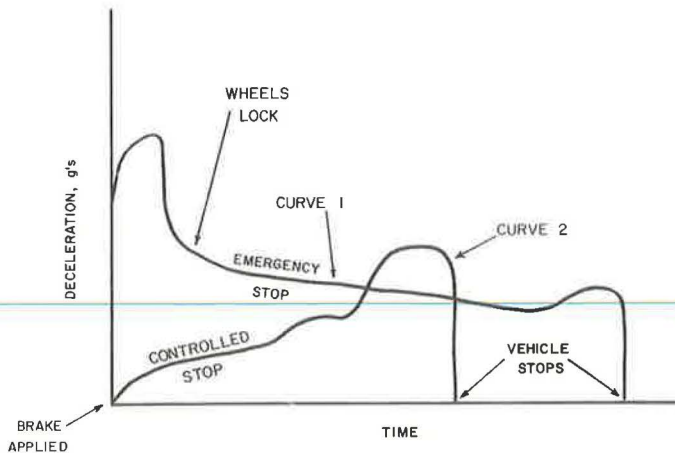

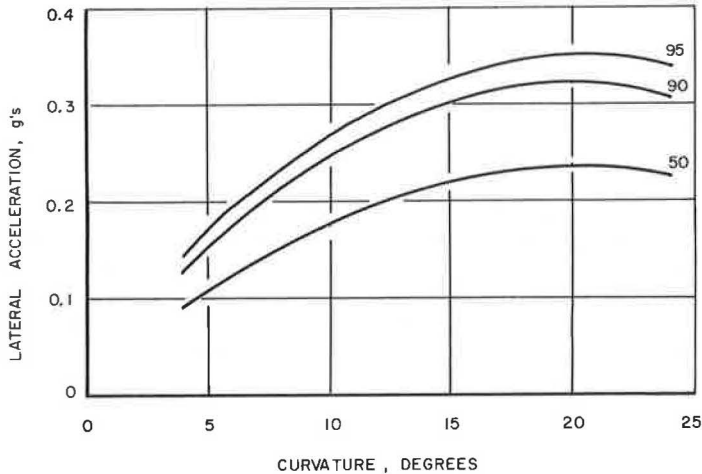Figure 4. Deceleration patterns for controlled and emergency stops.

Figure 5. Taragin's relationship between lateral acceleration and curvature.

and degree of curvature. He developed a relationship between curvature and cornering force expressed in g's by using the classic relationship for lateral acceleration as a function of friction and superelevation, $F + E = V^2/15R$ (Fig. 5). The maximum lateral acceleration, or lateral friction demand, of 0.32 g for the 95th percentile driver occurred at a curvature of 20 deg. For the longer radius curves, 2 to 6 deg, the 95th percentile demand ranged from 0.1 to 0.2 g. The reference to 95th percentile means that 95 percent of the drivers observed made a smaller demand on lateral friction. In a recent study (11), the relationship between lateral acceleration and speed reported by Taragin was substantiated. Further substantiation is offered in other publications (12, 13). All of these studies, except the one by Ritchie (11), used the classic point-mass equation to calculate the friction demand and are, therefore, subject to the invalid assumption that the driver is traversing the same arc defined by the roadway.

Combinations

The demand for friction in combinations such as decelerating and cornering and accelerating and cornering has not been studied in the field, although Taragin observed that vehicle speed was relatively constant during cornering maneuvers. These combinations are scheduled to be studied by Farber at the Franklin Institute (1). The phenomenon of friction capabilities of a tire in the cornering-braking and cornering-tractive modes has been studied extensively in the laboratory (14). Highly sophisticated measuring equipment developed by the National Aeronautics and Space Administration, University of Michigan, Stevens Institute, and others is currently being used to study these combinations of tire operating conditions in the field. The Mobile Tire Tester at the University of Michigan is currently providing data for studies of the National Cooperative Research Program and the National Bureau of Standards. These studies should provide insight to the field observations of driver demand during these combination maneuvers.

ROADWAY GEOMETRIC REQUIREMENTS

Because of the difficulty in determining maximum friction requirements for vehicles, current geometric standards are not based on known factors of safety. They are based by necessity on the way people have been observed to drive. The knowledge of how the highway user's demand for friction relates to the total friction available is not well defined. The fact that a number of drivers each year are exceeding the friction supply is documented by the fatalities resulting from skid-initiated accidents. This fact in

itself is not sufficient to indict our existing codes, but it does require us to continually re-evaluate the codes to ensure that they are consistent with contemporary demand.

Potential Problem Areas

A current study at the Texas Transportation Institute is devoted to defining the phenomenon of vehicle-pavement interaction during the cornering maneuver. Early results seem to indicate that the use of the classic point-mass equation in developing policies for highway curve design can be a fairly good approximation, provided it is coupled with accurate estimates of available lateral friction. The primary limitation of current curve-design policies is that the safety factor is directly dependent on an assumed available level of friction. Available friction varies widely on many pavements with vehicle speed and surface water depth as shown in Figure 6 (22). The other limitation of the point-mass equation is that it does not take into account the decrease in net available friction with shifts in the wheel load. The wheel load shift on vehicles approaching the critical skidding condition during the cornering maneuver can be as much as 50 percent (e.g., all wheel loads are 1,000 lb as a 4,000-lb vehicle moves through a tangent section of highway; however, during the cornering maneuver, the outside vertical wheel forces may go up to 1,500 lb, while the inside vertical wheel forces are decreasing to 500 lb per tire). Figure 7 shows that the resulting available friction decreases as wheel load increases. The result of load shift is a net lowering of available lateral friction.

Nondesign Maneuvers—Recent studies by Weaver and Glennon (15) have shown that the assumption that the driver traverses the arc defined by the highway lane is a tenuous one. Early data from this project, which concentrates on the observation of highway users, show that the radius of curvature driven by the vehicle may vary widely from the radius of curvature of the lane centerline and, consequently, that the instantaneous demand for lateral friction may be significantly greater than the average demand computed by using the lane curvature. Further verification of this is given by Kummer and Meyer (6) who state that vehicles occasionally demand as much as a 0.2 lateral coefficient when driving on straight tangent sections.

The passing maneuver is not treated by present curve-design standards. Figure 8 shows that a passing vehicle on a two-lane road must go through a minimum of four distinct curves. If the vehicle is on a horizontally curved, superelevated section of highway, two of these curves are against the superelevation; i.e., superelevation is reducing the potential for developing cornering forces rather than increasing them. A further decrease in the available cornering friction is produced by the tractive force necessary for acceleration.

Deterioration of Friction—Another potential problem in our geometric standards is the way in which the friction supply level is evaluated. This evaluation has been based
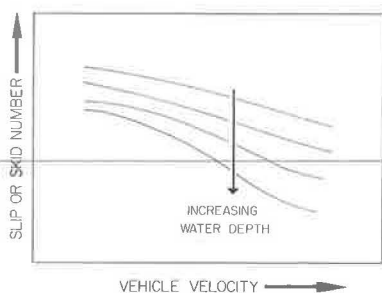

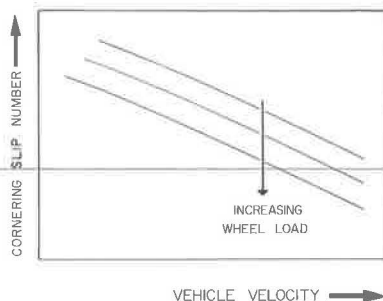Figure 6. Variation of friction with water depth.

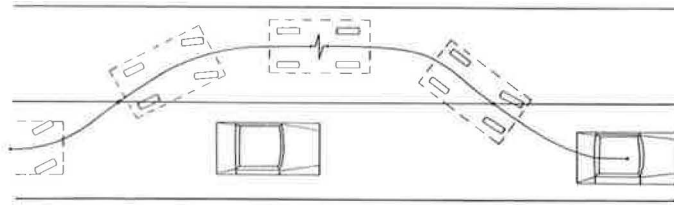Figure 7. Variation of friction with wheel load.

Figure 8. Curves traversed during passing.

in the past almost entirely on ASTM trailer locked-wheel skid numbers. The skid number of a particular pavement is not a constant but varies with a number of factors. The major factors are vehicle speed, surface moisture conditions, and polishing of the pavement under traffic conditions. The locked-wheel skid number at a speed of 40 mph determined by ASTM trailers has been widely used as indicative of available friction. For most pavements it is actually indicative of available friction in the locked-wheel mode at that particular time at a trailer speed of 40 mph. For many pavements, the skid number is highly dependent on the testing speed, and at higher speeds the ASTM trailer skid tester may actually give misleading results because the trailer's internal watering system does not adequately wet the surface before the test tire encounters it. For this reason, much of the skid number data determined at high speeds (more than 40 mph) may be biased. That is, skid numbers determined at 60 mph by using the ASTM trailer internal watering system may be higher than the skid number determined by using an external water system. One example of an external system is a tank truck depositing water on the pavement in advance of the skid tester. Another example is rain.

FACTORS INFLUENCING FRICTION FORCES

Vehicle

Brakes—When vehicle brakes are activated, the wheel rotation is slowed. Because the wheel-tire unit moves at a slower speed then does the vehicle, slip occurs at the tire-pavement interface. In addition, a force resisting the motion of the vehicle develops at the interface. This force, F, which is dependent on the tire, road surface, and lubrication is directly proportional to the braking coefficient, μ, which is defined as $\mu = W/F$, where W is the vertical force and F is the longitudinal force. This proportionality is true if W is held constant.

The braking coefficient varies with slip as shown by a typical curve in Figure 9. At 0 percent slip, the free-rolling case, the longitudinal force is zero, whereas at some small percentage of slip the maximum μ is generated. At 100 percent slip, the coefficient of friction is less than the maximum. A curve of similar shape will describe the lateral friction coefficient.

Figure 9 shows that the 100 percent slip value of μ is less than the maximum and corresponds to the locked-wheel case. If a driver applies the brakes such that the wheels continue to roll at the critical slip rate, he will generate a larger deceleration force than he will by locking the wheel. This will be true as long as the percentage of slip does not exceed that value of slip at the maximum μ. If it does, the wheels will lock and the μ will be reduced to that which exists at 100 percent slip. In some tires this value may
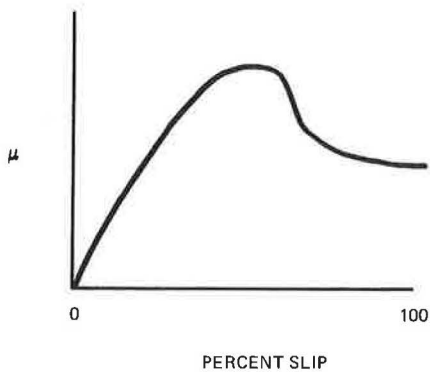

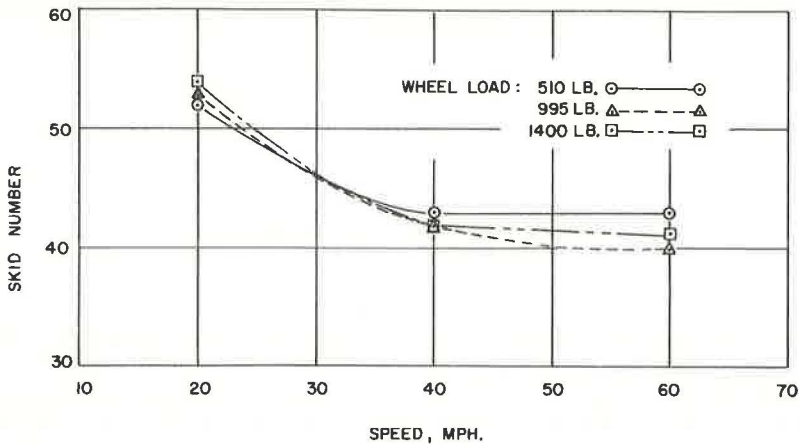Figure 9. Typical curve of tire on wet pavement.

Figure 10. Skid number variation with wheel load and speed on wet concrete during locked-wheel test.

be up to 50 percent less than at the peak. The purpose of antilocking brakes is to prevent the percentage of wheel slip from exceeding the value at which maximum μ occurs. Such systems will ensure that vehicles will stop with maximum efficiency.

Suspension System—The suspension system on a car determines how the load shifts in cornering or stopping maneuvers. Although the lateral braking coefficient for each tire is affected by the load, the effects are not significant in the case of the longitudinal coefficient (16). Figure 10 shows the results of recent NBS work in which a skid trailer carried a wheel load of 500 to 1,400 lb. No significant differences in shape or slope were found.

In a maneuver that shifts 50 percent of its load off the rear axle onto the front axle, the potential braking coefficient as far as the vehicle is concerned may not be greatly changed. The danger is that the load distribution or shift may cause one of the rear wheels to lock at a relatively low brake force, which causes the driver to lose steering capability.

Braking Coefficient—It would be desirable to use the same trailers to evaluate the stopping capabilities of vehicles as well as pavement traction properties. Figure 11 shows the braking coefficient for an SAE tire as determined by both a trailer and a vehicle. The lack of agreement explains why it is unsafe to predict vehicle behavior from results obtained by using a trailer. Lack of correlation exists primarily because the trailer is maintained at a fixed speed, whereas the coefficient for the vehicle is calculated from the stopping distance in a locked-wheel skid with a given initial speed. In this case the vehicle's velocity varies from the velocity at wheel lock-up to velocity at rest. Air drag will influence the rate of deceleration.

Current work at NBS and elsewhere gives promise to the development of procedures that will give good correlation between trailer measurements and vehicle behavior.

Tire—Figure 12 (16) shows the slip curves for a belted-bias, a radial, and a bias-ply tire. The radial and bias-ply tires give very similar curves, whereas the belted-bias tire gives a higher value of friction coefficient at slip values of 10 percent and greater.

Figure 13 (6) shows a comparison of bald and treaded tires on two wet surfaces. On the smooth surface, the effect of tread grooves is more pronounced than on a skid-resistant surface.

Figure 14 (7) shows a comparison of the critical region for skidding on wet and dry surfaces. On a wet surface this region begins at a lower slip value than on a dry surface. On a dry surface, the braking coefficient curve drops very little after the maximum is passed. This means that near maximum efficiency in stopping is retained
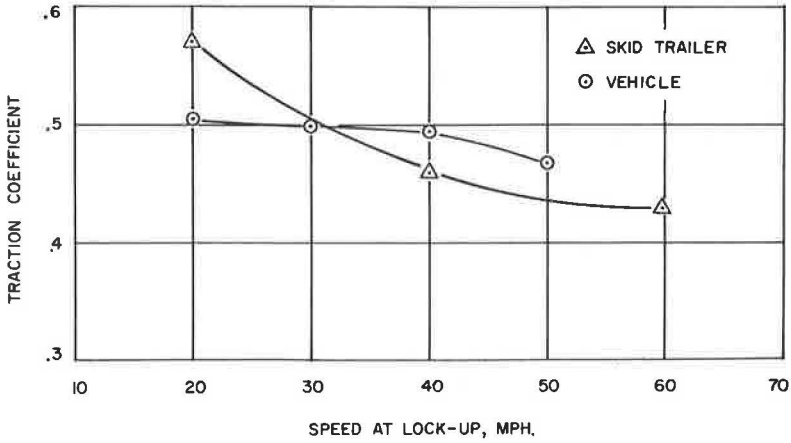
Figure 11. Comparison of traction coefficients by using SAE tires on wet concrete.

even if the wheels lock. With locked wheels, steering control will be lost on dry as well as on wet surfaces.

In the determination of skid number (SN) for a particular surface, care must be taken to ensure that the surface is free of contamination such as loose rocks, ice, or bacterial growth. Tests at NBS have shown a rapid increase in coefficient at the onset of testing on any site that has been free of traffic at least one night. Close inspection showed a fungus type of
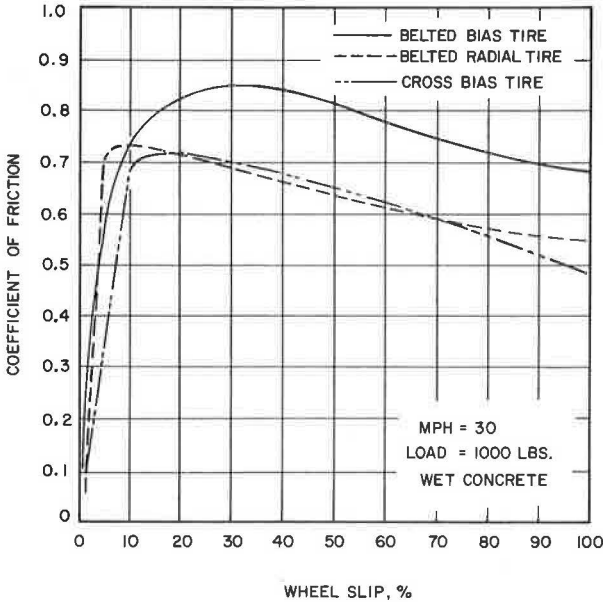

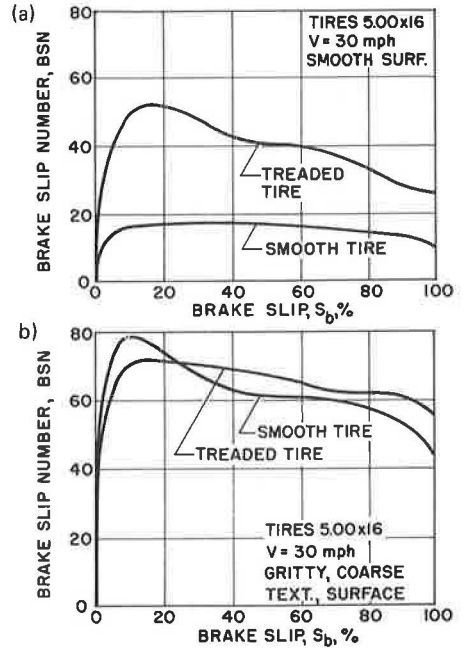Figure 12. Effect of tire construction on slip curve.

Figure 13. Typical brake slip resistance curves of slippery surfaces (top) and skid-resistant surfaces (bottom).

growth and dust on the pads, which was quickly burned or washed off.

Surface—The influence of surface type on available friction cannot be overemphasized. Kummer and Meyer (6) have defined five basic pavement types that exhibit extreme differences in the friction available at different speeds on wet surfaces. As shown in Figure 15, taken from their work, the very coarse, gritty surface (pavement 5) has the highest overall friction potential and the lowest sensitivity to speed—varying from a skid number of about 60 at 20 mph to 40 at 80 mph. Pavement 1, which has a very smooth surface, exhibits a low skid number at all speeds and an extreme sensitivity to sliding speed, approaching zero at a speed of 40 mph.

There are some vary basic conflicts of interest among pavement designers, vehicle

Figure 14. Relationship of friction and circumference slip.

manufacturers, and tire manufacturers. A smooth, wet pavement will have the following effects on drivers, vehicles, and tires: (a) The hazard of a skid-initiated accident will be high; (b) the noise level will be low; (c) the rolling resistance will be low and fuel consumption will be low; and (d) tire wear will be low. A high friction pavement will have exactly the opposite influences: (a) The hazard of skid-initiated accidents will be decreased; (b) the noise level will increase; (c) the rolling resistance will be higher and fuel consumption will increase; and (d) tire wear will increase. Therefore, it would appear that a well-defined compromise may be necessary among safety, driver comfort, environmental effects, and vehicle-tire economy.

Probably the greatest cause of skid-initiated accidents is the spectacular difference between the friction available on pavements in dry and wet conditions. As shown in Figure 16 (6), available tire-pavement friction in the dry condition is very high and is influenced only slightly by vehicle speed. In contrast, the available friction deteriorates rapidly with the application of water and, depending on the type of surface, may be extremely sensitive to vehicle speed. On many surfaces the available friction is greatly reduced at the high speeds encountered on the Interstate System. Many engineers have stated that a film of dust and oil causes a very slick pavement condition when rainfall begins and triggers many skid-related accidents. Kummer and Meyer (6) have reported that they can find no documentation of this initial slipperiness. Gallaway (17)
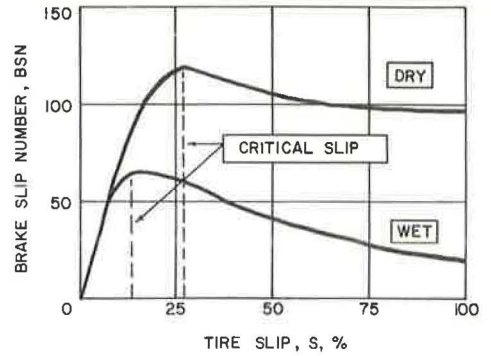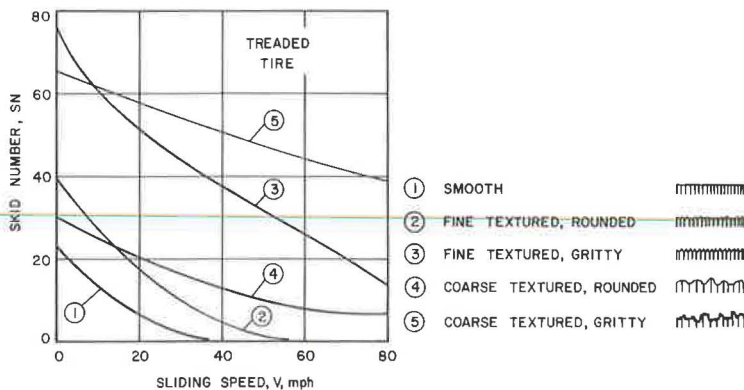

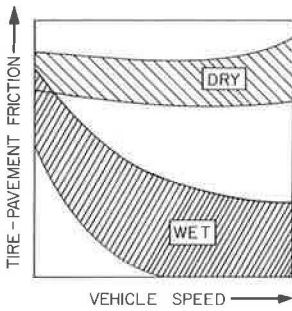Figure 15. Available friction as a function of pavement texture.

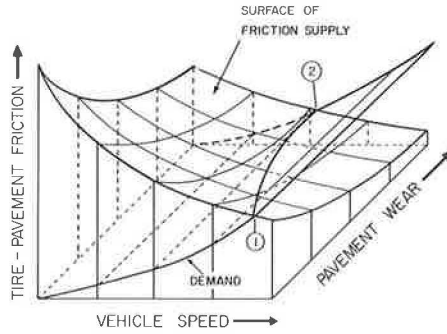Figure 16. Sensitivity of friction to vehicle speed.

Figure 17. Comparison of friction supply and demand.

has stated that another contributing factor may be that drivers are unaware of the tremendous decrease in available friction that a little moisture can produce and therefore drive less conservatively when rain begins than they do after it has been falling for some time.

Figure 17 (6) shows a comparison of friction supply and demand as a function of vehicle speed and pavement wear. The height of the available friction surface decreases with vehicle speed and pavement wear. The construction of skid-resistant pavements involves techniques that are widely available. The construction of surfaces that maintain a high friction level during pavement life is a relatively new area. Considerable developmental work has been done by Gallaway (17), and a number of experimental highway test sections have been constructed. The results are very promising.

An understanding of the basic mechanisms at work in producing friction forces between tires and pavements is essential to the discussion of building and maintaining high-friction surfaces. Almost all pavement surfaces are adequate when dry and clean. Therefore, consideration of the friction capabilities of dry, clean pavements is somewhat academic, and this discussion will be limited to wet pavements.
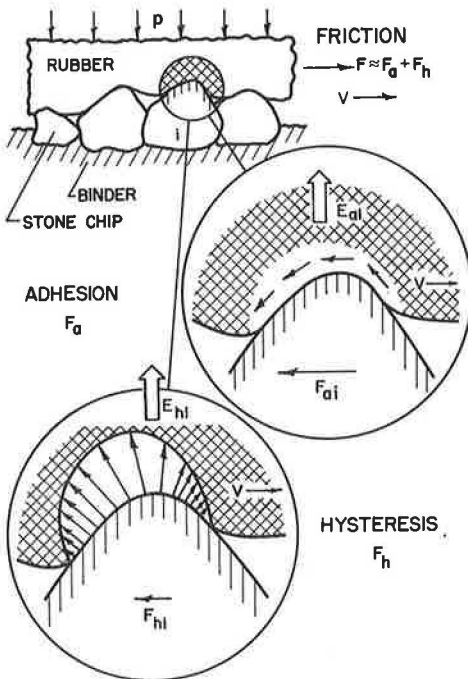
Figure 18 (6) shows the two principal factors, adhesion and hysteresis, that produce forces between a tire and a pavement. Adhesion is analogous to the force developed when a hand slides over the smooth surface of a desk. Adhesion is a microtexture interaction. If a paperweight is on the desk and the hand runs into it, the forces developed as the hand slides into, over, and out of contact with the paperweight are analogous to the forces causing causing energy absorption by the tire through hysteresis. Hysteresis is a macrotexture phenomenon that occurs when the tire is deformed by projections in the pavement, such as semi-exposed aggregate particles, and in the process absorbs energy.

Figure 18. Components of friction.

When a pavement is covered with a layer of water, two events must occur in order for hysteresis and adhesion to exist:

1. The macrolayer of water must be expelled from the tire-pavement interface in order for the tire to be deformed by pavement macrotexture. The avenues for this water to escape are formed by the valleys of the pavement macrotexture and by the openings in the tire tread. As the speed of a vehicle increases, the time available to expel this macrolayer of water decreases. When there is no longer enough time to move this layer of water from underneath the tire, dynamic hydroplaning occurs and the tire is planing on a surface of water. This phenomenon is roughly analogous to water skiing.

2. The film, or microlayer of water, that remains on the pavement particles after the macrolayer has been expelled must be squeezed aside or penetrated by sharp aggregate projections so that adhesion between rubber and pavement materials can occur. As the speed of the vehicle increases, the time available to squeeze this film of water away from the aggregate particles decreases, and the available friction decreases due to loss of adhesion.

An excellent research program on tire-pavement interaction with very small layers of water (0.05 to 2.0 millimeters, or less than $\frac{1}{14}$ in.) has recently been reported by Gengenbach (14). Additional information on thin surface-water films was recently reported by Ludema (26). Work concerned with greater water thicknesses has been done by NASA and the Road Research Laboratory, but a significant program in this area is now being conducted at the Texas Transportation Institute (18). The difficulty that will be faced by the highway engineer in applying the information developed in these programs is that there is no such thing as constant water depths on highways. Every pavement section is a panorama of water conditions. The prediction of water layer buildup as a function of pavement slope, surface characteristics, and rainfall intensity is under investigation by Gallaway (19). The development of open-textured, self-draining pavements (20) may be an important breakthrough in the prevention of hydroplaning.

Gallaway has recently proposed several methods for prolonging or renewing skid resistance of the surface. He first published an article in 1967 defining aggregate produced for the refractoring industry and theorized that such materials would serve as nonpolishing aggregates for road surfacing purposes. Since the mid-1950s, researchers in the United States have experimented with manufactured aggregates and pavement materials. These manufactured aggregates have been produced by heating raw materials such as clays, shales, and slates in a rotary kiln to about 2,000 F. These aggregates have been referred to as lightweight or synthetic aggregates and are widely used in reinforced concrete construction. It was soon discovered that these aggregates have exceptional nonskid properties that are essentially independent of the volume of traffic on these surfaces. Figure 19 shows this type of nonpolishing aggregate and is taken from the work by Gallaway, who explains the formation of these high skid-resistant aggregates as follows (17):

> If one starts with the right raw material (clay, shale, or slate), and heats it to the pyroplastic state, gas in the form of very small bubbles will form within the heated particle. Bloating will occur. If the bloated particle is then cooled, the result is a stone or aggregate suitable for many uses such as lightweight masonry blocks, lightweight structural concrete and a vesicular aggregate highly suitable for producing non-skid pavements.

Other methods of producing prolonged skid resistance are: (a) the use of two aggregates that wear at distinctly different rates, (b) the use of natural material, such as sandstone, that renews surfaces by granulation, and (c) the dispersion of hard particles in a soft matrix. Some limestones contain discrete impurities in the form of hard particles dispersed throughout the softer limestone matrix. Some of the particles were described by James and are show in Figure 20 (21). The technology needed to greatly improve both initial and long-term skid resistance of pavements is rapidly becoming available.
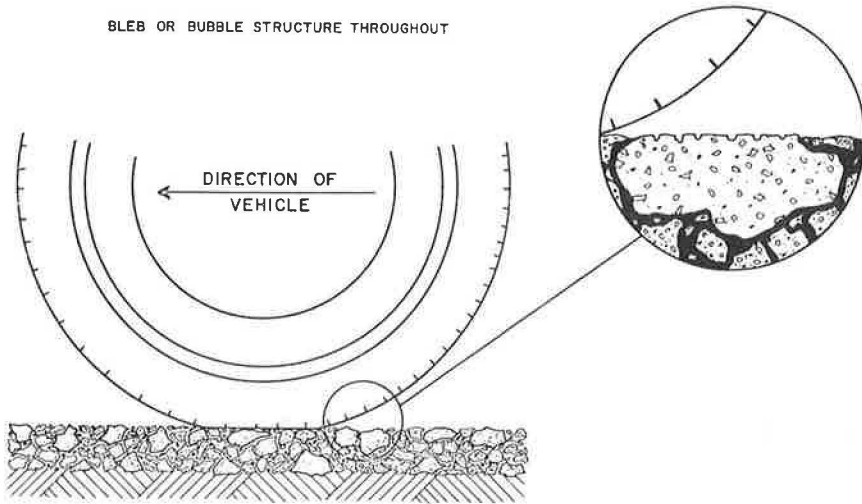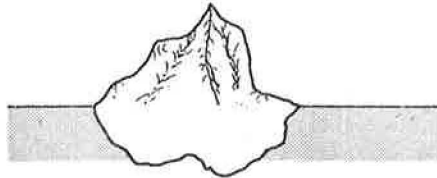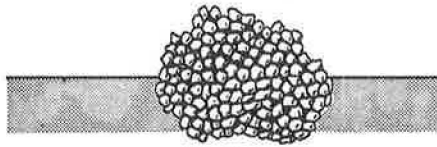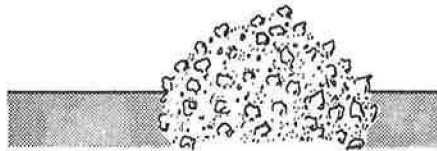
DIRECTION OF
VEHICLE
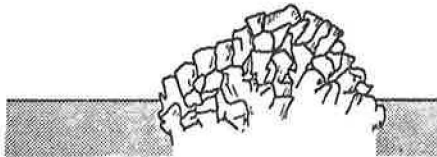
Figure 19. Lightweight synthetic aggregate.

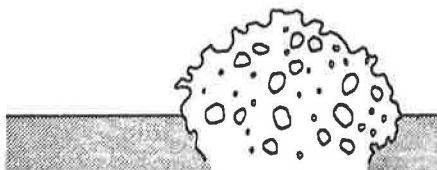VERY HARD CRUSHED
MATERIALS

CONGLOMERATIONS OF SMALL
HARD PARTICLES, i.e. IRON
ORE AND CEMENTED SAND
PARTICLES

DISPERSIONS OF HARD PARTICLES
IN A SOFTER MATRIX,
i.e. LIMESTONE WITH
SILICA INCLUSIONS

MATERIALS WHICH FRACTURE
IN AN IRREGULAR ANGULAR
MANNER, i.e. SANDSTONE, etc.

VESICULAR MATERIALS, i.e.
SLAG, LIGHTWEIGHT
AGGREGATE, etc.

Figure 20. Theoretical types of polish-resistant roadstone.

SUMMARY

An accurate synthesis, or simulation, of the vehicle-pavement system that will reflect the interaction of the variables during vehicle maneuvers is critically needed. Important efforts in this area are being made by McHenry (22) at the Cornell Aeronautical Laboratory, by Dugoff (23) at the University of Michigan, and by Tiffany (24) at the Bendix Research Laboratory. Modifications to the McHenry program (CALSVA) are being made by Hirsch and Ross at the Texas Transportation Institute, in an effort to evaluate vehicle performance on highway curves. It should be emphasized, however, that these sophisticated computer simulations are based completely on empirically derived information. For example, variables such as vehicle spring constants, damping constants, moments of inertia, and tire-pavement force development under specified conditions must all be determined by tests before a vehicle can be simulated. Dugoff recently supported this by stating, "The principal difficulty in vehicle simulation is not in writing the equations of motion, but is in representing the subsystems of tires, brakes, and suspension." Significant progress is being made, and early results are very encouraging. It appears that a definite breakthrough in understanding the vehicle-pavement interaction will be forthcoming. Although a breakthrough of this sort will be most helpful to our overall analysis of the vehicle-pavement interaction, it should not be implied that such a breakthrough is necessary before meaningful action can be taken to alleviate problem areas. Considering the present state of knowledge, there is a great amount of technology that is ready to be applied.

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