

1. HIGHWAY AND RUNWAY TRACTION STUDIES – THE PROBLEM, HISTORY, OBJECTIVES, AND NASA PROGRAM

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SUMMARY

The problem toward which most traction research is directed is to describe quantitatively by theory and experiment the major causes of pavement slipperiness in terms of pavement, vehicle, tire, operator, and atmospheric or precipitation parameters. Scientific research on the phenomenon of pavement slipperiness has been underway since the early 1920's. Some of the milestones achieved in highway and runway traction research in the United States are summarized in the following listing.

Highway research:

- (1) Research at Iowa State College (1920-1934)
- (2) First International Skid Prevention Conference (1958)
- (3) Establishment of Committee E-17 by American Society for Testing and Materials (1959)
- (4) Tappahannock skid correlation study (1962)
- (5) Florida skid correlation study (1967)

Runway research:

- (1) Operation of Langley landing-loads track (1954)
- (2) Initial hydroplaning studies (1956)
- (3) FAA-NASA slush drag studies (1961)
- (4) Completion of landing research runway at NASA Wallops Station (1967)

INTRODUCTION

Everyone knows that pavements tend to become slippery to both pedestrians and vehicles when they are wet or flooded or are covered with slush, snow, or ice; however, no one yet has a complete understanding of the physical effects causing this slipperiness,

which in turn can cause accidents. For this reason, papers on pavement traction have been produced in the United States since the late 19th century.

The problem toward which most traction research is directed is to describe quantitatively by theory and experiment the major causes of pavement slipperiness in terms of pavement, vehicle, tire, operator, and atmospheric or precipitation parameters. In simple terms, the objectives of this research are to define these parameters in practical terms and then find means to control the primary parameters which cause or contribute to slipperiness.

HIGHWAY RESEARCH

Although published reports dealing with the phenomenon of pavement slipperiness may be found at least as early as the late 19th century (ref. 1), scientific or quantitative research of the phenomenon had its origin with Agg (ref. 2) in the early 1920's. Agg's investigations were continued by Moyer (ref. 3). Other agencies and individuals slowly became interested in this research area, but developments in the field were very limited until the late 1940's.

In the late 1940's and early 1950's, a considerable surge of interest in pavement slipperiness occurred, sparked primarily by studies performed by Moyer in California (ref. 4), Shelburne and Sheppe in Virginia (ref. 5), Whitehurst and Goodwin in Tennessee (ref. 6), and Normann of the Bureau of Public Roads (ref. 7).

Perhaps the greatest impetus to progress in the field was achieved when the late Tilton E. Shelburne, Director of Research of the Virginia Council of Highway Investigation and Research, called the First International Skid Prevention Conference in Charlottesville, Virginia, for September 1958. Two weeks prior to that conference, a correlation study was conducted in Virginia in an effort to determine whether test equipment then available and in use at a variety of agencies did, indeed, correlate. The test equipment included such devices as skid trailers, stopping-distance cars, and small nonvehicular portable test apparatus from both the United States and abroad.

Results of this correlation study presented at the international conference (ref. 8) indicated that all the available equipment agreed in the relative slipperiness ratings of the pavement surfaces. However, rather wide differences in the measured absolute value of friction coefficient existed between the different test devices, and the correlation of friction values was therefore poor.

The Board of Directors of the American Society for Testing and Materials (ASTM) approved the establishment of a new technical committee on skid resistance (Committee E-17) in October 1959. The first meeting of this committee was held in June 1960,

and it rapidly acquired a broad membership of interested automobile, tire, pavement, state, and federal government organizations.

The first major endeavor of Committee E-17 was to formulate a specification for a standard tire for conducting pavement slipperiness tests. By 1962 such a specification had been prepared and the test tire was available from one rubber company. In 1962 the first major skid-resistance correlation study in the United States was held at Tappahannock, Virginia, under sponsorship of the Virginia Council of Highway Investigation and Research with full cooperation from Committee E-17.

The Tappahannock correlation study of 1962 was conducted on an airstrip and involved tests of five specially constructed surfaces ranging from very slippery to very skid resistant. Eight different organizations provided skid trailers of various designs for use throughout the study. Eight stopping-distance vehicles, ranging from a compact automobile to a bus, were available for some or all of the study. Eleven British portable testers were used in the study, as were four other types of portable testers. The standard tire developed by ASTM Committee E-17 was used throughout the study but only on vehicles which could use this specific tire size. The tire company providing these standard tires supplied additional tires of the same composition and the nearest possible tread design for all vehicles requiring tires of other sizes.

The results of this correlation study (ref. 9) were far more promising than those of earlier studies. A number of skid trailers representing three distinctly different designs were found to correlate very well. Although there were some tests involving devices for which correlation was not as good as desired, there was ample evidence that well designed and calibrated test equipment of a variety of basic designs could be made to correlate very closely.

As a result of several years of successful use of the proposed standard tire, Committee E-17 recommended to the American Society for Testing and Materials the adoption of a tentative standard for the tire in 1964. After two further years of successful use, the Society adopted the Standard Specification for Standard Tire for Pavement Tests under ASTM Designation: E 249-66 (ref. 10).

During this same period of time, Committee E-17 was preparing standardized methods of tests for the measurement of pavement slipperiness. In 1965 the Committee recommended and ASTM adopted the Tentative Method of Test for Skid Resistance of Pavements Using a Two-Wheel Trailer under ASTM Designation: E 274-65 T (ref. 11). This method of test specifies certain features of a skid test trailer, which were believed to be important, and specifies the manner in which such a trailer should be used in conducting tests on a pavement.

In 1966 Committee E-17 recommended and the Society adopted the Tentative Method of Test for Measuring Surface Frictional Properties Using the British Portable Tester under ASTM Designation: E 303-66 T (ref. 12).

A significant increase in activities of State highway departments with respect to studies of pavement slipperiness occurred in 1966 and continues to the present time. This increased interest was at least in part occasioned by the passage of the 1966 Federal Highway Safety Act, which requires the Secretary of the Department of Transportation (DOT) to report at specified intervals on a variety of factors bearing upon highway safety. It authorizes him to conduct or to have conducted certain studies to provide the information necessary for these reports. The language of the Act makes specific reference to, among other things, highway surface treatments.

The report of the Secretary of the DOT submitted to the Congress in July 1967 includes a statement of the Highway Safety Program Standards proposed for adoption by the National Highway Safety Advisory Committee. One of these standards deals with highway design, construction, and maintenance. Sections ID and IE of this standard describe in part the minimum requirements for the program in each state. These sections read as follows:

"D. There are standards for pavement design and construction with specific provisions for high skid resistance qualities.

E. There is a program for resurfacing or other surface treatment with emphasis on correction of locations or sections of streets and highways with low skid resistance and high or potentially high accident rates susceptible to reduction by providing improved surfaces."

It is widely believed that one result of these provisions will be a requirement in the near future that each State highway department conduct a continuing survey of the skid resistance of the surfaces of all its highways included in the Federal Aid System. No information is currently available as to what will constitute an adequate "continuing survey." Important decisions must be made concerning the permissible distance between tests along the highway, in order that the tests constitute a "survey," and the permissible time interval between repeated tests on the same sections, in order that the work constitute a "continuing" survey. Regardless of the final decisions, it is apparent that a great deal of effort will be required and that those states having a high mileage of Federal Aid System highways will probably be required to have one or more skid trailers in operation almost continually. In apparent anticipation of these requirements a number of states have recently undertaken the construction or other acquisition of one or more skid trailers.

The most recent major correlation study of equipment measuring pavement slipperiness was conducted at Ocala, Florida, in the fall of 1967. This study was sponsored by

the Florida State Road Department, again with the cooperation of ASTM Committee E-17. Experiments were conducted at an airport on the runways of which 10 experimental surfaces had been constructed. These surfaces varied from relatively slippery to highly skid resistant and included a wide range of surface textures.

The correlation study was performed in three parts. The first involved skid trailers, the second involved stopping-distance automobiles, and the third involved a tractor-semitrailer combination. In the first portion of the study, 11 skid trailers and one vehicle which might be anticipated to perform in the same manner as a skid trailer were used. Nearly half of the skid trailers were very new and had had minimal opportunities for shakedown and for crew training. As might be expected, many difficulties were experienced by the crews operating these trailers; some of the trailers were unable to complete all the experiment, and correlation between the newer trailers was not good. In general, however, reasonably adequate correlation was found to exist between those trailers which had been in use for some period of time, which had been carefully calibrated prior to the study, and whose crews were well trained (ref. 13).

In the second portion of the study, four stopping-distance automobiles were involved. As with the trailers, all test vehicles were mounted on ASTM standard tires. The correlation for the four stopping-distance automobiles was very good (ref. 14).

In recognition of the growing awareness of the necessity for providing highly skid-resistant pavements, the Highway Research Board through the National Cooperative Highway Research Program awarded a contract (Project No. 1-7) to Pennsylvania State University for a study "Development of Interim Skid Resistance Requirements for Highway Pavement Surface." The major objective of the study was to provide, on the basis of the best information then available, recommendations for standards for minimum pavement skid resistance which would serve until sufficient information could be developed to justify the adoption of appropriate national standards. The final report of the project (ref. 15) summarized most of the available data and presented the required recommendations. To date, however, there is little evidence that the recommendations have been or are soon likely to be widely adopted.

During the time interval when interest and activities in pavement skid testing have been increasing rapidly, particularly since about 1950, the results of the experiments of those active in the field have been instrumental in introducing a number of changes in the pavement specifications of several states. The net result of such changes has been to produce pavement surfaces having and retaining, under traffic, higher coefficients of friction. Those persons active in the field are well aware, however, that much remains to be learned about methods of testing, performance of materials, influence of pavement texture, and perhaps other variables before optimum results can be generally obtained in the form of pavement surfaces providing maximum skid resistance to the traveling public.

It was for these reasons that a large number of organizations involved primarily in the testing of highway pavements for skid resistance participated in the tests on the landing research runway at NASA Wallops Station. The wide variety of pavement surfaces available for test and comparison and the many types of test equipment belonging to the participants in the experiment provided an excellent opportunity for those active in the field to extend their knowledge of both techniques and equipment for testing and of possible surfaces or surface treatments which might be beneficially used in highway systems.

RUNWAY RESEARCH

Interest in the skidding of aircraft on wet runways polarized in the United States in the early 1950's when the advent of the jet-engine-type aircraft quickly established that these higher performance craft, with accompanying higher take-off and landing speeds, were much more difficult to control on wet runways than the piston-type aircraft they replaced. The Langley landing-loads track, shown in figures 1 and 2, was placed in operation in 1954. This research facility has the capability of testing full-size aircraft landing gear and tires at rated load and at landing impact conditions of up to 19-ft/sec vertical sinking velocity and ground speeds up to 130 knots. A short description of the landing-loads track is given in reference 16. By means of full-scale instrumented aircraft tests and the landing-loads track, NACA (as NASA was formerly known) was able to study the wet-runway problem.

In 1956 a significant research milestone was reached. In testing a small pneumatic tire on a treadmill type of apparatus, Harrin (ref. 17) demonstrated that it was possible for this tire in an unbraked condition to spin down to a complete stop on a wetted surface at a critical belt or ground speed. This research reported in reference 17 was the first to document quantitatively a manifestation of tire hydroplaning. Loss of traction and wheel spin-down resulting from hydroplaning of a full-size aircraft tire were observed during landing-loads-track studies and full-scale flight tests conducted during the late 1950's and early 1960's. These results are reported in references 18, 19, and 20. It was during these studies that the now well-known hydroplaning and slush drag equations were developed. Full-scale instrumented aircraft testing conducted jointly by the Federal Aviation Administration (FAA) and NASA on a four-engine jet transport also disclosed hydroplaning in terms of aircraft slush drag reduction and unbraked wheel spin-down (see ref. 21). In 1963 the information on the hydroplaning phenomenon, as it was then known, was summarized by NASA in reference 22.

In 1965 NASA conducted a study on aircraft skidding accidents and discovered that the majority of the tires on aircraft experiencing these accidents had reverted-rubber patches, as shown in figure 3. These patches, when fresh (immediately after an accident),

were sticky and tacky to the touch, and the surface rubber in the patch appeared to have reverted to its uncured state. Since the reverted-rubber patch was elliptical, it was obvious that the tire must have undergone a locked-wheel skid of some duration. Also white tire tracks were present on the runway after such accidents. The surface of the pavement in these tracks appeared to have been steam cleaned. Reverted-rubber studies were conducted by NASA in 1965 and the results obtained confirmed the fact, borne out by accidents, that extremely low values of friction could develop when the tires were experiencing this condition (ref. 23).

By 1965 then, the major causes of low aircraft tire friction were defined – that is, dynamic hydroplaning, viscous skidding, and reverted-rubber skidding. The problem still remained to find methods to alleviate the causes of low friction. In this regard, NASA or NACA had conducted tests on air jets as early as 1958 (see ref. 24). In this study an air nozzle was placed in front of the tire to allow a high-pressure air blast to displace the runway water in front of the moving tire and enhance tire friction. Further air-jet studies were made by NASA in 1964 and reported in references 25 and 26. Full-scale studies were made by the Douglas Aircraft Company on a DC-7 equipped with an air-jet system, and the results were promising (ref. 27). The advantage of this type of system is that it can be carried by the aircraft and be activated on whatever runway is used.

Another promising means of improving tire traction is pavement grooving. This is a British innovation and was first tried in 1956 on several airfields in England. At the present time, pavement grooving (see fig. 4) for highways is predominantly longitudinal – that is, parallel to the direction of vehicle motion. On the other hand, transverse grooving – that is, grooves cut crossways to the direction of vehicle motion – is predominantly used on airfields. The pitch is the distance between grooves; in the papers of the present compilation the convention is to mention pitch first, then the width and depth of the groove. At the present time, grooves are cut in pavements by means of a diamond-studded-saw technique or by a flailing technique using hardened steel cutters. Research is presently underway by several organizations to determine whether grooves can be cast in the pavement at the time it is first laid.

Pavement grooves were studied by NASA at the landing-loads track first in 1962 and again in 1964. Results from these studies were very encouraging and are reported in reference 23. In 1966 the Langley Research Center held an industry conference to discuss pavement grooving as a means of improving aircraft performance on wet runways. At that time, Langley presented a program for evaluating the pavement grooving technique. The program consisted of running landing-loads-track tests to determine the most effective groove pattern for traction purposes. At the same time, the program called for NASA to assist the FAA in installing the 18 test groove patterns under study at the track

at several airfields scattered throughout the United States where climatic conditions were significantly different. It was hoped that some useful information on the effects of grooving on pavement deterioration or life due to high temperatures or freeze-thaw cycles at low temperatures could be established. The program also called for the construction of a landing research runway at NASA Wallops Station where full-scale instrumented aircraft tests could be made on grooved and ungrooved runway surfaces under controlled test conditions. The landing research runway was completed in December 1967.

Results of the combined NASA and FAA program on pavement grooving are, of course, one of the subjects of the present compilation and will be discussed in subsequent papers.

SLIPPERINESS PROBLEM

Prediction of Runway Slipperiness

Paramount to safety of flight is the adequate reporting of runway slipperiness at time of take-off or landing. The pilot needs information with regard to both reduced braking action and ground directional control to decide whether to land, seek an alternate airfield, or delay his landing (or take-off) until safer conditions prevail on the runway.

In this regard, several techniques have been used in the United States and abroad. The Runway Condition Reading (RCR) system was introduced by the Air Force in the United States, and the Swedish Skiddometer was introduced in Europe. These techniques appear to give reasonable results on snow- and ice-covered runways but appear to be deficient on wet or flooded runways. This deficiency is illustrated by results of the correlation study performed by the FAA and NASA in 1961 and reported in reference 21, where both the RCR and Swedish Skiddometer techniques were compared with the performance of a four-engine jet transport.

As a result of conversations between the NASA and the British Ministry of Technology in 1965 and 1966, it was decided to hold a joint NASA-British Ministry of Technology skid correlation study at Wallops Station when the landing research runway was completed and when several instrumented aircraft braking tests under wet runway conditions had occurred. This correlation study was conducted on the landing research runway at NASA Wallops Station in June 1968, and the results are reported in references 28 and 29.

Definitions

For those readers who have not been working in the traction field, several definitions are given as an aid in understanding the subsequent papers.

Definition of friction coefficient.- As shown in figure 5, friction coefficient μ is defined as the ratio of the drag load acting on the tire to the vertical load acting on the tire at the same time. Slip ratio is defined as the ratio of the unbraked wheel speed minus the braked wheel speed ($\omega_0 - \omega_B$) to the unbraked wheel speed (ω_0). A slip ratio of 0 means the tire is unbraked and is in a freely rolling condition. A slip ratio of 1 means that the wheel has been braked to the point that it is locked and the tire is in a full skid condition on the pavement. The maximum friction coefficient developed by the braked tire μ_{max} usually occurs at a slip ratio between 0.05 and 0.30. The sliding friction coefficient μ_{skid} occurs when the wheel is fully locked at a slip ratio 1.0, and μ_{eff} is the effective friction coefficient developed by an aircraft during braking as modulated by its antiskid braking system or the pilot's manual braking technique.

Diagonal braking.- The NASA and several other organizations are currently using a diagonal braking technique to measure tire traction on pavements with ground vehicles at high ground speeds. The technique, as shown in figure 6, is simply to install valves in the brake lines of the vehicle. A diagonal pair of valves is closed at time of testing so that when wheel brakes are applied, one diagonal pair of wheels is locked by the brakes, and the other diagonal pair receives no braking and thus is free to turn. This technique allows one freely rolling front wheel for steering and one freely rolling rear wheel for directional stability. Since this technique always brakes one-half of the vehicle mass, weight transfer during braking (a problem for the front-wheel braking technique) does not pose a problem for the diagonal braking technique.

Factors Important to the Slipperiness Problem

Current traction research indicates that various pavement, tire, and vehicle factors are important to the slipperiness problem.

Pavement.- A proper surface texture can provide external drainage for bulk water trapped between the tire footprint and pavement, as well as the asperities for penetrating and displacing viscous fluid films on the pavement. Pavement porosity provides means for internally draining bulk water trapped in the footprint-pavement interface. The contaminants on the runway are very important factors.

When rain contaminates the runway, the thickness of the water film significantly affects the relative slipperiness of pavements. Under ice, snow, or slush conditions, effects of pavement texture are minimized and pavements can become very slippery at all speed ranges.

Tire.- Tire tread design can alleviate some but not all pavement slipperiness conditions. The tire inflation pressure plays an important role in dynamic hydroplaning or in determining dynamic hydroplaning speed. Tire pressure plays lesser roles in the cases of viscous or reverted-rubber skidding. Tread-rubber compounds affect the basic

level of friction coefficient developed between tire and ground under different conditions. Tire construction, whether of the bias-ply, radial-ply, or belted-bias-ply type, can affect tire stiffness differently and thus change the shape of the tire contact patch. Tire construction at this time appears to play a small role with regard to pavement slipperiness. However, the fact that radial-ply or belted-bias-ply tires wear longer than bias-ply tires affects highway and runway safety in that the tire tread design for these tire types remains in effect considerably longer than that for the bias-ply-type tires.

Vehicle.- Definite path clearing effects which alleviate pavement slipperiness have been noted for tandem or dual-tandem landing gear wheel arrangements. Similar effects have been noted for ground vehicles. The directional control of both air and ground vehicles is affected by the operational mode of the vehicle wheels.

Tires can produce cornering or side forces for vehicle lateral stability or steering only when the wheels are rotating. Locked-wheel skids reduce the tire cornering or side-force capability to zero. When manual braking, the vehicle operator must understand this fact or severe losses of vehicle directional control will occur during combined vehicle cornering and braking. The use of automatic wheel antiskid control systems during braking alleviates this problem, but vehicle-operator education is also necessary in this regard.

CURRENT NASA PROGRAM FOR TRACTION RESEARCH

The current NASA program for traction research involves various areas of study. Research on tire mechanical properties, especially at high speeds, is underway. Knowledge of these properties is essential for improving antiskid systems. Also being studied are tire tread design, pavement texture, pavement grooving, air jets, and automatic braking systems. University research in the areas of reverted rubber, tire mechanical properties, and hydroplaning are currently being supported by NASA grants. Studies of the effects of spray ingestion and combined vehicle braking and cornering are also included in the NASA program. Finally, methods for predicting pavement slipperiness either from pavement measurements or vehicle braking measurements are under study.

CONCLUDING REMARKS

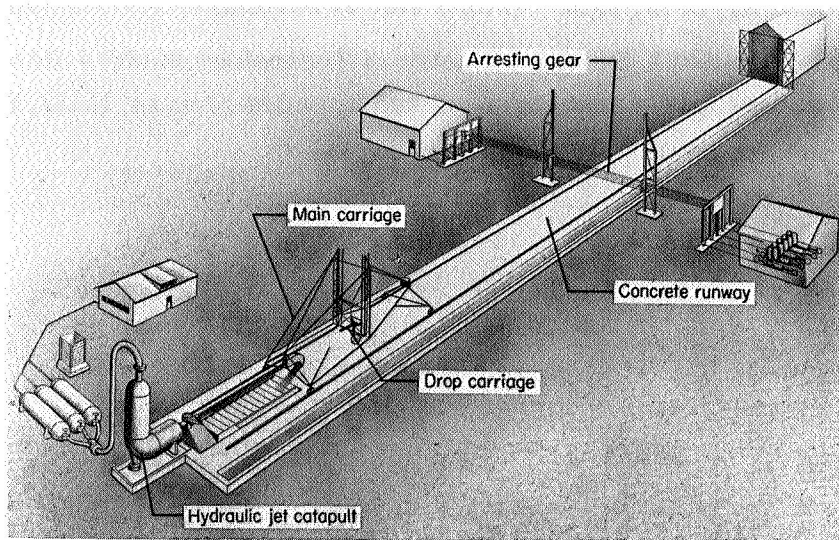
The problem toward which most traction research is directed is to describe quantitatively by theory and experiment the major causes of pavement slipperiness in terms of pavement, vehicle, tire, operator, and atmospheric or precipitation parameters. Scientific research on the phenomenon of pavement slipperiness has been underway since the early 1920's, and many milestones in highway and runway research have been achieved in the United States, especially since the late 1940's.

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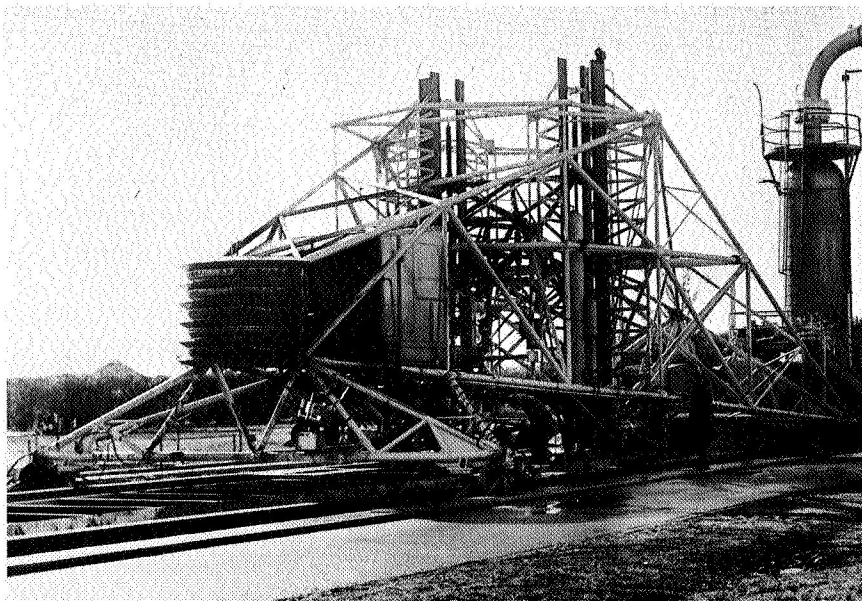
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Figure 1.- Schematic diagram of Langley landing-loads track.



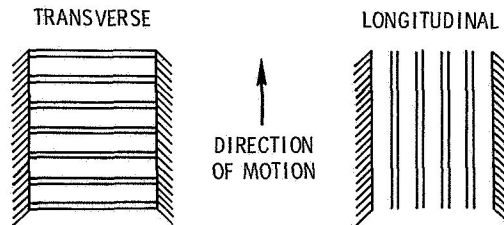
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Figure 2.- Main test carriage at landing-loads track, with catapult in background.

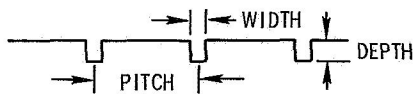


Figure 3.- Reverted-rubber skid patch obtained with four-engine jet transport on wet runway.

TYPES



GEOMETRY



METHODS

- DIAMOND SAW
- FLAIL
- PRECAST

Figure 4.- Description of pavement grooving.

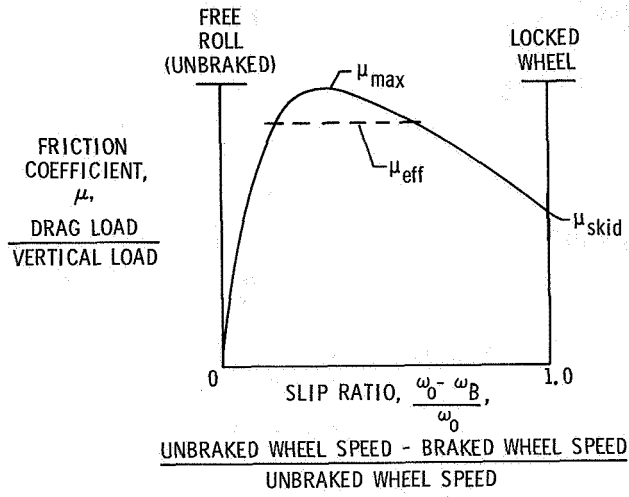


Figure 5.- Definition of friction coefficient.

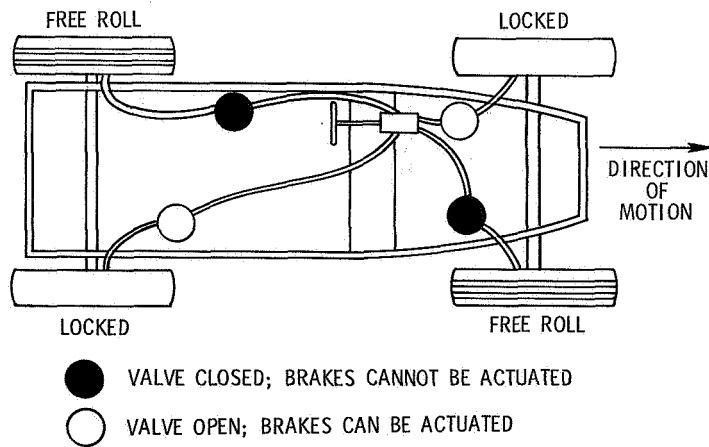


Figure 6.- Diagonal braking system.