NASA SP-5073

PAVEMENT GROOVING AND TRACTION STUDIES

A conference held at
LANGLEY RESEARCH CENTER
Hampton, Virginia
November 18-19, 1968

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Technology Utilization Division
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FOREWORD

The NASA Langley Research Center has been actively involved in research on critical problems relative to the landing and braking of aircraft for a number of years. The results of this research and the available information on incidents and accidents associated with aircraft operations on wet runways clearly demonstrated a need for substantial improvements in aircraft braking and steering capabilities through improvements in the skid resistance of runway pavements. Hence in 1965, based on the pioneering research of the British and on subsequent in-house research at the Langley landing-loads track, NASA decided to undertake a comprehensive research program on the effectiveness of runway grooving as a means for increasing tire traction under operational conditions. The program involved many elements, such as construction of a research runway, selection of test pavements, selection of groove patterns and grooving techniques, control of water levels during testing, selection and operation of test aircraft, and data acquisition.

During the planning and execution of this research program, it was clear that the results would be of great interest to all groups associated with aircraft operations, and the Langley Research Center worked closely with these groups in the implementation of the program. The runway, referred to as the landing research runway at NASA Wallops Station, was completed in early 1968 and flight tests were begun. On the basis of the results obtained from the flight tests of the first two aircraft (an Air Force McDonnell Douglas F-4D and the NASA Convair 990 aircraft) and from the Joint NASA-British Ministry of Technology Skid Correlation Study and in view of the great interest expressed in the available data, NASA decided to hold a Conference on Pavement Grooving and Traction Studies on November 18 and 19, 1968, at the Langley Research Center to present the results available at this time.

The objective of the conference was to provide an opportunity for all persons working in the area to present and discuss their findings and, in many cases, their opinions. The 27 papers presented in this publication represent the results of that conference.

It should be emphasized that this publication essentially represents a compilation of papers presented by various participating governmental and civil organizations as noted in the table of contents. Only limited editing was performed to provide reasonable consistency in format, with careful attention to assure the preservation of the viewpoints and conclusions of the authors.

The reader should observe that the information presented was provided at an early state of development in the technology and that some of the conclusions are subject to change as new and more complete information is generated in the on-going program.

Nevertheless, the Langley Research Center believes the conference provided a meaningful and timely evaluation of the state of the art and hopes the reader will find the results useful.

The Langley Research Center wishes to express its appreciation to all authors, and to the organizations they represent, for their substantial contributions to this program and for the timeliness of their responses both to the program activities and to the conference.

George W. Brooks, General Chairman
Assistant Director, Langley Research Center

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DESCRIPTION OF HYDROPLANING FILMS

The Langley Research Center has prepared three motion-picture films pertaining to hydroplaning which are available on loan or may be purchased for the cost of reproduction. These films are described as follows:

I. HAZARDS OF TIRE HYDROPLANING TO AIRCRAFT OPERATION

Film serial L-775

The film (16 mm, 15 min, color, sound) is based on tire studies at the NASA Langley Research Center and draws attention to the potentially dangerous phenomenon of tire hydroplaning on wet runways.

II. AUTOMOBILE TIRE HYDROPLANING – WHAT HAPPENS!

Film serial L-944

The film (16 mm, 12 min, color, sound) was prepared to point out and to alert the public to the dangerous hazards of tire hydroplaning on the highways.

III. HAZARDS OF TIRE HYDROPLANING – A SEQUEL

Film serial L-957

The film $\left(16 \text{ mm}, 14\frac{1}{2} \text{ min, color, sound}\right)$ describes the loss of tire traction from dynamic hydroplaning and viscous and reverted rubber skidding. Tests using air jets and grooved pavements for the reduction of skidding are shown and the effectiveness of these techniques is described.

Requests for loan copies of these films should be addressed to:

Technology Utilization Office
NASA Langley Research Center
Langley Station
Hampton, Virginia 23365

Copies of films I and III (L-775 and L-957) may be purchased for $61.69 (f.o.b. Washington) from

Byron Motion Pictures, Inc.
65 K Street N.E.
Washington, D. C. 20002

Copies of film II (L-944) may be purchased for approximately $42 from

Mr. J. J. Saunders
Motion Picture Service
U.S. Department of Agriculture
Washington, D. C. 20250

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) dmonstrated 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 Unites 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 $(\omega_o - \omega_B)$ to the unbraked wheel speed (ω_o). 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.

REFERENCES

1. Byrne, Austin T.: A Treatise on Highway Construction. John Wiley & Sons, Inc., 1896.
2. Agg, T. R.: Tractive Resistance and Related Characteristics of Roadway Surfaces. Iowa State Coll. Bull., vol. 22, no. 36, Feb. 6, 1924.
3. Moyer, R. A.: Skidding Characteristics of Road Surfaces. Proceedings of the 13th Annual Meeting of the Highway Research Board, Vol. 13, Pt. I, 1934, pp. 123-168.
4. Moyer, R. A.: Report of Committee on "Antiskid Properties of Road Surfaces." Road Surface Properties, Bull. No. 27, Highway Res. Board, Nat. Res. Counc., Sept. 1950.
5. Shelburne, Tilton E.; and Sheppe, R. L.: Skid Resistance Measurements of Virginia Pavements. Res. Rep. No. 5-B, Highway Res. Board, Nat. Res. Counc., Apr. 1948.
6. Whitehurst, E. A.; and Goodwin, W. A.: Pavement Slipperiness in Tennessee. The Proceedings, 34th Annual Meeting Highway Research Board, Vol. 34, 1955, pp. 194-209.
7. Normann, O. K.: Braking Distances of Vehicles From High Speed and Tests of Friction Coefficients. Public Roads, vol. 27, no. 8, June 1953, pp. 159-169.
8. Anon.: Proceedings First International Skid Prevention Conference. Parts I and II. Virginia Counc. Highway Invest. Res. (Charlottesville), Aug. 1959.
9. Dillard, Jack H.; and Mahone, David C.: Measuring Road Surface Slipperiness. Spec. Tech. Publ. No. 366, Amer. Soc. Testing Mater., c.1964.
10. Anon.: Standard Specification for Standard Tire for Pavement Tests. ASTM Designation: E 249-66. Pt. 11 of 1968 Book of ASTM Standards With Related Material. Amer. Soc. Testing Mater., 1968, pp. 832-835.
11. Anon.: Tentative Method of Test for Skid Resistance of Pavements Using a Two-Wheel Trailer. ASTM Designation: E 274-65 T. Pt. 11 of 1968 Book of ASTM Standards With Related Material. Amer. Soc. Testing Mater., 1968, pp. 836-847.
12. Anon.: Tentative Method of Test for Measuring Surface Frictional Properties Using the British Portable Tester. ASTM Designation: E 303-66 T. Pt. 11 of 1968 Book of ASTM Standards With Related Material. Amer. Soc. Testing Mater., 1968, pp. 848-853.
13. Smith, L. L.; and Fuller, S. L.: Florida Skid Correlation Study of 1967 – Skid Testing With Trailers. Paper presented at 1968 Fall Meeting of Amer. Soc. Testing and Mater. (Atlanta, Ga.), Oct. 1968.

14. Rizenbergs, Rolands L.: Florida Skid Correlation Study of 1967 – Skid Testing With Automobiles. Paper presented at 1968 Fall Meeting of Amer. Soc. Testing Mater. (Atlanta, Ga.), Oct. 1968.

15. Kummer, H. W.; and Meyer, W. E.: Tentative Skid-Resistance Requirements for Main Rural Highways. Rep. 37, Nat. Cooperative Highway Res. Program, Nat. Res. Counc., 1967.

16. Joyner, Upshur T.; Horne, Walter B.; and Leland, Trafford J. W.: Investigations on the Ground Performance of Aircraft Relating to Wet Runway Braking and Slush Drag. AGARD Rep. 429, Jan. 1963.

17. Harrin, Eziaslav N.: Low Tire Friction and Cornering Forces on a Wet Surface. NACA TN 4406, 1958.

18. Sawyer, Richard H.; Batterson, Sidney A.; and Harrin, Eziaslav N.: Tire-to-Surface Friction Especially Under Wet Conditions. NASA MEMO 2-23-59L, 1959.

19. Horne, Walter B.; Joyner, Upshur T.; and Leland, Trafford J. W.: Studies of the Retardation Force Developed on an Aircraft Tire Rolling in Slush or Water. NASA TN D-552, 1960.

20. Horne, Walter B.; and Leland, Trafford J. W.: Influence of Tire Tread Pattern and and Runway Surface Condition on Braking Friction and Rolling Resistance of a Modern Aircraft Tire. NASA TN D-1376, 1962.

21. Anon.: Joint Technical Conference on Slush Drag and Braking Problems. FAA and NASA, Dec. 1961.

22. Horne, Walter B.; and Dreher, Robert C.: Phenomena of Pneumatic Tire Hydroplaning. NASA TN D-2056, 1963.

23. Horne, Walter B.; Yager, Thomas J.; and Taylor, Glenn R.: Review of Causes and Alleviation of Low Tire Traction on Wet Runways. NASA TN D-4406, 1968.

24. Harrin, Eziaslav N.: Investigation of Tandem-Wheel and Air-Jet Arrangements for Improving Braking Friction on Wet Surfaces. NASA TN D-405, 1960.

25. Horne, Walter B.: Air Jets – A Possible Solution to Hydroplaning and Other Associated Runway Wetness Problems. 17th Annual International Air Safety Seminar, Clifford P. Seitz, ed., Flight Safety Found., Inc., Oct. 1964, pp. 59-65.

26. Horne, Walter B.; and Joyner, Upshur T.: Pneumatic Tire Hydroplaning and Some Effects on Vehicle Performance. [Preprint] 970C, Soc. Automotive Eng., Jan. 1965.

27. Steckel, S. S.; and Westberg, J. V.: Full Scale Evaluation of an Airjet System as a Means To Eliminate the Harmful Effects of Wet Runways. LB-32662, Douglas Aircraft Co., Inc., Oct. 19, 1965.

28. Horne, Walter B.; and Tanner, John A.: Joint NASA-British Ministry of Technology Study – Results From American Vehicles. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 23 herein.)

29. Sugg, R. W.: Joint NASA-British Ministry of Technology Study – Results From British Vehicles. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 24 herein.)

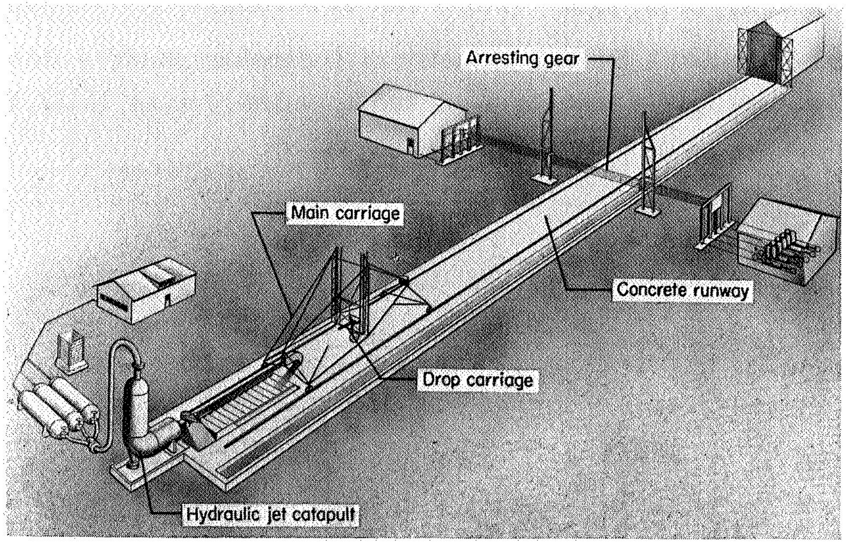

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Figure 1.- Schematic diagram of Langley landing-loads track.

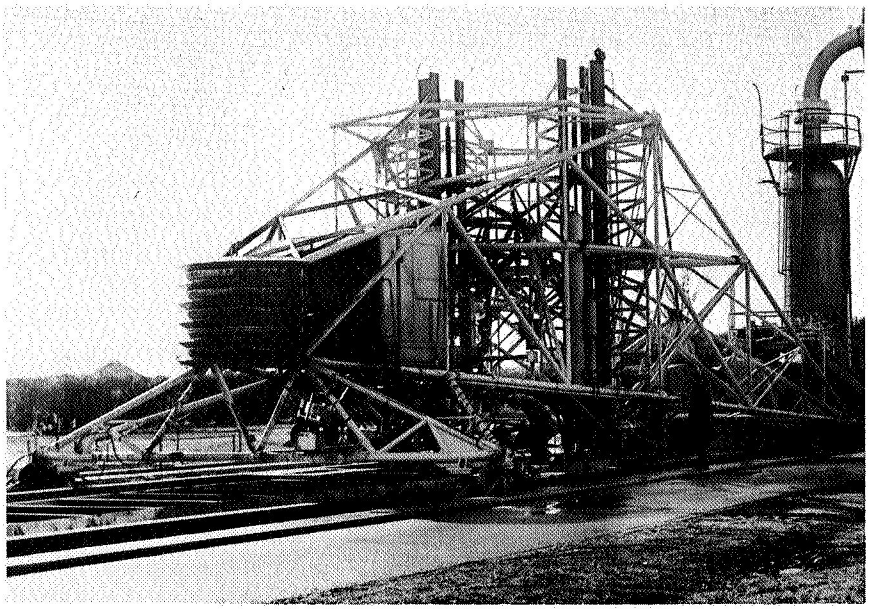

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Figure 2.- Main test carriage at landing-loads track, with catapult in background.

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

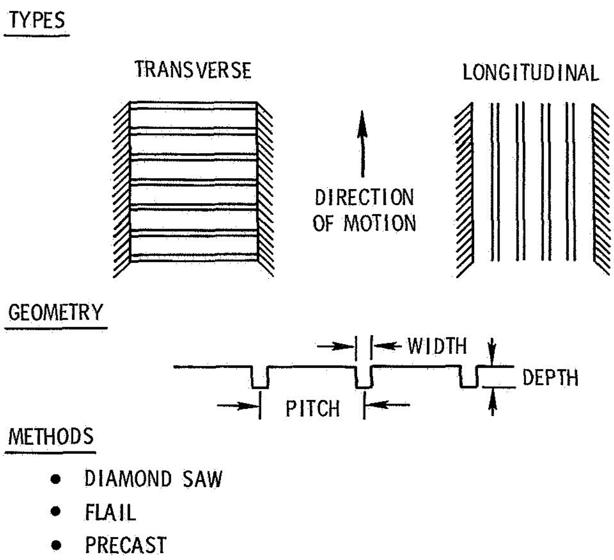

Figure 4.- Description of pavement grooving.

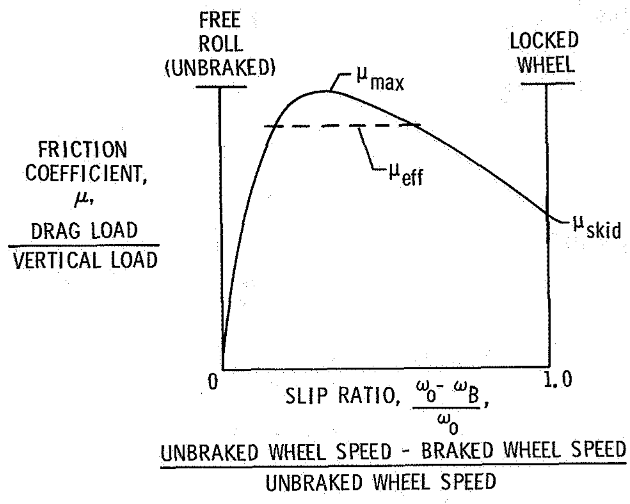

Figure 5.- Definition of friction coefficient.

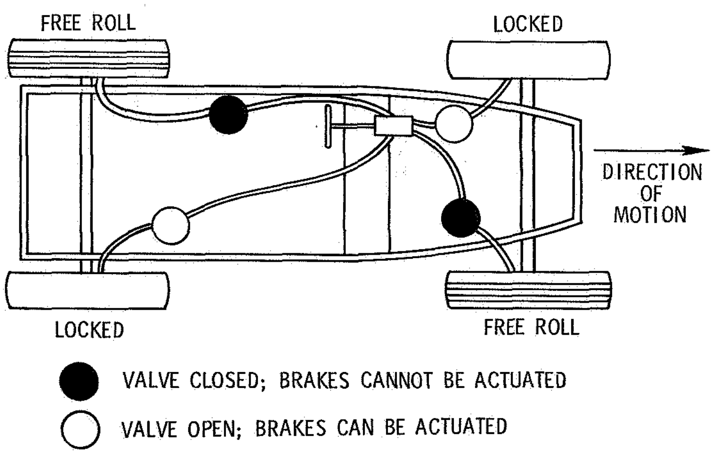

Figure 6.- Diagonal braking system.

2. RUNWAY AND HIGHWAY TRACTION STUDIES – THE PROBLEM, THE OBJECTIVES, AND THE PROGRAMME IN GREAT BRITAIN

PART I – RUNWAY TRACTION STUDIES

By L. J. W. Hall

Air Registration Board

SUMMARY

In addition to fundamental studies of friction, the traction research programme in Great Britain is aimed at minimising the risk of accidents due to inadequate friction. Attempts are being made to discover which paving surfaces provide the highest level of wet friction and least susceptibility to aquaplaning. The durability of the surfaces and their influence on tyre wear are also being studied. Criteria and methods for assessing when substandard friction conditions exist and when aircraft are liable to aquaplane are being developed in order to provide engineering and operational control.

It is recognised that the programme may not result in a sufficient reduction in the number of accidents and that it may be necessary to tackle more vigorously the tyre and aircraft aspect of the problem.

THE PROBLEM

Magnitude

The world-wide rate of occurrence of accidents in which modern transport aircraft overrun the end of the runway or leave the side of the runway with resultant serious damage to aircraft and/or fatalities is 2.2 per million flights. Although the rate of occurrence of injuries and fatalities to passengers and crew is relatively low (7.6 percent of accidents), there is, nevertheless, a high potential risk. This fact, the aircraft loss involved, and the disruption of service at airports following such occurrences make a strong case for action to be taken.

Causes

The circumstances in which these accidents occur indicate that a loss or reduction of adhesion with the runway is a feature in 35 percent of them. These may be broken down as follows:

Ice or snow 9.7%
Wet runway:
  Low normal wet friction 10.8%
  Virtual disappearance of friction (aquaplaning) 14.6%

It is apparent from this that there is a case for improving adhesion between runway and tyre in normal wet conditions and in conditions where aquaplaning can occur. There is also a case for improving the situation in ice and snow conditions because, although the total number of ice and snow accidents is relatively small, the rate of occurrence is high, in view of the relatively small proportion of operations which take place in such conditions.

A feeling has been expressed by some experts that aquaplaning is a rarity which is blamed too readily in accident investigations. However, there is considerable evidence of loss of contact between tyre and runway in overrun and loss-of-control accidents. Moreover, the rarity of aquaplaning is belied by the fact that 1 percent of damaged tyres returned to one tyre manufacturer for retreading have evidence of rubber reversion, a phenomenon which can be the end product or the cause of aquaplaning.

FUNDAMENTAL STUDIES OF FRICTION

Three basic activities are involved in our fundamental studies of friction.

Firstly, laboratory tests are made to examine the effect of runway surface asperities on a moving rubber block. Secondly, flow visualisation methods are applied to model tyres to examine the manner in which contact between tyre and runway changes. This work, if successfully concluded, could lead to an explanation of phenomena which are described empirically but which are not understood. In particular, an understanding of the mechanism of the influence of rubber resilience could have a considerable impact on design of both tyres and runways.

Thirdly, a test vehicle has been developed and used to obtain braking friction data at relatively low speed, and now a second vehicle is being developed to enable full-scale tyres to be tested in simulated high-speed conditions in order to obtain friction and side-force data, which are not currently available.

CORRELATION TRIALS

A series of trials are to be carried out on a number of runway surfaces, embracing the range likely to be used on airport runways. Two aircraft with braking characteristics typifying those of modern transport aeroplanes will be run over test strips simultaneously, with various friction-measuring apparatus, in varying conditions of wetness.

The objective of these trials will be to establish (1) whether the apparatus are suitable for indicating the level of friction that can be developed by an aircraft braking on the runway in given conditions of contamination and, hence, whether they provide a suitable indication of the basic friction qualities of runways; (2) whether the apparatus can indicate the likely braking performance of an aircraft as runway conditions change and hence provide up-to-the-minute indications of friction conditions for aircraft crews; and (3) that the apparatus perform these functions in a practical and reliable manner. It is important in these trials to emphasise simultaneous measurement of braking action by aircraft and calibration apparatus in view of the lack of knowledge of the parameters which influence braking friction.

FACTORS INFLUENCING AQUAPLANING

Work is already advanced on a series of tests designed to determine the correlation between the minimum depth of water needed to sustain aquaplaning and the physical shape of the runway surface and tyre tread design. The purpose of establishing such correlation is twofold: firstly, to indicate whether particular tyre treads or runway surface designs have advantages over others in preventing the occurrence of aquaplaning and, secondly, to provide data which can be used as design criteria for developing drainage systems for the runways and also as criteria for the possible development of operational water-depth warning systems.

FACTORS INFLUENCING DRAINAGE

Clearly, if there were no tendency for water to remain on runway surfaces there would not be even a wet braking problem; however, it may be possible to achieve a minimisation of the depth of water which can persist on a runway surface to the point where the risk of aquaplaning is negligible. Consequently, an experiment is being conducted for which an inclined plane, whose slope can be varied and which can be subject to controlled rates of simulated rainfall, has been built in order to assess the drainage characteristics of various types of runway surface.

This apparatus is used in conjunction with a wind tunnel to assess the combined effect of lateral wind and runway slope on the depth of water retained on particular surfaces. The objectives of these trials are (1) to discover whether particular surfaces are superior to others, (2) to provide more data on the influence of runway cross fall or crowning slopes, and (3) to provide possible operational criteria which would enable warning to be given that the combination of rainfall rates and surface wind conditions would be likely to give rise to critical water film depths from the point of view of aquaplaning. The achievement of the last objective is obviously dependent upon the derivation of an adequate knowledge of critical aquaplaning depths from the trials referred to in the previous section.

WARNING SYSTEMS

It is apparent, from both accident experience and the results of aquaplaning trials so far completed, that a knowledge of the depth of water covering a runway could serve to warn a pilot of the hazards he might encounter when attempting to land. It is also apparent that a number of accidents and incidents in icy conditions might have been avoided if the airport authorities and the operating crews of aircraft landing and taking off were aware that runway icing was occurring. Consequently, an attempt is being made to develop apparatus which will indicate remotely whether a runway is wet and, if so, what depth of water covers the runway or, alternatively, whether ice is forming on the runway surface.

The major problem involved in developing such apparatus would appear to be to establish locations for the detector systems which would make their indications representative of the major part of the runway used in the course of operational landings. Another factor, of course, is the availability of authoritative data on critical water depths, as mentioned previously.

DURABILITY OF RUNWAY SURFACES AND EFFECT UPON TYRE WEAR

In the United Kingdom there are a range of runway surface designs in operational use, including grooved runways, whose behaviour is being monitored over a relatively long period. The object of this process is to record any susceptibility of the runway to mechanical or structural damage, the rate of deterioration in wet friction characteristics with time, any tendency for the drainage systems to become choked by various forms of local contamination, and, as far as possible, any influence on tyre wear. At the same time, a number of experimental surfaces have been laid whose performance in braking is being assessed at intervals by specially instrumented aircraft and whose wearing characteristics are being observed. Inevitably such programmes as these are slow in producing positive results and because of the difficulties of exercising proper scientific and statistical controls, the results of such experiments may not be quite so positive as those of other experiments which are conducted on this general subject. Nevertheless, it is important that such work be carried out in order to ensure that the benefits which the introduction of new runway surfaces is intended to provide are likely to be maintained over a reasonable life span and are not offset by undesirable characteristics.

FUTURE OBJECTIVES

The current programme of research in the United Kingdom consists of fundamental studies which, because of their nature, cannot be said to have a particular objective apart from increasing our knowledge of the subject. However, future research consists of an interlocking set of studies with specific objectives. These may be briefly described as follows:

We are seeking to find runway surface designs which, taken in conjunction with current tyre designs, will be practicable and will provide a high level of wet friction and ensure a minimum risk of aquaplaning.

The absolute attainment of these objectives is recognised as unlikely; consequently the need to measure the level of friction developed by a surface over both long and short time periods is recognised. In order to achieve this, friction-measurement apparatus are being developed and their correlation with aircraft performance is being established.

Similarly, the ability to prevent flooding of runways to the point where aquaplaning is very likely to occur cannot completely be avoided. In order to deal with this shortcoming, we are endeavouring to establish critical water film depth for runway surface and tyres which may be used in conjunction with warning criteria based on a range of possible measurement methods, in order to enable operational crews to delay landings until more favourable conditions exist.

It must be recognised that although such a programme of testing and development appears logical and should be capable of a successful outcome, there is insufficient knowledge at the present time concerning some of the fundamental processes involved in friction between tyres and runways, and alternative approaches may have to be made.

Work on automobile tyres indicates that low-resilience rubbers are capable of producing high levels of friction on wet runways having suitable surface roughness characteristics. The use of such rubbers in aircraft tyres has not been found feasible at the present time. However, if other research is insufficiently productive it may be necessary to pursue this line of activity more vigorously.

Another aspect of the general problem is the lag between establishing improved methods of runway construction and their general introduction into airport constructional practice. This is particularly acute for aircraft of a small country like Great Britain, because some 80 percent of all take-offs and landings occur abroad where we have no direct control or influence over the airport design. It may therefore be necessary to pursue the development of systems for improving wet braking and minimising the risk of aquaplaning which are self-contained within aircraft. Here the work done by NASA and McDonnell Douglas on air jets comes to mind.

CONCLUSIONS

The programme of runway friction research and development in Great Britain is aimed at defining runway surface designs which will enable the consistent achievement of higher levels of traction under wet conditions than have been achieved hitherto. The programme seeks to answer the following questions:

(1) What runway surfaces must be provided at airports to avoid risk of overrunning the end of the runway or loss of control leading to the aircraft leaving the side of the runway?

(2) What control methods can be used to ensure that the minimum design friction characteristics are still in existence after the runway has been worn and/or contaminated?

(3) How can the risk of aquaplaning be reduced to negligible proportion, either by suitable runway design or by the introduction of measuring systems and associated criteria which can be used to advise aircraft operating crews when hazardous conditions are likely to exist?

(4) What are the fundamental parameters that influence friction characteristics of tyres and runways?

Finally, the programme recognises that there is scope for research and development of tyres and braking systems on aircraft and that this aspect will have to be pursued more vigorously if the first three questions cannot be answered satisfactorily.

2. RUNWAY AND HIGHWAY TRACTION STUDIES – THE PROBLEM, THE OBJECTIVES, AND THE PROGRAMME IN GREAT BRITAIN

PART II – HIGHWAY TRACTION STUDIES

By F. T. W. Lander

Road Research Laboratory

2-II

SUMMARY

In Great Britain, skidding has always featured prominently in road accidents; it is reported in one of every three accidents occurring on wet roads. Much research has been carried out to identify and study the numerous factors that influence skidding. It has been shown that to maintain high resistance to skidding – or good traction – on wet roads at the lower speeds, the road surface should have a harsh feel; to cater for high-speed travel, the surface should incorporate in its construction materials having large and angular projections. Whilst these requirements can be met with a freshly laid surface, it is difficult to maintain them because of the polishing and compressing action of traffic. The increasing volume and speed of traffic has aggravated the problem, and methods of resisting polishing are being studied at the Road Research Laboratory. Research is also in progress to relate the skidding resistance of road surfaces to the incidence of accidents and to set up standards for different classes of road and for specific types of road layout – such as intersections – where skidding is a greater potential hazard than on a straight road. To locate road surfaces that are slippery and to ensure that standards of skidding resistance are maintained, equipment for monitoring the skidding resistance of the country's roads has been developed.

INTRODUCTION

Research on road accidents, carried out for many years, has shown that skidding continues to be a problem in Great Britain. It is on wet roads that the problem is most difficult. This paper discusses the wet-road problem, and describes the research and the future programme at the Road Research Laboratory aimed at reducing the number of skidding accidents on wet roads.

THE PROBLEM

Although much is known about skidding and the measures necessary to prevent it, the improving performance of motor vehicles makes greater demands on the skidding resistance of road surfaces. The main problem therefore becomes one of producing and maintaining a skidding resistance sufficient to prevent accidents.

Dry road surfaces have a high resistance to skidding, practically independent of speed, whereas wet surfaces generally have a lower resistance to skidding and the resistance decreases as the speed is raised, the rate of decrease being a characteristic of surface texture. On icy surfaces, the resistance to skidding is obviously very low at all speeds. The relative proportions of accidents in which skidding is reported on dry, wet, and icy roads in Great Britain can be obtained from police reports. In the United Kingdom it is a statutory requirement that all accidents on roads involving fatalities or injuries must be reported to the police. Details of these accidents are recorded in a uniform and systematic manner and are then reported to the Ministry of Transport. (See ref. 1.) From these forms data such as those shown in table I can be obtained.

TABLE I.- SKIDDING IN PERSONAL-INJURY ACCIDENTS IN 1967

State of road surface	Number of accidents in which skidding was reported	Total number of accidents	Skidding rate
	(A)	(B)	$\left(\frac{A}{B} \times 100\right)$
Dry	31 350	180 320	17
Wet	29 470	88 400	33
Icy	4 740	6 060	78
All conditions	65 560	274 780	24

To put these figures into perspective, it is necessary to take into account the varying times that roads are dry, wet, or icy and the amount of traffic, in terms of vehicle mileage, using the roads under these conditions. Unfortunately these data are not readily available; therefore the total number of accidents under the different weather conditions are used as a basis for comparison. The number of skidding accidents, expressed as a percentage of the total number of accidents in each weather condition, is known as the skidding rate. The last column of table I gives the relative risk of skidding in accidents in terms of the skidding rates for the different surface conditions. The fact that the skidding rate for wet roads is about twice that for dry roads indicates quite clearly the room for improvements in the skidding resistance of wet roads. The national accident data can be further analysed to show the skidding rate on roads having different speed limits, and table II shows data for 1966.

TABLE II.- SKIDDING IN PERSONAL-INJURY ACCIDENTS ON WET ROADS IN 1966

Speed limit on road, miles/hour	Number of accidents in which skidding was reported	Total number of accidents	Skidding rate
	(A)	(B)	$\left(\frac{A}{B} \times 100\right)$
30	18 920	69 030	27
40 or 50	2 130	5 250	41
70	11 020	24 420	45
Total	32 070	98 700	32

Although this table highlights the effect of speed on the skidding rate for the country as a whole, surveys of accidents and measurements of skidding resistance on long lengths of unrestricted* roads showed that the skidding rate varied between 25 and 70 percent, the higher values occurring on surfaces which were classified as "smooth" textured.

Again, by studying the locations of individual skidding accidents on wet roads it was shown that the frequency of skidding increased on busy roads at sites such as bends, steep hills, and roundabouts where combined braking and manoeuvering tended to make more demands on the frictional characteristics of the surface.

THE OBJECTIVES

Main Objective

The objectives of a rational programme to prevent skidding accidents are obviously to be based on analysis of the accident data; it is therefore of the utmost importance that these data be reliable. The original forms for reporting personal-injury accidents in the United Kingdom have been amended so that the reporting officer is not required to make a subjective assessment of the cause of the accident but merely to state whether or not skidding occurred.

The ultimate aim of all highway engineers and those concerned with skidding accidents should be to progressively reduce the skidding rate until it becomes equivalent to that on dry roads; with further developments in tyre/road adhesion it may even be possible to reduce the large number of skidding accidents occurring on dry roads. In order to keep the skidding rate at a low level, road surfaces should have high frictional coefficients at all speeds throughout the year.

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*Since December 1965 these roads have been subject to an overall speed limit of 70 miles/hour.

Requirements for good skidding resistance.- The requirements for good skidding resistance on wet roads have been investigated at the Road Research Laboratory and are clearly defined. (See refs. 2 and 3.) The first requirement is to facilitate breaking through the water film to establish local areas of dry contact between the road and the tyre. This can be achieved only if there are sufficient fine-scale sharp edges; these give the surface a harsh feel. This fine-scale texture is the dominant factor in determining the skidding resistance at speeds of about 30 miles/hour. As speed increases, drainage channels provided by the large-scale texture of the road as well as the pattern on a tyre become important in permitting the removal of the bulk of the water, but the residual portion of the water layer is more difficult to remove in the short time available (1/200 sec at 60 miles/hour), however harsh the surface texture. Hence, at high speeds additional requirements for good skidding resistance are necessary. These are met to a large extent by making use of the energy losses in the rubber of the tyre as it is deformed by projection in the road surface. It is, therefore, essential on high-speed roads to have sufficiently large and angular projections in the road surface to deform the tread, even though a film of water may still be present, and so take advantage of the higher hysteresis tread materials now in use in Great Britain for passenger car tyres. It has been recommended that these projections should provide a minimum texture depth of 0.025 inch (ref. 3 and p. 80 of ref. 4) on roads where speeds are likely to be high.

Effect of traffic.- Although surfaces can be produced with textures that give high skidding resistance, it is difficult to maintain this high coefficient under the compacting and polishing action of heavy traffic. Road surfaces therefore have to be laid with materials that resist this polishing and "pushing in" action. Because of this stringent requirement, the polished stone test was introduced in British Standard 812 (ref. 5). It is important that this aspect of the problem be considered if the grooving of road surfaces is to be used as a practical remedial treatment for slippery roads. British experience with the transverse grooving of heavily trafficked motorways (p. 150 of ref. 4 and pp. 98 and 165 of ref. 6) has shown that although the treatment can be effective when new, its effectiveness at low speed can be reduced in a comparatively short time. In a particular example, when a slippery concrete surface was grooved, the braking force coefficient at 30 miles/hour was increased from 0.44 to 0.60, while at 80 miles/hour it was increased from 0.13 to 0.49. After a year of heavy traffic, however, the coefficient at 30 miles/hour had fallen to 0.40 and the coefficient at 80 miles/hour to 0.31. These remarks do not necessarily apply to runway surfaces, since in comparison to roads, traffic is very light even at the busiest of airports.

Subsidiary Objectives

The subsidiary objectives of the programme were: (1) to examine the reliability of methods to determine the suitability of road surfacing materials to resist polishing by traffic and (2) to relate the skidding resistance of road surfaces to the incidence of skidding accidents so that standards can be established in terms of measured values of frictional coefficient for different classes of road, road layout, and density of traffic.

In Great Britain the first of these subsidiary objectives has been met by British Standard 812 and the second by standards based on measurements with the laboratory's test vehicles (p. 80 of ref. 4). Over the long period covered by the measurement of skidding resistance and its correlation with skidding accidents, it has been found that if the test vehicles are to be used as a standard they must reliably and consistently indicate skidding-accident risk. To do this the measurements should be made under closely controlled standardised conditions; this is already done in the case of the laboratory's testing vehicles and procedures.

As an example of the importance of careful control over the measuring techniques, it has been found that subtle changes in tyre profile and in the resilience of the tread compound can give variations in coefficients on the same road surface. Special tests have therefore been devised to ensure that all the laboratory's test vehicles are fitted with tyres with standardised physical properties. (See ref. 7.)

THE PROGRAMME

The programme for the future in Great Britain is, in the main, to apply throughout the country the knowledge recently obtained in the hope of bringing about a substantial reduction in the numbers of skidding accidents on wet roads. It is estimated that an average increase nationally of 0.05 in the friction coefficient at 30 miles/hour corresponds to a reduction in skidding rate of $3\frac{1}{2}$ percent. Nationwide, this would represent a reduction of about 2000 personal-injury accidents per year.

Artificial Roadstones

In Great Britain there is a shortage of supplies of natural roadstone with a sufficiently high polished-stone value (PSV) to meet the required standard of skidding resistance for those sites requiring special treatment. Investigations have already revealed several artificial materials with very high PSV, and further research will be carried out to develop artificial road aggregates which can eventually be produced on a commercial scale. (See pp. 31 and 134 of ref. 4.)

Pervious Layers

Allied to the need for high PSV roadstones is the need to remove rainwater quickly from roads. This becomes more important as vehicle speeds and the width of carriageways increase. Consequently, studies are being made of various forms of pervious layers as wearing courses which can withstand heavy traffic without losing their permeable nature. (See p. 114 of ref. 4.)

Monitoring Systems

As the engine performance, suspension, and braking system of cars have improved, the skidding rate on dry roads has increased substantially. This indicates that drivers are demanding more and more in terms of tyre/road adhesion from the road surface. It is only the overall improvement in skidding resistance that has prevented a similar upward trend in the wet-weather skidding rate. Recently, the ratio of skidding rates on wet and dry roads, which indicates the overall standard of skidding resistance under wet conditions, has, in fact, shown a downward trend. However, with the continued increase in volume and speed of traffic the problems of maintaining the proposed standards of skidding resistance will increase in the future. For this reason plans have been made to set up a unified system of monitoring the skidding resistance of the whole of the country's 30 000 miles of main roads.

To enable this to be done a new skid test vehicle has been developed (fig. 1) which is especially designed to measure the slipperiness of some 1500 miles of road in the summer testing period. The vehicle employs the sideway force coefficient principle of measuring skidding resistance, and average values of sideway force coefficient for every 10 or 20 metres of the road will be recorded digitally.

The vehicle will carry its own water supply, sufficient for some 20 miles of continuous testing, and will be capable of a maximum test speed of 60 miles/hour. Unlike any of the machines used before, it will be able to operate in traffic. The organisation of the proposed monitoring system will involve the setting up of a central calibration centre and the deployment of 30 test vehicles throughout the country.

It is hoped that this overall system for measuring the skidding resistance of the country's roads under controlled conditions, together with the establishment of standards, will lead to the general upgrading of skidding resistance and, in consequence, to a reduction in the number of skidding accidents on wet roads. It is also reasonable to hope that this monitoring service will enable the £125 million spent on the maintenance of the country's roads to be allocated in such a way that all roads that need to be resurfaced because of their low coefficients will receive attention.

Tyres

In addition to the improvement of road surfaces, development of tyres for improved wet-road adhesion should continue. Efforts should be directed towards making full use of the greater texture depth of future roads by increasing the energy losses within the tyre tread compound but without undue tyre wear. Figure 2 shows the advantage of tyres with low-resilience tread compounds. Although past work has shown that tread pattern design does not play a great part in improving skidding resistance on surfaces with large texture depths at low speeds, the basic tread-pattern mechanism needs investigation, particularly for high speeds.

CONCLUDING REMARKS

Great Britain is now embarked on a countrywide road-improvement programme including a comprehensive motorway network. Although this will do much to promote the overall flow of traffic, it will be difficult to cope with the steady growth of traffic, which is increasing at the rate of about 6 percent per year. Also there are continual advances in the performance of vehicles, and it is logical to conclude that, as time goes on, the problem of keeping the skidding accidents on wet roads to a minimum will become more difficult.

The basic concepts for providing road surfaces with high skidding resistance are known, and now it is required to use the monitoring system and apply the findings as soon as possible to those surfaces requiring attention.

ACKNOWLEDGEMENTS

Contributed by permission of the Director of Road Research.

REFERENCES

1. Anon.: Ministry of Transport Form Stats 19: Accident Coded Sheet Final Report of the Committee on Road Safety, Appendix, May 1947. H.M.S.O.

2. Sabey, B. E.: Road Surface Characteristics and Skidding Resistance. J. Granite and Whitstone Fed. (London), vol. 5, no. 2, 1965, pp. 7-18.

3. Sabey, B. E.: The Road Surface and the Safety of Vehicles. AD/ASAE Symposium, Institution of Mechanical Engineers, 1968.

4. Anon.: Road Research 1967. Ministry of Transport. H.M.S.O.

5. Anon.: Methods for Sampling and Testing Mineral Aggregate Sands and Fillers. British Standard 812, British Standards Institution, 1960.

6. Anon.: Road Research 1965/6. Ministry of Transport. H.M.S.O.

7. Lupton, G. N.: Description of a Modified B. S. Lupke Resiliometer for Measuring the Resilience of Standard Test Tyres. Road Research Laboratory LN 287.

Figure 1.- Skid test vehicle to be used in monitoring the skidding resistance of roads in Great Britain.

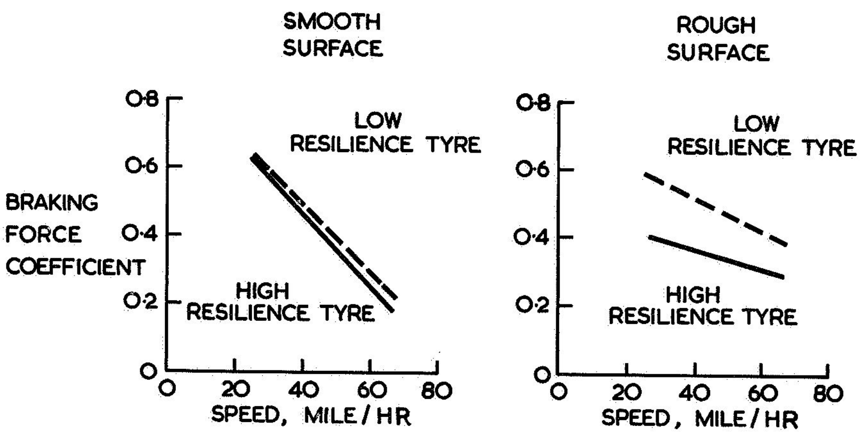

Figure 2.- Skidding resistance of tyres of different resilience on surfaces of different textures.

3. COMPARATIVE BRAKING PERFORMANCE OF VARIOUS AIRCRAFT ON GROOVED AND UNGROOVED PAVEMENTS AT THE LANDING RESEARCH RUNWAY, NASA WALLOPS STATION

By Thomas J. Yager

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SUMMARY

The transverse groove configuration of 1 in. $\times \frac{1}{4}$ in. $\times \frac{1}{4}$ in. installed at the landing research runway at NASA Wallops Station for full-scale aircraft test evaluation was selected on the basis of aircraft tire traction tests conducted at the Langley landing-loads track on 19 different transversely grooved test surfaces. In order to provide the reader some background for the full-scale aircraft tests, some of the test results obtained at the track are presented and discussed. These results indicate that grooved pavements offer great promise for increasing aircraft ground performance during landing and take-off operations under adverse conditions. Also discussed are the comparative aircraft braking test data obtained on similar grooved and ungrooved surfaces at the landing research runway with a fully instrumented McDonnell Douglas F-4D jet fighter aircraft and the Convair 990 4-engine jet transport aircraft. The aircraft test results substantiate and supplement the track data and indicate that transverse runway grooves provide greatly increased aircraft braking and steering capability for wet, flooded, and slush-covered runway surfaces.

3

INTRODUCTION

In order to provide the reader some background for the full-scale aircraft tests on the transversely grooved landing research runway at NASA Wallops Station, some test results obtained during aircraft tire braking tests on several different grooved and ungrooved surfaces at the Langley landing-loads track are discussed. The purpose of the evaluation at the track was to determine which groove configuration, out of 19 configurations tested, offered the best aircraft tire braking capability; on the basis of these test results, the 1-in. $\times \frac{1}{4}$-in. $\times \frac{1}{4}$-in. groove configuration was selected.

Having obtained very promising test results at the Langley landing-loads track on the effects of transverse pavement grooving as a means of improving aircraft tire traction capability and recognizing the limitations of the landing-loads track, a search was initiated in late 1966 for a suitable test runway for use in making similar tests on full-scale aircraft. Runway 4/22 at NASA Wallops Station was selected, with test surface modification work (including installation of the selected groove configuration) being completed in late 1967. Full-scale aircraft tests to determine the effects of grooved runway surfaces on aircraft landing and take-off operations under dry, wet, flooded, and slush-covered conditions were started in February 1968.

The aircraft braking test results obtained on the landing research runway at NASA Wallops Station during nearly 200 test runs with an F-4D jet fighter and the 990 4-engine jet transport are presented and discussed. These comparative aircraft test results on grooved and ungrooved surfaces for dry, wet, flooded, and slush-covered conditions substantiate and supplement the test results obtained earlier at the landing-loads track.

PAVEMENT GROOVING EVALUATION AT THE LANDING-LOADS TRACK

Test Equipment and Procedure

The pavement grooving evaluation was conducted at the Langley landing-loads track by using the large test carriage. The test tire fixture, mounted in the center of the carriage, is instrumented to measure the loads developed by the tire during a test run at speeds up to 100 knots. References 1 and 2 give a more detailed description of the equipment and operation of the track. Excellent repeatability of test conditions can be obtained with this equipment, and by means of an 18-channel oscillograph recorder, complete time histories of tire performance during a test run were recorded for data evaluation. The five different aircraft tires used in this investigation varied in size and tread design from a smooth, fabric-reinforced rubber tread, type VIII, 27.5 × 7.5 tire to a 7-groove, all rubber tread, type VII, 49 × 17 tire. The transversely grooved test surfaces were constructed of removable, precast concrete strips, 10 ft in length, which were frozen in place in the 200-ft-long brine pipe section of the track normally used to obtain an ice test surface. Photographs and a plan drawing of these precast concrete test strips are shown in figure 1. A minimum test-surface length of 20 ft (two concrete strips placed end to end) was used during actual test runs in addition to the permanent concrete and asphalt surfaces located in the remaining 1000 ft of the track test section. With this surface arrangement a maximum of 10 different grooved surfaces could be evaluated and compared to the permanent ungrooved surfaces during each test run. Two concrete test strips were also left ungrooved for comparing and evaluating tire performance on the grooved surfaces. The various groove configurations were sawed or flailed into each of these concrete strips prior to installation.

The values of groove pitch and width for the configurations tested are given in the following table:

Groove width, in.	Groove pitch, in.		
$\frac{1}{8}$	1	$1\frac{1}{2}$	2
$\frac{1}{4}$	1	$1\frac{1}{2}$	2
$\frac{3}{8}$	1	$1\frac{1}{2}$	2

Each of these configurations was tested for groove depths of 1/8 in. and 1/4 in. which resulted in test data being obtained on 18 different groove configurations. The 1/8-in.-deep grooves were cut with a flailing tool which resulted in rounded corners at the top and bottom edges of these grooves. The 1/4-in.-deep grooves were cut with a saw which resulted in relatively sharp corners.

As a means of determining the optimum groove configurations of those considered in this study, tests were conducted to evaluate the effect of transversely grooved pavement surfaces on aircraft tire performance; namely, (1) rolling resistance, (2) cornering capability, and (3) braking effectiveness. Additional tests were conducted to determine the effect of freeze-thaw cycles on grooved pavement surfaces. Although all the test results obtained from the pavement grooving evaluation are not given herein, the general data trends which were established during the investigation are presented.

Test Results

Aircraft tire rolling resistance.- Rolling resistance coefficient values were obtained with a smooth, fabric-reinforced rubber tread, type VIII, 27.5 × 7.5 tire inflated to 400 lb/in^2. Tests were made at 4° yaw on various surfaces for both flooded and damp conditions, and the results are shown in figure 2 as a function of ground speed. The solid line is faired through the ungrooved concrete test strip results and used for comparison with the results obtained on the other test surfaces. The surface roughness or texture of the three ungrooved test surfaces shown in figure 2 varied from an average texture depth (see refs. 3 and 4) of 0.04 mm for the smooth concrete to 0.32 mm for the float-finished concrete. The ungrooved concrete test strip had an average texture depth of 0.15 mm. With the pavement surface under flooded conditions (water depth varied from 0.2 to 0.3 in.), the rolling resistance coefficient of the smooth 27.5 × 7.5 test tire increases with speed but the data indicate no significant difference in the values obtained on the ungrooved concrete from those obtained on the other test surfaces. For damp conditions with no standing water on the surfaces, the rolling resistance values obtained on the ungrooved surface remain constant between 0.03 and 0.04 with increasing forward velocity. Less deviation from the tire rolling resistance coefficient values for the ungrooved surface was obtained on the other grooved test surfaces not shown in figure 2. The results of these unbraked tire tests indicate that transversely grooved pavement surfaces do not significantly affect tire rolling resistance.

Aircraft tire cornering capability.- The effect of pavement surface configuration on the side or cornering force developed by the smooth 27.5 × 7.5 type VIII tire operated at 4° yaw is shown in figure 3. In this figure the cornering force obtained for each particular surface configuration is divided by the cornering force value obtained under the same conditions on the dry ungrooved surface. This value is then multiplied by 100 to express it as percent of dry ungrooved cornering force. The percent of dry ungrooved cornering force is plotted against the velocity ratio which is the actual ground speed divided by the computed critical hydroplaning speed. (See ref. 5.) A velocity ratio of 1 for the test conditions shown in figure 3 is equal to a ground speed of 180 knots. Comparative data are presented for three ungrooved test surfaces, nine sawed groove configurations, and seven flailed groove configurations for both flooded (water depth varied from 0.2 to 0.3 in.) and damp conditions. Data were not obtained on the flailed groove configurations of $1\frac{1}{2}$ in. × $\frac{1}{8}$ in. × $\frac{1}{8}$ in. and 2 in. × $\frac{1}{8}$ in. × $\frac{1}{8}$ in. with the smooth 27.5 × 7.5 test tire.

In general, the data show that a greater percent of the dry ungrooved surface cornering force was obtained on the damp test surfaces as compared to that obtained for flooded conditions. For similar surface wetness conditions, the data obtained on the ungrooved test surfaces are significantly lower than the data obtained on the sawed-groove and flailed-groove test surfaces. However, the degradation in tire cornering force developed on the sawed-groove test surfaces for flooded conditions is substantially less than that for the damp surface condition, particularly at the higher, more critical speeds. A greater degradation in tire cornering force is shown by the data obtained on the ungrooved and flailed-groove test surfaces for flooded conditions compared to the data obtained for damp conditions.

The percent of dry ungrooved surface cornering force data shown in figure 3 also indicate the effect of groove spacing and groove width on tire cornering force. By increasing the spacing between the grooves from 1 in. to 2 in., a proportionately lower percent of dry ungrooved surface cornering force was developed at the higher test speeds. Increasing the groove widths from 1/8 in. to 3/8 in., however, did not result in proportionately higher tire cornering traction for the critical flooded surface condition. The data in figure 3 show that under flooded conditions the sawed groove configuration of 1 in. × $\frac{1}{4}$ in. × $\frac{1}{4}$ in. maintained the greatest percent of dry ungrooved surface cornering force throughout the test speed range.

Aircraft tire braking effectiveness.- Previous tire traction research has shown that tire braking capability reaches a peak or maximum value at a slip ratio which depends primarily on the tire elastic properties and the maximum available coefficient of friction. A slip ratio of 0 corresponds to the free-rolling condition and a slip ratio of 1 corresponds to the locked-wheel or full-skid condition (ref. 6). As the tire is allowed to spin down from this peak braking friction condition, tire braking capability is significantly reduced and tire side force or steering capability is also reduced. For the locked-wheel condition the side force is reduced to zero. Data showing the variation of skidding friction coefficient values obtained on the three principal types of surfaces tested are shown in figure 4 as a function of velocity ratio. These data were obtained with the smooth 27.5 × 7.5 tire operated at 4° yaw and for flooded (water depth varied from 0.2 to 0.3 in.) surface conditions. In general, the locked-wheel friction coefficient data obtained on both the sawed- and flailed-groove surfaces are significantly higher than the data obtained on the ungrooved concrete test surface throughout the test speed range. However, as speed is increased, there is a rapid reduction in the locked-wheel friction coefficient obtained on the ungrooved and flailed-groove test surfaces. On the sawed-groove test surfaces, a high level of locked-wheel friction coefficient is maintained throughout the test speed range. As the data shown in figure 4 indicate, the highest level of locked-wheel friction coefficient was maintained on the sawed 1-in. × $\frac{1}{4}$-in. × $\frac{1}{4}$-in. groove configuration.

In addition to these comparative tests to determine the optimum of the various groove configurations, the effect of alternately freezing and thawing several flooded grooved pavement surfaces was studied. Since the grooved concrete test strips were frozen in place during the aircraft tire test runs, it was a simple matter to add additional water to a depth slightly greater than the surface of the groove lands. Complete freezing was accomplished overnight by the refrigeration system. The solid ice formation on top of the grooved surfaces was then quickly thawed by means of a water hose, and several low-speed (4 knots) locked-wheel braking test runs were conducted before adding water to freeze the surfaces again. In this manner, the grooved test surfaces were subjected to 22 freeze-thaw cycles. As shown in figure 5, the 22 freeze-thaw cycles did not have a significant effect on the locked-wheel friction coefficient developed by a 3-groove, fabric-reinforced rubber tread, type VIII, 30 × 11.5-14.5 tire on a 1-in. × $\frac{1}{4}$-in. × $\frac{1}{8}$-in. grooved surface and a 1-in. × $\frac{1}{8}$-in. × $\frac{1}{8}$-in. grooved surface for flooded conditions. Between each of the freeze-thaw cycles, closeup photographs of the grooved test surface, as well as silicone rubber molds, were taken in the area of the test tire path. No significant change or deterioration of the grooved surfaces was found during the process of being subjected to not only 22 freeze-thaw cycles but nearly 50 low-speed locked-wheel braking tests.

SUMMARY OF RESULTS OBTAINED FROM STUDIES OF VARIOUS GROOVE CONFIGURATIONS

Test results were obtained during the evaluation of various groove configurations by use of a variety of aircraft tires at the Langley landing-loads track. Comparison of data from these grooved surfaces and from similar ungrooved concrete surfaces under the same test conditions indicates that pavement grooving results in

(1) No significant increase in aircraft tire rolling resistance

(2) Substantial improvement in aircraft tire cornering force or steering capability

(3) Greatly improved aircraft tire braking capability

On the basis of aircraft tire traction performance on flooded surfaces at speeds up to 100 knots, the 1-in. $\times \frac{1}{4}$-in. $\times \frac{1}{4}$-in. sawed groove configuration was determined to be better than the other groove configurations tested. During all the yawed rolling and braking test runs and during the 22 alternate freeze-thaw cycles, no significant surface deterioration of the groove configurations was observed.

AIRCRAFT TEST EVALUATION AT THE LANDING RESEARCH RUNWAY

Test Procedure

Nearly 200 test runs with an F-4D jet fighter and the 990 4-engine jet transport have been made on the landing research runway at NASA Wallops Station. With the data obtained from these two fully instrumented test aircraft, several factors affecting aircraft ground performance were evaluated. On similar grooved and ungrooved surfaces, comparative free-rolling touch-and-go type tests as well as accelerate-stop type maximum antiskid braking test runs were made at ground speeds up to 150 knots for dry, wet, flooded, and slush-covered surface conditions. In comparing the F-4D and 990 aircraft braking performance, the effects of runway surface grooves, tire tread design, and antiskid braking systems on aircraft braking and directional control were studied. The different configurations of the main-wheel landing gears on the two aircraft were also considered in this investigation.

A schematic view of the landing research runway indicating the nine different test surfaces is shown in figure 6. The overall dimensions of the runway are 8750 ft by 150 ft with the 3450-ft by 50-ft test section located in the middle. A level (both transversely and longitudinally) 1400-ft concrete section and a 1400-ft asphalt section are separated by a 650-ft Gripstop transition surface (see ref. 7) having a longitudinal slope of 0.1 percent. The terms "smooth" and "textured" used in figure 6 indicate the relative roughness of the test-surface finishes. Half of each of the four 700-ft concrete and asphalt sections having different surface finishes is transversely grooved so that comparative aircraft tire traction values could be obtained on grooved and ungrooved sections of the same pavement. The groove configuration is 1 in. $\times \frac{1}{4}$ in. $\times \frac{1}{4}$ in. The surface code letters A to I are used to identify the test surface, as follows:

Surface A	Canvas-belt drag finished concrete, ungrooved
Surface B	Canvas-belt drag finished concrete, grooved
Surface C	Burlap drag finished concrete, grooved
Surface D	Burlap drag finished concrete, ungrooved
Surface E	Gripstop transition surface
Surface F	Small-aggregate asphalt, ungrooved
Surface G	Small-aggregate asphalt, grooved
Surface H	Large-aggregate asphalt, grooved
Surface I	Large-aggregate asphalt, ungrooved

A detailed description of these test surfaces is given in reference 7.

The two different wetness conditions used on the surfaces of the landing research runway during the aircraft tests are shown in figure 7. In attempting to obtain a wet condition with a runway surface water depth of less than 0.1 in., some surface water collected in surface depressions to form isolated puddles. For the flooded surface condition, numerous water-depth measurements were taken before each test run on the runway center line and on each side in the main-gear wheel path area of the test aircraft to establish a surface water-depth profile. As a result of wind effects on the surface water during the aircraft test runs, some areas of the test surface were damp and other areas had a water depth greater than 0.3 in. For the flooded surface condition, however, the aircraft braking test data evaluation was confined to the test-surface area having a water depth between 0.1 and 0.3 in.

From aerial photographs of the wet test surfaces with isolated puddles, similar to the one shown in figure 8, the effect of runway grooves on water drainage is indicated. The two wet test surfaces shown in the photograph (fig. 8) are grooved and ungrooved asphalt. Although the same amount of water has been applied to both test surfaces, the ungrooved surface has a thin water film (as indicated by the light reflection in the photograph) but the water on the grooved surface has drained into the pavement grooves, resulting in only isolated puddles and no significant water film. It is apparent that the grooved pavement is faster draining than the ungrooved pavement for the same wetness condition.

Test Instrumentation and Data

By means of 36-channel oscillograph recorders, shown in figure 9, complete time histories of aircraft ground performance during a test run were recorded for data evaluation. Individual aircraft wheel velocity, brake pressure, and antiskid valve action as well as variations in engine speed and in nose- and main-gear strut pressure were monitored by the onboard instrumentation. Since most of the aircraft test runs were conducted at idle thrust and maximum braking conditions, variations in the F-4D brake pedal pressure metering valve were monitored and during the 990 aircraft tests the brake pedal positions were recorded. An instrument package (fig. 9), consisting of longitudinal, lateral, and normal accelerometers, pitch angle indicators, yaw attitude indicator, and a vertical gyro, was located at the center of gravity of the test aircraft. Location of the aircraft on the test section during a run was recorded by means of an event marker activated by the instrument man on board the aircraft during the test. By means of a wheel velocity gauge in the cockpit calibrated to true aircraft ground speed, the pilot could obtain the desired test-section entrance speed just prior to brake application. With the recorded data and data from a series of tare runs made throughout the test speed range of the aircraft to determine aerodynamic lift and drag coefficients, aircraft braking performance could be evaluated.

Some examples of the oscillograph traces obtained during tests of the F-4D and 990 aircraft are shown in figures 10 to 13. The data shown in these figures were obtained on the same grooved and ungrooved concrete test surfaces. It should be noted that the F-4D brake pedal pressure metering valve traces have been faired in figures 10 and 11. During both the F-4D and 990 aircraft braking tests the longitudinal accelerometer traces indicate a significant improvement in aircraft deceleration or braking effectiveness on the grooved concrete surface for both wetness conditions when compared with the low deceleration level obtained on the ungrooved concrete under similar test conditions. At a relatively high initial ground speed V of 107.5 knots, the longitudinal accelerometer trace recorded during a 990 aircraft braking test (fig. 12) indicates no significant difference in aircraft braking effectiveness on a dry grooved surface and a wet grooved surface with isolated puddles. From the wheel velocity traces shown in figures 10 to 13, complete wheel lockups did not occur during the F-4D aircraft braking tests but numerous multiple wheel spin-downs and complete wheel lockups occurred during the 990 braking tests on the ungrooved surfaces. On the grooved surfaces, only front wheel lockups occurred for flooded conditions during the 990 aircraft braking tests. This difference in wheel tire behavior during the F-4D and 990 braking tests could be attributed to differences in antiskid braking system characteristics and main-landing-gear configurations.

Test Results

With the initial test conditions for each of the aircraft braking test runs established and recorded, the oscillograph data reduction resulted in a time history profile of aircraft braking friction coefficients and ground speeds obtained throughout the assigned test surfaces at idle aircraft engine thrust. The computer data-reduction program considered corrections for aerodynamic lift and drag, wind direction and velocity, and ambient temperature and pressure. The aircraft braking friction coefficient data presented includes fluid inpingement drag and slush drag on the aircraft.

Effects of runway grooves.- Comparative F-4D and 990 aircraft faired braking coefficient levels obtained at ground speeds up to 135 knots on grooved and ungrooved test surfaces for the wet and the flooded conditions are shown in figures 14 to 19. The F-4D aircraft braking data (figs. 14 and 15) were obtained with 3-groove fabric-reinforced rubber tread, type VIII, 30 × 11.5-14.5 main-gear tires. The 990 aircraft braking data (figs. 16 to 19) were obtained with 5-groove and smooth, all rubber retread, type VIII, 41 × 15.0-18 main-gear tires. The data obtained for flooded conditions are shown in figures 15, 17, and 19, but aircraft test time did not permit a complete evaluation of nine different runway surfaces. The dry braking friction coefficient curve was established from data obtained on several different dry grooved and ungrooved surfaces. Although there is a difference in the dry braking data curves for the F-4D aircraft and 990 aircraft, changes in runway surface configuration and tire tread design did not significantly affect the dry braking friction coefficient level obtained with each of the test aircraft.

For both wetness conditions shown in figures 14 to 19, the F-4D and 990 aircraft braking friction coefficient levels obtained on the grooved runway surfaces are substantially higher than those obtained on the similar ungrooved surfaces throughout the test speed range. The variation in aircraft braking data obtained on the five ungrooved surfaces under the wet condition with isolated puddles can be attributed to differences in runway surface texture or roughness as well as to surface texture type or configuration. By using the grease technique described in reference 4, the average runway surface texture depth was measured on the runway center line and varied as follows: 0.12 mm on surface A, 0.20 mm on surface D, 0.14 mm on surface E, 0.19 mm on surface F, and 0.32 mm on surface I.

In comparing the F-4D and 990 aircraft braking traction data obtained under similar test conditions, some of the differences in aircraft braking friction coefficient μ levels can be attributed to differences in antiskid braking system characteristics, landing gear response to runway roughness, and main-landing-gear wheel configurations. Although both aircraft antiskid braking systems reduce brake pressure when a critical wheel deceleration is reached, the antiskid braking system on the F-4D aircraft reduces brake pressure on both main wheels but the system on the 990 aircraft reduces brake pressure on only the wheel or wheels operating at slip ratios beyond the peak of the μ-slip curve. Furthermore, the 990 aircraft has nose-wheel braking, whereas the F-4D has no brakes on the nose wheels. Considering the effects of the single main wheels of the F-4D main landing gear and the 4-wheel tandem bogie configuration of the 990 main landing gear, the forward pair of main-gear tires on the 990 aircraft displaces the runway surface water and enables the rear tires to maintain higher traction, particularly for flooded conditions.

In order to determine the effect of runway grooves on aircraft braking performance, an attempt was made to normalize these differences in aircraft antiskid braking system characteristics, main-landing-gear wheel configurations, and main-gear tire inflation pressures. In figure 20, the variation in the effective braking ratio (i.e., μ_{wet} divided by μ_{dry}) obtained with the F-4D and 990 aircraft on ungrooved and grooved asphalt (surfaces F and G) for wet conditions with isolated puddles is shown as a function of the ground velocity ratio. The 990 aircraft data were obtained with 5-groove rib-tread main-gear tires inflated to 160 lb/in^2 and the F-4D aircraft data were obtained with 3-groove rib-tread main-gear tires inflated to 280 lb/in^2. With these tire inflation pressures, the computed critical hydroplaning speed of the 990 and F-4D aircraft is 114 knots and 150 knots, respectively. In figure 20, the braking data obtained on the wet grooved asphalt with both aircraft throughout the speed range show very little reduction in aircraft braking effectiveness from the data obtained for a dry condition. On the wet ungrooved asphalt, the braking effectiveness of both airplanes reduces rapidly with increased speed to values between 20 and 30 percent of dry braking at a ground velocity ratio of 1 which represents the critical hydroplaning speeds of the two test aircraft. These test results, which are similar to the aircraft braking data obtained on the other test surfaces, indicate that runway grooves provide a substantial improvement in aircraft braking capability for wet conditions.

For a flooded condition on the same surfaces, figure 21 shows that the braking effectiveness of the two test aircraft reduces with speed on the grooved asphalt but there is a significant improvement compared with that obtained on the flooded ungrooved asphalt surface. The 990 aircraft maintained 65 percent of its dry braking capability on the flooded grooved asphalt at the calculated hydroplaning speed, but only achieved 20 percent on the flooded ungrooved asphalt. The F-4D aircraft maintained 35 percent of its dry braking capability on the flooded grooved asphalt at the calculated hydroplaning speed but on the flooded ungrooved asphalt, the braking effectiveness of the F-4D was completely lost.

During the 990 aircraft test program the effect of runway grooves on aircraft braking performance for a slush-covered surface condition was also evaluated. A 50-ft-wide by 600-ft-long slush bed on grooved and ungrooved concrete (surfaces C and D) was prepared early in the morning by feeding 50 tons of ice in the form of 300-lb cakes into ice crusher-slinger machines and spraying the resulting snow-ice mixture onto the runway. The slush test bed which resulted from this operation is shown in figure 22. In order to expedite the application of the snow-ice mixture and achieve a uniform slush-bed consistency, four ice crusher-slinger machines were used, with two machines starting on each side of the test bed at the midpoint. As the snow-ice spraying operation progressed, the two machines on each side of the test bed moved apart until the desired test bed length, width, and depth were obtained. The snow-ice sprayed on the test surface was uniformly leveled and allowed to melt into the ice-water consistency of slush. Just prior to the initial aircraft test run, 12 samples were taken by using the method described in reference 8 to determine the average depth and specific gravity of the slush. The average slush depth on the runway test surfaces was 0.5 in. with an average specific gravity of 0.83.

For this slush-covered condition, the 990 aircraft braking performance data obtained on grooved and ungrooved concrete (surfaces C and D) are shown in figure 23. For comparison, effective braking ratios obtained for the wet condition with isolated puddles and for the flooded condition are also shown as a function of the ground velocity ratio. Significant improvement in 990 aircraft braking capability throughout the test speed range is indicated by comparison of the data obtained on the grooved concrete test surface with the data obtained on the similar ungrooved surface for the wet, flooded, and slush-covered conditions. The increase in effective braking ratio on the slush-covered ungrooved concrete surface as the aircraft approached the critical hydroplaning speed of 114 knots is a result of the buildup in slush spray impingement drag on the 990 aircraft. This slush drag on the aircraft decreases at or above critical hydroplaning speed on the ungrooved surface because the tires are displacing less slush from the runway. Similar aircraft braking test results on slush-covered ungrooved surfaces were obtained during the joint FAA-NASA slush tests with the 880 aircraft discussed in reference 8.

During the 990 aircraft braking tests on the slush-covered surfaces, the improvement in aircraft directional control provided by runway grooves was also demonstrated. In the time-lapse aerial photographs shown in figure 24, the 990 aircraft entered the slush-covered grooved concrete surface at an initial ground speed of 93.5 knots. With a 4-knot cross wind present and maximum antiskid braking being applied, the 990 aircraft maintained directional control on the runway center line on the slush-covered grooved concrete surface. The main-wheel velocity traces on the oscillograph record indicated no wheel lockup during this phase of the test run. However, when the aircraft entered the slush-covered ungrooved surface, main-wheel lockups did occur because of the abrupt reduction in the friction level provided by the runway surface. As a result of the locked-wheel condition combined with the 4-knot cross wind, directional control of the 990 aircraft was not possible and the aircraft rotated into the wind, or weathercocked, as indicated in photograph 4 of figure 24.

The effect of runway grooves on the 990 aircraft main-wheel spin-up rate was also evaluated during a series of touch-and-go type tests on flooded grooved and ungrooved concrete (surfaces C and D). During these touchdown tests without braking a direct comparison of the main-wheel spin-up rates occurred during one test when the left main gear touched down first on the flooded grooved concrete and moments later the right main gear touched down on the adjacent flooded ungrooved surface. A time history of the outboard main-wheel velocity traces obtained during this test is shown in figure 25. The 990 aircraft was equipped with smooth main-gear tires during this test. As indicated by the wheel velocity traces (fig. 25), full main-wheel spin-up occurred in approximately 0.6 sec from touchdown on the flooded grooved section compared with approximately 0.9 sec on the flooded ungrooved section for the rear outboard wheel. The front outboard wheel on the right main gear, however, did not attain full spin-up until encountering a dry surface, a result which is indicative of the relatively low friction developed between the smooth tire and the flooded ungrooved surface. The path clearing of the surface water by the front tire resulted in the shorter spin-up time for the rear wheel on the right main gear than for the front wheel. The rapid wheel spin-up provided by runway grooves for flooded conditions is important in alleviating not only dynamic hydroplaning but also reverted rubber skids which occur during prolonged wheel lockups. (See ref. 9.)

Effect of runway surface water depth.- On the Gripstop (see ref. 7) transition section (surface E) having a length of 650 ft and a slope of 0.1 percent, aircraft braking test runs were conducted with just the lower half of the surface wet or flooded, leaving the upper half dry. During the braking tests on this surface, however, the wetness condition of the surface varied from a damp condition with no standing water to a deeply flooded condition with a water depth of 0.4 in. at the lower end of the surface. For these test-surface conditions, figure 26 shows a time history of main-wheel velocity and longitudinal accelerometer traces obtained during a high-speed maximum antiskid braking run with the 990 aircraft equipped with smooth tires. Maximum braking was obtained on the dry portion of the Gripstop test surface resulting in a 0.5g deceleration prior to the aircraft entering the damp surface area. As the 990 aircraft under maximum braking traveled through the damp area into the deeply flooded surface, braking effectiveness was reduced to near zero and numerous wheel lockups resulted. When brake release occurred as indicated in figure 26, the two forward wheels on the left main gear remained locked under hydroplaning conditions until encountering a dry, high friction level surface.

This hazardous locked-wheel condition, shown in figure 26 and discussed in references 3 to 6, results in complete loss of directional control or the inability of the tire to develop appreciable side force. The effect of this locked-wheel condition combined with a 12-knot cross wind which was present during the 990 aircraft braking test run on the Gripstop surface is shown in figure 27. The time-lapse photographs of the 990 aircraft were taken with a camera located at the end of the runway center line. The sequence of test-run events was as follows: (1) the aircraft entered the dry portion of surface E off the runway center line; (2) during maximum antiskid braking on the dry and the damp test areas of surface E, the pilot had directional control of the aircraft and was able to regain the runway center line (see photographs 1 and 2 in fig. 27); (3) upon entering the deeply flooded test area, numerous main-wheel lockups occurred (see fig. 26) which resulted in complete loss of aircraft directional control; and (4) the aircraft started to drift laterally off the runway center line (see photograph 4 in fig. 27). The severe lateral drifting of the 990 aircraft during this braking run with a 12-knot cross wind continued until the pilot released brakes and the aircraft encountered a dry high friction surface. With these hazardous conditions present on the entire length of an active ungrooved runway, safe aircraft landing operations would certainly be jeopardized.

Effect of tire tread design.- In past research work (see refs. 3 to 6), aircraft tire tread design has been shown to be an important factor in developing traction on wet or flooded ungrooved runway pavements. To evaluate further the effects of tire tread design, specially molded, smooth retread tires having new tire tread skid depths, as well as 5-groove rib-tread tires, were used during the 990 aircraft test program. A comparison of the aircraft braking data obtained with the 5-groove and the smooth tires on wet grooved and ungrooved concrete (surfaces C and D) is shown in figure 28. The dry braking friction coefficient level indicated in figure 28 did not vary significantly with tire tread design or surface configuration. For the wet ungrooved concrete, however, the 5-groove-tire data indicate a significant improvement in braking capability compared with the smooth-tire data. On the wet grooved concrete, the transverse runway grooves provided substantially greater braking friction levels with both tire tread designs than were shown by the data obtained on the wet ungrooved concrete. The data also indicate that runway grooves tend to minimize the effects of tire tread design and tire wear on braking friction capability.

CONCLUDING REMARKS

The F-4D and the 990 aircraft braking test results obtained on dry, wet, flooded, and slush-covered grooved and ungrooved surfaces at the landing research runway at NASA Wallops Station have substantiated and supplemented the results obtained at the Langley landing-loads track. The comparative aircraft test results indicate that transverse runway grooves provide (1) substantially increased aircraft braking capability and directional control, (2) improved runway surface water drainage, and (3) more rapid wheel spin-up rates. Runway grooves were also shown to minimize the effects of tire tread design or tire wear and the susceptibility to dynamic tire hydroplaning and reverted rubber skids. To obtain a complete evaluation of the effects of runway grooves on aircraft landing and take-off operations, more aircraft tests are planned at the landing research runway. The effects of traffic, loading, and weathering on grooved surface deterioration have yet to be determined although the test results obtained with the F-4D and 990 aircraft are very encouraging.

REFERENCES

1. Joyner, Upshur T.; and Horne, Walter B.: Considerations on a Large Hydraulic Jet Catapult. NACA TN 3203, 1954. (Supersedes NACA RM L51B27.)

2. Joyner, Upshur T.; Horne, Walter B.; and Leland, Trafford J. W.: Investigations on the Ground Performance of Aircraft Relating to Wet Runway Braking and Slush Drag. AGARD Rep. 429, Jan. 1963.

3. Horne, Walter B.; Yager, Thomas J.; and Taylor, Glenn R.: Review of Causes and Alleviation of Low Tire Traction on Wet Runways. NASA TN D-4406, 1968.

4. Leland, Trafford J. W.; Yager, Thomas J.; and Joyner, Upshur T.: Effects of Pavement Texture on Wet-Runway Braking Performance. NASA TN D-4323, 1968.

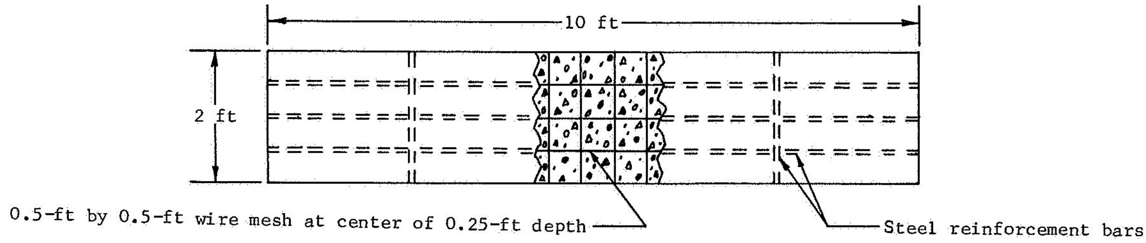
5. Horne, Walter B.; and Dreher, Robert C.: Phenomena of Pneumatic Tire Hydroplaning. NASA TN D-2056, 1963.

6. Horne, Walter B.; and Leland, Trafford J. W.: Influence of Tire Tread Pattern and Runway Surface Condition on Braking Friction and Rolling Resistance of a Modern Aircraft Tire. NASA TN D-1376, 1962.

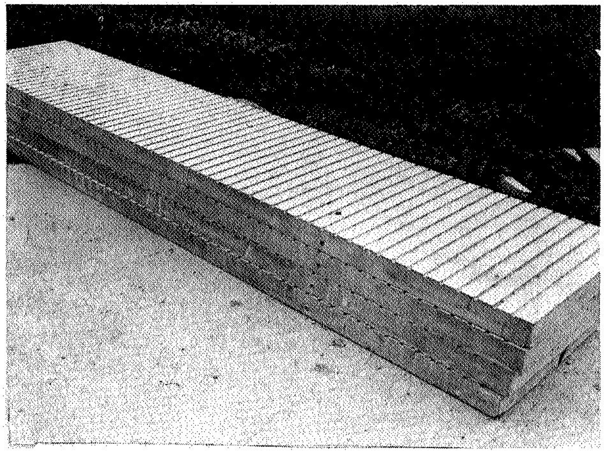
7. Horne, Walter B.: Results From Studies of Highway Grooving and Texturing at NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 26 herein.)

8. Anon.: Joint Technical Conference on Slush Drag and Braking Problems. FAA and NASA, Dec. 1961.

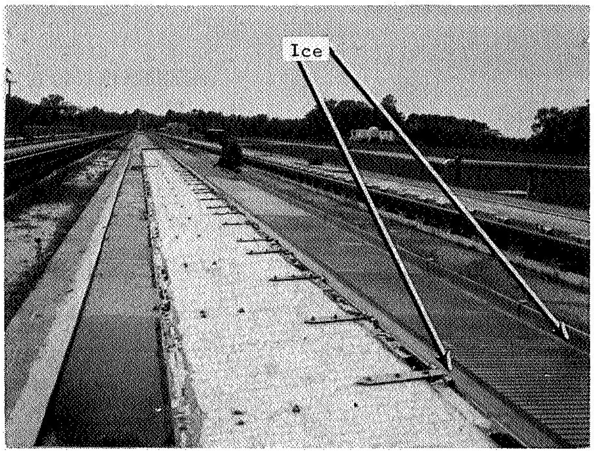
9. Nybakken, G. H.; Staples, R. J.; and Clark, S. K.: Laboratory Experiments on Reverted Rubber Friction. Tech. Rep. No. 7 (NASA Grant No. NsG-344), College Eng., Univ. of Michigan, Oct. 1968.



(a) Plan drawing of precast concrete test strips.



(b) Grooved concrete strips before testing.



(c) Concrete strips installed in runway.

Figure 1.- Precast concrete test strips.

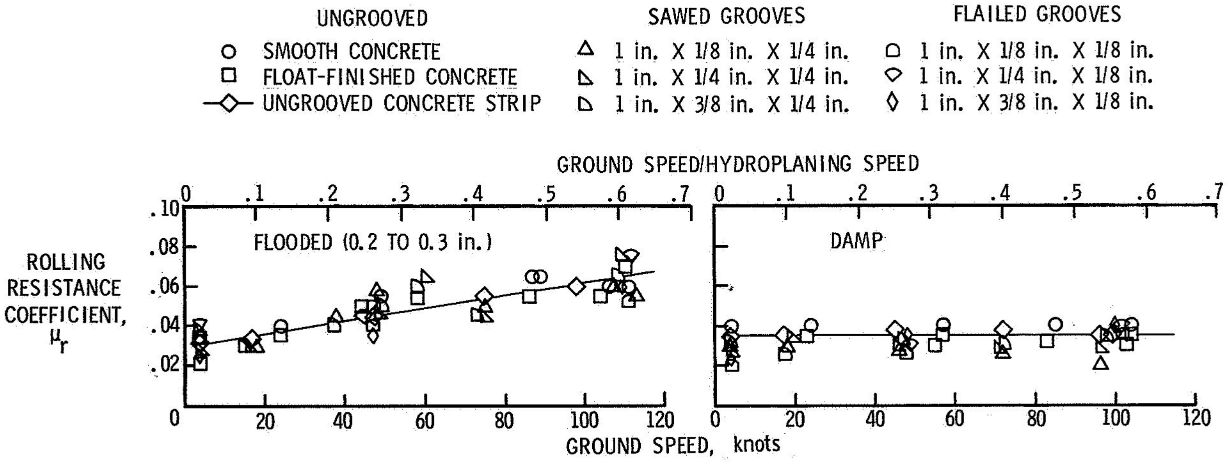
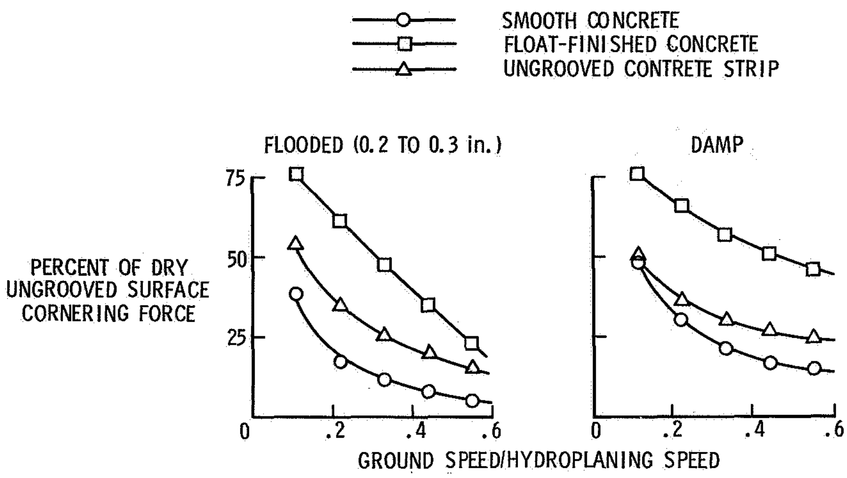
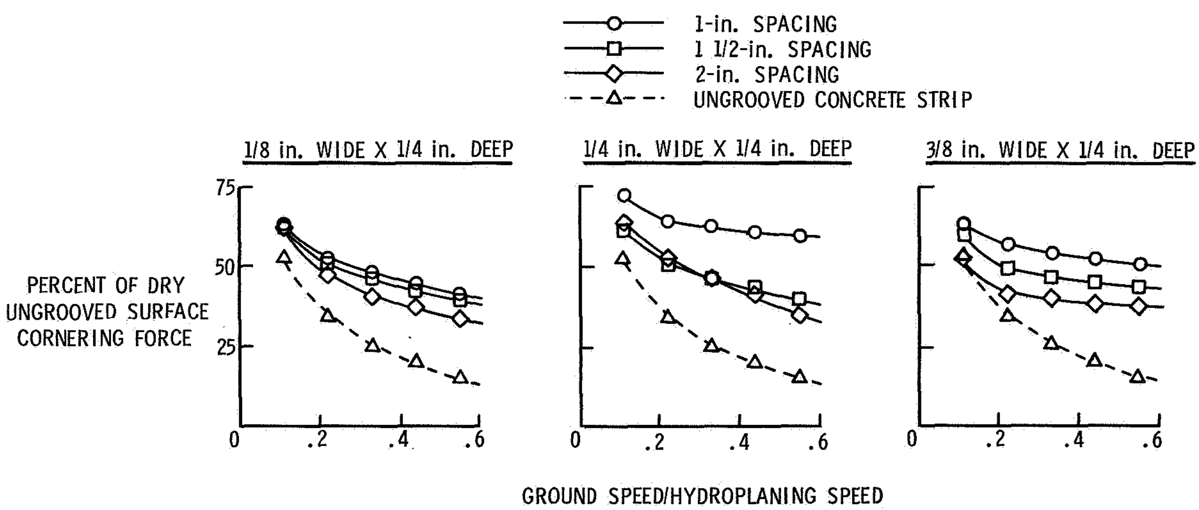


Figure 2.- Effect of runway wetness condition and surface configuration on rolling resistance of unbraked smooth, type VIII, 27.5 × 7.5 tire. Yaw angle, 4^0; inflation pressure, 400 lb/in^2.

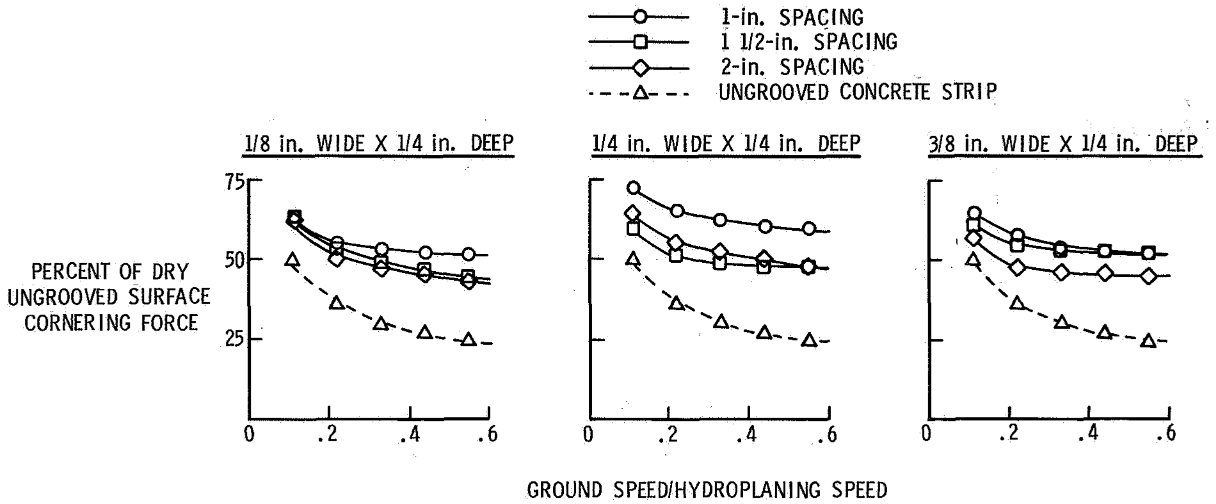


(a) Ungrooved surfaces.

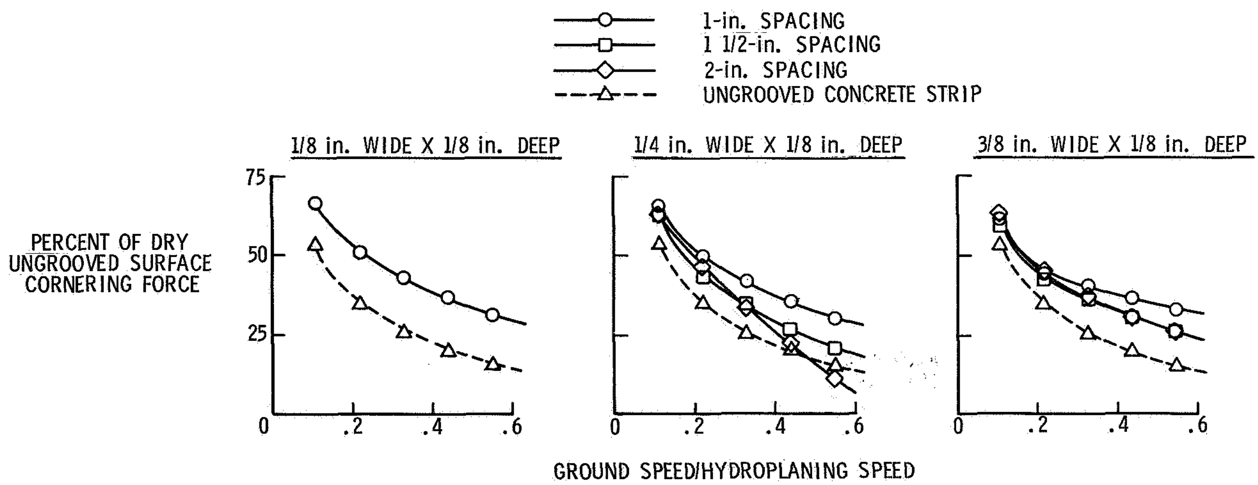


(b) Sawed grooves; flooded (0.2 to 0.3 in.).

Figure 3.- Effect of runway wetness condition and surface configuration on the cornering force of smooth, type VIII, 27.5 × 7.5 tire. Yaw angle, 4°; inflation pressure, 400 lb/in².

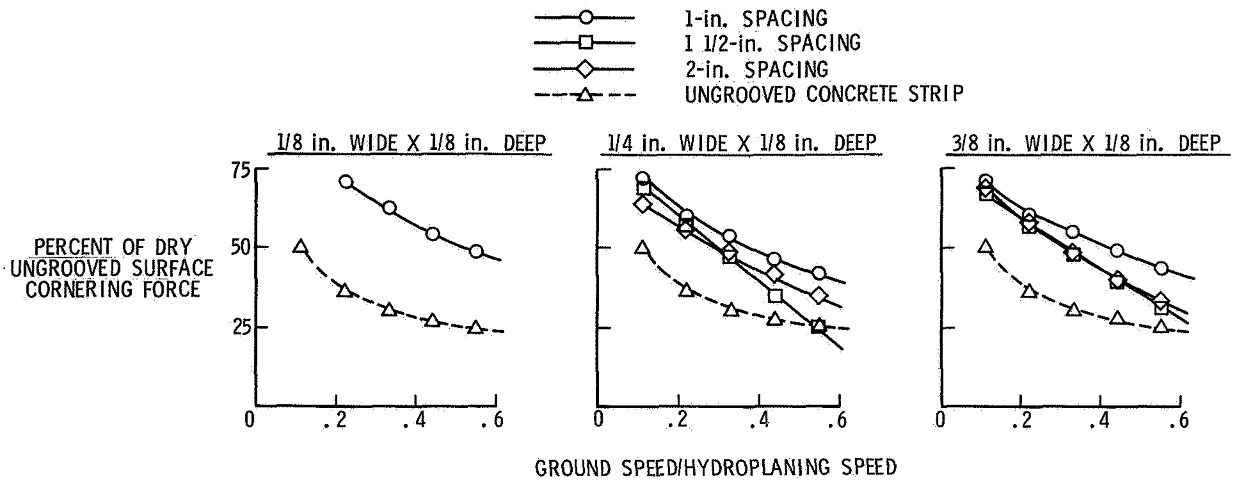


(c) Sawed grooves; damp.



(d) Flailed grooves; flooded (0.2 to 0.3 in.).

Figure 3.- Continued.



(e) Flailed grooves; damp.

Figure 3.- Concluded.

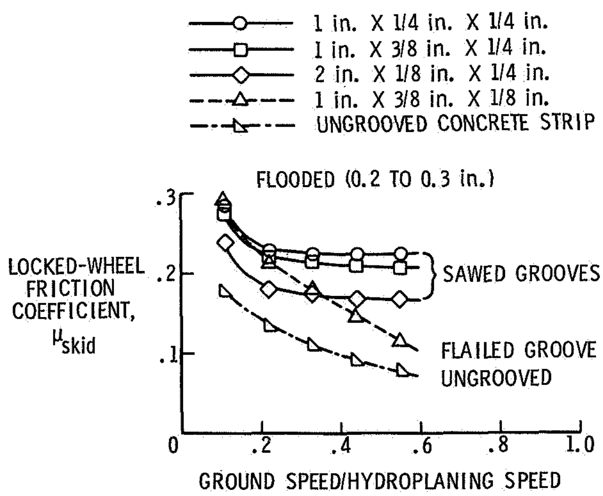


Figure 4.- Effect of runway surface configuration on locked-wheel friction coefficient of smooth, type VIII, 27.5 × 7.5 tire. Yaw angle, 4^{o}; inflation pressure, 400 lb/in^2.

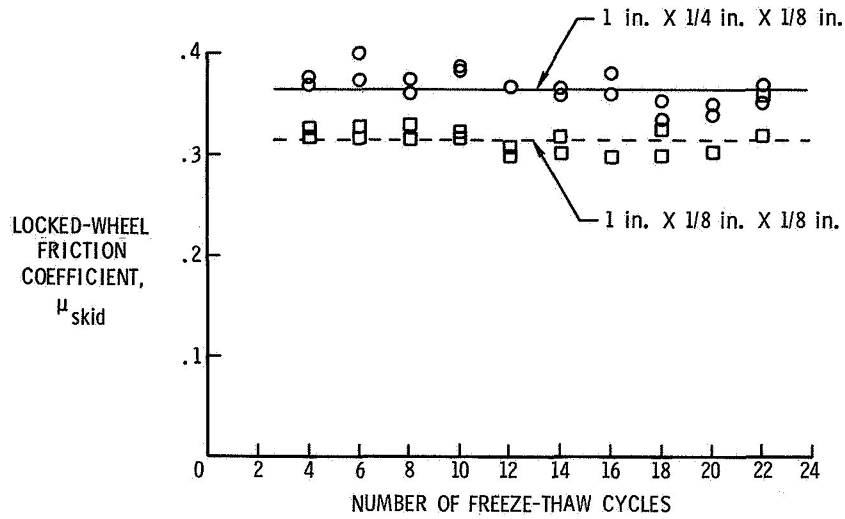


Figure 5.- Effect of alternately freezing and thawing flooded grooves on locked-wheel friction coefficient of 3-groove, type VIII, 30 × 11.5-14.5 tire. Yaw angle, 0°; inflation pressure, 210 lb/in^2; ground speed, 4 knots.

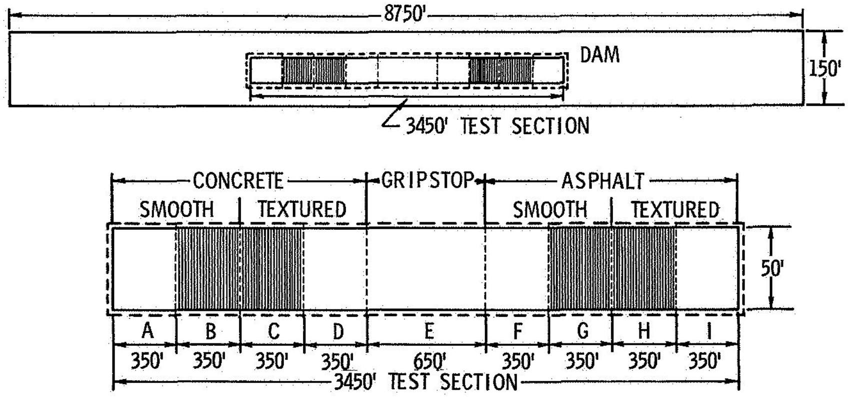
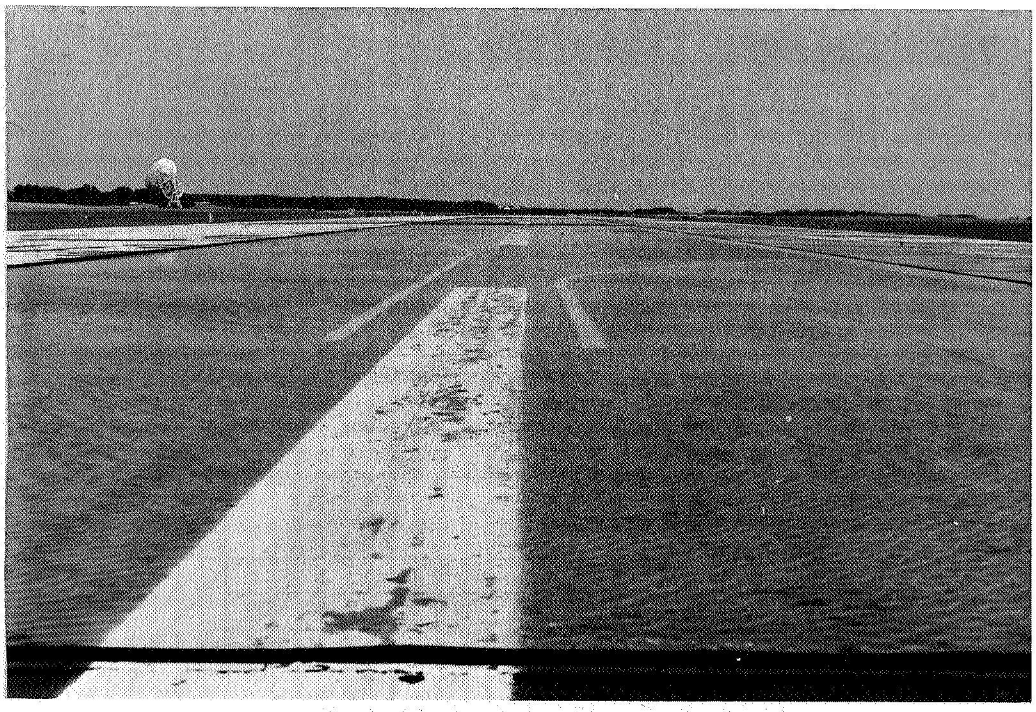


Figure 6.- Landing research runway at NASA Wallops Station.

(a) Wet with isolated puddles.



(b) Flooded.

Figure 7.- Surface wetness conditions on landing research runway.

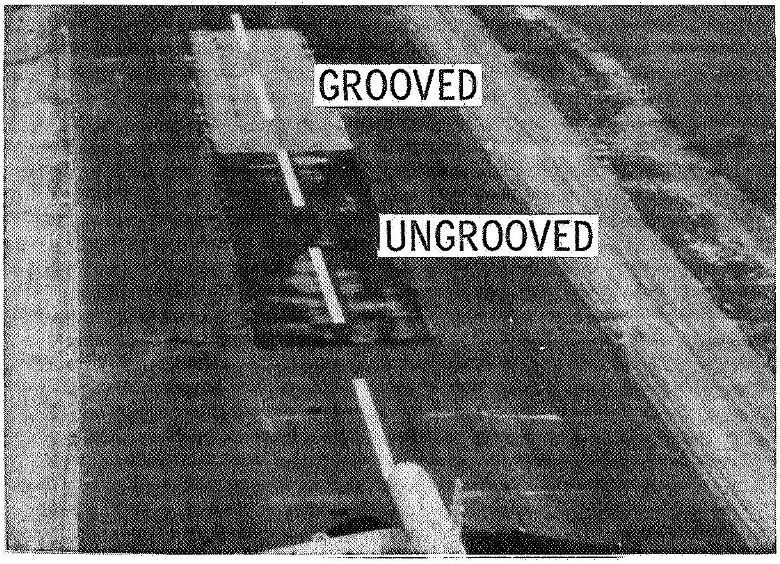


Figure 8.- Effect of runway grooves on water drainage.

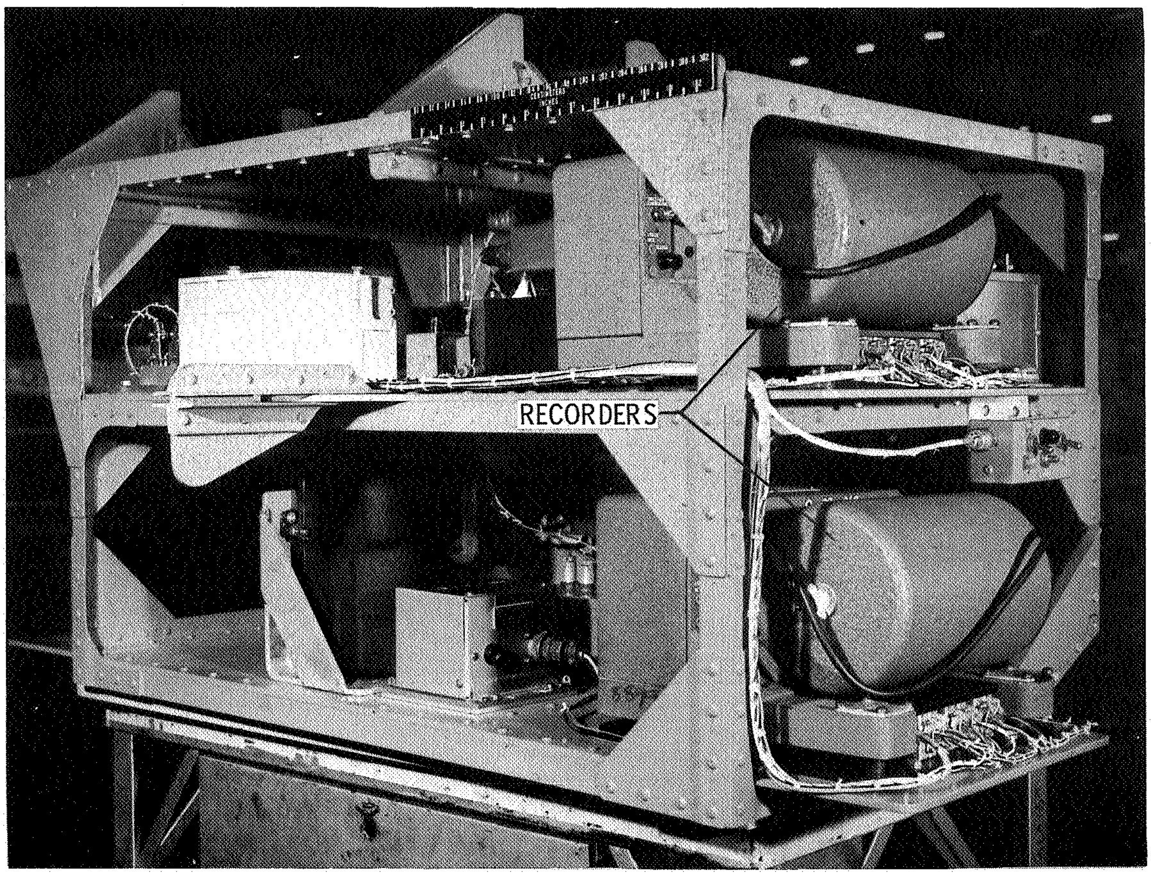


Figure 9.- Onboard instrument package for aircraft tests.

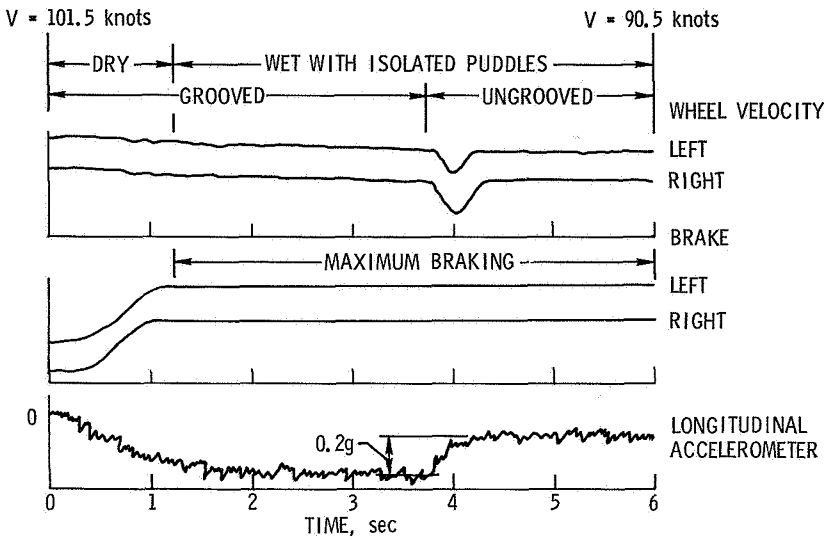


Figure 10.- Effect of wet grooved and ungrooved surfaces on F-4D aircraft braking. 3-groove tires; inflation pressure, 280 lb/in^2; concrete.

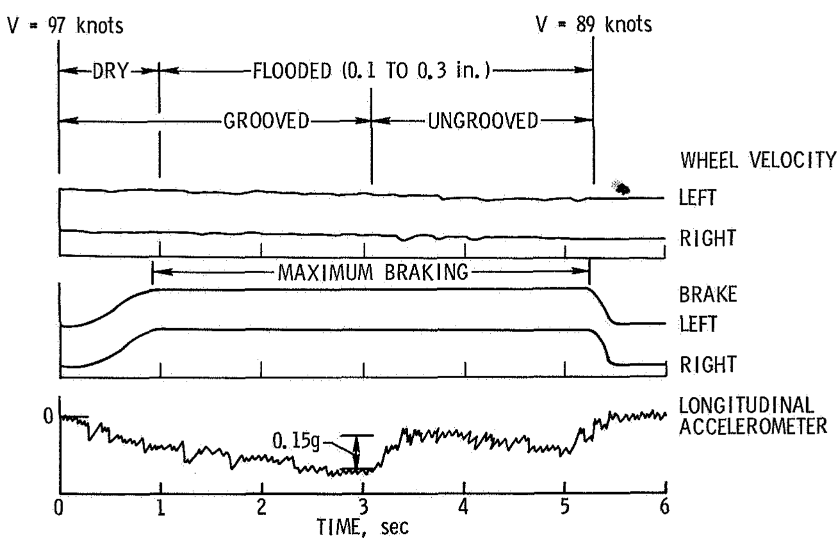


Figure 11.- Effect of flooded grooved and ungrooved surfaces on F-4D aircraft braking. 3-groove tires; inflation pressure, 280 lb/in^2; concrete.

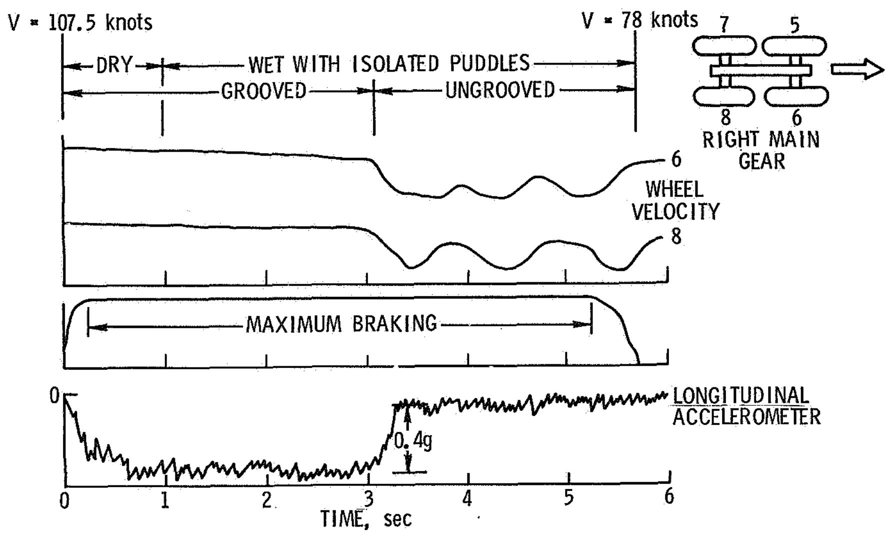


Figure 12.- Effect of wet grooved and ungrooved surfaces on 990 aircraft braking. Smooth tires; inflation pressure, 160 lb/in^2; concrete.

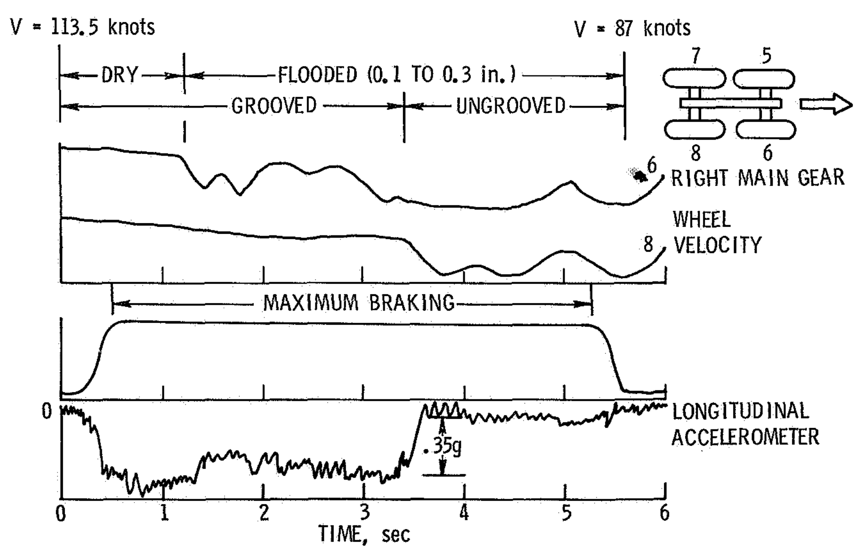


Figure 13.- Effect of flooded grooved and ungrooved surfaces on 990 aircraft braking. Smooth tires; inflation pressure, 160 lb/in^2; concrete.

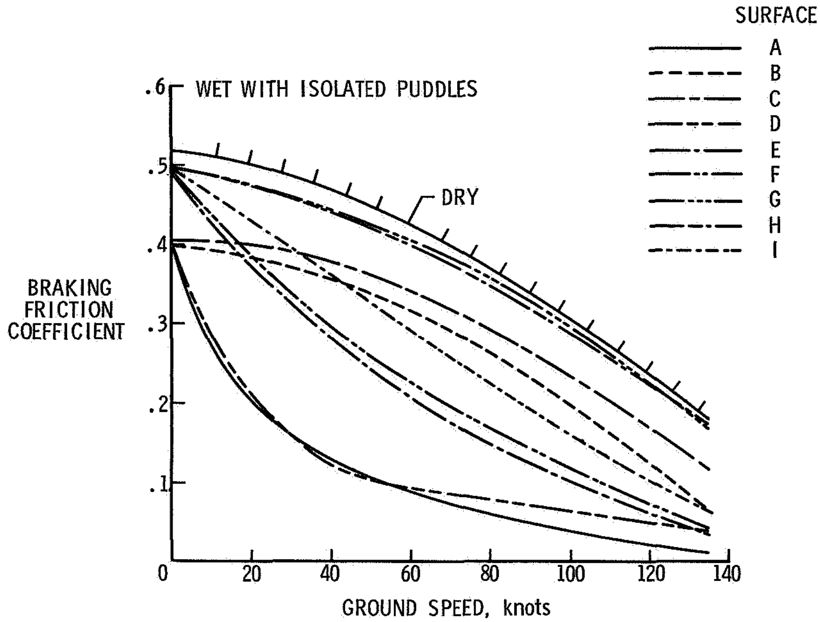


Figure 14.- Variation of F-4D aircraft braking friction coefficient with ground speed on wet grooved and ungrooved surfaces. 3-groove, type VIII, 30 × 11.5-14.5 main tires; inflation pressure, 280 lb/in^2.

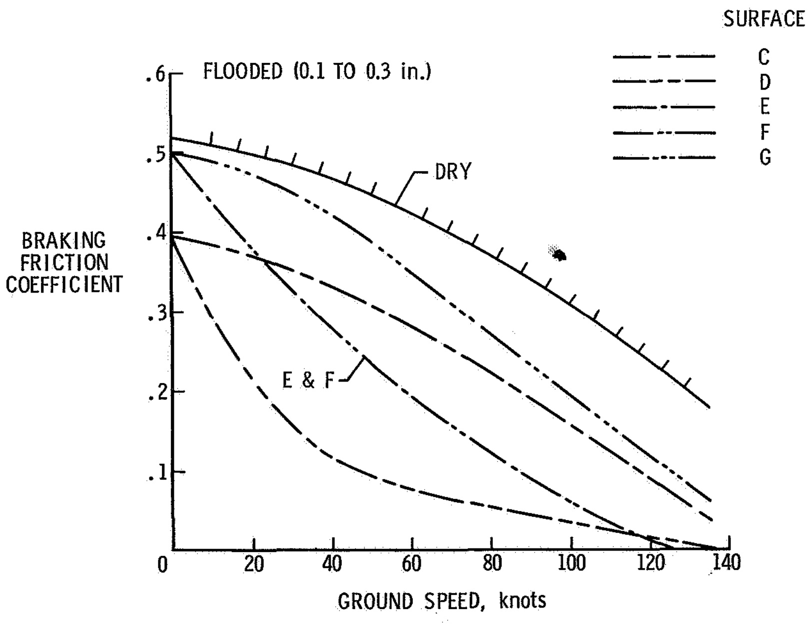


Figure 15.- Variation of F-4D aircraft braking friction coefficient with ground speed on flooded grooved and ungrooved surfaces. 3-groove, type VIII, 30 × 11.5-14.5 main tires; inflation pressure, 280 lb/in^2.

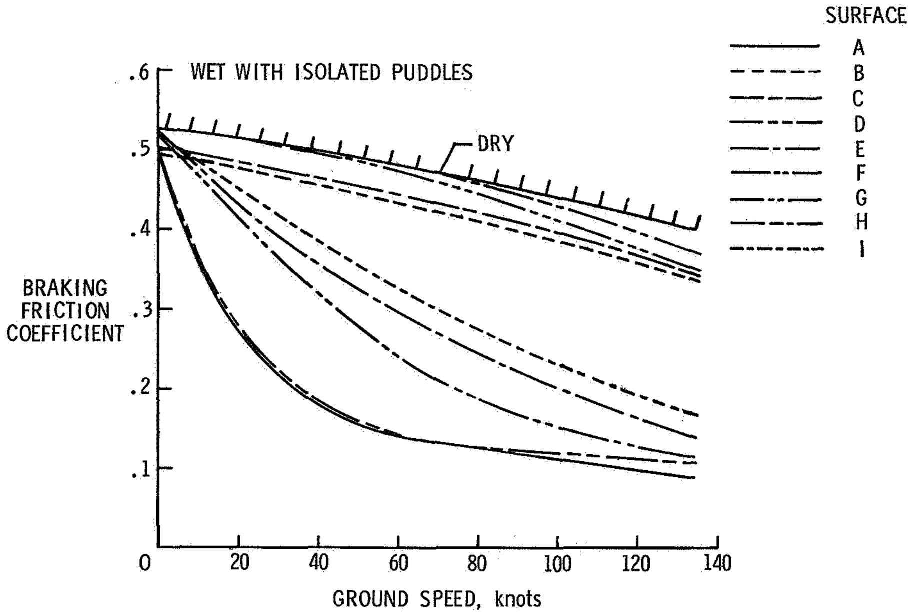


Figure 16.- Variation of 990 aircraft braking friction coefficient with ground speed on wet grooved and ungrooved surfaces. 5-groove, type VIII, 41 × 15.0-18 main tires; inflation pressure, 160 lb/in^2.

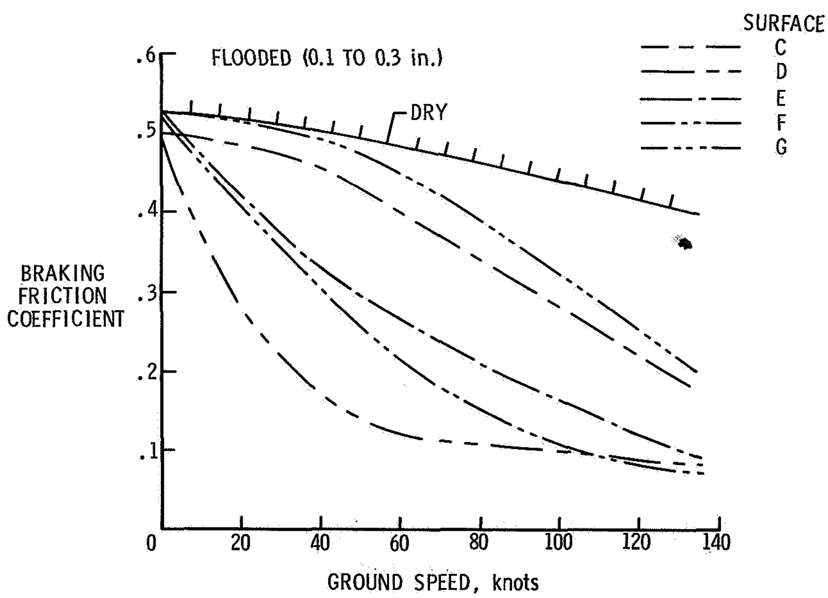


Figure 17.- Variation of 990 aircraft braking friction coefficient with ground speed on flooded grooved and ungrooved surfaces. 5-groove, type VIII, 41 × 15.0-18 main tires; inflation pressure, 160 lb/in^2.

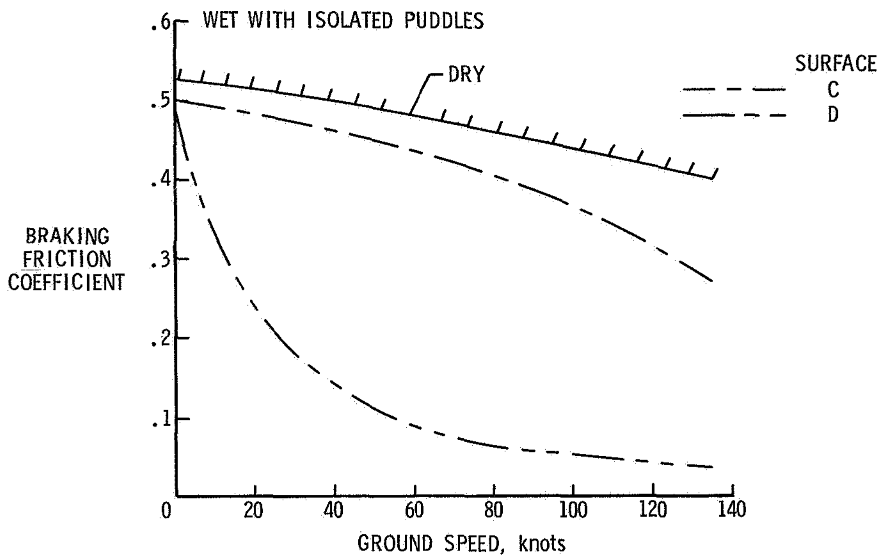


Figure 18.- Variation of 990 aircraft braking friction coefficient with ground speed on wet grooved and ungrooved surfaces. Smooth, type VIII, 41 × 15.0-18 main tires; inflation pressure, 160 lb/in^2.

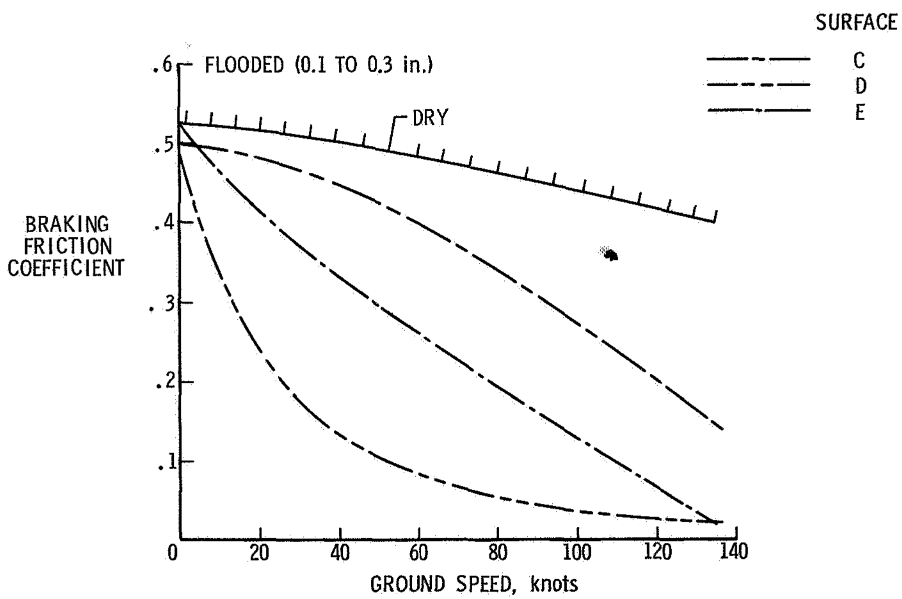


Figure 19.- Variation of 990 aircraft braking friction coefficient with ground speed on flooded grooved and ungrooved surfaces. Smooth, type VIII, 41 × 15.0-18 main tires; inflation pressure, 160 lb/in^2.

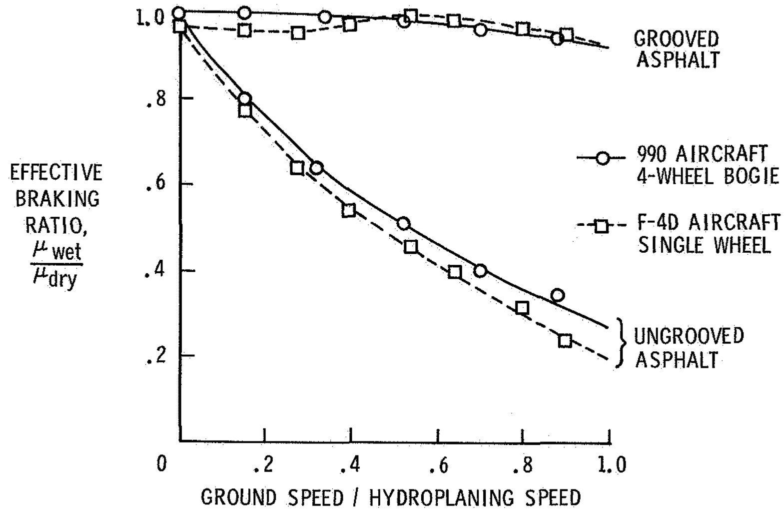


Figure 20.- Effect of runway grooves on aircraft braking performance. Wet with isolated puddles.

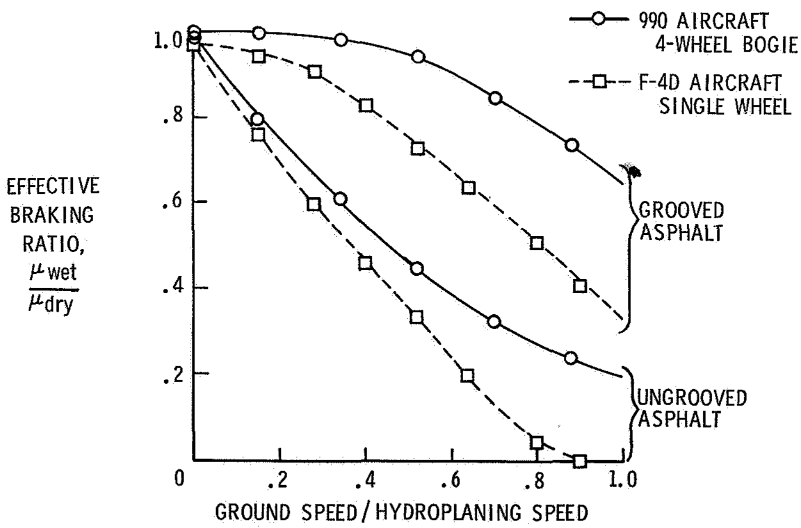


Figure 21.- Effect of runway grooves on aircraft braking performance. Flooded (0.1 to 0.3 in.).

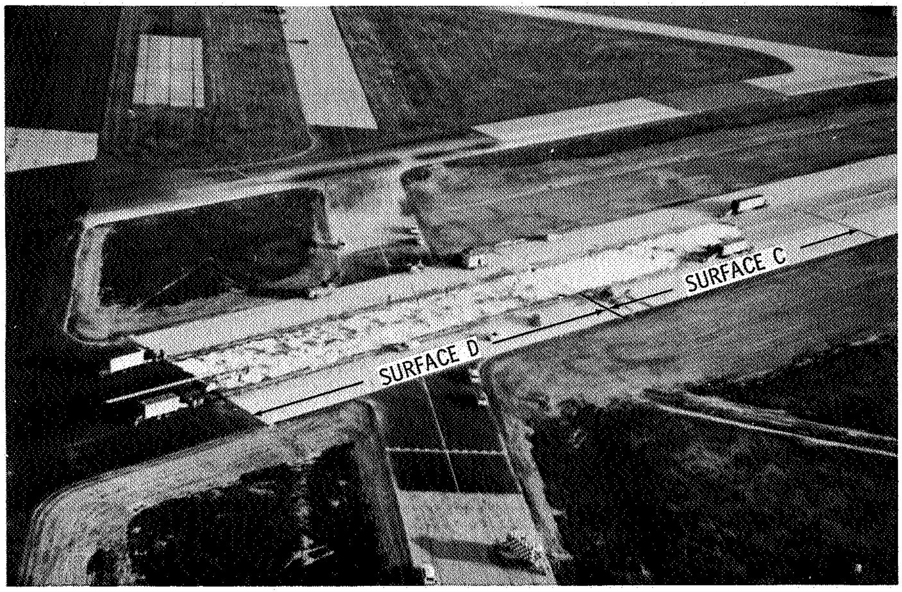


Figure 22.- Slush-covered runway surface condition.

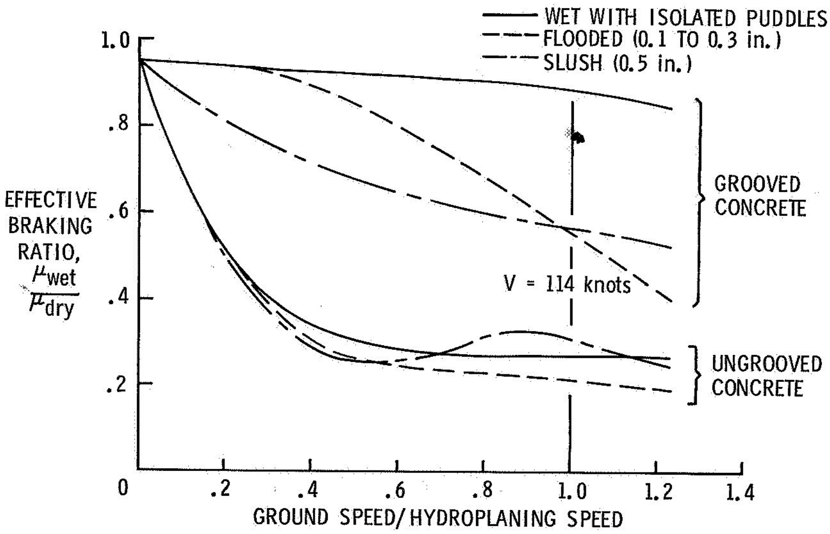


Figure 23.- Effect of runway grooves on 990 aircraft braking performance. 5-groove tire; inflation pressure, 160 lb/in^2.

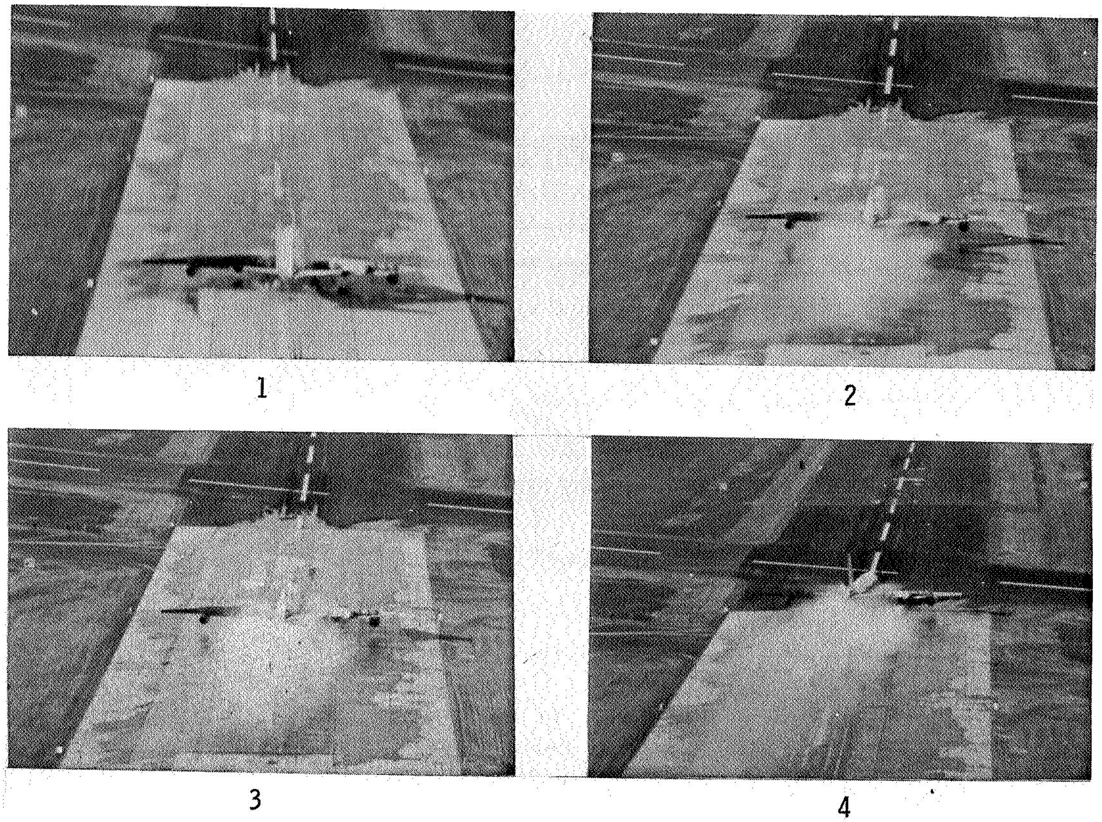


Figure 24.- Effect of slush-covered runway grooves on directional control of 990 aircraft. Cross wind, 4 knots.

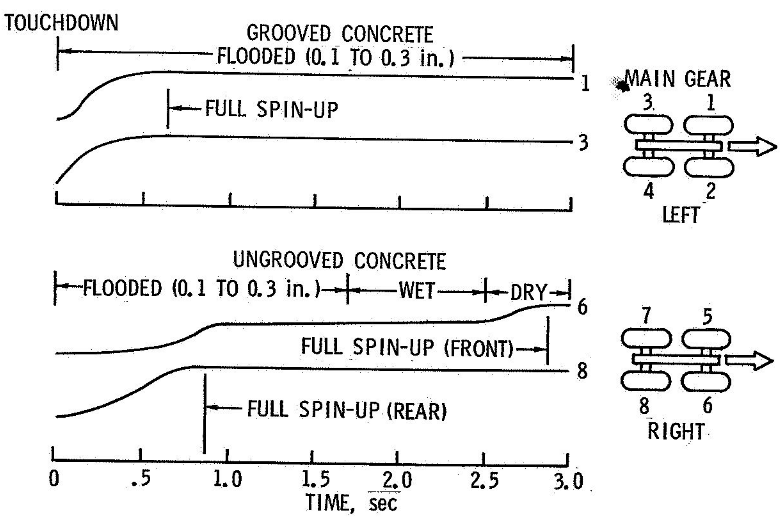


Figure 25.- Effect of runway grooves on 990 aircraft main-wheel spin-up rate. Smooth tires; inflation pressure, 160 lb/in^2.

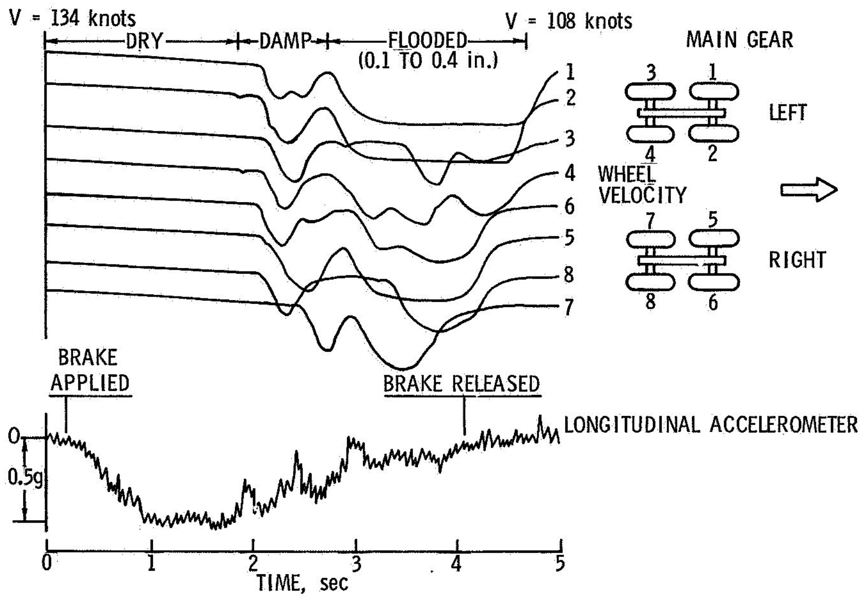


Figure 26.- Effect of water depth on 990 aircraft braking performance. Smooth tires; inflation pressure, 160 lb/in^2; Gripstop; cross wind, 12 knots.

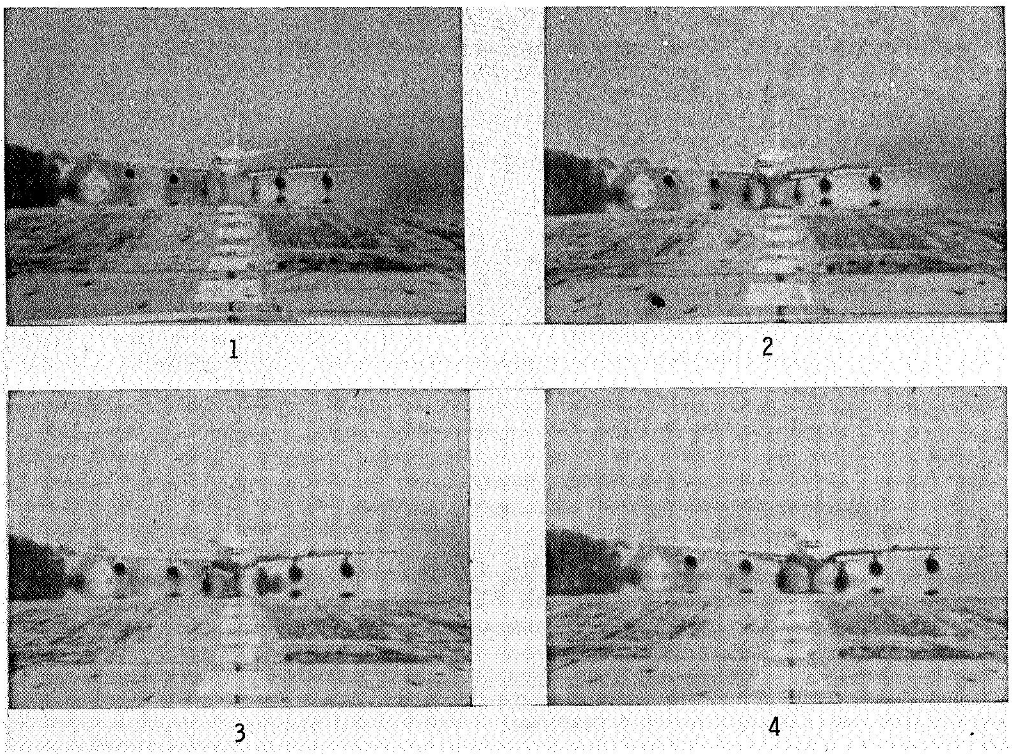


Figure 27.- Loss of directional control of 990 aircraft during braking test run on Gripstop. Cross wind, 12 knots.

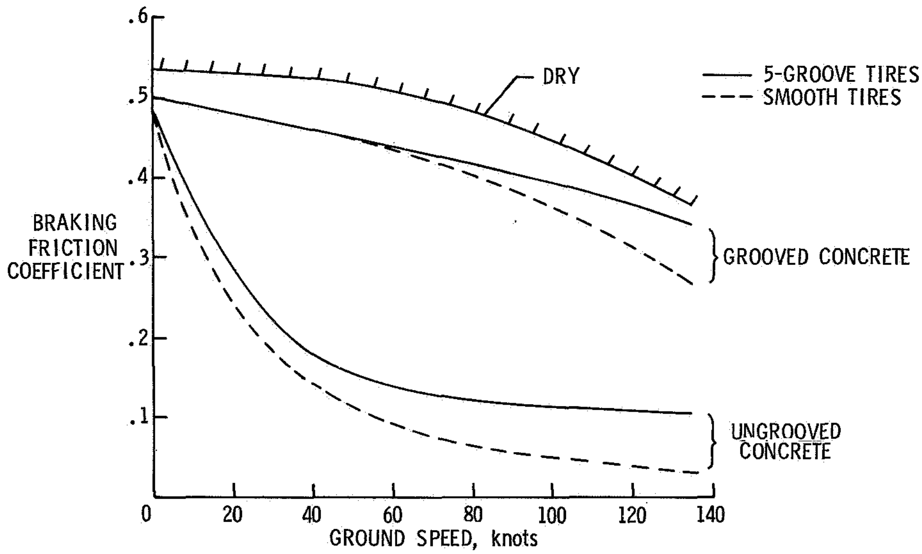


Figure 28.- Effect of tire tread design on 990 aircraft braking friction coefficient.
Wet with isolated puddles.

4. R.A.E. AIRCRAFT TESTS ON GROOVED, OPEN GRADED AND ASPHALT RUNWAYS IN GREAT BRITAIN

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SUMMARY

Plans for aircraft tests to determine the wet braking force coefficients obtainable on runways with widely differing surface textures are given. Initial tests made with a Scimitar aircraft on the runways at the Royal Aircraft Establishment at Farnborough, and the allied work, are described. The results support the view that a harsh, coarse textured surface will give improved braking at aircraft touchdown speeds.

INTRODUCTION

For some years it has been appreciated that the braking forces which can be developed in wet conditions by a vehicle tyre are far more dependent on the characteristics of the surface on which the tyre is running than on the tyre or its tread. In particular, it has been established that the wet friction coefficient, especially with a natural rubber unpatterned tread, does not decrease with increasing speed to the same extent on harsh, coarse textured surfaces as on other surface finishes (ref. 1). It was thought that this finding would hold for the much more highly stressed aircraft tyre also; therefore, for such tyres it would also be better to introduce coarse textured runway surface finishes rather than to modify the tyre tread in order to obtain the higher wet braking coefficients now likely to be required. Also, it was thought that, inasmuch as tyre wear now causes considerable concern, footprint drainage should preferably be through interstices built into the runway surface instead of by channels or grooves cut in the tread rubber and, further, that any significant technological advances in tread material should be employed to improve the tyre life rather than to build a complicated siped and patterned high friction tread.

Runway grooving has already been employed widely on military aerodromes and an open graded macadam friction course has been developed and laid at one aerodrome. Tests on the latter surface have been confined to measurements made with a locked wheel trailer or a vehicle and the results have indicated improved wet friction. Pilots' reports were also very favourable. No specific measurements of the rate of tyre wear associated with the surfacing have been made. Road experience has suggested that the frictional properties of grooving would be lower than that of coarse textured surfacing at aircraft landing speeds and would, moreover, be directional. It was decided, therefore, to supplement the tests made for the Air Ministry and the Ministry of Public Building and Works engineers on different runway surfacing with a series of tests to determine the wet braking coefficients which could be obtained with aircraft fitted with antiskid systems on as wide a variety of surfaces as possible. The initial tests made on the runways at the Royal Aircraft Establishment at Farnborough, and the supporting work, are described in this paper.

It is a widely held view that if harsh, coarse-texture surfacing is used on runways, greatly increased tyre wear must result. It was reasoned at the Establishment, however, that wear is related to the kinetic energy destroyed in braking and the texture of surface finishes would have little direct effect on wear; nevertheless, it was thought advisable to plan comparative wear tests on different surfaces. One such test has been completed and is reported.

In addition, a study which was made of the available statistics on tyre life is included inasmuch as this study indicates the magnitude of the problem facing tyre designers if the demand for increased wet friction, together with adequate tyre life, is to be met by tyre modification alone.

TEST SURFACES

The three runways at Farnborough have the following friction courses:

Main runway – Grooved Marshall asphalt to BS 594

Subsidiary runways – Plain Marshall asphalt and open graded macadam of larger aggregate than the standard recommended (The standard open graded macadam was developed for the Air Ministry to provide a friction course through which water could drain.)

Figure 1 shows plaster casts of the three surfaces. Casts were taken as they bring out the texture. Figure 2 shows the concrete finishes recently laid at a Royal Air Force aerodrome, together with a type of road surface finish similar to that recommended for motorways, which is being laid at Cranfield. Tests of these surfaces are planned.

SPIN-UP WEAR ON DIFFERENT FRICTION COURSES

Before it was finally decided to lay a friction course at Cranfield aerodome similar to the recommended road finish, a rig test was made to determine the damage caused to both the tyre and the surface by wheel spin-up (ref. 2). It was done on an undercarriage drop test rig using a 40 × 12, type VII, 16-ply-rating nylon tyre at 140 psi. The wheel was spun up to the equivalent of a touchdown at 105 knots and dropped at $7\frac{1}{2}$ ft/sec on slabs of the recommended road, open graded macadam, and Marshall surfacing. The maximum vertical reaction was 35 000 lb. Some twenty drops were made on each surface with one tyre and the damage to the tyre was up to $\frac{1}{10}$-in-deep striations in the centre three ribs of the tread rubber on the recommended road surface; these striations were widened on the open graded macadam finish with small sections of the rubber being torn out of the tread on this surface and on the Marshall surface which was tested last. No stone was lost from the recommended road surface and the damage to the tyre was limited (fig. 3). On the basis of these results, laying of a section of the recommended road surfacing is proceeding at Cranfield for aircraft tests.

COMPARATIVE WEAR TESTS

One test comparing the wear on the open graded macadam subsidiary runway with that on the grooved asphalt main runway has been completed (ref. 3). Thirty-five landings were made on each runway in dry weather with a Meteor Mk.7 aircraft equipped with low pressure tyres (60 psi). Five pilots participated in the test and each made, insofar as it was practicable, the same number of landings on each surface. They aimed for a touchdown speed of 105 knots and a brakes-on speed of 95 knots. The aircraft brakes did not develop sufficient torque to lock the wheel on a dry runway so that maximum braking could be used and almost the same decelerations (0.2g) could be achieved on every landing. It was found that the wear was significantly less on the open graded macadam friction course, being 8.2 percent less as determined by groove depth measurement and 10.6 percent less by loss of weight.

This result was supported by accelerated wear tests carried out by the Natural Rubber Producers Research Association on motor vehicle tyres (ref. 4). In these tests, tyres were mounted on a towed trailer with the wheels alternately toed in and out to give slip angles of $\pm 7\frac{1}{2}^{\circ}$.

It is believed that by making tests with an aircraft, in which similar decelerations are recorded by all test pilots, the true wear rating of the runway is obtained; moreover, these decelerations were comparable with those normally used in Civil airline operation. Further wear tests with higher pressure tyres are planned.

FOOTPRINT DRAINAGE THROUGH THE FRICTION COURSE

An investigation of the drainage available under the tyre footprint from the different surface finishes has been started. The object is to provide a rig which gives a measure of the flow of water through the footprint—runway-surface interface under a given pressure. The rig is illustrated in figure 4. Water is supplied from a fire engine through a measuring venturi to the centre of a 11-in-diameter circular rubber pad held down on the test surface by a loaded beam pivoted on a bridge piece, which in turn is held down by two heavy vehicles. The preliminary results obtained with this rig are given in figure 5 and indicate the advantage of either a coarse textured or open graded surface, inasmuch as at the same pressure a much greater quantity of water is discharged with these surfaces than with the smoother textured finishes. It is intended to compare the interface discharge with grooved rubber pads representing new and worn ribbed tyres.

BRAKING COEFFICIENT TESTS ON THE FARNBOROUGH RUNWAYS

Preliminary trials were made first with a Meteor aircraft and later with a Lightning aircraft. It is realised that the tests would be conducted much more expeditiously if they were not flight tests and the aircraft could be accelerated and braked within the length of the runway under test. It was also apparent that if the undercarriage flexed appreciably, the measurements would be affected. It was decided that a Scimitar aircraft would be used for the trials proper. It has a high thrust-weight ratio and an antiskid braking system while, being a Naval aircraft, the undercarriage and airframe structure are sturdy. The aircraft was tested at an all up weight of 28 000 lb.

Instrumentation

The Scimitar aircraft was equipped with an accelerometer, stabilised against aircraft pitching by mounting the instrument in a modified master reference gyro. Brake pressure and brake supply pressure were recorded for both port and starboard brakes by pressure transmitters and enabled the antiskid operation to be followed. An airspeed indicator with a low speed range was installed to enable the pilot to gauge his ground speed. As a check on the accelerometer, the aircraft speed was measured at entry to and exit from the test section by the aircraft nose wheel interrupting two light beams across the runway 10 ft apart, which were focused on photoelectric cells starting and stopping an electric timer. (See fig. 6.) A high-speed cinefilm, portraying the aircraft against marker posts along the runway and with a time base, was made and served as an additional check.

Tests

After the first test run with the Scimitar on a dry runway showed that the braking was limited by both the brake pressure and the antiskid system, the brake pressure was increased and the threshold of the antiskid unit was raised. Tests were then made on the grooved asphalt main runway when the weather was fine and showed that with the modification there was no brake torque limitation. Inasmuch as the brakes were operated at increased pressure, it was decided to strip and inspect them after every test run; however, no undue wear was observed.

For each test the aircraft was accelerated to reach the intended speed, allowing for either head or tail wind, at a point some 350 ft short of the test section. The port engine was then flamed out and the starboard engine throttled back to a fast idle. After a free run of about 200 ft, while engine thrust died down, maximum braking was applied; the aircraft then was about 150 ft short of the test section. Maximum braking was maintained until the aircraft came to a halt.

For the tests on a wet surface, water was distributed over the runway surface to a depth of 0.2 inch by water bowsers in a total time of between 5 and 10 minutes, and the test run was made within 5 minutes on this being done. Figure 7 illustrates the aircraft leaving the wetted test section on the open graded surface.

Some trouble was experienced with the interrupted light beam timer, which is experimental, but sufficient readings were obtained to check the operation of the accelerometer on three tests. The differences in the speeds at entry to and exit from the test section agreed, within 2 mph, with those obtained by integration of the acceleration recorded from these two points and until the aircraft came to rest.

Unbraked free running trials were made on the grooved asphalt surface to determine the effect of residual engine thrust, aerodynamic drag, and rolling resistance at four speeds and the aircraft was tracked by a kinetheodolite. These results were used to obtain the net braking. The instantaneous values of the braking force coefficient, as a function of ground speed, are shown in figure 8 for the open graded macadam friction course.

Results

The results of the tests made so far are given in figure 9, together with some measurements made by the Road Research Laboratory (ref. 5) with the Ministry of Technology heavy load vehicle using a similar tyre. The significant features of the aircraft results are as follows:

(1) The marked drop in wet friction on the grooved asphalt surface at high speed was from 0.3 at 90 knots to 0.18 at 110 knots.

(2) The wet friction on the grooved asphalt and on the Marshall surfaces is the same at 90 knots – that is, 0.3.

(3) The open graded coarse aggregate macadam gave a slightly higher wet friction at both 70 and 90 knots than either the Marshall or the grooved asphalt. The tests on this coarse aggregate macadam surface at 110 knots could not be made because the end of the runway was being reconstructed at the time.

(4) The dry friction measured on the grooved asphalt surface at 90 knots is only a little higher than the wet friction on the same surface and is the same as the wet friction on the open graded macadam.

The low dry friction obtained with the Scimitar without brake or brake torque limitations led to a look at some American results for dry friction coefficients where a value of 0.51 at 90 knots was recorded with a tyre at 140 psi and a load of 25 000 lb. The gross footprint area of this tyre is approximately 180 square inches compared with that of 117 square inches of the Scimitar main wheel tyre. This fact together with the lower value found for the Lightning tyre which has a gross footprint area of only 65 square inches and the fact that dry friction values for vehicle tyres are in many cases over 1.0 suggested that since the forces necessary for braking must be developed in the footprint, a study of the kinetic energy dissipated in braking in relation to tyre size might be valuable from both the wear and friction aspects.

TYRE LIFE AND DUTY

It seemed reasonable to expect that the reduction in tyre life in recent years, which is causing some concern, might be related to the increased kinetic energy of the aircraft at landing and some factor affected by tyre size. Landing kinetic energies have risen rapidly. For example, the kinetic energy is nearly 50 times greater for the Concorde than for the DC-3 while tyre sizes have in general decreased, the higher loads being catered for by increasing the number of wheels and the tyre inflation pressure. The idea of a tyre duty, which is defined as the designed braking energy capacity per unit of wearable tread volume, was therefore put forward. Figure 10 shows the relationship between tyre life and tyre duty for a wide range of aircraft tyres. Despite the inadequacies of much of the data on the actual energies which have been absorbed by braking, on tread volumes, and on tyre lives, the correlation is reasonable. It is seen, for example, that the life of the tyres of the Twin Pioneer with a duty of 6×10^3 ft-lb/in^3 was about 900 landings per tread, whereas the Boeing 707 tyres with a duty of 35×10^3 ft-lb/in^3 have a life of 72 landings per tread. In particular, it is worth noting that the short tyre lives of the higher performance military aircraft are a continuation of current civil tyre life and indicate the likely future civil position with the present trends.

DISCUSSION

Tyre Friction

The results obtained with the Scimitar aircraft and the Ministry of Technology heavy load vehicle show the expected decrease in braking coefficient with increasing ground speed. The decrease is, however, less for the coarser textured open graded macadam than for the grooved asphalt friction course.

At the same time that the heavy load vehicle tests were made, some measurements of the locked wheel braking force coefficient were made with the Road Research Laboratory small braking force trailer at speeds up to 87 knots on both grooved asphalt and the open graded runways. Above 70 knots the braking force coefficient increased rather than decreased as the speed was raised on both surfaces. This result confirms the view that aircraft braking performance cannot be estimated from locked wheel measurements (ref. 6), particularly if these measurements are made with lightly loaded vehicle tyres. Because of the time required to make aircraft tests, and the associated difficulties, a test vehicle using a driven, instead of a braked, test tyre has been proposed inasmuch as this type of vehicle enables the important actions taking place in the tyre footprint during braking to be reproduced at much lower speed (ref. 7). Although to make realistic tests the fully laden weight of such a vehicle would need to be about twice the load to be carried by the test wheel, involving a vehicle weight of, say, 20 to 30 tons, the test vehicle could readily be moved from aerodrome to aerodrome as it could be driven on the public roads. The primary object of this proposal was to avoid the difficulties associated with operating a heavy test vehicle at aircraft rejected take-off and touchdown speeds, but the stable operation of a driven test tyre at any slip ratio has many advantages. The friction values are obtained by steady, as against instantaneous, measurements so that at constant slip ratio and steady speed it will be possible to assess the average friction characteristics of any runway or any type of surface-tyre combination.

The wet braking force coefficients obtained with the Scimitar aircraft, even on the open graded macadam surface, are appreciably below those obtained with vehicle tyres of either natural rubber or high wet friction synthetic rubber. (See fig. 9.) The difference in the braking force coefficients of the aircraft tyre and the natural rubber vehicle tyre is perhaps accounted for by the reduced efficiency due to the antiskid operation on the aircraft and the very much lower tyre duty of the vehicle. However, the considerably higher braking force coefficients obtained with the high wet friction synthetic rubber vehicle tyre suggests that appreciable benefits might be gained if the low temperature requirements for aircraft tyres were relaxed so that tread compounds based on synthetic rubbers might be used.

Experience with the Open Graded Macadam Friction Course

The open graded macadam friction course was laid at Farnborough over 2 years ago. The winters had been mild but on one occasion a fall of a few inches of snow cleared remarkably rapidly from the open graded surface due, it is believed, to the dark colour and good drainage; this runway was in use several hours before the grooved asphalt main runway. No damage has resulted from the few night frosts experienced and intensive tests, in a cold chamber, on a sample of this surface did not cause breakup of the surface.

It was observed that the flocks of lapwings, which from time to time settle on the runways not in use at Farnborough, never collected on the open graded surface although there might be a hundred or so on the asphalt surfaced ends.

CONCLUSIONS

The limited aircraft tyre tests made so far support the view that greatly improved wet friction at aircraft brakes-on speed may be obtained with harsh, coarse textured friction courses and that such finishes will not increase the tyre wear problem. Additionally, such finishes will provide the drainage under the footprint necessary to prevent aquaplaning and will not necessitate the use of a grooved tread, with the attendant disadvantage of inadequate drainage when the ribs are worn away. A plain tread in turn would increase tyre life and make fabrication easier.

Although a major improvement tyre-runway friction will undoubtedly be gained by alterations to the texture of runway surfacing, some gain could be expected from the use of the high friction synthetic rubber tread compounds which might prove practical if the low temperature requirements for aircraft tyres were relaxed.

REFERENCES

1. Allbert, B. J.; and Walker, J. C.: Tyre to Wet Road Friction. Proc. Inst. Mech. Eng. AD (London), vol. 180, pt. 2A, no. 4, 1965-1966, pp. 105-121.
2. Key, E. J.: Drop Tests on Runway Wearing Course Test Slabs at B.A.C. Weybridge. Test Note No. 949, Brit. R.A.E., 1966.
3. Key, E. J.: Tyre Wear Tests on an Open Graded Macadam Runway Friction Course. Tech. Rep. 67178, Brit. R.A.E., Aug. 1967.
4. Grosch, K. A.: Wear of Passenger Car Tyres on Aerodrome Runway Surfaces. Natur. Rubber Prod. Res. Ass., 1966. (Unpublished)
5. Lander, F. T. W.; and Williams, T.: The Skidding Resistance of Wet Runway Surfaces With Reference to Surface Texture and Tyre Conditions. Rep. No. LR 184, Road Res. Lab., Brit. Min. Transp., 1968.
6. Williams, T.: The Relation Between Braking Force Coefficient and Slip for an Aircraft Tyre Braked on Four Wet Surfaces. Rep. No. 50, Road Res. Lab., Brit. Min. Transp., 1966.
7. Shilling, B.: Proposal for a Vehicle for the Measurement of Tyre/Runway Friction. Tech. Rep. 67244 (Rev.), Brit. R.A.E., 1967.

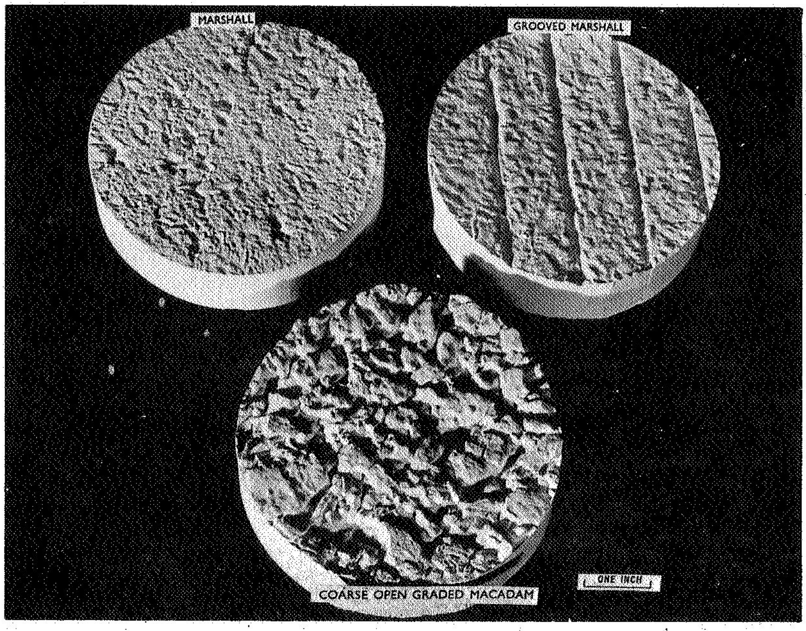

Figure 1.- Plaster casts of R.A.E. runway surfaces.

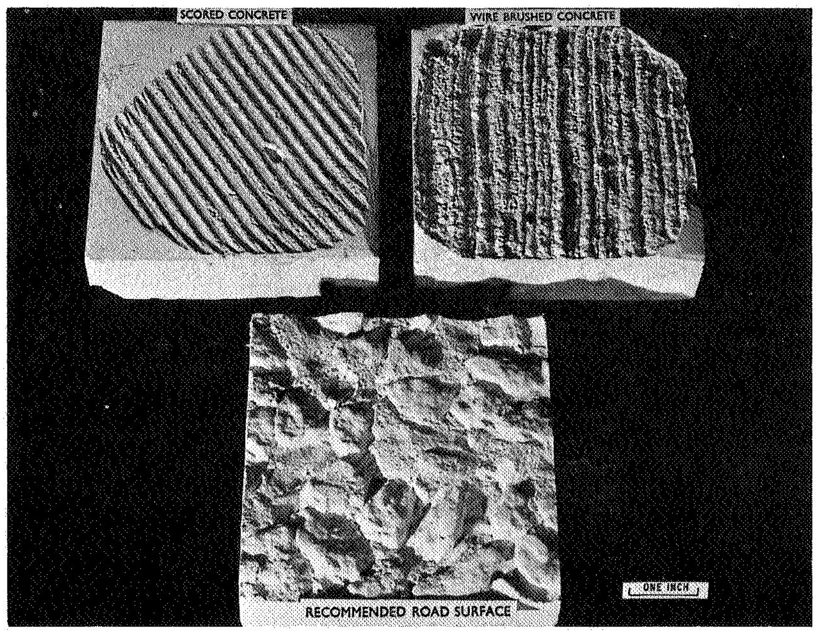

Figure 2.- Plaster casts of two concrete runway surfaces and a recommended road surface.

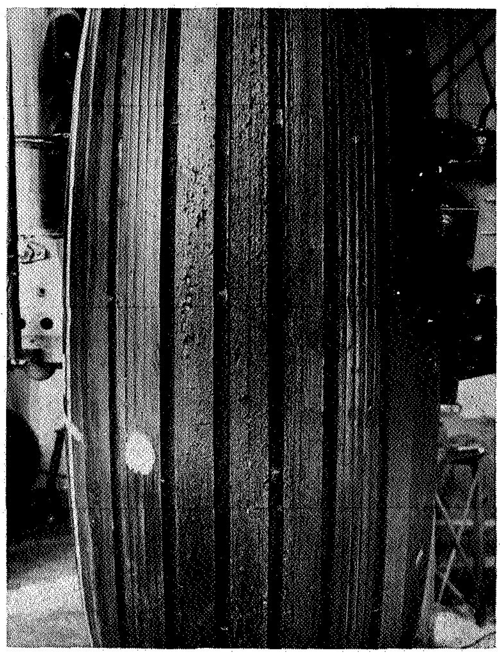

Figure 3.- Worst area of tread damage after 56 spin-up wear tests on three surfaces.

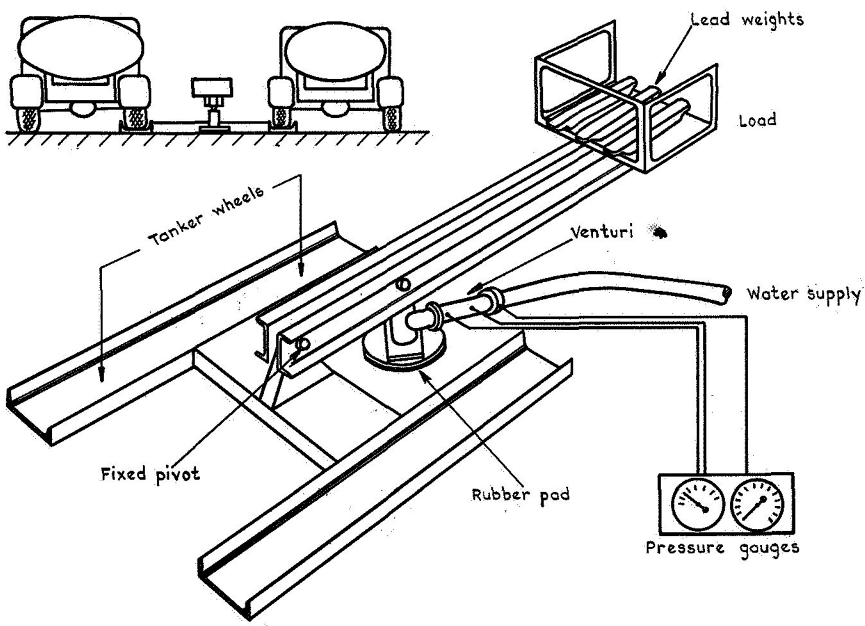

Figure 4.- R.A.E. surface texture test rig.

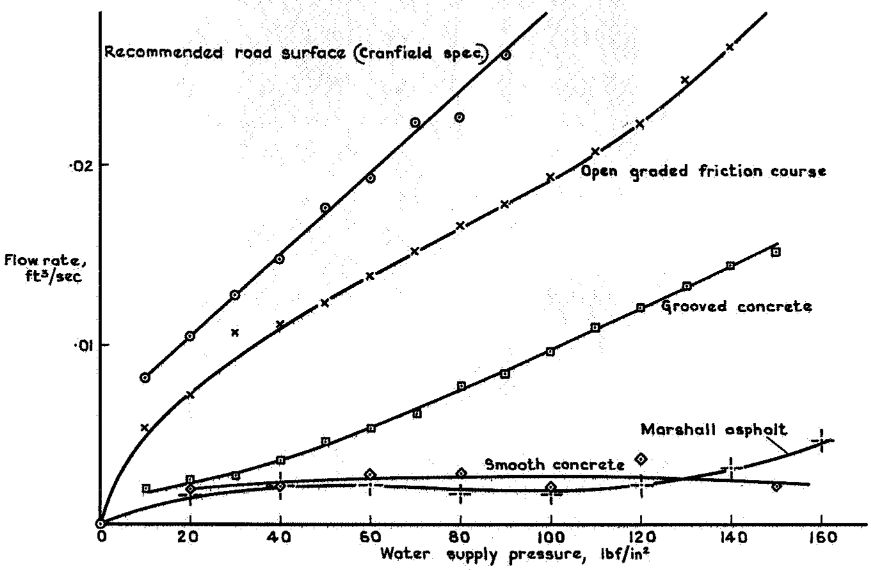

Figure 5.- Water flow rate against water supply pressure with 100 lbf/in^2 pad pressure.

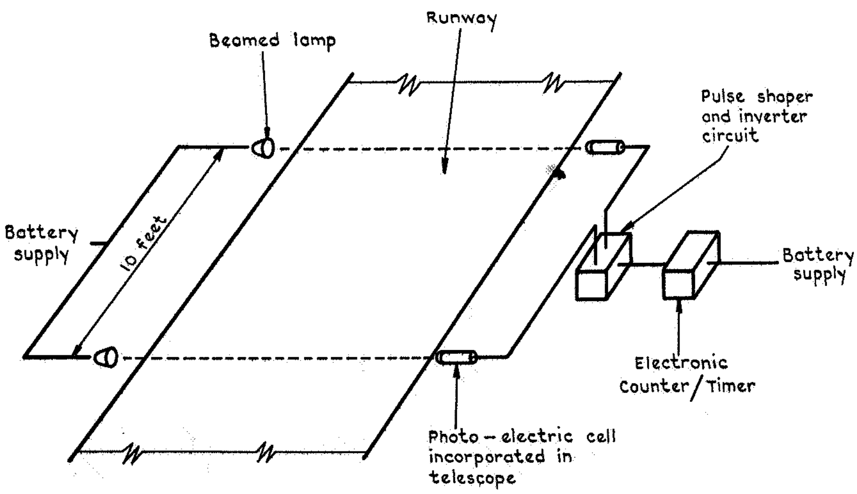

Figure 6.- Interrupted light beam equipment.

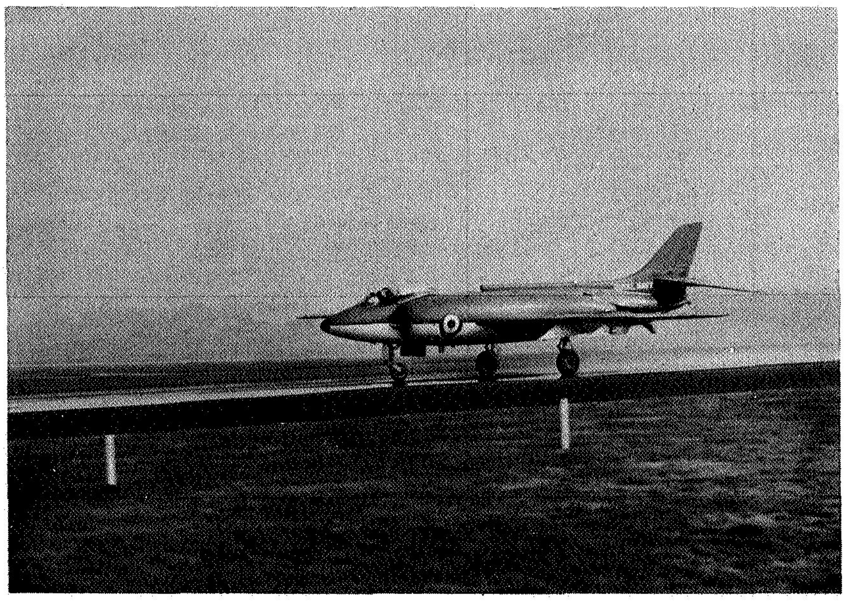

Figure 7.- Scimitar on wetted test section of open graded surface.

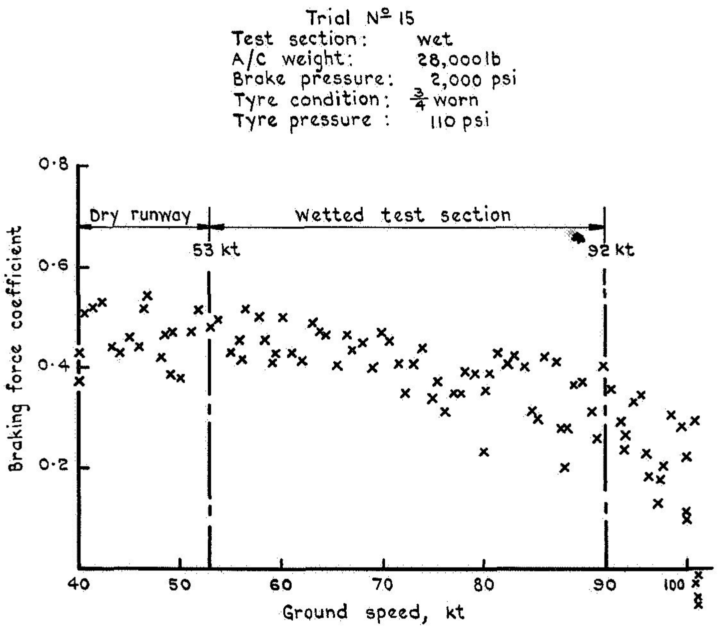

Figure 8.- Instantaneous values of braking force coefficient on the open graded friction course.

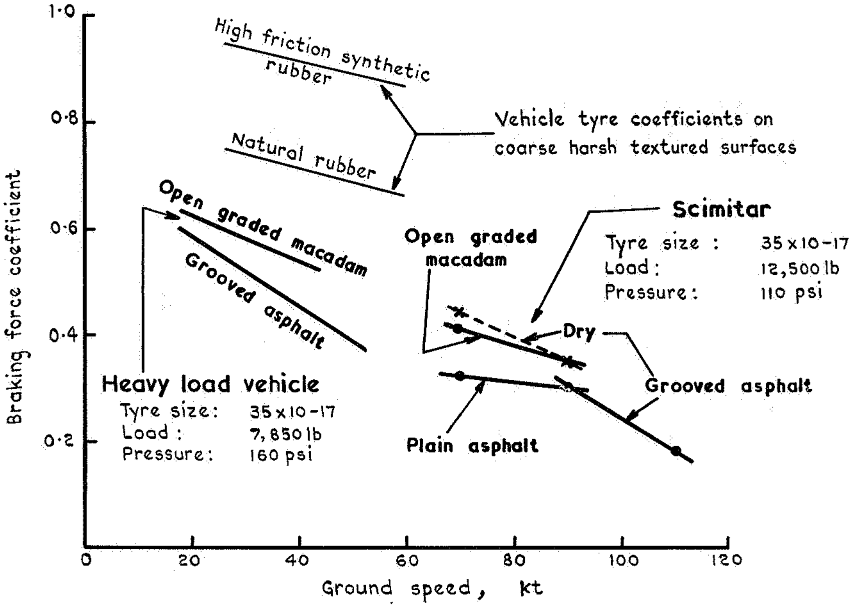

Figure 9.- Scimitar braking force coefficients measured in wet conditions on R.A.E. runways.

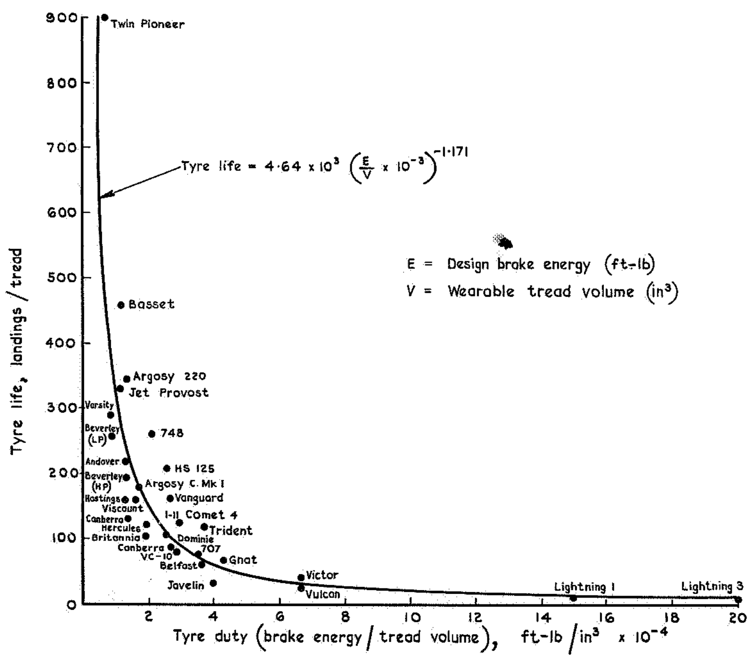

Figure 10.- Relationship between tyre life and tyre duty.

5. AQUAPLANING

THE BRITISH MINISTRY OF TECHNOLOGY PROGRAMME

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SUMMARY

Research at the College of Aeronautics, Cranfield, using a Hawker Siddeley Hunter F.6 has been concerned with discovering the minimum depth of standing water required to support an aquaplaning tyre and to evaluate the effects of runway texture and tyre pressure on this critical depth. The method used was to measure the height of the aquaplaning tyre above the runway surface and the report discusses briefly the probe devised for this purpose. Attempts have been made to obtain criteria for runway surface texture and to correlate these with the aquaplaning characteristics of the runway.

The height of the aquaplaning tyre above the runway surface is proposed as an important "characteristic" of the phenomenon which can be used as a measure of runway and tyre performance. Measurements made have yielded some information on tyre distortions during aquaplaning, which assists in the description and understanding of the phenomenon.

5

INTRODUCTION

The phenomenon of pneumatic tyre aquaplaning must now be familiar to everyone employed in the aircraft and vehicle operating fields. The importance of the research and the relevance of the problem is brought into focus periodically by accidents in which aircraft overrun or lose directional control whilst landing in heavy rain or on a flooded runway.

It would appear that two basic requirements have to be present to produce aquaplaning conditions:

(i) A speed above a certain critical aquaplaning speed

(ii) A certain minimum depth of standing water on the runway or pavement.

Previous research notably by NASA in the United States has produced the now familiar simple formula $V_c = 9\sqrt{p}$, where V_c is expressed in knots and p is tyre pressure in psi, for the estimation of the critical aquaplaning speed for a vehicle. This formula has been shown to be quite accurate generally, although it now appears that this basic planing speed varies slightly with deflexion, loading, and tyre design (ref. 1).

From a practical point of view, education of the automobile driver and an awareness of the problem could go someway toward reducing aquaplaning accidents on the highways. However, there is very little that a pilot can do about his speed on the runway – this to all intents and purposes is fixed.

The Ministry of Technology research programme at Cranfield sprang from a requirement for a system to warn landing pilots that aquaplaning conditions were present so that if considered advisable, a short standoff period for standing water drainage or, in the worst case, a diversion could be initiated.

To meet the requirement for an indicator of standing water on a runway, the Ministry of Technology issued a contract to Inertia Switch Limited for a water depth gauge for use on runways. This first appeared in prototype form in 1963 and has since been installed under development at Gatwick, London. The indicator was also installed on the landing research runway at NASA Wallops Station for the Joint NASA-British Ministry of Technology Skid Correlation Study. The system measures water depth at selected points on the runway and records this information remotely in the airport control tower. To use this device, it is obviously necessary to know precisely at what water depth aquaplaning is likely to occur, and it was to meet this requirement that the Cranfield aquaplaning research programme was initiated by the Ministry of Technology.

It was thought at the outset that runway texture might affect the critical water depth required for aquaplaning; thus, to have this variable present in the trials, a special test area was constructed on the main runway at Cranfield.

This area measuring 200 by 60 feet was composed of six different types of surfaces covering a large range of surface texture and generally being representative of standard runway surfaces in use in the U.K. at the time. (See figs. 1 to 6.)

The specific object of the trials then was to determine the minimum depth of water required for aquaplaning on the six surfaces and to observe the effect of any variation in tyre pressure on this minimum depth; the answers obtained could then be used as a danger datum for the water depth indicator.

EXPERIMENTAL PHILOSOPHY

An aquaplaning tyre appears to have two unique measurable characteristics: its distortion, or shape, and the minimum height above or the minimum separation between it and the pavement surface, which will be referred to as the aquaplaning height. These two dependent variables appear to be functions of normal load, tyre pressure, tyre design (tread and mechanical properties), ground speed, water depth, and pavement surface texture. Wheel rotational speed may also exert a small influence on these two characteristic parameters.

In the programme at Cranfield attempts were to be made to measure the aquaplaning height and also to obtain some idea of the tyre shape when aquaplaning. To study the effect of all the previously mentioned controllable parameters on these two, although desirable, was considered to be excessive for the present programme, and to achieve the stated aims, it was decided to measure the variation of aquaplaning height and tyre shape with water depth for the six different surfaces available at Cranfield at two tyre pressures.

To obtain the values of the minimum water depth to support aquaplaning, it would then be required to observe the relationship between aquaplaning height and water depth for a given surface and pick off the depth at which this aquaplaning height became zero, that is, when the tyre achieved ground contact. This technique had already been used by Gray at the Royal Aircraft Establishment, Farnborough, with some success using plasticine strips as a measuring device (ref. 2).

It was also considered that this information together with any data on tyre deformation would provide additional understanding of the mechanism of aquaplaning.

THE AQUAPLANING HEIGHT INDICATOR

After a series of attempts at using mechanical devices operated by contact with the tyre, it was eventually decided to develop an electrical probe to measure the clearance between runway surface and tyre. The reasons for abandoning the use of mechanical devices were many, the chief ones being the restrictive effects of such devices on the water under the tyre and the difficulties of separating tyre effects from those of the local water under pressure. These devices also required an involved resetting procedure between runs and therefore limited the number of runs possible per aircraft sortie.

Following considerable development the sensor shown in figure 7(a) was produced and this has since functioned successfully, measuring aquaplaning heights with an excellent degree of consistency.

The sensor consists of 36 individual probes, each capable of measuring the height of the particular area of tyre immediately above it. The basic principle of the probe lies in the measurement of the conducting power of the column of water immediately surrounding it. Any interfering body reduces the height of the column and hence the conducting power; thus, there is a drop in output current between centre pole and surrounding earth plate. A charged guard ring surrounding the centre pole ensures that the probe is sensitive only to restrictions vertically above it; there is no sideways looking. This guard ring also improves the range of the probe.

For processing and recording purposes the probes have been grouped into units of six. One probe in each unit is connected in parallel and has its own individual electronic circuit, being completely independent of the other probes in the unit. There are, therefore, six electronic channels. Test tyre dimension and the spacing of the probes at 1-inch intervals result in only four or five probes being affected by the tyre traversal; thus, no two probes in the same channel can be affected.

The output voltages from each of the six channels are conditioned and stored on magnetic tape from which they can be played back at leisure on an oscilloscope and analysed.

The resulting outputs give a time history of the aquaplaning height at four or five points on the cross section of the tyre. Since these are all measured from a flat surface this also conveys the tyre distortion and provides a three-dimensional picture of the tyre foot print.

Laboratory tests have been carried out to determine environmental effects on the sensitivity of the probes. Since the basic principle relies on the water conductivity, temperature and contamination were found to influence the sensitivity, as was expected.

It was found after intensive laboratory work that the effect of both temperature and contamination on the sensitivity of the probes was to increase the output signal for any given aquaplaning height by a constant multiplying factor. Thus the measuring of the output signal for any fixed aquaplaning height would supply this multiplying factor for any given water condition. The laboratory calibration curve could then always be used to analyse the results once the water factor had been evaluated. This water factor was obtained in situ during the trials, immediately prior to each run.

A micrometer system was devised to enable accurate calibration to be achieved. This was conducted in the laboratory and was found to be repeatable to within 0.005 inch in height measurement.

TEST TECHNIQUE

The aircraft used in the trials was a Hawker Siddeley Hunter F.6 jet fighter, the mainwheels equipped with standard Goodyear 29×16, 14 ply tyre having seven circumferential grooves. Average operating all up weight of the aircraft was 18 000 pounds.

The range of ground speeds required in the ponds was such that a touch-and-go procedure was necessary, using the throttle to adjust to the required pond entry speed. Constant centre-of-gravity position and fully down elevator ensured an aircraft attitude consistent with small aerodynamic lift and a reasonably constant wheel loading.

The aircraft was fitted with wheel speed generators, the output being recorded on paper by a Hussenot A13 type recorder. It was discovered after some time that wheel speed prior to entry gave values of ground speed accurate to within 1 knot once the system had been calibrated using a take-off camera.

The aquaplaning height indicator was installed with precision in the test area, great care being taken to ensure that it was at the same level as the runway surface to within 0.01 inch. The discrepancy in level between surface and each individual probe was measured with a micrometer system to 0.001 inch (fig. 7(b)).

Water depth was measured on the hypotenuse of a 20^{o} wedge. Such a method, although less accurate than the needle micrometer type device used by Road Research Laboratory, avoided any local texture effects and gave the water depth from the peaks of the asperities. In calm weather it was possible to measure the water depth to an accuracy of 0.025 inch. This method of water depth measurement, however, became impracticable at depths below 0.1 inch. The needle type method was rejected for use at these low depths since it was thought that the texture variations on the surfaces to be tested, being of the same order as the water depths, would prevent any reasonable useable value being obtained.

The water spray patterns were photographed and their behaviour with variations of speed, water depth, and tyre pressure studied.

Prior to each run, one probe in each channel was covered with a bridge 0.1 inch above it as a reference. The magnitude of the output signal, when compared with that achieved in the laboratory calibration, provided the water constant for that run.

Analysis was simple and involved playing back the tape to obtain a visual signal on a storage oscilloscope. This could then be photographed, traced, or analysed on the tube itself. By using the calibration curve and the water correction factor the traces of output voltage against time for each channel could then be converted into aquaplaning height-time curves which were also tyre profiles. The use of a long strip of Secomastic along the sensor enabled the tyre passage to be located with respect to the individual channels and so fix the position of each trace in the tyre cross section.

SURFACE TEXTURE MEASUREMENTS

Attempts were made during the trials to obtain some numerical rating to describe the texture and the drainage characteristics of the test surfaces in order to observe whether there existed any correlation between these and the aquaplaning characteristics of the surfaces. Three methods were used to obtain some measure of the surface characteristics:

(1) Sand-Patch Method

The sand-patch method devised by the Road Research Laboratory is intended to obtain the mean depth of the asperities. This is done by working a known volume of sand into the surface texture to form a circular patch in which all the indentations in the surface are filled. From the known volume and the measured area of the patch a mean asperity depth may be calculated.

(2) Outflow Meter

An outflow meter as described by Moore (ref. 3) was constructed and used to measure the channel drainage characteristics of the surface. The meter consists basically of a loaded open cylinder sitting on a rubber ring base. The cylinder is set on the surface and filled with water. The time taken for the water to fall from one fixed level to another through the drainage between rubber base and the surface is recorded and used directly as a measure of the surface characteristics.

(3) Impression Method

Plasticine blocks were squeezed into the surfaces to obtain casts of the texture. Magnified shadow images of the cross-sectional profiles were then projected onto a paper screen and drawn. A straight line was drawn over the tops of the asperities and the drainage area per inch length under this line was measured.

RESULTS

Aquaplaning Height

Figure 8 shows the curves obtained for aquaplaning height of the tyre against water depth for a tyre pressure of 120 psi. The speed used throughout these tests was 140 knots ground speed, equal to 1.47 V_c.

The intercepts with the horizontal axis give the critical water depth for aquaplaning for the various surfaces. The Marshall asphalt surface gave identical results to the lightly brushed pavement concrete, and the grooved concrete gave identical results to the grooved asphalt. These facts seem to indicate that the microtexture of the surface has little or no effect on the aquaplaning characteristics of a surface.

The grooved surface proved to be the least prone to aquaplaning, requiring some 0.12 inch of water to support the tyre clear of the runway; the scored concrete followed, with the lightly brushed pavement quality concrete and Marshall asphalt decidedly the worse. It is worthwhile noting that on the very lightly brushed concrete under these test conditions, it required less than 0.05 inch of water to cause aquaplaning, and runs in slightly less than 0.1 inch showed all the characteristics, including spin-down and suppression of the bow wave, as well as an indicated separation from the surface.

Figure 8 shows that the grooved and scored surface characteristics actually cross and this caused some concern for a time. It was noted, however, that tests carried out by Moore (ref. 3) in an aquaplaning study involving the experimental measurements on the sinkage of flat plates onto surfaces of different texture show similar characteristics for similar surfaces. One can consider the flow of water from beneath the tyre (fig. 9) to be composed of a bulk flow between the tyre undersurface and a point just clear of the surface, a boundary flow in the region immediately adjacent to the asperity peaks, and a channel flow in the asperity troughs. With the tyre some distance from the surface, the greater openness of the texture at the peaks of the asperities for the scored concrete (fig. 10) allows the boundary flow to be much larger than for the grooved surface. When the tyre approaches the surface, however, the predominating flow is the channel flow and the measured drainage area per inch is larger for the grooved surface. The square grooves also have superior discharge characteristics to the triangular ones.

It is also interesting to note that for both concrete and asphalt, the curves of aquaplaning height against water depth with and without grooves have the same shapes with a near constant displacement of aquaplaning height. This apparently common influence of the grooving can be attributed directly to the increased water drainage in the grooves themselves. In this context, tests on a surface having grooves of different dimensions could prove interesting and illuminating.

Effect of Tyre Pressure Variation

Figure 11 shows plots of aquaplaning height against water depth for two surfaces at two tyre pressures, 200 psi and 120 psi, with all other conditions constant. It can be seen that the softer tyre aquaplanes considerably higher in the water, and thus is more prone to aquaplaning on a given surface. The reduction of pressure will, of course, also reduce the aquaplaning speed so that the two conditions really represent two different ratios of speed to aquaplaning speed $\frac{V}{V_c}$. Whether this is the influencing parameter as opposed to pure shape difference of the softer tyre will not be known until tests can be carried out at two different speeds giving the same two ratios at equal tyre pressures. It is worthwhile noting here that the figures quoted in the previous section for critical aquaplaning depth for the various surfaces are pessimistic. The normal aircraft would be more likely to touch down in the region of 1.1 V_c than 1.47 V_c, and therefore, as can be seen from figure 11, the critical depth for the lightly brushed concrete and Marshall asphalt would be slightly less than 0.1 inch. This value, although extremely possible to envisage on a runway, is far less frightening than the previous figure of 0.05 inch.

To justify the interpolation of these curves and to show that no strange occurrences were taking place at their lower ends, a further experiment was devised to verify the results obtained. In steady headwind conditions of about 15 knots the water in the ponds tends to heap at the downwind end giving a longitudinal water profile which could be measured and recorded as shown in figure 12. Tests conducted over a period of time showed that in the right conditions this profile remained constant. The aircraft was then taxied at the appropriate speed into the deep end, spin-down occurring at the entry point. By observing the time elapsed before spin-up commenced, one could pinpoint the location of spin-up in the pond and hence read off the water level at this point. This test was only possible when the critical depths were 0.1 inch or above owing to the difficulty in depth measurement below 0.1 inch. The results obtained for these surfaces, however, showed close agreement with the values obtained by extrapolation.

Wheel Spin-Down

Figure 13 shows the variation of spin-down rate with water depth for two surfaces, the lightly brushed concrete and the grooved concrete, both at tyre pressures of 120 psi.

The rate of spin-down for the grooved concrete is seen to be considerably higher than for the lightly brushed pavement concrete. Since the rate of spin-down is proportional to the hydrodynamic spin-down moment, this is obviously less for the pavement concrete. The main difference between the two is the depth to which the tyre has sunk in the water and the aquaplaning height (fig. 14). Thus these two factors must have produced either a reduction in hydrodynamic force or a large change in its orientation.

It is seen also that for a given surface the spin-down rate and hence the spin-down moment both decrease with decreasing water depth, the main difference again being a reduction of both sinkage depth and aquaplaning height. It is interesting to note that the curve of spin-down rate for the grooved concrete starts reducing rapidly with water depth from 0.2 inch. This value at which the gradient changes coincides with the value of the critical water depth under these conditions.

Observations on the Mechanism of Aquaplaning

The longitudinal shape of that portion of the tyre influenced by the water shows a forward wedge region where the tyre elements have a velocity relative to the water generating the hydrodynamic force. Behind this area and about the instantaneous centre is a region where the tyre and water velocity vectors are in the same direction. In this region it is difficult to envisage a hydrodynamic force, although cross sections of the tyre here indicate a large pressure beneath it, distorting it as shown in figure 15. The pressures in this region appear to be decidedly more of a viscous nature, and theorists may feel that this demonstrates the type of distortion which would arise from the classic parabolic viscous pressure distribution generated beneath a flat plate. Tests have shown that a large amount of water from under the tyre is displaced in the sideways direction and the presence of this transverse pressure gradient across the tyre would generate this flow.

Such a viscous pressure would tend to increase as the gap between tyre and surface decreases and this is borne out by comparing the distortions of the tyres shown in figure 15. The tyre planing in the lower depth has a far larger distortion of the centre portion indicating an increase in viscous pressure in this region.

This increase of viscous pressure in what is termed the "squeeze film region" suggests a decrease in the hydrodynamic force as the water depth is decreased. Figure 15 shows that the depth of sinkage into the water reduces with water depth and this together with the marked reduction in spin-down moments tends to confirm this reduction in hydrodynamic force and increase in viscous pressure force as the level of water is reduced, the tyre walls approaching closer to the surface in order to generate the increased viscous pressure.

Thus it would appear that the information obtained from these tests tends to support the now generally accepted theory that the aquaplaning tyre is supported partly by hydrodynamic force and partly by viscous forces in the "squeeze film region." This mechanism has been proposed recently by a number of people. There does, however, appear to be an interchange between the two forces and in small depths of water the viscous force appears to become predominant.

Surface Texture Correlation

Figure 16 shows a plot of critical water depth for three types of surfaces against their value of texture obtained using the outflow meter. Here again there was no distinguishable difference between the grooved asphalt and grooved concrete, the large volume of drainage in the grooves presumably masking the differences in microtexture.

It was found that the sand-patch method was extremely difficult to use on the grooved surfaces, the sand tending to run out along the grooves making the true area covered extremely difficult to evaluate.

The third method used, obtaining casts of the surface and measuring channel area per inch, proved to be possible only for the surfaces with large drainage channels, that is, the scored and grooved surfaces.

It may be added also that very little consistency was achieved with any of these texture measurements on any particular one of the surfaces, this being more a reflection on the consistency of the surfaces than the measuring equipment. The values used are average values from a large sample which showed a great deal of scatter. It would appear that texture measurements on such surfaces may require some form of statistical analysis.

As a result of these limitations only two points were obtainable for the sand-patch and the casting methods, whereas three were obtained from the outflow meter values. Figure 16 shows a rapid improvement with any reasonable texture followed by small gains due to variations in the form of drainage. A similar type of curve has been obtained by NASA in a correlation of friction coefficient and surface texture obtained in a similar manner to the sand-patch method but using grease instead of sand (ref. 4). Further tests are required on other surfaces to confirm the form of this correlation. The casts of the scored and grooved surfaces gave average values for channel cross-sectional area per inch as 0.013 square inch and 0.016 square inch. These figures support the theory that the grooved surface is superior to the scored surface with regard to critical water depth.

CONCLUDING REMARKS

Critical water depths have been obtained for a Hunter F.6 aircraft at two tyre pressures and on six surfaces. The critical water depth required for aquaplaning varies considerably with surface texture and tyre pressure at a given speed. Aquaplaning has been shown to be possible on lightly brushed concrete pavements at water depths of less than 0.1 inch. Grooving appears to improve the characteristics of a runway considerably, increasing the critical aquaplaning depth by as much as a factor of 5. The predominant factors in the grooving seem to be channel drainage area per inch and also the shape of the channel cross section. Data on tyre deformation appear to indicate that the aquaplaning tyre is supported partly by hydrodynamic and partly by viscous forces, with the viscous pressure force predominating at low water depths.

REFERENCES

1. Allbert, B. J.: Tires and Hydroplaning. Proc. Soc. Automot. Eng., Jan. 8-12, 1968.

2. Gray, W. E.: Measurements of "Aquaplaning Height" on a Meteor Aircraft, and Photos of Flow Pattern Under a Model Tyre. Tech. Note No. Aero. 2855, Brit. R.A.E., Nov. 1962.

3. Moore, Desmond F.: Drainage Criteria for Runway Surface Roughness. J. Roy. Aeronaut. Soc., vol. 69, May 1965, pp. 337-342.

4. Horne, Walter B.; and Joyner, Upshur T.: Traction of Pneumatic Tires on Wet Runways. Conference on Aircraft Operating Problems, NASA SP-83, 1965, pp. 9-17.

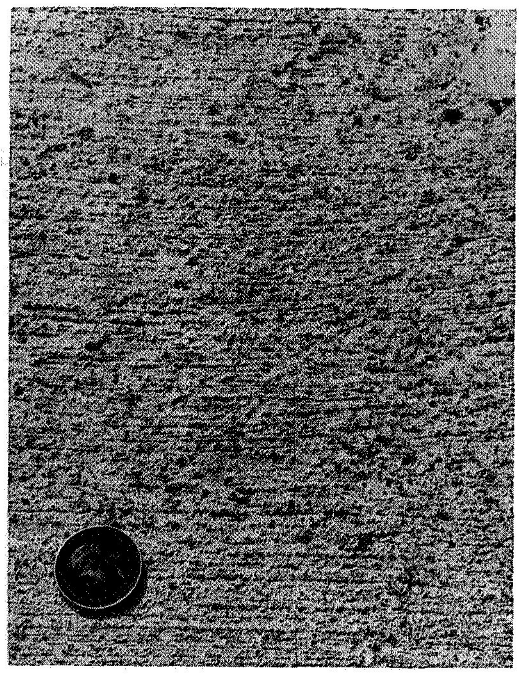

Figure 1.- Lightly brushed concrete.

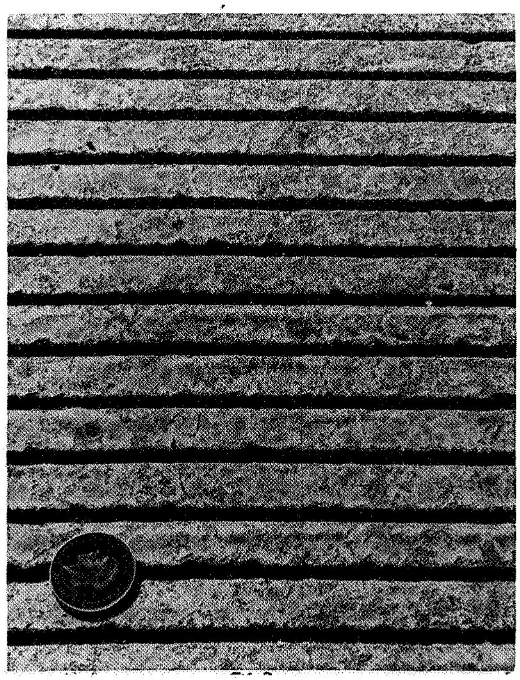

Figure 2.- Grooved concrete.

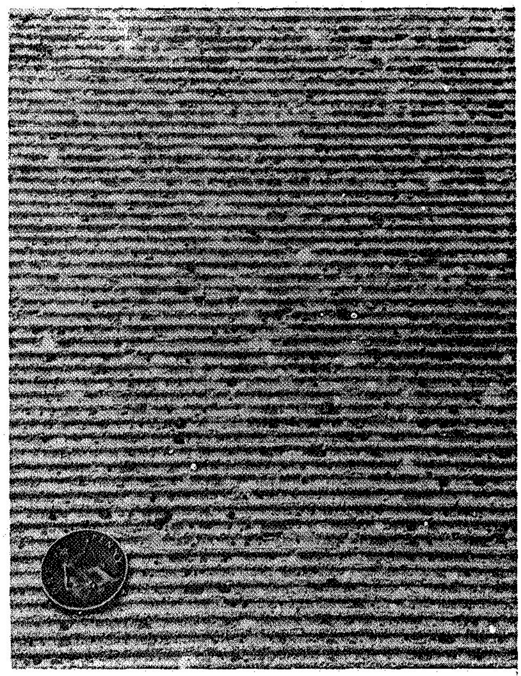

Figure 3.- Scored concrete.

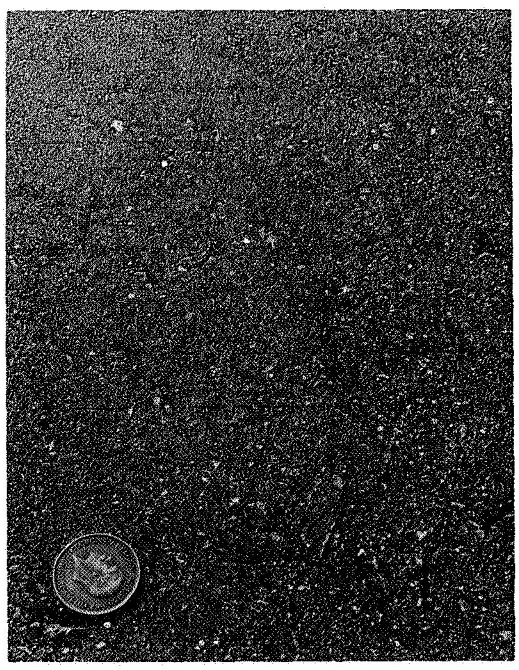

Figure 4.- Marshall asphalt.

Figure 5.- Grooved asphalt.

Figure 6.- Asphalt dressing.

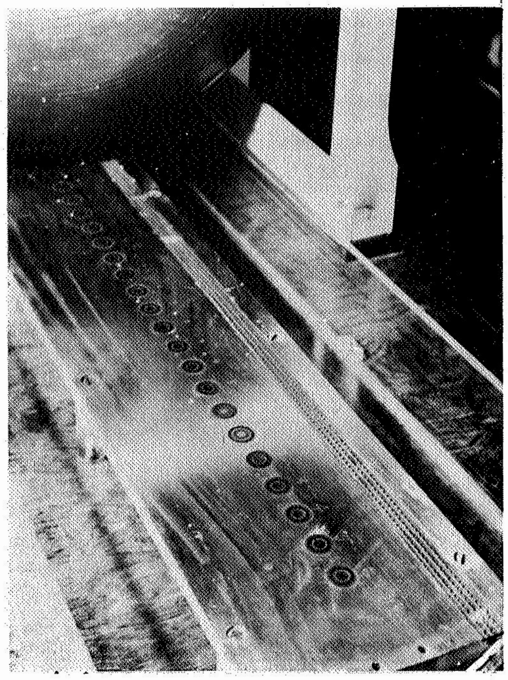

Figure 7(a).- Sensor used to measure aquaplaning height.

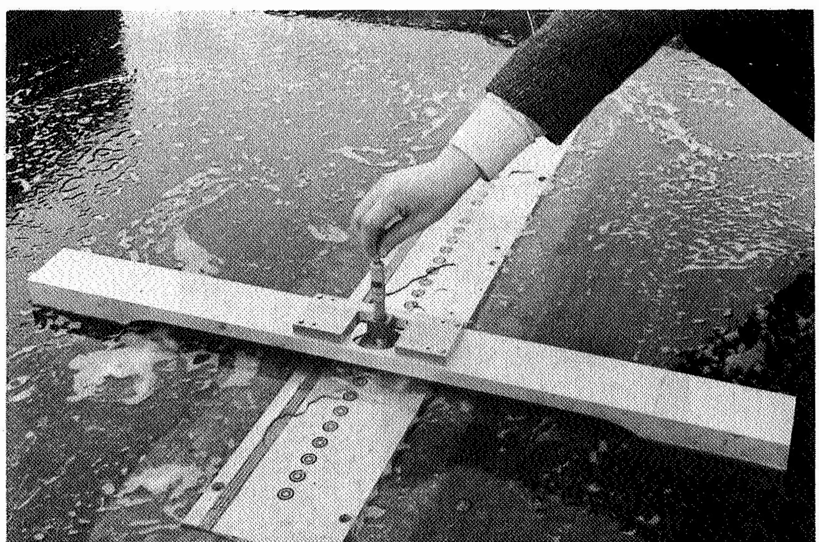

Figure 7(b).- Micrometer system used to measure discrepancy in level between surface and each probe.

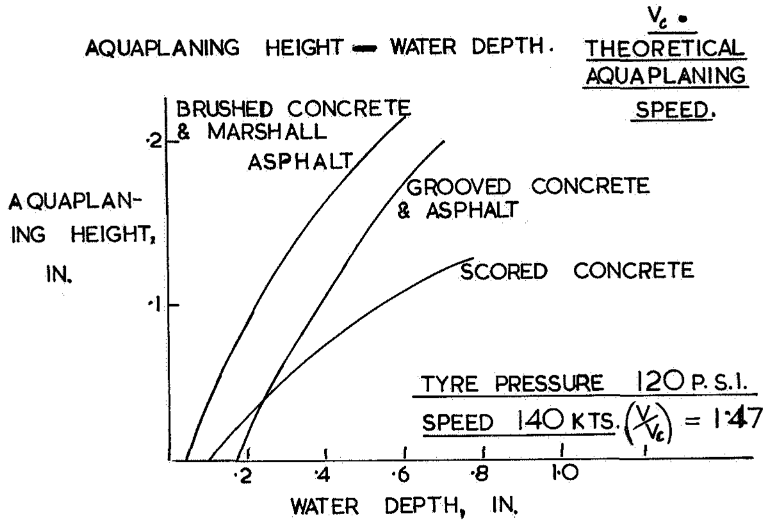

Figure 8.- Aquaplaning characteristics of test surfaces.

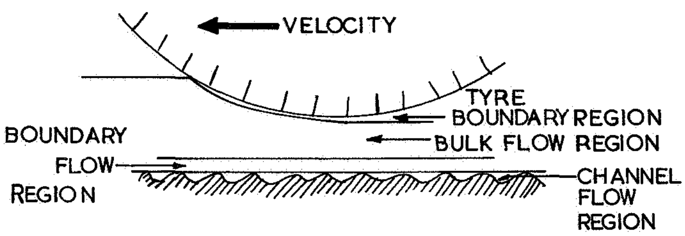

Figure 9.- Flow regions under tyre.

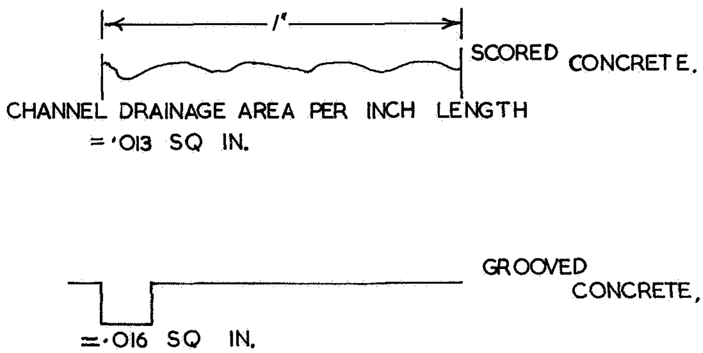

Figure 10.- Magnified profiles of two surface textures showing channel drainage per inch length.

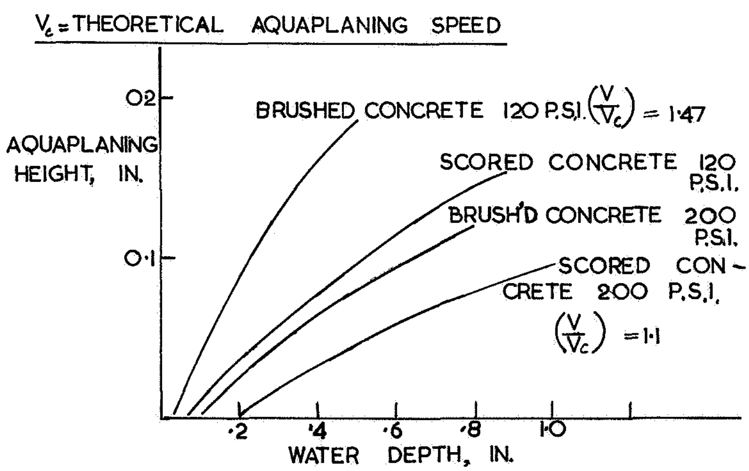

Figure 11.- Effect of tyre pressure on aquaplaning characteristics.

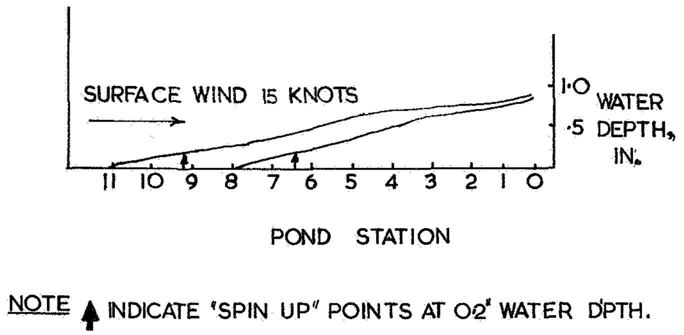

Figure 12.- Longitudinal water depth profiles in heaped ponds.

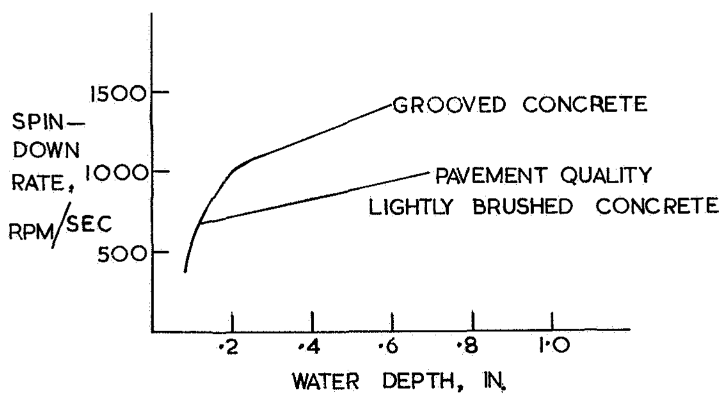

Figure 13.- Effects of surface texture on spin-down rate.

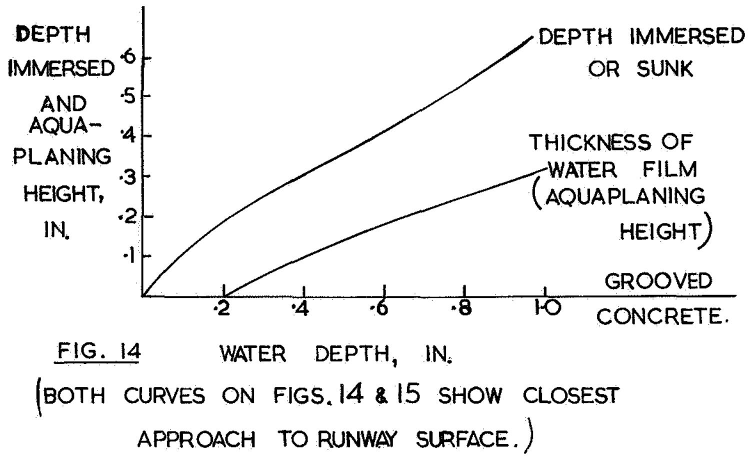

Figure 14.- Water layer characteristics.

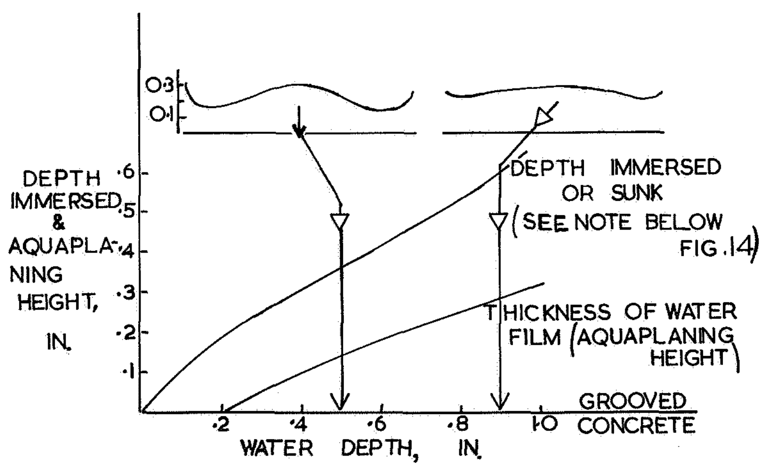

Figure 15.- Tyre distortion at points of closest approach to ground.

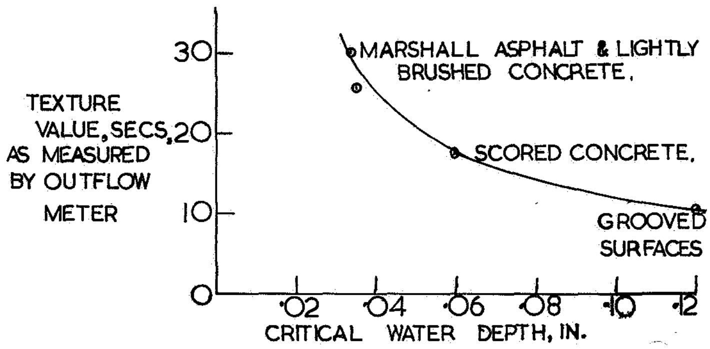

Figure 16.- Critical water depth-surface texture characteristics correlation.

6. CALCULATED AIRPLANE STOPPING DISTANCES BASED ON TEST RESULTS OBTAINED AT THE LANDING RESEARCH RUNWAY, NASA WALLOPS STATION

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SUMMARY

Data are presented from an analytical study made to predict improvements in adverse-weather landing and balanced take-off field performance levels for transversely grooved runways. The results indicate that the use of the landing-research-runway transverse-groove configuration (1-inch pitch by 1/4-inch width by 1/4-inch depth) effectively reduces landing field lengths for the Convair 990A and McDonnell Douglas F-4D airplanes under adverse weather conditions on a variety of runway surfaces.

In addition, essentially dry balanced field take-off performance is attainable for grooved runway surfaces in a wet and puddled condition, since grooving increases the critical engine-failure speed to practically dry-surface values. Only slight reductions in balanced field lengths are provided by grooving for take-offs from slush-covered runways.

INTRODUCTION

Recent airplane braking research programs conducted by the National Aeronautics and Space Administration have shown that pavement grooving is an effective means of producing higher friction levels for airplanes involved in adverse-weather runway operations (ref. 1). The braking programs were conducted with 990A and F-4D airplanes on the landing research runway at Wallops Station, Virginia.

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The purpose of this paper is to indicate the effects of transverse runway grooving on airplane ground operating distances for the 990A and F-4D. The results were obtained from an analytical study made to determine all-weather landing and balanced take-off field lengths for hypothetical operations from ungrooved and grooved concrete and asphalt runways of various surface textures. The pavement groove configuration and surface textures of the runways included in this study were assumed to be identical to those reported in reference 1, since the braking data used herein were obtained from tests on surfaces A to D and F to I of the landing research runway. Also included is a brief assessment of some effects of pavement grooving with regard to cross-wind landings made on flooded runways.

All comparisons used in the study were selected to place the results applicable to ungrooved and grooved runways on a consistent basis and do not necessarily reflect actual day-to-day runway operations of either commercial or military airplanes.

SYMBOLS

C_m	pitching-moment coefficient
h_2	obstacle clearance height
$\dot{h}$	rate of sink
L	lift
n	normal load factor, L/W
T	thrust
Δt	time increment following engine failure
V	velocity
V_1	critical engine-failure speed
V_2	velocity at obstacle clearance height
W	weight
γ	flight-path angle
$\ddot{\psi}$	angular acceleration about vertical axis

Subscripts:

app	approach
BR	conditions at brake engagement
G	grooved

R	remaining engine(s) after a single engine failure
r	conditions at take-off rotation point
TD	conditions at touchdown
T_1	thrust from failed engine
3PT	conditions at nose-wheel touchdown in landing

DISCUSSION

Landing Analysis

The conditions considered in the landing analysis are indicated in figure 1. Standard-day sea-level ambient conditions were assumed with no wind and level runway surfaces. The landing field length is defined as the horizontal distance from a height of 50 feet to a full stop. The airplane weights used in the landing analysis were assumed to be constant at 202 000 pounds for the 990A and at 36 000 pounds for the F-4D. Initial conditions included stabilized flight at 50 feet, with approach flight-path angles of 3.0° for the 990A and 2.75° for the F-4D. Corresponding sink rates were 13.33 and 11.60 feet per second, respectively. Constant normal-load-factor flares were executed from the stabilized approach to reduce the sink rates at touchdown (T.D.) to acceptable levels. After attaining a three-point attitude the throttles were retarded to idle, the spoilers were deployed for the 990A, and the F-4D horizontal stabilizers were deflected to produce maximum positive C_m. Then maximum antiskid braking was initiated and maintained to a stop by assuming friction values obtained from new to moderately worn tires. No other braking aids were employed, such as reverse thrust for the 990A or the F-4D parabrake.

The computed comparisons of ungrooved and grooved all-weather landing field lengths (i.e., landing distances) for the 990A are shown in figure 2. Identical approach and landing characteristics up to brake engagement were assumed for each landing represented; therefore, the distance traveled prior to brake engagement (2800 feet) is the same for all the field lengths shown. This distance was held constant to facilitate comparison of all-weather braking distances and does not allow for increased decelerations due to spray and slush drag for the flooded and slush-covered runway surfaces.

For dry runway surfaces similar to the landing-research-runway test surfaces, the landing field length was approximately 4480 feet with or without grooving. The calculated dry-surface stopping distance from 135 knots is approximately 12 percent lower than that given in reference 2 for the same brake-engagement speed. Landing distances for the two wet and puddled ungrooved concrete surfaces A and D (see ref. 1 for descriptions of all lettered surfaces) were increased to approximately 7000 feet. Grooving these two surfaces by using the landing-research-runway transverse-groove configuration (represented by surfaces B and C) reduces the field-length increase attributable to wetness to approximately 100 feet.

An interesting effect of introducing smooth worn tires to the study is an increase in ungrooved-wet-surface braking distance of approximately 1500 feet on surface D, with no significant change in wet-surface stopping distance for worn tires on a grooved pavement having a texture similar to surface D (represented by surface C). The large increase in the landing distance for a wet and puddled ungrooved surface when worn tires are used emphasizes the importance of tire tread design and particularly the necessity for early replacement of worn tires for ungrooved-runway operations. If the runway is grooved, however, the use of worn tires instead of new tires does not significantly degrade the stopping capability on wet and puddled surfaces.

The wet and puddled ungrooved asphalt surfaces F and I exhibit much higher braking friction coefficients than did the wet ungrooved concrete surfaces A and D; therefore, relatively smaller landing-distance reductions (approximately 1000 feet) result from grooving these surfaces (see results from surfaces F, G, H, and I in fig. 2). Grooving is also effective in reducing landing distances for concrete runway surface D under flooded and slush-covered conditions, as indicated by the reductions in landing field length obtained for similarly textured grooved surface C under both flooded and slush-covered conditions. Slush contamination of the grooves, however, apparently causes a larger reduction in braking efficiency than does the flooded-surface condition.

A brief analytical study of the equations of motion as applied to flooded-runway braking was made for the 990A to determine some effects of cross-wind operations on landing field length. Since reference 3 had shown that negligible side forces were developed by locked wheels on wet surfaces, the flooded-surface locked-wheel 990A airplane braking data obtained on ungrooved surface D (ref. 1) were used to calculate the point of departure from the runway side boundary for assumed cross-wind conditions. Zero wheel side forces were assumed as were the required rudder deflections to maintain $\ddot{\psi} = 0$. Again, the approach-to-brake-engagement conditions of the landings in figure 2 were assumed. Results of this study indicate that a 10-knot direct cross wind could cause the 990A to exit the side boundary of an ungrooved concrete runway, flooded to a depth of from 0.1 inch to 0.3 inch and similar in texture to surface D, at approximately 6000 feet from the 50-foot obstacle clearance height and at a forward velocity of 82 knots. No sustained wheel lockups or directional control losses in cross winds were noted in analyzing the braking data obtained for the 990A on the flooded grooved surfaces of the landing research runway, so it is believed that the transverse-groove configuration did alleviate losses in directional stability and control.

Comparisons of all-weather landing field lengths for the F-4D are presented in figure 3. The allowable reductions in field length as a result of grooving are much more significant for the F-4D than for the 990A, since the braking friction coefficients were lower than for the 990A. For both airplanes, braking was initiated at approximately the same speed (see fig. 1), and the F-4D required 3200 feet to stop from the point of initial brake application as compared with about 1700 feet for the 990A under dry-surface conditions. This result reflects a significant reduction in dry-surface braking effectiveness for the F-4D as compared with the 990A airplane. This minimum dry-surface braking distance (3200 feet) calculated for the F-4D from landing-research-runway test results correlates with demonstrated and flight-manual values obtained for the airplane without parabrake (see fig. 3). Calculated landing field lengths for the wet and puddled ungrooved concrete surfaces A and D are approximately twice the corresponding dry-surface values. Grooving these wet surfaces (represented by surfaces B and C) results in increases of only 700 to 1200 feet over the dry-surface landing distance. For the wet ungrooved asphalt surfaces F and I, landing distances are only 340 to 1700 feet greater than for the wet grooved concrete surfaces tested. Grooving these asphalt surfaces reduces the wet-surface field length to about the dry-surface value. Results obtained for flooded concrete surface D indicate that approximately 11 500 feet would be required to land the F-4D under the assumed conditions. Introduction of grooving reduces this distance by approximately 40 percent. Asphalt surfaces similar to the landing-research-runway surface F provide flooded-surface landing distances of approximately 8700 feet. Grooving surface F (represented by surface G) reduces this flooded-surface field length by approximately 2800 feet.

Take-off Analysis

The definitions used in the take-off (T.O.) analysis are shown in figure 4. Balanced field lengths and critical engine-failure speeds were selected as parameters in comparing adverse-weather take-off performance levels for ungrooved and grooved runways with dry performance of the 990A and F-4D. Standard-day ambient conditions are assumed with no wind and level runway surfaces. The balanced field length is defined herein as the distance required, starting from brake release, to either successfully conduct a take-off or make a stop, with the assumption of a single engine failure at some critical airplane speed (called V_1 in this paper).

In either case (take-off continued or refused), maximum thrust accelerations are assumed from brake release up to a selected engine-failure speed. For the continued take-off the throttles are retained in maximum thrust settings, with linear thrust decay on the failed engine terminating 3.0 seconds after engine failure. Rotation velocities of 165 and 172 knots were chosen for the 990A and F-4D, respectively, with obstacle clearance heights of 35 feet for the 990A and 50 feet for the F-4D defining the terminal point of the continued take-off field length (see fig. 4). The refused take-off assumptions were a 1.5-second delay from engine failure to pilot recognition, a 0.5-second delay after recognition to apply maximum antiskid braking, a 3.0-second delay for the failed engine to lose thrust linearly, and a 3.0-second delay from the time of pilot recognition to idle thrust on the remaining engines. Spoiler deployment for the 990A and stabilizer deflection for the F-4D to produce maximum positive C_m were assumed complete at 3.0 seconds after the engine failure.

The method used in determining the balanced field lengths and V_1 speeds is shown in figure 5 for some particular all-weather runway condition. Calculated field lengths required for continued and refused take-offs are plotted as functions of engine-failure speed. The intersection indicates the balanced field length and the critical engine-failure speed V_1.

The implication associated with V_1 speed is that the pilot obtain from the flight manual a value of V_1 suitable for the existing runway length, and other conditions, prior to each take-off. A stop should be attempted in the case of take-off emergencies occurring below V_1, since the refusal field length is shorter in this region. Take-off should be continued at speeds above V_1 to utilize the favorable field lengths.

Some examples of the chosen technique are shown in figure 6 wherein balanced field lengths and V_1 speeds are determined for the 990A in the maximum take-off weight condition on wet and dry concrete surfaces. The continued take-off curve shown is representative for all the conditions indicated, since landing-research-runway test results show no appreciable spray drag for either airplane on wet and puddled surfaces. The dry-surface balanced field length is approximately 9600 feet, and the corresponding V_1 speed is 163 knots. Wetting the ungrooved concrete surface A increases the balanced field length to 10 800 feet, and the V_1 speed is reduced by some 20 knots. Establishing the V_1 speed for the wet surface A points out the potential hazards in attempting a refused take-off above this speed. If this same wet runway is, however, grooved (surface B), one might expect to exceed only slightly the dry-surface balanced field length at essentially the dry-surface critical engine-failure speed (see fig. 6). The increase in V_1 speed produced by grooving allows a significant delay in making a continued take-off decision from wet pavements. A similar analysis of F-4D balanced field lengths is shown in figure 7. Refused take-off field length for the wet ungrooved runway surface A is more than doubled at engine-failure speeds occurring at the dry-surface critical value, and the wet-surface V_1 occurs 50 knots below the dry-surface V_1. Grooving wet surface A (represented by surface B) brings the critical engine-failure speed and the balanced field take-off performance up to nearly the dry-surface level.

Figures 8 and 9 present a comparison for both airplanes of the dry and wet, ungrooved and grooved balanced field lengths. Critical engine-failure speeds are listed opposite the corresponding balanced field lengths required. The wet-surface critical engine-failure speeds are included, since they have been shown to be indicative of balanced field performance levels when compared with the dry-surface values. These figures indicate that grooving the runway surfaces of this study would, in essence, allow the use of dry-surface values for V_1 and for balanced field length during wet and puddled operations of both airplanes. All these values are, of course, amendable with the use of auxiliary deceleration aids such as reverse thrust for the 990A in the absence of appreciable cross winds (e.g., see ref. 4) or the F-4D parabrake, which were not included for purposes of this investigation.

Figure 10 shows some predicted results for the 990A regarding balanced field lengths and critical engine-failure speeds for concrete surfaces having a slush covering of 1/2 inch. Also shown are the predetermined dry-surface values for the maximum take-off weight. It is interesting to note the displacement of the take-off curve for grooved and ungrooved surfaces covered by 1/2 inch of slush. This displacement is primarily the result of slush drag on the nose and forward tires of the main gear as determined by the FAA investigation of slush effects in take-off of the Convair 880 (ref. 5), which has similar landing gear and tire configurations. This effect, coupled with reduced accelerations and friction coefficients for the refused take-off, increases the slush-covered ungrooved balanced field length to approximately 12 000 feet. The critical engine-failure speed is, in turn, reduced by approximately 20 knots from the dry-surface value. A reduction in balanced field length of only 500 feet and an increase in V_1 speed of about 10 knots is allowable through grooving of this concrete surface.

CONCLUSIONS

The present study of the effects of transverse runway grooving for the 990A and F-4D airplanes with regard to adverse-weather landing field lengths and balanced take-off field lengths indicates the following conclusions:

1. Transverse runway grooving effectively reduces landing field lengths under adverse weather conditions for a variety of runway surfaces.

2. Essentially dry balanced field take-off performance is attainable for grooved runway surfaces in a wet and puddled condition, since grooving increases the critical engine-failure speed to practically dry-surface values.

3. Only slight reductions in balanced field lengths are provided by grooving for take-off from slush-covered runways.

REFERENCES

1. Yager, Thomas J.: Comparative Braking Performance of Various Aircraft on Grooved and Ungrooved Pavements at the Landing Research Runway, NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 3 herein.)

2. Smith, H. R.: Anti-Skid Systems – Convair 880/880M/990. Convair Traveler, vol. XV, no. 1, May/June 1963, pp. 3-9.

3. Byrdsong, Thomas A.: Investigation of the Effect of Wheel Braking on Side-Force Capability of a Pneumatic Tire. NASA TN D-4602, 1968.

4. Horne, Walter B.; and Dreher, Robert C.: Phenomena of Pneumatic Tire Hydroplaning. NASA TN D-2056, 1963.

5. Sommers, Daniel E.; Marcy, John F.; Klueg, Eugene P.; and Conley, Don W.: Runway Slush Effects on the Takeoff of a Jet Transport. Final Report, Project No. 308-3X, FAA, May 1962.

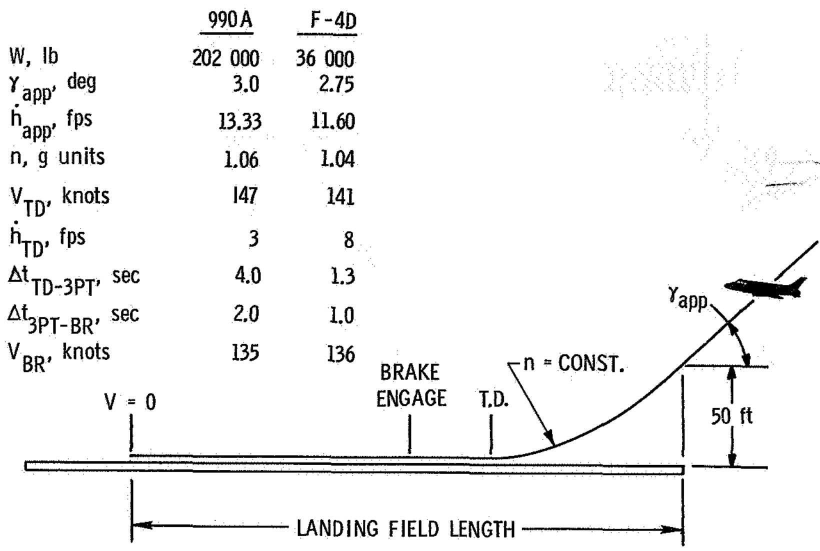

Figure 1.- Landing analysis. Standard day; sea level; no wind.

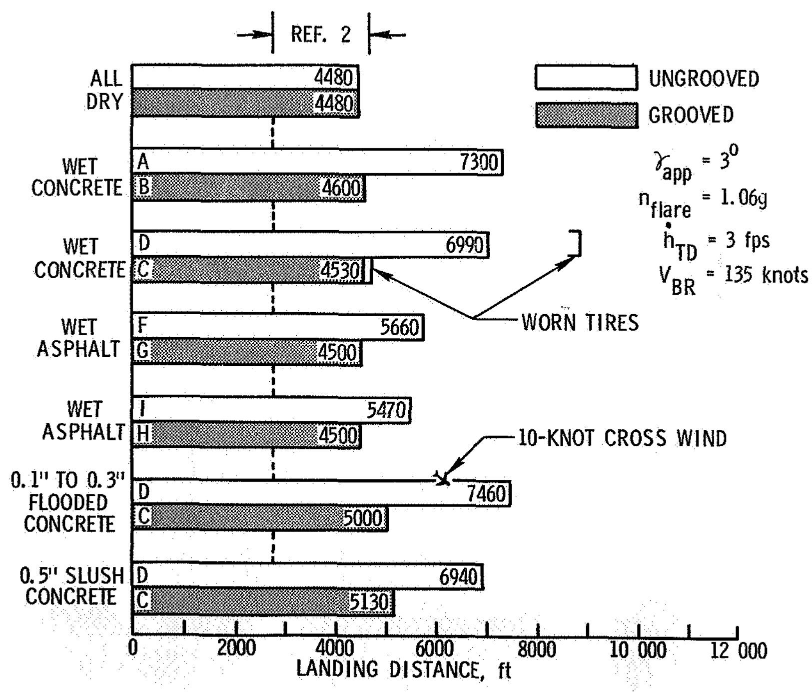

Figure 2.- Landing field lengths for 990A. Standard day; sea level; W = 202 000 lb.

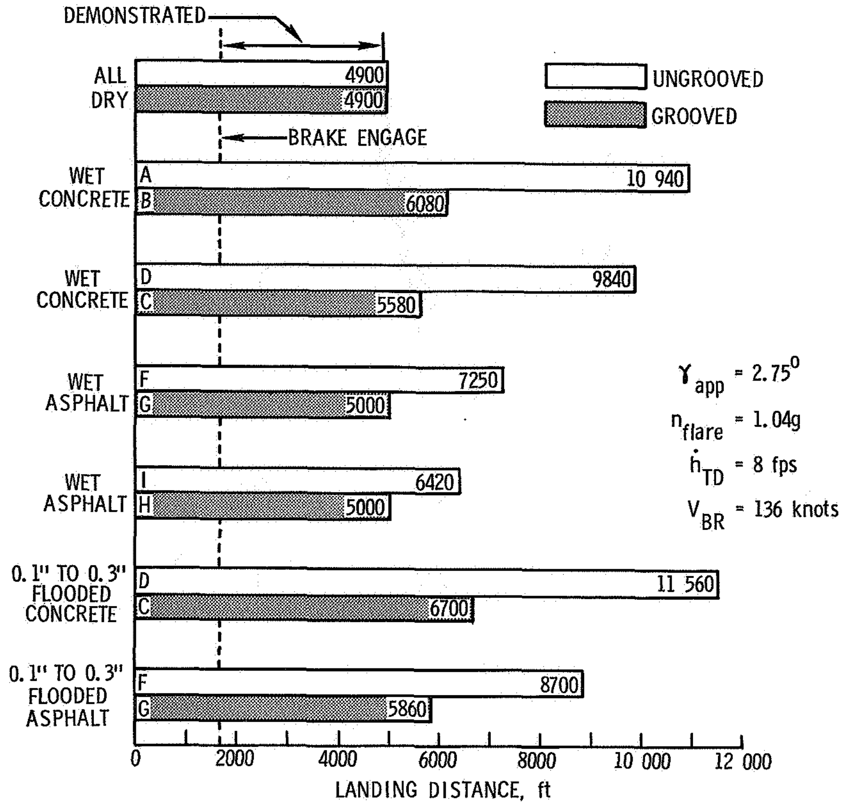

Figure 3.- Landing field lengths for F-4D. Standard day; sea level; W = 36 000 lb.

T.O. CONTINUED

$\Delta t_{T_1 = 0} = 3.0$ sec

	990A	F-4D
V_r, knots	165	172
h_2, ft	35	50

T. O. REFUSED

Δt, sec	EVENT
0	ENGINE FAILURE
1.5	PILOT RECOGNITION
2.0	BRAKES ON
3.0	SPOILERS OR HORIZONTAL STABILIZERS DEPLOYED (T_1=0)
4.5	IDLE T_R

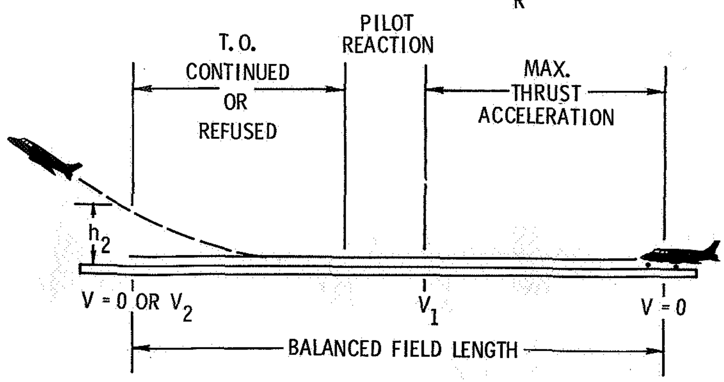

Figure 4.- Take-off analysis. Standard day; sea level; no wind; level runway.

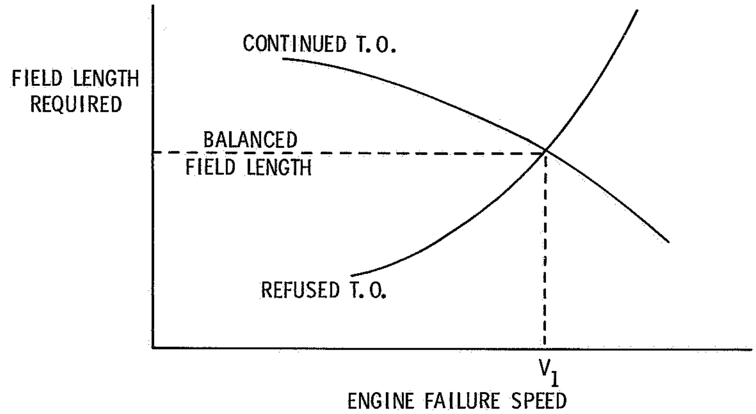

Figure 5.- Take-off balanced field length. Constant weight and ambient conditions.

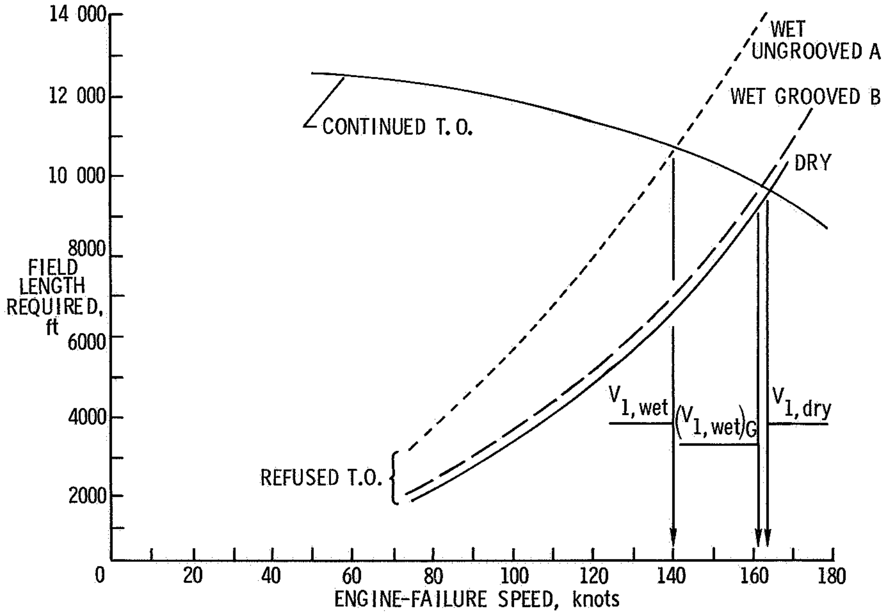

Figure 6.- Dry- and wet-surface balanced field lengths for 990A. W = 246 000 lb; concrete.

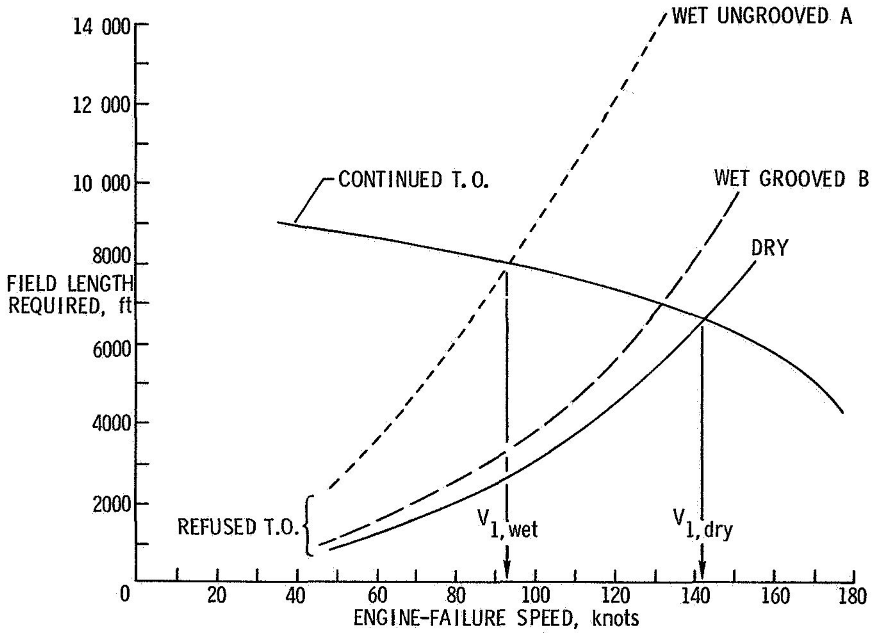

Figure 7.- Dry- and wet-surface balanced field lengths for F-4D. W = 48 000 lb; concrete.

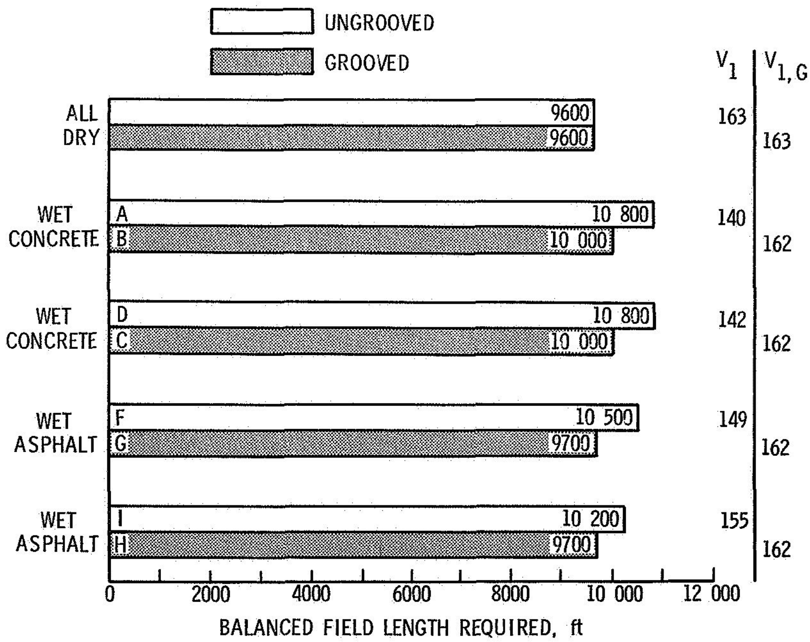

Figure 8.- Effect of grooving on take-off balanced field lengths for 990A. W = 246 000 lb.

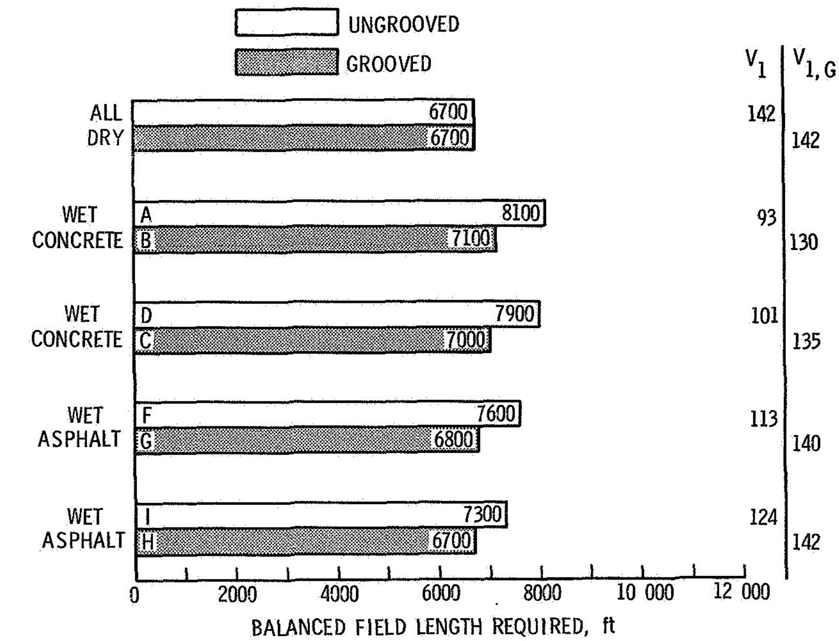

Figure 9.- Effect of grooving on take-off balanced field lengths for F-4D. W = 48 000 lb.

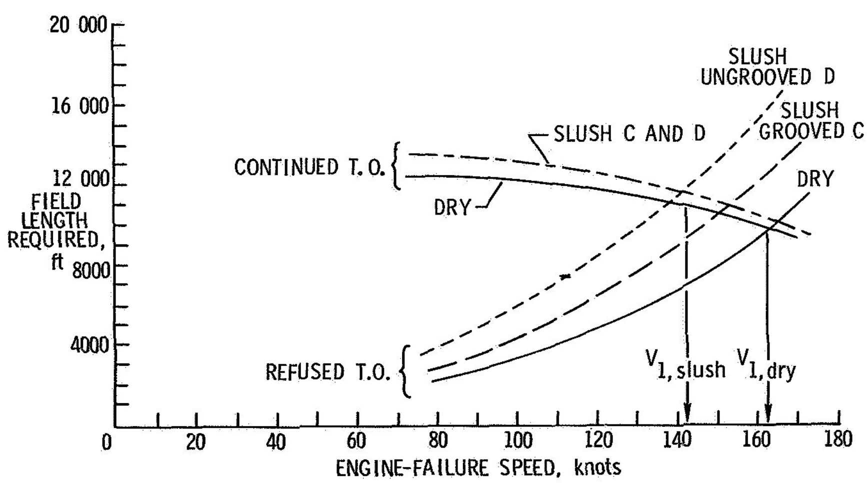

Figure 10.- Balanced field lengths for 990A on dry and slush-covered surfaces. Standard day; sea level; W = 246 000 lb; concrete.

7. RESEARCH PILOTS' OBSERVATIONS OF AIRCRAFT PERFORMANCE ON A GROOVED RUNWAY

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SUMMARY

Braking effectiveness tests of two airplanes have been completed on the landing research runway at NASA Wallops Station. The pilots' observations indicated that transverse-groove surfaces drastically reduced all types of skids on a wet or flooded runway and provided positive nose-gear steering during the landing roll-out. The grooved surfaces also prevented the onset of drift and weathervaning. The overall airplane ground handling and stopping characteristics on the grooved surfaces showed a dramatic improvement over those on corresponding ungrooved surfaces with no observable adverse characteristics from the pilots' point of view.

INTRODUCTION

In March 1968, a flight test program was conducted on the landing research runway at NASA Wallops Station to investigate the differences in wet runway braking effectiveness resulting from grooving various types of surface materials. Previous tests (ref. 1) had shown grooving of the surface to be an effective method for maintaining high friction on a wet surface. The changes in airplane behavior in terms of direct braking effect as well as in cross winds were of particular interest to the pilots, since most hydroplaning accidents involve a loss in directional control or a drift off the side of the runway. Separated test sections on the research runway allowed comparative braking measurements to be made directly during each run and provided the pilots with a unique opportunity to observe the corresponding changes in airplane response to braking and directional control. Pilot observations which form the basis for this paper supplement other measurements of braking performance given in references 2 and 3.

DISCUSSION

Research Airplanes

The test airplanes were a McDonnell Douglas F-4D fighter made available by the U.S. Air Force and an NASA Convair 990 jet transport. These airplanes were selected to provide a range of tire pressures, an important factor in wet runway braking. The F-4D tires were inflated to a pressure of 280 psi, and the 990 tires are normally inflated to a pressure of 160 psi.

The 990 airplane shown in figure 1 has a typical eight-wheel main landing gear and a dual-wheel nose gear. The nose gear is steerable and provides primary directional control during the landing roll-out below 60 to 70 knots. After touchdown, spoilers are used to get the airplane weight on the wheels and the full-power rudder is effective for high-speed directional control.

The antiskid system on the 990 airplane is representative of the systems on current jet transports. Each main gear wheel is braked individually, and the nose gear wheels are braked as a unit in the antiskid mode when full pedal deflection is applied. Transducer-type skid detectors, one for each main gear wheel and a single one for the nose wheels, sense the rate of change of wheel speed. Signals from the detectors are fed to a control box which, in turn, transmits controlling signals to the antiskid control valves. If the deceleration rate of a wheel indicates an impending skid, the associated antiskid valves reduce metered pressure to the affected brakes in proportion to wheel slip until the wheels recover normal speed.

The tires on the 990 were maintained at a pressure of 160 psi which would produce a hydroplaning speed of 112 knots according to reference 1. The 990 landing touchdown speed ranges roughly from 120 to 150 knots.

The F-4D airplane is shown in figure 2. It is a typical fighter configuration with two main gear wheels and a dual-wheel nose gear. No braking is available to the nose wheels. The nose gear is steerable; however, normal operating procedures dictate that nose gear steering be engaged after the rudder is no longer effective for directional control. After touchdown, the horizontal stabilizer in the full-up position adds aerodynamic drag which increases the aircraft weight on the main gear wheels.

The F-4D is equipped with essentially the same antiskid brake system as the 990. A notable difference in the two systems is that the F-4D antiskid control valve reduces metered pressure to both brakes regardless of which wheel is indicating an impending skid, whereas the 990 system only reduces pressure to the affected wheel.

The F-4D landing speed ranges from 135 to 145 knots. Tire pressures utilized during the test would produce a hydroplaning speed of 150 knots.

Landing Research Runway

A diagram of the landing research runway at the NASA Wallops Station is shown in figure 3. The test sections are level and are bounded by 2-inch-high rubber dams to provide an even water depth. Each test section was identified for the pilots by lettered side markers. Approximately 2500 feet of normal runway at each end of the test area provide adequate distance for speed stabilization prior to entering the test sections and for a safe stop or take-off following the data run. Additional information regarding the research runway is available in reference 2.

Test Procedure

Braking effectiveness data were obtained for ground speeds ranging from about 50 to 150 knots. The wheel rotational speed signal from the antiskid system operated a meter which was previously calibrated to read ground speed by timing the airplane between measured points along the runway at constant meter readings. The meter was placed directly in the pilot's view to allow him to establish desired speeds prior to entering the test sections. The tests involved accelerating to the test speed from a standstill to the take-off position or landing short of the test section and adjusting speed by referring to the ground speed indicator. This speed, or a slightly higher speed, was held until about 100 yards before the appropriate test sections. At this point, power was reduced to idle and the spoilers extended. The timing was such that the engines would be spun down to idle thrust before entering the test area. The brake pedals were abruptly applied to maximum deflection while the wheels were still on the dry reference section and were maintained through two wet or flooded test surfaces, one grooved and one ungrooved. When feasible, the stop was completed and a brake and tire check was made before the next run. At the higher speeds, a take-off was made directly after the run to cool the brakes and tires. One hundred twenty-five braking runs including 75 landings were made with the 990 airplane; 72 runs and 25 landings were made with the F-4D airplane.

For the slush tests, the 990 turbocompressor air inlets, lower rotating beacon, and antennas were shielded since previous FAA slush tests indicated the vulnerability of these areas to impact damage. The airplane withstood this abuse well and required no additional maintenance. Slush tests were not conducted with the F-4D airplane.

Although most of the effort was directed toward obtaining braking effectiveness data, other measurements and observations were made. For example, the braking tests were repeated with new conventional tread tires so that the results could be compared with the results obtained with bald tires. In addition, treaded and bald tires were placed in alternate positions on one four-wheel truck to determine whether the clearing effect of the forward wheel would make a difference in rear wheel braking corresponding to tread wear on the rear tire. The results would determine the effectiveness of moving worn tires to the rear truck wheels. Landing touchdowns were also made in each flooded test section to measure wheel spin-up characteristics.

Test Observations

The three physical phenomena associated with wet-pavement skidding – thin-film lubrication (viscous hydroplaning), dynamic hydroplaning, and reverted rubber skids – were repeatedly encountered during these tests. Dynamic hydroplaning was consistently encountered at high speeds, even to the point of preventing wheel spin-up at touchdown on a flooded surface. Reverted rubber skidding occurred several times with the 990 following a phase of dynamic hydroplaning and at lower speeds. There were no reverted rubber skids with the F-4D. Viscous hydroplaning occurred even at taxi speeds on the smooth wet concrete surface, and it was very noticeable to the pilots because the speed was low enough to prevent antiskid operation.

The data in time history form from a typical braking test with the 990 are shown in figure 4. The time history selected is for dynamic hydroplaning at about 110 knots on a flooded ungrooved surface followed by a phase of high brake effectiveness on the flooded grooved surface. The first trace at the top of the figure is a time history of the nose-gear-wheel rotational speed, with the rotational-speed traces of the four right main gear wheels below. The brake pressure traces are in the same sequence, and a longitudinal-acceleration trace is included at the bottom of figure 4 to show the braking effectiveness.

The point of brake application is clearly shown by the rise in brake pressure. The rise in the nose-gear-wheel brake pressure verifies that the brake pedals are fully deflected since nose-gear-wheel braking is only obtained through the antiskid system with full pedal deflection. At this point, the wheels are on a dry ungrooved surface and very little change in rotational speed can be seen, yet a deceleration of nearly 0.5g is indicated. This deceleration corresponds to a very abrupt stop in an automobile when full brakes are applied on a dry surface. In less than a second, the airplane traveling at over 150 feet per second entered the wet ungrooved section and, as the acceleration trace shows, the retardation has almost returned to the no-braking level because the wheels started to skid. The wheel rotation rate falls nearly to zero even though the antiskid system rapidly released the brake pressure. Even without brake pressure, all wheel rotation had ceased and the airplane is sliding free in a condition of dynamic hydroplaning.

When the nose wheels are hydroplaning, they have lost their steering effectiveness and, as observed in runs where a cross wind existed, a yawing moment and lateral drift would be produced. The yaw can be controlled to some extent at this speed (but not at lower speeds) by use of the rudder; however, the drift would continue. A change in heading with the rudder does not appreciably alter the path of the airplane as it translates toward the side of the runway.

On the research runway when the wheels entered a grooved section which is also flooded, there was an abrupt buildup in retarding force, as shown in figure 4, even though full brakes had been applied continuously. The feeling of applying full brakes on a dry surface is repeated when entering the flooded grooved section from the ungrooved surface with full brakes applied. The wheels spin up on the grooved surface, and brake pressure is applied by the antiskid control unit with a corresponding increase in the retarding force. A deceleration level almost equivalent to the dry surface value is obtained, and nose-gear steering returns.

The pilots were appreciative of the fact that during these tests there were grooved sections on which to recover from skids and a long section of dry runway to complete the stop or to take off to cool the brakes. On the ungrooved flooded surface, the pilot was helpless. No braking technique had any significant effect, since under these conditions wheel rotation had often ceased even without brake pressure. Some directional control remained through use of the rudder, but the cross-wind drift could not be stopped by any process until some side force could be generated through wheel friction. The improved braking on a transverse-groove surface was impressive, but the fact that the wheels could generate a side force to prevent lateral drift was considered to be equally important to the pilot. There can be few worse feelings to a pilot than when his airplane is skidding out of control on a wet runway.

The tests were made in a sequence involving first the dry reference surface and then the wet ungrooved surface which led to an entry into the wet grooved surface in a skid. Since the prevailing winds gave a consistent cross-wind component, occasionally over 15 knots, a lateral drift occurred during many skids. The drift was straightened out by the grooved surface so abruptly that there was concern over the magnitudes of the associated side loads on the landing gear. Accordingly, the tests were altered so that the airplane entered the grooved surface first. This procedure tended to reduce the aircraft speed at the end of the drift with a consequent reduction in landing-gear side loads.

Five types of ungrooved surfaces were used in the tests. The subjective differences in braking on them were difficult to determine when they were flooded. When the surfaces were just damp, the textured sections gave noticeably better braking, especially at the lower speeds. The measured data which are presented in reference 2, however, provide a definitive comparison between the surfaces.

The difference in braking effectiveness between new tires with a tread pattern and bald tires was not readily apparent to the pilot. Again, the measured data of reference 2 must be studied to reveal the advantages of tread pattern.

Incidentally, one tire was damaged due to a miswired brake control valve, and hydroplaning damage and wear required several other tire changes. The brake control valve was newly overhauled with the internal wiring reversed. This service error caused the skid signal to release brake pressure on the opposite wheel so that one wheel of the pair had full pressure applied and the other was free rolling. There is no way to detect this condition in the cockpit or even from tire wear obtained by landing on dry runways, because until a skid is sensed, the brake pressure would be applied evenly. This problem is mentioned as a matter of interest; however, it should be pointed out that the overhaul was not provided by the manufacturer of the antiskid controls for this aircraft.

CONCLUDING REMARKS

The grooved runway surfaces drastically reduced all types of skids, including dynamic hydroplaning, and allowed positive nose-gear steering during the landing rollout. The grooved surfaces also prevented the onset of drift at touchdown in a flooded area because wheel spin-up provided high cornering forces.

The overall airplane ground handling and stopping characteristics on the grooved surfaces showed a dramatic improvement over those on corresponding ungrooved surfaces with no observable adverse characteristics from the pilots' point of view.

REFERENCES

1. Horne, Walter B.: Skidding Accidents on Runways and Highways Can Be Reduced. Astronaut. Aeronaut., vol. 5, no. 8, Aug. 1967, pp. 48-55.

2. Yager, Thomas J.: Comparative Braking Performance of Various Aircraft on Grooved and Ungrooved Pavements at the Landing Research Runway, NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 3 herein.)

3. Phillips, W. Pelham: Calculated Aircraft Stopping Distances Based on Test Results Obtained at the Landing Research Runway, NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 6 herein.)

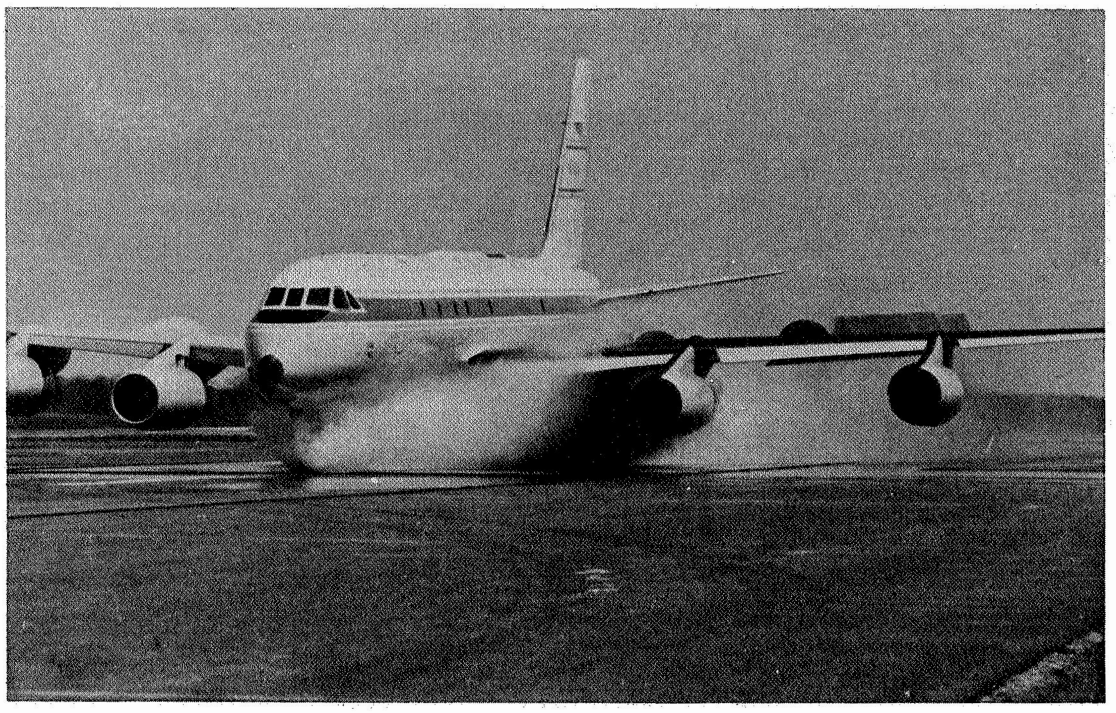


Figure 1.- The 990 test airplane.

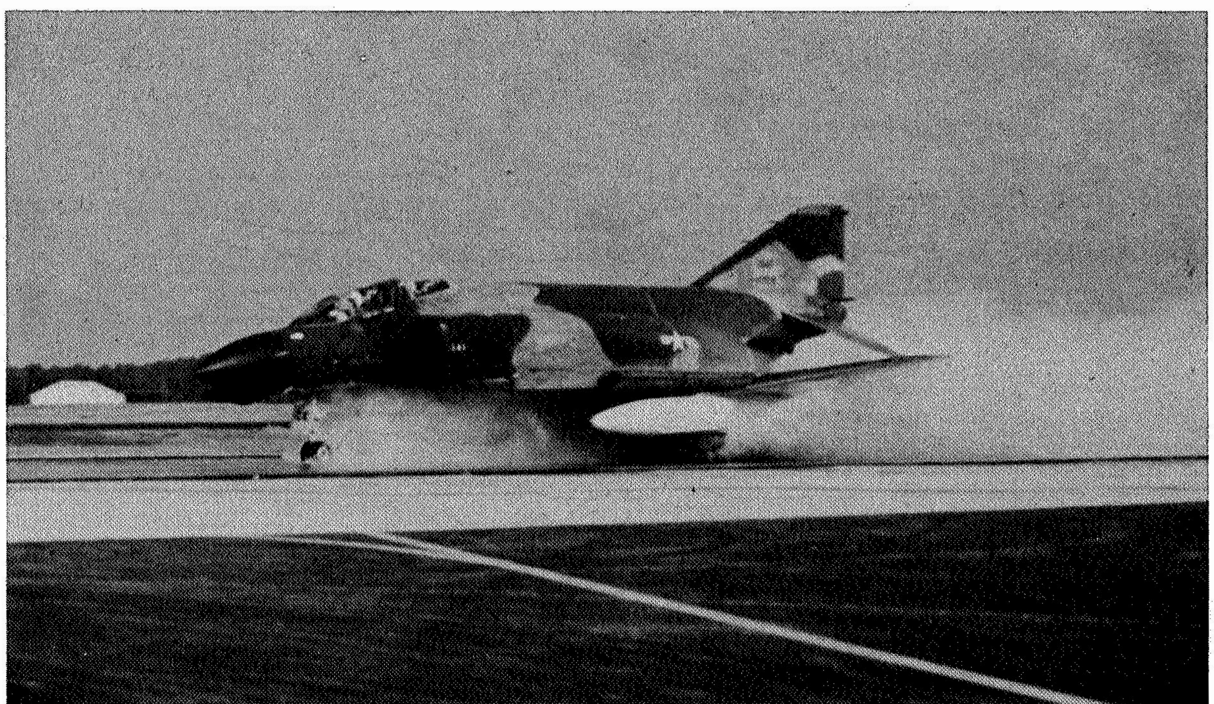


Figure 2.- The F-4D test airplane.

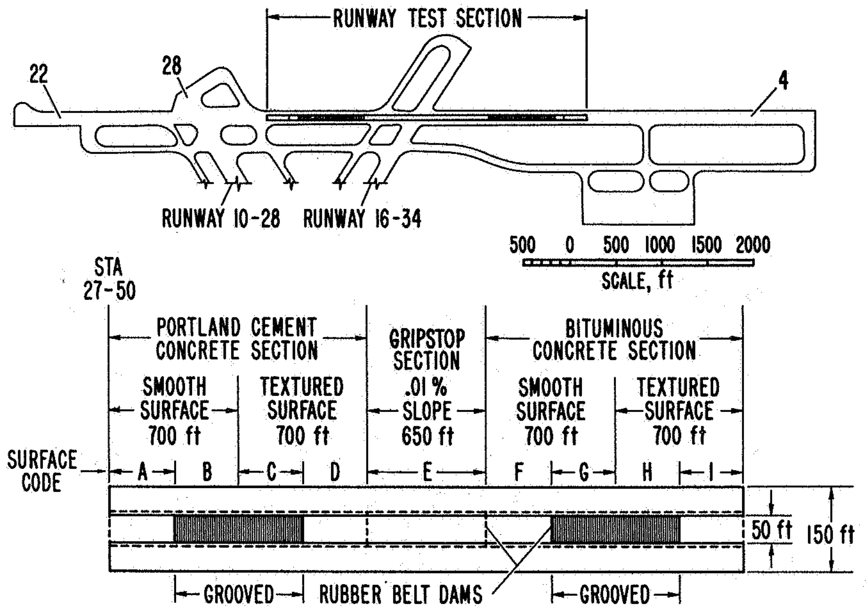


Figure 3.- Schematic view of landing research runway at NASA Wallops Station.

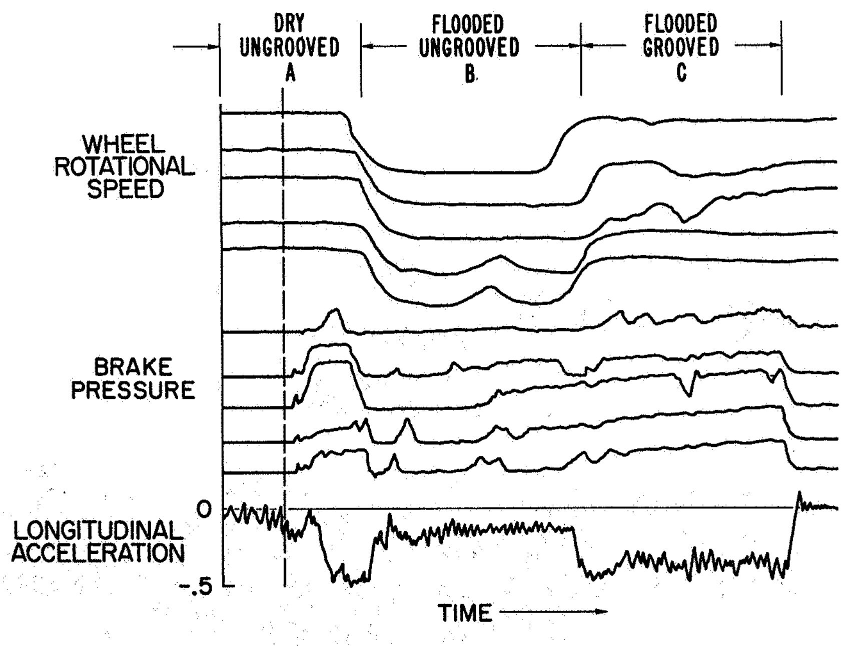


Figure 4.- Typical 990 test data.

8. PROBLEM AREAS ASSOCIATED WITH THE CONSTRUCTION AND OPERATION OF THE LANDING RESEARCH RUNWAY AT NASA WALLOPS STATION

By Curtis R. Allen and James W. Quillen

NASA Wallops Station

SUMMARY

This report covers the final phases of the construction of a landing research facility at the NASA Wallops Station which was begun late in 1967 and completed early in 1968. The test area had grooved and ungrooved sections of concrete and asphalt with various types of finishes. Also discussed are the problem of finding a suitable method for containing predetermined depths of water and slush required for the various tests and the solution of this problem. Problem areas encountered are cited and some adverse side effects which the tests brought to light are described in detail.

INTRODUCTION

The landing research runway at NASA Wallops Station is unique in that it was constructed for the primary purpose of testing the effectiveness of pavement grooving in increasing aircraft take-off and landing performance on dry, wet, water-flooded, and slush-covered runways having different surface textures. Also, the runway had to be of such configuration that normal aircraft operations could be conducted at other times. A secondary purpose of the landing research runway is to determine the effects of aircraft loading and climatic conditions on the life of grooved runways with both asphalt and concrete surfacing materials.

DISCUSSION

Runway 4-22 is the landing research runway at Wallops Station. The runway is 8750 feet long and 150 feet wide; the test section, which is almost centrally situated, is 3450 feet long and extends 25 feet on either side of the runway center line. Figure 1 shows the test section relative to the overall length and width of the runway.

Test surfaces A, B, C, D, F, G, H, and I are 350 feet long; surface E is 650 feet long. The grooves in sections B, C, G, and H are 1/4 inch deep by 1/4 inch wide and are cut on 1-inch centers. This grooving represents the most effective pattern thus far determined (provides the highest friction coefficient). The various sections of the test area have the following construction and finish (see table I of ref. 1 for detailed description):

Surface A – Ungrooved concrete with canvas belt surface finish (fig. 2)

Surface B – Grooved concrete with canvas belt surface finish (fig. 3)

Surface C – Grooved concrete with burlap surface finish (fig. 4)

Surface D – Ungrooved concrete with burlap surface finish (fig. 5)

Surface E – Ungrooved, smooth rock asphalt (Gripstop) (fig. 6)

Surface F – Ungrooved, smooth, small aggregate asphalt (3/8 inch or less) (fig. 7)

Surface G – Grooved, small aggregate asphalt (3/8 inch or less) (fig. 8)

Surface H – Grooved, large aggregate asphalt (3/4 inch or less) (fig. 9)

Surface I – Ungrooved, smooth, large aggregate asphalt (3/4 inch or less) (fig. 10)

This test area was designed to be as flat and level as possible by using standard construction methods to aid in maintaining the constant depth of water or slush necessary for obtaining reliable data during the tests. The rest of the runway proper is crowned to the standard 1-percent slope to permit water runoff (fig. 1).

When the grooving machine is cutting, it is necessary to continually cool the diamond-tipped cutting blades with water to prevent them from overheating. In the cutting process on concrete, the dust created combines with the water and forms a fine slurry which must be cleaned off the runway by high-pressure washing before it dries and hardens. The reason that the runway must be thoroughly washed was shown in actual tests by both the McDonnell Douglas F-4D and the Convair 990 aircraft. As these aircraft made repeated runs over the grooved concrete sections, large amounts of concrete dust were blown loose by the jet blasts from the aircraft engines and formed huge dust clouds. These clouds were created from the cutting residue which had adhered to the wet runway surface; this indicated that sufficient care had not been exercised in the removal of the slurry. The dust clouds caused some photographic difficulties and resulted in reduced visibility to participating test personnel. This condition might very well pose a serious problem for busy airports where reduced visibility due to such dust could impair the safety of aircraft during landing roll-out and taxiing and also could create a problem for the control-tower operator in the control of air and ground traffic. It is quite conceivable that damage to jet engines could result from ingestion of this dust. Thus, quite a problem is created and it should be given serious consideration in any future grooving on concrete surfaces.

An unsatisfactory occurrence took place on grooved asphalt sections G and H. During routine inspection following each braking run, it was discovered that the asphalt grooves were being completely obliterated during hardover 180° turns by the 990 aircraft. Figure 11 shows the damage produced by a 180° hardover turn made by the 990 aircraft on the grooved asphalt surface. Some damage occurred also on the ungrooved sections.

Another problem associated with grooving occurred on the large aggregate asphalt section H where the 1/2- and 3/4-inch aggregate stones had a marked tendency to break loose from the grooved surfaces. Because of this problem, numerous runway inspections and sweepings were necessary to keep the runway clean. These stones, if left on the runway, would present a most serious hazard to jet aircraft because of possible ingestion into the engines. Therefore, the continual care required to keep this particular type of surface clean is believed to be too extensive to justify grooving on asphalt with aggregate greater than 3/8 inch in diameter.

Probably the most significant problem that had to be resolved before completion of the landing research facility was the method of containing the desired level of water and slush so necessary in the varying nature of the different tests scheduled. Specifically, the problem was to maintain a given depth of water or slush on adjoining grooved and ungrooved sections while maintaining comparatively dry surfaces on the rest of the runway. The following significant requirements had to be kept in mind in the solution of this problem:

(1) Selection of materials with near watertight capabilities yet durable enough to withstand repeated braking and skidding runs

(2) Means for immediate drainage of wet sections with the capability for instant flooding of adjacent sections

(3) Minimum amount of shock to the aircraft landing gear during roll-out and braking runs, which might adversely affect data readings and computations

(4) Simplicity of installation and maintenance

No previously known method or published data were available for the construction of a test facility meeting all the preceding requirements. Therefore, the Contractual and Support Services Branch at Wallops Station was given the task of designing a dam to enclose the test section of the runway and to further subdivide the several sections to provide the varying water and slush depths required.

After numerous methods and plans were discussed, tested, and discarded, the idea of inserting rubber belting into a groove cut into the runway surface was conceived. The procedure used in construction of the prototype of the test model (fig. 12) was as follows: a groove 1 inch deep and 5/16 inch wide was cut in a standard piece of 2- by 4-inch wood framing, and a two-ply canvas-reinforced rubber belting $2\frac{1}{2}$ inches wide and 17/64 inch thick was inserted in the groove. This produced a somewhat snug fit while still allowing the rubber belting to fit fairly easily into the groove. The information gained from this model was then applied to the research runway. A groove 1 inch deep and 10 feet long was cut into one of the concrete sections of the landing research runway. A 10-foot length of rubber belting was inserted into this groove, over which numerous high-speed runs were made with a heavy truck. Some runs were made with locked brakes to determine whether the belting would hold in the grooves, withstand tearing or stretching, and retain its resiliency. It was noted that the passage of the truck wheels over this piece of rubber belting in no way damaged or dislodged the material, nor did it cause the wheels to bounce or swerve. Thus, this system seemed to meet all the test requirements with the exception of providing a constant water level; this requirement still had to be investigated. Therefore, a groove 1 inch deep and 5/16 inch wide was cut around the full perimeter of the 3450-foot-long test area and across each 350-foot section. When these grooves were finished, four men installed the 7400 feet of rubber belting in less than 8 hours. Tests showed that this system did perform the desired function. Hundreds of subsequent tests have proved the durability of both the grooves and the rubber belting. The rubber belting was easy to install and it was a simple matter to lift out selected sections of belting on a previously flooded section for drainage while an adjacent section was being flooded. The consensus of the Project Engineers and all participants of the tests conducted thus far is that the conception, the development, and the final installation of this rubber dam system was perhaps the most important single factor which contributed to the immediate and rapid success in carrying out the actual test operations.

No damage to concrete sections has been experienced thus far in the tests. However, surface damage has resulted from turns on asphalt sections and this alone points to the obvious need for having all aircraft roll free of grooved asphalt surfaces prior to making hard turns on the runway. Furthermore, on the basis of results obtained thus far, aggregate larger than 3/8 inch is not recommended as a wearing course.

CONCLUDING REMARKS

Tests made on the NASA landing research runway brought to light these adverse side effects of runway grooving on concrete and asphalt surfaces:

(1) The reduced visibility due to the concrete dust

(2) The surface failure of aggregate asphalt materials used in sections G and H

(3) The possibility of foreign object damage that can occur when large aggregate (larger than 3/8 inch) is used as a wearing course in asphalt

All these problems are considered to be easily resolved. It is recommended that airport planners contemplating runway grooving on concrete or asphalt surfaces take into consideration these known adverse effects prior to grooving operations.

Continued surveillance and investigation of all damage, wear, and unsatisfactory occurrences will be noted and documented for publication.

REFERENCE

1. Horne, Walter B.: Results From Studies of Highway Grooving and Texturing at NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper 26 herein.)

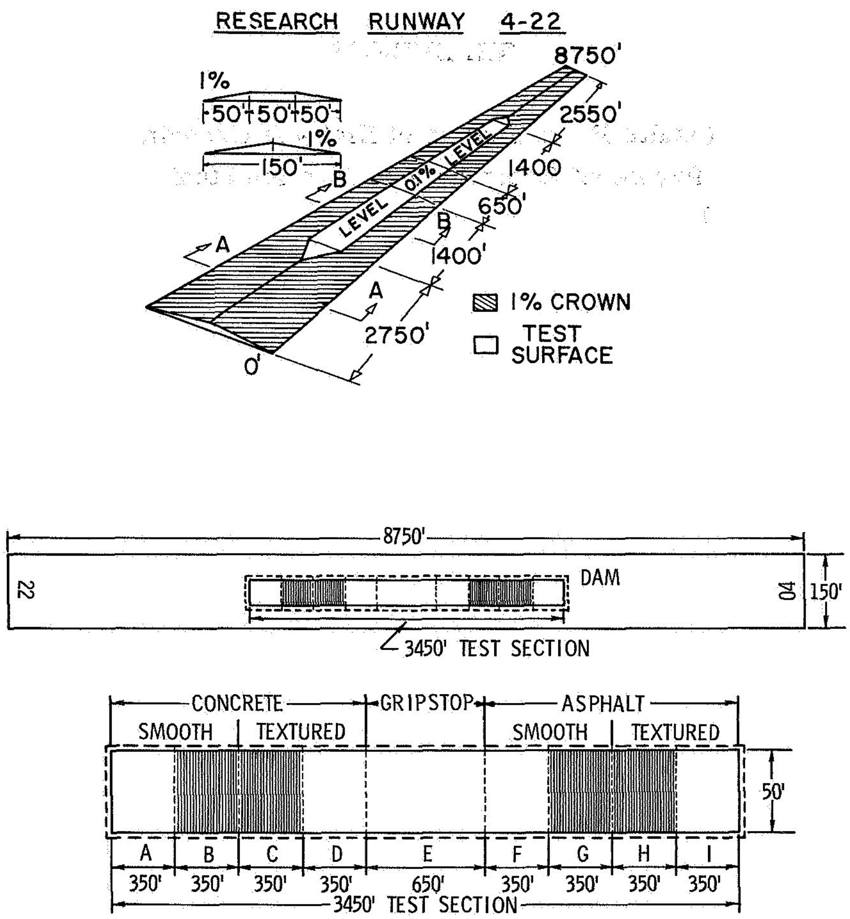


Figure 1.- Landing research runway 4-22 at NASA Wallops Station.

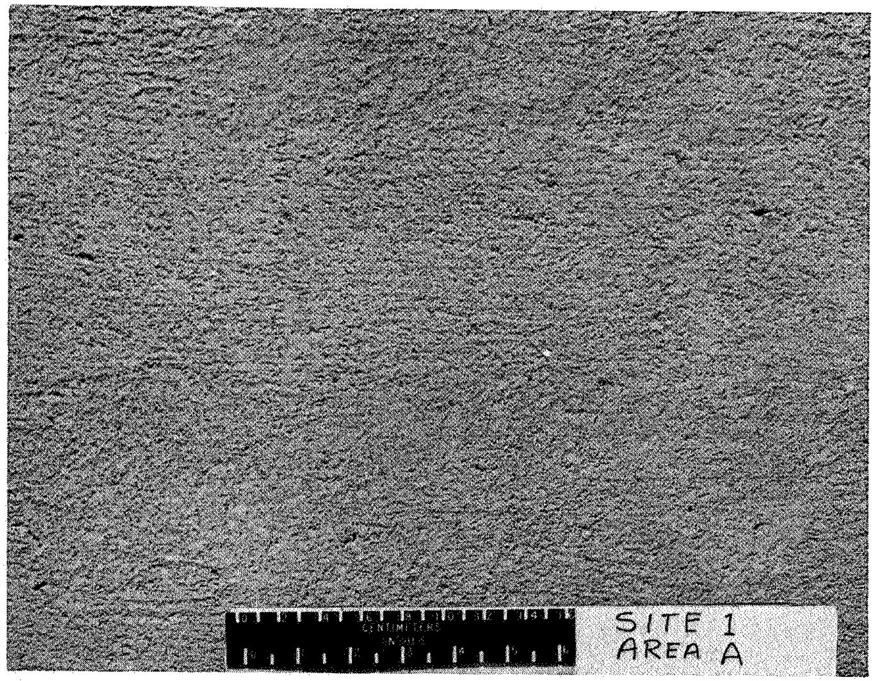


Figure 2.- Surface A.

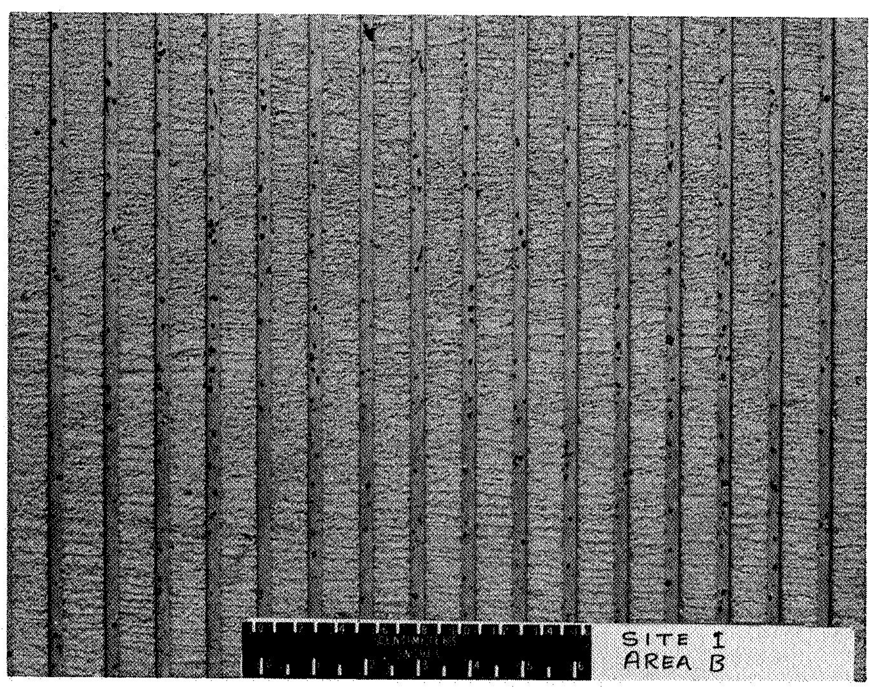


Figure 3.- Surface B.

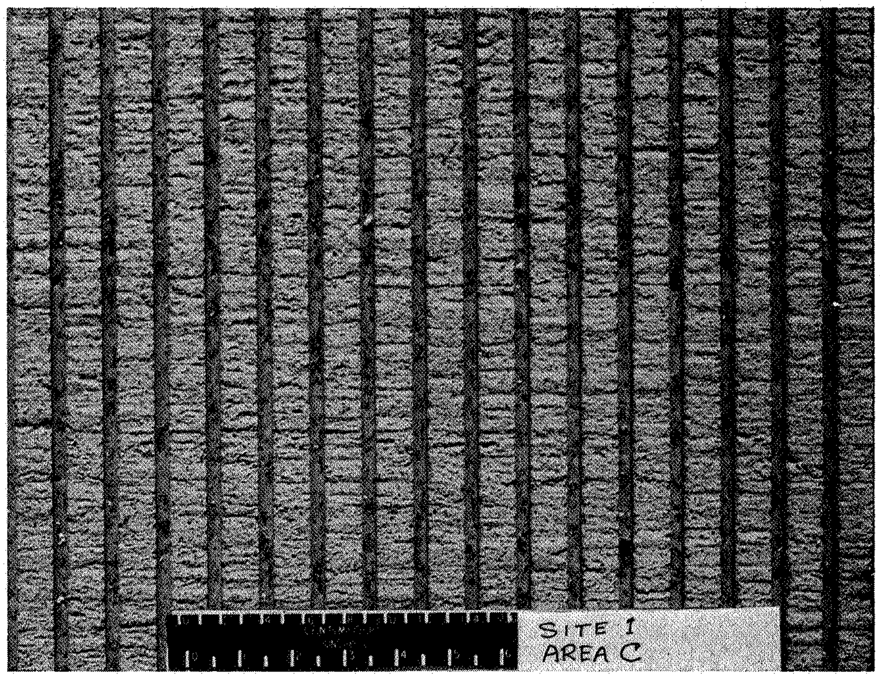


Figure 4.- Surface C.

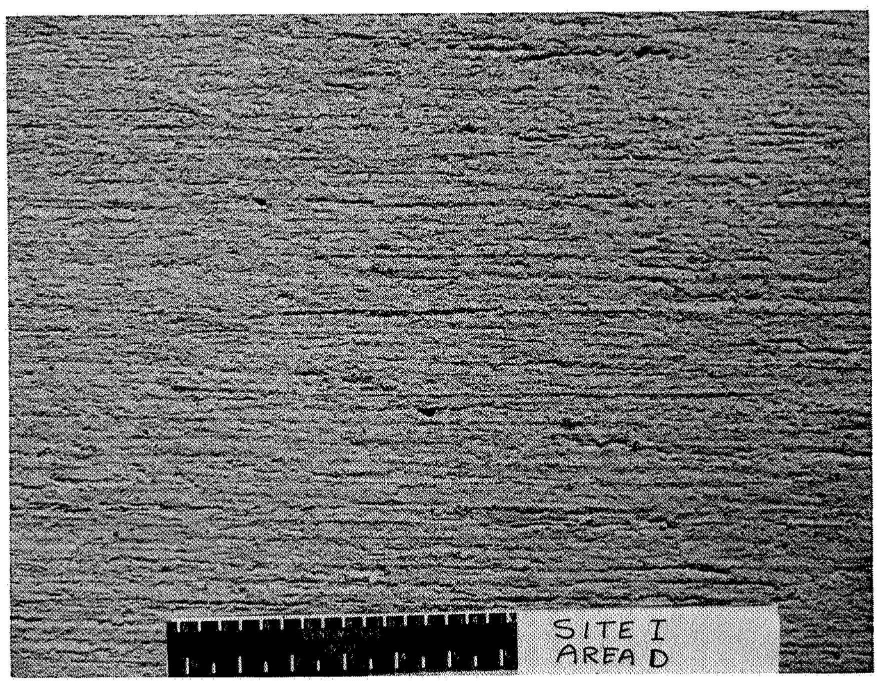


Figure 5.- Surface D.

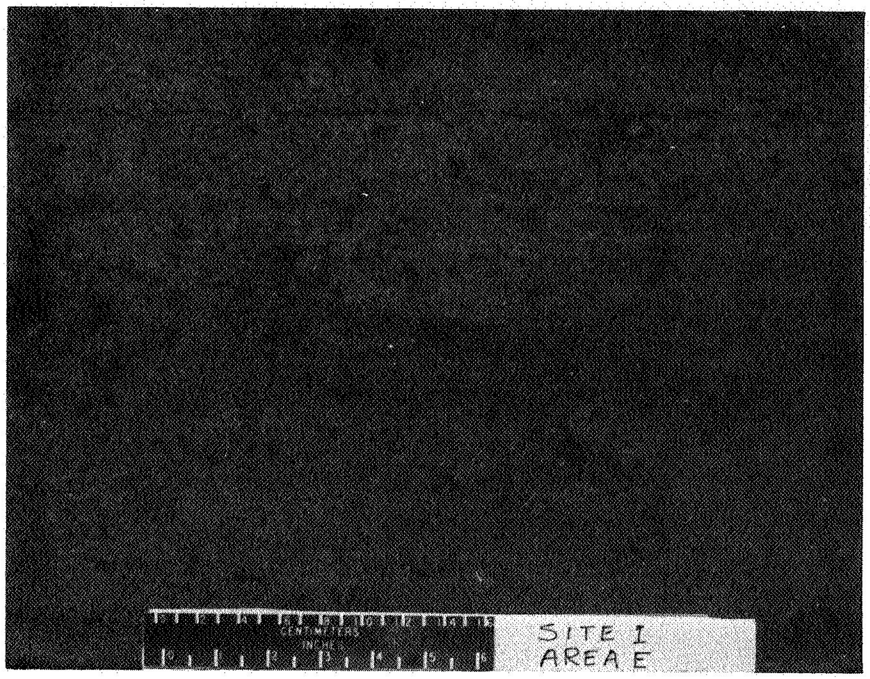


Figure 6.- Surface E.

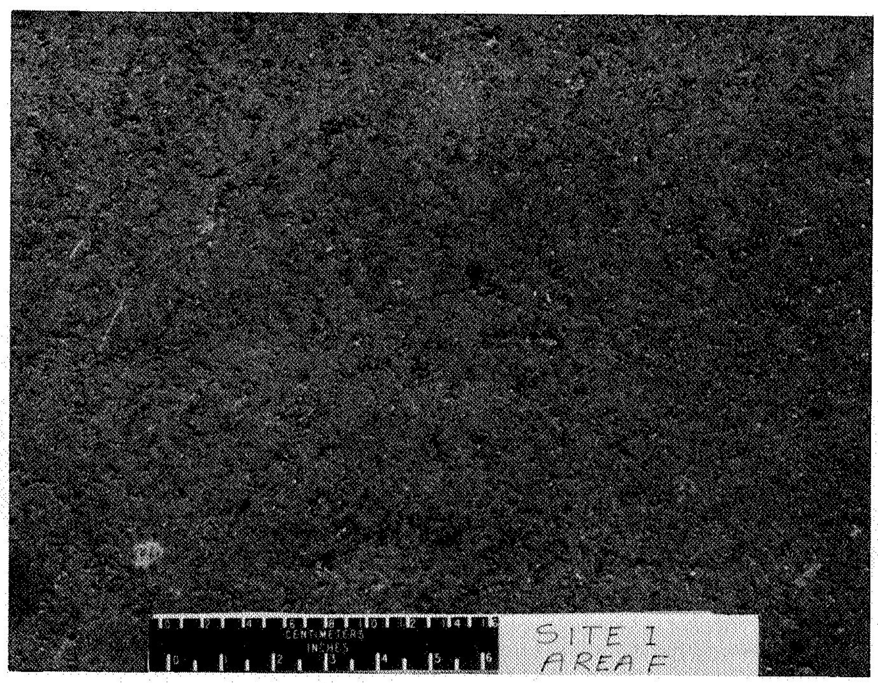


Figure 7.- Surface F.

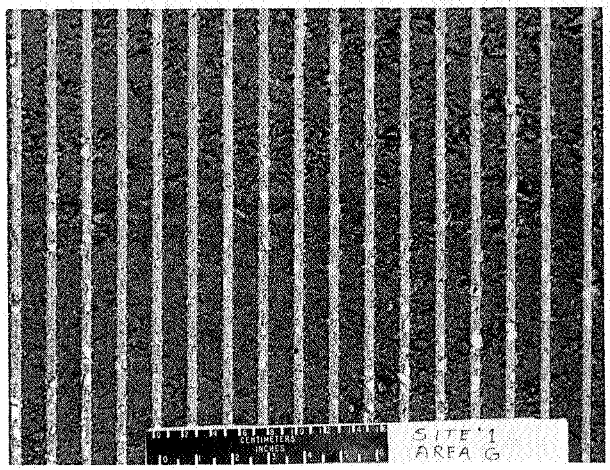


Figure 8.- Surface G.

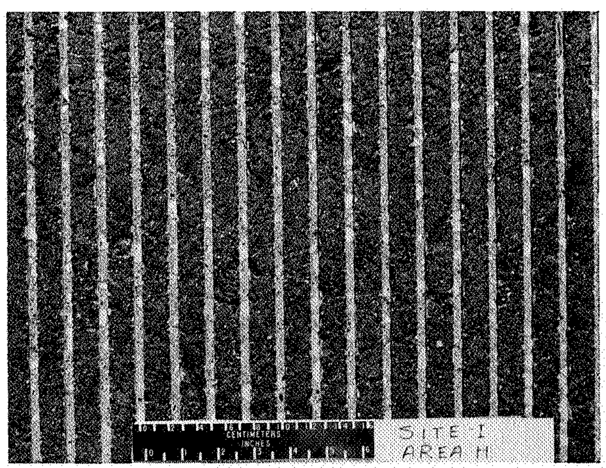
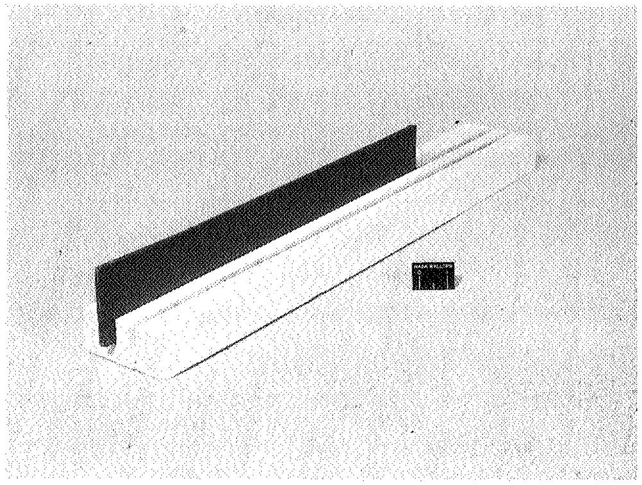


Figure 9.- Surface H.

Figure 10.- Surface I.

Figure 11.- Damage produced by 180^0 hardover turn by 990 aircraft on grooved asphalt surface.



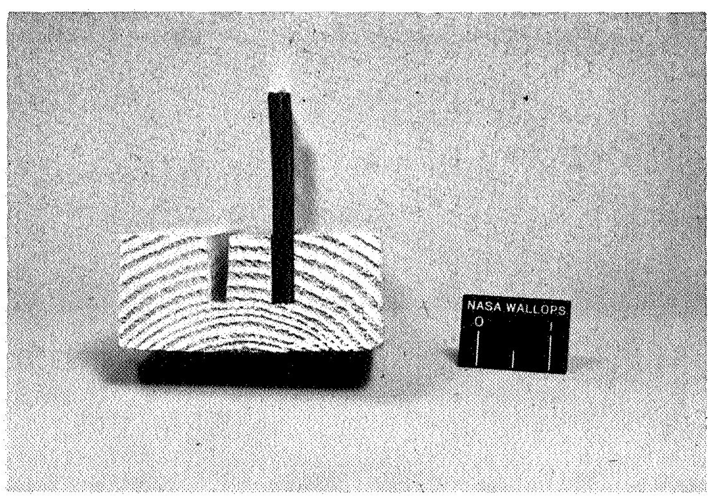


Figure 12.- Model of belting-groove system.

9. COMMERCIAL AIRLINES AND THE GROOVED RUNWAY CONCEPT

By Edwin W. Abbott

Air Transport Association of America

SUMMARY

Early research and grooving programs undertaken by the National Aeronautics and Space Administration and the United Kingdom prompted the airline industry to develop a runway grooving program of its own over 2 years ago. Behind this decision was the airlines' desire to increase safety and to advance the state of the art in aircraft stopping capability. The airlines felt, however, that before grooving could be considered for widespread use in the United States, operational experience would be needed with grooved runways exposed to heavy use and variable weather conditions.

This experience has been provided by 15 to 19 months' use of grooved runways at three major U.S. airports. On the basis of the airlines' evaluation, the Air Transport Association of America (ATA) is actively seeking the expansion of runway grooving to other airports.

INTRODUCTION

Because heavy turbine-powered aircraft are exposed to the risk of skidding on wet, slippery runways, the airlines have followed with great interest research efforts concerned with ways to reduce such risks. Airline interest was quickly focused on the phenomenon of aircraft hydroplaning since it was found to be a contributing factor in many "off runway" type of accidents, either in which an aircraft ran off the side of a runway or off the far end of the runway following a touchdown or an aborted takeoff. It was recognized that a hydroplaning aircraft tends to weather-vane in a crosswind. If reversing were applied while the aircraft was in this cocked position on the runway, it would actually help the crosswind move the aircraft off the side of the runway. As a result, airlines developed landing techniques to cope with this effect and all pilots were well indoctrinated in the hazards of hydroplaning.

However, the possibility of skidding on wet runways was by no means eliminated, but only minimized, by using such control methods. The airlines recognized the limitations of such operational techniques and began to look into a runway grooving test program because the data expected from the government programs, by NASA and the Federal Aviation Administration (FAA), were not yet completed. It was felt the problem was serious enough and the benefits to be derived were important enough, that airlines should not wait for the outcome of these more comprehensive investigations.

DISCUSSION

During the summer of 1966, a representative of NASA Langley Research Center made a presentation on runway grooving before the ATA Flight Operations Committee. The Committee then recommended that ATA investigate the merits of an airline industry program on runway grooving in order to determine its operational benefits and future applications. The reasons for pursuing operational tests were threefold: First, the airlines were aware in the summer of 1966 that it would be at least a year before the NASA test would commence at Wallops Island using airline, military, and business aircraft on a specifically modified runway; it would probably take another year before qualitative results would become available. Second, an operational test at a heavily used airport would provide valuable information on the effectiveness of runway grooving as well as the runway's ability to withstand deterioration in heavy traffic. The United States appeared to offer a more varied climatic environment compared with that experienced in the United Kingdom during the use of grooved runways there. Third, the airlines were aware that although such an operational test would not supply an abundance of qualitative technical data, it would supplement NASA's endeavors and provide useful information at an earlier date. Also, not much was known about the possibility of increased vibration and noise which might result when an aircraft operated on grooved runways.

Following this decision by the ATA Flight Operations Committee, ATA and its member airlines began laying the groundwork for an operational evaluation of runway grooving in the U.S. In order to shed some light on the concern over the possibility of increased airframe vibration induced by grooved runways, American Airlines conducted flight tests on a grooved, dry, British runway with a newly delivered BAC 111 aircraft during the summer of 1966. No noticeable differences in vibration and noise levels between ungrooved and grooved runways were reported.

At about the same time, the airlines developed a list of preferred candidate runways for a grooving evaluation. Between the summer of 1966 and the following spring, discussions, deliberations, and studies were conducted by ATA member airlines and airport authorities to determine which runway or runways should receive priority consideration for a test grooving program. By early 1967 airline financial participation in the grooved runway test effort was fairly well assured.

The program that resulted represented a cooperative effort between the airlines serving Kansas City, Missouri, and the Kansas City Municipal Airport Authority and a similar joint effort by the airlines serving New York's John F. Kennedy International Airport (JFK) and the Port of New York Authority.

In May 1967, Kansas City Municipal's instrument runway 18-36, made up of both concrete and asphalt sections, was grooved for over 130 feet of its 150-foot width and for over 4500 feet of its 7000-foot length. The groove pattern was transverse, measuring 1/8 inch wide and 1/4 inch deep with 1 inch between centers. In early August 1967, the main instrument runway at JFK, concrete runway 4R-22L, was grooved from end to end and side to side. The transverse groove pattern was 3/8 inch wide by 1/8 inch deep on a $1\frac{3}{8}$-inch pitch. At Kansas City the grooves were rectangular in cross section, but at JFK they had 45^{o} sloping sides with a groove width of 3/8 inch at the top and 5/32 inch at the bottom. These and similar data for the two airports are summarized in table 1.

These runways and Washington National Airport's runway 18-36, which was completed April 25, 1967, were selected for grooving tests by the airlines out of 40 potential candidates and proposed to the airport authorities. The airlines paid for the grooving operation at both Kansas City ($87 000) and JFK ($178 500), but the grooving operation at Washington National was paid for by FAA.

In order to determine the effects of runway grooving on aircraft landing performance during wet conditions, ATA sent questionnaires to the airlines for use by their pilots immediately following a wet-runway landing on any of the three grooved runways. Pilots were asked to describe the precipitation, the amount of standing water on the runway, crosswind component, aircraft touchdown speed, and the number of times they had landed on the particular runway, both before and after grooving. The pilots were also asked to comment on the degree of improved lateral stability and to estimate the number of feet that stopping distance was reduced by grooving the runway.

Table 2 briefly summarizes some of the more pertinent factors which were considered significant in determining the effectiveness of runway grooving. Four different precipitation conditions were experienced during the period of the evaluation. More than 80 percent of landings reported were made when the rain had stopped before landing or when a light rain was falling during the actual touchdown and braking phase of the landing. The runway surface condition which generally resulted from these types of weather conditions was reported to vary from a thin film of moisture up to and including the condition in which pools of collected water formed over most of the used runway surface. The average touchdown speed of each type of aircraft used appeared to be within the approximate range experienced during normal operations. The reported stopping distance reduction attributable to grooving averaged better than 1000 feet. Pilots generally included in the comment section of their report statements to the effect that they strongly endorsed the concept. Directional-control capability was considered greatly improved by 86 percent of the pilots; 7 percent felt that it was not improved, and 7 percent offered no comment.

Once the pilot operational evaluation produced such a favorable reaction, it appeared prudent and timely to determine whether grooving had produced any detrimental effects on the runway surface and whether any complaints had developed regarding increased vibration or abnormal tire wear. With close to a year's operations at both Washington National and Kansas City and 9 months at JFK, including a full winter's operations at all three, the ATA sought comments from representatives of these three airports on the following four areas:

(1) The changes, if any, observed in rate of pavement deterioration resulting from normal aircraft use and use of ground equipment (for example, snow removal)

(2) Increased drainage rate observed (spraying effects reduced during landing and runout)

(3) Maintenance problems reported by airlines (tire wear, nose wheel vibrations, etc.)

(4) Other problems experienced or anticipated as a result of grooving

Based on the responses by these airports, the outlook for operational use of the grooving concept grew even more encouraging. A consolidation of these responses is presented in table 3. Although two of these airports indicated no noticeable increase in the rate of pavement deterioration, Kansas City Municipal has stated that there is some deterioration in the surface of the concrete, but it has been difficult to determine how much of this is the result of grooving. Kansas City Municipal also stated that there has been a noticeable increase in aggregate pop outs, which is not considered serious. Spalling has also taken place around cracked areas but it cannot be determined if this is the result of grooving. It is understood by ATA that the FAA made a walkover inspection of the Kansas City runway and considered that the noticeable pop outs and joint deteriorations were typical of this type of aged concrete paving. Figures 1 to 4 are recent photographs of airline aircraft on the grooved runways at Kansas City and JFK airports. Figures 1 and 2 show the landing gear of an aircraft on runway 18-36 at Kansas City Municipal after more than 150 000 landings have been completed since it was grooved. Figures 3 and 4 show an aircraft on runway 4R-22L at JFK, which has experienced more than 72 000 landings on its grooves.

The results of year-long tests at these three airports were reviewed by the ATA Flight Operations Committee during June 1968, and a decision was made to seek an expansion of runway grooving at U.S. airports served by the airlines. The Air Transport Association of America, on behalf of its member airlines, is in the process of preparing a list of candidate airports for runway grooving based on recommendations of member airlines.

Specific proposals for grooving will be made from this list of candidates by the airlines working through ATA Regional Operations Managers. Runways proposed for grooving and the priority they should receive will be shown in the airlines' Airport Survey which is prepared and revised regularly by the airlines through ATA.

Since runway grooving must compete with other airport surface improvements for funding and since there is some merit in picking optimum times for grooving (from the standpoint of runway use and other runway improvements), the airlines recognize that the expansion of the runway grooving program will be a gradual process. Nevertheless, the airlines are encouraged by the progress that has already been made since the June 1968 decision to seek more grooved runways.

The grooving of runways 13R-31L and 4R-22L at Chicago's Midway Airport, which was completed last September, represents the first time Federal Aid to Airports Program (FAAP) funds were used to help defray the cost of grooving. Figures 5 and 6 show an aircraft on the grooved Midway runways.

Late in October, grooving was completed on Charleston, West Virginia's Kanamha County Airport runway 5-23. Grooving recently started on Atlanta Airport runway 9R-27L should be completed around early 1969. The next runway to be grooved could well be 4R-22L at Boston's Logan International Airport. This is now under consideration by the airlines and the Massachusetts Port Authority.

CONCLUDING REMARKS

The airlines are convinced that runway grooving is an effective aid in overcoming hydroplaning. Grooving also helps to increase the stopping capability of large turbine-powered aircraft when landing on wet runways or runways with standing water. Airline operational evaluation of grooving during a period of 15 to 19 months at three U.S. airports not only demonstrated in an operational environment the conclusions reached as a result of NASA research but also dispelled earlier fears that grooving might damage runways or aircraft. The airlines believe the evidence to date shows that (1) grooving has produced no increased rate of runway deterioration, (2) runway drainage has been improved by grooving, and (3) there are no aircraft maintenance problems that appear related to operations on grooved runways.

In conclusion, the airlines have tried grooving and found that it works. They are now engaged in bringing this new safety aid into widespread operational use by working with airport authorities and the FAA to have more runways grooved. Finally, the airlines have asked me to express their appreciation to NASA for the research which made this evaluation possible. ATA will continue to work closely with NASA's pavement grooving and runway traction research program.

TABLE 1.- AIRLINE RUNWAY GROOVING EVALUATION DATA FOR JOHN F. KENNEDY INTERNATIONAL AIRPORT AND KANSAS CITY MUNICIPAL AIRPORT

	JFK	KC
Cost per square foot, dollars	0.13	0.14
Cost to airlines, dollars	178 500	87 000
Material	Concrete	Concrete and asphalt
Daily grooving time	6 a.m. to 3 p.m.	12 p.m. to 7 a.m.
Runway use during grooving operations	Closed	15 min open 15 min closed
Groove pattern:		
Width, in.	3/8	1/8
Depth, in.	1/8	1/4
Pitch, in.	$1\frac{3}{8}$	1
Shape		
Completed	Aug. 1967	May 1967

TABLE 2.- AIRLINE RUNWAY GROOVING EVALUATION

Summary of Airline Pilot Survey
August-September 1967

[Airports: Washington National, Kansas City Municipal, and John F. Kennedy International. Airplanes: DC-8, DC-9, 707, 720, 727, and 188]

Percent of landings with following conditions:	
Rain stopped just before landing	34
Light rain during landing	47
Showers during landing	9
Heavy rain during landing	10
Touchdown speed, knots:	
Maximum	135
Minimum	105
Average	118
Comments on directional control, percent of pilots questioned:	
Improved	86
Not improved	7
No comment	7
Reduction of stopping distance, feet:	
Maximum	3000
Minimum	500
Average	1081

TABLE 3.- AIRLINE RUNWAY GROOVING EVALUATION

Summary of Airport Survey
May 1968

	JFK	WN	KC
Changes in rate of pavement deterioration	None indicated	None indicated	Slight increase for concrete; none for asphalt
Drainage rate	Increased – absence of spray in front of airplane	Increased – no reports of spraying	Increased – difference in spray pattern normally experienced
Maintenance problems reported by airlines	None	None	None
Other problem areas	Accumulation of rubber deposits anticipated, but none formed	Rubber deposits filling grooves anticipated, but none formed	None except for increased deterioration of concrete pavement

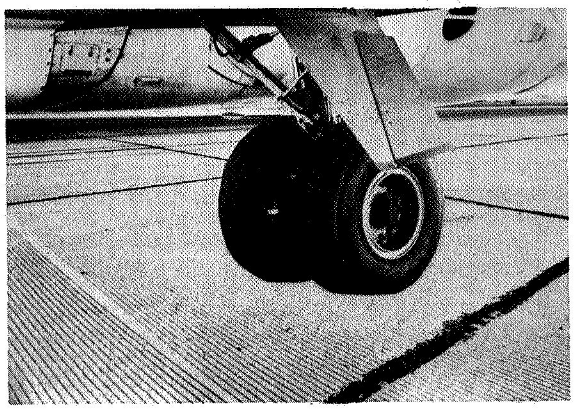


Figure 1

Figure 2

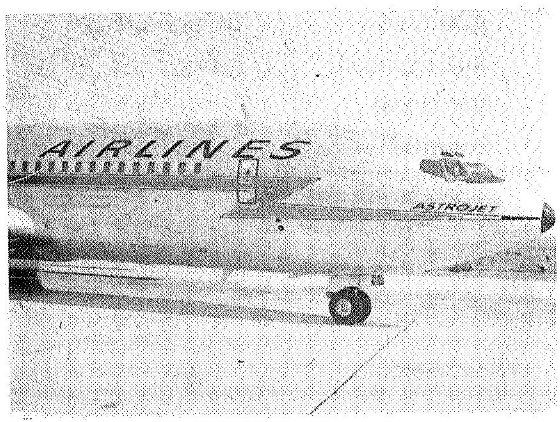


Figure 3

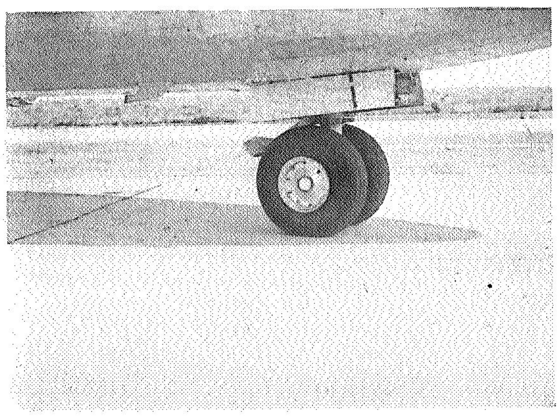


Figure 4

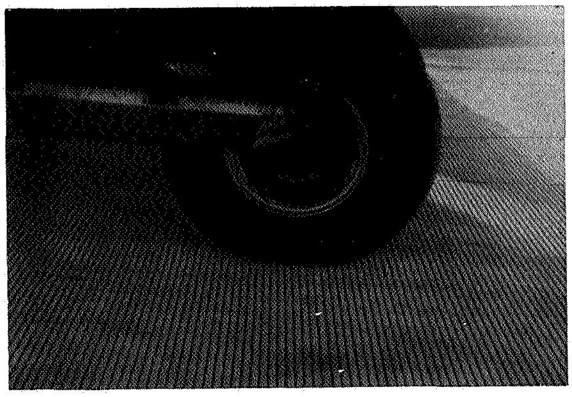


Figure 5

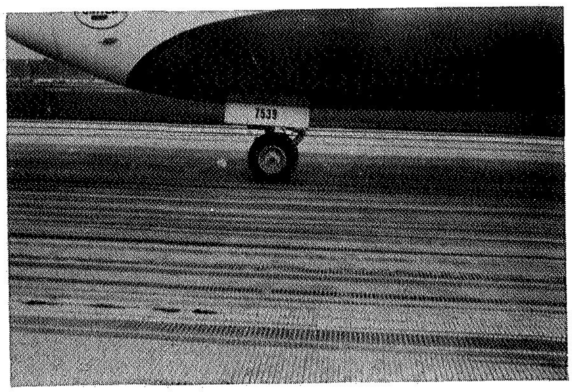


Figure 6

10. THE AIRLINE PILOTS LOOK AT RUNWAY GROOVING

By Carl F. Eck

Air Line Pilots Association, International

SUMMARY

The airline pilots have now had the opportunity to use grooved runways operationally for over a year. They have found significant benefits from this development and desire its universal application at all airports. Because of variable operating conditions and the fact that grooving only allows a wet runway to approach the braking capability of a dry runway, they do not believe that any reduction in runway length requirements on wet runways should result from this grooving.

INTRODUCTION

Every airline pilot has learned from experience that the braking capability that can be reasonably expected on a dry, clean runway surface is not attainable on all dry surfaces. Even this lesser braking capability deteriorates rapidly when various amounts of water and other contaminants are present. Safety representatives from Air Line Pilots Association, International (ALPA) have searched long and hard for the best way to remove the hazards associated with this condition. Take-off and landing runway distances are all computed on the basis of hard dry runways, and there is for all practical purposes, no extra safety margin available for this braking deterioration in the case of abort at V_1 during take-off. (V_1 is the speed at which the pilot must decide whether to abort or continue take-off.) Landing distances are also too marginal when all the variable stopping factors involved are considered.

DISCUSSION

In August 1965, ALPA published in the AIR LINE PILOT an article entitled "The Short Runway" (ref. 1), which is a case history of what happens when adequate braking capability is not present. The following are excerpts from this article.

"On June 29, 1965, a Federal Aviation Regulations amendment designated as 121-9 was signed by FAA Administrator Najeeb Halaby. The amendment states that beginning on January 15 of next year (1966), a 15 per cent increase in the effective landing runway length will be required for airline turbojet aircraft when landing on a runway which is forecast to be wet at the aircraft's estimated time of arrival, regardless of ceiling and visibility.

"Less than 48 hours later, on July 1, the need for longer runways and adequate over- and under-run areas was once again brought vividly into focus by the crash of a Boeing 707 loaded with 59 passengers and a crew of seven at the end of its landing roll on a rain-slick 7,000-foot runway at Kansas City Municipal Airport (MKC).

"It was only the skill of the pilot and extreme good fortune that averted a tragic fatal crash as the airplane skidded past the end of the wet runway and struck a dike. Hitting the dike head-on would have resulted in an even more severe break-up of the airplane. Knowing this, and realizing that he could not stop the aircraft before reaching the end of the runway, the captain succeeded in swerving the plane, thus hitting the dike sideways.

"Current certification rules require landing aircraft to be able to come to a full stop from a 50-foot threshold height on a dry runway within 60 per cent of the runway's total length. In the case of a 7,000-foot runway, for example, the required distance under current rules for coming to a full stop would be 4,200 feet or less. The remaining 40 per cent, or 2,800 feet, would be provided as a safety margin for adverse runway conditions or for unavoidable variations in landing situations involving touchdown speeds and distances.

"These current rules will remain in effect for turbojet aircraft operation on dry runways only. Under the new rules for wet runway operations, for example, an 8,050-foot runway length would be required instead of 7,000 feet in order to avoid a reduction in landing weight.

". . . Kansas City Municipal Airport is just one of many airports which has been the subject of concern to ALPA during recent years as having inadequate runway length margins for adverse weather operation of jet transports. MKC (the designation for Kansas City Municipal Airport) was 'lucky' in this July 1 crack-up, as it has been in numerous others, in that no fatalities resulted. Only four of the 66 persons aboard the airliner were injured--none seriously.

". . . Over-runs are caused initially by one or more of a number of unavoidable (and usually compounded) conditions--slippery runways, worn, smooth tires, crosswinds and high or fast approaches due to adverse weather--but the causal factor underlying all over-run crack-ups is the fact that most runways are too short for operations under those conditions!

"An over-run on landing is not the only situation in which tragedy lurks on a short runway. A great danger of over-run exists in the case of an aborted take-off, especially during hot weather or on icy or slushy runway surfaces (both are frequent conditions at MKC). It is extremely doubtful whether a jetliner pilot could stop his aircraft before the end of a 7,000-foot runway if he were to experience a power failure at or near V_1, the speed at which he must decide whether to continue the take-off or abort (stop).

"Adding to this problem is the fact that natural and/or man-made obstructions surrounding many airports might make it impossible for him to follow through with the take-off with reduced power capability. It is this area of danger--the aborted take-off--that the new FAR amendment fails to recognize, in that it allows only for landing on wet runways and disregards the need for adequate safety margins for take-offs.

"Another danger connected with landing on a short runway is the fact that the pilot knows that he must touch down fairly close to the threshold end of the strip, especially in bad weather, therefore increasing the possibility of an undershoot. (For a detailed report on the over-all short runway situation and other ALPA investigations and recommendations on the matter, see 'The Need for Longer Runways' in the September, 1964 issue of the AIR LINE PILOT [ref. 2].)"

In order to alleviate the conditions cited above, ALPA has reviewed several ways of reducing the hazards on marginal-length runways besides lengthening the runway, which is obviously one of the best ways. These measures for improvement include adding overrun/underrun, improving the drainage, and increasing the braking capability on the runway. ALPA has especially encouraged these corrective measures at Kansas City as well as at other similar marginal-length-runway locations. Because of the limited ground available at Kansas City, one of the most expeditious ways of improving the safety of operations was believed to be through the improvement of stopping capability by grooving the North/South runway. Thankfully, the airlines and the airport management cooperated and grooved 4500 feet of this runway. However, ALPA is distressed to note that repeated efforts to obtain grooving of the remaining 500 feet at the south end of the runway and 1900 feet at the north end have not been successful. Comments from pilots flying into Kansas City attested to the benefits derived from the grooved portion of the runway. Regrettably, the safety benefits possible from runway grooving at Kansas City have not been completely realized because the portions of the runway where the need is most – that is, the last 500 feet of the runway at each end – are still not grooved. On at least one occasion recently, a jet airliner has almost gone off the north end of the runway. This is attributed by ALPA to the ungrooved condition of the north end of the runway.

The grooved runways at Washington National, John F. Kennedy International, and Chicago's Midway airports, as well as at Kansas City Municipal, have been well accepted by the airline pilots as a step forward toward improved stopping capability on wet runways. It has been found that runway surfaces which are slippery as a result of jet soot, rubber, dust, water, and so forth can be connected to safe stopping surfaces by the use of runway grooving.

Pilots have known for years that the runway length regulations do not provide them with the stopping capability under all operating conditions that they must have.

Invariably, pilots that have used grooved runways under wet operating conditions have obtained improved stopping capability. However, this improvement has only allowed the pilot's stopping capability to approach the dry stopping distances. Therefore, there are a number of operating considerations which necessitate ALPA's demand that the runway length now required for jet aircraft on wet runways be continued. Among these are the following:

(1) The amount of improvement in braking will vary with conditions of the pavement grooving due to wear and the amount of water on the runway.

(2) The 15 percent added landing length for wet runways is marginal because even grooving would not increase friction under snow and ice conditions. Take-off abort distances from V_1 are especially marginal under these conditions.

(3) Stopping distance is affected by variations in touchdown points, speed at touchdown, and aircraft braking efficiency and technique, some of which are affected by the wind and weather involved as well as runway surface.

At the present, the number of jet airports with the following limited runway lengths is

5 below 5000 feet
20 below 5500 feet
35 below 6000 feet
50 below 6500 feet

Runways on which particularly slippery conditions exist should be given high priority. Pilots have named airports at the following cities as needing early attention:

New Orleans, Louisiana (Runway 10)
Boston, Massachusetts (Runway 4R)
Lehue Kauai, Hawaii (Runway 3)
Atlanta, Georgia (Runway 9R)
Cincinnati, Ohio (Runway 27L)
St. Louis, Missouri (Runway 24)
Cleveland, Ohio (Runway 27)
New York's LaGuardia (Runways 22 & 31)
Columbus, Ohio (Runway 10L)
Newark, New Jersey (Runway 22)
Chicago, Illinois, O'Hare (Runway 27R)
Hilo, Hawaii
Grand Junction, Colorado (Runway 11)
Little Rock, Arkansas (Runway 4)
Fayetteville, Arkansas (Runway 16)
Paris, Texas (Runway 21)
Joplin, Missouri (Runway 13)
Honolulu, Hawaii (Runways 4L & 4R)
Rochester, New York (Runway 28)
Akron, Ohio (Runways 19 & 23)
Charleston, West Virginia (Runway 23)

CONCLUDING REMARKS

The airline pilots who have used runways that are grooved have found them to be of distinct assistance in improving stopping capability and maintaining runway alinement.

Therefore, ALPA strongly recommends that runways be grooved similarly to those at Chicago's Midway Airport. However, since the benefits derived from grooving assist only in bringing the runway braking coefficient closer to that for dry pavement, there should be no change in the regulations that presently require additional runway length for wet runways. The extended benefit of runway grooving on blacktop and concrete over a long period of time has not been assessed completely, but ALPA is strongly convinced that there are important benefits to be obtained by runway grooving.

ALPA looks forward to the acceptance of this very worthwhile safety feature by the aviation industry for use at all airports. Runways on which particularly slippery conditions exist should be given high priority for grooving. Even where runway grooving has been provided, ALPA strongly recommends that periodic cleaning schedules be established for removal of carbon, rubber, loose materials, and other contaminants from ALL runways.

REFERENCES

1. Linnert, T. G.; and Burroughs, K. L.: The Short Runway. Air Line Pilot, vol. 34, no. 8, Aug. 1965, pp. 10-13.

2. Linnert, T. G.; and Burroughs, K. L.: The Need for Longer Runways. Air Line Pilot, vol. 33, no. 9, Sept. 1964, pp. 12-16.

11. GENERAL-AVIATION PILOT REACTIONS TO AND OPINIONS ON GROOVED RUNWAYS

By George E. Cranston
Flight Safety Foundation

SUMMARY

A survey and analysis study of general-aviation pilot reactions to and opinions on grooved runways was conducted by the Flight Safety Foundation. At the time the survey was performed, there were four commercial airports in the continental United States that had at least one grooved runway. Personal interviews were conducted between general-aviation pilots and aviation safety specialists at these sites by using a prepared questionnaire to obtain the data discussed in this paper. The results of the survey and study show that the grooving of runways has a pronounced beneficial effect and provides increased safety for high-speed general-aviation aircraft operations by the reduction of hydroplaning and increasing braking action during wet runway conditions. Pilots operating light, low-speed aircraft did not generally realize these benefits as the runway lengths and widths at these airports far exceeded their operational requirements under all anticipated circumstances involved with this problem.

INTRODUCTION

The Flight Safety Foundation (FSF) conducted a survey analysis study (under NASA Contract No. NAS1-8668) to determine the reactions and opinions of general-aviation pilots to grooved runways. A total of 1444 persons were contacted – 1404 pilots, 36 FAA airport air traffic controllers, and 4 airport managers. Of the 1404 pilots, 700 of them gave insufficient information to be used in this survey. This paper is a report on the results of this survey. The term "general aviation" covers all flight operations and activities except those conducted by scheduled air carriers and the military. At the time of this survey there were four major civil airports that had one or more grooved runways. These airports were John F. Kennedy (JFK) International, Washington National, Chicago Midway, and Kansas City Municipal. The diverse groove designs and runway surface materials at these airports provided a comparative base for determining whether runway grooving was practical on the hard surfacing materials commonly used in this country. (See table I.)

The objectives of the study were: First, to obtain pilot opinions on the effectiveness of runway grooving towards improving braking action, directional control, and visibility of the runway details from the approach during wet runway surface conditions; second, to obtain pilot reactions as to whether they consider runway grooving a safety contribution to their flight operations; and, third, to find out whether they recommend the application of grooves to all runways. Several additional areas related to operating on the grooves – noise and vibration, tire wear, and aircraft damage – were covered; all 704 pilots interviewed thought grooving had no detrimental effect on aircraft operation in these areas. The interviews were conducted by a team of two specialists at each airport by using a prepared questionnaire. The questions were of the type that could be answered with a simple yes or no or a number. This approach proved to be an asset to the team in that the desired survey data could be obtained with little inconvenience to the busy pilots. A copy of the two-page questionnaire is included as table II. Prior to embarking on the interview, campaign letters were sent to each airport manager, FAA area manager, and each fixed-base operator at each of the four airports to solicit their support. This proved to be very helpful and contributed greatly to the success of the effort.

The program at the airport called for the team to visit the Airport Manager's office. The purpose of the survey was explained in detail and in discussions that followed with his staff, the technical and historical information concerning the runway grooving at the airport was gathered. The next step was to visit the FAA tower chief and arrange to interview as many controllers as he felt could provide useful inputs. The FAA personnel interviews involved two questions, the sole purpose of which was to establish a different source of information on the subject to reinforce the findings. The questions and the results are given in tables III and IV.

The fixed-base, corporate, supplemental, and air-taxi operators were each visited and their pilots interviewed. Fixed-base operators were extremely helpful in providing the team members with the use of their facilities for accomplishing the pilot interviews.

DISCUSSION

During the interview periods the initial attention was directed toward seeking the opinions and reactions of all pilots based at the airport. The rationale of this approach was that a better comparison could be realized from a pilot who operated consistently from the airport before and after the application of grooves. The probability of such a pilot using the runway under wet or slushy conditions was also much greater than those of the transient. This group included local corporate, cargo, charter, air-taxi, commuter, flight training, business, and private pilots. (See fig. 1.) In between and whenever available, transient pilots of all general-aviation categories were interviewed. The interviews would be terminated if the pilot could not answer the first two questions in the affirmative. This procedure was adopted to obtain only the best information from the available interviews rather than the largest total number. This theory was qualified in subsequent discussions with pilots who could not state they had knowingly experienced hydroplaning or poor braking and, in addition, never heard of runway grooving. About 50 percent of the pilots contacted fell in this category with little or nothing to contribute to the survey.

JFK International Airport presented a peculiar problem in obtaining a cross section of general-aviation interviews as well as the predicted total number. The imposition of an unusually high landing fee base discouraged the use of JFK by all except supplemental carriers, air taxis, and some corporate activities. The air-taxi and commuter pilots, although highly experienced and knowledgeable on runway grooving, were unable to provide convincing information as to its beneficial effects because of the equipment they operated. Light twin-engine, single-engine, and STOL aircraft comprised the type equipment they operated. Braking was not usually required due to long runway length and aircraft performance. Occasionally pilots reported that cross-wind conditions were more easily coped with on the grooved runway than on ungrooved runways, and some pilots reported more positive braking action on the grooves than that noticed on the taxiway after turnoff. A majority of pilots reported they had noticed no significant difference in seeing the runway markings from the approach during wet conditions. This was not a fair evaluation as most pilots stated they had not paid any particular attention to comparing the view wet or dry.

From the standpoint of actual experience and being able to relate the effect of runway grooving during wet runway conditions, the corporate jet pilots and the supplemental airline pilots provided the best information at each survey location. There is no doubt in the minds of these pilots that the grooving of hard-surfaced runways is a contribution to safer operations. (See table V.) Their reactions to the interview on the subject were so enthusiastic that they would recite specific instances of accident prevention attributed to grooving.

While the team was on site at Kansas City during a heavy rain a pilot of a corporate jet was landing to the south and the first 2000 feet are not grooved. He intentionally touched down on the numbers and checked his brakes which were ineffective. Having no reverse thrust he had just made up his mind to apply power and head for Mid-Continent International Airport when he heard the hum of the grooves. He tried the brakes and the effect was shocking. This pilot thought he had pulled the rubber off his main tires – the grip was so strong. However, after his passengers departed he examined the tires and to his amazement they showed no excessive wear.

At Chicago Midway in two instances jet pilots enthusiastically discussed how they escaped from a certain overshoot accident. They both were fortunate enough to run onto the grooves 1000 feet from the fence. The braking action went from nothing to good so quickly that one pilot stated, "It almost put me through the windscreen." The runways are notoriously slick at Midway during wet conditions. With two runways to groove, the procedure was to work on the runway that was inactive at the time. Grooving began at both ends working towards the middle. Consequently, the pilot's dilemma and remarks were understandable.

In discussions with Airport Managers and Engineers the subject of grooving macadam versus concrete was raised. JFK International and Chicago Midway Airports have concrete runways. Washington National Airport has macadam runways. Kansas City Municipal Airport has a combination of both concrete and macadam. The consensus of opinion is that at this date there is not much difference between the two surface materials grooved so far. Kansas City has concrete about 18 years old and macadam about 4 years old. The macadam had been thoroughly compacted and cured during the 4 years of use and took the grooving very well. After 18 months, which includes one winter, the grooving shows no deterioration. The concrete although satisfactory has shown some minor spalling and chipping.

At Washington National Airport the macadam was also cured well before grooving and is doing very well. In fact at the touchdown zones the impact of the heavy jets has moved the surface of the macadam so that the once straight cut grooves are now wavy. However, this did not destroy the function of the grooves in any way. The grooves appear to purge themselves of debris and show little tendency toward clogging. Questions were raised about the effects that resealing concrete joints and patching would have on drainage and the recommended cure time of each material before grooves should be cut. Since experience in these parameters is quite new, the answers were based on speculation with no serious problems predicted.

There were no complaints registered by pilots against the operational performance of the grooves, nor were there any derogatory comments on detrimental operational side effects from runway grooving. In most interviews the vibration and accompanying noise were described as a low level buzz or hum, which was discernible but far from annoying. Tire wear was reported as being normal with no perceptible increase in cuts or cracks. With the grooving of more runways more landings would be made on the grooves and what is now an acceptable circumstance could develop into a problem of excessive tire wear. The opinion of FSF is that the tire wear increase, if any, will still be acceptable and will be more than offset by the operational benefits.

At Kansas City Municipal Airport there were complaints from aircraft operators against the groove cutting procedure. It seems that the concrete dust and chips were not removed from the runway and arriving and departing traffic would raise a cloud of dust when dry. When wet, debris would form a slurry that would splash into wheel and flap assemblage causing removal of lubricants and clogging to microswitches and relays. One aircraft in particular on landing roll passed through a large puddle of the slurry and required considerable maintenance to remove the grit from critical areas.

One of the ancillary areas covered with the controllers was the size of spray patterns generating from the tires and reverse thrust during wet conditions. The purpose was to substantiate from another source how well the grooves did or did not drain standing water from the runway surface. In most instances the controllers felt there was some reduction in the amount of water spray since the grooving. At JFK the controller opinion was unusual by reason that the extreme distances involved made such observations virtually impossible. (See table III.).

The other area covered was in runway traffic management during wet surface conditions. The majority of the controllers definitely felt that runway grooving aided most pilots in controlling their aircraft's landing roll with improved effectiveness and that the turnoff point from the wet grooved runway in most instances was identical to that for dry operations. This definitely improved runway traffic management and increased the acceptance over the original ungrooved surface. (See table IV.)

CONCLUDING REMARKS

The opinions and reactions of the general-aviation pilots interviewed during the survey indicate a strong support in favor of the runway grooving program as a method of improving aircraft operations on wet or slushy runways. Although grooving the long runways has little beneficial effect for the light-airplane pilot, he is cognizant of the effect grooves would have on the short narrow strips which he more frequently uses and voiced his recommendations to consider grooving those strips. There were no detrimental effects noted to any type or size aircraft operation on any of the four groove designs now in operation. Noise, vibration, or tire wear were not factors for complaint. The benefits derived from grooved runways extend beyond the cockpit inasmuch as shorter landing rolls and normal turnoffs on wet runways increased runway acceptance rates at a time when expeditious traffic handling is most needed.

Runway grooving serves its intended purpose well and deserves consideration as a standard safety specification for all hard-surfaced runways.

TABLE I

AIRPORTS

	Washington National	JFK	Midway	Kansas City
Runway grooved	18/36	4R/22L	31L/13R 22L/4R	18/36
Distance grooved, ft	6870	8400	6500 6100	4000 (600 from 36 threshold or 2400 from 18 threshold)
Surface material	Macadam	Concrete	Concrete	Concrete and macadam
Groove design	Rectangular groove 1/8" × 1/8" 1" apart	"V" groove 3/8" × 1/8" 1" apart	Rectangular groove 1/4" × 1/4" 1" apart	Rectangular groove 1/8" × 1/4" 1" apart

TABLE II

NASA GROOVED RUNWAY SURVEY

GENERAL-AVIATION PILOT REACTION/OPINION QUESTIONNAIRE

DATE ______/______/ 1968 ________
Month Day Year

AIRPORT JFK________ MDY________ DCA________ MKC________

RUNWAY DATA Direction ______/______ Length ____________Ft.

Date Grooved ______/______/6______
Month Day Year

Type Groove ________________________________

Distance Grooved ________________________________

Runway Surface Material ________________________________

ACTIVITY

Supplemental Carrier	☐	Pleasure	☐
Corporate	☐	Air Taxi/Charter	☐
Business	☐	Training	☐

Other ________________________________

AIRCRAFT Jet______ Turbo-Prop ______ Piston______

Number of Engines: 4______ 3______ 2______ 1______

Landing Gear: Tri-cycle______ Conventional______

Reverse Thrust: Yes__________ No__________

Anti-Skid Brakes: Yes__________ No__________

Nose Wheel Steering: Yes__________ No__________

OPERATIONS

1. Have you experienced hydroplaning or poor braking on a wet or slushy runway?

   Yes_____ No_____ Wet_____ Slushy____ No. of times________

2. Have you heard of Runway Grooving? Yes______ No_____________

3. Are you aware that runway ___/____ is grooved? Yes___ No_____

4. How did you acquire that information?

   Tower Advisory__________ Felt Vibration__________ Saw Grooves__________ Noise__________ Other____________________

5. Have you landed on runway _____/______ prior to __/__/____

   How many times___________________ Wet______________ Dry_____

6. Have you landed on runway _____/_____ since it was grooved?___

   If yes, how many times?____________ Under what conditions?

   Dry___________________ Wet________________ Slushy__________

7. Have you landed on other grooved runways? Yes_____ No______

   Under what conditions? Wet________ Dry_________ Slushy______

   If yes, where? ___________________ No. of times______________

8. Did you notice any improvement landing on a grooved runway in:

   Braking Action? Yes______ No______ Wet_____ Dry___________

   Crosswind Directional Control? Yes____ No____ Wet____ Dry____

   Reducing Landing/Takeoff Roll? Yes____ No____ Wet____ Dry____

   Visibility During Reverse Thrust? Yes__________ No__________

   Seeing the Runway During Approaches?

   Day/VFR Yes___ No___ Day/IFR Yes___ No___

   Night/VFR Yes___ No___ Night/IFR Yes___ No___

9. In your opinion, do you think Runway Grooving helps you to operate your aircraft more safely?

   Yes___________________________ No____________________________

10. Do you recommend grooving for all runways? Yes_____ No______

TABLE III

WATER SPRAY OBSERVATIONS

Question: Do you notice any reduction in the size spray patterns of aircraft operating on grooved runways versus those not grooved?

	Washington National	JFK	Midway	Kansas City
FAA airport traffic controllers				
No change	2	(a)	2	0
Less	8	(a)	3	10
Pilot visibility	No noticeable effect			

[a]The distances between the control tower and the grooved runway were considered too far to permit observations of spray within reasonable accuracy.

TABLE IV

RUNWAY TRAFFIC MANAGEMENT

Question: Do you notice any significant improvement in runway traffic management during adverse conditions on grooved runways?

	Washington National	JFK	Midway	Kansas City
FAA airport traffic controllers				
No change	1	2	2	0
Improved	9	9	3	10

TABLE V

REDUCED HYDROPLANING AND IMPROVED BRAKING

Pilot Activity	Yes		No	
	Number	Percent	Number	Percent
Supplemental	23	3.3	5	0.7
Corporate	235	33.4	60	8.5
Air taxi	113	16	51	7.2
Business	37	5.3	65	9.2
Private	29	4.1	35	5
Training	5	.7	18	2.6
Other	19	2.7	9	1.3
Total	461	65.5	243	34.5

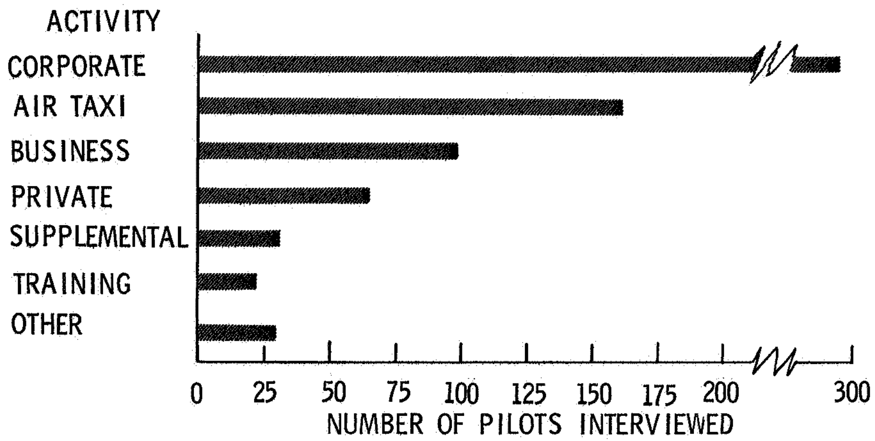


Figure 1.- Pilot activity involved.

12. EFFECT OF GROOVED-RUNWAY OPERATIONS ON AIRCRAFT TIRE WEAR AT BEALE AIR FORCE BASE, CALIFORNIA

By Captain David S. McRae

Beale Air Force Base

12

SUMMARY

Grooving of the runway at Beale Air Force Base, California, was completed in February 1968. As part of the follow-on test program, tire wear has been monitored for the B-52G, KC-135, and T-38 aircraft operating at the base. Of these three aircraft, only the KC-135 has shown a sustained decrease in tire life since grooving was completed.

Chevron-shaped cuts have been occurring on retread B-52G and KC-135 tires since grooving was completed. Preliminary results indicate that these cuts have little effect on tire wear or operational parameters.

INTRODUCTION

The runway-grooving project at Beale Air Force Base began in September 1967 and was completed in February 1968. The grooving pattern used was 1/4-inch-wide by 1/4-inch-deep grooves on 1-inch centers, transverse to the runway center line. The area grooved is 10 800 feet long by 140 feet wide and is centered on the 12 000-foot by 300-foot runway. The project was undertaken as an Air Force experiment to investigate the feasibility of runway grooving as a method of improving aircraft traction.

A follow-on investigation is being conducted in three areas: aircraft traction, aircraft tire wear, and runway surface life. This paper will present current information on aircraft tire life on the grooved surface. Data will be presented for three aircraft types which normally operate from the runway: the B-52G, KC-135, and the T-38.

DISCUSSION

Tire-Wear Data

Tire-wear data for the three aircraft (B-52, KC-135, and T-38) were collected as a result of normal maintenance actions and do not reflect any special test conditions or parameters. All tires removed from the aircraft were included in the data.

Significant factors affecting the data are the completion of the grooving project and the appearance in the supply system of significant numbers of retread tires for the B-52 and KC-135 in February 1968. In addition, a minor criterion change to reduce maximum allowable tire wear for the B-52 and KC-135 was made in March 1968. Data obtained after February 1968 should be compared with that prior to February 1968 in order to determine the effect of grooving. The number of landings per tire change was chosen as the most indicative parameter to use in presenting tire-wear data.

For trend analysis, 3- and 6-month cumulative averages of these data are given for July 1967 to September 1968. (See figs. 1 to 3.) The percentage of tires changed for cuts is also presented for this period. (See fig. 4.)

B-52 Tire Wear

Tire-wear data for the B-52 are plotted in figure 1. Tire size is 56 × 16 and pressure is 200 to 220 psig. The extreme scatter of the monthly average landings per tire change (L/TC) is due primarily to the small number of aircraft monitored (approximately 16) and to the fact that each aircraft averages only 10 to 15 landings per month. The 6-month average L/TC line starts out in December at 36 L/TC and rises to 45 L/TC during the winter months until February 1967. This rise is considered normal and was primarily due to cool temperatures and considerable rain during the winter of 1967-68. After February the 6-month average line starts downward and continues this trend until July 1968. Significant events were the completion of grooving and the appearance of significant numbers of retread tires in February. The 6-month average line then levels out at 32 to 33 L/TC. Six-month average L/TC for this period at Castle Air Force Base, California, and March Air Force Base, California, are 89 and 31 L/TC, respectively.

The faster reacting 3-month average L/TC line (fig. 1) shows essentially the same profile with the exception that a rise occurs to 39 L/TC in September 1968. The trend, as noted by the 3-month average line, is therefore upward. It is apparent, based on this limited period, that grooving has had little effect on B-52 tire wear.

KC-135 Tire Wear

Tire wear for the KC-135 is given in figure 2 for the same period and under essentially the same conditions as for the B-52. Tire size is 49 × 17 and pressure is 120 to 140 psig. The number of aircraft monitored for these data ranged between 11 and 19. The 6-month average L/TC line starts out at 48 L/TC and begins a gradual descent in February which has not completely leveled out as of this writing. The latest 6-month average for September 1968 is 31 L/TC. Again, the significant events were the completion of grooving and the appearance of significant numbers of retread tires in February 1968. Comparison of the recent 31 L/TC figure with Castle Air Force Base (170 L/TC) and March Air Force Base (83 L/TC) reveals large differences between bases. These differences are primarily due to runway surface and operational variations.

The percentage of tires removed for cuts, as shown in figure 4, has remained at the same level since July 1967 with the exception of the months of August and September 1968. The sudden rise in percentage of tires removed for cuts does not show up in the other two aircraft using the Beale runway. It must be concluded that this condition is either a transient condition or a maintenance coding problem.

No firm conclusion is apparent at this time as to why the KC-135 is exhibiting more tire wear since grooving. These aircraft do occasionally land at higher than normal landing gross weights. This fact, in conjunction with lower tire pressure than the B-52 could be contributing to the higher wear on the grooved surface. Another possible contribution is the fact that the KC-135 does not have cross-wind gear as the B-52 does. The grooves may be removing more rubber in cross-wind conditions. More detailed investigation is planned beginning in January 1969 to attempt to discover causes of the increased wear on KC-135 tires.

T-38 Tire Wear

T-38 tire wear is given in figure 3 for the same period and under the same conditions as the B-52 and KC-135, with the exception that no recapped tires are used on this aircraft. Tire size is 20×4.4, and pressure is 250 psig. The tire also has fabric-reinforced tread. Six aircraft were monitored to obtain these data. The 6-month average L/TC line begins at 50 L/TC for the base line data in 1967. The line then drops to 41 to 44 L/TC, and remains at this approximate value until June 1968. The number of L/TC then climbs to 54 by September 1968. The 3-month average L/TC line shows an even larger increase from July 1968 to September 1968. The number of tires removed for cuts has been minimal for this aircraft. Grooving has had little apparent effect on T-38 tire wear.

Chevron Cuts

Chevron-shaped cuts have been occurring on the retread B-52 and KC-135 tires since the completion of grooving. In order to investigate these cuts, one B-52 and one KC-135 were used as test aircraft. On two different locations on each of these aircraft, one unworn retread tire and one new "ice grip" wire and fabric-reinforced tread tire were mounted laterally in positions 1, 2 and 7, 8. This arrangement gives essentially the same impact loading and operating conditions for each pair of these tires. Photographs were taken of the tires after each mission to record tire conditions. The results of these tests are preliminary, inasmuch as further information will be required before final conclusions can be stated.

One set of these test tires has been worn out on the B-52G aircraft at this time. Photographs of the tires are shown in figures 5 to 16. The following is a listing of the photographs in these figures along with pertinent remarks:

Figure	Touchdowns	Remarks (tires 1 and 7 are ice grip, tires 2 and 8 are recaps)
5	7	Tire 8 (left) – Two cut areas – One on center two ribs and one almost four ribs wide. Tire 7 (right) – No evidence of cuts.
6	7	Tire 2 – One small cut area showing.
7	13	Tire 1 – No evidence of cuts.
8	13	Tire 2 – One small cut area showing and one hidden on top of tire.
9	13	Tire 7 – No evidence of cuts.
10	13	Tire 8 – Cuts on center two ribs.
11	19	Tire 2 – Cuts wearing off – still primarily in center ribs.
12	19	Tire 8 (mislabeled 7) – Cuts showing wear as tire wears – Not deepening or spreading to other ribs.
13	19	Tire 7 (mislabeled 8) – No evidence of cuts.
14	30	Tire 2 (left) – Cuts become finer as tread wears.
15	30	Tire 8 (right) – Cuts worn off in center and spreading to outside ribs as tread wears.
16	47	Tire 2 – Note that cuts are almost worn away and do not extend appreciably past depth of tread groove.

Tire 1 was worn out and replaced after 19 touchdowns.
Tire 7 was worn out and replaced after 27 touchdowns.
Tire 8 was worn out and replaced after 43 touchdowns.
Tire 2 was worn out and replaced after 47 touchdowns.

As can be observed from these photographs, the "ice grip" wire-reinforced tread tires did not exhibit these chevron-shaped cuts on the B-52 tires. However, the retread tires gave approximately twice as many landings even though cuts were present.

The KC-135 tire photographs are shown in figures 17 to 23. The experiment was not completed as the aircraft departed Beale for another assignment after 21 touchdowns on the tires. The photographs made prior to aircraft departure are:

Figure	Touchdowns	Remarks (tires 1 and 7 are ice grip, tires 2 and 8 are recaps)
17	2	Tire 2(left) – One patch of fine cuts on center ribs. Tire 1 (right) – No evidence of cuts.
18	2	Tires 7 and 8 – No evidence of cuts.
19	7	Tire 2 (left) – Two small cut patches on center rib. Tire 1 (right) – Fine cuts on center two ribs of ice grip tire – much smaller and less deep than on recap.
20	7	Tire 7 – Small cuts on large portion of center ribs – appears abraded rather than cut.
21	7	Tire 8 (right) – Two small cut areas showing.
22	19	Tire 1 – One small abraded patch on top of tire.
23	19	Tire 2 – Showing more extensive cuts.

Although some cuts or abrasions are appearing on the ice grip KC-135 tires, the cuts do not appear to occur on the retread tires as extensively or as early in the tire life as on the B-52. Further investigation into KC-135 tire wear is warranted, both to explain the cutting-problem differences from the B-52 and to investigate the drop in tire life since grooving.

Figure 24 shows a collection of thrown tread obtained from two retread tires which came apart on the Beale runway. The tread separated from the carcass at the fabric reinforcing strip added by the retreader. The severity of the cuts on these strips may indicate improper curing or may have occurred under high loading after the tread was partially thrown.

Figures 25 and 26 illustrate rubber deposits in the grooves. The deposits occur in both granular and high-temperature form on the side and bottom of the groove in the direction of travel. Under full-skid impact conditions, the high-temperature rubber completely coats the groove with a thin film, heavier on the side of the groove in the direction of travel. Some granular deposits occur in the grooves under full skid also.

CONCLUDING REMARKS

Although not enough time has elapsed for final conclusions to be made concerning aircraft tire wear on the grooved runway at Beale Air Force Base, the following preliminary results can be stated:

1. Grooving has not appreciably affected B-52 and T-38 tire life.
2. KC-135 tire life has steadily decreased since grooving was completed.
3. The chevron-shaped cuts on the retread tires do not appear to have any detrimental effect on tire life or operating parameters.

Monitoring of aircraft tire wear at Beale Air Force Base will continue until July 1969. Detailed tests are planned to investigate the reduced KC-135 tire life and to explore further the mechanics and effects of the chevron cuts appearing on the retread tires. Final conclusions on these tests and the tire wear results will be available after July 1969.

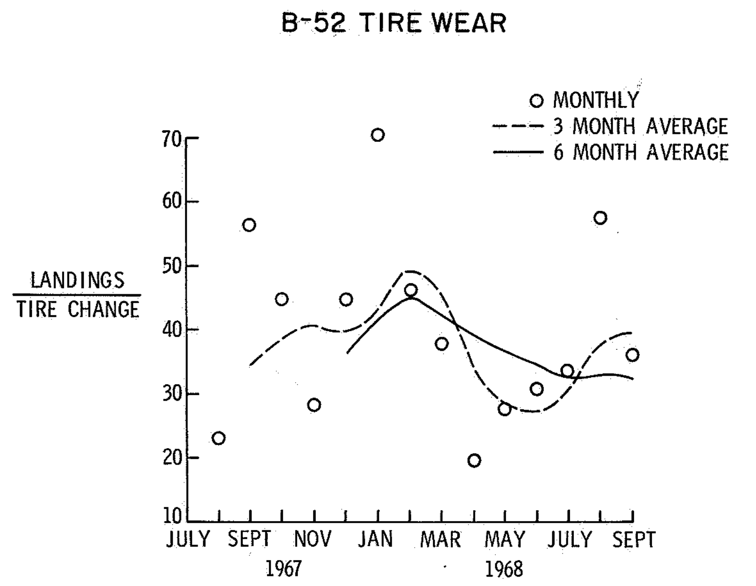


Figure 1

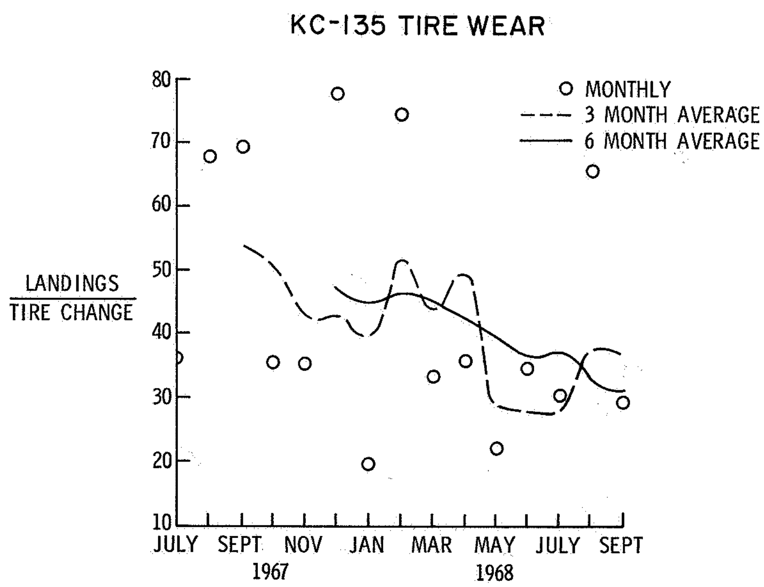


Figure 2

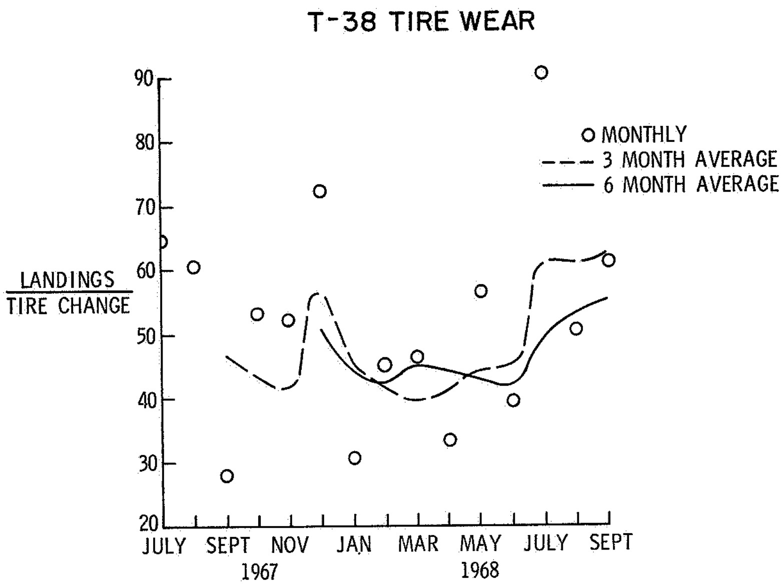
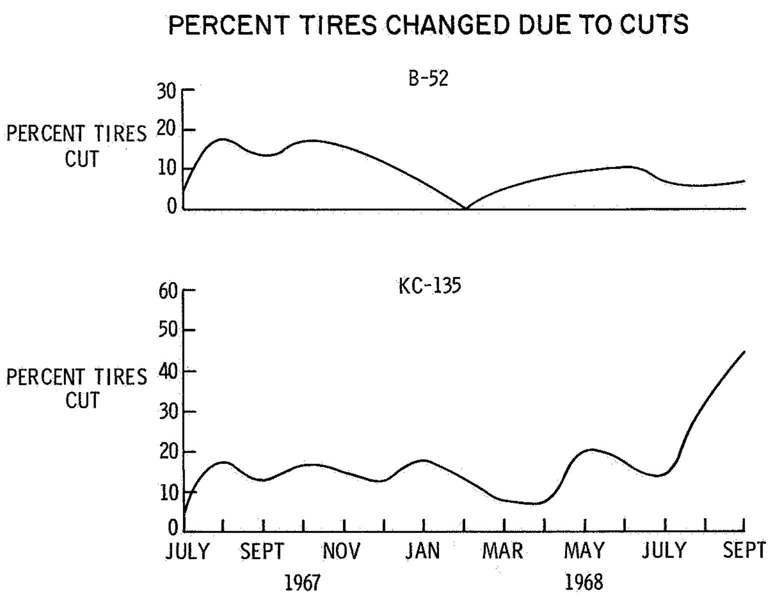


Figure 3



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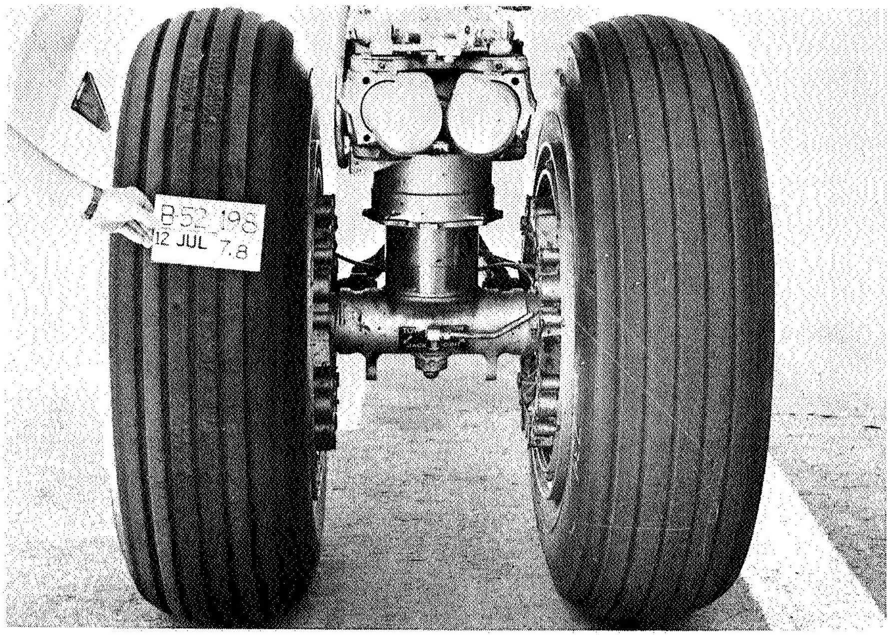
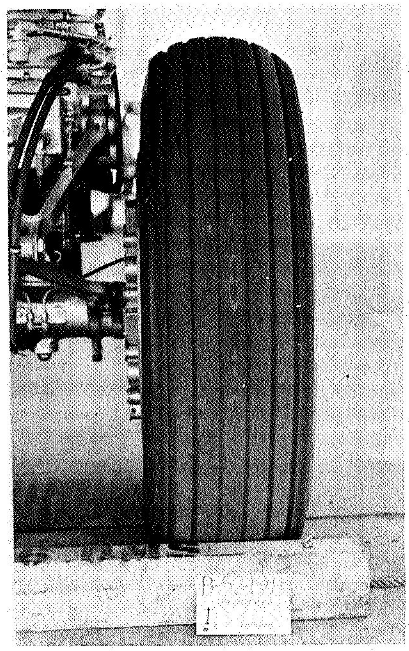


Figure 5

Figure 6



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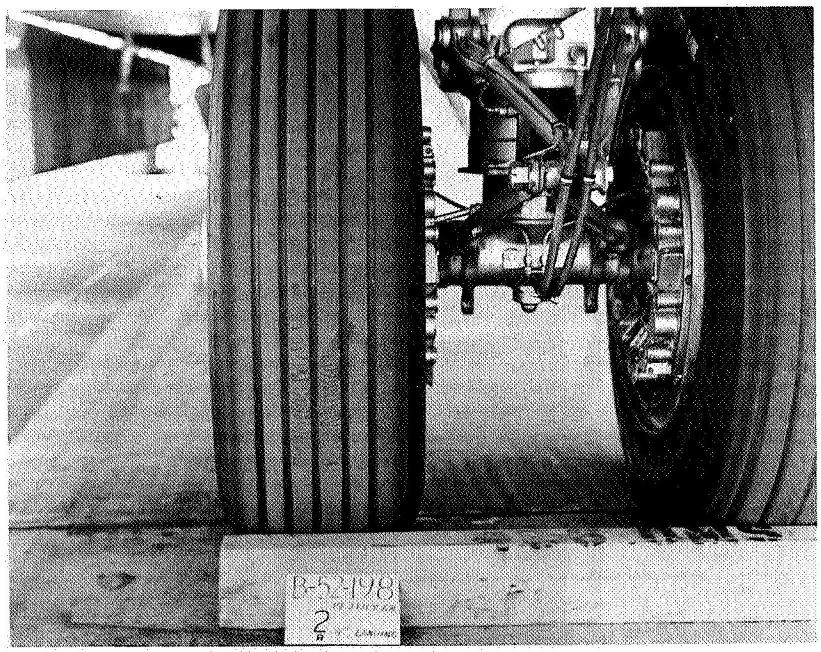

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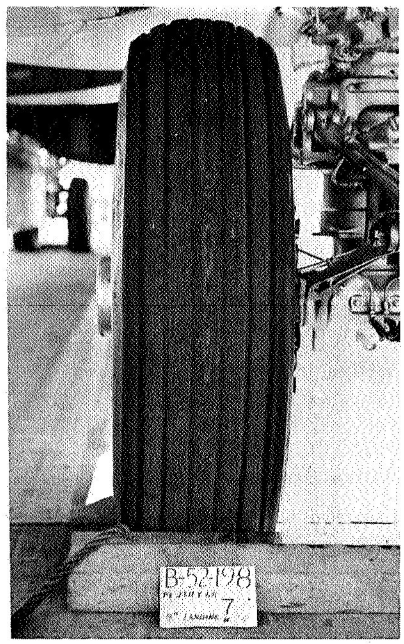
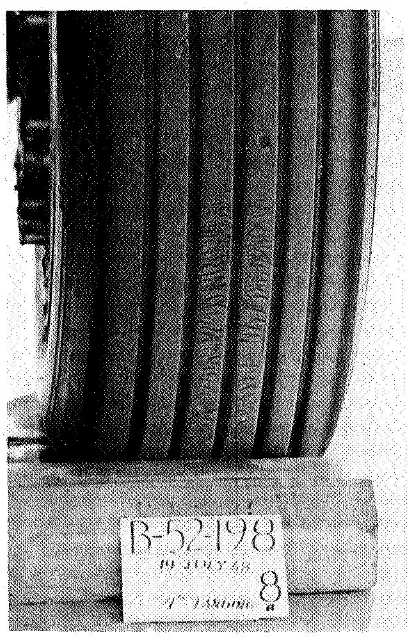


Figure 9



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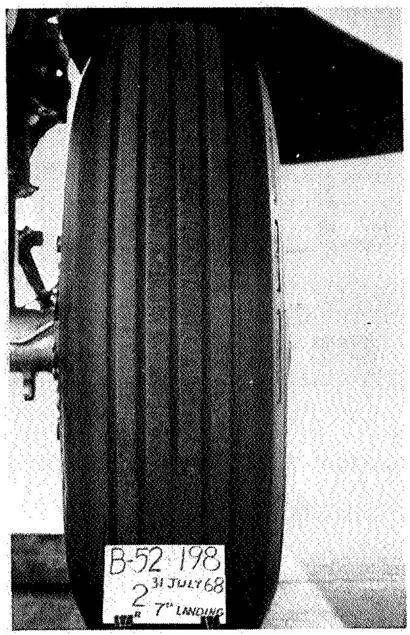


Figure 11

Figure 12

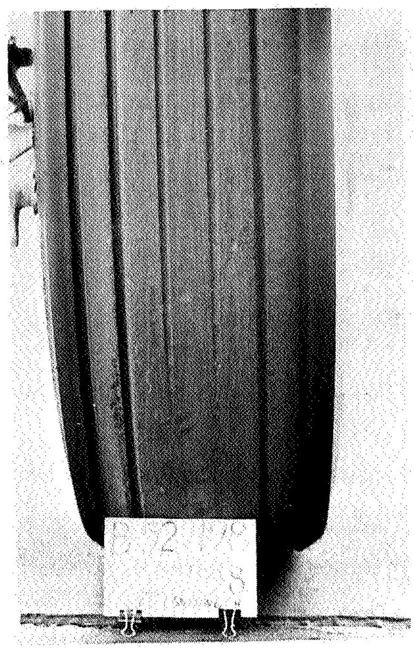


Figure 13

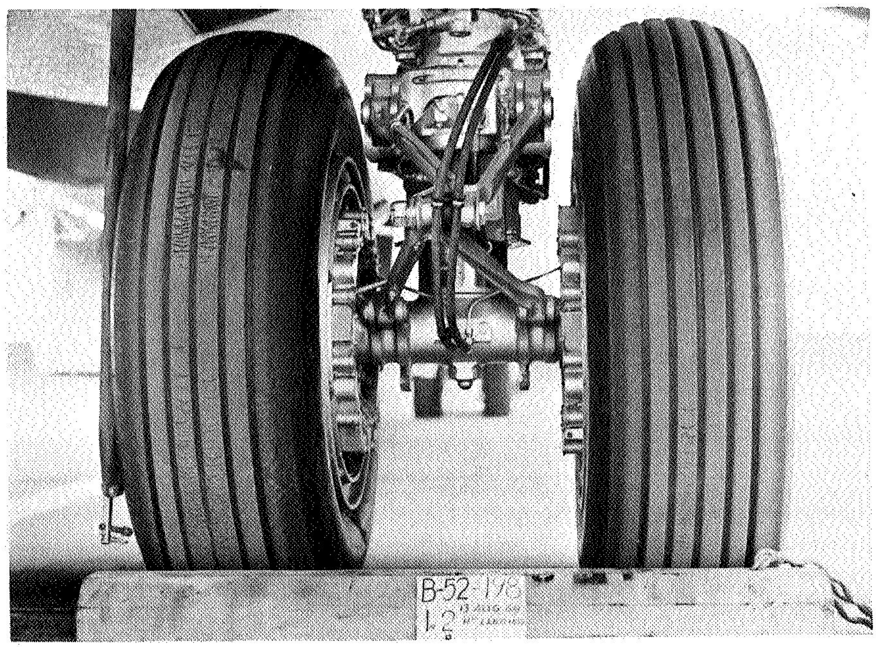


Figure 14

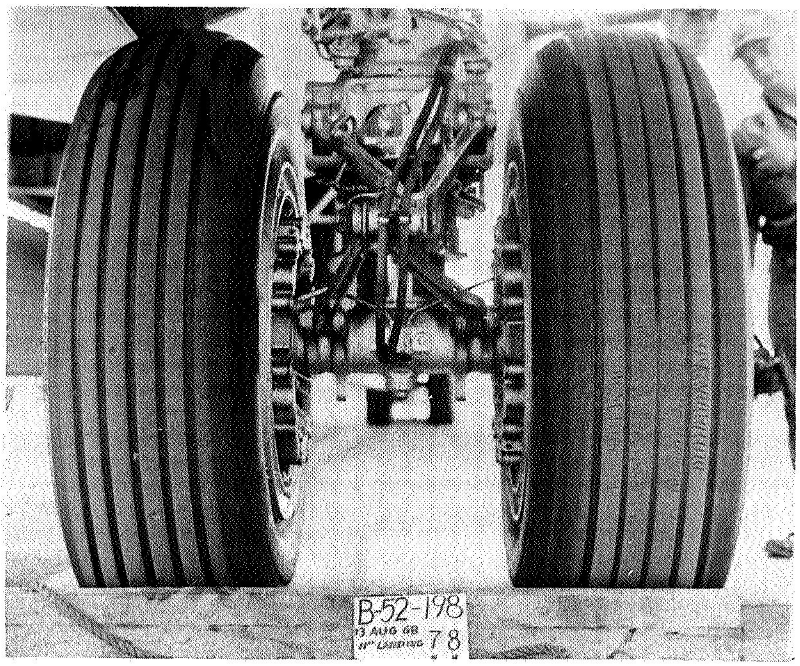


Figure 15

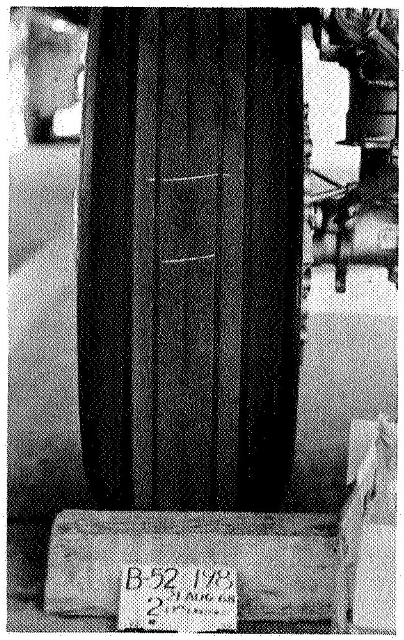
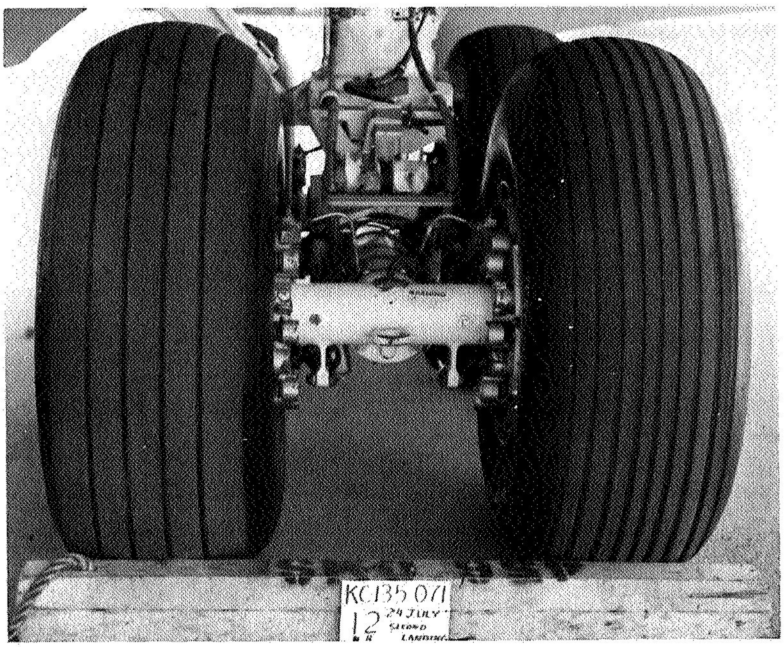


Figure 16



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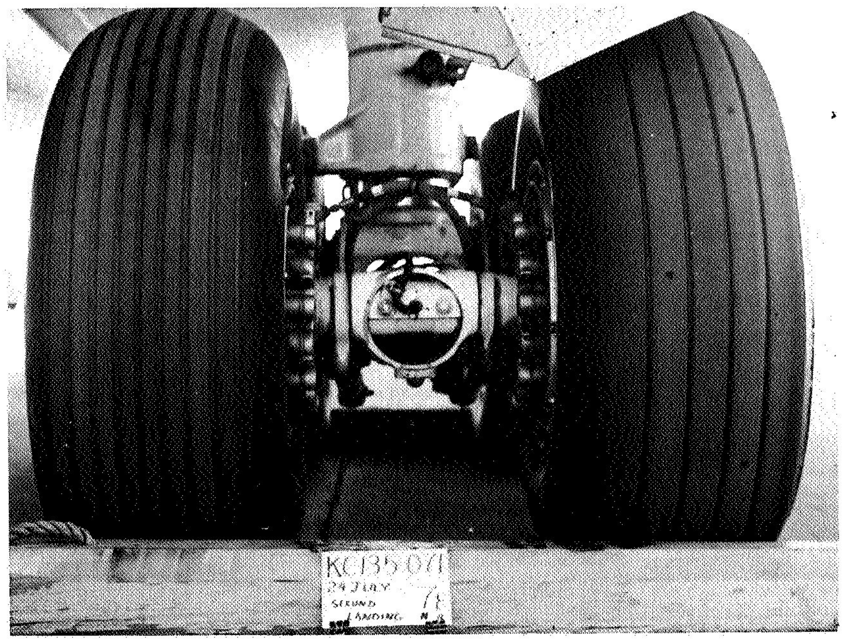

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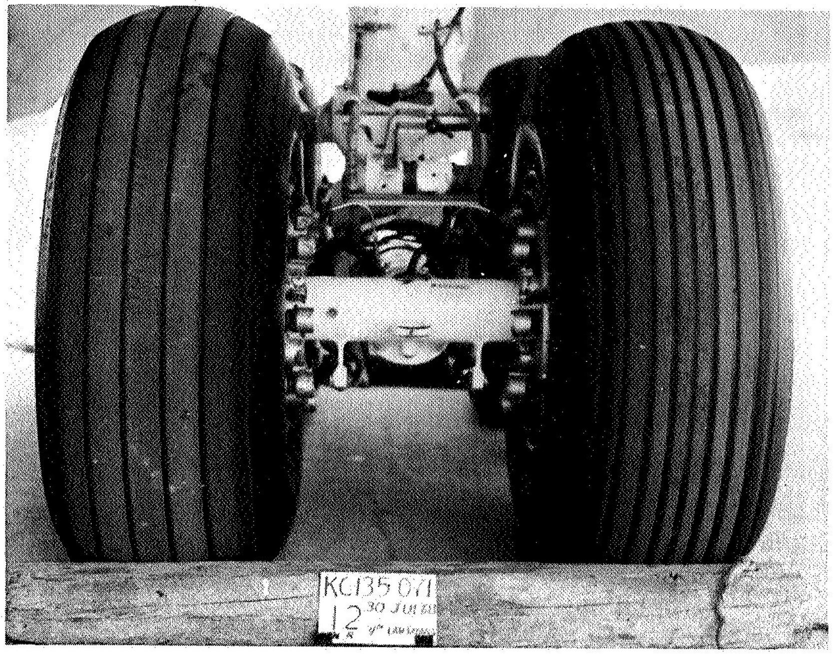

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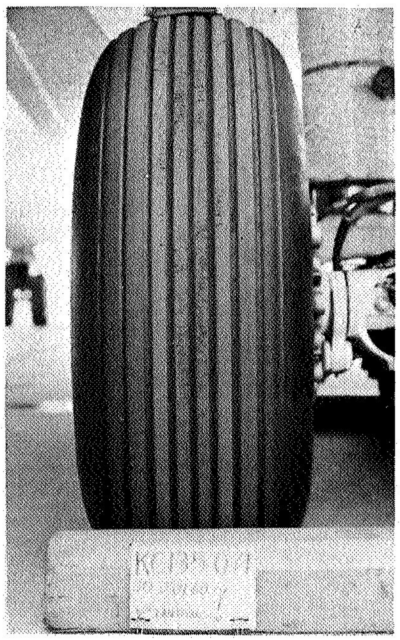

Figure 20

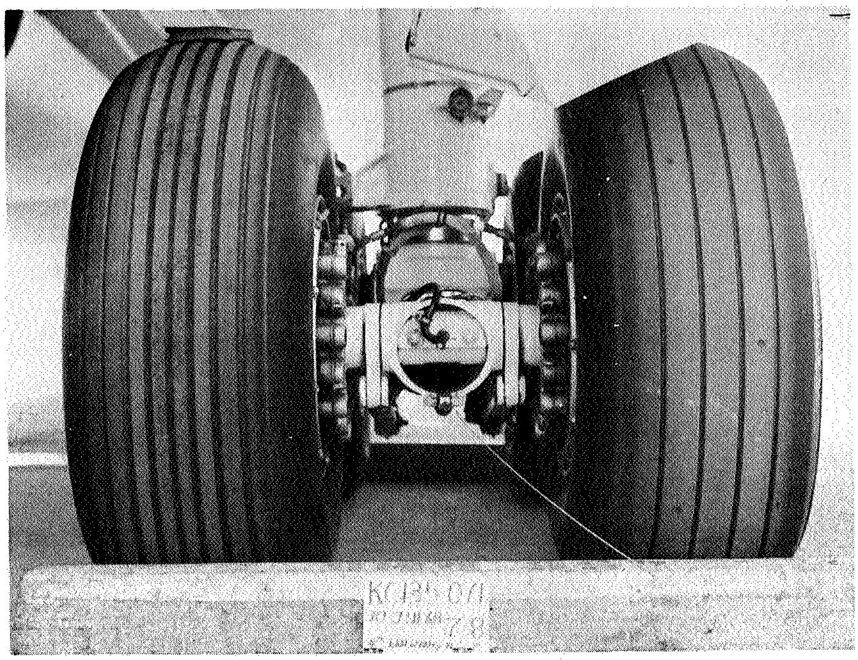

Figure 21

Figure 22

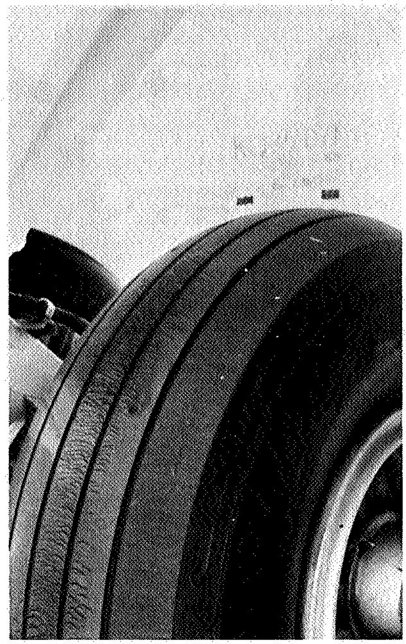

Figure 23

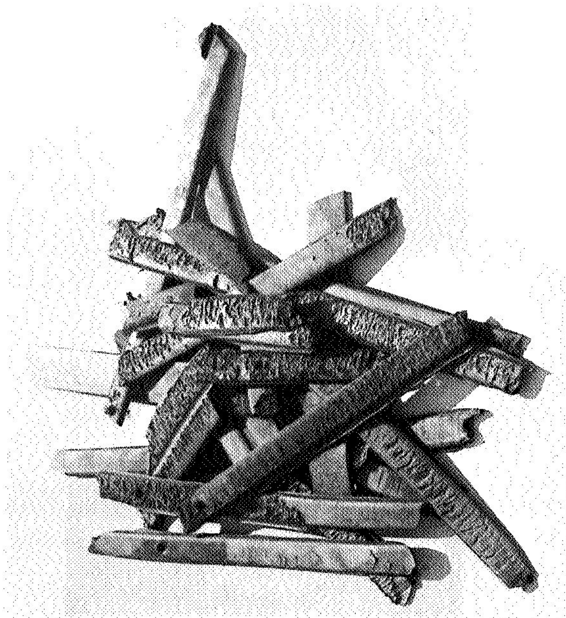

Figure 24

Figure 25

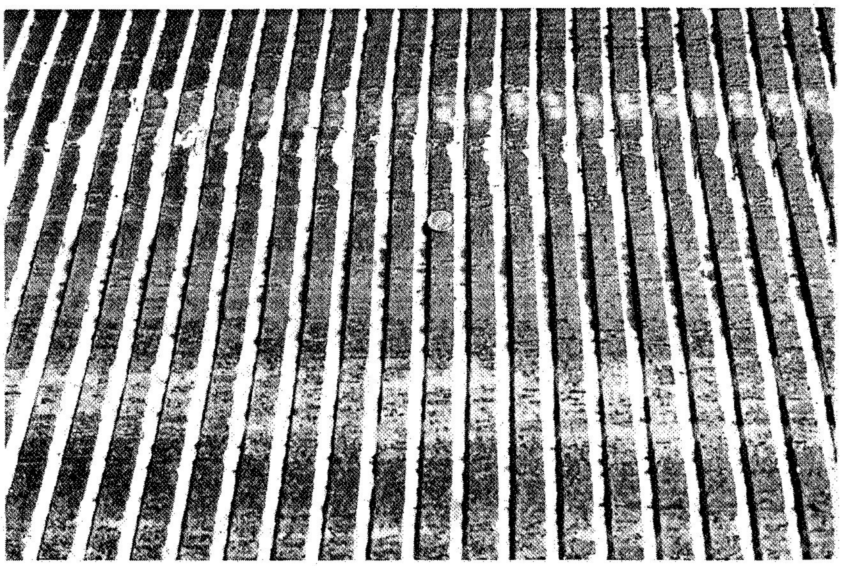

Figure 26

13. SOME EXPERIENCE WITH TIRE WEAR AND DAMAGE ON GROOVED RUNWAYS

By Robert H. Hout

Hill Air Force Base

The Ogden Air Materiel Area (OOAMA), Hill Air Force Base, Ogden, Utah, has the prime responsibility for new tires for out-of-production aircraft and the total responsibility for the retread tire program of the U.S. Air Force. Since March 1968, this command has become increasingly alarmed with tire tread stripping problems associated with the B-52 and KC-135 aircraft. It was not until July 1968 that OOAMA associated the grooved runway at Beale Air Force Base, California, as the primary contributory cause of this problem.

Castle Air Force Base, California, is presently involved with extensive crew training in B-52 and KC-135 aircraft. These aircraft perform a majority of their training touch-and-go landings at Beale AFB. The Castle AFB tire problems, therefore, have been directly associated with the grooved runway at Beale AFB.

Some recent published reports are claiming extensive improvements in traction with no tire damage during braking on grooved runways at slip ratios up to and well beyond peak braking. Contrary to these published reports, the Air Force is experiencing considerable damage, such as depicted in figures 1, 2, and 3, to cargo- and bomber-type aircraft tires. Considerable damage is also being inflicted on tires on some aircraft that are performing only touch-and-go training missions. This damage is being experienced on both new and retreaded tires.

A recent visit to three overseas Air Force Bases, which have grooved runway construction, revealed that the new tires on fighter aircraft were being badly chevron cut and some chipping was occurring. Base maintenance personnel were blaming the barrier cables on the runway for the damage; however, examination of the tires revealed them to be typical chevron-type cuts. The same aircraft operating from other bases, with the runway not grooved but equipped with barrier cables on the runway, are not experiencing the same type of damage.

OOAMA is presently exploring a new-tire procurement program entitled "Life Cycle Procurement" which involves a special testing program to evaluate wear and performance of each manufacturer's tire. The Air Force then procures tires based on performance instead of low bid price. This program is inducing manufacturers of new and retread tires to produce improved designs for competition. The present industry practice for tire qualification is a dynamic wheel test to a specific profile. This method of qualification may not suffice for future procurement unless a specific service test is performed on a grooved runway for final qualification.

Hill AFB is impressed with the results of runway grooving for aircraft control in adverse weather conditions. This approach appears to be the most promising yet undertaken. It should be pointed out, though, that considerable work remains to be done to arrive at a workable solution. The tire manufacturers must be allowed to test their products further and thereby to arrive at a groove configuration or tire design that can be properly handled. Therefore, OOAMA recommends that further runway grooving on USAF runways be discontinued until the problems can be rectified. OOAMA also feels that commercial operators may be confronted with the same problems when the frequency of their operations on grooved runways reaches the level encountered by the Castle AFB aircraft.

OOAMA is deeply concerned with tire tread stripping. Safety of flight is involved in that a thrown tread can damage hydraulic lines, wheel wells, and gear uplock mechanisms. The Beale AFB runway is being swept daily for one aircraft to prevent jet engine compressor damage. Considerable research should be accomplished on the effects of runway grooving on tires from all manufacturers and retreaders. Rubber compounding or grooving configurations must be changed to correct the cited problems. Further grooving of any USAF runways at this time would negate the OOAMA current tire improvement program and pose serious safety-of-flight problems.

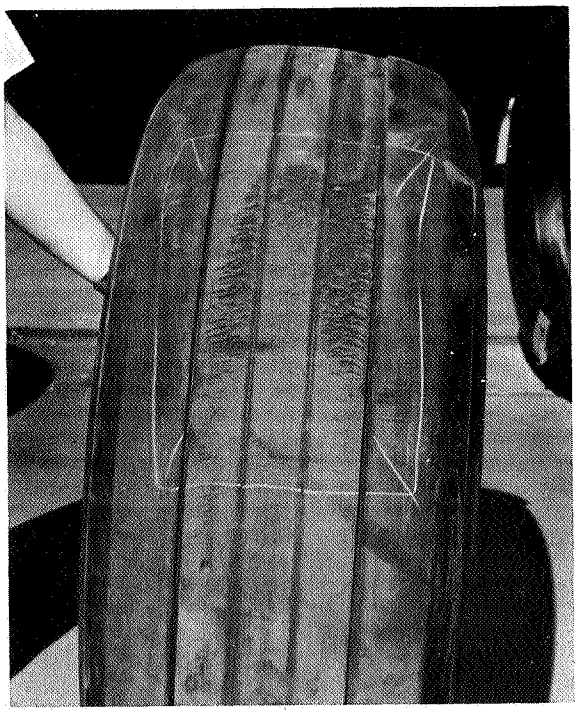

Figure 1

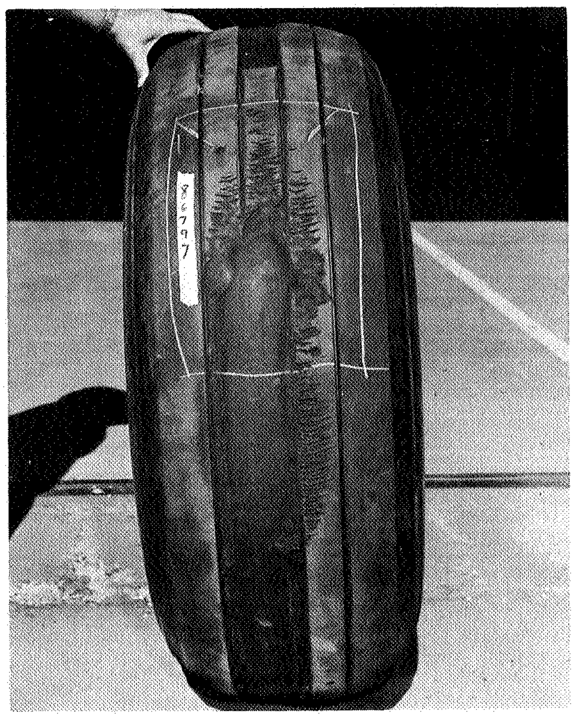

Figure 2

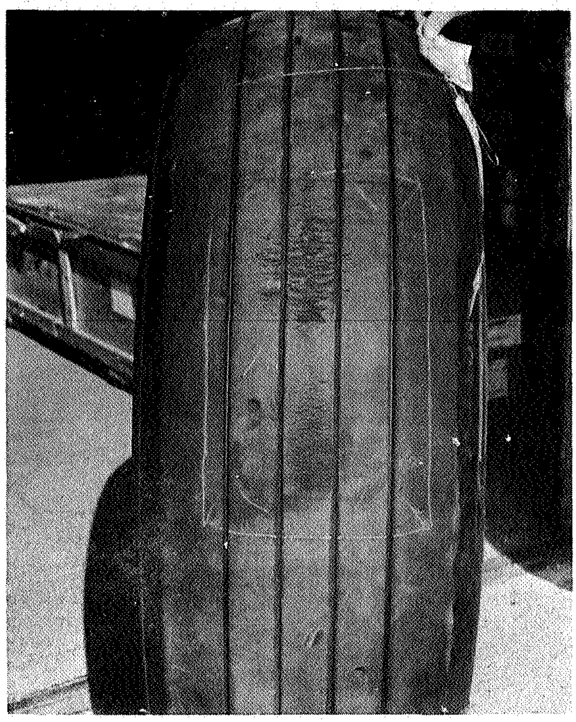

Figure 3

14. NASA STUDIES ON EFFECT OF GROOVED RUNWAY OPERATIONS ON AIRCRAFT VIBRATIONS AND TIRE WEAR

By Thomas J. Yager

NASA Langley Research Center

SUMMARY

Some tire tread wear data obtained from tests conducted at the Langley landing-loads track for a variety of aircraft tire sizes and types on various transversely grooved surfaces are presented and discussed. Comparative tire tread wear data and main strut vibration data obtained during the McDonnell Douglas F-4D and Convair 990 aircraft tests on grooved and ungrooved surfaces at the landing research runway at NASA Wallops Station are also discussed. Within the test limitations of these studies the results indicate that transversely grooved runway surfaces do not significantly increase aircraft vibrations or tire tread wear.

INTRODUCTION

The purpose of this paper is to discuss the effects of transverse runway grooves on aircraft tire tread wear and aircraft vibrations. Tire tread wear data obtained with various aircraft tires tested at the Langley landing-loads track and the landing research runway at NASA Wallops Station are presented. Vibration data obtained from vertical accelerometers mounted on the right main strut of the F-4D and 990 aircraft during the full-scale tests at NASA Wallops Station are also presented.

AIRCRAFT TIRE TREAD WEAR

During normal aircraft operations on a relatively high friction level surface, some tread wear, cutting, and/or damage occurs. The extent or magnitude of this tire tread degradation is dependent on several different factors, some of which are as follows:

(1) Pavement texture or roughness

(2) Pavement contaminants

(3) Tread type and construction

(4) Amount of skidding

(5) Loading

Pavement texture or roughness and the amount and type of pavement contaminants, such as water, slush, ice, dirt, oil, or rubber deposits, directly affect the level of friction developed between the tire and pavement that causes tire tread wear. Tire tread type and construction (that is, whether the tire has all rubber tread or fabric-reinforced rubber tread) also affect the susceptibility of the tread to shear or cut. The wear associated with skidding depends on the amount of time a tire is subjected to finite slip ratios, the slip-ratio value, and the drag load. (See ref. 1.) Tire loading includes the amount and the variation of tire loading such as occurs at touchdown or during abrupt changes in the friction level developed between the tire and the pavement.

In an attempt to determine the effect of transverse pavement grooves on aircraft tire tread wear and cutting, tests with various types of aircraft tires were made at the landing-loads track. Figure 1 shows the results obtained with a 3-groove fabric-reinforced 30 × 11.5-14.5, type VIII, aircraft tire during a low-speed (4 knots) braking test run on the 1- × 1/4- × 1/8-inch transversely grooved test surface for a dry surface condition. The test tire was inflated to 210 lb/in^2 and the test was conducted at 0° yaw. As shown in the photographs of figure 1, tread rubber was deposited on the test surface but the tire tread did not receive any cuts or damage during this run from a free-rolling condition to a locked-wheel condition. Some tread wear, however, did occur at relatively high slip-ratio values. In contrast to the normal trend observed on smooth surface runways where the rubber deposits adhered to the surface, the tread rubber deposited in the dry surface grooves during locked-wheel braking was powdery or granular in form and could be easily brushed away.

Comparative braking test runs at a ground speed of 4 knots were also made on grooved and ungrooved surfaces for damp conditions. The grooved concrete surface had a groove configuration of 1 × 1/4 × 1/8 inch. The ungrooved surface was a bituminous asphalt overlay containing abrasive aggregate material. The aircraft tire used in these tests had a fabric-reinforced rubber tread and was constrained to run at 4° yaw. Results obtained from these tests are shown in figures 2 and 3.

As indicated by the photographs of the tire skid area, some tire wear occurred for locked-wheel conditions on the 1- × 1/4- × 1/8-inch grooved surface, but on the ungrooved abrasive asphalt surface for the same test conditions, substantial damage to the tire tread occurred. Some of the tread cuts resulting from the braking run on the ungrooved surface were as deep as the tire cord. Considerable side force was developed by this test tire at 4° yaw during the run prior to the locked-wheel condition but no other tread wear or cutting occurred except for that shown in figures 2 and 3.

After the braking runs with this tire, the tread deposit on the grooved test surface was also composed of powdery or granular rubber particles which could be easily brushed off. On the ungrooved surface the tire tread deposit consisted of rubber and fabric in an abraded form which could also be brushed off.

By using a new 30 × 11.5-14.5, type VIII, aircraft tire, a braking test run at 102 knots was made at the landing-loads track to evaluate further the effect of pavement grooves on tire tread wear. The test tire had a 3-groove fabric-reinforced rubber tread, and the variation in friction developed between the tire and the grooved pavement during braking is shown as a function of slip ratio in figure 4. The damp test surface was grooved 1 × 3/8 × 1/4 inch. Figure 5 shows the 5-foot-long rubber deposit from the tread on this grooved surface and the tire tread damage area resulting from the braking run. By measuring the length of the tread damage area and by calculating the rolling circumference and angular velocity of the tire, it was determined that the surface rubber deposit was initiated at a slip ratio of about 0.8. Prior to this point in the braking cycle, no significant tread wear occurred. The tire tread wear and the chevron-type cuts shown in figure 5 occurred between slip ratios of 0.8 and 1.0. Therefore, the results of this test indicate that to minimize tire tread wear and cutting, high slip-ratio values should be avoided during aircraft ground operations.

In order to evaluate further the type and extent of the tire tread damage, locked-wheel tests were conducted at the track with a smooth 49 × 17, type VII, all rubber tread tire. The data obtained from these tests are shown in figure 6.

The time histories of the variation of slip ratio and drag friction coefficient μ_{drag} shown in figure 6 were obtained at a speed of 100 knots on 10 different grooved and ungrooved surfaces for damp and flooded conditions. The high friction that developed between the tire and the 1- × 1/4- × 1/4-inch grooved surface (fig. 6) exceeded the torque limitations of the brake system used on the test carriage and resulted in partial wheel spin-up as indicated by the variation in slip ratio. The other ungrooved and grooved test surfaces, which were flailed-type grooves of 1/8-inch depth, did not develop sufficient friction to overcome the brake torque limitation. The slip-ratio value of 1.0 indicates that the wheel remained locked on the other test surfaces for damp and flooded conditions.

The condition of the tire tread as a result of the locked-wheel runs is shown in figure 7. The numerous, small chevron-type cuts in the all rubber tread of the smooth 49 × 17, type VII, test tire did not exceed 0.06 inch in depth. In subsequent test runs with this tire, the results indicated that these chevron-type cuts did not significantly impair the tire tread life.

These chevron-type cuts in the tire tread were also observed during the tests of the 990 aircraft on the landing research runway. Figure 8 shows the condition of the tire and surface after a firm touchdown of the 990 aircraft on dry grooved concrete. The aircraft was equipped with new 5-groove all rubber tread main tires. Although only the right main gear touchdown area is shown here, the left main gear touchdown area showed similar rubber deposits and all eight main gear tires had similar tread cut areas. In analyzing these results, the width of the rubber deposit on the runway at the point of initial touchdown equaled the width of the tread cut area on the main tires. Since the tires did not have any other cutting around the tread and the rubber deposit on the runway is shown to increase in width, it would indicate that the chevron-type cuts shown in figure 8 occurred only at initial touchdown when the tire was stationary. As soon as wheel spin-up started, the tire tread had no further cutting.

During the maximum antiskid braking tests of the F-4D aircraft, some tire tread wear was experienced but no chevron-type cutting was observed. However, no prolonged wheel lockups occurred during the braking tests of the F-4D, and the main tires of the F-4D had a 3-groove fabric-reinforced rubber tread. During the maximum braking tests of the 990 aircraft on wet and flooded surfaces, prolonged wheel lockups occurred on the ungrooved surfaces particularly with the smooth all rubber tread main tires. Because of the normal test run procedure of applying maximum antiskid braking through adjacent ungrooved and grooved tests surfaces, chevron-type cuts developed on the tire tread when the tire encountered the grooved surface at locked-wheel conditions. Some of the smooth tire tread cuts are shown in figure 9. No further cutting occurred during maximum braking test runs from a grooved to an adjacent ungrooved surface. Approximately 50 maximum antiskid braking test runs were made with the chevron cuts in the tire tread. Again the maximum measured depth of these cuts did not exceed 0.06 inch. As a result of further braking tests, these cuts increased in number but did not increase in depth.

In summary, the tests at the landing-loads track and the aircraft tests on the landing research runway have shown that tire tread wear and/or cuts occur on grooved and ungrooved pavements. The extent or magnitude of tire tread wear or cutting appears to be greatest at or near the locked-wheel condition. The small chevron-type cuts in the aircraft tire tread occurred only at touchdown, when the tire was stationary, or under a locked-wheel condition on a high friction level surface. It can be theorized that at very high slip-ratio values, particularly at the locked-wheel condition, local tension failures of the tread rubber result in the chevron-type cuts. These test results indicate, however, that tire tread life is not significantly impaired because of the chevron-type cutting.

AIRCRAFT VIBRATION

Two vertical accelerometers were mounted on the right main landing gear strut of the F-4D and 990 aircraft during the tests made on the landing research runway to determine the effect of transverse runway grooves on aircraft vibration. An accelerometer was mounted on the upper section of the main strut close to the wing; another accelerometer was mounted on the lower section of the main strut close to the wheel or wheels. The upper strut accelerometer had a natural frequency of 1000 cycles per second, and the lower strut accelerometer had a natural frequency of 3000 cycles per second. Some typical vibrations obtained from these strut accelerometers during the tests of the F-4D aircraft on grooved and ungrooved surfaces are shown in figures 10 and 11.

The upper and lower strut accelerometer traces shown in figure 10 were obtained for free-rolling conditions on dry ungrooved and grooved concrete. These data show that the magnitude of the lower strut vibration is greater than that measured at the upper strut on both test surfaces. As the aircraft ground speed increased from 61.5 to 96.0 knots (fig. 11), the amplitude of the strut vibrations also increased. No change in amplitude could be observed when results obtained on grooved and ungrooved surfaces at the same speed were compared. When the time scales of figures 10 and 11 were expanded, no significant difference was measured in the frequency of the lower strut vibration on the dry grooved surface as compared with the dry ungrooved surface at both test speeds.

Strut accelerometer data similar to the data for the F-4D aircraft were obtained at speeds of 83 knots and 123 knots during the tests of the 990 aircraft on grooved and ungrooved surfaces as shown by the examples in figures 12 and 13. The magnitude of the strut vibrations for the 990 aircraft on dry grooved and ungrooved asphalt at both test speeds is less than that shown for the F-4D aircraft in figures 10 and 11. As in the case of the vibration data of the F-4D aircraft, no significant difference was measured in the frequency or amplitude of the lower strut vibration of the 990 aircraft on the dry grooved surface as compared with the dry ungrooved surface at both test speeds. On the basis of these test results, it is believed that grooved runways do not significantly alter aircraft vibration.

CONCLUDING REMARKS

Braking tests using several types of aircraft tires were conducted at the Langley landing-loads track on various grooved and ungrooved surfaces. The results indicated that the grooves caused no significant increase in tire wear or tire damage. Tire tread degradation, however, was found to increase at the higher slip ratios and was greatest during the locked-wheel skid condition. Full-scale aircraft tests conducted on the landing research runway at NASA Wallops Station substantiated these test results and furthermore indicated that the chevron-type cuts that were developed in the tire tread at the higher slip ratios on the grooved surfaces did not reduce tire tread life. Aircraft strut vibrations measured during operations on 1- × 1/4- × 1/4-inch transversely grooved surfaces were found to be the same as those measured on ungrooved surfaces. Full-scale tests at the landing research runway for a variety of additional aircraft types and tire loadings are planned to obtain further evaluations of the effect of grooved runway operations on aircraft vibrations and tire tread wear.

REFERENCE

1. Batterson, Sidney A.: A Study of the Dynamics of Airplane Braking Systems as Affected by Tire Elasticity and Brake Response. NASA TN D-3081, 1965.

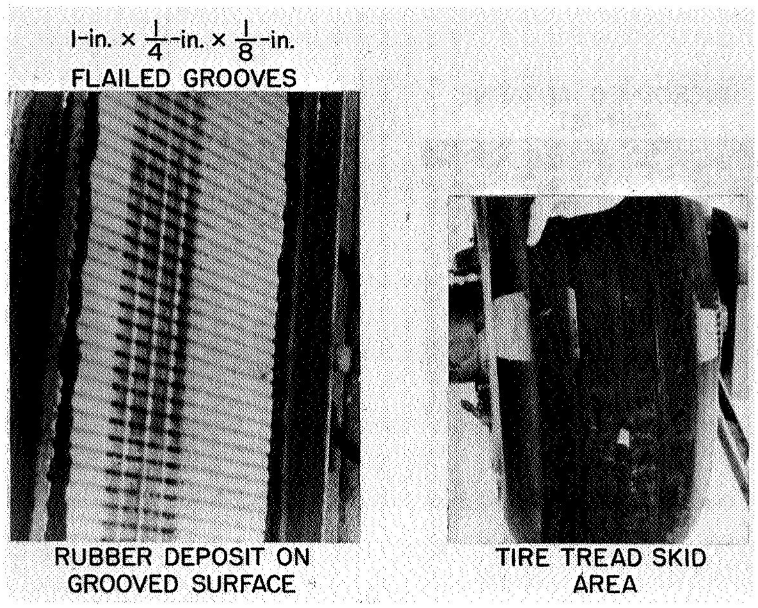

Figure 1.- Condition of grooved surface and tire after braking test. 3-groove fabric-reinforced 30 × 11.5-14.5, type VIII, tire; inflation pressure, 210 lb/in^2; dry surface; ground speed, 4 knots; 0° yaw.

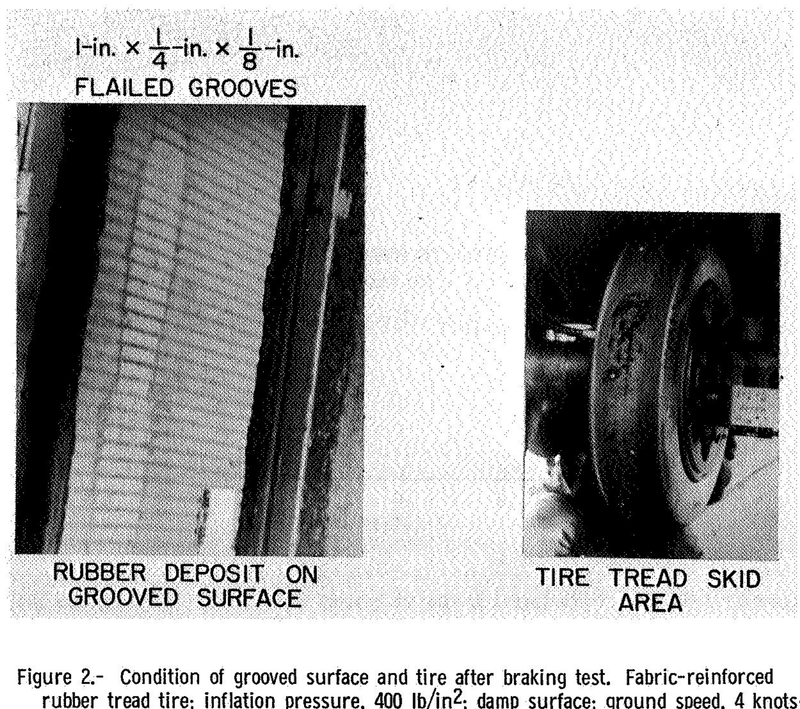

Figure 2.- Condition of grooved surface and tire after braking test. Fabric-reinforced rubber tread tire; inflation pressure, 400 lb/in^2; damp surface; ground speed, 4 knots; 4° yaw.

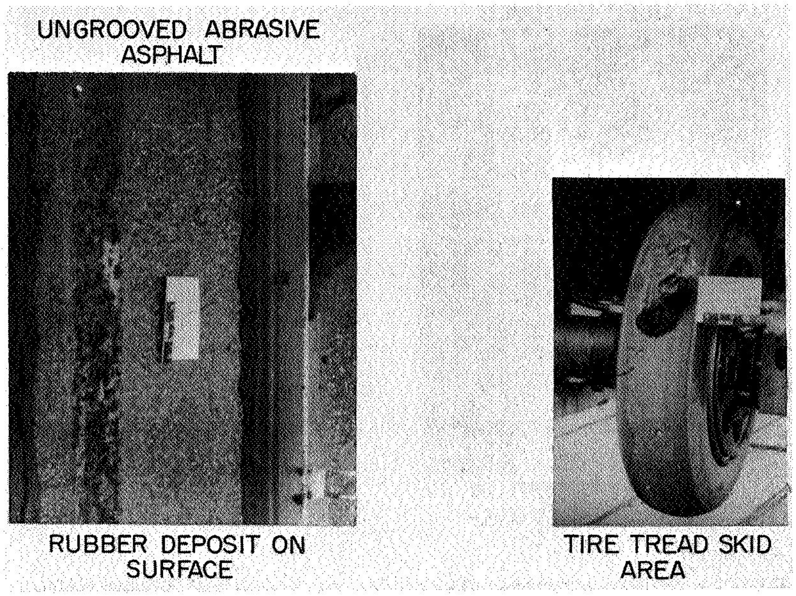

Figure 3.- Condition of ungrooved surface and tire after braking test. Fabric-reinforced rubber tread tire; inflation pressure, 400 lb/in^2; damp surface; ground speed, 4 knots; 4° yaw.

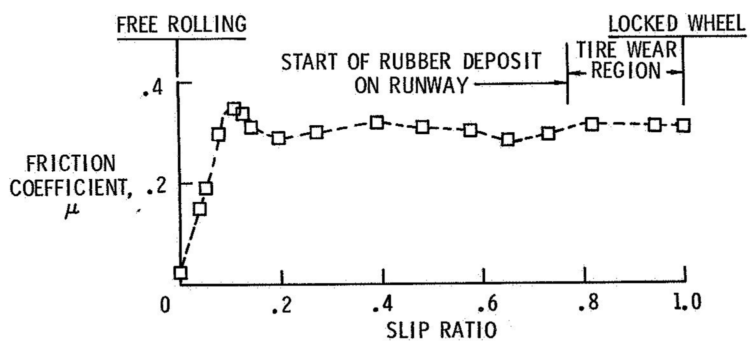

Figure 4.- F-4D aircraft tire during braking on grooved surface. 30 × 11.5-14.5, type VIII, tire; damp concrete; ground speed, 102 knots.

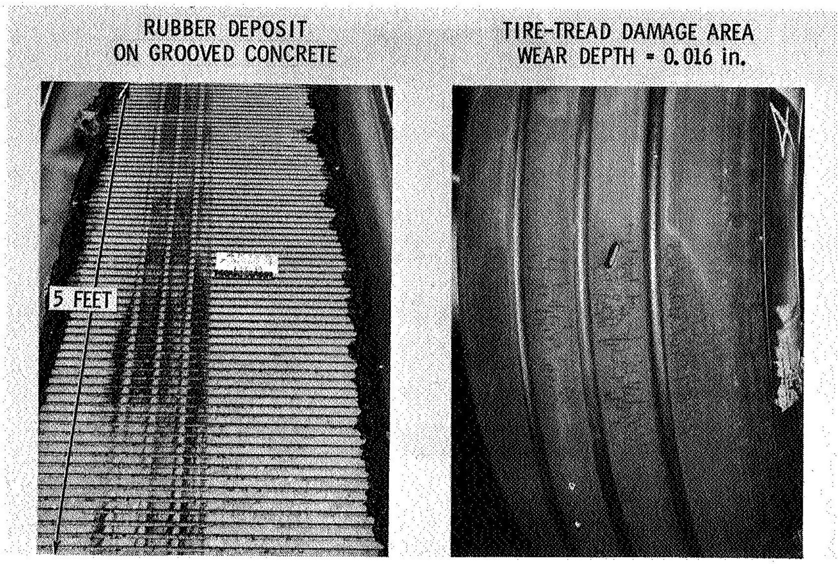

Figure 5.- Condition of test surface and tire after braking.

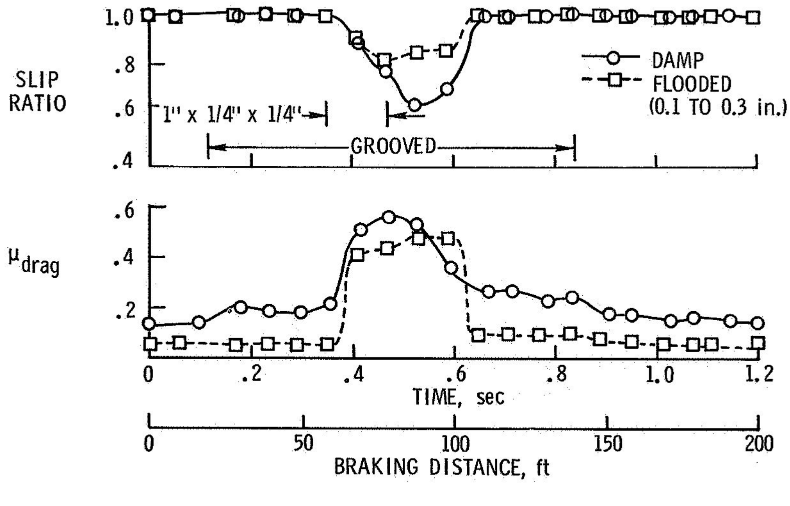

Figure 6.- Comparison of locked-wheel braking on various test surfaces. Smooth 49 × 17, type VII, tire; inflation pressure, 170 lb/in^2; ground speed, 100 knots; yaw angle, 4°.

Figure 7.- Condition of tire tread after locked-wheel runs.

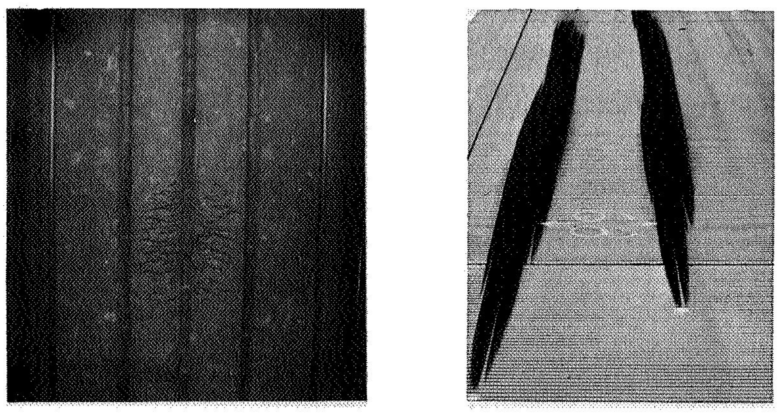

Figure 8.- Condition of grooved surface and tire tread after firm touchdown of 990 aircraft. Dry concrete; inflation pressure, 160 lb/in^2.

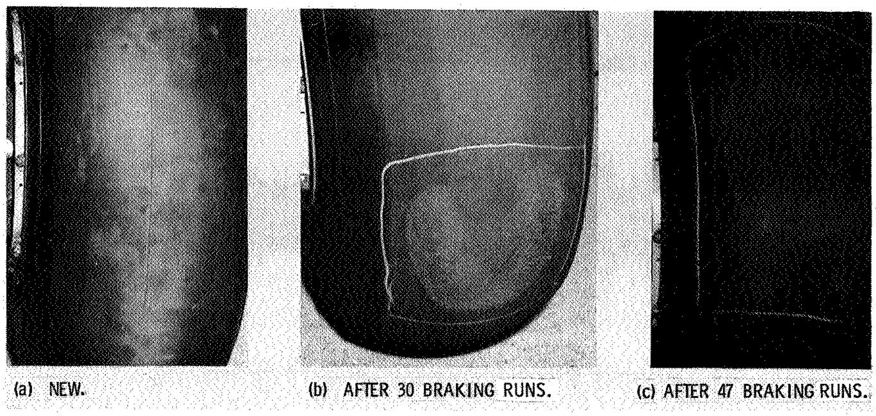

Figure 9.- Effect of braking tests on smooth main tire tread of 990 aircraft. 41 × 15.0-18, type VIII, main tires; inflation pressure, 160 lb/in^2.

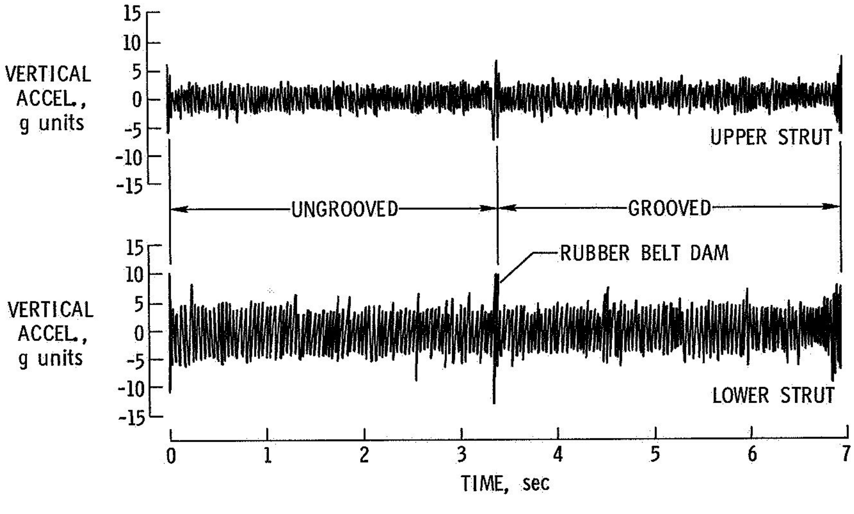

Figure 10.- Free-rolling vibrations from main strut of F-4D aircraft. Dry concrete; ground speed, 61.5 knots.

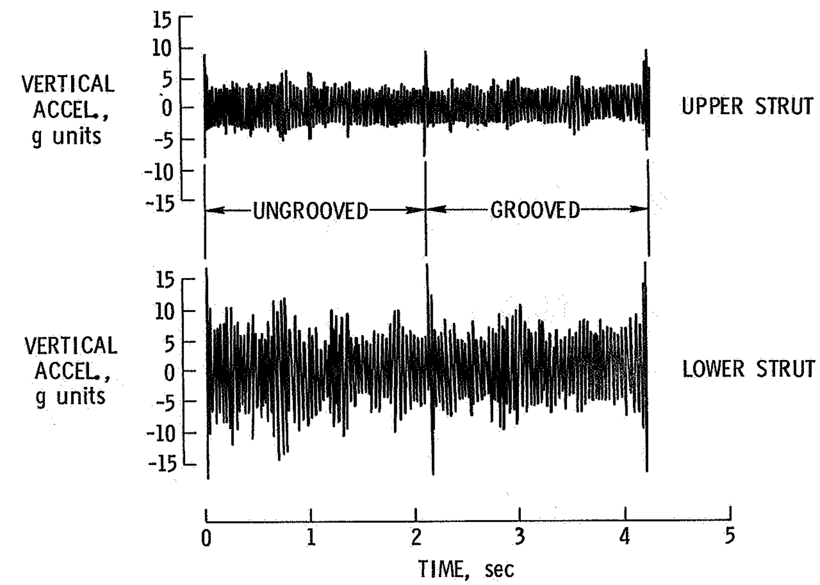

Figure 11.- Free-rolling vibrations from main strut of F-4D aircraft. Dry concrete; ground speed, 96.0 knots.

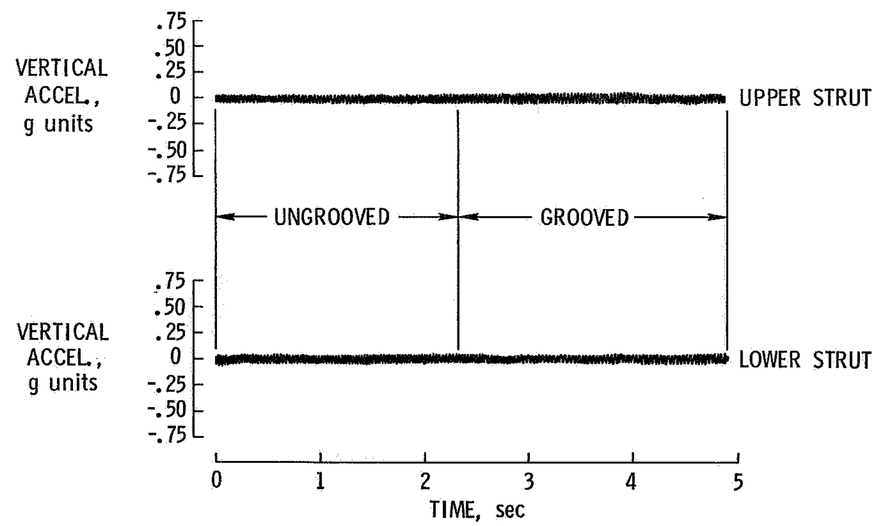

Figure 12.- Free-rolling vibrations from main strut of 990 aircraft. Dry asphalt; ground speed, 83 knots.

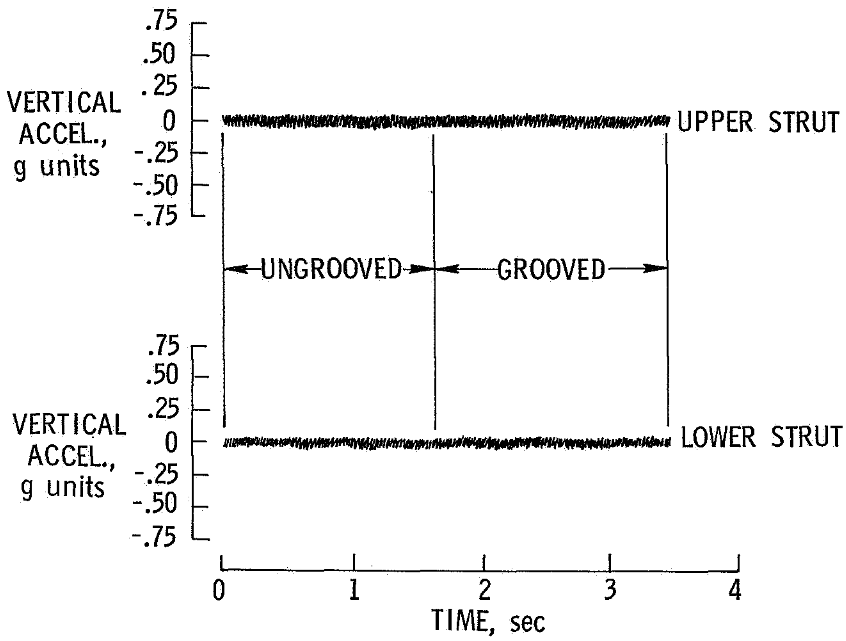

Figure 13.- Free-rolling vibrations from main strut of 990 aircraft. Dry asphalt; ground speed, 123 knots.

15. A SURVEY OF THE EFFECT OF GROOVED RUNWAY OPERATIONS ON THE WEAR OF COMMERCIAL AIRLINE TIRES

By James M. Petersen

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SUMMARY

Commercial airlines have been exposed to grooved runways for less than 2 years. The investigation of worn commercial aircraft tires indicates that grooved runways have not contributed to any apparent change in tire-wear patterns. The incidence of chevron cutting has increased since grooved runways have become operational, but these superficial cuts have not been considered to be detrimental to aircraft tire wear.

INTRODUCTION

Safer operation of high-speed aircraft can be achieved by a system that improves tire traction. Current aircraft braking systems, as well as tire-tread designs and runway-surface materials are able to cope with most wet or flooded runway conditions. Under extraordinary operating conditions, hydroplaning can occur and can result in loss of braking control and tire traction. Considerable research has been carried out to find useful and effective ways in which to solve this extraordinary operational problem. Techniques explored in the solution of this problem included new tire design, change in tire-tread patterns, various pavement textures, air jets to remove water ahead of the tire tread, and pavement grooving. Each of these techniques display some level of performance in solving the sliding and skidding problems encountered by pilots. 15

Research was carried out in Great Britian at Farnborough (ref. 1) to determine tire wear on an open graded macadam surface and a grooved runway of similar asphalt construction. The open macadam surface contained a considerable amount of coarse aggregate and was therefore very porous in appearance. As a reference for this tire-wear study, a grooved runway was used which was cut transversely with grooves 1/8 inch deep, 1/8 inch wide, and 1-inch pitch. A Meteor Mk. 7 aircraft was used in this study to determine tire wear. The amount of tire wear was determined by measuring groove depth and loss in tire weight. The results indicated that the grooved surface caused approximately 8 percent more wear than the open macadam surface. The increased tire wear was considered to be acceptable when considering the alternative of landing on smooth wet runways with hydroplaning situations being encountered. Similar research at NASA Langley Research Center (ref. 2) has indicated that runway grooving presented the most effective approach in solving the problem of low tire ground friction and traction losses. This research effort was concerned primarily with optimizing the groove configuration with respect to aircraft control. This investigation evaluated groove spacings of 1 inch, $1\frac{1}{2}$ inches, and 2 inches. Groove widths were 1/8 inch, 1/4 inch, and 3/8 inch with groove depths of 1/8 inch and 1/4 inch. These groove configurations displayed various levels of improved braking performance but none of the configurations exhibited any excessive tire wear under the conditions of this research investigation. This preliminary work was not conclusive as to tire-wear—grooved-runway relationships, but these initial studies were very optimistic regarding tire wear under these operating conditions.

The research at Langley Research Center resulted in the recommendation for grooving runways at Washington National Airport, Kansas City Municipal Airport, John F. Kennedy International Airport, and Midway Airport at Chicago. The groove configuration and surface composition for the four grooved commercial runways in the continental United States are summarized in table I. These runways have been grooved in different configurations as part of the overall program of increased tire traction and ground safety. This program of runway grooving by NASA Langley Research Center and NASA Wallops Station is coordinated with Federal Aviation Administration, Air Transport Association of America, and U.S. Air Force to find solutions to this critical problem of aircraft safety.

TABLE I.- GROOVED RUNWAYS IN UNITED STATES

Airport	Date completed	Groove	Construction
Washington National	April 1967	$\frac{1}{8}$ inch wide × $\frac{1}{8}$ inch deep × 1 inch	Asphalt
Kansas City Municipal	May 1967	$\frac{1}{8}$ inch wide × $\frac{1}{4}$ inch deep × 1 inch	Asphalt and concrete
John F. Kennedy International	August 1967	$\frac{3}{8}$ inch wide × $\frac{1}{8}$ inch deep × $1\frac{3}{8}$ inch (sloped to 5/32 inch)	Concrete
Chicago Midway	September 1968	$\frac{1}{4}$ inch wide × $\frac{1}{4}$ inch deep × $1\frac{1}{4}$ inch	Concrete

DISCUSSION

Operations At Grooved Runways

The four domestic grooved runways in the continental United States have been in operation 2 to 18 months. Washington National Airport was the first U.S. commercial terminal to have regularly scheduled airlines operating from grooved runways. Since the grooved runways at Washington National became operational, approximately 600 000 individual main-landing-gear tires covering a large spectrum of tire sizes have been exposed to landing and take-off from this modified surface. The commercial high-speed jet airplanes that are operational from this airport include Boeing 727 models equipped with 49 × 17 tires as well as smaller aircraft that are fitted with 40 × 14, 40 × 12, or 39 × 13 main-gear tires.

The grooved runway at Kansas City Municipal Airport became operational shortly after the Washington National Airport. The Kansas City Airport traffic has approximately 50 percent of the domestic Washington National operation and has the large high-speed jets operating at their facilities in addition to the smaller jets used by the trunk airlines. The John F. Kennedy International Airport completed the grooving of the main runway in August 1967. Since the completion of this grooving, the runway has been utilized by the scheduled airlines, the tire contact levels established for the John F. Kennedy Airport runway being comparable with those of the Washington National Airport. The domestic operations at the John F. Kennedy Airport have Boeing 707 airplanes with 46 × 16 tires and DC-8 airplanes equipped with 44 × 16 tires in addition to similar distributions of aircraft types and tire sizes that were observed at Washington National. The Midway Airport has just completed the grooving of its runways in September 1968 and has not had the grooved runways in operation long enough to establish aircraft types or operational levels. When the overall commercial domestic operation originating from grooved runway surfaces is considered, the data indicate that statistically about 6 percent of all commercial aircraft tires are exposed to grooved runway landings and take-offs. However, if specific airline operations are separated from the overall national averages, the frequency of grooved operations varies considerably. One airline, for instance, has approximately 15 percent of its domestic operations originating from grooved runways. In a similar manner, other airline operations can be separated and demonstrate grooved runway operations above the so-called "6 percent average." The incidence of chevron cuttings has been noticed by these airlines, but they did not express particular concern with this slight cutting.

A leading independent tire retreader solely concerned with aircraft tires has observed approximately 12 000 aircraft tires per month that have been returned for retreading. This company services most of the international airlines as well as domestic airlines. During the processing of commercial tires prior to production, all tires are inspected for structural defects or service damage. As the grooved runways became operational, the incoming worn tires have been monitored for any changes in wear patterns or deep cut propagation as well as for interply separations or bead failures. The investigation of the incoming tires did not show any particular change in ordinary tread wear except for the increased amount of chevron cutting. During this period of tire observations, no tires were removed early for chevron cutting associated with grooved runways.

The field representatives are continually monitoring airline tire maintenance operations at grooved runway airports and have noted little, if any, adverse effects from these runways. Increased chevron cutting has been noted by airline maintenance personnel as the grooved runways became operational, but this type of cutting was not considered to be detrimental to aircraft operation. In the operations an increase in customer response to chevron cutting has been noted, but this condition has not been the cause of premature tire removal. Deep cuts from foreign objects and cut propagation are the principal reasons for tire removal. The chevron cutting associated with grooved runways appears not to contribute to the deep cut problems mentioned previously.

Normal Tire Wear

Normal tire wear for an aircraft tire is a compilation of tread wear, sidewall cracking, bead separations, chafer failure, interply delaminations, cut propagation, groove cracking, as well as rubber reversion due to skid burns. These factors are aggravated by the tire deflection of 30 percent which permits extensive sidewall flexing and resultant heat buildup. All these factors are contributory to tire wear, but the most prevalent cause of premature tire removal is foreign-object cuts. The preventative maintenance for foreign-object cutting is not controllable by tire design but is primarily a housekeeping situation. This type of tire damage has been pointed out in order to demonstrate the distinction between chevron cutting and deep cuts. Chevron cutting has been an integral part of overall tire wear for years. These superficial cuts are generally less than 2/32 inch in depth and can be found well distributed around the circumference of the tread. These cuts can be generated from brake chatter conditions in the aircraft and do not necessarily reflect the condition of the landing surface. These chevron cuts have never been considered to be detrimental to aircraft operation and were never considered as the cause for premature tire removal.

Tire-Wear Pattern Indicative of Grooved Runways

The grooved runways for commercial airlines have been operational for 18 months and represent approximately 1.5 million main-gear tire contacts with these modified surfaces. The exposure to these surfaces, as stated earlier, represents 6 percent of total domestic operation, but will be slightly higher for certain airlines. Since the beginning of 1968, incoming worn tires have been monitored for indication of wear patterns attributable to grooved runway operations. The appearance of chevron cutting on the center rib portions of the tire was the characteristic most noted for grooved runway operation.

Photographs of 49 × 17 commercial aircraft tires showing examples of chevron cutting are presented as figure 1. This type of cutting is rather superficial and was not the cause of tire removal. Since the tires have been observed for indication of grooved runway effects other than the chevron cuts, no other common wear characteristic has been noted. As can be seen in the photographs, the chevron cuts in some tires appear to have been worn away by normal operations. From the observations the commercial grooved runways are not contributing significantly to increased tire wear. The field representatives maintain a continuing surveillance of customer operations and tire-maintenance related problems. This field contact provides the manufacturer with the current status of his products and informs him of any change in operations that affect tire wear. The incidence of increased chevron cutting was promptly recognized by the tire maintenance personnel, but this condition was not considered to be a factor in aggravated tire wear. This type of cutting has been observed for years and has never been considered a reason for tire removal. The operations personnel felt that grooved runways were contributing significantly to safer aircraft ground operations and that any increase in tire wear was readily compensated by the safer operations.

Grooved Runway Studies at NASA Wallops Station

Since grooved runway operations have less than 2 years experience in this country, the wear characteristics associated with this type of runway operation are not clearly established at this time. The major problem in monitoring such a program with commercial airlines is the fact that the airlines do not have consecutive landings on grooved surfaces. The most intensive study of grooved runways and aircraft operations has been conducted by NASA on the landing research runway at NASA Wallops Station located at Wallops Island, Virginia.

Wallops Station is the site of an intensive program on runway grooving and its effect on aircraft tire traction under dry, wet, and slush-ice conditions. Runway 4/22 at Wallops Station was modified to contain both asphalt and concrete surfaces with grooved and smooth configurations. The surfaces were grooved 1/4 inch wide by 1/4 inch deep on 1-inch pitch configuration which was considered to be optimum for aircraft tire traction. Although the primary interest in this study was aircraft braking and ground control, a supplementary part of this study was the effect of grooving on overall tire wear. A Convair 990 aircraft was used in this study equipped with 41×15.0-18 tires. The study involved the plane being taxied at various speeds and then the brakes being applied on the various surfaces to determine aircraft control and braking. Also included in the study were several touch-and-go landings to evaluate hydroplaning conditions on all surface configurations. During one phase of this investigation, the field representatives participated in the study to ascertain the type and severity of tire-wear characteristics that would be generated on grooved runways. In this phase the conditions of the tires were monitored before and after each operational sequence to detect any change in overall tire appearance.

The Wallops study considered the smooth or worn tire configuration to be the most conducive to hydroplaning and loss of ground control. The use of worn tires in the study was considered to be unsafe; therefore, a smooth tire profile was fabricated to offer pseudoworn tire conditions and the most aggravated situation for hydroplaning.

These special tires were run through the sequence of taxiing and touch-and-go landings and were monitored for wear after each sequence. The usual tire-wear determinations based on groove depth were not applicable to these smooth tires; therefore, overall appearance, cutting, or surface changes were the criteria for evaluation. These test conditions were extraordinary with respect to tire punishment. The aircraft would touch down on wet or iced surface smooth-configuration runways and hydroplane until the grooved section was reached, which would initiate wheel spin-up from the hydroplaning condition and provide braking conditions and ground control. This abrupt change from hydroplaning to rolling conditions leads to extreme stresses being placed on the aircraft tire during the landing. This particular test sequence involved approximately thirty-seven (37) individual operations on the various runway surfaces. Examination of the smooth tires after this severe punishment showed only slight chevron cutting, 2/32 inch deep, which was not considered to be detrimental to continued aircraft operations. These tires did not exhibit deep cuts or other surface changes; therefore, the wear level was not considered to be severe.

The second phase of this study involved the evaluation of conventional tire treads and effect of grooving on tire performance. As in the earlier studies, the aircraft would go through a series of taxis at various speeds and touch-and-go landings. These tires permitted the determination of tire wear by means of tread-groove-depth measurements. Again, the field representative monitored tire conditions during the test sequence. The initial studies were carried out on dry surfaces and were then repeated on damp and flooded runways. After each phase of the test, the tires were checked for wear and cuts. The wear patterns on the tires were considered to be normal. Some chevron cutting was noted, but was not considered to be detrimental to aircraft operation. Operations on damp or flooded smooth surfaces resulted in hydroplaning and when the aircraft reached a grooved area, wheel spin-up occurred and braking control was established. Although these operating conditions were severe, tire wear was considered to be normal and chevron cutting to be nominal. In all these studies where wheel lock-up had occurred, there was no evidence of rubber reversion.

The results of this specific tire study in the overall program of increased tire traction indicated that tire wear was essentially normal for operations on grooved runways under severe operating conditions. These studies involving precisely controlled studies of tire wear and grooved runways clearly indicate that tread wear and cutting are not adversely affected by these modified surfaces. Deep cuts and cut propagation were not detected in these studies; therefore, it appears that grooved runways will be beneficial to safe aircraft operations and will not introduce adverse maintenance problems for commercial airlines.

FUTURE RESEARCH

Research efforts are directed exclusively toward retreading of aircraft tires to improve cut resistance and tread life. These two parameters are considered to be paramount in improved maintenance performance for commercial aircraft operations. Actively under development in the research facilities are new tread profiles designed to reduce hydroplaning characteristics and provide better traction.

CONCLUSIONS

Operations of high-speed aircraft on four commercial grooved runways in current use in addition to tests on the landing research runway at NASA Wallops Station have indicated the following conclusions:

1. Commercial aircraft operations on grooved runways have not demonstrated any significant changes in tire wear.

2. The grooved runways cause superficial chevron cuts on the commercial aircraft tires, but these cuts are not considered to be detrimental to tire service.

3. Observations of worn commercial tires indicate that grooved runways do not tend to propagate deep cut growth or to increase cut migration.

4. There is no evidence to date that suggests grooved runways are contributing to other tire damage problems such as interply delamination, chafer failures, bead separation or groove cracking.

REFERENCES

1. Key, E. J.: Tyre Wear Tests on an Open Graded Macadam Runway Friction Course. Tech. Rep. 67178, Brit. R.A.E., Aug. 1967.

2. Horne, Walter B.; and Brooks, George W.: Runway Grooving for Increased Tire Traction – The Current Program and an Assessment of Available Results. NASA paper presented at 20th Annual International Air Safety Seminar (Williamsburg, Va.), 1967.

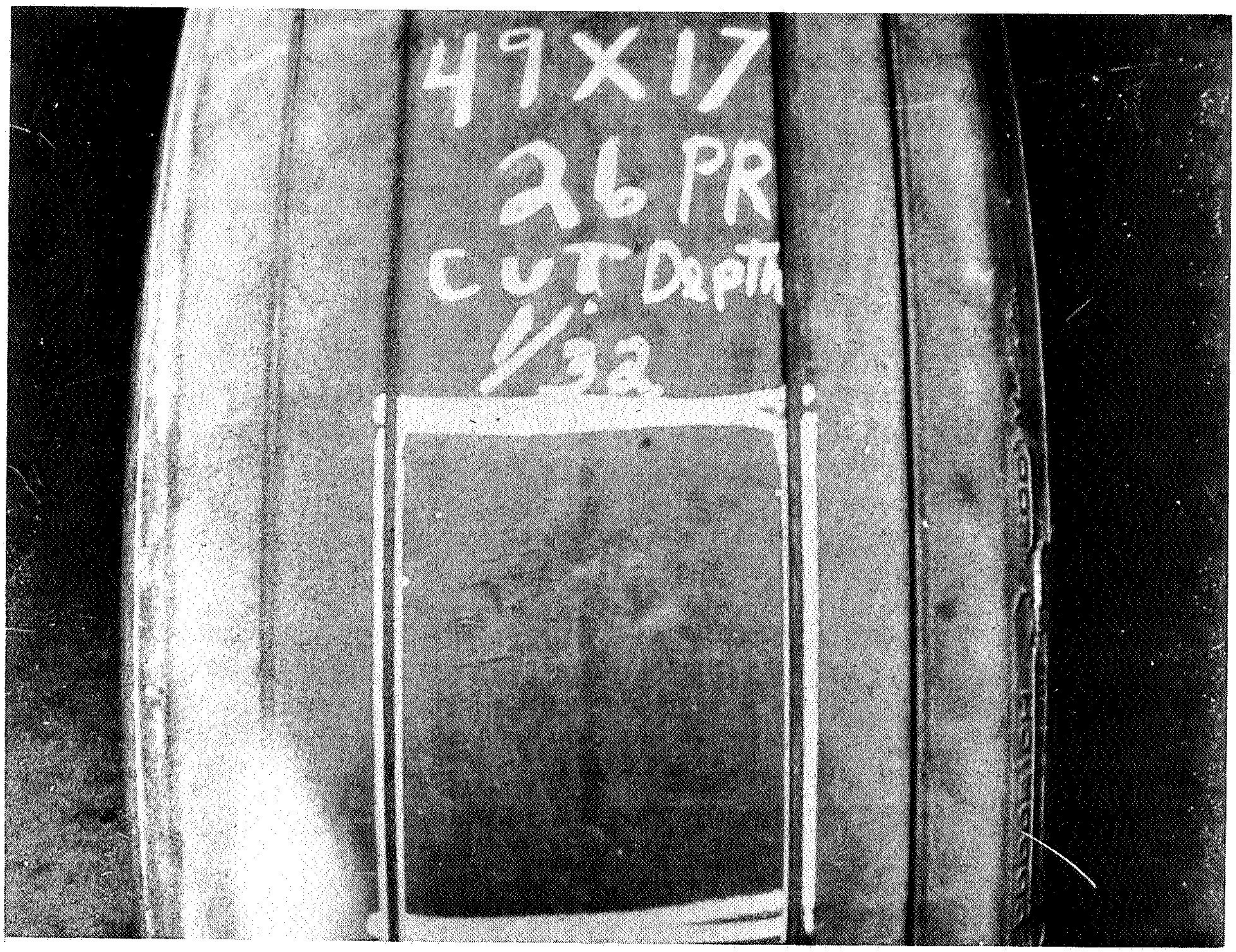

Figure 1.- 49 × 17/26 ply rating tire.

Figure 1.- Continued.

Figure 1.- Continued.

Figure 1.- Continued.

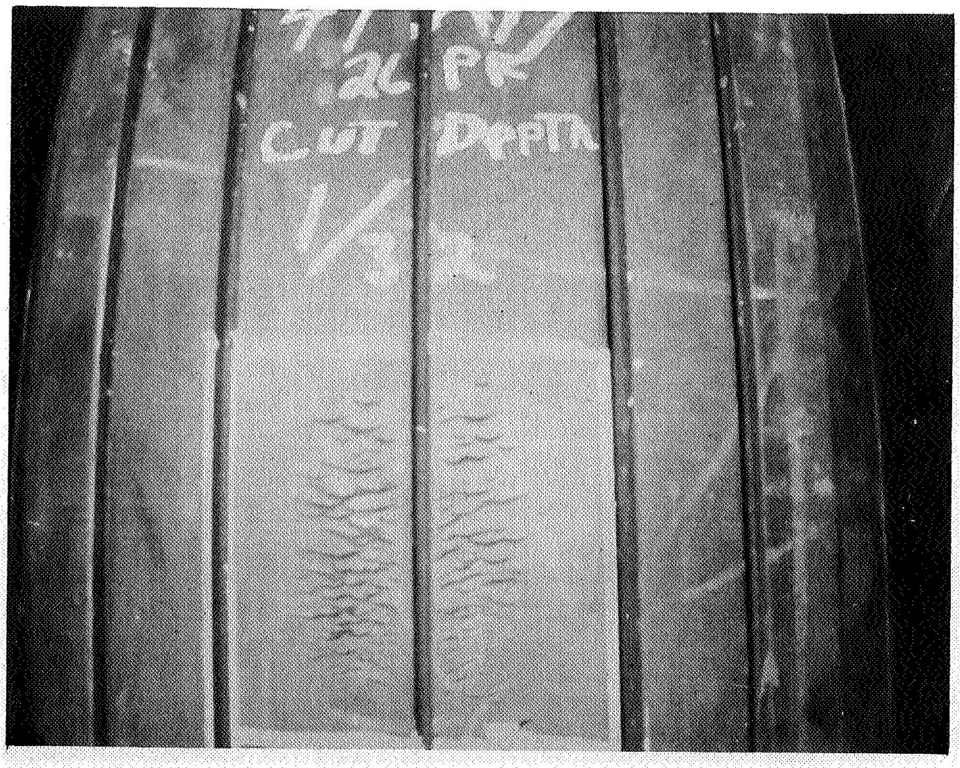

Figure 1.- Concluded.

16. WATER DEPTH AND SLUSH DRAG INSTRUMENTATION

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SUMMARY

The equipments which have been developed with the Ministry of Technology of Great Britain for measuring water depth on runways and for measuring the drag due to slush residue are described and their calibrations and application are outlined. The test evaluation programmes are assessed.

The forms in which information regarding runway conditions can be presented to the operational user are described and related to modern airport practice. In the case of water depth measurements the relevance of water depth instrumentation is discussed in the light of grooving techniques and of high rainfall rate possibilities and cross winds.

In the case of slush drag the importance of predicted drag and its effect on typical aircraft take-off distance is illustrated by theoretical calculation. Some attention is given to the nature of slush, and the significance of conditions in which enhanced drag may be encountered is examined.

INTRODUCTION

This paper is concerned with the description of two instrumentation systems, both connected with the sensing of phenomena on the surface of a runway. The two equipments described measure these two parameters – slush drag and water depth. They have been developed in support of the British Ministry of Technology programme.

The first of the instrumentation systems is for localised measurements of the depth of water on the runway and for presenting this information in the control tower – this system is called the Runway Surface Monitor. The second is an equipment involving a small aircraft wheel which is adapted to be propelled by a motor vehicle along a runway and which responds to the drag forces it encounters – this is called the Slush Drag Meter. It was known, before these concepts were developed, that the manner in which the data obtained by them could be used would require substantial correlation work with aircraft and substantial evaluation programmes of the systems themselves. However, the idea of direct measurement on slush and the closest parameter to the aquaplaning phenomena was felt to be an optimum starting point. The correlation work which has already been reported in previous publications has gone a long way towards enabling the relative usefulness of the two instrument systems to be understood. Other studies, particularly of runway grooving and porous surfaces (ref. 1), have created the situation usual in major engineering fields where alternative techniques exist so that the ultimate system designer may exert a choice based on the suitability to particular needs of the equipments he may desire to use and based on their cost effectiveness.

To provide the maximum relevance to this conference, each of the two equipments is dealt with in sequence by a description of the hardware and the method by which the parameters are measured. A description is given of the evaluation programmes of the instrument as a device in its own right, of the way in which it presents data, and of the interpretation of the data it provides in the light of the correlation work that has been carried out. Certain systems concepts which arise from the nature of the measured parameters are presented.

THE RUNWAY SURFACE MONITOR

Equipment

The schematic of the system is shown in figure 1. As can be seen in figure 2(a) a number of pointed metal probes are held under a dome which is designed to sit snugly on the runway surface, each probe at a different height above the lower surface of the housing in which it is contained (fig. 2(b)). Thus when the water, which is allowed to flow in under the dome through a channel, reaches a level at which it contacts one of the probes, a substantial change in the conductivity occurs and an electronic circuit causes a step change to occur which is fed into a signalling system. In order to eliminate effects of surface conductivity from the probe through the surrounding insulator a guard ring system is employed. The effect of water rising to the point where it touches the tip of the probe is a dramatic change in resistance, and this is large enough to actuate the switching of the electronic circuit, regardless of the degree of purity or contamination of the water involved. It is appropriate here also to say a word on accuracy. The point at which the water touches the tip of the probe is associated with a meniscus which forms as the water jumps up around the probe. Thus when the water recedes there is a difference in height of water between the contact making and the contact breaking, producing a difference of some 7 to 10 thousandths of an inch. It will be seen that this provides a safety time delay after a particular level has been reached, before the instrument will decide that the water has receded below that level. The control boxes (fig. 3) are designed to be fitted into manholes beside the runway. A miniature control circuit has also been devised which can be fitted into the sensing head. The control tower system can comprise a meter display (fig. 4) which supplies the operator with data on the individual water depth at each sensing head and also a recording system (fig. 5) such as the one installed at Gatwick.

Evaluation

In terms of evaluation this system has been used for a number of years at Gatwick and some features of the system have been changed. The main difficulties however have been waterproofing of cable junctions and alternating current pick-up in power cables and not in the fundamental concepts of the device. The overall accuracy of depth measurement is very good indeed, probably 1 or 2 thousandths of an inch consistently. However, the surveying problems of deciding the datum from which one is to measure depth must in most circumstances be of inferior accuracy. A system of water depth instrumentation has been in use in the trials at Wallops Island.

One meter with associated warning lamps is provided for each runway sensing head and the depth of water there is presented as step changes in the meter reading. At Gatwick the unit fits into the Air Traffic Controller's desk and can be readily interpreted by the Controller. Other warnings, such as ringing bells, can readily be provided from a system of this kind.

Data Presentation and Interpretation

Figure 6 shows a possible method of operational presentation of data in digital form, such that it could be offered to a computer programmed with the digested results of research into the behaviour of different kinds of aircraft in different depths of water. Whether such automatic use of the system would be desirable will depend on the reliance that can be associated with aircraft performance data as a function of depth of water and on the manner in which control of aircraft operation develops. The fact that it is feasible should be recognised at this time and should be related to the incontestable fact that any operating control must place the onus on somebody to take a "yes" or "no" decision – to land or not to land – to take off or not to take off. Such decisions will inevitably be better when based on the "best fit" to known physical characteristics, just as an artillery officer's responsibility to "decide the range of the target" grew into a methodology capable of better results and finally gave way to instrumentation.

Meteorological Aspects (Rain)

The charts obtained at Gatwick have been analysed and recorded for significant periods of time, and while the results are not primarily relevant to this instrumentation paper, it is noteworthy that

(a) In any six week period at least one occasion, and probably two or three occasions, will occur when runway sensing heads are showing significant water levels – usually two or three probes touching in any one head.

(b) Often one or more sensing heads will remain dry while others show water depth thresholds (i.e., there is a significant microstructure of rainfall over a distance that is small compared with runway size).

The relevance of water depth measurement is best shown by the following table which shows the incidence of extremely heavy rainfalls in England and Wales.

Duration, min	Frequency	Rate, in./hr	Depth in the time interval, in.
2	1/year	2.72	0.09
	1/5 years	4.24	0.141
	1/20 years	5.57	0.186
5	1/year	2.00	0.18
	1/5 years	3.19	0.265
	1/20 years	4.30	0.357
10	1/year	1.41	0.23
	1/5 years	2.36	0.39
	1/20 years	3.29	0.55

Typical rainfall intensity is likely to be achieved within the stated times (duration) on any one day within the given return period. The actual duration of the storm will normally be much longer.

These figures are based on a modification of Bilham's original formula by Holland and are derived from data from stations in England and Wales, mainly situated on airfields.

These heavy rainfalls may of course be preceded by rain at a somewhat lower rate making excessive water depths all the more certain. It is known that cross winds cause two effects of importance in relation to aquaplaning risks. Firstly, there is a tendency for cross wind to hold water on a slope by offsetting the run-off effect – programmes to measure this more precisely are under way. Secondly, in aquaplaning conditions with cross wind an aircraft can run into trouble at the edge of the runway more readily than it may run off the end. Grooving provides a reservoir for initial rain and a sideways bleed to relieve the hydrodynamic pressure under the tyre. Reliance on it in icing conditions may prove misplaced. Again it seems likely, in the light of present concepts, that grooving provides an increase in the speed at which a given tyre at a given pressure will aquaplane and not a total solution.

THE SLUSH DRAG METER

Equipment

The prime element of the slush drag meter is a wheel which moves slightly against a linear spring restraint (fig. 7). The drag forces cause the wheel to be thrust back stretching the springs and to move the potentiometer to an extent proportional to the force applied to the wheel in the horizontal plane.

The wheel in its frame may be mounted in a special stand together with the instrumentation box (fig. 8) and with a spare wheel. It may be moved about by one man without difficulty (fig. 9).

Figure 10 shows the wheel in its frame on the Land Rover with the lead weights in position. The pressure normally used in this tyre is about 40 psi which is as high as it is convenient to go in the small wheel. The deflexion of the tyre is typical of aircraft usage and is achieved by putting 300 lb of lead weights on the loading trays. The purpose of putting the wheel in front of the vehicle pushing it is to avoid the impingement of any slush thrown up by the wheels of the propelling vehicle onto the measuring wheel. Also, by placing the wheel in front, it attacks virgin slush. The potentiometer transducer provides a voltage proportional to drag. The wheel is also equipped with a contactor which closes the circuit once for every wheel revolution.

The instrumentation box shown in figure 8 provides on dials and counters the elapsed time, the distance travelled by the wheel, and the integrated drag (i.e., drag force in pounds times the time). Thus the distance and the integrated drag can be divided by the time after a known run and the average velocity and the average drag obtained. Another meter reads instantaneous drag, though this is only intended as a guide to prove that the equipment is working.

It may seem a complicated way of going about a simple problem to provide these kinds of integration. However, a moment's reflection will enable one to appreciate that the drag in any given magnitude of slush is not a linear function of speed. The drag does not accurately follow a square law either, but its counterpart has been determined in plain water for a number of special cases in a test programme taking a considerable period of time. These results are shown in figure 11(a) and (b). It is impractical to try to drive a vehicle at a controlled fixed speed particularly in slushy conditions, and this would be necessary if it were desired merely to integrate the drag and rely on the hypothesis that the vehicle speed was known.

Evaluation

The evaluation of the slush drag meter began with a programme intended to show that it was stable when driven over rough ground, through water troughs, and through sand representing the kind of resistance to movement which might be expected of slush. These tests were then followed by a calibration process because it was decided that the the correct method of calibration would be to refer all measurements of drag to the equivalent depth of water which would cause the same drag at the same speed. For this reason, trials were done in a water trough and, for convenience, the water trough was so arranged that the vehicle propelling the test wheel need not put its own wheels in the water. This reduced the drag on the vehicle as a whole and allowed each test run to be carried out at a more consistent speed. These curves in figure 11 are a digest of the test data. Variations of drag in fixed depths are shown as a function of speed, and by interpolation the variation of drag with water depth at different fixed speeds has been determined.

Data Processing

Full interpretation of these data, of which a great deal has been obtained in a fairly extensive Ministry supported evaluation programme, has resulted in a complete calculator for use with the slush drag meter. It is possible to set into the calculator, shown in figure 12, the time, the integrated drag, and the distance travelled, and the water depth nearest to that which would provide the drag which has been encountered can be read. Thus the calculator directly determines a water equivalent depth (W.E.D.) which correlates with the work under way to measure the drag effects on various aircraft types of various depths of water.

Slush and Its Characteristics

Most of the work to date (refs. 2 and 3) confirms the concept that the drag exerted by slush is the same as the drag it would exert if it were melted. Hence the water equivalent depth deduced from the slush drag meter calculator should be expected to equal the actual quantity of water in the slush. However, there is also evidence (ref. 4) that there may be some conditions of slush in which significantly greater drag than the "water content drag" occurs. Because this is a relatively little understood phenomenon, a discussion of its characteristics is contained in the appendix. If this phenomenon occurs on ordinary airfields with slush residues it is almost certainly associated with refreezing of the slush matrix and particularly with keying of the slush to frozen ground. It is thought that at high speeds, with the tendency of tyres to override the slush, the enhancement factors would disappear. It is also likely that in some conditions of slush, the effects of higher tyre pressure would eradicate the phenomenon. Nevertheless, an examination of the critical data for the variation of the melting point of ice with pressure shows that it takes over 300 atmospheres to reduce the melting point by 2.5° C. Thus, since temperature depression is fairly linear with pressure, the tyre pressures currently in use are only capable of reducing the melting point of ice by a small fraction of a degree Centigrade.

Fortunately, the slush drag meter will not give an optimistic interpretation of enhancement drag; it may, when it encounters enhancement drag, give an unnecessarily pessimistic view. However, if enhancement drag is rare then it will not often give a pessimistic result, and if it is less rare in operating conditions than in research conditions (usually done with artificial slush in warm weather), due allowance will be made for it by the slush drag meter readings. This would not be the case with methods of weight sampling of slush residues. The phenomenon can, for present operational use of slush drag meters, be treated as irrelevant because there is no likelihood that a dangerously optimistic interpretation of runway conditions could be given by the instrument. The case for fixed force enhancement drag rests quite simply on work done by the tyre pressure over the area of the track being equated to the (maximum) enhancement drag times the horizontal travel of the vehicle.

The salient factors in this discussion can be summarized as follows:

Water content drag = Drag from melted slush

(For example, drag from 0.65 in. of water is equivalent to water content drag from 1 in. of slush with a density of 0.65.)

$$\frac{\text{Actual drag}}{\text{Water content drag}} = K = \text{Enhancement drag factor}$$

For 1 in. slush ($\rho = 0.65$), K values measured at 30 mph on March 31 and April 1, 1965, were 1.35, 2.6, 3.6, 1.15, and 3.2.

Reduction of melting point due to pressure:

Pressure of over 300 atmospheres is required to reduce the melting point by 2.5° C.

Therefore, a pressure of 225 psi would reduce the melting point approximately $1/8^{\circ}$ C.

Fixed force enhancement:

$$(\text{Work done vertically})_{max} = \text{Area} \times \text{Pressure} \times \text{Depth}$$

$$\equiv \text{Drag}_{fixed} \times \text{Travel}$$

Area = Travel × Track width

Therefore, the maximum fixed force enhancement at 40 psi is 30 lb in 1/4 in. of slush for a 3 in. width wheel.

Aircraft Performance

Having discussed drag force and enhancements it is advisable to see how much effect exists in a typical case. The case chosen is hypothetical and comprises an aircraft of nominal 75 000 lb weight powered by two Avon engines giving a thrust of 15 000 lb corresponding to 0.2g at zero velocity and with an assumed 90 mph take-off speed. A level of water or slush with residual force at take-off of 6000 lb is supposed and the curves in figure 13 are for enhanced drag conditions with fixed force laws. Four cases have been computed in terms of take-off distances in the appendix.

The effects of fixed force enhancements (at 30 mph) are very serious in distance-travelled time. However, if the enhanced measurement is the yardstick, then a safe interpretation ensues.

CONCLUSIONS

The primary conclusions from the work described are as follows:

The measurement of water depth may be accomplished accurately with simple inexpensive equipment and the data presented readily to the Air Traffic Controller.

The drag due to slush may be measured accurately and converted to the equivalent depth of water which would exert the same drag.

The known depth of water may be related to the threshold depths at which various aircraft types (with specific tyre pressures) will begin to aquaplane.

From the measurement of drag coefficients for various aircraft types in known water depths, the water equivalent depth (W.E.D.) predicated by the slush drag meter can be used to predict take-off distance for a particular aircraft in the measured conditions.

Two equipments have been developed which measure basic parameters of aircraft environment and which can take their places against the background of increasing knowledge of the behaviour of aircraft on the ground in wet and winter conditions.

While the two instrument systems described are in a state of readiness for operational application, they must be considered against the following as yet unanswered questions:

Where rainfall statistics and slush incidence are known, what are the criteria for operational acceptability of brief periods of known operation, predicated by the use of accurate knowledge of water depth and slush drag? How does one compare this acceptability with possibly more complete solutions involving runway grooving and total slush removal?

How do the overall operating costs compare and should additional tyre wear from grooving be brought into consideration?

How do the risks, due to increased tyre hazard because of grooving, compare statistically with the risks of occasional need to allow landing (or take-off) in known aquaplaning water depths?

Is there really such a thing as total slush removal to the point where no measurement is desirable?

It is felt that these two equipments proffer a philosophy for wet and winter operations, related to improved safety in the present environment of aircraft and runways.

ACKNOWLEDGMENTS

Throughout the work which my firm has carried out in this area I and my colleagues have been constantly aided and advised by the Officer of the Ministry of Technology responsible for this work in the United Kingdom – Mr. R. W. Sugg – whose help has been greatly appreciated.

I should also like to mention that the rainfall statistics have been contributed by permission of the Director General, Meteorological Office (Copyright – Controller, H.M.S.O.).

APPENDIX

ENHANCEMENT DRAG

Test Data Obtained With Slush Drag Meter in Sweden

These trials took place at Bromma Airfield with the cooperation of the Swedish Authorities on March 31 and April 1, 1965, and the weather conditions were fairly constant; that is, humidity < 50%, temperature 3^{o} to 8^{o} C during the day. The density of the slush was approximately 0.65 throughout the work. No other equipment was used to measure drag, but comparative measurements of the density of the respread slush were made throughout the tests.

Relationship between the wheel drag measured and the drag which occurs in a water depth equal to the water content is the most important single factor. One inch of slush with density 0.65 is equivalent to 0.65 in. of water. From its water calibrations the drag that the wheel should experience in 0.65 in. of water is

Speed, mph	Drag, lb
10	1.30
20	5.2
30	11.7

Corresponding selected Swedish data follows. The left-hand side of the table contains the measurements made and the right-hand side converts the drag to what it would be in 1 in. deep slush at the nearest of the three speeds listed (linear variation with depth and square law variation with velocity assumed). The value of K finally tabulated is the ratio of the drag measured to the water content drag.

Run	Depth, in.	Speed, mph	Drag, lb	Nearest speed, mph	Equivalent drag at nearest speed and in 1 in. of slush, lb	K
March 31, 1965						
12	1.25	18	28.5	20	28.0	5.4
14	1	17.6	19.0	20	24.5	4.8
16	1.75	18.1	61.0	20	42.5	8.2
17	1.75	19.4	68.0	20	41.5	8.0
22	1.0	28.0	13.7	30	15.4	1.34
28	1.0	27.4	25.5	30	30.5	2.6

APPENDIX

Run	Depth, in.	Speed, mph	Drag, lb	Nearest speed, mph	Equivalent drag at nearest speed and in 1 in. of slush, lb	K
April 1, 1965						
5	1.0	27.0	34.3	30	42	3.6
12	2.0	10.3	67.0	10	31.5	24.2
15	1.0	9.3	6.0	10	7.0	5.4
19	1.0	31.6	15.0	30	13.5	1.15
22	1.0	10.3	9.6	10	9.0	7.0
23	1.0	30.2	38.0	30	37.5	3.2

The value of K ranges from 1.15 to 24.2, and since the highest K values relate to lowest speeds, the inference that the enhancement decreases as speed increases is born. However since the highest K values are also at the greatest depths, it may be that more slush than in proportion to depth is 'worked' in the deeper cases because of track residue.

The Nature of Slush

The fact that serious enhancement of wheel drag can take place with a particular slush requires explanation. However, the best that can be attempted here are hypothetical suggestions. Slush is, generally, a mixture of ice crystals, air, and retained water. Enhancement of drag must comprise an increase in the force required to push it out of the way and ergo must be related to the strength of the ice crystal matrix. Additionally, the matrix may be bonded to the (frozen) ground, and there may be air in it but no water. Alternatively, the water might, just conceivably, be of such purity that it can be supercooled and freeze instantly when it is disturbed. Allowing for slush to embrace the condition of being significantly below 0° C there is a case for regarding it as a material with a very great range of strengths, that is, from a sloppy substance in its frequent melting state, indistinguishable from water except in its inability to run away quickly, to a strong ice matrix capable of supporting tyre pressure.

To a marginal extent tyre pressure increase should work to eradicate enhancement, but if it is tenable that enhancement only occurs at "slush" temperatures significantly below 0° C, the pressures available will not do more than shift the initiating temperature for enhancement drag by a small fraction of a degree Centigrade $\left(300\right.$ atmospheres gives -2.5° C, and since the phenomenon is reasonably linear, 225 psi $\equiv -\frac{1}{8}^{\circ}$ $\left.\text{C}\right)$.

Apart from providing a working hypothesis, these considerations lead to a fairly simple theory for wheel drag in enhancement conditions. It is logical that a constant force (invariant with speed) is required to crush the matrix, so that a simple theory may depend on a fixed force addition to the approximate square law dependent water drag term. This may be modified to some slight extent by the forces exerted by the adjacent matrix on the displaced material. The extremely large enhancements measured at very low speeds are supporting evidence for a fixed force concept.

Fixed force enhancement would involve

$$F = F_o + \rho C_{DS} V^2 d$$

where

F = Total drag force

F_o = Fixed term due to matrix strength

ρ = Density of slush

C_{DS} = Drag factor for the drag meter wheel

V = Velocity of test

d = Depth of slush

and from which F_o and $\rho d C_{DS}$ can be determined by drag measurements at two speeds V_1 and V_2. The corresponding total drag forces F_1 and F_2 are written

$$F_1 = F_o + \left(\rho d C_{DS}\right) V_1^2$$

$$F_2 = F_o + \left(\rho d C_{DS}\right) V_2^2$$

This would then allow the effect on aircraft to be predicted.

A fixed force law in enhancement conditions may be related to the work done by a tyre in crushing slush out of the way of the wheel track through the distance represented by the slush thickness, which cannot be more than the work done by tyre pressure over the whole area of the tyre. If the slush is stiffer than the tyre pressure, less drag will be exerted since the wheel will ride up. Consider for the slush drag meter a nominally 3 in. wide track crushing optimally resistant slush with a 40 psi tyre pressure. Thus, an area of $3l$ sq in. (l = Travel) representing a force of $120l$ lb will have been worked through a distance of say d inches (d = Slush depth). This may be equated to the work done over horizontal travel (i.e., $l \times$ Maximum drag form in lb). Hence 120d lb represents a maximum fixed force drag (i.e., 1/4 in. of slush can exert a maximum drag of 30 lb due to its structural strength).

Effect on Aircraft

The drag coefficients of wheels of different size may be measured in water and a conversion ratio established.

$$C'_{DS} = \text{Aircraft wheels factor}$$

Then for a fixed force law

$$F_{A/C} = F_o \frac{C'_{DS}}{C_{DS}} + 2\left(\rho d C_{DS}\right)\frac{C'_{DS}}{C_{DS}} V^2$$

The factor 2 arises in the second term because it is commonly assumed that impingement drag is equal to wheel drag and total drag is equal to 2 × wheel drag. It would be wholly unreasonable to assume that enhancement occurs in impingement, hence the form of the equation. The effects of these considerations are discussed in the main text in the section on "Slush and Its Characteristics."

The distance calculations were obtained by integration of the net thrust equations.

Case	Assumptions	Distance to reach speed of 135 ft/sec
1	Thrust gives 0.2g, falling linearly to 0.173g at 135 ft/sec as per thrust curve	1554 ft
2	Net acceleration = $0.2g\left(1 - \frac{2}{15}\frac{V}{135} - \frac{8}{15}\frac{V^2}{135^2}\right)$ (i.e., it falls to 0.067g at 135 ft/sec with drag term $\propto V^2$) The supposed operation of an aircraft in the worst case with 1/2 in. of slush (on the water content theory)	2403 ft
3	Net acceleration = $0.2g\left(1 - \frac{2}{15}\frac{V}{135} - \frac{12}{15}\frac{V^2}{135^2}\right)$ (i.e., equivalent enhancement or wheel drag × 0.2 and V^2 dependence maintained)	4583 ft
4	Net acceleration = $0.2g\left(1 - \frac{2}{15}\frac{V}{135} - \frac{8}{15}\frac{V^2}{135^2} - \frac{3.5}{15}\right)$ Fixed force theory Enhancement × 8.8 at 45 ft/sec or Enhancement × 3 at 90 ft/sec	4641 ft

These represent particular curves in figure 13.

Thus, there is little difference between take-off distances for cases 3 and 4 which represent wheel drag enhancement times 0.2 with V^2 dependence maintained and wheel drag enhancement of fixed force form but times 8.8 at 45 ft/sec.

It is important that quite modest further increases in slush depth involved will make much longer take-off distances occur and where the drag curve intersects the thrust curve at the take-off speed the distance approaches infinity.

REFERENCES

1. Martin, F. R.; and Judge, R. F. A.: Airfield Pavements Problems of Skidding and Aquaplaning. Civil Engineer, Dec. 1966.

2. Horne, Walter B.; Joyner, Upshur T.; and Leland, Trafford J. W.: Studies of the Retardation Force Developed on an Aircraft Tire Rolling in Slush or Water. NASA TN D-552, 1960.

3. Maltby, R. L.; Slatter, N. V.; and Illingworth, J. K. B.: Some Measurements of the Drag Due to Slush on an Ambassador Aircraft. Tech. Note No. Aero. 2968, Brit. R.A.E., Apr. 1964.

4. Clarke, W. W. H.: Correlation Between Instruments and Aircraft. Symposium on Winter & Wet Conditions, July 1965. (Sponsored by Inertia Switch Limited in collaboration with Liverpool Airport.)

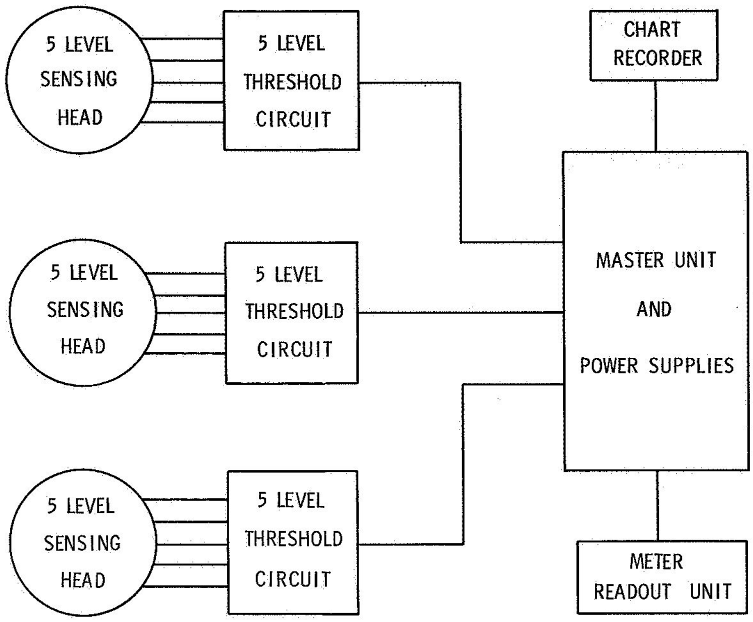


Figure 1.- Block schematic of a typical installation of the runway surface monitor.

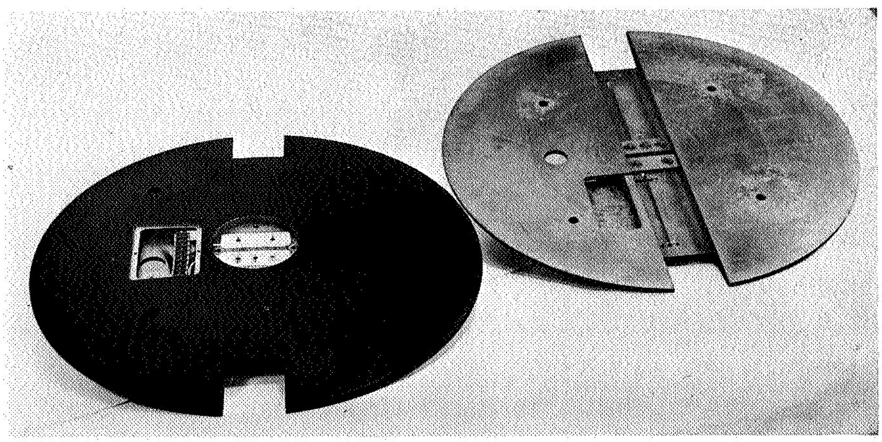


Figure 2(a).- Pointed metal probes in runway surface monitor.

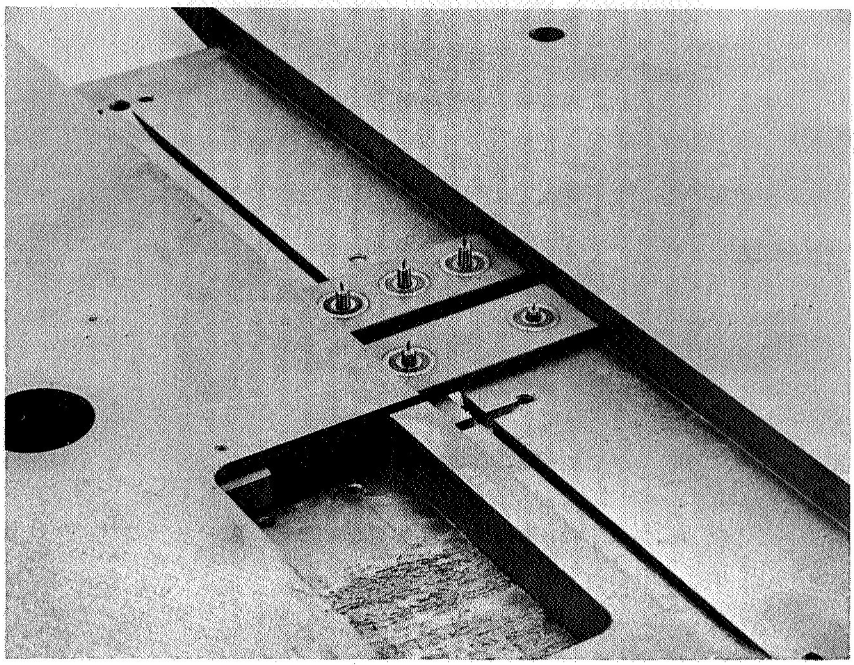


Figure 2(b).- Probes of different height in runway surface monitor.

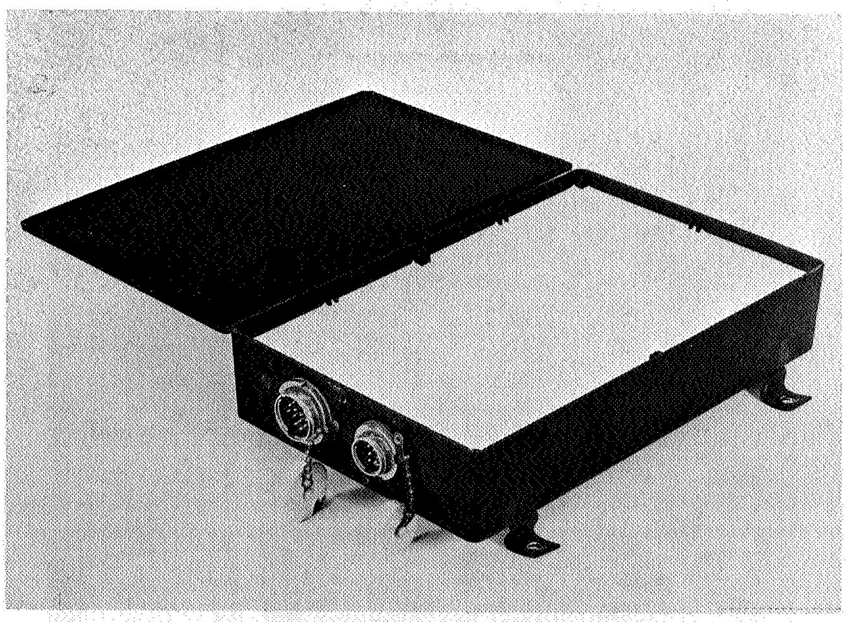


Figure 3.- Control box for runway surface monitor.

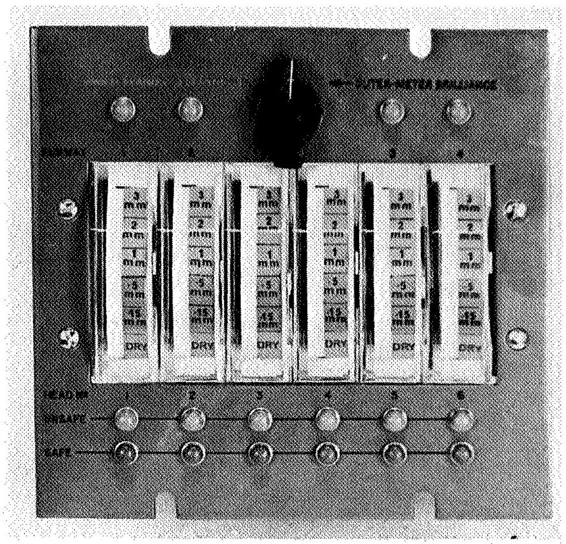


Figure 4.- Meter display.

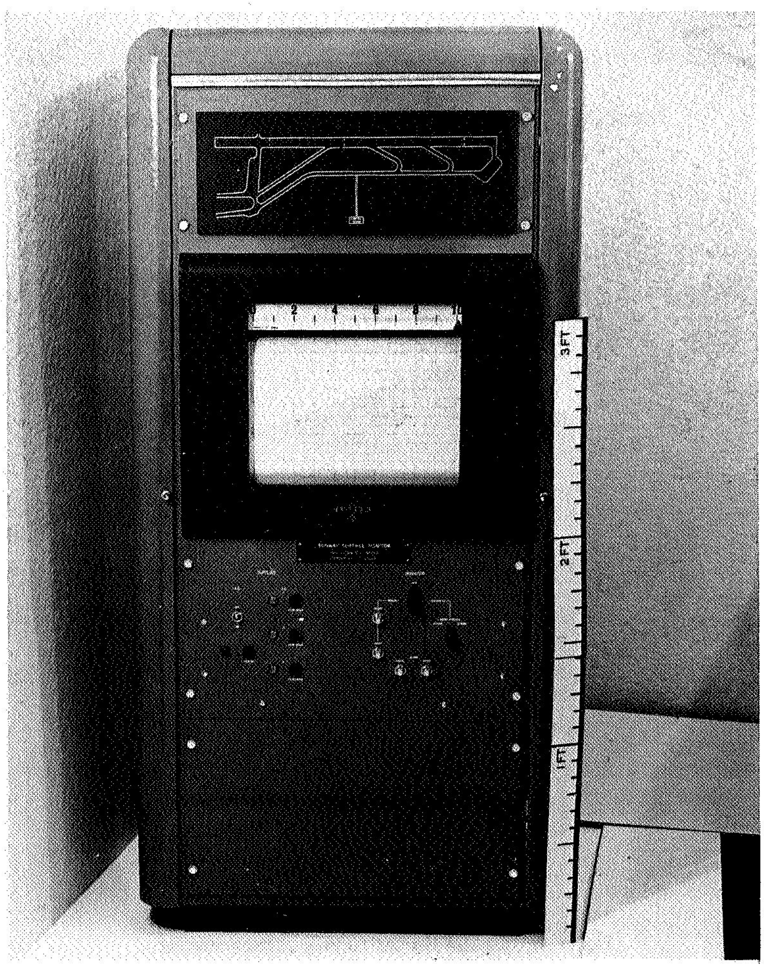


Figure 5.- Recording system.

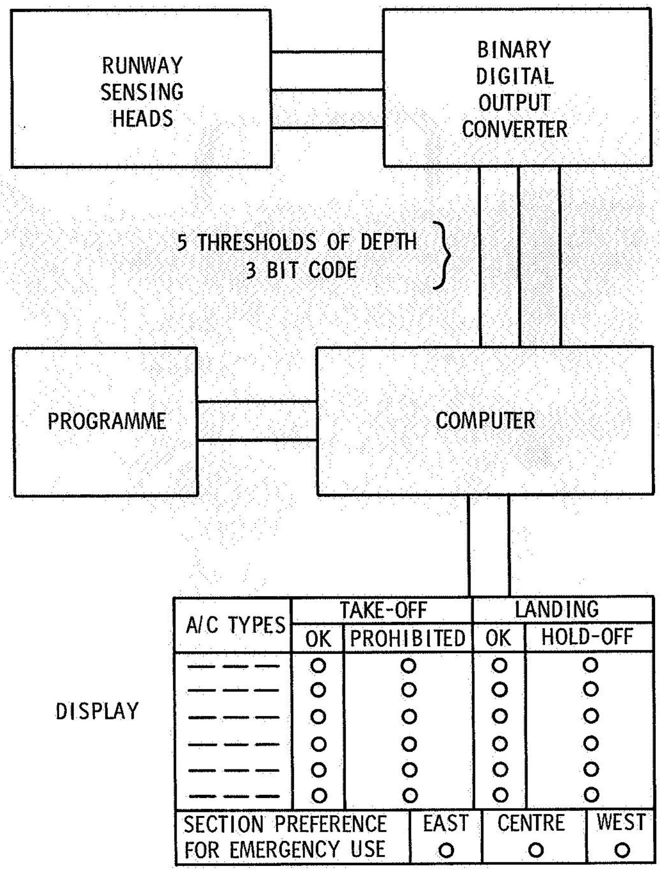


Figure 6.- A method of data presentation.

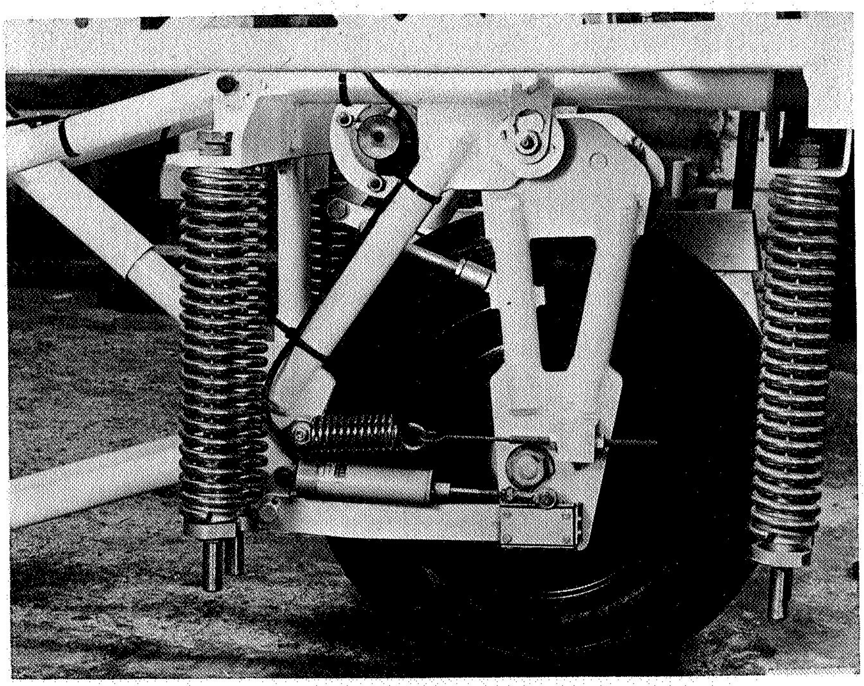


Figure 7.- Wheel in slush drag meter equipment.

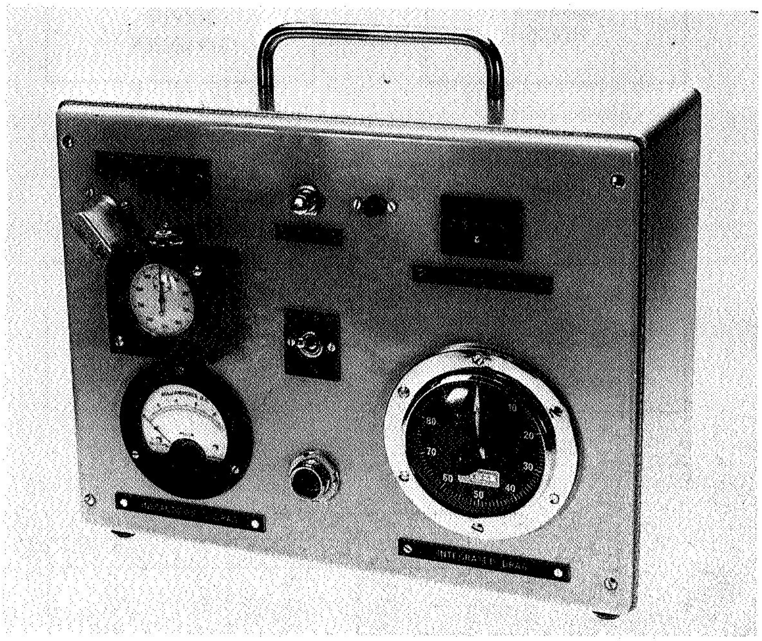


Figure 8.- Instrumentation box for slush drag meter.

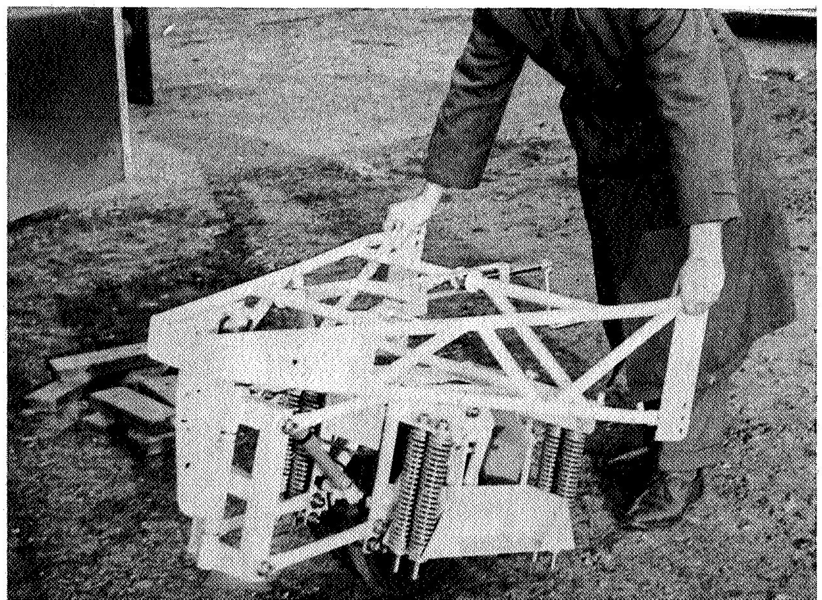
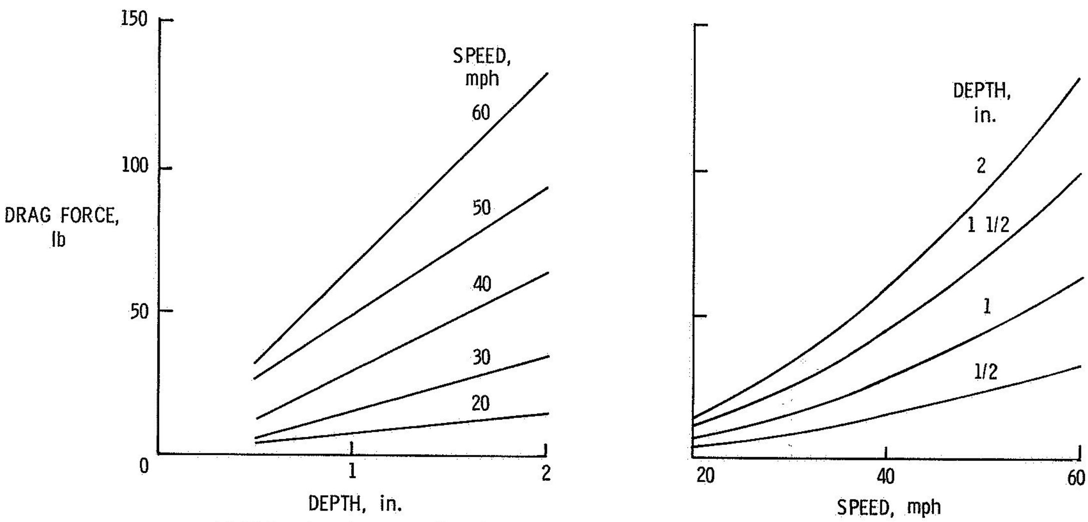


Figure 9.- Wheel in frame, with lead weights removed.

Figure 10.- Wheel in frame on Land Rover.



(a) Water drag as a function of depth at different speeds.

(b) Water drag as a function of speed at different depths.

Figure 11.- Calibration curves for slush drag meter.

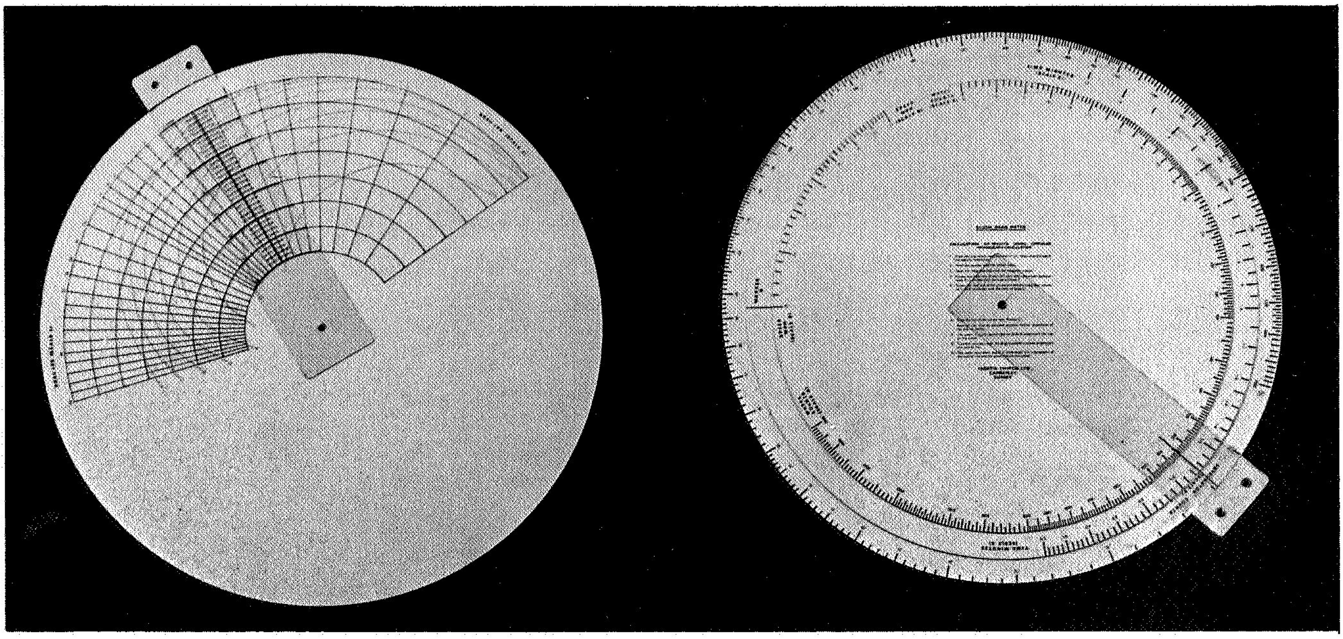


Figure 12.- Calculator for slush drag meter.

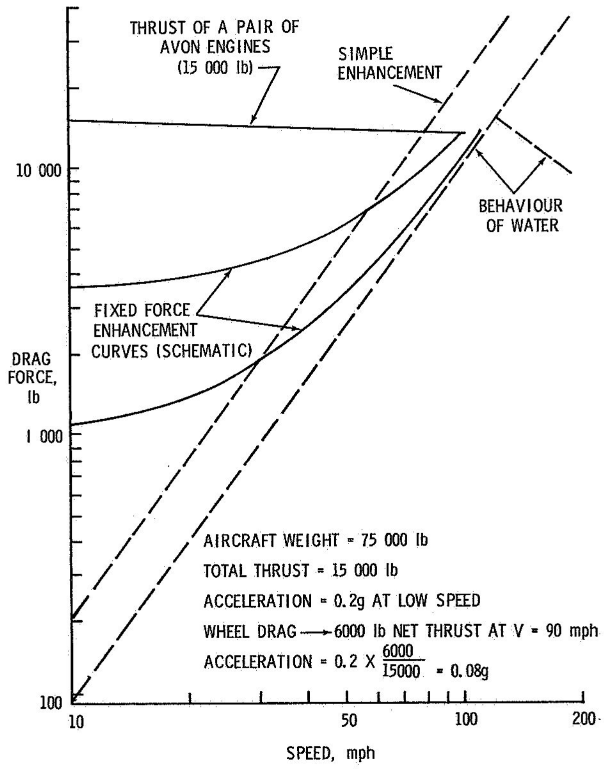


Figure 13.- Effects of drag force and enhancements on aircraft performance at take-off.

17. PAVEMENT SURFACE TREATMENTS AT AIRPORTS IN GREAT BRITAIN*

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SUMMARY

This paper describes the civil engineering work of the past 12 years, at airfields in the United Kingdom, to deal with the skidding and aquaplaning problems which first arose there in 1955 when the Royal Air Force began to operate high-performance aircraft from relatively short and smoothly finished runways without arrester-gear installations.

Until 1962, the works were carried out by the Directorate General of Works of the Air Ministry who up to that time had dealt with all airfields, civil and military, in the United Kingdom. In 1962, a new Ministry of Public Building and Works was formed by merging the separate Works Organisations of the existing Ministry of Works, the Royal Navy, the Army, and the Royal Air Force; since 1962, the works have been continued by Civil Engineers of the new Ministry, many of whom have been associated with the problems since 1955.

The possible treatments of existing concrete and asphalt surfaces to improve their skidding resistance, as well as the materials and methods which can be used in new construction, are described and illustrated. Detailed specifications for runway surface treatments which have been used extensively are included as appendices.

Although the paper is largely oriented to pavement-construction engineers' viewpoint, it also includes reference to Airport Operators' opinions obtained from the Civil Aviation Division of the Board of Trade and military pilots' opinions obtained from the Ministry of Defence (Air).

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*This paper includes data already published by F. R. Martin and R. F. A. Judge, Civil Engineer of the British Ministry of Public Building and Works and data supplied by the Board of Trade (Civil Aviation Division) and by the Ministry of Defence. It also makes reference to joint activities of the British Ministry of Public Building and Works, The Road Research Laboratory, the Board of Trade, and the Ministry of Technology on airfield pavement surface problems.

INTRODUCTION

In 1955, the Royal Air Force began to operate supersonic aircraft from runways in the United Kingdom which had been lengthened from 6000 feet to 7500 feet. The runways had maximum cross gradients (or cambers) of 1 in 100, many less steep, and the surfacing was of lightly broomed concrete (fig. 1) or hot rolled asphalt (fig. 2). The riding quality of the runways had been the most important single requirement allowed for in the design and construction of the pavements, and the full significance of surface texture needed to combat skidding had not been fully appreciated. It soon became apparent that an increase in surface friction was needed to prevent aircraft from running off the runway ends in wet weather conditions, in some cases because of what was undoubtedly aquaplaning although it was not recognized as such at that time. No arrester cables were provided on these runways because the aircraft were not provided with hooks.

In 1955, the equivalent U.S. Air Force aircraft with hooks operated from runways, in the United Kingdom, 9000 feet long. The runways had all been reshaped to give cambers or crossfalls of 1 in 67, all surfaces except for concrete runway ends were of Marshall asphalt (fig. 3), and arrester cables were provided for hook engagement. Problems of skidding and aquaplaning did not arise.

The first lessons learned, therefore, were that length of runway, rapid surface drainage from relatively steep surfaces, and reasonably rugous texture of the runway surface materials were all important, from an operator's point of view, if skidding and aquaplaning problems were to be avoided on runways where arrester cables were not provided.

For the Royal Air Force, in 1955, there were three possible civil engineering solutions: firstly to lengthen the runways, secondly to reshape them to improve the surface-water drainage characteristics, and thirdly to attempt to increase the wet-surface friction either by texturing the existing surfaces or by adding a new surface to them. Any one, or all, of these possible solutions could have been adopted, but lack of available land in a small island, allied to a natural reluctance to spend more large sums of money on recently developed runways, led to the third (cheapest) alternative being investigated first. A start was therefore made to look into the possibility of "roughening" both concrete and asphalt surfaces by mechanical means. Concurrently, other surface treatments for both existing and new runways were investigated. A history of all this work to date is given herein.

SKID RESISTANCE – MEASUREMENTS

Some measure of the skid resistance of a surfacing was needed, and a method developed by the United Kingdom Road Research Laboratory for road surface measurements was adopted initially for runway surface measurements. By this method, measurements are made with a lightweight trailer mounted at the rear of a Jaguar car. The trailer carries a test wheel, with a tire manufactured to aircraft standards, but 16 inches in diameter and 4.0 inches wide with pressure of 20 lb/sq in. The trailer is towed at speeds up to 100 mph over typical pavement sections which are maintained thoroughly wet.

The test wheel is braked, whilst being towed, by a disc brake controlled from the Jaguar. The brake action also clamps the trailer about the towing point to prevent trailer swing and car oscillation. A sprung load of about 250 pounds is carried on a separate frame. The suspension is damped by a hydraulic shock absorber. Braking forces with the wheel locked are measured by means of a torque arm, and a continuous record of braking force for differing speeds is obtained on a chart.

It was appreciated that measurements made with such a trailer would not necessarily reflect the effect of surface conditions on aircraft travelling at higher speeds with very different loads and tire pressures, and the Ministry of Aviation (now the Ministry of Technology) put into operation aircraft flight trials with specially instrumented aircraft. These trials, and laboratory tests in the Ministry of Public Building and Works Civil Engineering Laboratories at Cardington with aircraft tires (appendix 1), although not showing the same range of values, gave results which were broadly comparable with those obtained on the same surfaces with the light trailer. The trailer method of measuring braking force coefficients was therefore accepted as a reliable and economic way of indicating a good surface from a bad one as far as surface friction properties were concerned. Such measurements allied to an experienced Civil Engineer's engineering study of pavement surfaces and their drainage systems have therefore been used since 1956 in the United Kingdom to indicate whether runways are likely to encourage skidding and/or aquaplaning in wet weather conditions. Further flight tests are however being arranged by the Ministry of Technology's Royal Aeronautical Establishment at Farnborough, in conjunction with the Civil Engineers of the Ministry of Public Building and Works, on many different types of surfacing to attempt to correlate the surface effects on the light trailer with those on aircraft. The development of a heavy test vehicle has also been proposed. In the meantime the trailer measurements continue to be used as an indication of the type of surfaces demanded by aircraft. The success of this approach, as far as the Civil Engineer is concerned, is measured by full-scale "experiments" which have led to pilot opinions of the kind given in appendix 2. Appendix 3 summarises all the relevant tests made by the light trailer since 1954. Figure 4 shows braking force coefficient values for speeds up to 100 mph on typical runway surfaces in the United Kingdom.

Mechanical Roughening

At first a number of methods of mechanical roughening were tried on both concrete and asphalt surfaces. These included the use of –

(1) High-speed percussion rotary hammers (fig. 5) to texture the surfaces;

(2) Disc flails (fig. 6) to groove the surfaces; and

(3) Thermal shock (fig. 7) to roughen the surfaces (of concrete only) by spalling.

These experiments showed that –

(1) All mechanical treatments were difficult to control, since they depended on the differing skills of operators and on the varying quality and uniformity of the pavement surfaces;

(2) The rate of progress of surface treatment was very slow and consequently the costs were high;

(3) Grooving in the same direction as the aircraft landing direction did not improve the surface frictional value; and

(4) Only the disc flails for both concrete and asphalt surfaces seemed likely to produce acceptable economic finishes.

Following these tests, transverse grooving of asphalt surfaces with flails was carried out between 1956 and 1963 at all Royal Air Force Fighter Command Stations at which high-performance aircraft operated. In 1961 and again in 1964, on the Ministry of Public Building and Works advice, both the original asphalt and the newly surfaced runway at Manchester Airport were grooved in this way. By this method, a number of hard steel discs indent the surface and create grooves 1 inch apart, 1/8 inch wide by 1/16 to 1/8 inch deep. A specification for this form of treatment is given in appendix 4.

The first concrete runway to be grooved with flails was treated in 1960.

One big advantage of the flail method of grooving is that the machines work dry and can therefore operate without too much interference with normal flying activities, an important consideration, particularly at busy Civil Airports.

In 1960, saws were developed (figs. 8 and 9) for grooving both concrete and asphalt surfaces with grooves similar to those obtained with flails, but since they needed a large supply of water during their operation, they were considered to be less satisfactory than flails. One other drawback to their use is the tendency for the saws to ride over low areas and thereby produce a rather patchy treatment. In 1961, the asphalt main runway surface at Farnborough was grooved with saws.

In 1963, the diamond drum method of roughening a concrete surface by scoring was introduced. In 1966, on the Ministry of Public Building and Works advice, this method was used on the runway at Leeds Airport. This method now appears to be the most effective for treatment of a concrete surface to produce uniform results, and several other military runways have now been roughened in this way. A specification for the treatment is given in appendix 5. See also figures 10 and 11.

Acid etching of concrete has also been tried but has been abandoned because of the very variable and temporary improvement only that it produces.

Other Surface Treatments

Asphalt.- Between 1956 and 1958, "surface dressing" of asphalt surfaces with tar and bitumen binders (and their emulsions), with and without rubber, using pre-coated and uncoated chippings of various gradings, both hot and cold, were tried. From a large number of such trials, it soon became clear that surface dressing was the simplest, cheapest, and most effective method of improving the skid resistance of an existing asphalt surface. At first, surface dressing was not welcomed on many airfield pavements by the operators of aircraft. The small propeller type aircraft sustained propeller damage from flying chippings, and for jet aircraft taking off closely behind each other – which was often the case at Fighter Command airfields – loose chippings were not an acceptable hazard. Improved specifications and application did, however, result in the acceptance by the Royal Air Force of surface dressing at the main Bomber Command airfields in 1957, and at some Fighter airfields in 1963 (fig. 12). Appendices 6 and 7 reproduce the Ministry of Public Building and Works Specification for surface dressings with bitumen and tar, respectively, in which 1/8-inch single size, pre-coated rock crushings were applied hot. On the Ministry of Public Building and Works advice, both Birmingham (in 1960 and again in 1964) and Belfast (in 1960 and again in 1962) civil airports have adopted this specification for the treatment of their runways. Victors, Vulcans, Valiants, and Hunters have all operated successfully from surfaces laid to this specification.

Concrete.- A short length of a concrete runway surface was surface dressed in 1960 by using an epoxy-pitch binder and coarse grit. The results obtained were excellent (see appendix 3, Airfield Test No. 1) but the cost of such treatment in the United Kingdom is still too high to consider for large scale use. Other binders do not fix the dressing sufficiently well to concrete surfaces and are not therefore acceptable.

NEW SURFACINGS TO EXISTING AIRFIELD PAVEMENTS

In 1959, a number of trial areas of permeable bitumen macadam surfacings were laid over existing impervious asphalt surfaced pavements. The aims of these trials were –

(1) To find a surfacing material which was stable but which did not allow the buildup of a water film on it;

(2) To measure the skidding resistance of such surfacings; and

(3) To compare the weathering properties with those of normal asphalt surfacings.

Such a "friction course" surface is shown in figure 13, and Airfield Tests Nos. 15, 24, 29, 30, 32, 40, and 47 (appendix 3) give results of skidding tests carried out. These skidding tests showed the potential of such surfacings.

Because of the need to make observations of the effects of the weather on such open-textured surfacings, it was not until 1962, after three winters without any obvious deterioration in the surfacings, that a decision was taken to surface part of a military runway with the best of the surfacings tested.

Between 1962 and 1966, a minimum temperature of -8.2° C was recorded at this station and the number of days on which zero temperatures were recorded was 170 but the surfacing shows no sign of deterioration. Two other military runways have now been treated in the same way and an experimental, slightly coarser, material has been laid on the secondary runway at Farnborough for flight trials and for further weathering observations. A specification for this type of surfacing now known as a "friction course" is given in appendix 8. A surface to this specification has been laid by Liverpool Airport as the final surfacing of the new runway there.

Friction courses can only be recommended when they are to be laid over a new or an existing runway surface which is impervious to water and has good drainage. There must not only be free penetration of the surfacing by the water falling on it but the water must drain to an underlying impervious surface and flow quickly to the runway drainage channels. Any underlying surface on which water lies or which is pervious can only lead to a deterioration of the friction course itself.

NEW AIRFIELD PAVEMENTS

Concrete

Various methods of producing a skid resistant surface on new concrete pavements during their construction have been tried and include the transverse texturing with soft and bass brooms (Airfield Test Nos. 79 and 80) and wire combs (fig. 14, Airfield Test No. 56) as well as the mechanical application of carborundum grains and granite chippings (Airfield Test Nos. 95 and 96). The most satisfactory of these surfaces was that obtained with the wire comb, and the new concrete runway recently laid at Glasgow Airport had the following clause written into its specification: "The concrete surfacing of the runway (except for 300 feet at each end) is to be textured by drawing a purpose-made wire broom across the pavement at right angles to the side forms whilst the concrete is still soft enough to take an impression. The broom head is to be 24 inches in minimum width and wire filled with 32 gauge by 1/20 inch wire tapes."

Asphalt

The main specified requirements for a stable dense bituminous surfacing are –

(1) To resist deformation by aircraft at high loads with high tire pressures; and

(2) To be impermeable to protect the natural foundation on which the complete pavement is built.

These requirements are not normally conducive to a finished surface of high skid resistance. The large number of tests on many types of dense bituminous surfacings of all ages show the wide range of results and the difficulty of ensuring high skid resistance with the normal "blacktop" specifications (Airfield Test Nos. 18, 19, 27, 33, 38, 41, 43, 44, 46, 52, 53, 54, 55, 59, 64, 65, 75, 76, 78, 83, 84, 89, 93, 97, 101, 102, 103, 104, and 105).

The most carefully controlled dense asphalts have been found to have a range of braking force coefficients at 80 mph of 0.08 to 0.46.

Weather and wear continue to affect braking efficiency of all bituminous surfacings throughout their useful life. In general, it can be anticipated that their skid resistance improves with age.

Choice of binder is also known to influence the weathering quality of bituminous surfacings. For some roadwork in the United Kingdom, mixtures of tarpitch and bitumen have been used as binders to accelerate weathering and hence increase surface friction. Since, however, the weathering of road surfaces and airfield pavements proceeds at very different rates due to difference in trafficking patterns and intensity, the use of blended binders for airfield pavements is not considered to be a desirable proposition. Weathering of runways is normally fast enough with normal binders and the problem usually is in trying to extend the life of pavements so as to increase the period between resurfacings.

Methods of roughening new "blacktop" surfaces during construction have also been tried. Grooving hot asphalt with "banded" rollers failed because of the difficulty of controlling the finish. As a final operation, the creation of the grooves depended on the virtual reshaping of a fully compacted material and the process tended to create a surface of unacceptable riding quality. "Backblinding" of hot asphalt with the coarser fractions from the hopper of the asphalt spreading machine (Airfield Test No. 20) and the rolling in of pre-coated chippings of various sizes and at varying rates of spread were also tried (Airfield Test Nos. 13, 14, 16, 21, 22, 26, 31, and 35). Although the tests were promising, the chippings tended to become dislodged from the surface over large areas after only a few years and these methods of treatment are not now recommended. Similar methods used on roads in the United Kingdom where the passage of traffic is much more frequent have, of course, proved satisfactory.

From the results it is obviously not possible to ensure that dense asphalt or tarbound surfacings to any acceptable specification will have a specific resistance to skidding. The variables in the mixtures, even under the most carefully specified and controlled conditions, are too great. Variations in the shape of aggregate, both coarse and fine, affect surface friction values; but it is not considered economical, even if it were physically possible, to control friction by being too restrictive in the allowed aggregate type.

For new asphalt pavements, therefore, the solution would appear to be the laying of a "friction course" surfacing over the dense asphalt or to groove or to surface-dress the top surface.

EXTENT OF SURFACE TREATMENTS

For all special surface treatments, it has been the practice in the United Kingdom to exclude a length at each end of a runway up to the "start line" to –

(1) Reduce the effect of fuel and oil spillage in clogging a textured surface and making it difficult to clean;

(2) Avoid an increase of slipperiness when an aircraft moves from a taxiway to a runway where treatments depend on directional grooving;

(3) Avoid increased rate of destruction of surfaces by fuel spillage, heat, and jet blast; and

(4) Take advantage of the fact that at lower speeds the braking force coefficients of special treatments are no better than those for normal surfaces.

For runway ends, concrete remains the best surfacing material. It is not damaged by fuel spillage, heat, or jet blast and is easier to clean. Where concrete cannot be provided, then an asphalt surfacing with a normal finish sealed with tarpitch emulsion is an alternative. It resists damage by fuel and oil spillage and only the smallest aircraft with jet effluxes near the ground will destroy it by heat and blast. The surface can, however, become very slippery in wet weather.

Complaints about the slipperiness of markings, particularly in turning from taxiway to runway, have led to an enquiry into the real need for many of the markings at present called for at runway ends. Complaints about slipperiness generally arise because of the differences of texture of the surface of the markings with the surrounding pavement. It is not necessarily the lines themselves which are at fault. Calcined flints added to paint markings, or lines made with material incorporating calcined flints – such as hot applied thermoplastic material – give high friction values. On the other hand, glass beads which are frequently added to painted lines to improve visibility give low values.

THE FUTURE

Some aspects of the skidding problem still need to be examined. For example, it is not yet clear exactly how the longitudinal gradients of a runway allied with crossfalls or cambers affect skidding, but quite obviously the longer the path that surface water has to take to get to the drains the greater the problem will be.

The provision of a much more positive method of getting water away from runway surfaces, perhaps by providing a close pattern of slotted drains to take surface water immediately down below the surface rather than allowing it to flow over the surface at all, may be worthwhile.

Plastic or metallic grids of shallow depth might be fixed, perhaps in the centre width of the runway only, to provide a "dry landing lane" at all states of the weather, or an electrically heated strip might in some cases be an economical solution to create a dry landing area.

Whatever the long-term solution may be, the civil engineer has for the past 10 years, as this paper shows, tried and has had considerable success (see fig. 4) in keeping pace with the requirements of high-performance aircraft, particularly if the pilot opinions given in appendix 2 are accepted as the main measure of achievement rather than comprehensive scientific quantitative assessments with aircraft, which in many cases are yet to come. This is in keeping with the tradition that has persisted quite rightly from the start of aviation history that the aircraft designers have been able to design aircraft which have largely been the undisputed dictators of runway lengths, surface textures, etc. It could be argued, perhaps, that a time might come when the civil engineer should say just what he can provide economically and let the aircraft designers start from there. It may be it is just not an acceptable idea that the planned performance of an aircraft in the air should be restricted in any way by limiting the facilities for it on the ground, but aircraft safety – particularly for civil aircraft – might at some time dictate otherwise.

CONCLUDING REMARKS ON BEST PRACTICES FOR AIRFIELD PAVEMENT SURFACINGS

The best techniques* that have so far been evolved by civil engineers in practice in the United Kingdom for improving the surface finish of runways so that the twin hazards

*Now all included in the British Ministry of Public Building and Works (M.P.B.W.) Airfield Specifications.

of skidding and aquaplaning may be reduced are summarised in this section. The methods can be recommended with the confidence born of pilot opinion rather than from measurements of fully correlated ground vehicle/aircraft performance, provided that a full engineering appreciation of existing pavements is made at each site before any particular method is adopted and that the selected method is suitable for the types of aircraft operating.

1. Existing Asphalt (figs. 2 and 3)

   (a) Surface dressing (fig. 12)

   (i) Operational considerations

   Surface dressing is not recommended where the frequency of air movements is heavy, where propellers or jet engines are close to the ground, or where aircraft take off side by side or follow closely behind each other either in landing or take-off. There is no limit to the size of aircraft, providing these restrictions do not apply. Aircraft with twin-tandem undercarriages at tire pressure 280 lb/sq in. and all-up weights exceeding 200,000 pounds have been operating regularly for a number of years from runways which have been deliberately surface dressed to improve friction. There is no evidence of an increase in tire wear.

   (ii) Consideration of existing pavement

   The overall shape and profile of the existing runway is not as important as it is with other treatments and, where a number of transverse and longitudinal slope changes occur in the runway length, surface dressing is probably the only suitable method other than expensive reshaping. Nevertheless, in spite of the fact that the overall shape need not be ideal, for a successful application of this treatment, the compacting equipment must be capable of following the minor surface irregularities to ensure a uniform adhesion of the chippings. Where this condition cannot be assured, a new asphalt wearing course may be necessary before applying the surface dressing.

   (iii) Effectiveness of treatment

   A satisfactory surface dressing will initially raise the braking force coefficient of the surface to a high value which thereafter, depending on the intensity of trafficking, will slowly decrease. Normally, an effective life of up to 5 years can be expected.

   (iv) Runway ends

   Runway ends used for take-off should not be treated. Aircraft scuff in turning, and both fuel spillage and heat will soften the binder, and blast will lead to loose chippings.

(v) Specification

See appendix 6 or 7.

(vi) Cost in United Kingdom

1s. 3d. per sq yd.

(b) Grooving (fig. 15)

(i) Operational considerations

There do not appear to be any operational objections to the grooving of existing asphalt surfaces. In the United Kingdom, high-performance aircraft with single main wheels at tire pressure 300 lb/sq in. and all-up weight 40,000 pounds have been successfully operating from grooved asphalt surfaces for over 10 years. Undoubtedly there is no limit within the foreseeable future to the aircraft size, loading, or type for which such surfaces will be satisfactory. There is no evidence of a greater rate of tire wear.

(ii) Consideration of existing pavement

The engineer will have to be satisfied that the existing asphalt wearing course is a dense well compacted layer. If the surface exhibits fretting or where large particle fractions of coarse aggregate are exposed on the surface itself, then other methods will need to be considered, or resurfacing will have to be undertaken before grooving. Apart from the condition of the surface itself, the ratio between crossfalls and longitudinal slopes becomes important. More work on this aspect of the problem is required, though it is clear that if the longitudinal slopes are such that the water runoff is directed along the runway instead of flowing quickly to the runway side drains, then a condition could arise when the grooves would fill with free water, fail to drain quickly, and possibly encourage aquaplaning.

(iii) Effectiveness of treatment

Transverse grooving will always result in a measurable increase of the braking force coefficient though the extent of the improvement will be related to the quality of the existing surface. This improvement will be maintained throughout the life of the asphalt wearing course. Observations since 1956 confirm that grooving has not resulted in an increase in the rate of deterioration of the asphalt. In the United Kingdom there have been no reports of grooves becoming clogged with dirt, industrial waste, or other contaminants.

(iv) Runway ends

In the United Kingdom, a length at each end of the runway has been left ungrooved to make it easier to wash down and clean off fuel and oil droppings. Moreover, it would seem that engine blast could be more damaging on a grooved than on an untextured surface. It is also considered that the control of an aircraft moving from the taxiway onto the runway end could become tricky, as test measurements indicate that the improvement in the braking force coefficient is dependent on trafficking across the grooves and that there is a loss of friction in tests carried out along the grooves.

(v) Specification

See appendix 4.

(vi) Cost in United Kingdom

3s. 6d. per sq yd.

2. Existing Concrete (fig. 1)

Scoring (fig. 11)

(i) Operational considerations

There do not appear to be any operational objections to the scoring of existing concrete surfaces, and this method of treatment seems to be suitable for all types of aircraft.

(ii) Consideration of existing pavement

It will be understood that it would be difficult uniformly to score concrete surfaces which are "rough." Pavements with damaged or poorly formed joints, or on which laitance has led to extensive spalling of the surface, would be equally difficult to score. If the existing surface is reasonably free of these defects, there are no other engineering limitations to scoring.

(iii) Effectiveness of treatment

Transverse scoring of concrete has been adopted in preference to the earlier grooving of existing concrete surfaces, which was similar to the method specified previously for asphalt surfaces. The tests show this treatment to give more uniform results than the grooved concrete surfaces. In all cases, there is a considerable improvement in the braking efficiency of pavements initially textured at the time of construction, with belts, burlap, or soft brooms. The useful life of the treatment will depend on the frequency of trafficking but it is expected that at the majority of airfields the scoring will remain effective for the life of the concrete, which it in no way affects.

(iv) Runway ends

As when grooving asphalt so also when scoring concrete, the United Kingdom does not carry this treatment over the runway ends. Similar reasons apply. In addition, it is thought that in the case of scoring, a possibility of an increase in tire wear in turning cannot be totally discounted.

(v) Specification

See appendix 5.

(vi) Cost in United Kingdom

5s. 0d. per sq yd.

3. New Pavements

All new runways should be designed to a uniform transverse profile with the maximum crossfall permitted by the International Civil Aviation Organization (ICAO), and the longitudinal profiles should be as nearly level as possible. A cambered transverse section from a centre crown is preferable but if for any reason this cannot be provided then the single runway crossfall should be carefully related to prevailing wet winds to ensure that surface water drainage is not impeded by the wind blowing up the transverse gradient. (In the case of single crossfalls, it may be necessary at certain sites to provide cut-off drainage along the higher edge to prevent water from the shoulder strip spilling over the runway surface.) If these ideal shape criteria are met, aquaplaning incidents should be reduced; but departures from these ideals will result in an increase of aquaplaning probability no matter how good the braking force coefficient of the surface itself may be. Aside from other operational needs affecting this aspect, it is highly desirable that maximum crossfalls permitted by ICAO should be increased. Similarly, there is a need to establish a practical ratio between crossfall and longitudinal gradients. Meanwhile, it is suggested as a guide for new runways that the longitudinal slope at any point along the runway should not exceed 1/3 the crossfall at that point; thus, a 1-66 crossfall should not have a longitudinal slope sharper than 1-200. These comments hold true for major reconstruction projects; in addition, when old runways become due for resurfacing, the opportunity should be taken wherever possible to improve the levels to assist surface drainage. Every improvement in shape, no matter how small, helps.

It is also known that changes of surfacing materials and of surface textures at intervals along the runway length cause disconcertingly different responses in the aircraft during its ground run, particularly during braking, and it is therefore important to maintain a uniform surface material and texture between runway ends. This should be taken into account when new extensions are planned. If different materials are proposed for the extensions, it may be necessary to consider resurfacing the existing runway at the same time with a similar material, though obviously the opportunity to provide a texture to an improved standard on the new extension should not be missed. Changes of surfacing at runway intersections should be avoided.

(a) New concrete (fig. 14)

(i) Operational considerations

There appear to be no operational objections to the current United Kingdom method of texturing new concrete runways during construction with wire brooms.

(ii) Effectiveness of treatment

A comparison of measurement on a new concrete runway constructed in 1966, which was the first to be textured to the current specification, with measurements on previous runways textured to earlier specifications shows the marked improvement achieved. The life of the treatment will depend on the intensity of trafficking, but it is anticipated that at most airfields it will remain effective throughout the life of the concrete surface.

(iii) Runway ends

The current specification excludes the coarse texturing of runway ends. It is considered that the coarse texture which this specification provides if applied in the take-off areas could aggravate the difficulties of removing fuel and oil deposits; and if these deposits could not be removed, slippery areas could develope at these points.

(iv) Specification

Runways textured with soft brooms and with bass brooms have been laid and tested over the years, but the current specification calls for a wire brooming. The contractor is required to texture trial areas for approval of the finished surface, and is thereafter "to reproduce a uniform texture throughout the runway length." In order to assist the engineer in his choice of the trial areas, a sand-patch test which measures the area of spread of a carefully defined quantity and grading of fine sand over the surface as a guide to texture depth has been devised.

(v) Specification

See appendix 9.

(vi) Cost in United Kingdom

6d. per sq yd.

(b) New asphalt – grooving, surface dressing, or "friction course"

(i) Operational considerations

Where aircraft with high tire pressures operate, it is essential that the asphalt surfacing on the pavements should be of high stability. This can only be achieved with an asphalt design mixture of high density, compacted in the field virtually to refusal, so that thereafter air trafficking will not deform the surfacing and cause irregularities in the surface which might result in a bumpy ride and ponding water. These requirements are not conducive to a finished surface of high skid resistance, and after a large number of tests on asphalt surfacing it became apparent that it is not possible to ensure surfacing to any acceptable stability which will at the same time have a specific resistance to skidding. Trials were carried out in an attempt to improve the braking force coefficient of the asphalt during laying, including the rolling in of chippings, and grooving with banded rollers, but so far these methods have not been successful.

(ii) Surface treatments

It has been the normal practice in the United Kingdom to specify a high-stability asphalt and to provide a high skid resistance after completing the usual laying and compacting techniques by treating the new asphalt surfacing with a surface dressing to the specification already given, or by grooving it as previously described.

(c) Friction courses (new asphalt) (fig. 13)

(i) Introduction

As an alternative to the surface dressing or grooving of new asphalt wearing courses, a new venture was undertaken in 1962, when following a series of trials laid some years earlier, a permeable bitumen-macadam surfacing was laid as a special additional course over a normal high-stability asphalt wearing course, after reshaping of the runway. This so-called "friction course" was deliberately designed not only to improve the skid resistance but to reduce aquaplaning incidence by providing a highly porous material to ensure a quick getaway of water from the pavement surface directly to the underlying impervious asphalt.

(ii) Limitations of friction course

Friction courses of this kind should only be laid on new runways of good shape, or on reshaped runways approaching the criteria outlined above for new runways. They must always be over densely graded impervious asphalt wearing courses of high stability. Both of these requirements are necessary to ensure a quick flow of the water through the friction course over the impervious asphalt to the runway drainage channels.

(iii) Effectiveness of treatment

It is still too soon to give an accurate assessment of the effective life of the friction course. The course laid in 1962 shows no sign of deterioration so far.

(iv) Runway ends

The friction course is not recommended at the runway ends. Oil and fuel droppings would clogg the interstices and soften the bitumen binder, and jet engine heat would soften the material which blast would then erode.

Erosion would tend to be deeper than on a normal dense asphalt. Scuffing might occur in turning movements during the first few weeks after laying.

(v) Specification

See appendix 8.

(vi) Cost in United Kingdom

4s. 6d. per sq yd.

APPENDIX 1

M.P.B.W. CIVIL ENGINEERING LABORATORY TESTING RIG FOR PAVEMENT ROUGHNESS TESTS

The Cardington static friction test rig consists of a "Lightning" aircraft wheel mounted in a frame which is loaded to give a known total weight upon the tire, inflated to 300 lb/sq in. A sample of pavement is fixed below the wheel in a trolley which is carried on rollers and is free to move horizontally against a proving ring. A shower of water plays upon the sample throughout the test. The wheel frame is suspended so that the tire is just clear of the pavement, and the wheel is rotated by an electric motor. The current is cut off, and when the wheel has slowed to a predetermined speed it is dropped upon the pavement sample. The horizontal thrust upon the sample caused by friction between it and the tire is measured by the distortion of the proving ring.

APPENDIX 2

PILOT OPINION

Civil Airports

The Aerodromes Operations Policy and Flight Safety Branches of the Board of Trade (Civil Aviation Division) maintain that high-friction well-drained runways provide the primary method of preventing wet-skidding accidents and that there is already sufficient known for this approach to be implemented on a wide scale. They have compiled brief consolidated reports from a number of United Kingdom civil airports of their experience with the various types of texture and these reports are given below: All these airports are operated by Municipalities but are regulated by a national system of licensing and advice by the Board of Trade on matters considered at the Conference. For example, licensed airports have been advised that –

(a) Plans for new runways or resurfacing should ensure that good drainage and friction qualities are provided; and

(b) Known poor existing surfaces should be rectified urgently, or, in borderline cases, improved when the runway is due for major maintenance.

In order to take a first step in implementing this policy, the Board of Trade and Ministry of Public Building and Works have in hand a programme of runway surveys designed to identify the poor or below average surfaces, to indicate where remedial action is required to the authorities concerned, and to classify runways vis-à-vis each other in terms of their wet friction characteristics.

Table 1 summarises relevant statements from the following airports on the various types of runway surface that exists:

<u>Birmingham</u> – Asphalt; grooved $\frac{1}{8}''$ wide $\frac{1}{8}''$ deep at 1" centres; extension only, 1967

<u>Glasgow</u> – New reinforced concrete runway; crowned to 1 in 67; wire combed; 1966

<u>Leeds/Bradford</u> – Concrete; some scored and some wire broomed; 1965 and 1966

<u>Liverpool</u> – New runway; crowned 1 in 67 plus "friction course" surfacing; 1965

<u>Manchester</u> – Asphalt; grooved $\frac{1}{8}''$ wide $\frac{1}{8}''$ deep at 1" centres; 1961 and 1965

<u>Southend</u> – Reshaping to 1 in 67 plus macadam "friction course"; 1967

APPENDIX 2

TABLE I

Airport	Reason for treatment	Effects on –		Operators' views	
		Drainage	Maintenance	Wet braking	Tire wear
Birmingham	Original surface of old asphalt extension when tested by light trailer gave low braking force coefficients: At 100 mph: Existing runway . . . 0.41 Extension: Before . . . . 0.12 After 0.61		With regard to mud accumulation and deposits, no change More difficult to clear ice No evidence of more rapid deterioration of asphalt	No adverse comment	No adverse comment
Glasgow	Complete resurfacing and extension for strengthening on change of role Braking force coefficient: At 80 mph assessed at 0.6	Dries quickly after rain	No visible deterioration	Satisfactory Glasgow operators are completely "sold" on this type of treatment	No adverse comment
Leeds/Bradford	Original lightly broomed concrete surface giving rise to pilot complaints of skidding etc. Braking force coefficient: At 80 mph: Original concrete . . . 0.16 Wire brushed concrete . . . . . . 0.41 Scored concrete 0.54	Improved Water stays in scored surface and leaves top surface dry	No evidence of any abnormal wear or deterioration	Original complaints from operators stopped after treatment Appears far superior to lightly broomed runways Crosswind limits have not changed but wet handling has improved	Tire wear has not increased
Liverpool	New runway Braking force coefficient: At 80 mph 0.51		Virtually no loosening of aggregate In $2\frac{1}{2}$ years, vacuum cleaned only once. No frost damage	Runway gives a very smooth ride Crosswind operations are not difficult Runway has been described as "the best in Europe" A.D.C. 8 Pilot landing in wet, gusty weather said that he could have turned off the runway after 4600 feet	Seems to be no abnormal effect on tire wear
Manchester	Original Marshall asphalt produced an extremely slippery surface when wet Braking force coefficient: At 80 mph: Original surface . . . 0.22 Grooved surface assessed 0.5	Improved, probably because of the grooves forming minor drainage channels	Not sufficient evidence yet to say what effect grooving has on the life of the asphalt Generally speaking, the runway keeps very clean	Before grooving, some operators reduced crosswind limitations by about 5 knots for the wet runway whilst others inserted warning notes in their manuals; these limitations were removed after grooving had been successfully proved; any doubts about crosswind operation were removed A slight increase in tire noise has been mentioned	No real evidence on which to base comment
Southend	Resurfacing due Braking force coefficient: At 80 mph: Original surface . . . 0.1(?) New surface . . . . . 0.41 At 105 mph: New surface 0.51	Improved due to increase in surface gradients	No visible deterioration to date No sweeping difficulties but brush wear slightly more	No complaints even during heavy rain	No adverse comments

APPENDIX 2

Military Airfields

Pilot opinions on three runway surfaces are quoted below:

1. Original surfaces – soft broomed smooth concrete.

   New surfaces – wire broomed new concrete in reshaped areas; scored texturing of old concrete.

"A very great improvement. A by-product is the new "white" surface caused by the scoring process, making the airfield much more easily seen from the air in low visibility."

"Tire wear. Some evidence of increased wear but some may be attributed to higher crosswinds experienced." (See below.)

"Drainage characteristics of runway, much better."

"The braking characteristics improved on runway when dry, and very much improved on runway when wet. Many of the flying restrictions which were imposed during the use of the original runway have been lifted. Aircraft are now allowed to land with a crosswind of 25 knots. (Previously, a limit was imposed of 20 knots for a dry runway decreasing with the extent of the surface wetness. Stream landings were not permitted when the crosswind component exceeded 10 knots on the dry runway and never when the runway was wet). Unless the runway is now "flooded" by a very recent downpour, it seems to make little difference to normal braking distances whether the runway is wet or dry. The restriction on stream landings have been lifted altogether."

"The new surfaces are extremely "confidence building," especially in crosswind conditions. The tendency to feel that one has to land in the first few feet of the runway (when it is wet for example), and therefore risk undershooting, appears to have been eliminated."

2. Orginal surfaces – smooth asphalt.

   New surfaces – reshaped with asphalt plus "friction course."

"It has a far more effective braking surface than the other runways."

"Water drains off the surface quickly and it needs prolonged heavy rain before any surface water is seen."

"Dry crosswind limits can be safely used even when the surface is wet."

"Frost and ice do not form as quickly on the surface as they do on the other asphalt and concrete surfaces at the [Air Force Fighter Command] Station."

"Tire wear has not significantly increased with the introduction of a 'friction course.' In fact, if anything, tire consumption has fallen slightly due, in part, to the reduced braking required."

"Because of the excellent braking surface presented by the 'friction course,' it has been possible to treat this runway as a 'dry surface' in all weathers."

3. Original surfaces – smooth asphalt.

New surfaces – grooved asphalt.

"Fighter Command have gained active experience on the effect of grooving on wet runways and are very satisfied with the results."

APPENDIX 3

SUMMARY OF SKIDDING TESTS ON AIRFIELD PAVEMENTS

Airfield Test Number	Date of surface treatment (or laying)	Date of skidding tests	TEXTURE OF TEST AREA AT TIME OF TESTING (with Test Nos. before and after treatment)	VALUE OF BRAKING FORCE COEFFICIENT (Light trailer 320lb/20lb. sq. in.) taken from smooth curves drawn through plotted points at the following speeds (miles per hour) (Figures in brackets indicate results before special surface treatment)			M.P.B.W./C.E. Laboratory Friction Test Rig, (16,000 lb./ 300 lb. sq. in.) Mean co-ef. at 75/150 m.p.h.	"Swift" Aircraft Flight Tests, (16,000 - 18,000 lb./ 300/320 lb. sq. in.) Mean co-ef. at 120 Knots
				20	50	80		
1	1960	1960	Concrete treated with epoxy-pitch and 1/8 in. porphyry chippings (Test 68).	.84 (.74)	.68 (.38)	.63 (.25)		
2	1958	1958	Asphalt treated with tar and 1/8 in. pre-coated basalt chippings (Test 105).	.62 (.34)	.61 (.11)	.61 (.06)		
3	1959	1959	Acid etching of concrete finished with purpose-made wire comb (Test 56).	(.63)	(.46)	.58 (.28)		
4	1960	1960	Asphalt grooved by flails; 1/8 in. grooves one inch apart (Test 93).	.73 (.73)	.60 (.28)	.57 (.15)		
5	1963	1963	Eighteen year old concrete scored transversely (Test 73).	.65 (.57)	.57 (.33)	.56 (.23)		
6	1958	1958	Asphalt treated with outback bitumen and 1/8 in. uncoated chippings.	.60	.55	.55		
7	1960	1960	Marshall asphalt grooved by flails; 1/8 in. grooves one inch apart (Test 89).	.66 (.58)	.56 (.37)	.54 (.16)	0.130	
8	1960	1960	Marshall asphalt grooved by saws; 1/8 in. grooves one inch apart (Test 89).	.65 (.58)	.53 (.37)	.53 (.16)	0.124	
9	1956	1956	Asphalt grooved by flails; 1/8 in. grooves one inch apart (Test 64).	.72 (.65)	.58 (.44)	.52 (.26)		
10	1959	1959	Open-graded macadam friction course; 3/4 in. quartzite aggregate (Test 53).	.63 (.57)	.54 (.42)	.52 (.31)	0.136	
11	1960	1960	Marshall asphalt grooved by saws; 1/8 in. grooves one inch apart (Test 103).	.61 (.70)	.53 (.23)	.51 (.08)		
12	1959	1959	Open-graded macadam friction course; 3/8 in. hornfels aggregate (Test 53).	.59 (.57)	.51 (.42)	.50 (.31)	0.140	
13	1958	1958	Asphalt roughened with 3/8 in. coated chippings at 200 sq. yd./ton (Test 102).	.64 (.57)	.54 (.28)	.50 (.10)		
14	1958	1958	Asphalt roughened with 3/4 in. coated chippings at 150 sq. yd./ton (Test 102).	.62 (.57)	.53 (.28)	.50 (.10)		
15	1962	1963	Open-graded macadam friction course; 3/8 in. hornfels aggregate	.55	.52	.50		
16	1958	1958	Asphalt roughened with 3/8 in. coated chippings at 225 sq. yd./ton (Test 102).	.66 (.57)	.54 (.28)	.49 (.10)		
17	1961	1961	Asphalt grooved by saws; 1/8 in. grooves one inch apart (Test 93).	.75 (.73)	.51 (.28)	.49 (.15)		
18	1957	1958	Asphalt with 50% limestone aggregate	.53	.53	.48		
19	1952	1956	Four year old limestone asphalt	.68	.56	.48		
20	1958	1958	Marshall asphalt with backblinding	.82	.53	.48		

APPENDIX 3

Airfield Test Number	Date of surface treatment (or laying)	Date of skidding tests	TEXTURE OF TEST AREA AT TIME OF TESTING (with Test Nos. before and after treatment)	VALUE OF BRAKING FORCE CO-EFFICIENT (Light trailer 320lb/20lb. sq. in.) taken from smooth curves drawn through plotted points at the following speeds (miles per hour) (Figures in brackets indicate results before special surface treatment)			M.P.B.W./C.E. Laboratory Friction Test Rig, (16,000 lb./300 lb. sq. in.) Mean co-ef. at 75/150 m.p.h.	"Swift" Aircraft Flight Tests, (16,000 - 18,000 lb./300/320 lb. sq. in.) Mean co-ef. at 120 Knots
				20	50	80		
21	1958	1958	Asphalt roughened with $\frac{3}{8}$ in. coated chippings at 250 sq. yd./ton (Test 102).	.64 (.57)	.53 (.28)	.48 (.10)		
22	1958	1958	Asphalt roughened with $\frac{1}{2}$ in. coated chippings at 175 sq. yd./ton (Test 102).	.61 (.57)	.51 (.28)	.48 (.10)		
23	1958	1958	Asphalt roughened with $\frac{1}{2}$ in. coated chippings at 150 sq. yd./ton (Test 102).	.59 (.57)	.52 (.28)	.48 (.10)		
24	1959	1959	Open-graded macadam friction course; $\frac{3}{4}$ in. quartzite aggregate (Test 53).	.65 (.57)	.52 (.42)	.48 (.31)	0.136	
25	1950	1956	Six year old limestone asphalt.	.66	.53	.47		
26	1958	1958	Asphalt roughened with $\frac{3}{4}$ in. coated chippings at 120 sq. yd./ton (Test 102).	.60 (.57)	.51 (.28)	.47 (.10)		
27	1959	1959	Marshall asphalt with basalt aggregate.	.77	.61	.46		
28	1959	1959	Acid etching of concrete finished with bass broom.	.69 (.62)	.53 (.28)	.46 (.19)		
29	1959	1959	Open-graded macadam friction course; $\frac{3}{8}$ in. quartzite aggregate (Test 53).	.52 (.57)	.47 (.42)	.46 (.31)	0.139	
30	1959	1959	Open-graded macadam friction course; $\frac{3}{8}$ in. hornfels aggregate (Test 53).	.53 (.57)	.47 (.42)	.46 (.31)	0.140	
31	1958	1958	Asphalt roughened with $\frac{1}{2}$ in. coated chippings at 200 sq. yd./ton (Test 102).	.60 (.57)	.50 (.28)	.46 (.10)		
32	1959	1959	Open-graded macadam friction course; $\frac{3}{8}$ in. quartzite aggregate (Test 53).	.51 (.57)	.47 (.42)	.45 (.31)	0.139	
33	1957	1958	Asphalt with 50% limestone aggregate.	.65	.53	.44		
34	1956	1958	Asphalt with 1 in. coated chippings rolled in.	.60	.47	.44		
35	1958	1958	Asphalt roughened with $\frac{3}{4}$ in. coated chippings at 180 sq. yd./ton (Test 102).	.64 (.57)	.49 (.28)	.44 (.10)		
36	1959	1959	Acid etching of concrete finished with soft broom (Test 80).	(.62)	(.28)	.44 (.19)		
37	1959	1959	Acid etching of concrete finished with granite chippings (Test 96).	(.63)	(.28)	.44 (.14)		
38	1950	1954	Four year asphalt with granite aggregate.	.74	.59	.43		
39	1957	1957	Asphalt grooved by flails; $\frac{1}{8}$ in. grooves one inch apart (Test 76).	.70 (.59)	.49 (.33)	.43 (.21)	0.148	0.165
40	1959	1959	Open-graded macadam friction course; $\frac{3}{4}$ in. hornfels aggregate (Test 53).	.57 (.57)	.43 (.42)	.42 (.31)	0.139	
41	1955	1957	Asphalt with 55% limestone aggregate.	.80	.57	.40		
42	1959	1959	Dense tar surfacing.	.83	.55	.40		

APPENDIX 3

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				20	50	80		
43	1958	1958	Marshall asphalt with limestone aggregate.	.69	.52	.39		0.115
44	1963	1963	Marshall asphalt.	.76	.52	.38		
45	1956	1958	Asphalt with ½ in. coated chippings rolled in.	.65	.44	.38		0.112
46	1955	1961	Five year old asphalt with 55% limestone aggregate.	.85	.55	.37		
47	1959	1959	Open-graded macadam friction course; ¾ in. hornfels aggregate (Test 53).	.61 (.57)	.42 (.42)	.35 (.31)	0.139	
48	1958	1958	Asphalt treated with tar and ⅛ in. pre-coated chippings.	.68	.43	.34		
49		1959	Asphalt with 1 in. chippings rolled in.	.70	.41	.34		
50	1959	1959	Acid etching of concrete finished with carborundum grains (Test 95).	(.61)	(.31)	.34 (.15)		
51	1958	1958	Asphalt treated with cutback bitumen and ⅛ in. pre-coated chippings (Test 101).	.69 (.63)	.45 (.30)	.33 (.12)		
52	1956	1959	Asphalt with granite aggregate (Tests 74 and 92).	.75	.49	.33		
53	1959	1959	Marshall asphalt with basalt aggregate (Tests 10, 12, 24, 30, 32, 40 and 47).	.57	.42	.31		
54	1957	1958	Marshall asphalt.	.62	.42	.30		
55	1961	1963	Marshall asphalt with gritstone aggregate.	.69	.45	.29	0.096	
56	1958	1958	Concrete finished with purpose-made wire comb (Test 3).	.63	.46	.28		
57	1956	1957	Reinforced concrete finished with broom (Test 98).	.74	.45	.28		0.09
58		1959	Concrete finished with broom.	.62	.37	.28		
59	1957	1958	Marshall asphalt with granite aggregate.	.63	.42	.27		
60	1946	1954	Eight year old belted concrete.	.56	.37	.27		
61	1957	1958	Concrete finished with broom.	.57	.36	.27		
62	1958	1958	Asphalt roughened by heating and brushing (Test 104).	.73 (.63)	.44 (.18)	.27 (.08)		
63		1959	Reinforced concrete finished with broom.	.73	.44	.26		
64	1955	1956	Asphalt (Test 9).	.65	.44	.26		
65	1956	1960	Four year old asphalt with 45% basalt aggregate.	.80	.44	.25		
66	1963	1963	Concrete finished with broom.	.81	.42	.25		
67	1957	1958	Marshall asphalt	.56	.33	.25		
68		1960	Concrete finished with broom (Test 1).	.74	.38	.25		

APPENDIX 3

Airfield Test Number	Date of surface treatment (or laying)	Date of skidding tests	TEXTURE OF TEST AREA AT TIME OF TESTING (with Test Nos. before and after treatment)	VALUE OF BRAKING FORCE COEFFICIENT (Light trailer 320 lb./20 lb. sq. in.) taken from smooth curves drawn through plotted points at the following speeds (miles per hour) (Figures in brackets indicate results before special surface treatment)			M.P.B.W./C.E. Laboratory Friction Test Rig, (16,000 lb./ 300 lb. sq. in.) Mean co-ef. at 75/150 m.p.h.	"Swift" Aircraft Flight Tests, (16,000 - 18,000 lb./ 300/320 lb. sq. in.) Mean co-ef. at 120 Knots
				20	50	80		
69	1955	1957	Concrete.	.61	.34	.25		
70	1959	1960	Concrete finished with broom.	.68	.37	.25		
71	1955	1956	Concrete finished with broom.	.60	.36	.24		
72	1960	1960	Four year old concrete grooved by flails; $\frac{1}{8}$ in. grooves one inch apart (Test 87).			.24 (.17)	0.096	0.10
73	1945	1963	Eighteen year old concrete (Tests 5 and 81).	.57	.33	.23		
74	1959	1960	Emulsion slurry sealing of asphalt six months after sealing (Tests 52 and 92).	.64	.31	.22		
75	1958	1960	Asphalt (Test 107).	.80	.41	.21		
76	1955	1956	Asphalt (Test 39).	.59	.33	.21	0.096	
77		1959	Concrete	.71	.38	.21		
78	1956	1958	Marshall asphalt	.71	.31	.19		
79	1958	1958	Concrete finished with bass broom (Test 28).	.61	.34	.19		
80	1958	1958	Concrete finished with soft broom (Test 36).	.62	.26	.19		
81	1963	1963	Eighteen year old concrete scored longitudinally (Test 73).	.66 (.57)	.35 (.33)	.18 (.23)		
82		1954	Concrete.	.48	.26	.18		
83	1955	1957	Asphalt.	.62	.35	.18		
84	1956	1958	Asphalt with 45% basalt aggregate.	.67	.42	.17		
85	1950	1954	Four year old belted concrete.	.52	.26	.17		
86	1959	1960	Asphalt with gravel aggregate.	.47	.25	.17		
87	1956	1960	Four year old concrete.			.17	0.088	0.10
88	1956	1958	Concrete finished with broom.	.65	.33	.16		
89	1960	1960	Marshall asphalt with granite aggregate (Tests 7, 8 and 11).	.58	.37	.16	0.089	
90	1948	1954	Six year old belted concrete.	.51	.30	.15		
91	1948	1962	Fourteen year old belted concrete.	.61	.29	.15		0.10
92	1959	1959	Emulsion slurry sealing of asphalt (Tests 52 and 74).	.72 (.75)	.28 (.49)	.15 (.33)		
93	1956	1960	Asphalt (Tests 4 and 17).	.73	.28	.15		
94	1956	1960	Concrete.	.73	.33	.15		
95	1958	1958	Concrete finished with carborundum grains (Test 50).	.61	.31	.15		

APPENDIX 3

Airfield Test Number	Date of surface treatment (or laying)	Date of skidding tests	TEXTURE OF TEST AREA AT TIME OF TESTING (with Test Nos. before and after treatment)	VALUE OF BRAKING FORCE COEFFICIENT (Light trailer 320 lb./20 lb. sq. in.) taken from smooth curves drawn through plotted points at the following speeds (miles per hour) (Figures in brackets indicate results before special surface treatment)			M.P.B.W./C.E. Laboratory Friction Test Rig, (16,000 lb./ 300 lb. sq. in.) Mean co-ef. at 75/150 m.p.h.	"Swift" Aircraft Flight Tests, (16,000 - 18,000 lb./ 300/320 lb. sq. in.) Mean co-ef. at 120 Knots
				20	50	80		
96	1958		Concrete finished with granite chippings (Test 37).	.63	.28	.14		
97		1956	Asphalt.	.54	.27	.14		
98	1956	1957	Concrete treated with concealment stain (Test 57).	.40 (.74)	.18 (.45)	.14 (.28)		
99	1960	1960	Concrete roughened by thermal shock (Test 87).			.12 (.17)		0.10
100	1960	1960	Acid etching of four year old concrete (Test 87).			.12 (.17)		0.10
101	1957	1958	Asphalt with 35% gravel aggregate and density control (Test 51).	.63	.30	.12		
102	1958	1958	Asphalt with 45% gabbro aggregate (Tests 13, 14, 16, 21, 22, 23, 26, 31 and 35).	.57	.28	.10		
103	1960	1961	Marshall asphalt (Test 11).	.70	.23	.08		
104	1957	1958	Asphalt with 35% gravel aggregate and density control (Test 62).	.63	.18	.08		
105	1957	1957	Asphalt with 30% gravel (Test 2).	.34	.11	.06		
106	1959	1959	Asphalt with 45% basalt and density control.	.52	.17	.04		
107	1960	1960	Bituminous surfacing with epoxy-bitumen binder (Test 75).	.28 (.80)	.04 (.41)	.01 (.21)	0.075	

APPENDIX 4

M.P.B.W. SPECIFICATION FOR GROOVING ROLLED ASPHALT WEARING COURSES

The surface of the asphalt wearing course is to be grooved across the runway at right angles to the runway edges with grooves which follow across the runway in a continuous line without break. The machine for grooving is to be equal to the Traffic Mobile machine incorporating disc flails (Universal Highways Ltd.), the EDCO machine incorporating flail cutters (Errut Products Ltd.), or a sawing machine incorporating a minimum of twelve blades equal to Clipper Consawmatic (Clipper Manufacturing Co. Ltd.), or Concut (Concrete Sawing Equipment Ltd.). Sawing machines are to include supporting equipment such as water tankers and pressure sprays.

The machines are to be provided with flails or saw blades set to form grooves in the surface 1/8 inch wide by 1/8 inch deep at approximately 1 inch centres. After cutting, the surface is to be swept thoroughly and all loose material is to be removed.

APPENDIX 5

M.P.B.W. SPECIFICATION FOR SCORING EXISTING CONCRETE SURFACING

The runway is to be scored transversely by a single pass of a cutting drum incorporating not less than 50 circular segmented diamond saw blades per 12-inch width of drum. The drum is to be set at 1/8-inch setting on a multiwheel articulated frame with outrigger wheels, fixed to give a uniform depth of scoring over the entire surface of the runway, to ensure the removal of all laitance and the exposure of the aggregate, all as shown at the trial area and as shown on the plastic cast available in the Engineer's office. The machines to be used are to be equal to The Concut Bumpcutter (Concrete Sawing Equipment Ltd.) or the Christensen Concrete Planer (Christensen Longyear U.K.).

APPENDIX 6

M.P.B.W. SPECIFICATION FOR SURFACE DRESSING OF EXISTING BITUMINOUS SURFACING USING BITUMEN BINDER

[This specification is based on weather conditions in the United Kingdom. For use at overseas airfields, some amendments may be necessary, particularly in binder requirements]

Materials

Binder: The binder for spraying the surface to be dressed is to be cutback bitumen conforming with British standard BS 3690, Grade 50 secs. It is to have the following properties when tested in accordance with BS 3235:

Viscosity at 40^{o} C (104^{o} F), 50±10 secs
Solubility in carbon disulphide, 99.5 per cent by weight
Ash content, 0.5 max. per cent by weight

Distillation is to be determined in accordance with the appendix to BS 3690 and is to show –

Distillate to 225^{o} C (437^{o} F), 1 max.
360^{o} C (680^{o} F), 8-14 per cent by volume
Penetration of residue at 25^{o} C, 100-300

Immediately prior to the application of the hot binder, a wetting agent at the rate of $1\frac{1}{2}$ per cent by weight is to be added and thoroughly mixed in accordance with the manufacturer's written instructions.

Bitumen for coating chippings: The binder for coating the chippings is to be petroleum bitumen conforming with BS 3690, Grade 200 pen.

Wetting agent: The wetting agent is to be stearine amine or other equal and approved substance.

Chippings: The chippings are to be 1/8 inch nominal single-sized from one of the following groups: Basalt, gabbro, granite, gritstone, hornfels, porphyry, or quartzite. They are to be of the grading and particle shape given in table I of BS 63.

Aggregate crushing value: A sample of chippings similar to those proposed for use, but of a size passing a 1/2-inch but retained on a 3/8-inch BS sieve, is to be tested in accordance with BS 812 to determine the aggregate crushing value. To be acceptable, this value is to be less than 16.

Coated chippings: The chippings to be coated are to be dried in an approved rock dryer and heated to a temperature of 240^{o} to 280^{o} F (116^{o} to 138^{o} C). They are then to be coated in an approved mixer with bitumen at a rate of $\frac{3}{4}$ to $1\frac{1}{2}$ per cent by weight at a temperature of 300^{o} to 350^{o} F (149^{o} to 177^{o} C).

Stripping test: The stripping test is to be carried out on the selected chippings in the following manner. After heating, a test sample is to be taken from the dryer, coated with bitumen at a temperature of 320^{o} F (160^{o} C) at the rate specified above, and thoroughly mixed. The sample is to be transferred to a screwcap glass jar of 1-quart capacity. The jar should not be more than one-half full; then, it is to be completely covered with distilled water. The screwcap is to be fitted tightly to the jar, which is then allowed to stand for 24 hours. The sample is then to be examined for stripping of the bitumen from the chippings. If stripping has occurred, the chippings are not to be used.

Plant

Heater and distributor for surface binder: The heated binder is to be applied by a mobile combined heater and distributor with pressure feed, all complying with BS 1707. When the test set out in appendix A to BS 1707 is carried out, the deviation of binder delivered on each 2-inch strip is not to be greater than 15 per cent from the mean for all the 2-inch units over the effective width. Furthermore, the mean of the amount of binder collected in any three adjacent trays within the effective width is not to differ from the average by more than 10 per cent. A certificate to this effect, not more than 1 month old from an independent laboratory, is to be submitted to the Specification Officer (S.O.) for each heater and distributor prior to its use.

Mechanical gritter: The heated and coated chippings are to be distributed by a mechanical gritter of approved type incorporating a mechanical feed for the chippings capable of ensuring that the selected rate of spread is rigidly maintained throughout the work.

Rollers: Not less than three multiwheeled smooth tread rubber-tire rollers, each loaded to at least 6 tons, are to be used in conjunction with each distributor. They may be either self-propelled or towed by smooth treaded rubber-tire tractors.

Workmanship

Restrictions during bad weather: Work is not to be carried out during periods of rain, snow, or sleet or on frozen surfaces or on those on which water is lying. When, in the opinion of the S.O., weather conditions make it necessary, suitable protection is to be afforded to the heated and coated chippings during delivery.

Existing pit covers, gully gratings, and airfield markings: Such items as existing pit covers, gully gratings, and airfield markings are to be protected by masking, and the surface dressing is to be finished neatly around them. When masking of the airfield markings is not indicated, they may be obliterated. Reinstatement by the contractor will not be required.

Preparation of the existing surfacing: Immediately before spraying the binder, the existing surfaces are to be cleaned thoroughly by mechanical brooms, supplemented by hand brooming if necessary. All vegetation, loose materials, dust, all debris, etc. are to be removed as indicated.

Trial areas: Trial areas are to be laid prior to the commencement of the works in order to determine the precise rates of spread required for the binder and chippings. The range from which the rate of spread of binder is to be selected is from 10 to 12 sq yd/gal. The first area is to be spread at the rate of 12 sq yd/gal working towards 10 sq yd/gal if the former rate does not cover the entire surface. The coated chippings are to be applied at a rate that ensures complete coverage of the binder after final sweeping.

Application of surface binder: The surface binder during application is to be maintained at a temperature between 300° and 320° F (149° and 160° C). At junctions with surfaces not to be dressed, clean lines are to be defined by masking with waterproof building paper, or other means. The binder is to be applied at the selected rate without variation in such a manner that a film of uniform thickness results. Particular care is to be taken to avoid dripping, spilling, and areas of excessive thickness. The rate is likely to be about 250 sq yd/ton of chippings.

Application of coated chippings: The temperature of the heated and coated chippings when applied to the sprayed surface binder is to be not less than 180° F (83° C). Before and during the rolling operation, any bald patches are to be repaired with fresh chippings.

Rolling: The coated chippings are to be rolled immediately after spreading and before loss of heat. Rolling is to consist of at least one complete coverage by each of the three rollers, following closely one behind the other.

Final sweeping and rolling: Within 3 days of the gritting operation, all loose chippings are to be swept from the surface with hand brooms, loaded into lorries, and removed as directed. The surface is then to be further rolled with at least three complete coverages of the area. The finished surface is to have all chippings firmly adhering thereto, is to be of uniform surface texture and colour throughout the work (entirely free from surface irregularities due to scabbing, scraping, dragging, droppings, excessive overlapping, or faulty lane or transverse junctions, or other defects), and is to be left clean and tidy to the satisfaction of the S.O. Under no circumstances are sweptup chippings to be reused.

Test certificates: Prior to the commencement of work, the contractor is to produce to the S.O. for approval the following test certificates:

(a) Manufacturer's certificate showing details of the surface binder;
(b) Manufacturer's certificate showing details of the wetting agent;
(c) Grading analysis of chippings and aggregate crushing strength;
(d) Details and results of stripping tests;
(e) Certificate for each combined heater and distributor to be used; and
(f) Details of trial areas, giving precise rates and spread agreed for both binder and chippings.

Records to be maintained: The contractor is to maintain the following records throughout the work:

(a) Temperatures, at half-hourly intervals, of binder and coated chippings; and
(b) Air temperatures, at hourly intervals.

APPENDIX 7

M.P.B.W. SPECIFICATION FOR SURFACE DRESSING OF EXISTING BITUMINOUS SURFACING USING TAR BINDER

[Clauses applicable to both bitumen and tar binders are not repeated]

Materials

Surface binder: The binder for spraying the surface to be dressed is to be road tar having properties which conform with table I of BS 76 when tested in accordance with the appendices in that standard. During the months of June, July, and August, the tar is to be Grade A50; for the remaining months, it is to be Grade A42. Immediately prior to the application of the hot binder, a wetting agent, at the rate of $1\frac{1}{2}$ per cent by weight, is to be added and thoroughly mixed in accordance with the manufacturer's written instructions.

Tar for coating chippings: The tar for coating the chippings is to be road tar Grade A34/B34.

Coated chippings: The chippings to be coated are to be dried in an approved rock dryer and heated to a temperature of 200° to 240° F (94° to 116° C). They are then to be coated in an approved mixer with road tar at a rate of 1 to 2 per cent by weight at a temperature of 200° to 240° F (94° to 116° C).

Stripping test: The stripping test is to be carried out on the selected chippings in the following manner. After heating, a test sample is to be taken from the dryer, coated with tar at a temperature of 220° F (105° C) at the rate specified above, and thoroughly mixed. The rest of the procedures is the same as that for bitumen-coated chippings.

Workmanship

Trial areas: The trial areas are to be laid prior to the commencement of the works in order to determine the precise rates of spread required for the binder and chippings. The range from which the rate of spread of binder is to be selected is from 12 to 14 sq yd/gal. The first area is to be spread at the rate of 14 sq yd/gal working towards 12 sq yd/gal if the former rate does not cover the entire surface. The coated chippings are to be applied at the rate of approximately 250 sq yd/ton, the rate finally selected being that which ensures complete coverage of the binder after final sweeping.

Application of surface binder: The surface binder during application is to be maintained at a temperature between 220° and 275° F (105° and 135° C). The application for the tar binder is then the same as for the bitumen binder.

APPENDIX 7

Application of coated chippings: The temperature of the heated and coated chippings when applied to the sprayed surface binder is to be not less than 160° F (72° C). Before and during the rolling operation, any bald patches are to be repaired with fresh chippings.

APPENDIX 8

M.P.B.W. SPECIFICATION FOR OPEN-GRADED MACADAM FRICTION COURSE

[This mixture is for runways only (excluding runway ends). It allows the free penetration of surface water to the underlying layer, which must be a densely graded impervious wearing course of high stability. It should be of uniform compacted thickness throughout and is not suitable over deformed or poorly shaped surfaces]

Aggregate: Crushed rock from one of the following groups: Basalt, gabbro, granite, hornfels, or porphyry.

Crushing value: Less than 16 per cent (BS 812).
Flakiness index: Less than 25 per cent (BS 812).
Stripping: Immersion test.

Binder: Petroleum bitumen, Grade 200 pen.

Filler: Portland cement or limestone but at least $1\frac{1}{2}$ per cent by weight of total mixed material is to be hydrated lime.

Aggregate grading: The aggregate grading (including filler) are –

BS sieve	Percentage by weight passing
1/2 in.	100
3/8 in.	90-100
1/4 in.	40-55
1/8 in.	22-28
No. 200	3-5

Binder content: Percentage by weight of total mixed material, 4.75 to 5.25.

Mixing temperatures:

Aggregate:	175° to 250° F (80° to 122° C)
Binder:	200° to 275° F (94° to 135° C)

Rolling temperature: Not less than 160° F (72° C).

Roller: As necessary to compact to refusal.

Compacted thickness: 3/4 inch.

Tack coat: Bitumen emulsion at 15 to 20 sq yd/gal.

Surface accuracy: 1/8 inch in 10 feet (in any direction).

APPENDIX 9

M.P.B.W. SPECIFICATION FOR TEXTURING NEW CONCRETE

The concrete surfacing of the runway, except for 300 feet at each end, is to be textured by drawing a purpose-made wire broom across the pavement at right angles to the side forms whilst the concrete is soft enough to take an impression. The broom head is to be 24 inches minimum width, wire filled with 32 gauge by 1/20 inch wire tape.

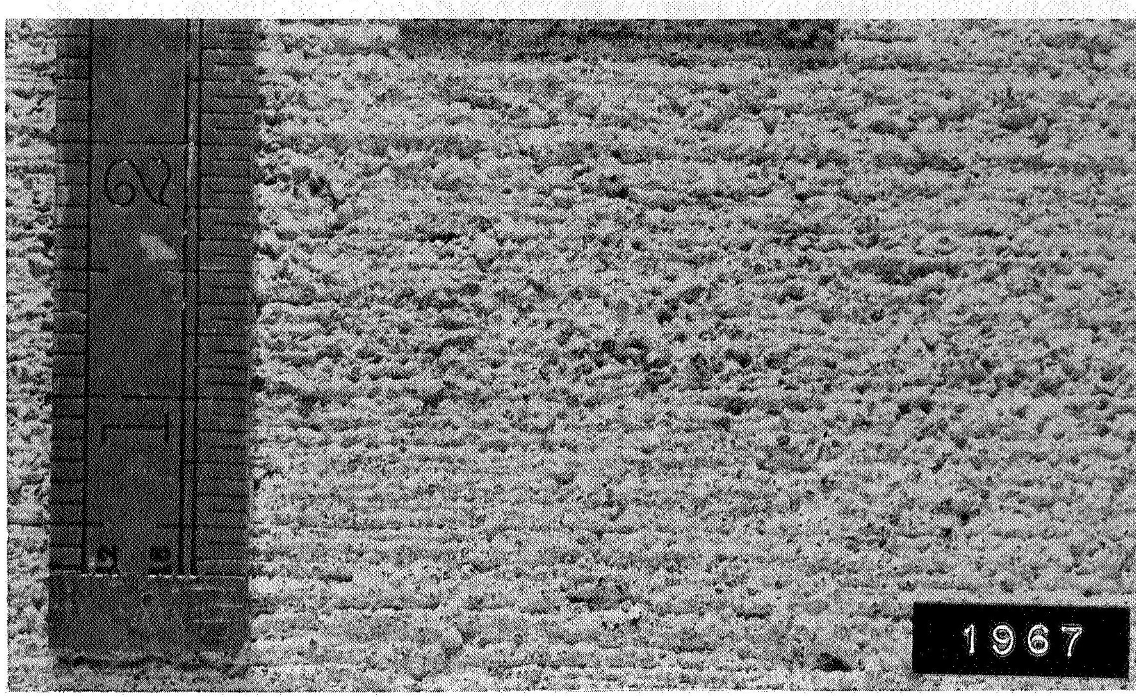


Figure 1.- Lightly broomed concrete.

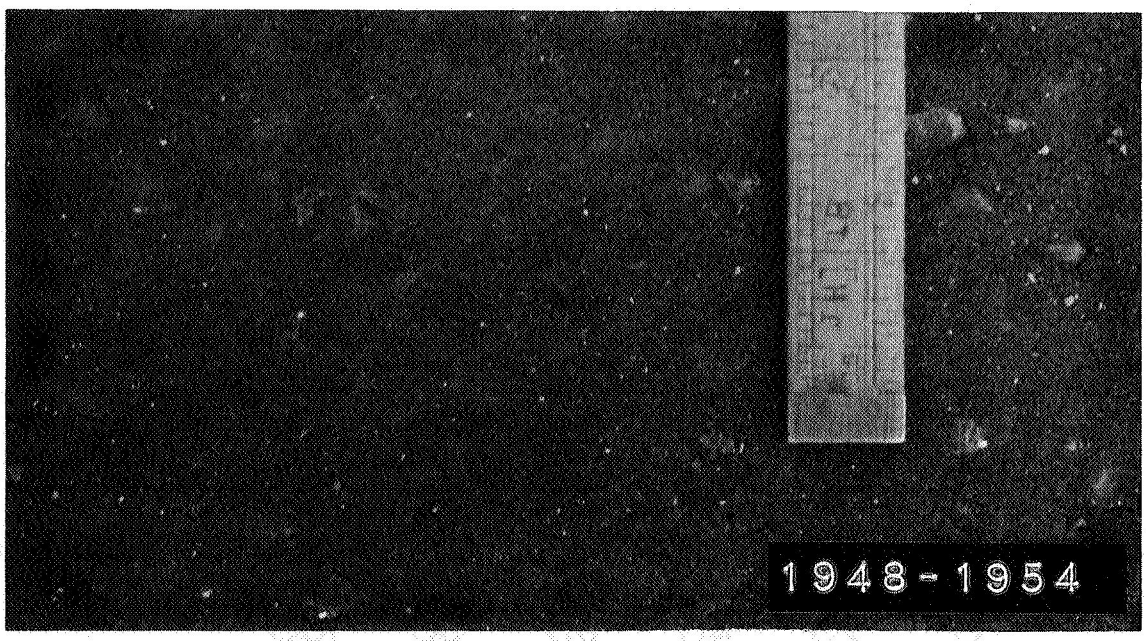


Figure 2.- Hot rolled asphalt.

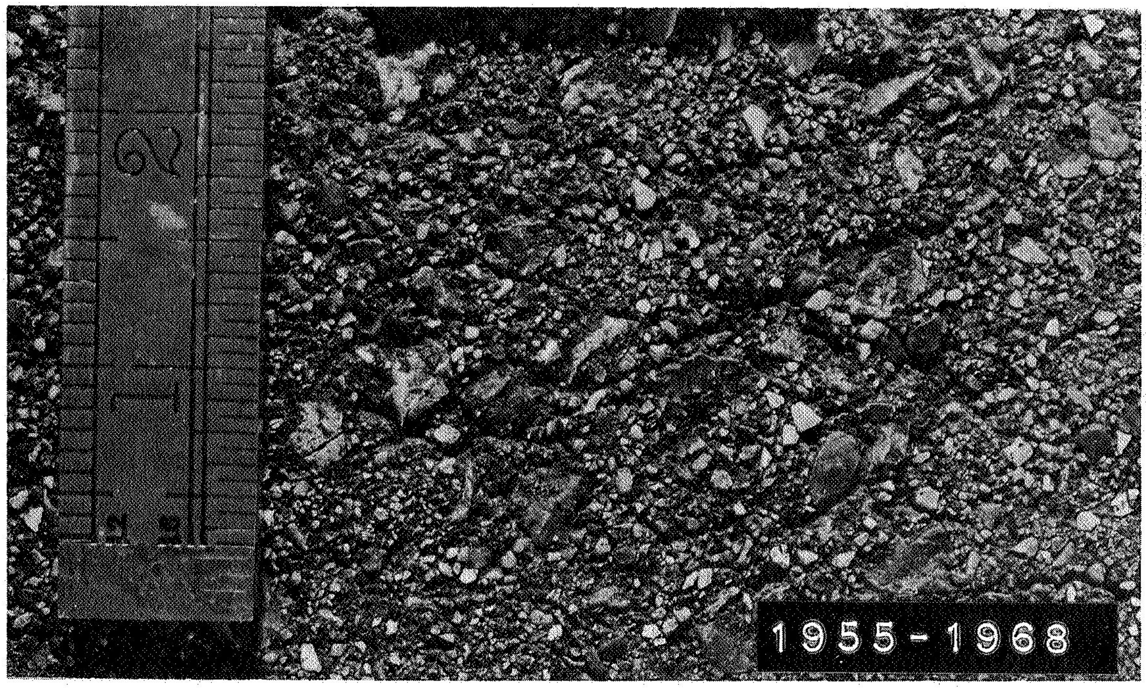


Figure 3.- Marshall asphalt.

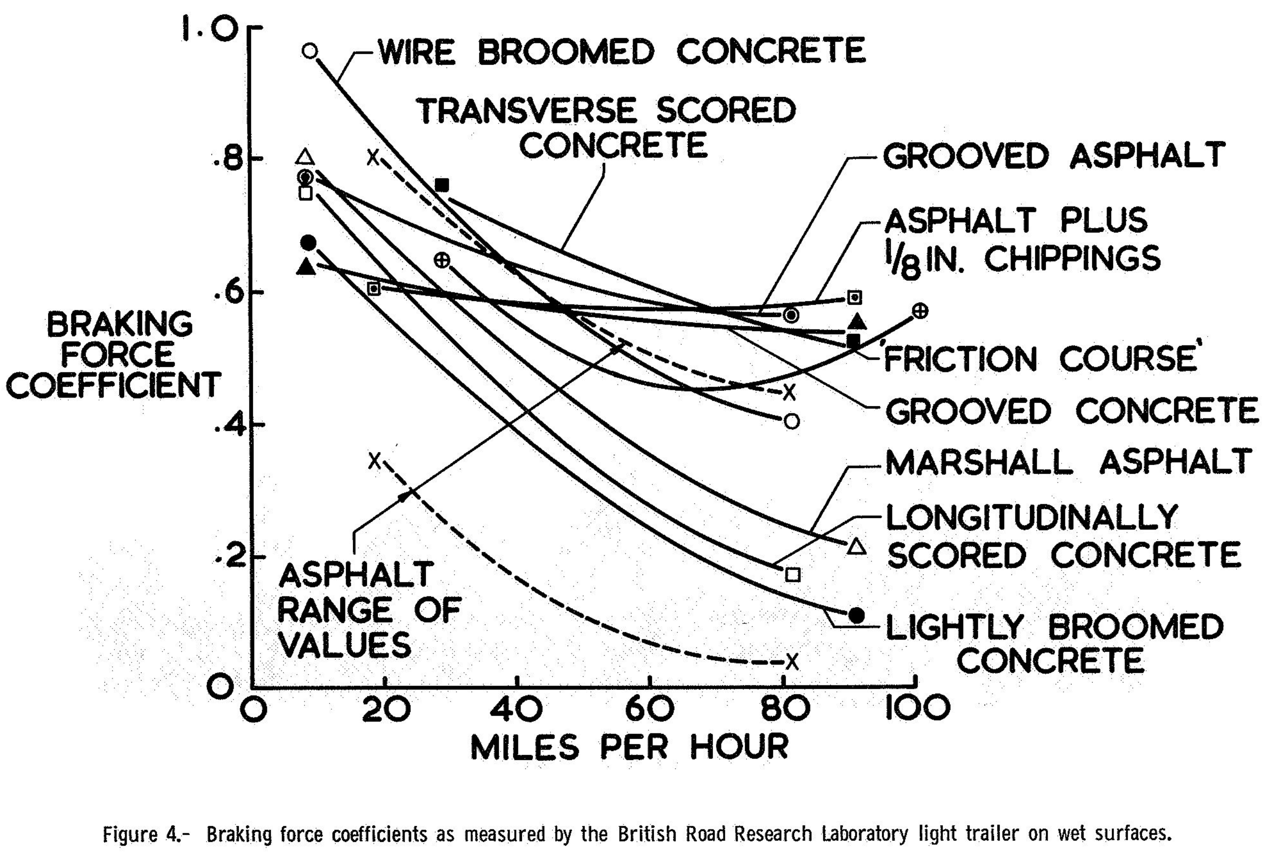


Figure 4.- Braking force coefficients as measured by the British Road Research Laboratory light trailer on wet surfaces.

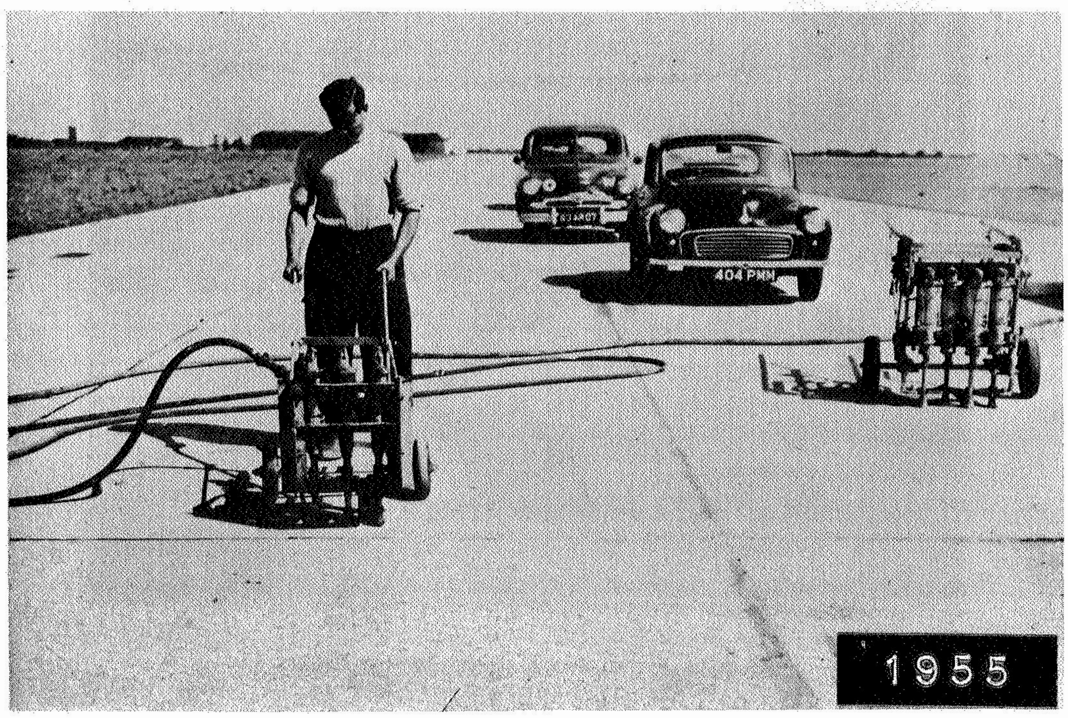


Figure 5.- High-speed percussion rotary hammers to texture concrete or asphalt.

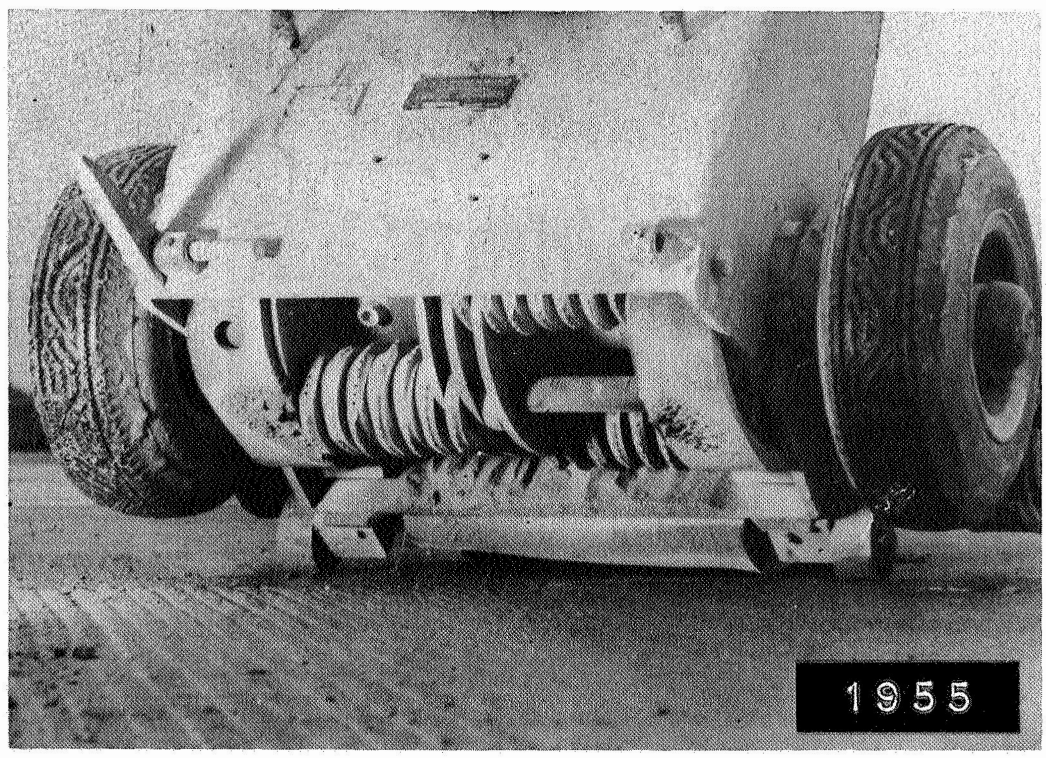


Figure 6.- Disc flails to groove concrete or asphalt surfaces.

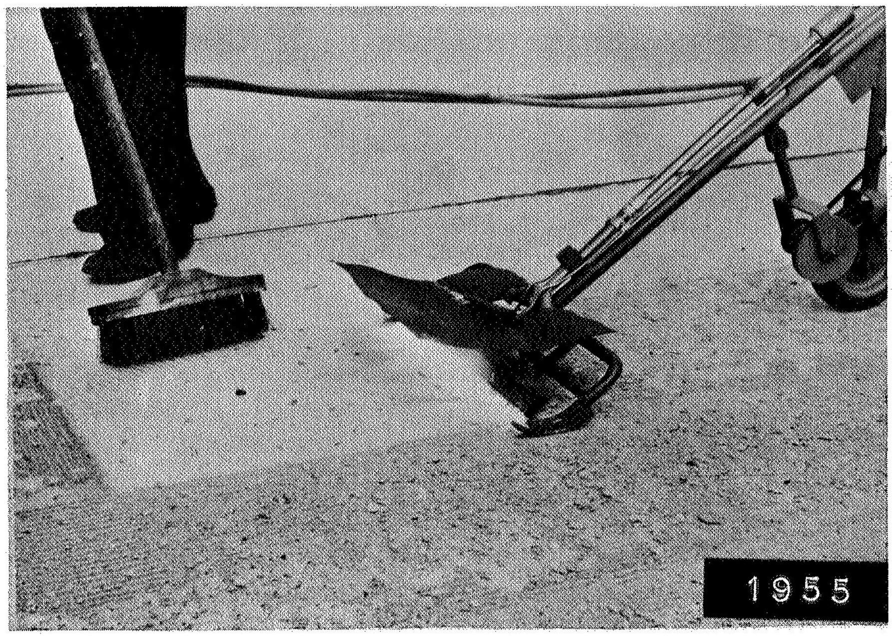


Figure 7.- Thermal shock to roughen concrete surfaces.

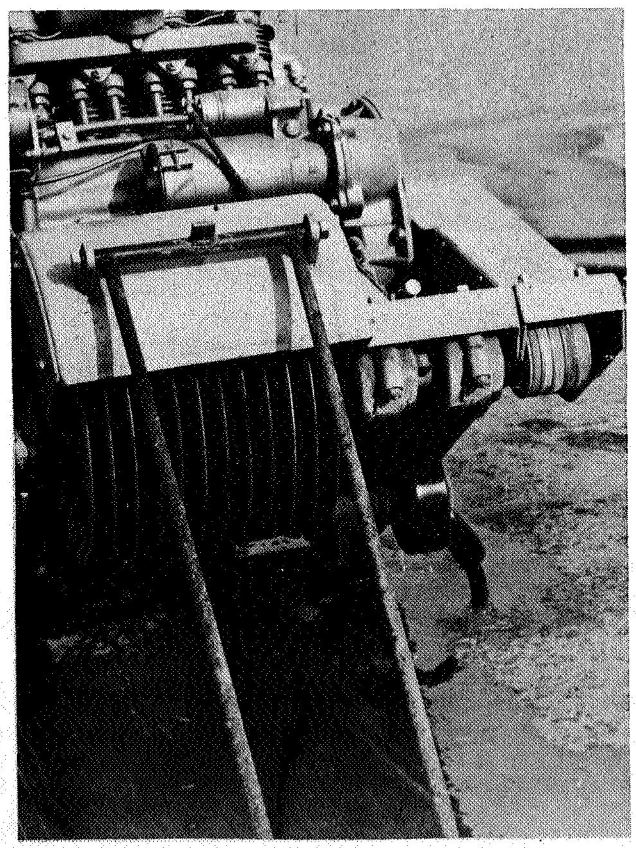


Figure 8.- Grooving saws for concrete or asphalt.

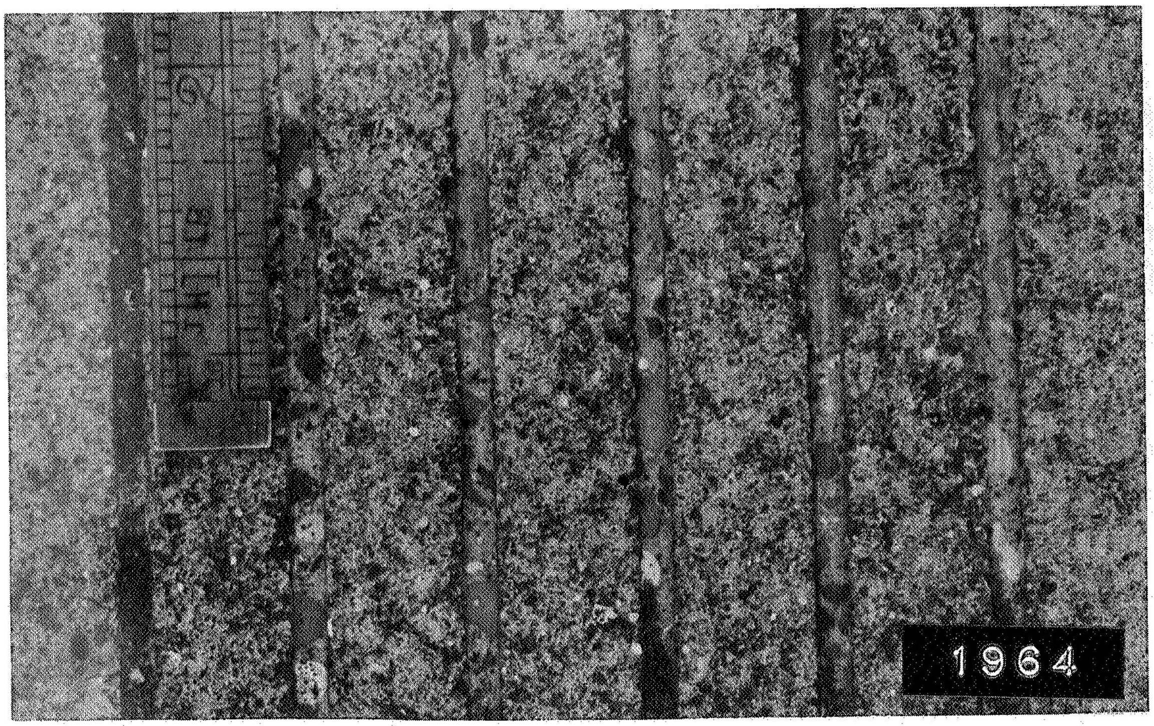


Figure 9.- Grooved concrete.

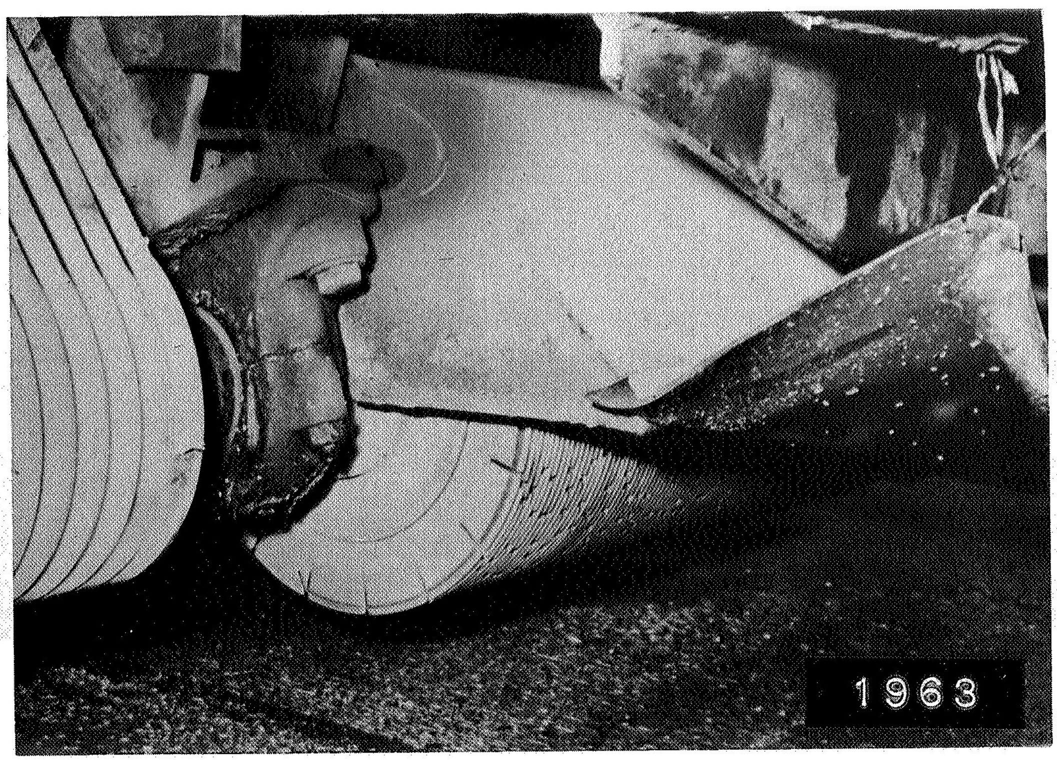


Figure 10.- Diamond cutting drums to score concrete.

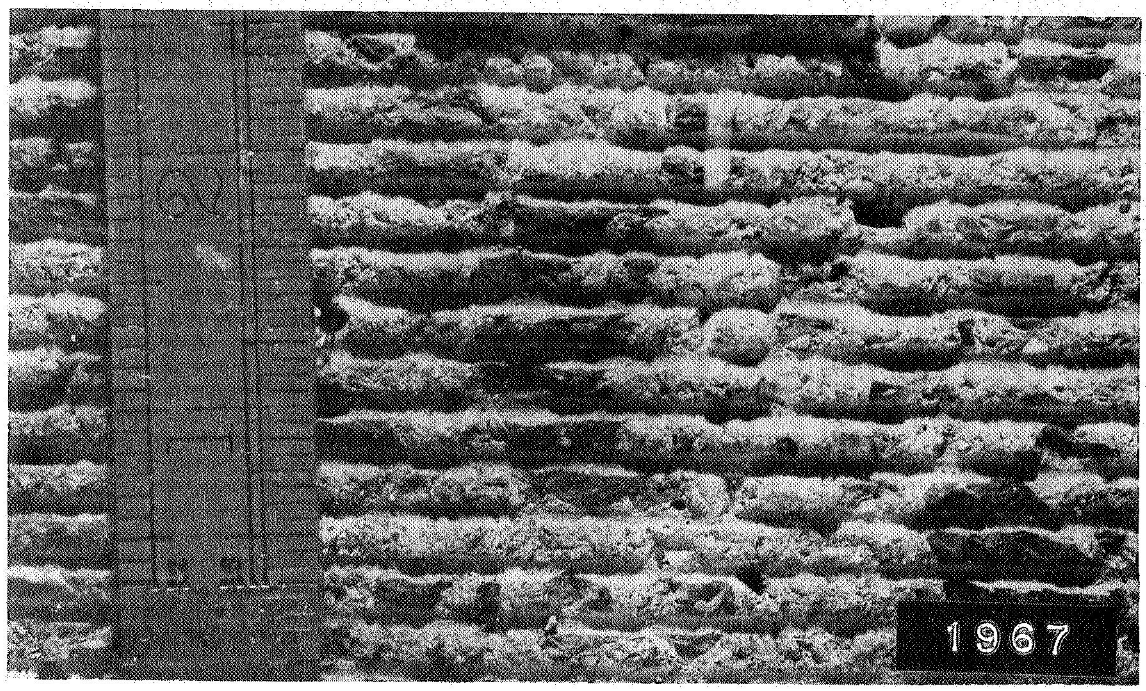


Figure 11.- Scored concrete.

Figure 12.- Surface dressing of existing asphalt.

Figure 13.- "Friction course" surfacing of asphalt.

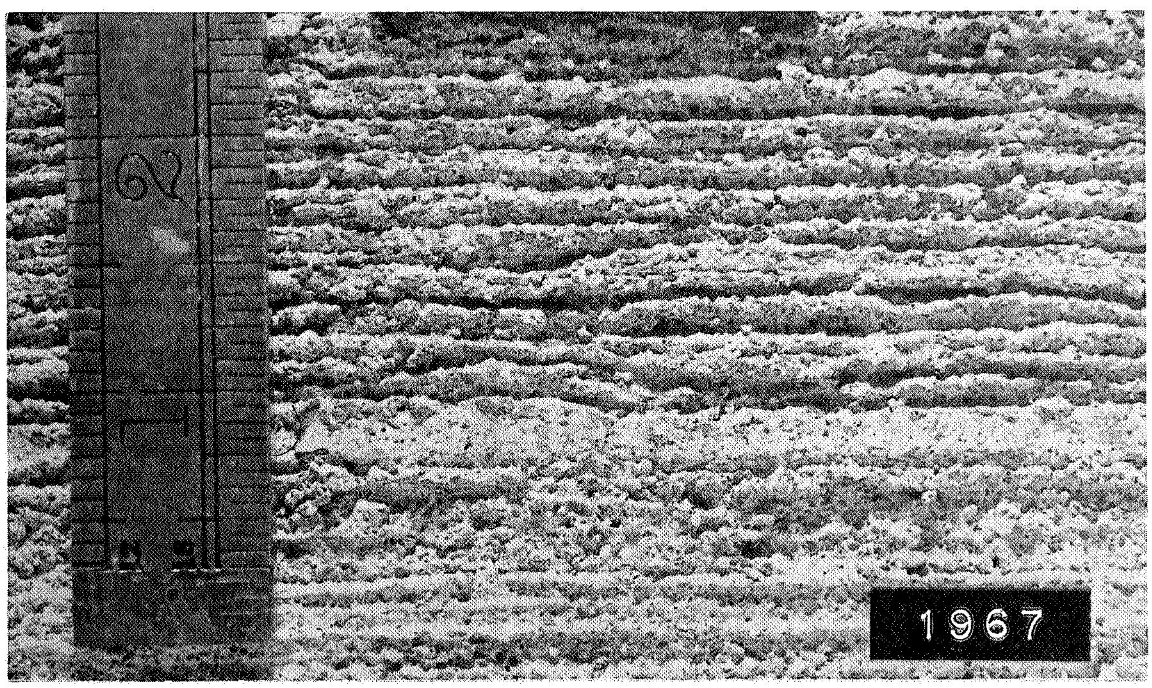


Figure 14.- Wire combed concrete.

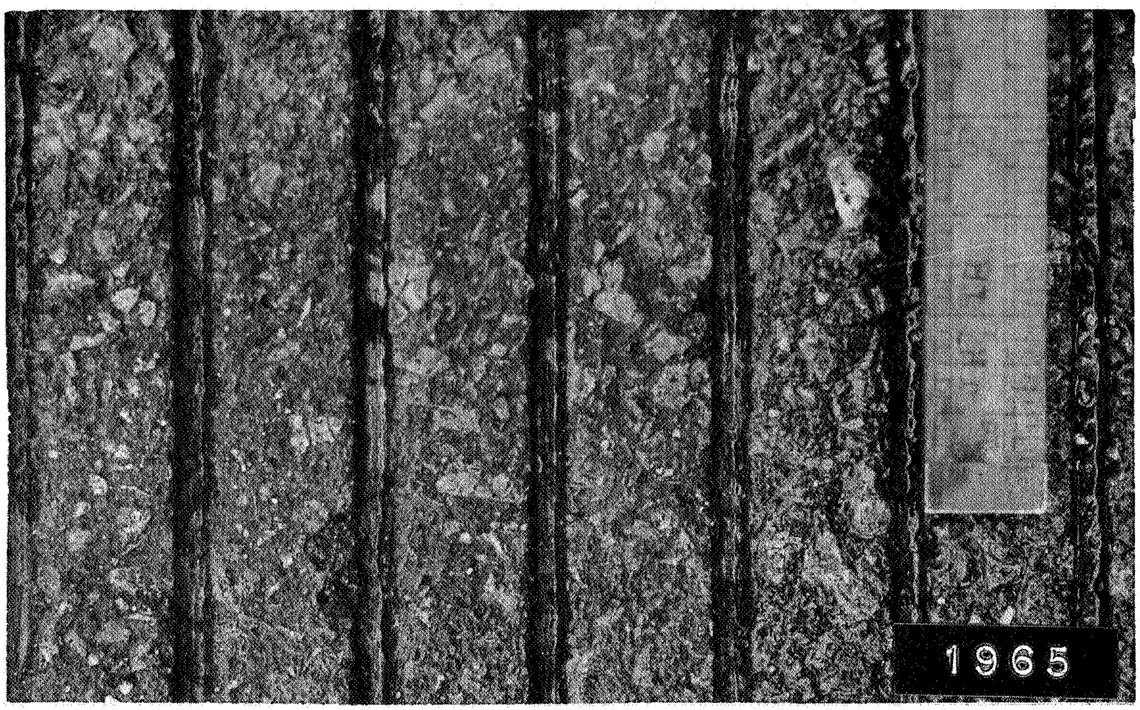


Figure 15.- Grooved asphalt.

18. PAVEMENT GROOVING AT JOHN F. KENNEDY INTERNATIONAL AIRPORT

By I. J. Dornfeld and James P. Muldoon

Port of New York Authority

SUMMARY

In August of 1967, The Port of New York Authority completed the grooving of essentially the entire surface of runway 4R-22L at John F. Kennedy International Airport. The grooving pattern was somewhat different from that used at other airports. Major problems included the requirement to return the runway to service on short notice and the disposal of the concrete dust generated by the grooving operation. After 16 months of use, all observations indicate that the grooves are performing their intended function by reducing aircraft stopping distance during wet and flooded conditions. No pavement deterioration or maintenance problems have been noted to date.

INTRODUCTION

The Port of New York Authority had for many years followed closely the efforts of various agencies to develop an improved or modified pavement surface that would increase the coefficient of friction between aircraft tires and the pavement surface during wet or flooded conditions, thereby minimizing the tendency of aircraft to hydroplane under these conditions. Most of the original work with grooved and porous pavement surfaces was done by the British and dates back to 1956. In this country, the California Department of Highways first applied the principle of surface grooving to roadways in locations where accident rates were high under wet or flooded conditions. A great deal of analytical work on the phenomenon of aircraft hydroplaning was done by the National Aeronautics and Space Administration (NASA), and in 1966 a concentrated effort in the area of runway grooving was initiated by NASA.

On the basis of the generally favorable results reported by the British, the California Highway Department, and NASA, The Port of New York Authority, late in 1966, decided to install grooves on a fully operational runway. The grooving was supported by the using airlines through the Air Transport Association (ATA) and was intended to supplement the work being done by NASA at Langley Field and Wallops Island, as well as the environmental testing being carried out through joint NASA-FAA auspices at various locations throughout the country.

INSTALLATION

Runway 4R-22L at Kennedy International Airport (fig. 1) was the logical choice for a grooving test for several reasons. The runway is fully instrumented from both the northeast and the southwest and accepts virtually all the bad-weather landings at the airport. The runway, which is 8400 feet in length, received approximately 70 000 landings during 1967. This level of activity, which indicates the advisability of grooving this particular runway, is also indicative of the operational problems which would attend any prolonged shutdown of the runway.

With the runway selected, decisions then had to be made on how much of the runway to groove, the type of groove to be used, and the pattern to be specified.

While it was recognized that grooving might be limited to the area in which hydroplaning was most likely to occur, the exclusion of any one portion of the runway was difficult to justify. The fact that the runway was used extensively in both directions extended the area of potential hydroplaning, leaving only relatively small areas at each end of the runway free of this problem. It was therefore decided to groove the entire runway, omitting only the concrete slabs that contained the Elfaka light units (see fig. 2) which, at that time, were the principal components of both the centerline and touchdown in-pavement lighting systems. (The centerline Elfakas have since been replaced by newer pancake-type fixtures.) Also omitted was the outer 5 feet of the runway pavement on each side to facilitate the turnaround of the cutting equipment without damage to shoulder pavement or runway edge lights.

Preliminary work done by NASA at that time, as well as reports from The United Kingdom, seemed to indicate that a pattern which provided approximately 1 inch of ungrooved pavement between adjacent grooves would, while helping under wet and slippery conditions, not reduce the coefficient of friction under dry conditions. It was therefore decided to establish a transverse pattern which would provide this 1-inch "land" between the grooves.

In selecting a groove depth and shape, the lack of any long experience in this area dictated a most conservative approach. Because of the ever increasing weight of aircraft and resulting pavement loading, any reduction in the effective thickness of the concrete slab had to be held to a minimum. It was therefore decided that the depth of groove should not exceed 1/8 inch. It was also decided that, if at all practical, the sharp interior corners of a rectangular cut would be avoided because of the tendency of these corners to develop stress concentrations which could lead to the failure of the rigid slab. To further enhance the ability of the groove to resist deterioration, the use of a V-shaped groove was considered, and accelerated weathering tests were conducted on both rectangular and V-shaped grooves. It was anticipated that a V-groove might prove superior to a rectangular groove in withstanding spalling caused by the freezing of entrapped water, since its shape would permit the expanding ice to move up and out of the groove rather than bear against the sides. The tests, while not extensive, did confirm the superiority of the V-groove in this respect. It was also believed that the V-groove would offer greater resistance to spalling or raveling during construction, as well as in an operating environment, by virtue of its lack of right-angled edges. The V- or sinusoidal-shaped groove illustrated in figure 3 was therefore chosen.

In the preparation of plans and specifications for the work, the operational problem noted earlier had to be carefully considered by the Port Authority staff. More than 32 percent of all landings at the airport are performed on either runway 4R or 22L. During certain summer months when strong winds from the south and southwest prevail, this percentage can rise to as high as 58, in spite of a noise-abatement preferential-runway system that strongly discourages landing on runway 22L unless required by wind and/or visibility conditions. Because of this high volume of activity which could not be "switched off" the runway, an extended shutdown of the runway could not be considered. Based upon a knowledge of the production capability of equipment which could be used to accomplish the grooving, it was decided that the contractor would be permitted to work on the runway only during nonpeak hours, which, at that time, were 6:00 a.m. to 3:00 p.m., and would be required to clear the runway within one-half hour upon notice from the control tower whenever weather conditions necessitated the use of the runway. Since the contractor was guaranteed compensation for men and equipment idled during these interruptions, records were maintained which indicate that he was denied the use of the runway about 10 percent of the time.

The contract for the work was awarded in early 1967 to Master Waterproofers, the lowest of three bidders, in the amount of $157 490, or about $0.13 per square foot. The contractor started work on May 1, 1967, and used two groove cutters manufactured by Concut, Inc., of El Monte, California. These machines, one of which is shown in figure 4, were self-propelled and employed a 38-inch-wide rotating drum with diamond-impregnated cutting elements to establish the groove pattern. The production of each machine was somewhat less than the 20 000 square feet per day that can be anticipated on highway work because of the numerous turnarounds required in a transverse grooving operation, as contrasted with the longitudinal highway operation, as well as the requirement to vacate the work area whenever required by the aeronautical operation.

The disposal of the 300 000 pounds of concrete dust generated by the grooving operation was a potential problem. Because of the extreme susceptibility of turbojet engines to damage or failure due to the ingestion of foreign material, it was decided to assure that the runway surface was clear of concrete dust by continually flushing the residue to the drainage inlets in the paved shoulder along each edge of the runway. To provide the large volume of water that was required for this flushing operation, the contractor was permitted to connect to the fire hydrant system that parallels the runway. Additional hand work was required along the shoulder to remove accumulated sediment around the inlets and in the silt traps.

Another problem to be considered in the grooving of runways that accommodate a high volume of landings is the handling of paint buildup. With the number of operations on both runways 4R and 22L, the accumulation of rubber deposits can require the repainting of the threshold portion of each runway as often as four times a year. In some areas, the buildup of sandwiched layers of paint and rubber deposits exceeded the 1/8-inch groove depth. In these areas, large sections of the surface tended to peel off after the grooving operation, leaving ungrooved spots. This condition is depicted in figure 5. The best remedy for this problem was found to be the grinding off of these buildups prior to the grooving operation with a "Bump Cutter" manufactured by Concut.

No other significant problems were encountered, and the contract work was completed on schedule by August 1, 1967.

EVALUATION

Since completion of the work, over 100 000 landings have been made on the runway (large aircraft do not take off from this runway because of length limitations). Regular inspections of the pavement reveal no surface damage or signs of pavement distress. In addition, no complaints of increased vibration or aircraft tire wear have been received from the users of the runway.

While admittedly only one relatively mild winter, from a snow-removal point of view, has been experienced since the grooving, no damage to the pavement caused by snow plowing has been observed. Normal snow-removal procedures were followed without special precautions for the grooved surface. Little or no ice removal was required last winter, and no observation can yet be made on the possibility that the grooves may actually facilitate ice removal because of the serrations built into the ice pattern. The effect of snow and ice removal operations upon the grooved pavement, as well as the effect of the grooves upon snow and ice removal operations, will be closely watched during future winters and any significant findings will be reported.

One problem which was anticipated but which has not materialized to date was the reaccumulation of rubber deposits within the grooves themselves. Apparently, the rubber material deposited in the grooves is not of the vulcanized type which is normally deposited on the flat surfaces, and so far this relatively soft material has generally been cleaned by the jet blast of the aircraft. In the future, should the grooves become filled to the point where drainage is affected, the surface could be treated with a cresylic acid compound which has been used successfully in the past to remove rubber.

Prior to the installation of the grooves, the coefficient of friction under dry and wet conditions was measured along the center and edges of the runway by means of a modified Swedish Skiddometer or braking trailer operated at speeds from 10 mph to 60 mph. In December 1967, after the grooving had been completed, these tests were repeated with the same equipment. The results indicated a substantial increase in the coefficient of friction under wet conditions. The magnitude of the improvement appeared to increase with the speed of the test vehicle, which, as noted earlier, attained a maximum speed of 60 mph. Thus the grooves are apparently effective at the higher aircraft speeds at which hydroplaning is likely to occur.

Questionnaires soliciting the comments of pilots on the effectiveness of the grooving were circulated by the ATA, and the results are reported in reference 1. Pilot comments that have come to the attention of the Port Authority have, without exception, been quite favorable. The two most common pilot reactions involved the elimination or reduction of the water spray normally encountered in landing during a heavy rain and the ability to exit the runway comfortably with a shorter ground roll under wet conditions. Visual observations of landings on runway 4R during wet runway conditions have confirmed that a higher percentage of the B-707 and DC-8 aircraft are now able to use the high-speed taxiway exit located approximately 2000 feet closer to the landing threshold. Likewise, in landing on runway 22L, a higher percentage of these same aircraft now seem to be using the taxiway exit about 2000 feet closer to the landing threshold. In addition to this apparent increase in the factor of safety in wet-runway landings, the use of a closer turnoff reduces the runway occupancy time for these operations and permits possible increases in the acceptance rate for the runway. The ability to use these turnoffs in all weather conditions also reduces the taxi distance to the individual terminals in the central terminal area at Kennedy.

THE FUTURE

Because of the apparent operational advantages offered by grooved runways as well as the lack of any demonstrated or anticipated maintenance problem, the Port Authority is seriously considering the grooving of other runways at our airports. We also plan, during next year's construction season, to groove the high-speed taxiway turnoffs on runway 4R-22L at Kennedy. These taxiways will represent our first significant grooving experience with asphalt pavement and will, it is hoped, provide the background required to confidently groove the 80 acres of asphalt runway pavement at Newark and the 35 acres at LaGuardia.

The grooving of runways at LaGuardia, while strongly indicated from an operational viewpoint, will require the solution of some unique problems. Both runways at LaGuardia were recently extended to a length of 7000 feet with extremely costly pier structures, and further expansion is not considered feasible. Any improvement which would, in effect, increase the runway length available during wet and flooded conditions would, of course, have considerable merit. One of the problems at LaGuardia which must be considered, however, is the structural effect of the grooves upon the prestressed-concrete deck, the design of which is currently being reviewed to determine its ability to accommodate various versions of the "Airbus." Another problem is the development of a groove especially tailored to the unusual settlement conditions at LaGuardia. The intersection of the runways lies immediately adjacent to the structural extension of the runways, and the differential settlement rate between the land and pier requires the overlay of the intersection with as much as 4 inches of asphalt each year.

CONCLUSION

After 1 year, The Port of New York Authority is pleased with the performance of the grooves installed on runway 4R-22L at Kennedy, plans the grooving of additional taxiways at Kennedy within the next year, and hopes eventually to groove all other runways where operational advantages can be gained without compromise of pavement integrity or maintainability.

REFERENCE

1. Abbott, Edwin W.: Commercial Airlines and the Grooved Runway Concept. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 9 herein.)

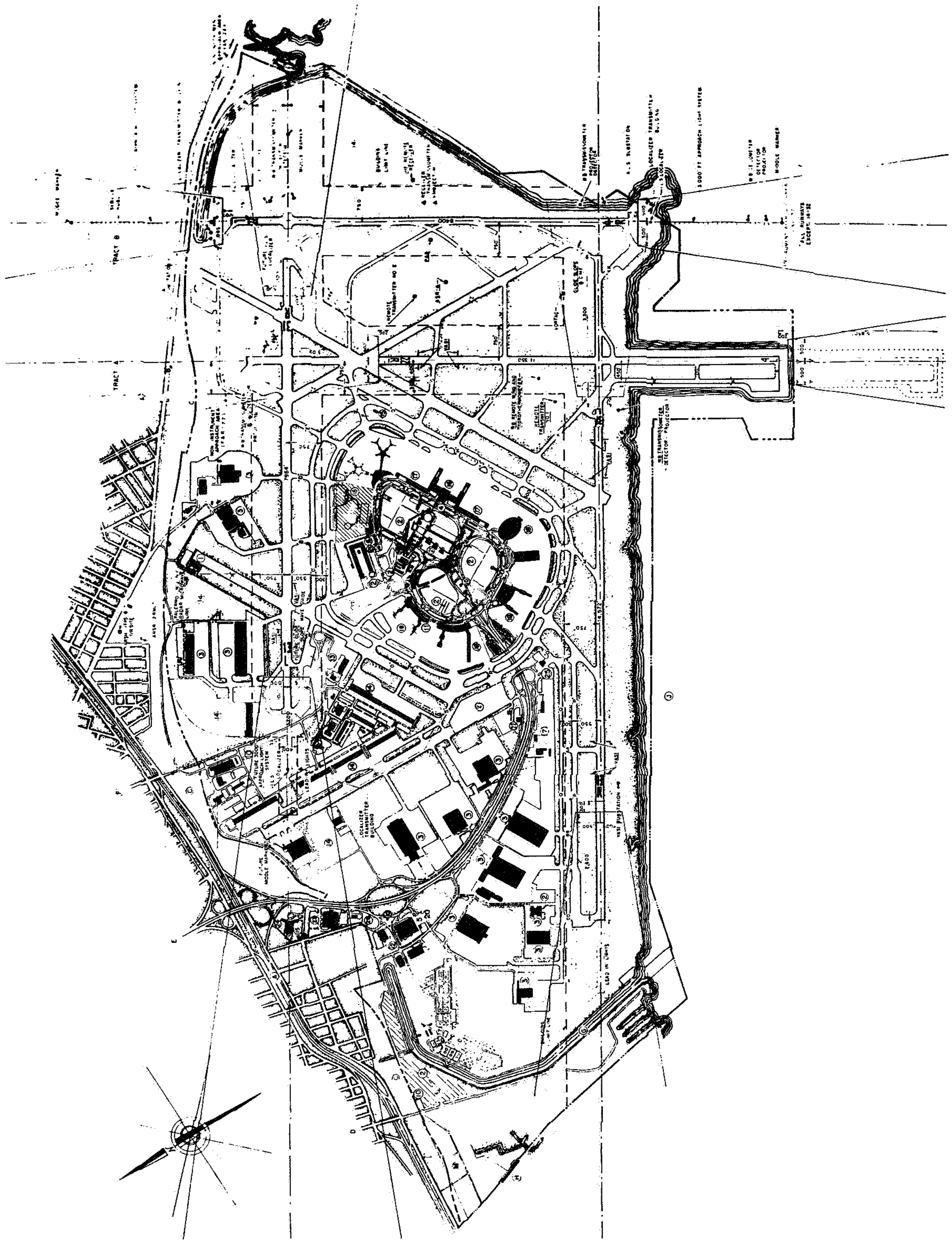


Figure 1.- Master plan of John F. Kennedy International Airport.

Figure 2.- Grooved runway with ungrooved slabs containing Elfaka light units.

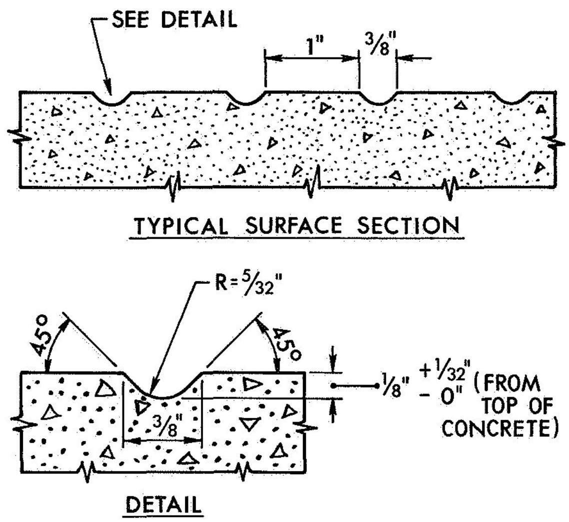


Figure 3.- Cross section of runway grooves.

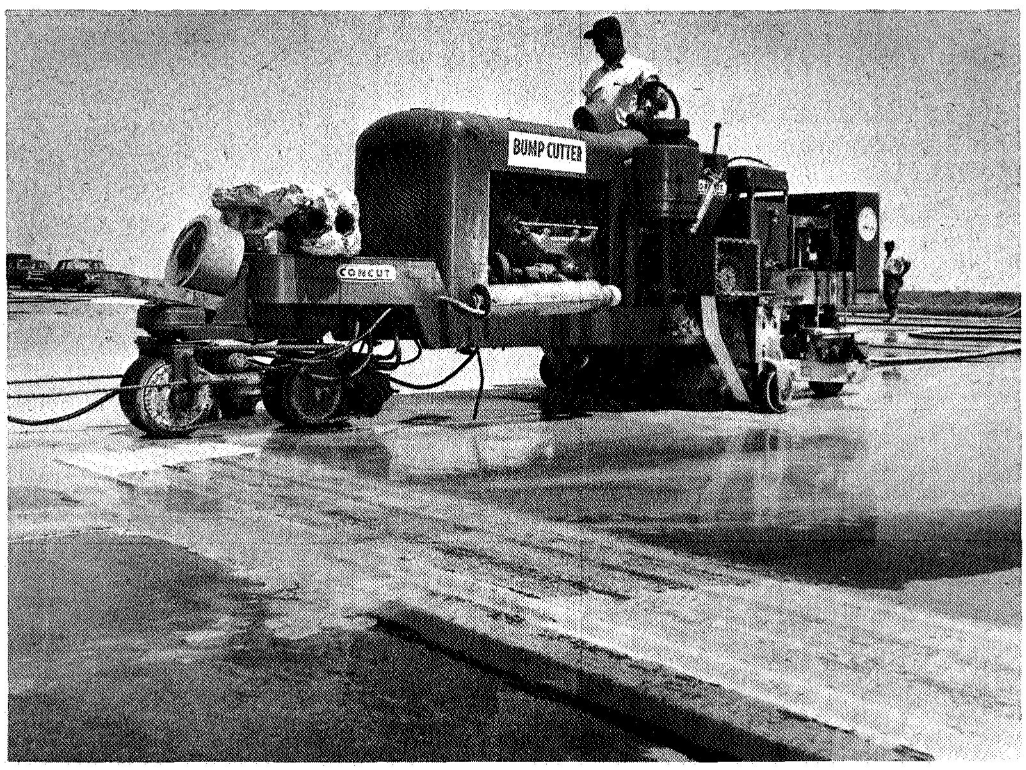


Figure 4.- Groove cutting at John F. Kennedy International Airport.

Figure 5.- Ungrooved areas left by peeling of paint and rubber deposits.

19. REPORT ON GROOVED RUNWAY EXPERIENCE AT WASHINGTON NATIONAL AIRPORT

By R. C. McGuire

Federal Aviation Administration

SUMMARY

The Federal Aviation Administration has had an active interest in runway grooving technology since December 1965. A noteworthy accomplishment was the grooving of Washington National Airport runway 18-36 in March 1967 – a first, as far as United States civil airports are concerned. Friction measurements of the runway, which has a 1/8" × 1/8" × 1" groove pattern, show that the grooving alleviates the extreme variations in wet traction caused by surfaces which have been worn smooth and coated with rubber. Tests to determine the effect of environment and traffic on the endurance of 18 groove patterns in concrete and asphalt taxiways are in process at five airports. The cost of grooving the runways at one airport (Chicago Midway) has been included in the Federal Aid to Airports Program. The FAA activities in runway grooving are being coordinated with NASA, the Air Transport Association of America (ATA), and airport authorities who are contemplating implementation of runway grooving.

INTRODUCTION

The Washington National Airport grooved runway 18-36 (fig. 1) has been the focal point of the Federal Aviation Administration interest in runway grooving. After observing the drainage of a grooved runway at Farnsborough, England, during a heavy rain in December 1965, and discussing British experience with several experts in the Ministries, a research and development project was implemented by the Aircraft Development Service to study and apply the technology to civil airports in cooperation with NASA and ATA. A special committee, representing the airport, engineering, and research branches of the agency, was established in the spring of 1966 to investigate, implement, and monitor the science of runway grooving.

The specifications for grooving Washington National runway 18-36 were developed during the summer of 1966. So far as is known, these were the first specifications written for an extremely active civil transport runway in the United States. The specifications were novel because they were gauged to an airport experiencing about 1000 operations a day, had to consider an asphaltic concrete pavement using hard aggregate from two sources, and had to avoid damaging subsurface wiring of the touchdown zone and centerline lighting systems. In short, this work was exposed to the problems normally associated with implementing a known technology in a new area under new conditions.

RESULTS AND DISCUSSION

The grooving job was scheduled to be accomplished during the winter of 1966-67. However, the job did not commence until March 1967. This delay was beneficial because of the large quantities of water needed for the work. The resultant sludge and winter conditions in general would have caused large deposits of ice and slush on the runway.

The contractor used Clipper grooving machines (fig. 2). These are small gasoline-engine-driven vehicles capable of sawing 13 grooves at a time. Since the specifications called for completion of the work in 35 days, seven machines were used. Each was assigned a daily task of 35 feet of runway length, 150 feet wide. Approximately 200 feet of runway length were completed per day. The work was done between 11 p.m. and 7 a.m. to minimize interference with traffic. (See figs. 3 to 7.)

As the NASA tests of various groove patterns had not yet commenced, the 1/8" × 1/8" × 1" groove configuration, which had been successfully developed in England, was chosen for the runway. However, unlike British practice of leaving 500 feet of runway ungrooved on each end, the full length of the runway (6870 feet) was grooved. This was done because the decelerative ability of the entire runway was considered more important for a "first" installation than any potential deterioration problem.

The postgrooving "dust" problem was first detected on this job as a "visibility" problem by landing aircraft. The need for daily thorough removal of postgrooving slurry of pavement grit and water (figs. 8 and 9) thus became apparent and was made known to other airport managers who were considering grooving.

The job was completed in April 1967, on schedule. The workmanship was very satisfactory.

To evaluate the endurance of the grooves, engineering "control" points were established in the touchdown areas to assess wear and tear. (See figs. 10 and 11.) These control points were photographed when the runway was grooved, and were again photographed recently after more than 400 000 operations. Several of these photographs are shown as figures 12 to 15.

No serious deterioration of the grooves was noted after 18 months of use, nor had the grooves collapsed due to summer heat or become filled with touchdown rubber. They were not damaged by snowplows, nor had they packed with antiskid sand. The surface was scarred by airport maintenance equipment on occasion (figs. 16 and 17) and experienced some "pop-outs" (fig. 18). However, the most noticeable recent change has been a shift of a portion of the surface in the touchdown area of runway 36 (fig. 19). This shift seems to be related to the pavement construction and further study is planned.

It should be noted that the runway was in very good condition before it was grooved and had no history of slick-runway incidents or accidents. However, some knowledge of the friction characteristics of the runway, dry and wet, before and after grooving was necessary. A Swedish Skiddometer, which the FAA purchased in 1964, was used to obtain these data. This trailer measures the surface drag of a smooth tread ASTM 7.50 × 14 tire at 13 percent slip and records it as a traction number on paper tape in terms of distance and time. The trailer-tow vehicle is also equipped with an FAA-designed 150-gallon water system capable of dispensing 20 000 feet of water film (approximately 0.020 inch thick) in the path of the test tire (fig. 20).

Wet and dry friction surveys of the runway were made at velocities of 10, 30, 50, and 60 miles per hour at locations on the runway centerline, 25 feet each side of the centerline, and along the runway edge. The edge survey was made to compare the friction characteristics of the unused part of the runway with those of the used part. The friction measurement pattern is shown in figure 21.

The resulting data showed that the grooves removed the great variation in the wet traction of the ungrooved runway. In essence, it equalized the wet friction characteristics of the entire runway by removing the "spikes" in the data (fig. 22). These spikes are the effect of rubber deposits, smoothly worn surfaces, and contaminants on the wet friction characteristics of an ungrooved runway.

It thus appears that grooving effects the following improvements in airplane performance on a wet runway:

1. It minimizes the probability of hydroplaning.
2. It alleviates the effect of rubber, contaminants, and smoothly worn surfaces on wet surface traction.
3. As a result of the influence of items 1 and 2, aircraft directional control, deceleration, and nose-wheel steering become more responsive to pilot technique.

These conclusions appear to be substantiated by the reports of airline pilots who have landed on the grooved runway under rainy weather conditions and have stated that aircraft deceleration and control were improved after the runway was grooved.

A more detailed discussion of the wet friction surveys made of the ungrooved and grooved runway will be released in the near future as an FAA Report.

At this point, mention must be made of the environmental test that the FAA Systems Research and Development Service has been conducting on 18 groove patterns at five airports, each in a different climate. This test is being conducted in collaboration with NASA and will serve to evaluate the traffic/wear/environmental effect on 18 groove patterns in concrete and asphalt taxiways. The patterns being tested are in two groups; one being 1/8" deep grooves, the other being 1/4" deep grooves. The spacings are 1", $1\frac{1}{2}$", and 2"; the groove widths are 1/8", 1/4", and 3/8". (See fig. 23.)

The test grooves were installed in 1967 at Miami, Cleveland, New York City (John F. Kennedy International Airport), Salt Lake City, and Las Vegas airports. Taxiways were used, instead of runways, as test beds because of the experimental nature of the project. A typical view of the surface at Salt Lake City is shown in figure 24.

All test beds have experienced at least four seasons. The groove patterns in the concrete taxiways have stood up well. Those in the asphalt taxiways have not been as successful, particularly those in Las Vegas, Salt Lake City, and Miami, because of the effect of high ambient temperature and of traffic on plastic flow and displacement of the stone chips in the wheel track areas. Although the individual reports on each test site have not yet been summarized, the following specific comment by the engineering observers of the Salt Lake City and Las Vegas tests are of interest (fig. 25):

> In all cases, 1/4" deep grooves (in asphalt) are structurally poorer than 1/8" deep grooves. At Salt Lake the 1/8" deep grooves were cut into the stone chips . . . the 1/4" deep grooves penetrated the bituminous course which is more plastic . . . From these observations, the 1/4" × 1/4" × 1" grooves (seem to) have less structural stability than the same pattern only 1/8" deep. 3/8" grooves would remain open longer . . . Grooves spaced 2" apart, 3/8" wide, 1/8" deep had the least deformation . . . All grooves 1/8" deep withstood deformation better than any 1/4" deep.

The report from Miami, after 10 months of service, was similar to that of Salt Lake.

Another problem experienced to date is that the application of a seal coat to a grooved surface will fill up the grooves, as shown in figure 26.

Although this experience at locations with high ambient temperatures is different from that with the grooved asphalt runway at Washington National Airport and the asphalt test bed at John F. Kennedy International Airport, the following general conclusions may be observed:

1. The asphalt mix and the size of the aggregate in a runway surface can influence the endurance of the grooves under high ambient temperature conditions.
2. Grooved asphalt surface courses tend to hold up better under traffic and high ambient temperatures than do grooved seal coats.

3. The surface structure of an asphalt runway should be considered when evaluating the potential effect of grooves on pavement endurance.

4. Grooves in portland cement runways appear to have greater endurance and resistance to environmental effects than those in asphaltic concrete runways.

5. Wider (3/8") grooves tend to accumulate debris – as shown in figure 27.

CONCLUDING REMARKS

The Federal Aviation Administration has been actively interested in runway grooving since December 1965. The FAA Washington National Airport runway 18-36 was the first civil transport runway in the United States to be grooved; it has successfully sustained over 400 000 take-offs and landings. The FAA has performed friction surveys of grooved and ungrooved runways with a Swedish Skiddometer. The data indicate that the grooves equalize the traction characteristics of the wet pavement. Airline pilots have reported that airplane deceleration and control during landings under rainy weather conditions are better on a grooved runway. It is believed that this improvement is related to equalization of traction. The FAA is testing 18 groove patterns at five airports to assess the effect of climate and traffic on these groove configurations. It has sponsored runway grooving under the Federal Aid to Airports Program. The FAA research and development activities in the science of grooving are being coordinated with ATA and NASA and will be continued to assure efficient, economic application of the new technology which was pioneered by our friends in the United Kingdom.

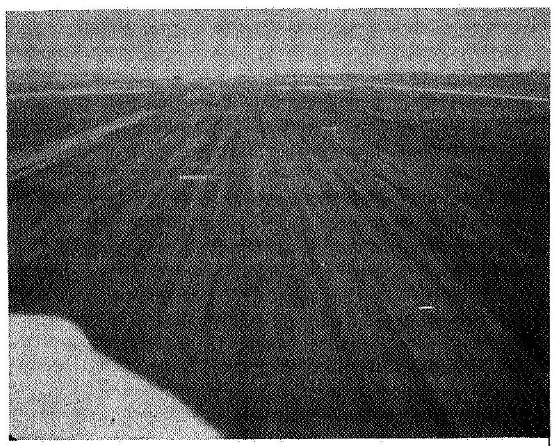


Figure 1

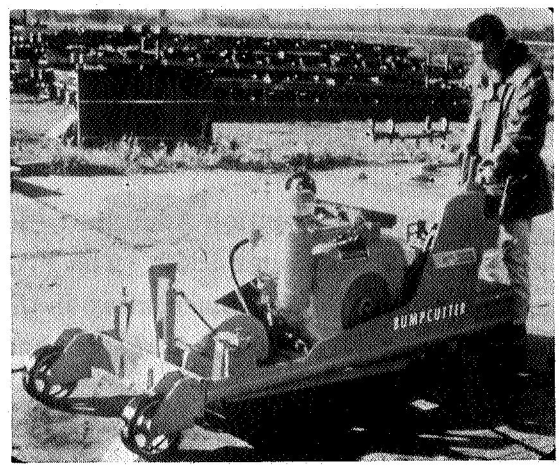
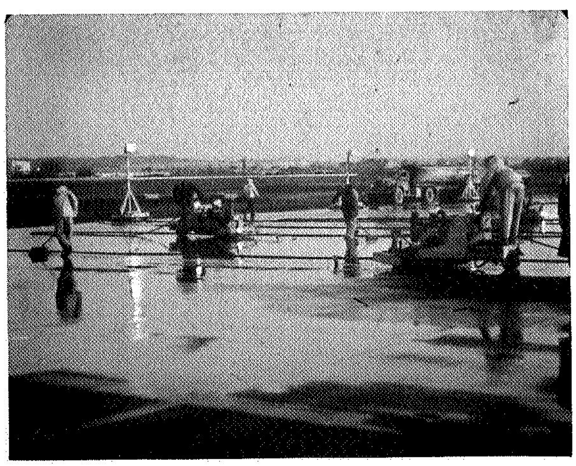


Figure 2



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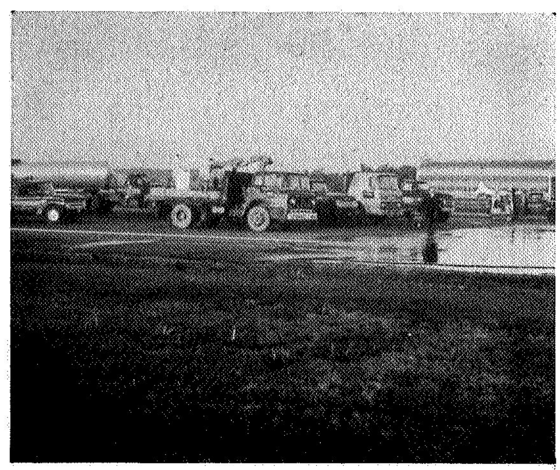

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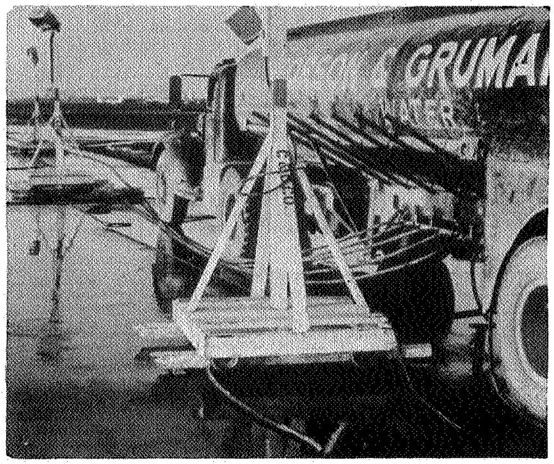


Figure 5

Figure 6

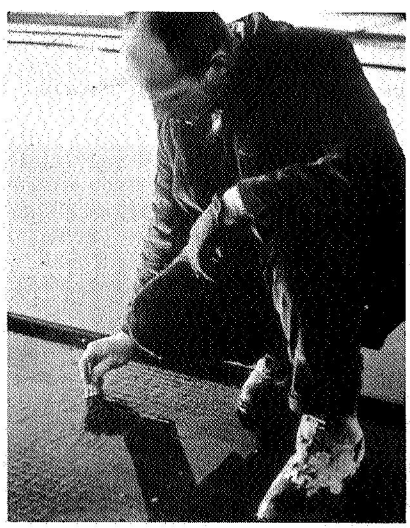
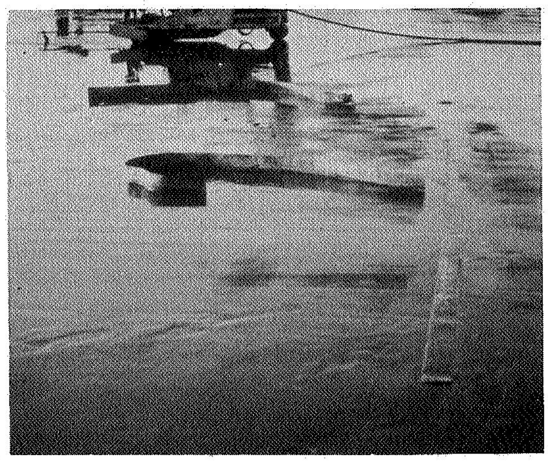


Figure 7

Figure 8



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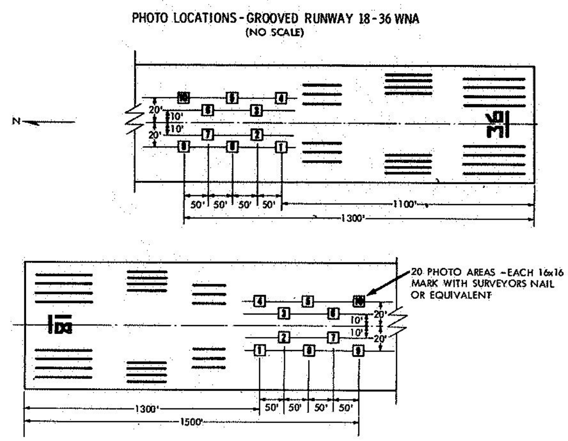


Figure 10

Figure 11

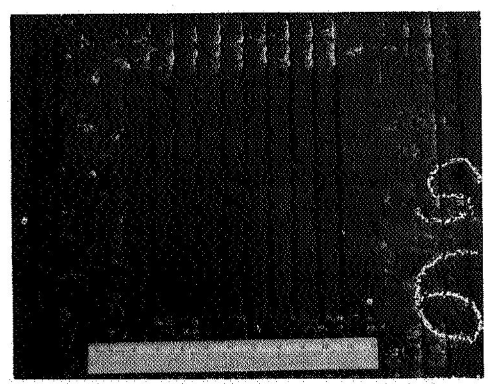
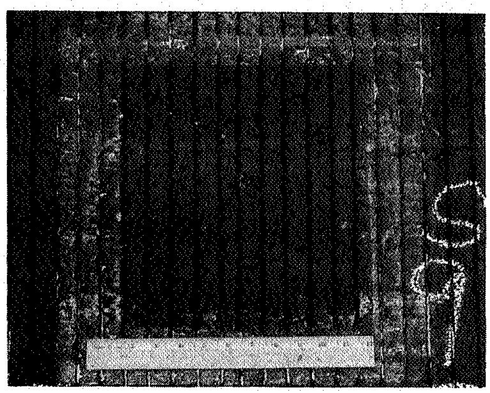


Figure 12



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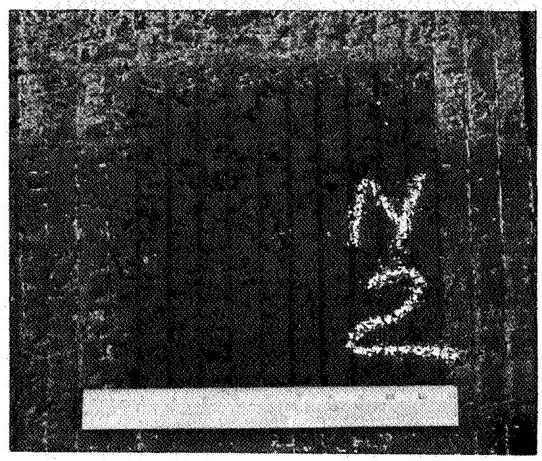

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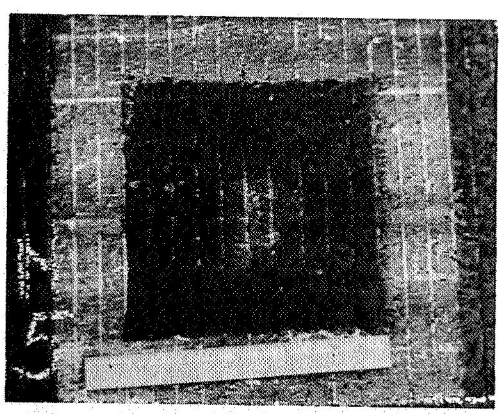

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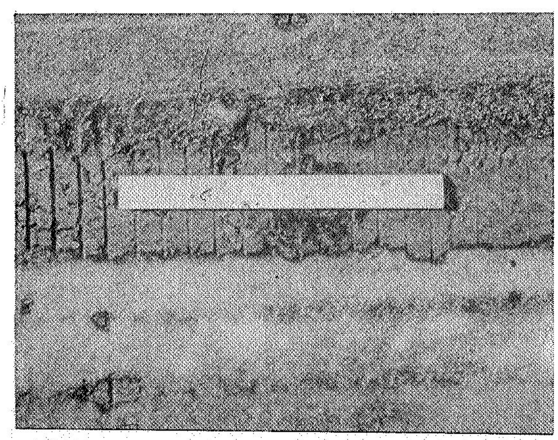

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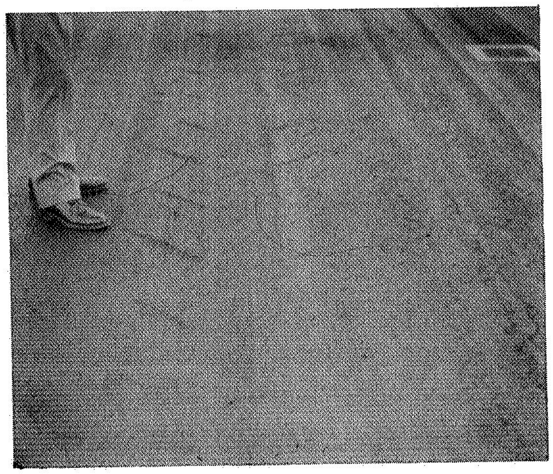


Figure 17

Figure 18

Figure 19

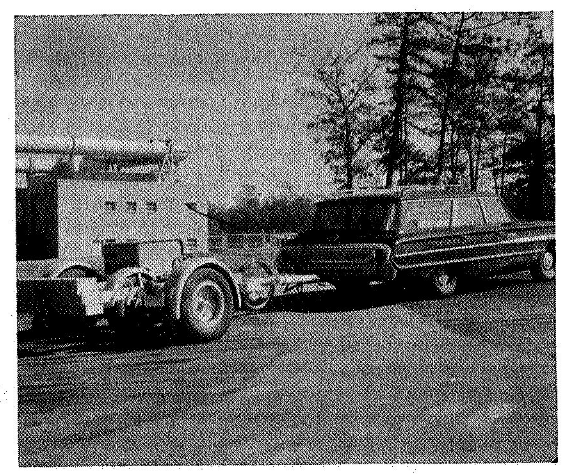


Figure 20

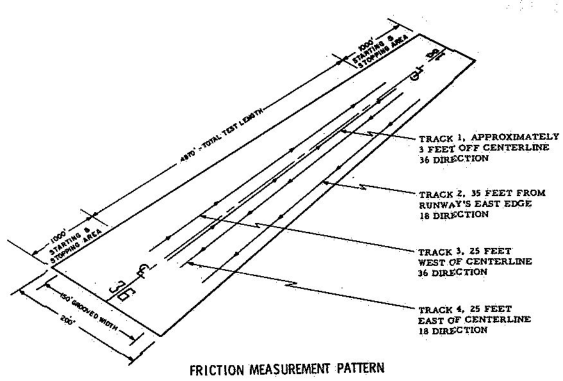
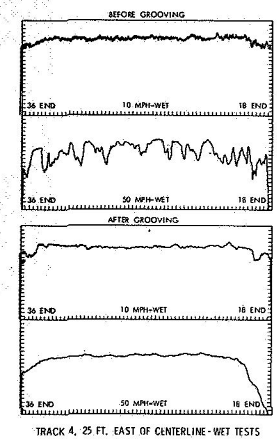


Figure 21



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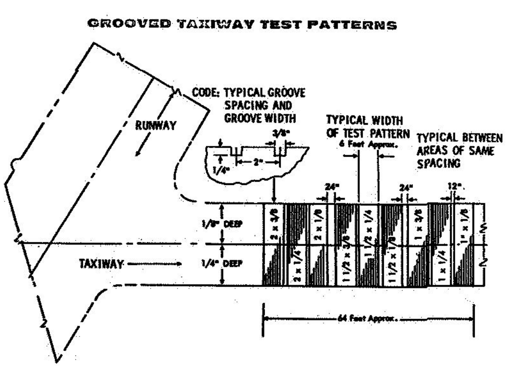
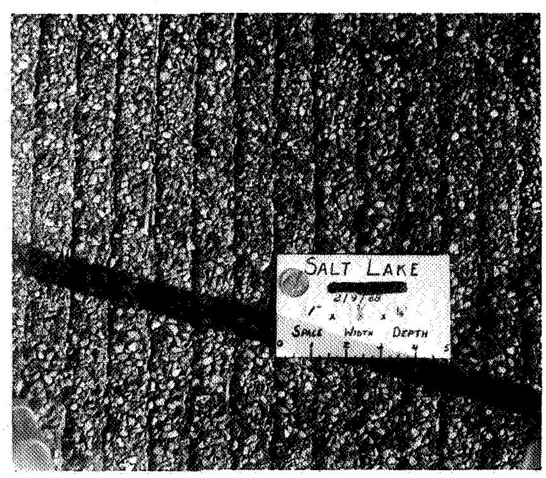


Figure 23



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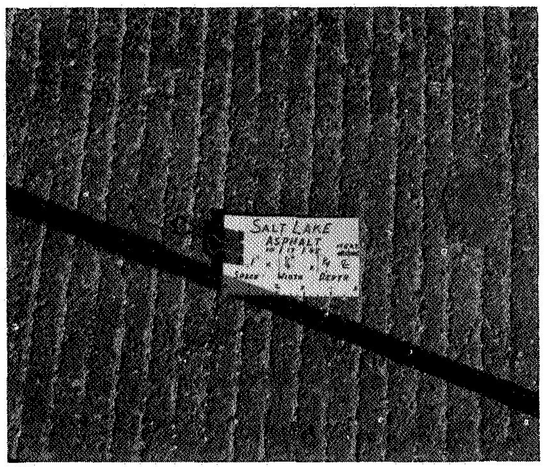

Figure 25

Figure 26

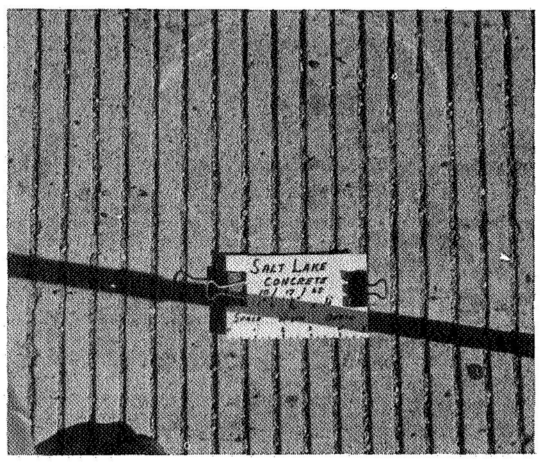

Figure 27

20. RUNWAY GROOVING AT KANSAS CITY MUNICIPAL AIRPORT

By Howard W. Willoughby

Kansas City Municipal Airport

SUMMARY

The runway grooving project at Kansas City Municipal Airport has now been completed for about 18 months. The problems encountered during construction and the results as observed by an airport operator will be discussed. Although some minor problems occurred during the grooving, the only major problem was control of the dust caused by the grooving machines. No major problems have been encountered insofar as runway maintenance is concerned after approximately 18 months of use. It would appear that runway grooving may have a place in the aviation industry for improving runway traction during inclement weather. No definite conclusions are being drawn from the observations of the project at Kansas City Municipal Airport. The results of this project should be evaluated with the results of projects at other airports in order to determine the effectiveness of the grooving and under what conditions grooving should be initiated at other airports.

INTRODUCTION

The subject of runway grooving on airports is important because grooving may have an effect on the length of runways recommended by the Federal Aviation Administration since additional runway is required when the surface is wet. While the theory of runway grooving has been accepted in the United States for some years, the effect of its application on commercial airports in this country has been unknown. Unknown areas include the effect of the grooves on aircraft vibrations and tire wear of both large commercial jets and general aviation aircraft and the effects of the aircraft upon the grooved surfaces of both asphalt and concrete paving. The grooving at Kansas City Municipal Airport offers a look at some of these problems in that both heavy jet aircraft and general aviation aircraft use the runway and both concrete and asphalt grooved surfaces exist on the same runway.

Before a definite decision was made to groove the runway at Kansas City Municipal Airport, many discussions were held with interested agencies involving the possibility of aircraft stopping in a shorter distance with a grooved runway and the effect the aircraft would in turn have upon the runway surface. A prime concern was the possibility that the grooving might cause rapid deterioration of the runway surface by spalling in the concrete areas or that the grooves in the asphalt might close up during the hot summer months. If the grooving caused rapid deterioration of the surface, the runway would have to again be closed to be resurfaced. This closing would create not only a financial problem but an operational problem since there is only one runway available for commercial aircraft.

Once the Aviation Department of Kansas City was convinced that no adverse effect would occur because of the surface grooving, those other agencies concerned, specifically the airlines operating at Kansas City and the Federal Aviation Administration, were notified that the grooving would take place at Kansas City Municipal Airport. The grooving commenced on April 2, 1967, and was completed on May 26, 1967.

DISCUSSION

Kansas City Municipal Airport has one main runway, which is 7000 feet long. A shorter 5000-foot crosswind runway crosses the main north-south runway at its approximate midpoint at a 30° angle. The crosswind runway has displaced thresholds at both ends of the runway so that its use for commercial aircraft is severely limited. With these runway conditions, the main problem in grooving was how to groove the runway without completely shutting down the airport for prolonged periods of time. While the crosswind runway could be used for general aviation and smaller commercial aircraft at times, the intersection area of the two runways including sufficient clearance on both sides of the intersection created a problem, in that at many times the airfield would have to be completely shut down.

The Aviation Department of Kansas City investigated the various types of equipment available for runway grooving and determined that the project could be completed within 60 days, working an 8-hour shift at night with approximately $5\frac{1}{2}$ to 6 hours available work time on the runway. The project was actually completed in 55 days.

The project officially began at 11:15 p.m. on April 2 and finished at 7:00 a.m. on May 26, 1967. The contractor worked approximately $5\frac{1}{2}$ hours per night. The basic plan was to close the runway for 30 minutes then open it for 15 minutes to allow traffic to take off or land. There were a few variations in the time on and off due to airline schedules, but basically no aircraft was forced to hold more than 30 minutes, nor was the contractor forced off the runway for more than 15 minutes at a time. Because of the slow travel speed of the cutting equipment and lost time in starting and stopping, a 1-hour cycle would have been better, that is, shutting down the runway for 45 minutes and then opening it for 15 minutes. Since flight departures tend to be on the hour, using intervals from the hour to 15 minutes after for arrivals and departures and from 15 minutes after to the hour for the grooving operation would have been better at Kansas City Municipal Airport.

The cooperation of the contractor, FAA tower, and airlines was excellent. The project was run on a schedule and everyone concerned adapted readily to the schedule and planned around it. There was an occasional interruption of the schedule due to weather or other unusual conditions but, in general, no problems existed insofar as scheduling was concerned.

The grooves were cut with a Christensen Diamond Service, Inc., concrete planner with 36 diamond cutting edges. The grooves were cut 1 inch on centers by 1/8 inch wide by 1/4 inch deep. It took approximately 12 minutes to cut a 130-foot groove across the runway in asphalt and close to 20 minutes in concrete. The grooves were cut 130 feet wide in order to leave a 10-foot shoulder on each edge for maneuvering the equipment. The equipment is heavy and equipped with steel wheels. The area at the edge of the runway becomes muddy from the large amount of water used, so it becomes impractical to run the equipment off the pavement to turn around.

The grooving started 600 feet from the south end of the runway and progressed north for 4500 feet. The north 1900 feet of runway were not grooved. Because of the unknown results of the method of cutting, the Aviation Department of Kansas City was skeptical about grooving the runway ends. It appeared that the most abuse to the grooves might occur while an aircraft was running its engines up prior to take-off. Because of the heavy vibrations and blast effect on the runway end, grooving was started just beyond the first touchdown marking. All landings during poor visibility and heavy rain are made to the south because of the instrument landing system. It was anticipated that an aircraft touches down and begins heavy braking about 2000 feet down the runway when landing south, so grooving was started at this point. It should be noted that the end result of this grooving was unknown and it was felt that a minimum area, consistent with being large enough to be practical, should be considered in the initial program.

The only major problem, which was a complete surprise, was the dust caused by the cutting. The dust turned to a slurry that was almost impossible to remove either wet or dry. The runway was washed, vacuumed, swept, and squeegeed but dust still remained when the surface dried. Both hand and machine operations were tried. It was impossible to remove the dust when dry by either sweeping or vacuuming. The dust is a very fine powder rather than granular. No particles or chips were seen during the operation. The dust, or powder, remained in the grooves, joints, and pores of the runway surface. Since no method was found to be effective in removing the powder, it must be a major concern to any airport attempting to groove a runway. It is believed that a large amount of high-pressure water would be the best solution to getting rid of the powder, but getting the water in large quantities to the runway can present a problem.

The danger of the powder appears to cause more of a psychological reaction than a danger to aircraft. The problem on take-off looks bad, but all dust is behind the aircraft.

On landing, dust or powder is kicked up from the reverse thrust. As long as the aircraft is moving at a relatively high speed, the dust stays well behind the aircraft. The real problem occurs when the aircraft is moving at a very slow speed with high reverse thrust. Undoubtedly, some powder is ingested at this time. This situation is accented with a four-engine aircraft that has drifted toward the edge of the runway because the edges are not blown clean by repeated take-offs as happens in the center of the runway.

Another problem area of the powder residue occurs at pavements that intersect at small angles. As the runway is washed, brushed, and so forth of residue, the residue spreads over other pavements off the runway being grooved. This causes the wet slurry material to spread over large areas before running off the pavement edge. In some areas, large amounts of slurry collect and create a problem of handling the material. Drainage, of course, has a major effect on how big a problem is created at intersections as well as on the runway itself. When powder accumulates at intersections and aircraft taxi over the area at low speed, the powder is blown loose. However, when an aircraft enters these areas at high speed with reverse thrust, large clouds of dust occur.

Possibly, arranging the grooving sequence to proceed from the high points on the longitudinal profile of the runway to the low points would have helped. The slurry would tend to run downhill over the ungrooved area rather than filling the freshly cut grooves. Starting the cuts at the runway center line and working toward the runway edges might also force the slurry to run off the runway.

Although not major, other unexpected small problems did occur. When the grooves were cut across cracks in concrete, the surface around the crack spalled. Some of the spalls were quite extensive, particularly when the angle across the cut was small. The cutting edges on the machine tend to tear out any loose concrete, and these areas had to be patched.

Another minor problem is the effect of the grooving on the asphalt overlay as it tapered or featheredged onto the concrete. Some of the asphalt came loose immediately. There is evidence that the asphalt was not properly bonded to the concrete in some areas. The Aviation Department of Kansas City now must watch the overlay in the area that feathers onto the concrete. There is no doubt that this has been weakened. What problem, if any, occurs remains to be seen. It is felt that some additional asphalt will break away, but no real difficulties are anticipated.

The results of the grooving as observed by the Aviation Department of Kansas City are considered very good. A James decelerometer in a vehicle is used to check braking action. The decelerometer shows readings of 20 or better under most conditions on the grooved pavement. Under extremely heavy rain, the reading may drop to 16 or 17. This is still good. The readings tend to remain fairly constant. Pilots have given braking action reports of "good" under conditions that normally would have been "fair" or "poor" prior to grooving.

The difference in appearance of the runway surface is remarkable. During rain storms, the ungrooved section of the runway has a slick, wet appearance. The grooved section is dull in appearance. The water spray under the wheels is cut drastically in the grooved area. It is therefore believed that the grooving is beneficial on take-offs as well as landings. The grooves in the center of the runway stay clean because of engine blast effects and the washing action created by the tire pressure on the water in the grooves. From visual observation, listening to pilots' reports on braking action, decelerometer checks, et cetera, it appears that braking action is definitely improved by the grooved surface.

Kansas City Municipal Airport is fortunate in that there are two fire hydrants on the airfield that the contractor was able to use for a water supply. Aluminum pipe was laid from the hydrants to the runway. This was a long distance and created problems in that it crossed taxiways and, on occasions, the other runway. The water pressure was low by the time it got to the grooving machines, but using the pipes was better than hauling water in by truck. One incident happened because of this waterline. A C-46 taxied over the line on the taxiway and caused the tubing to collapse. The pilot had been informed that the taxiway was closed, the pipe was marked with barricades and lights, and it was daylight at the time. There was no damage except to the pipe and the contractor's temper.

Two minor problems occurred during the construction of the runway that can easily be eliminated. Two and sometimes three machines were used for the grooving operation. The machines were spaced approximately 100 feet apart down the runway and worked independently of each other. The first problem occurred as one grooving machine approached the area already grooved by the machine ahead of it. An attempt had been made to space the initial pass so that as the grooved areas met there would be no void left on the surface of the runway. This was a mistake since in most cases an overlap problem did occur, and rather than leave a void of something less than 3 feet on the runway surface, an attempt was made to overlap adjoining grooved areas. This became impractical, if not an impossible problem, in that cutting in the same groove on an overlap caused wider grooves to occur and eventually some deterioration occurred at these locations. Second, attempts were made to make the cuts across the runway in one continuous pass. This was not always possible and in attempting to aline the machines and cut in the same groove again, some uneven cuts in grooves occurred. It is faster and the grooving is as efficient if the new grooves are cut close to the ends of the existing grooves without any attempt to make the groove continuous.

The Aviation Department of Kansas City was concerned about what effect joint seal in the concrete areas would have upon the grooves. There was some concern that the seal would close the grooves and make them ineffective. This situation has not occurred. While the water may not drain as well from the runway because of the blocking of some of the grooves, the pressure of aircraft tires upon the grooves squeezes water out of the grooves so that the tires still ride on the surface of the runway. Water may remain in the grooves; however, it appears that this has no adverse effect upon braking action.

There was some concern that water freezing in the grooves during the winter might cause a hazardous runway condition. The reaction of the grooves to ice was more than satisfactory. While ice did form in the grooves, it appears that the weight and blast effect of the aircraft on the runway broke the ice from the grooves and had an effect of breaking up ice on the entire surface of the runway; however, that ice causes no problems would be a dangerous conclusion to make without further study. Further study should be made in this area to determine if there is a possibility that grooving will be an asset to winter operations and icy runways.

After approximately 18 months of operation, the asphalt area has shown practically no deterioration. The grooves are clean and show no signs of rubber buildup or closing due to braking action. There is no chipping, spalling, or loss of aggregate in the asphalt areas. If there is any deterioration in the asphalt pavement, it is insignificant and cannot be seen by casual observation.

There is some deterioration in the surface of the concrete pavement; however, it is difficult to determine specifically how much of this is a result of the grooving. There are two deterioration processes taking place. First, there is a noticeable increase in aggregate pop out in the surface of the concrete; however, at this time it is not considered to be a serious problem. In all probability, the cutting action of the saws has loosened aggregate next to grooves, and this has worked loose due to freeze-thaw cycles and the traffic of aircraft over the loosened aggregate. It should be noted that there are also similar pop outs in the ungrooved portion of the runway; however, not to the extent that there are in the grooved area. Second, there is a very definite increase in spalling along pavement cracks in the concrete area. The same situation does not exist in the asphalt areas. It is impossible to determine if the concrete is spalling more than it would have if the grooving had not been accomplished. At this time, it is not causing any serious problems insofar as maintenance of the surface is concerned.

After 18 months of operation, the Aviation Department of Kansas City can say that it is favorably impressed with the results of the grooving at Kansas City Municipal Airport. Experience here has shown that grooving of asphalt surfaces is causing no deterioration of the runway. The grooving of concrete surfaces may cause a problem depending on the condition of the existing pavement. In all probability, any old surface would show signs of aggregate pop out or numerous cracks which deteriorate more rapidly when grooved. It would appear that the results of grooving would be worth the possibility of increased maintenance to the surface of this type of runway.

The runway at Kansas City Municipal Airport was grooved 4500 feet in length and 130 feet in width at a cost of just under $90 000. It should be noted that the contractor had to work under severe handicaps and that he was limited in his time on the runway. The work was done at night and 7 days a week until the job was completed. The contractor was forced to contend with a continuous operation which required him to move equipment on and off the runway at 30-minute intervals. If a contractor were allowed to work on the runway a continuous shift without paying premium time for weekends and holidays, in all probability, his costs would be cut considerably. Those agencies attempting to determine a price for future grooving should not attempt to compare various prices without knowing the details of the operation under which the contractor was subjected.

CONCLUDING REMARKS

It would appear that there is a place for runway grooving either in the manner constructed at Kansas City Municipal Airport or some variation thereof. While there may be problems in accelerated runway deterioration, it seems that the overall results will more than compensate for this slightly accelerated deterioration of the surface of the runway. There are problems in construction, primarily in time and method of construction, as well as the problem of handling the slurry formed by the dust. Continued work on the dust problem will yield a solution.

It is felt that those interested in runway grooving should determine a method of grooving runways while they are being constructed. This would be particularly true in concrete runways since a constructed groove will in all probability tend to deteriorate the runway surface less rapidly than a sawed groove. There appears to be no feasible way at this time to construct a groove in an asphalt runway as it is being laid. There is the possibility of sawing the asphalt immediately after it is laid. This method will tend to cut construction costs of the grooving since the fresh asphalt will cut easier; however, the end product may not be satisfactory. When an economical method of constructing grooves has been obtained, all runways, regardless of length, should be grooved.

Grooving an existing operational runway will create some operational problems during the construction that must be handled on a local level. As more runways in the United States are grooved, some of the existing problems will be answered and undoubtedly some new problems will be turned up. It behooves each agency contemplating a runway grooving project to gather all information available from other airports. Unfortunately, most of the information available from contractors has been obtained by hearsay or roadway projects. The problems encountered on an airport have no relationship to most contractors' previous experience.

In conclusion, it is believed that runway grooving has its place in the aviation industry; however, some national or international agency must determine what place this is.

21. RUNWAY GROOVING PROJECT AT CHICAGO MIDWAY AIRPORT

By Michael J. Berry

Chicago Midway Airport

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INTRODUCTION

In November 1967 the entire length of runways 13R/31L and 4R/22L (fig. 1) were resurfaced with a continuous pour of concrete 100 feet wide. After the normal curing period for concrete, a slipperiness-when-wet condition arose and caused aircraft hydroplaning.

A thorough investigation of this condition was made. Representatives of the airlines, Air Transport Association of America, Federal Aviation Administration, Air Line Pilots Association, Chicago Department of Public Works, and Chicago Department of Aviation participated in the study.

After a test demonstration of transverse grooving by Super-Cut, Inc., the Chicago Department of Aviation submitted a request for labor, material, and equipment necessary to groove both runways in their entirety. Accordingly, plans and specifications were drawn up by the Chicago Department of Public Works, bids were submitted, and Brighton Building and Maintenance Company was awarded the contract known as Public Works Project No. 419 and Federal Aid to Airports Program Project No. 9-11-016-11.

The work on this project commenced on July 29, 1968, with a time limit of 50 days from starting date. The project was completed, within the allotted time limit, on September 14, 1968.

DESCRIPTION OF PROJECT

The existing concrete runway surfaces and adjoining asphalt shoulders were grooved to a depth of 1/4 inch. The grooves were 1/4 inch wide and were spaced $1\frac{1}{4}$ inches from center to center. The grooving was placed across the 100 feet of concrete and extended an additional 1 foot on each asphalt shoulder. Accumulation of debris and slush resulting from the grooving operation was immediately washed from the runway into grass areas by high-pressure hoses attached to high-pressure sprinkling trucks.

Complete cooperation between Ralph Scafuri (Project Engineer), the Federal Aviation Administration control tower, the airport management, and the contractor permitted continuous aircraft operations during the entire period of this grooving project.

Final inspection was made on September 26, 1968, by H. F. Zalewski, R. J. Bronson, L. Weinberg, N. DiGuito, V. Cronin, and Ralph Scafuri of the Bureau of Engineering; Michael J. Berry and Charles O'Connor of the Chicago Department of Aviation; C. W. Carstens and H. W. Hopper of the Federal Aviation Administration; and J. F. Mann of the Air Transport Association of America. These gentlemen accepted the completed project as satisfactory and according to plans and specifications.

Independent inspections of the grooved runways were made by Larry Tennis (Flight Standards), George Davis (Manager of Dispatch), and Carl Johnson (Station Manager), representing American Airlines, and by Robert Fulton (Station Manager), John Kukar (Airport Engineer), Mel Volz (Flight Manager), and Clark Luther (Regional Manager of Flight Operations), representing United Air Lines. All were satisfied that the grooving of these two runways would give top performance to landing aircraft by improving braking action and providing perfect drainage during rainfalls.

COMMENTS

It is the opinion of the airport management, as well as of pilots questioned at random, that the grooving undoubtedly provides a great improvement and reduces the possibility of hazardous conditions for landing aircraft. It is too early at this time to make a determination as to any possible deficiencies in the construction of the runways due to the grooving.

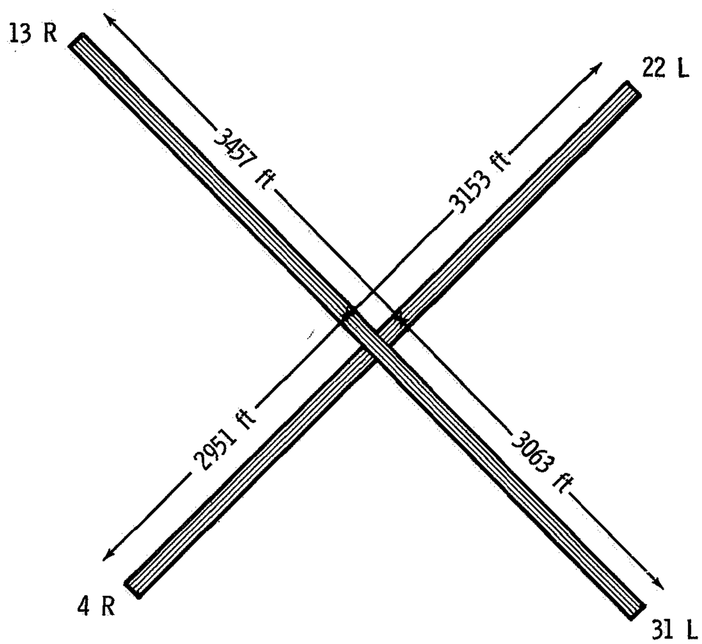

Figure 1.- Layout of runways 13R/31L and 4R/22L at Chicago Midway Airport.

22. CIVIL ENGINEERING ASPECTS OF GROOVING

By A. R. Miller

Beale Air Force Base

INTRODUCTION

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The grooving of runway and highway pavements has necessitated the Civil Engineering profession to develop methods and techniques to provide this requirement. The purpose of this paper is to discuss primarily the civil engineering aspects of runway grooving. However, most of the factors discussed have equal application to the grooving of highway pavements.

Significant items concerning design, preparation of plans and specifications, estimating, inspection of construction, and maintenance of grooving will be considered.

Data are based on experience gained as the result of grooving the portland cement concrete runway at Beale AFB with grooves 1/4 inch wide by 1/4 inch deep at 1 inch on centers. Beale AFB is a Strategic Air Command base located in a temperate climate approximately 50 miles north of Sacramento in California. Little or no freezing weather is encountered. The runway is extensively utilized by heavily loaded U.S. Air Force military aircraft including KC-135 tankers and B-52 bombers.

Prior to design of the grooving project, tests were conducted by the National Aeronautics and Space Administration on the Langley landing-loads track. In addition, available information was gathered concerning grooving both at Kansas City Municipal Airport and John F. Kennedy International Airport.

DESIGN

Design of a grooving project should consider groove configuration, location of grooving, runway pavement condition, and construction joints.

Groove Configuration

Groove configuration is dependent on the proposed purpose for the grooving. Spacing, width, and depth of grooves may be determined from tests or empirical calculations based on previous experience. Width of grooves should be based on standard blade widths of grooving equipment. Observations indicate that a minimum width of 1/8 inch is desirable to prevent premature filling of completed grooves and to allow necessary cleaning. Cost of grooving is a function of the volume of concrete removed.

Therefore, optimizing between groove configuration and volume of concrete removed should be considered.

Location of Grooving on Runways

The choice of location of grooving on runways should be made from a consideration of climatology, aircraft type, and use. With present-day and programed future high-performance aircraft, a minimum width of grooving of 100 feet is essential. Longitudinal placement is dependent on landing touchdown area and length of landing roll. At Beale AFB, the runway is 300 feet wide by 12 000 feet long with a 2000-foot overrun at the instrument end. The grooved area is 140 feet wide by 10 800 feet long, equidistant from both runway center line and runway midpoint. As an observation, grooving within 500 to 600 feet of each end of the runway should normally provide the optimum.

Correction of Defective Pavement Conditions

Correction of defective runway pavement conditions is essential prior to grooving. Therefore during design of grooving, provision should be made to repair spalls and to remove thin coatings of asphalt or rubber buildups. This repair-type work is probably best accomplished by utilizing runway maintenance forces. At Beale AFB spalling is repaired as part of a daily maintenance program. A "skid resistant" asphaltic seal coating approximately 1/4 inch to 5/8 inch thick had been previously applied to an area 150 feet wide by 4000 feet long in the landing touchdown area and had to be removed in addition to repairing the spalls. This asphaltic overlay was removed by using kerosene and mechanical road scrapers. A rubber buildup approximately 1/8 inch to 3/16 inch thick was under the overlay in some areas. This was removed by applying a rubber-dissolving chemical, by brushing, and by rinsing.

Existing Transverse Construction Joints

Existing transverse construction joints should be considered during design. At Beale a nominal 3 inches on either side of the joints was left ungrooved. Because of tolerances on groove alinement in some instances, actually only 1 inch was ungrooved.

PLANS AND SPECIFICATIONS

Plans and specifications adequately describing the following items are essential:

(1) Location of grooving on pavement keyed to some reference point

(2) Width, depth, spacing, and tolerances of grooves

(3) Type of concrete to be grooved including when constructed, class of concrete, aggregates utilized, slump, and compressive strength at 28 days

(4) Controls such as radio communication to be utilized during construction period

(5) Water supply – because of the large quantities used this is a very important item

(6) Power and lighting if work is to be accomplished at night

(7) Equipment – qualifications of bidders on proposed equipment to be used are important; provisions should be included to require the contractor to demonstrate cutting capability and control

(8) Patching of spalls as a result of contractor's operations

(9) Cleanup – this should be required continuously during grooving operations

(10) Traffic interruptions – time and compensation for removal of equipment is essential for this item.

ESTIMATING

Currently three methods of estimating cost of grooving are utilized for bidding purposes:

(1) Hourly – this method includes an hourly rate for cost of all equipment with operators, overhead (maintenance, rental, and adminstrative), and profit

(2) Unit price – this method is a cost per unit area to be grooved (usually 1 square foot); price includes all cost pertaining to equipment, operators, overhead, and profit

(3) Lump sum – this method is a lump-sum bid for all work to be performed; by necessity the contractor must include all of his cost including equipment, operation, overhead, and profit

Regardless of the method employed for bidding purposes, the actual direct cost of grooving is a function of the volume of concrete to be removed.

Data have been assembled by Beale AFB concerning the sawing characteristics of various portland cement concrete grooved pavements throughout the United States. This information presents comparative characteristics of each pavement as well as averages of all pavements analyzed. Beale conducted actual saw tests to compare its runway with California Freeways and the runways at Kansas City Municipal Airport, John F. Kennedy International Airport, and NASA Wallops Station. A 12-inch electric handsaw was placed in a guide for measuring saw cuts. Time required for a 12-inch-long cut was determined for cuts 1/8 inch wide by 1/8 inch deep and for cuts 1/4 inch wide by

1/4 inch deep. The 1/4-inch-wide cuts were made by placing two $\frac{1}{8}$-inch blades on the saw arbor. The same horizontal force was applied to the saw in all cases by means of a weight (19 lb, 7.51 oz) attached to the saw by a cable run through pulleys. Electric power was supplied to the saw from a gasoline-engine-driven electric generator (3000 watts, 115/230 volts, 26/13 amperes, 3600 rpm). Voltage and amperage were measured during each cut. At each location test cuts were made on at least two concrete slabs. A minimum of three cuts of each dimension were made in each slab.

The equipment utilized gave readings with an estimated accuracy of 95 percent. Variations in accuracy of readings generally were related to the roughness of pavements on which tests were made.

Measurements of voltage and amperage indicated that there was not a significant difference between start and finish of saw cuts for consideration in computation of comparative data. The only significant variations observed were during the cutting of aggregate embedded in the concrete. In all instances at all locations where large aggregate was encountered, there was a visible slowing of the saw as well as an increase in power requirement. These variations were particularly noticeable in the 1/4-inch-wide by 1/4-inch-deep cuts where more large aggregate was encountered at the 1/4-inch depth than at the 1/8-inch depth in all instances; also, at the 1/4-inch depth the size of aggregate was increased. These aggregate characteristics are normal for all the concrete pavements observed.

Results of comparative saw cuts for 12 locations are given in tables I, II, III, and IV.

Table I gives average volume, average of actual cutting times, and comparative time for 1 cubic inch of concrete removed for all cuts 1/4 by 1/4 by 12 inches. Table II gives the same information as table I but for cuts 1/8 by 1/8 by 12 inches. Table III gives average volume, average of actual cutting time, and comparative time for 1 cubic inch of concrete removed for all cuts within a tolerance of ±1/32 inch of the depth for 1/4- by 1/4- by 12-inch grooves. Table IV gives the same information as table III but for cuts 1/8 by 1/8 by 12 inches within a tolerance of 1/32 inch of the depth.

Time for cutting grooves is directly related to volume of concrete removed. This conclusion is based on the following calculations:

(1) The ratio of average volume for 1/4- by 1/4- by 12-inch grooves (table I) to average volume for 1/8- by 1/8- by 12-inch grooves (table II) is 0.747 cu in./0.216 cu in. or 3.4. The ratio of average time for cutting the same grooves is 17.1 sec/5.2 sec or 3.3.

(2) The ratio of average volume for 1/4- by 1/4- by 12-inch grooves ±1/32 inch (table III) to average volume for 1/8- by 1/8- by 12-inch grooves ±1/32 inch (table IV)

is 0.763 cu in./0.200 cu in. or 3.8. The ratio of average time for cutting the same grooves is 17.4 sec/4.8 sec or 3.6. These two values are considered the same since they fall within the accuracy of the test equipment.

(3) Comparative average times computed for cuts of 1 cubic inch all fall within the accuracy of the test equipment:

1/4- by 1/4- by 12-inch grooves	22.9 sec
1/8- by 1/8- by 12-inch grooves	23.9 sec
1/4- by 1/4- by 12-inch grooves ±1/32	22.7 sec
1/8- by 1/8- by 12-inch grooves ±1/32	24.2 sec

The fact that time for cutting is a function of volume is useful in calculating required time for cutting. Information is available from various governmental agencies indicating rate of advance of cutting machines. By correlating rate of advance with volume removed, the time required for any future work can be estimated very closely.

For example

Ventura Freeway
Grooves 1/8 by 1/8 inch at 3/4 inch on centers
Rate of advance of equipment, 5.2 ft/min

Beale AFB Runway
Grooves 1/4 by 1/4 inch at 1 inch on centers
Rate of advance of equipment, 1.7 ft/min

$$1/8 \times 1/8 \times \frac{12}{3/4} = 1/4$$

$$1/4 \times 1/4 \times \frac{12}{1} = 3/4$$

Therefore, three times the volume per unit width is removed when cutting the same length for a 1/4- by 1/4-inch groove at 1 inch on centers as compared with a 1/8- by 1/8-inch groove at 3/4 inch on centers. Since the rate of advance of the equipment used for cutting the 1/8- by 1/8-inch grooves was 5.2 ft/min, then

$$\frac{5.2 \text{ ft/min}}{3} = 1.7 \text{ ft/min}$$

which corresponds to the rate of advance of the equipment used to cut the 1/4- by 1/4-inch grooves at 1 inch on centers. The same equipment was used at both locations. Therefore, if this same equipment is used, the time required to cut the grooves can be estimated from the volume of material to be removed per cut.

INSPECTION

Inspection of actual contract grooving operations is extremely important. Particular emphasis is required in the following areas:

(1) Measurement of depth and width of cuts to assure accomplishment within tolerances specified

(2) Production rate. Sample timing of advance of grooving equipment during each shift is recommended. Observations should include location, pavement grade where sample is taken, and an estimate of percent and grading of aggregate exposed by cutting within sample area. Note that the production rate will vary from slab to slab because of the amount and size of aggregate encountered and the grade on which the machine is operating, that is, plus, minus, or level.

(3) Cleanup. The inspector should insure that cleanup proceeds continuously in accordance with specifications. Improper cleanup may seriously damage jet aircraft utilizing the grooved area.

MAINTENANCE

Nine months' experience at Beale AFB indicates that for the 1/4- by 1/4-inch groove pattern at 1 inch on centers, spalling due to grooving is not a factor. However, grooves in the landing touchdown area do fill with rubber at such a rate that approximately semiannual cleaning for rubber removal is anticipated. Rubber removal is accomplished by mixing one part cresylic acid (ref. 1) with three parts water. The mixture is applied by means of a liquid asphalt distributor equipped with a rear-mounted spray bar at a speed of 2 to 5 miles per hour. It is essential that this emulsion be pumped through the spray bar, not gravity fed.

Most effective results are obtained with air temperatures ranging between 65^{o} and 85^{o} F. The chemical emulsion is allowed to remain on the pavement surface 25 to 40 minutes, depending upon surface and temperature conditions. A metal-broom power sweeper is utilized to assist the chemical in loosening the rubber from the runway surface. The mixed solution is milky white and has the consistency of a very heavy, thick fluid. Simple spot checking with a stick or similar implement indicates the exact soak time. It is quite apparent when the rubber has been loosened from the runway.

The loosened rubber is rinsed off with water from tank trucks equipped with spray nozzles. The nozzles are pointed almost directly downward; thus a cutting action is created and the loosened rubber deposits are washed off the runway.

CONCLUDING REMARKS

Grooving at Beale AFB has eliminated the hydroplaning problems encountered previously with ungrooved runways. Also, the runway is completely drained in the grooved area even during heavy precipitation. No significant differences are discernible between the dry grooved runway and the wet grooved runway.

Nine months' experience with the grooved runway at Beale AFB has presented no particular problem to date from the civil-engineering aspect.

REFERENCE

1. Anon.: Carbon Removal Compound, Orthodichlorobenzene, for Engine Parts. Mil. Specif. MIL-C-25107(USAF), Apr. 18, 1955.

TABLE I.- $\frac{1}{4}$- BY $\frac{1}{4}$- BY 12-INCH GROOVES

Location	Ⓐ Average volume, cu in.	Ⓑ Average time, sec	$\frac{1.00}{Ⓐ} \times Ⓑ$ Comparative time for 1 cu in., sec
Sacramento Freeway	0.751	22.6	30.1
Ventura 101 Freeway	.734	18.6	25.4
Laguna Freeway	.742	15.3	20.6
San Diego Freeway	.777	16.8	21.6
Kennedy Airport	.805	16.8	20.9
Beale Runway	.682	13.9	20.4
Kansas City Airport	.735	17.0	23.1
Donner 1-80 Freeway	.751	22.6	30.1
Los Angeles 10 Freeway	.744	17.5	23.5
Los Angeles 405 Freeway	.750	15.9	21.2
Wallops Station	.813	14.9	18.3
Beale Taxiway	.685	13.5	19.7
Average of all locations	.747	17.1	22.9
Average of all locations excluding Beale	.760	17.8	23.5

TABLE II.- $\frac{1}{8}$- BY $\frac{1}{8}$- BY 12-INCH GROOVES

Location	Ⓐ Average volume, cu in.	Ⓑ Average time, sec	$\frac{1.00}{Ⓐ} \times Ⓑ$ Comparative time for 1 cu in., sec
Sacramento Freeway	0.211	6.0	28.44
Ventura 101 Freeway	.230	5.7	24.78
Laguna Freeway	.204	5.1	25.00
San Diego Freeway	.195	4.5	23.08
Kennedy Airport	.211	4.5	21.33
Beale Runway	.244	5.5	22.54
Kansas City Airport	.272	5.9	21.69
Donner 1-80 Freeway	.201	6.2	30.85
Los Angeles 10 Freeway	.207	5.3	25.60
Los Angeles 405 Freeway	.192	4.5	23.44
Wallops Station	.192	3.5	18.23
Beale Taxiway	.229	5.1	22.27
Average of all locations	.216	5.2	23.9
Average of all locations excluding Beale	.212	5.1	24.2

TABLE III.- $\frac{1}{4}$- BY $\frac{1}{4}$- BY 12-INCH GROOVES $\pm\frac{1}{32}$ INCH OF THE DEPTH

Location	(A) Average volume, cu in.	(B) Average time, sec	$\frac{1.00}{(A)} \times (B)$ Comparative time for 1 cu in., sec
Sacramento Freeway	0.806	23.4	29.0
Ventura 101 Freeway	.750	19.0	25.3
Laguna Freeway	.742	15.3	20.6
San Diego Freeway	.777	16.8	21.6
Kennedy Airport	.788	16.6	21.1
Beale Runway	.722	14.5	20.1
Kansas City Airport	.735	17.0	23.1
Donner 1-80 Freeway	.805	23.4	29.1
Los Angeles 10 Freeway	.744	17.5	23.5
Los Angeles 405 Freeway	.750	15.9	21.2
Wallops Station	.813	14.9	18.3
Beale Taxiway	.726	14.2	19.6
Average of all locations	.763	17.4	22.7
Average of all locations excluding Beale	.771	18.0	23.3

TABLE IV.- $\frac{1}{8}$- BY $\frac{1}{8}$- BY 12-INCH GROOVES $\pm\frac{1}{32}$ INCH OF THE DEPTH

Location	(A) Average volume, cu in.	(B) Average time, sec	$\frac{1.00}{(A)} \times (B)$ Comparative time for 1 cu in., sec
Sacramento Freeway	0.197	5.7	28.9
Ventura 101 Freeway	.223	5.5	24.7
Laguna Freeway	.204	5.1	25.0
San Diego Freeway	.195	4.5	23.1
Kennedy Airport	.183	3.9	21.3
Beale Runway	.192	4.8	25.0
Kansas City Airport	.200	4.4	22.0
Donner 1-80 Freeway	.201	6.2	30.8
Los Angeles 10 Freeway	.207	5.3	25.6
Los Angeles 405 Freeway	.192	4.5	23.4
Wallops Station	.192	3.5	18.2
Beale Taxiway number 3	.208	4.6	22.1
Average of all locations	.200	4.8	24.2
Average of all locations excluding Beale	.199	4.9	24.3

23. JOINT NASA-BRITISH MINISTRY OF TECHNOLOGY SKID CORRELATION STUDY

RESULTS FROM AMERICAN VEHICLES

By Walter B. Horne and John A. Tanner

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SUMMARY

An extensive skid correlation program was conducted on the landing research runway at NASA Wallops Station to study the degree of correlation existing among braking friction data obtained by 21 different highway vehicles and braking trailers, by a McDonald Douglas F-4D jet fighter, by a Convair 990 jet transport, and by several currently used methods of predicting aircraft stopping distance on slippery runways. Nine different runway surfaces were tested under wet and puddled and flooded pavement conditions by aircraft with ground speeds up to 135 knots and by ground vehicles with speeds up to 70 miles per hour. Braking results from the two aircraft showed good correlation in rating the relative slipperiness of the nine test surfaces for the pavement wetness conditions studied. Good correlation between the braking results obtained by the different highway vehicles and braking trailers on these surfaces was also shown when factors tending to mask correlation such as braking mode, water film thickness, and vehicle path clearing were accounted for. The current methods for predicting aircraft stopping performance on slippery runways were found to be inadequate. A promising new concept for estimating aircraft stopping distances on slippery runway surfaces, based on ground-vehicle stopping distance measurements, is presented.

INTRODUCTION

Accurate reporting of runway slipperiness at the time of take-off or landing on wet runways has been a goal of aeronautical research for many years. The pilot needs information with regard to both reduced braking action (increased aircraft stopping distance) and ground directional stability (cross wind limitation) to decide whether to land, seek an alternate airfield, or possibly delay the landing or take-off until safer conditions prevail on the runway.

A somewhat similar problem faces the highway safety engineer. Each state in this country has thousands of miles of highway of various types such as rural, urban, and interstate that may be new, old, slightly trafficked, highly trafficked, and so forth. The state of slipperiness of these pavements is constantly changing, and the highway engineer needs to know when the slipperiness of a pavement will reach the critical point at which its surface must be renewed to prevent accidents from occurring.

The most widely used method for obtaining this slipperiness information for both highways and runways at the present time is to employ friction measuring devices mounted on or towed by ground vehicles which are operating at selected speeds on the pavements to be tested. The problem most associated with this method is obtaining a good correlation among the various friction measuring devices. For the runways, correlation of the actual aircraft performance with the friction measurements made by ground vehicles under wet conditions has been most difficult.

For the highways, an even greater lack of correlation between friction measuring devices exists. Braking trailers which are built to similar specifications can give different results when tested upon identical wet pavements, as demonstrated by several past skid correlation studies. Before skid or friction numbers can be assigned to pavements on a nationwide basis to denote an acceptable or unacceptable slipperiness condition, it is mandatory to establish that a good correlation exists among the friction measuring devices used by the various states and interested organizations when testing identical pavements under similar wetness conditions.

This disturbing state of affairs led to discussions between the NASA and British Ministry of Technology personnel in 1965 and 1966 regarding the need for more adequate and extensive aircraft—ground-vehicle skid correlation studies. This need was also expressed to the ASTM Committee E-17 on Skid Resistance since most skid measuring equipment then in use was of highway origin. These informal discussions led directly to the organization of the Joint NASA-British Ministry of Technology Skid Correlation Study which was held on the landing research runway at NASA Wallops Station in June 1968. The study involved 21 different friction measuring highway vehicles or braking trailers from Great Britain and the United States. Also made available for the correlation study were the braking data obtained on the nine test surfaces of the landing research runway during braking tests of an instrumented F-4D jet fighter and a 990 jet transport performed during February-March and April-May 1968, respectively.

This paper has several primary objectives. One objective is the discussion of the degree of correlation in friction measurements obtained by the highway vehicles and braking trailers currently in use in the United States that participated in the present correlation study. The correlation of British friction measuring devices is discussed in reference 1. Another objective is to discuss the operation of present systems which attempt to correlate aircraft stopping performance with ground-vehicle braking action and to show why these systems fail to perform satisfactorily under wet pavement conditions. Finally, this paper will present a promising new concept for correlating aircraft stopping performance on wet runways with ground-vehicle stopping performance. This concept utilizes a diagonal braking technique which is also described.

LANDING RESEARCH RUNWAY AT NASA WALLOPS STATION

The site selected for the correlation study was the landing research runway at NASA Wallops Station (Site I). This runway has nine different test surfaces constructed of concrete and asphalt. Four of these surfaces are grooved and the five remaining surfaces are ungrooved. These surfaces are listed in table I and described in detail in references 2 and 3. The runway has a water distribution system of submerged hydrants spaced every 200 feet along the side of the level test sections of the runway. By using plastic irrigation pipe with the appropriate valves connected to the water distribution system, it is possible to wet or flood a traffic lane of all test sections, even simultaneously, if desired. Two wetness conditions were used for the correlation study. The first condition was classified "wet and puddled" and was obtained by intermittent usage of the plastic-pipe sprinkler system. Great care was taken to ensure that each test surface was just wet to the touch. However, some isolated puddles formed with this technique because of low spots in the surface. The second wetness condition studied was classified "flooded" and was obtained by continuous discharge of water from the plastic-pipe sprinkler system. Dependent on wind conditions, this technique usually allowed a fairly uniform water depth of between 0.1 and 0.2 inch to develop on each test surface. A photograph showing the sprinkler system in operation on a test surface is shown in figure 1.

HIGHWAY TEST VEHICLES AND BRAKING TRAILERS

Three vehicles from Great Britain and 18 vehicles from the United States participated in the skid correlation study. The results obtained from the British vehicles, however, will not be discussed in this paper. These results are discussed in detail in reference 1.

The U.S. vehicles studied included six two-wheel braking trailers built according to ASTM skid trailer specifications, a single-wheel braking trailer, a constant-slip three-wheel trailer built in Sweden, two diagonal braking automobiles, and five four-wheel braking automobiles.

Two-Wheel Braking Trailers

The following six organizations operated two-wheel braking trailers during the skid correlation study: Bureau of Public Roads (BPR), Florida State Road Department, Tennessee Highway Research Program, Virginia Highway Research Council, General

Motors Corporation (GM), Goodyear Tire and Rubber Company. All of these trailers conformed to ASTM Tentative Standard for Skid Trailers, ASTM Designation E 274-65 T (ref. 4).

Data were obtained for all of these trailers by braking either one or both of the trailer wheels to a full skid and recording ground speed and friction coefficients on direct-writing recorders. The General Motors braking trailer measured braking force rather than braking torque and thus had the additional capability of recording values of the transient peak friction coefficient as the test wheel was braked from a free-roll to a locked-wheel, or full-skid, condition. The trailer specifications are listed in table II. Photographs of the two-wheel braking trailers are shown in figure 2.

Single-Wheel Braking Trailer

The Pennsylvania State University Automotive Safety Research Program operated its single-wheel braking trailer during the skid correlation study. (See fig. 3(a).) This trailer measures braking force and, like the General Motors trailer, records the complete friction-coefficient variation of the tire as it is braked from a free-roll to a locked-wheel condition. Thus both transient peak and locked-wheel friction-coefficient data can be obtained. The vertical load applied to the test wheel was also different from that applied to the two-wheel trailers. The ASTM specification calls for 1080 pounds of vertical load per tire. The load applied on the Pennsylvania State University trailer wheel was only 800 pounds. Specifications for this trailer are given in table III.

Three-Wheel Braking Trailer

The Federal Aviation Administration operated a three-wheel constant-slip trailer (Swedish Skiddometer) designed by the Swedish Statinvaginstitut. (See fig. 3(b).) In this trailer, the centrally located test wheel is connected by a solid axle drive with appropriate universal joints to the two larger diameter outer trailer wheels. Thus the test wheel is forced to rotate at the same angular velocity as the outer trailer wheels. The ratio of test-wheel diameter to outer-wheel diameter is set such that the test wheel is forced to roll at a constant slip ratio of approximately 0.13. This slip ratio, which was determined by testing, usually produces a maximum braking friction condition on the test tire. Specifications for this trailer are given in table III.

Diagonal Braking Vehicles

The B. F. Goodrich Tire and Rubber Company (BFG) and NASA operated diagonal braking automobiles during the study (fig. 4). The braking systems on the B. F. Goodrich sedan and NASA station wagon were modified by installing cut-off valves in the brake lines. (See fig. 5.) These valves allowed one pair of diagonal wheels on each automobile to be braked while the opposite pair of wheels, unbraked and freely rolling, were free to steer or develop cornering or side forces for maintaining vehicle stability. This braking technique makes it possible for the test automobile to enter locked-wheel skids at high speeds on wet pavements and still maintain good directional control. Another useful feature of this technique is that diagonal braking automatically compensates for load transfer during brake application and one-half the vehicle mass is always braked. This technique simplified the computation of friction coefficients to simply subtracting the unbraked tire value of the vehicle deceleration from its braked value at a given ground speed and doubling the result.

The B. F. Goodrich diagonal braking sedan was equipped with a recording longitudinal accelerometer mounted at the vehicle pitch center and a trailing wheel for measuring ground speed. Outputs from both instruments were recorded on a direct-writing recorder. The NASA diagonal braking station wagon initially used a Tapley meter, which is a damped-pendulum maximum-reading accelerometer, to measure braking action during diagonal braking. Later instrumentation similar to that used in the B. F. Goodrich sedan was employed.

Four-Wheel Braking Vehicles

The United States Air Force, Federal Aviation Administration, NASA, and Ford Motor Company operated four-wheel braking automobiles during the study. This section of the paper will only describe the United States Air Force automobile since it was the only vehicle to acquire a complete set of data on the research runway. A Tapley meter and a James brake decelerometer were mounted securely to the front floor of a 1966 station wagon by NASA (fig. 6). This automobile was driven by an officer-engineer from the U.S. Air Force, Wright-Patterson Air Force Base who was versed in the U.S. Air Force Runway Condition reading (RCR) system. This system calls for an application of brakes hard enough to lock all four wheels at speeds of 20 to 30 miles per hour. The maximum reading of both the Tapley meter and James brake decelerometer was then recorded after each test brake application. Over 400 runs using this technique were made on the nine surfaces of the research runway under dry, wet and puddled, and flooded runway conditions.

CORRELATION BETWEEN HIGHWAY VEHICLES AND DIFFERENT BRAKING TRAILERS

It is the purpose of this section of the paper to demonstrate that present day instrumented automobiles and braking trailers used in the United States to determine pavement slipperiness do indeed correlate extremely well with one another when the factors which reduce the correlation, such as tire design, braking mode, vehicle path clearing, equipment calibration, and water film thickness are isolated or accounted for.

Tire Design

One of the first standard specifications for skid testing developed by ASTM Committee E-17 was for a standard test tire. An arrangement between tire makers in this country and ASTM guarantees that this tire will always be available for use in testing. The General Tire and Rubber Company is currently furnishing this standard tire for test purposes. This tire is furnished with four deep grooves as a tread design. The General Tire and Rubber Company also furnishes a tire built to the same ASTM specifications but without a tread design. These tires will hereinafter be referred to as the ASTM rib-tread and the ASTM bald-tread tires. These tires are shown in figure 7 along with a typical production tire currently used in the United States for comparison.

The General Motors braking trailer was equipped with an ASTM bald-tread tire on one trailer wheel and an ASTM rib-tread tire on the other wheel during the correlation study. Both wheels were braked to a complete lockup on the test surfaces of the research runway under wet and puddled and flooded pavement conditions. (See fig. 8.) Both transient peak (μ_{max}) and full-skid (μ_{skid}) values of friction coefficients are presented as a function of ground speed, and it can be seen that the bald-tread tire friction coefficients are generally more sensitive to pavement wetness and speed effects than the rib-tread tire. This fact is particularly noticeable on the ungrooved pavements. The grooved pavements, because of their better drainage capability, minimize the effects of differences in tread design and water film thickness.

The differences shown by the ASTM rib- and bald-tread tires in figure 8 illustrate the degree of traction loss possible if the ASTM standard test tire (rib tread) is tested in a badly worn condition. These data suggest that the greatest degree of sensitivity to pavement slipperiness and the least change in sensitivity from tire wear is obtained from tests in which the ASTM bald-tread tire was used.

Braking Mode and Path Clearing Effects

Both the two-wheel General Motors braking trailer and the single-wheel Pennsylvania State University trailer measure transient peak and full-skid coefficients of friction. The data obtained for the two trailers under wet and puddled and flooded pavement conditions are shown in figures 9(a) and 9(b), respectively. Both trailers used the ASTM rib-tread tire inflated to a pressure of 24 lb/in^2. The vertical loads on the trailer wheels were different in that the General Motors trailer used a tire load of 1080 pounds while the Pennsylvania State University trailer used a tire load of 800 pounds. Very good correlation between these trailers for both transient peak and locked-wheel braking modes was attained on the grooved test surfaces. This good correlation is attributed to two factors: First, the faster water drainage of the grooved surfaces tended to minimize pavement water film effects on friction measurements as contrasted with the results obtained on the ungrooved surfaces. Second, the effect of tire vertical load on the friction coefficients must be small at least within the load range of 1080 pounds (General Motors braking trailer) and 800 pounds (Pennsylvania State University braking trailer) used in this comparison.

A path clearing effect on friction coefficients obtained by the two trailers was anticipated since the General Motors trailer wheels tracked the towing vehicle wheels and the wheel of the Pennsylvania State University trailer did not. Unfortunately, the tests conducted on the two trailers were about a week apart in time. The data in figures 9(a) and 9(b) show that the path clearing effect was negligible. This effect may have been masked by the possibility that slightly different pavement wetness conditions existed at the time of the tests, especially on the ungrooved surfaces.

The Swedish Skiddometer used by the Federal Aviation Administration also has a centrally located test wheel. Since its mode of operation is to obtain steady-state peak friction coefficient (≈0.13 slip ratio), the skiddometer data can be compared with the transient peak data from the General Motors braking trailer to obtain a different braking-mode correlation. A comparison of the Federal Aviation Administration and General Motors trailers is shown in figure 10 for the wet and puddled runway condition. For this comparison, results for the trailers with ASTM bald-tread tires inflated to a pressure of 24 lb/in^2 were used, and the individual test tire load was maintained at 1080 pounds. A comparison of the data results obtained on the ungrooved test surfaces shows that the non-tracking Federal Aviation Administration trailer wheel experiences lower peak friction coefficients than the General Motors tracking wheel. This result confirms the fact that tracking trailer wheels can experience higher friction on wet pavements than can non-tracking trailer wheels because the towing vehicle wheels tend to clean or remove some of the water film from the tracking trailer wheel path.

On the grooved test surfaces of the research runway where water film thickness effects are minimized, practically no difference exists between friction coefficients obtained under transient peak (General Motors) or steady-state peak (Federal Aviation Administration) braking modes of operation. For the dry condition, where water cooling effects are not present, differences between transient peak and steady-state peak values may occur from tire surface temperature effects.

Some insight into the correlation between braking-trailer results and actual automobile braking performance can be obtained by comparing trailer and diagonal braking automobile results. Figures 11(a) and 11(b) compare the full-skid friction coefficients obtained by the General Motors trailer and the B. F. Goodrich diagonal braking automobile for the wet and puddled and flooded runway conditions, respectively. The ASTM rib-tread tire inflated to a pressure of 24 lb/in^2 was used by the vehicles for this comparison. The average vertical load on each front and rear tire of the B. F. Goodrich automobile was 1133 and 1135 pounds, respectively. The load on each General Motors trailer tire was set at the ASTM specified load of 1080 pounds.

Since the front wheels of an automobile are nontracking and the rear wheels track the front wheels in the normal driving condition, it would be expected that the results from the diagonal braking automobile would be lower than those obtained from the General Motors trailer. The data in figure 11 on ungrooved pavements are in agreement with this belief. On the grooved test surfaces, where water depth effects are minimized, the agreement between trailer and automobile results is good for the wet and puddled runway condition (fig. 11(a)). Some path clearing effects are present, however, for the flooded grooved runway condition (fig. 11(b)) and the values for the diagonal braking automobile are lower than the trailer friction values.

Another interesting correlation of trailer and automobile braking performance can be obtained by comparing results from the NASA diagonal braking automobile and General Motors trailer. This comparison is shown in figures 12(a) and 12(b) for the wet and puddled and flooded runway conditions, respectively. Only the data obtained by vehicles with the ASTM bald-tread tire are shown. The NASA braking-automobile data were derived from Tapley meter deceleration measurements. Since this instrument records the maximum deceleration of the vehicle during a braking cycle, correlation of the NASA data with General Motors transient peak friction values could be expected. However, spin-down occurring to the front and rear diagonal wheels during braking does not necessarily occur at the same instant of time because of different brake capacity and load transfer effects on the front and rear wheels. Thus the friction coefficient obtained should be an effective friction coefficient (μ_{eff}) which lies between the peak (μ_{max}) and locked-wheel (μ_{skid}) friction coefficient values.

The data shown indicate that the NASA automobile data fall between the General Motors transient peak and full-skid friction coefficient values. It is therefore apparent that even relatively crude instrumentation such as the Tapley meter can furnish pavement slipperiness information if its data are obtained and interpreted correctly.

Equipment Calibration

Data from the two-wheel braking trailers that participated in the correlation study are shown in figures 13(a) and 13(b) for the wet and puddled and flooded runway conditions, respectively. This comparison is shown for trailers using the ASTM rib-tread tires. With Virginia trailer results excluded, the best agreement of the data occurs for the trailers on wet and puddled grooved surfaces; however, for the flooded runway condition, the correlation between the trailers is poor. From previous discussion it is apparent that most of the lack of agreement on the surfaces arises from path clearing and water depth differences at the time of the test. The Virginia trailer results are usually higher than the values obtained from the other trailers. This discrepancy occurred because the Virginia equipment was found to be out of calibration after the tests were over. This unfortunate experience of Virginia points out that good correlation between trailers can be achieved only when a standard calibration procedure is specified and then used by all agencies concerned.

General Observations

Correlation between first generation braking trailers and instrumented automobiles studied at Wallops Station was outstanding on surfaces that minimized water depth effects. It is obvious that good correlation among trailer results on a nationwide basis cannot be obtained unless trailer self-watering of the test surface is employed and ASTM specifications on self-watering are made more stringent to ensure a uniform water film thickness on the pavement for all test speeds. This water film thickness must be the same for all trailers employed in skid resistance work. The proper film thickness to use is still in question. Possibly a research program should be undertaken on highways under rainstorm conditions to statistically determine this. The ASTM bald-tread tire was shown to be much more sensitive to pavement slipperiness in terms of both water depth and speed effects than the ASTM rib-tread tire. Perhaps, since this bald-tread tire gives a low limit boundary value of skid resistance, its usage should be preferred to the ASTM rib-tread tire for skid resistance standards.

For second generation highway friction measuring devices, braking trailers similar to the General Motors trailer should be made available. This trailer can test either wheel and measure instantaneous values of transient peak and full-skid braking forces as well as the vertical load acting on the tire. Friction coefficients obtained with this trailer can be corrected for load changes during braking that occur from pavement unevenness, vehicle bouncing, and load transfer. With an ASTM bald-tread tire on one side and an ASTM rib-tread tire on the other side, complete information can be gathered on pavement slipperiness for vehicle operating conditions, such as normal maneuvering or cornering (transient peak friction coefficient) and panic stop (full-skid friction coefficient) conditions.

Comparison of data for the ASTM bald- and rib-tread tires will make it possible to evaluate the skid resistance of a pavement for new as well as worn vehicle tires. The ASTM specification on trailer calibration should be made more stringent by allowing only one calibration technique to be used. If all agencies use the same calibration technique, the chances for calibration errors will be minimized.

CORRELATION BETWEEN AIRCRAFT

The landing research runway at NASA Wallops Station was completed in December 1967. The first braking studies performed on this runway were conducted with an instrumented F-4D, a well-known jet fighter, during February-March 1968. During April-May 1968, similar braking studies were conducted with an instrumented 990 four-engine jet transport, an aircraft which several airlines throughout the world currently operate. Detailed results obtained from these studies are reported in references 5 to 7. It is the purpose of this correlation study to show how these two widely different aircraft rate the relative slipperiness of the nine grooved and ungrooved test surfaces installed on the landing research runway for wet and puddled and flooded runway conditions. Figures 14(a) and 14(b) present the variation of the ratio of wet to dry effective friction coefficients with ground speed obtained for the two aircraft under wet and puddled and flooded runway conditions, respectively. It is necessary to use effective friction coefficients in this case because each aircraft had its braking effort modulated automatically by an antiskid system. For the 990 aircraft, each of the eight main-gear braking wheels had its own skid detector and skid control valve which constantly modulated brake pressure to prevent the wheel it controlled from locking up during brake application. The dual nose-gear wheels were also braked, but since these wheels were corotating, that is, splined to a common axle, they needed only a single detector and skid control valve. The F-4D aircraft braked only its single main-gear wheels. Each wheel had a skid detector but only a single skid control valve controlled the pressure at each wheel brake. Therefore, with this system a skid detected on one wheel would automatically reduce pressure on both main-wheel brakes. This system was necessary because the wide-spaced landing gear of the aircraft would enduce large yawing moments when unequal braking forces were allowed to develop on the main wheels.

The antiskid systems for both aircraft performed as designed when the aircraft underwent maximum braking under dry runway conditions and no wheel lockups were noted for either aircraft. The performance of the antiskid systems on wet and puddled or flooded runways was, however, quite different. For the F-4D aircraft, the antiskid system prevented the braking wheels from entering a locked-wheel skid. Only occasional deep wheel skids were noticed when the aircraft made the transition from grooved to ungrooved pavement. During braking tests of the 990 aircraft, many, sometimes simultaneous, wheel lockups occurred on the wet and puddled and flooded ungrooved pavements. These occurrences were almost entirely eliminated on the wet and puddled grooved pavement test sections; however, many lockups of the front wheels of the landing gear were noticed on all the flooded grooved pavement test sections.

With these observations in mind, the braking data shown in figure 14(a) for the wet and puddled runway condition indicate good correlation between aircraft in rating the slipperiness of the different pavements. For the flooded runway case (fig. 14(b)), the correlation is not as good perhaps because of the path-clearing ability of the dual-tandem wheel landing gear arrangement of the 990. It is important to note that the F-4D braking values go to zero at the higher speeds on the flooded ungrooved pavements. This condition indicates that a state of complete hydroplaning exists.

The braking ability of the two aircraft is more clearly demonstrated in table IV where calculated wet stopping distances from 135-knot brake engagement speed are shown along with ratios of wet to dry stopping distance for wet and puddled and flooded runway conditions. These data indicate that the 990 aircraft develops approximately twice the braking effectiveness of the F-4D for all conditions. This improvement is due to many factors including landing gear arrangement, tire pressure, antiskid system efficiency, use of spoilers, and so forth.

Even with this large difference in aircraft braking effectiveness, the ratio of wet to dry stopping distance for each aircraft is noticeably similar in value for each test surface and wetness condition. This similarity between aircraft stopping distance ratios is most encouraging since it increases the possibility of calculating aircraft stopping distance on wet runways if a suitable ground vehicle correlation can be found.

CORRELATION BETWEEN ACTUAL AIRCRAFT PERFORMANCE AND CURRENT METHODS FOR PREDICTING AIRCRAFT PERFORMANCE ON SLIPPERY RUNWAYS

Two methods are in use at the present time to predict aircraft stopping performance on slippery runways. The Runway Condition Reading system (RCR system) was developed by the U.S. Air Force to aid its pilots in determining whether a runway with a cover of slush, snow, ice, or water was safe to take off or land upon. The International Civil Aviation Organization also has adopted the use of the Swedish Skiddometer for reporting runway conditions at time of take-off or landing. It is understood that several European countries are currently using the Swedish Skiddometer for this purpose. It is further understood that both the Swedish Skiddometer and RCR system have met with success when reporting runway slipperiness due to a snow or ice cover. The present correlation study is limited to a discussion of wet and puddled and flooded runway conditions.

RCR System

The RCR system has a James brake decelerometer (damped-pendulum instrument) installed securely on the floor of the front compartment of an airport ground vehicle, usually a station wagon. The brakes of the vehicle are firmly applied until all four wheels are fully locked at a ground speed ranging between 20 and 30 miles per hour on the runway surface to be tested. The maximum position of the instrument needle is noted and the deceleration of the vehicle recorded. The vehicle must be equipped with standard or snow tires in good repair. The production tire shown in figure 7 is in this category. Depending upon the average level of deceleration recorded after a prescribed number of trials, the runway braking condition is classified according to an RCR number range which indicates whether aircraft braking is expected to be excellent, good, fair, or poor. Each aircraft operated by the Air Force has a pilot's handbook which translates the RCR number obtained into the probable increase in aircraft stopping distance at the time of measurement.

In figure 15 the ratio of wet to dry aircraft stopping distance obtained with the F-4D and 990 aircraft on the nine test surfaces of the landing research runway is compared with RCR values obtained with the automobile shown in figure 6 which was equipped with both Tapley meter and James brake decelerometers. The two different instruments agreed closely and the results shown are the average of about 400 RCR trials. The data presented in figure 15 indicate that the RCR system does not correlate with aircraft performance for the wet and puddled or flooded runway conditions. Indeed, while the RCR values indicate dry performance on the nine surfaces for both wetness conditions, the actual calculated aircraft stopping distance encountered was as much as three times the dry stopping distance.

Two factors contribute to the poor correlation of the RCR system with the calculated data: tire design and test speed. As illustrated in figures 16(a) and 16(b), the tire design is so efficient at speeds as low as 20 to 30 miles per hour that it can entirely mask pavement slipperiness for wet and puddled or flooded runway conditions for the nine surfaces of the landing research runway. Under these conditions it is impossible for the RCR system to tell when slippery conditions exist on the runway for aircraft.

Swedish Skiddometer and Other Ground-Vehicle Friction Measurements

The Swedish Skiddometer uses an entirely different technique to classify runway slipperiness on snow and ice. The method of operation is to make continuous measurements of friction coefficients under a steady-state peak condition over the entire runway length at selected test speeds. The runway length is divided into four parts and the braking action on each part is described as excellent, good, fair, or poor. The results of the tests are also used to determine whether remedial action such as snow removal by snow blowers or plows or sanding is required to provide sufficient runway skid resistance for safe aircraft operation. Figure 17 presents the correlation obtained between FAA Swedish Skiddometer dry-to-wet friction ratios and the test aircraft wet-to-dry stopping distance ratios at speeds of 20, 60, and 80 miles per hour for the skiddometer. The condition of the runway was wet and puddled and the ASTM bald-tread tire was used on the skiddometer. As with the RCR system, no correlation between these ratios exists at 20 miles per hour and better but still poor correlation exists at higher speeds.

A somewhat better correlation is obtained by the NASA diagonal braking automobile at 60 miles per hour for the wet and puddled runway condition as shown in figure 18; however, this good correlation could not be obtained when the runway was flooded. The reason for this lack of correlation for the flooded condition is obvious. Aircraft wet-to-dry stopping distance ratios on flooded runways are finite because aerodynamic drag as well as wheel braking forces are acting in concert to stop the aircraft. Ground-vehicle dry-to-wet friction coefficient ratios, however, must approach infinity because the friction coefficients for the flooded runway condition approach zero when complete hydroplaning occurs. Ground-vehicle friction measurements can supply a partial answer to the runway slipperiness problem. The friction coefficient measurements can indicate when pavements have enough fluid cover to create hydroplaning. This information can be supplied to the pilot to report a probable directional control problem in times of cross wind. This type of measurement obviously cannot supply reliable information on aircraft stopping distance.

CORRELATION BETWEEN AIRCRAFT AND GROUND-VEHICLE WET-TO-DRY STOPPING DISTANCE RATIOS

The lack of correlation between aircraft stopping distance ratios and ground-vehicle friction coefficients illustrated in the previous section of the paper emphasized the need for developing a new correlation concept. Comparing aircraft and ground-vehicle stopping distances under dry, wet and puddled, and flooded pavement conditions was thought to be a promising approach. While it is realized that the masses of the aircraft and ground vehicle are quite different, each vehicle type is exposed to similar-acting aerodynamic drag, wheel rolling resistance, and wheel braking forces during a stopping maneuver. Since most aircraft landing speeds are above the critical hydroplaning speed, it was felt that the ground vehicle must also be decelerated to a stop from a brake-engagement speed that was above its hydroplaning speed. Such a technique would insure as much similarity in stopping performance as was possible between vehicle types.

None of the ground vehicles participating in the correlation study measured stopping distance under braking conditions; however, the diagonal braking vehicles did measure vehicle deceleration. The values of deceleration obtained by these vehicles were integrated over the speed range of 60 to 70 miles per hour to a stop for dry, wet and puddled, and flooded runway conditions to obtain stopping distance information. Figure 19 shows the correlation of aircraft data using this concept with data from the B. F. Goodrich diagonal braking sedan equipped with ASTM rib-tread tires. The correlation obtained was remarkable in that such little scatter of data occurred about the line of agreement for both the wet and puddled and flooded runway conditions. However, the relationship shown does not indicate a direct correspondence between aircraft and ground-vehicle wet-to-dry stopping distance ratios. For example, an automobile ratio of 2.0 indicates that the aircraft stopping distance ratio is 3.0 for the same pavement wetness condition. An attempt was made to improve the correlation between aircraft and automobile stopping distance ratios by increasing the brake-application speed for the automobile from 60 to 70 miles per hour and by using the ASTM bald-tread tire on the braking wheels. Time permitted running this test on the wet and puddled runway only. The NASA station wagon was equipped with ASTM bald-tread tires for this study. The correlation achieved is shown in figure 20. It can be seen that the line of agreement is direct (45^{o} slope). These results, while preliminary, are extremely encouraging and indicate the possibility of estimating aircraft stopping distance on wet or flooded and possibly other slippery runway conditions. Further research must be carried out where full-stop aircraft and ground-vehicle tests are made under identical runway conditions to establish the validity of this concept.

CONCLUSIONS

This paper has attempted to correlate or explain the lack of correlation existing for braking data obtained by two aircraft, 21 different highway vehicles and braking trailers, and current methods for predicting runway slipperiness during participation in the Joint NASA-British Ministry of Technology Skid Correlation Study. The following conclusions were reached from this correlation study:

1. Good correlation exists between instrumented highway vehicles and braking trailers, regardless of braking mode, when vehicle path-clearing or water-film thickness variations on the pavement surface are minimized. This result leads to the corollary conclusion that better correlation between skid measuring equipment will exist if this equipment is furnished with a rigidly specified self-watering feature. The water film thickness deposited by each vehicle during the tests must be of the same uniform thickness. The ASTM bald-tread tire is much more sensitive to pavement slipperiness factors such as speed and water film thickness than is the currently used ASTM rib-tread tire.

2. The F-4D jet fighter and 990 jet transport, while having widely different stopping capabilities, demonstrated good correlation in defining the state of slipperiness existing during test on the nine different test surfaces of the landing research runway.

3. Results from the current methods for predicting runway slipperiness do not correlate well with actual aircraft performance under wet and puddled or flooded runway conditions. The Runway Condition Reading system cannot predict a possible hydroplaning

situation on the runway or be used for estimating aircraft stopping capability. The Swedish Skiddometer, or other techniques using ground-vehicle friction coefficients, can determine whether a hydroplaning situation is present on the runway. This information is useful for predicting possible loss of aircraft directional control in cross winds. These techniques cannot be used for estimating aircraft stopping capability.

4. A new concept for estimating aircraft stopping distance, based on ground-vehicle stopping distance measurements, appears to correlate extremely well with aircraft stopping performance. Further research is needed under full-stop conditions for both aircraft and ground vehicles to establish the validity of this concept.

REFERENCES

1. Sugg, R. W.: Joint NASA-British Ministry of Technology Skid Correlation Study – Results From British Vehicles. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 24 herein.)

2. Allen, Curtis R.; and Quillen, James W.: Problem Areas Associated With the Construction and Operation of the Landing Research Runway at NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 8 herein.)

3. Horne, Walter B.: Results From Studies of Highway Grooving and Texturing at NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 26 herein.)

4. Anon.: Tentative Method of Test for Skid Resistance of Pavements Using a Two-Wheel Trailer. ASTM Designation: E 274-65 T. Pt. 11 of 1968 Book of ASTM Standards With Related Material. Amer. Soc. Testing Mater., 1968, pp. 836-847.

5. Yager, Thomas J.: NASA Studies on Effect of Grooved Runway Operations on Aircraft Vibrations and Tire Wear. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 14 herein.)

6. Yager, Thomas J.: Comparative Braking Performance of Various Aircraft on Grooved and Ungrooved Pavements at the Langley Research Runway, NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 3 herein.)

7. Phillips, W. Pelham: Calculated Airplane Stopping Distances Based on Test Results Obtained at the Landing Research Runway, NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 6 herein.)

TABLE I.- LANDING RESEARCH RUNWAY SURFACES

Surface	Type	Surface finish
A	Ungrooved	Canvas belt concrete
B	[a]Grooved	Canvas belt concrete
C	[a]Grooved	Burlap drag concrete
D	Ungrooved	Burlap drag concrete
E	Ungrooved	Gripstop
F	Ungrooved	Small aggregate asphalt (3/8-in. diam or less)
G	[a]Grooved	Small aggregate asphalt (3/8-in. diam or less)
H	[a]Grooved	Large aggregate asphalt (3/4-in. diam or less)
I	Ungrooved	Large aggregate asphalt (3/4-in. diam or less)

[a]Groove dimensions:

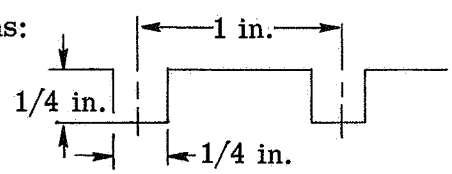


TABLE II.- TWO-WHEEL TRAILER SPECIFICATIONS

Braking trailers	Vertical load per tire, lb	Brake system		Watering system		Speed measuring system	Force measuring system	Suspension system	Calibration procedure
		Type	Activation	Pump	Water trace				
Bureau of Public Roads	1080	Shoe	Electric	Centrifugal	Constant discharge	Truck speedometer	Axle tube in torque	Leaf springs	Torque arm on wheel
State of Florida	1080	Shoe	Electric	Positive displacement	Constant film thickness to ASTM specifications	Fifth wheel	Stop bar in tension	Leaf springs	Platform load
General Motors	1080	Disc	Air over hydraulic	Positive displacement	Constant film thickness to ASTM specifications	Fifth wheel	Axle tube in torque	Coil springs	Platform load
Goodyear	1080	Disc	Vacuum over hydraulic	Positive displacement	Constant film thickness to ASTM specifications	Fifth wheel	Brake caliper in bending	Coil springs	Torque arm on wheel
State of Tennessee	1080	Shoe	Air over hydraulic	Centrifugal	Constant film thickness to ASTM specifications	Fifth wheel	Stop bar in tension	Leaf springs	Load through trailer tongue
State of Virginia	1080	Shoe	Vacuum over hydraulic	Positive displacement	Constant film thickness to ASTM specifications	Tachometer reading from drive shaft	Brake pin in bending	Coil springs	Platform load

TABLE III.- THREE-WHEEL AND SINGLE-WHEEL BRAKING TRAILER SPECIFICATIONS

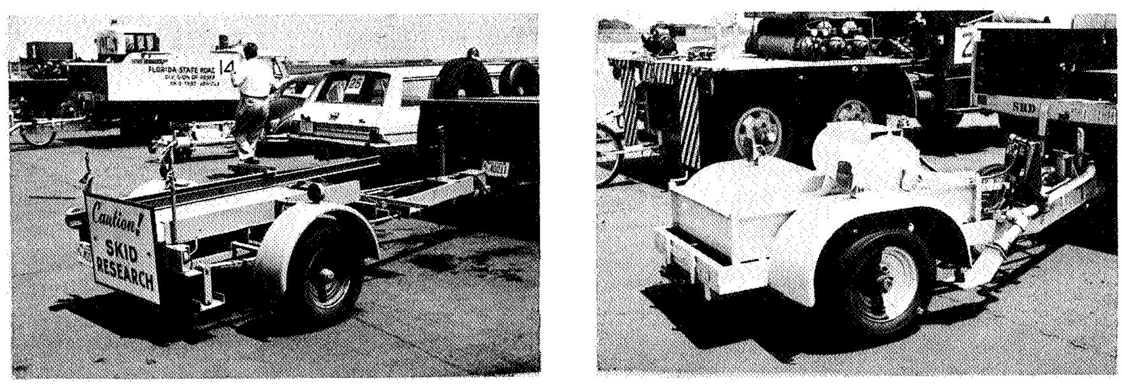
	Penn State	FAA
Vertical load on test tire, lb	800	1080
Brake system	Shoe type, activated by air over hydraulic	Driven wheel at constant slip ratio of 0.13
Watering system		
Pump	Centrifugal	Positive displacement
Water trace	Constant film thickness	Constant film thickness
Speed measuring system	Fifth wheel	Fifth wheel
Suspension system	Coil springs	Coil springs
Force measuring system	Parallel bars in tension and bending	Axle tube in torque
Calibration procedure	Platform load	Platform load

TABLE IV.- AIRCRAFT STOPPING DISTANCES FROM 135-KNOT BRAKE ENGAGEMENT SPEED

Surface	Calculated aircraft stopping distances, ft, for –		[a]Wet-to-dry stopping distance ratios for –	
	990	F-4D	990	F-4D
Wet and puddled runway surfaces				
A	4246	9 476	2.609	2.858
B	1810	4 539	1.112	1.369
C	1777	4 021	1.092	1.213
D	4112	8 337	2.526	2.514
E	2794	6 145	1.717	1.853
F	3265	5 785	2.006	1.745
G	1708	3 394	1.049	1.024
H	1663	3 417	1.022	1.031
I	2562	4 896	1.574	1.477
Flooded runway surfaces				
A	----	-----	----	----
B	----	-----	----	----
C	2269	5 215	1.394	1.573
D	4566	10 100	2.805	3.046
E	3210	7 586	1.941	2.288
F	3861	7 586	2.372	2.288
G	2059	4 507	1.265	1.359
H	----	-----	----	----
I	----	-----	----	----

[a]Dry stopping distance for the F-4D is 3315 ft and for the 990 is 1628 ft.

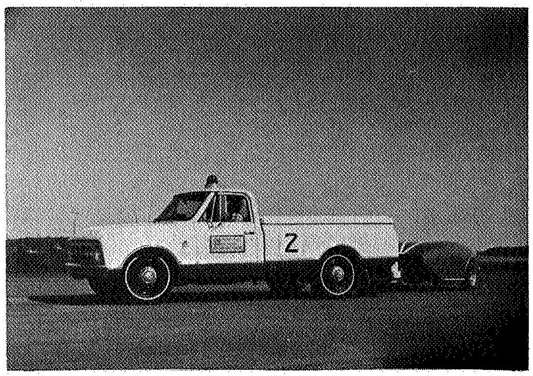
Figure 1.- Watering system of the landing research runway.



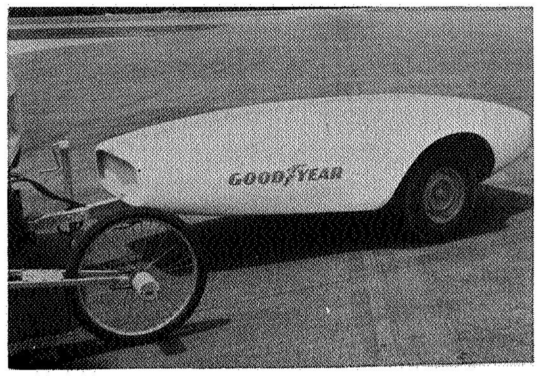
(a) Bureau of Public Roads.

(b) Florida State Road Department.

Figure 2.- Two-wheel braking trailers.

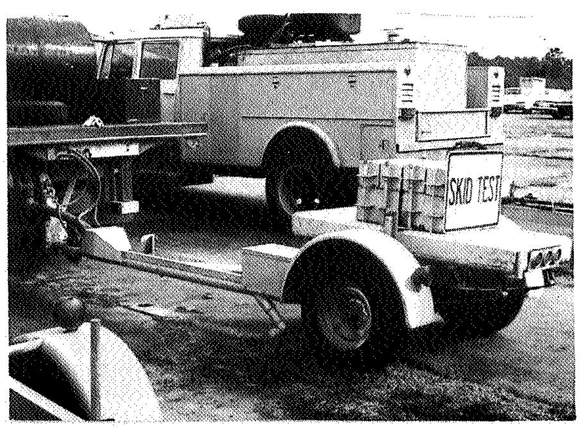


(c) General Motors Corporation.

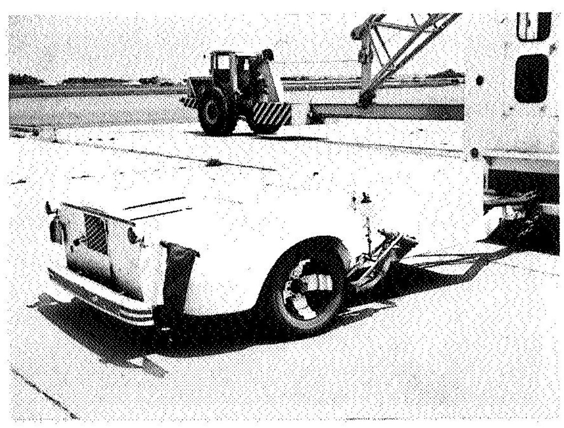


(d) Goodyear Tire and Rubber Company.

Figure 2.- Continued.

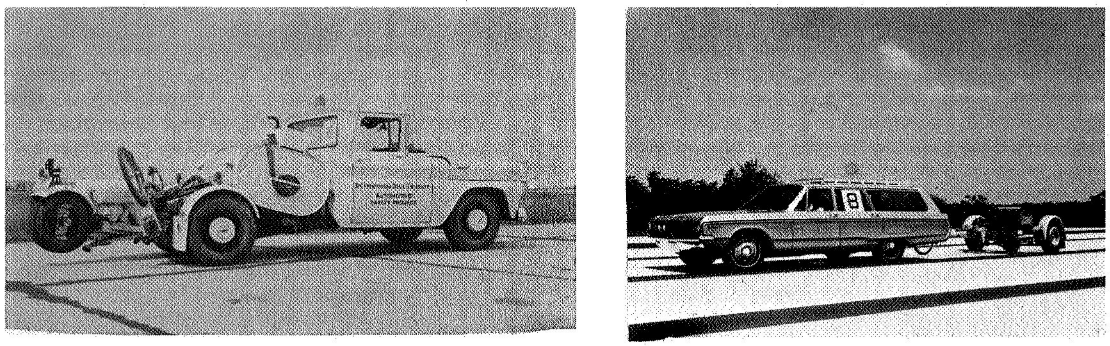


(e) Tennessee Highway Research Program.



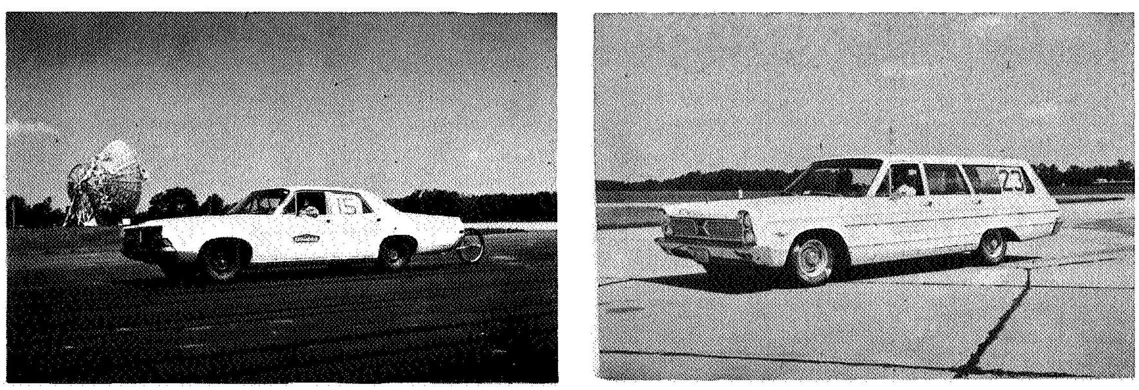
(f) Virginia Highway Research Council.

Figure 2.- Concluded.



(a) Pennsylvania State University.　　　(b) Federal Aviation Administration.

Figure 3.- Single-wheel (Penn State) and three-wheel (FAA) braking trailers.



(a) B. F. Goodrich Tire and Rubber Company.　　　(b) NASA.

Figure 4.- Diagonal braking automobiles.

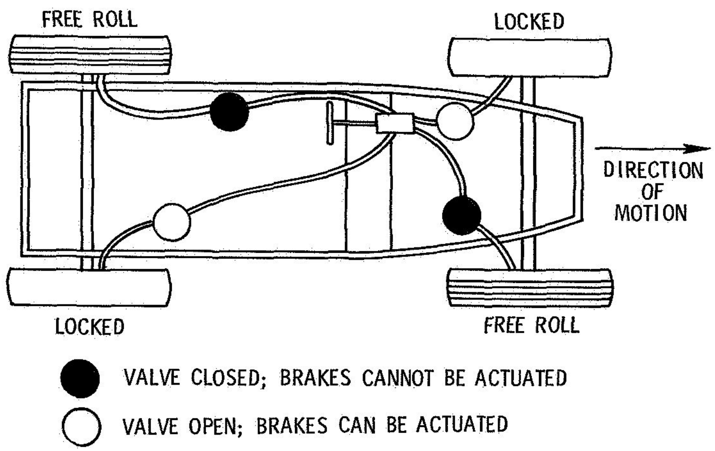


Figure 5.- Braking system for the diagonal braking vehicles.

Figure 6.- Four-wheel braking automobile.

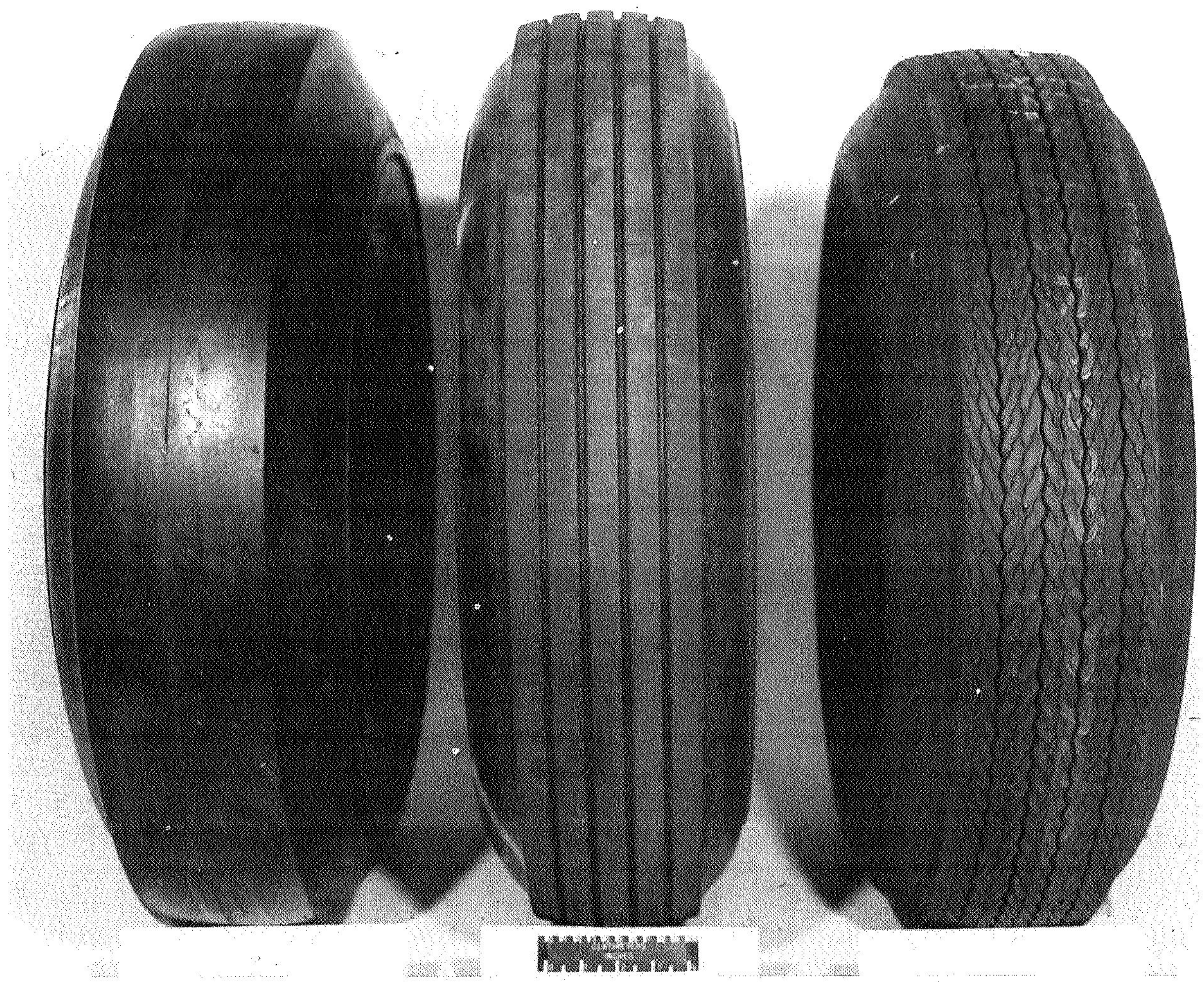
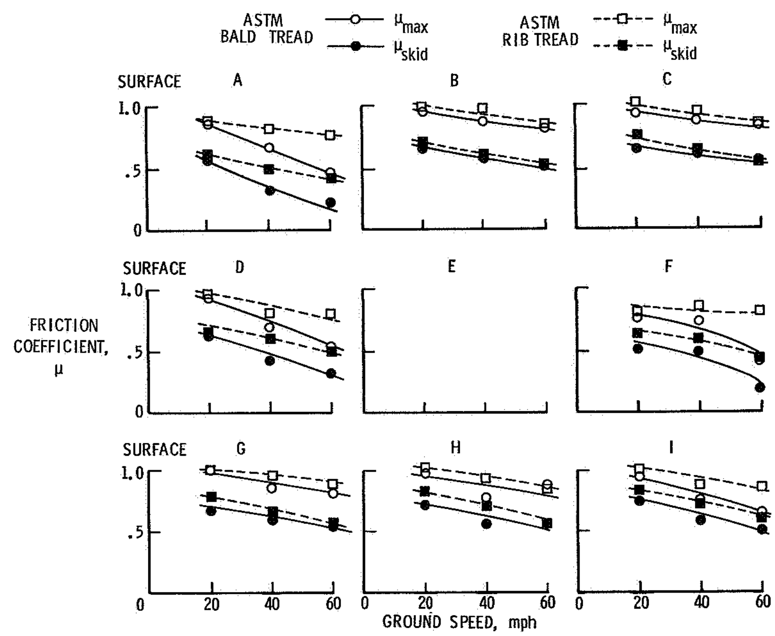
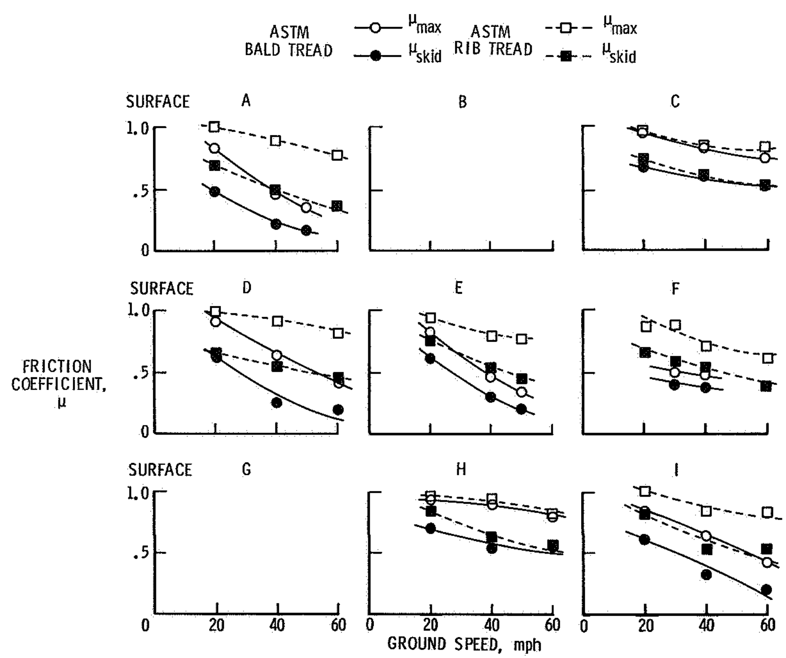


Figure 7.- Ground-vehicle tires.



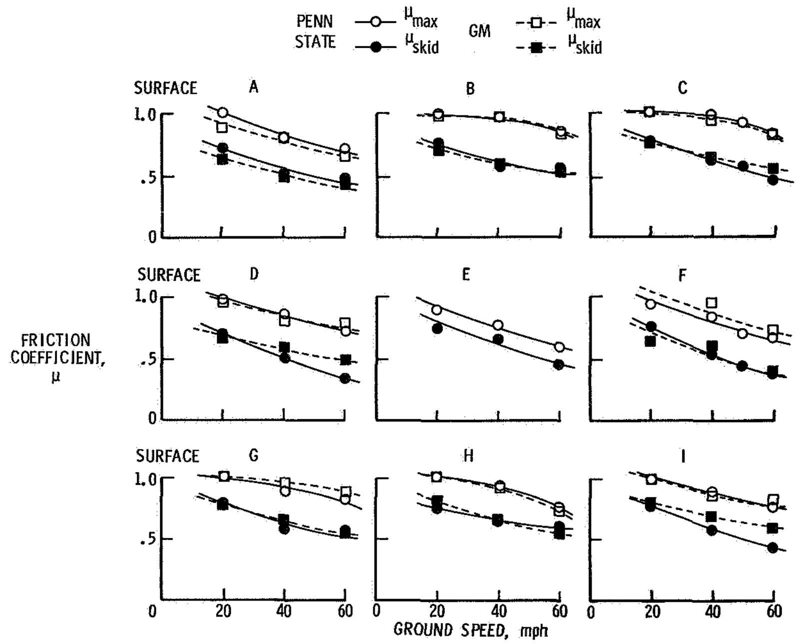
(a) Wet and puddled runway surfaces.

Figure 8.- Effect of tire tread design on friction coefficients for GM braking trailer. Tire pressure, 24 lb/in^2; tire vertical load, 1080 lb.



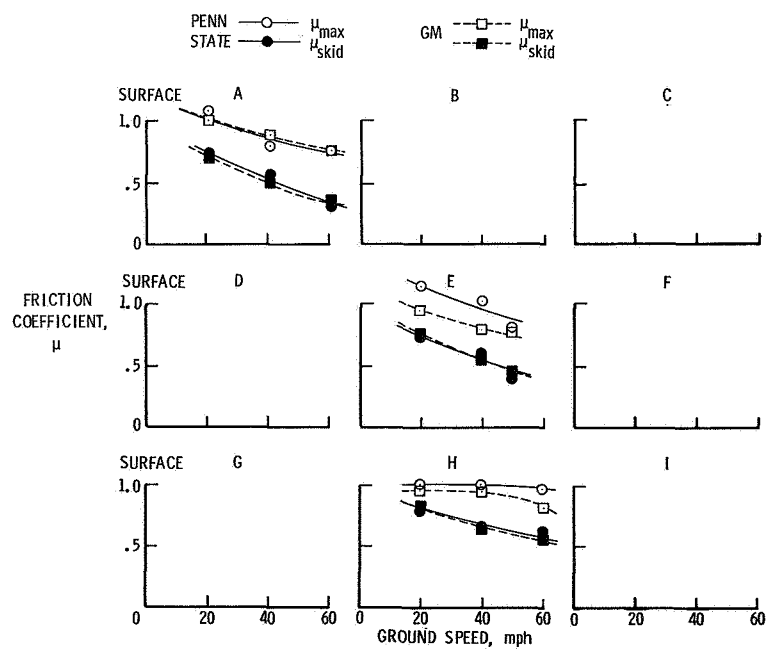
(b) Flooded runway surfaces.

Figure 8.- Concluded.



(a) Wet and puddled runway surfaces.

Figure 9.- Comparison of friction coefficients obtained from Penn State and GM braking trailers. ASTM rib-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 800 lb (Penn State) and 1080 lb (GM).



(b) Flooded runway surfaces.

Figure 9.- Concluded.

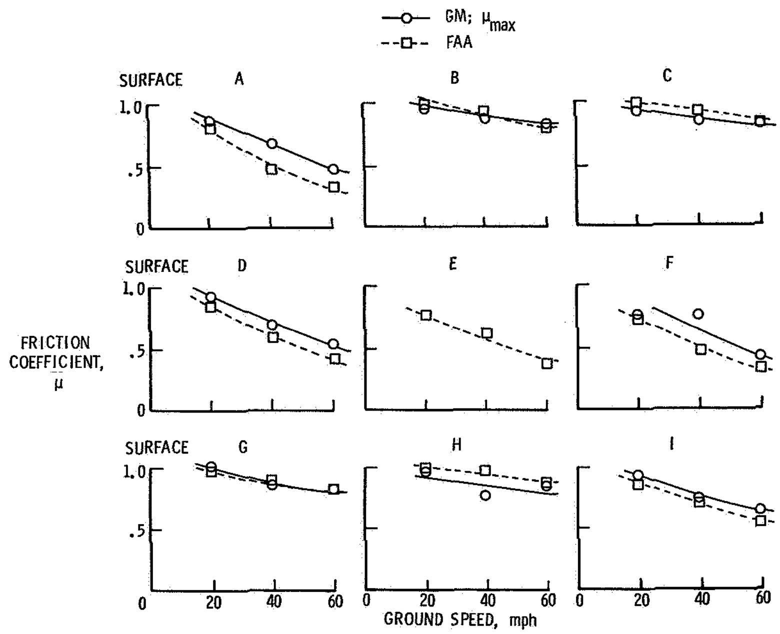
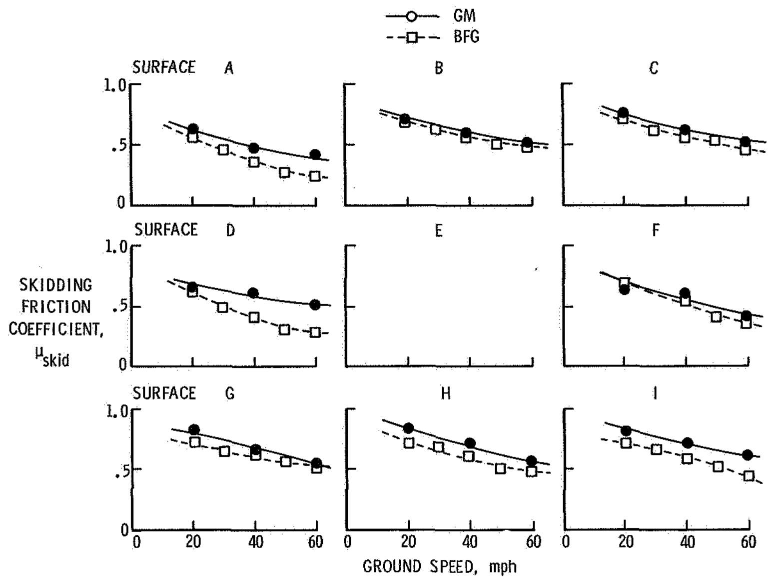
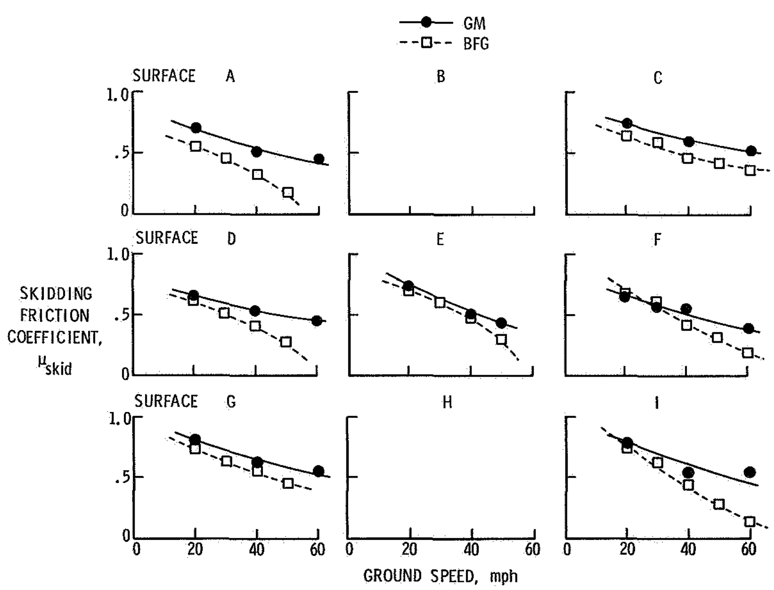


Figure 10.- Comparison of friction coefficients obtained from GM braking trailer and Swedish Skiddometer (slip ratio ≈ 0.13) on wet and puddled runway surfaces. ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1080 lb.



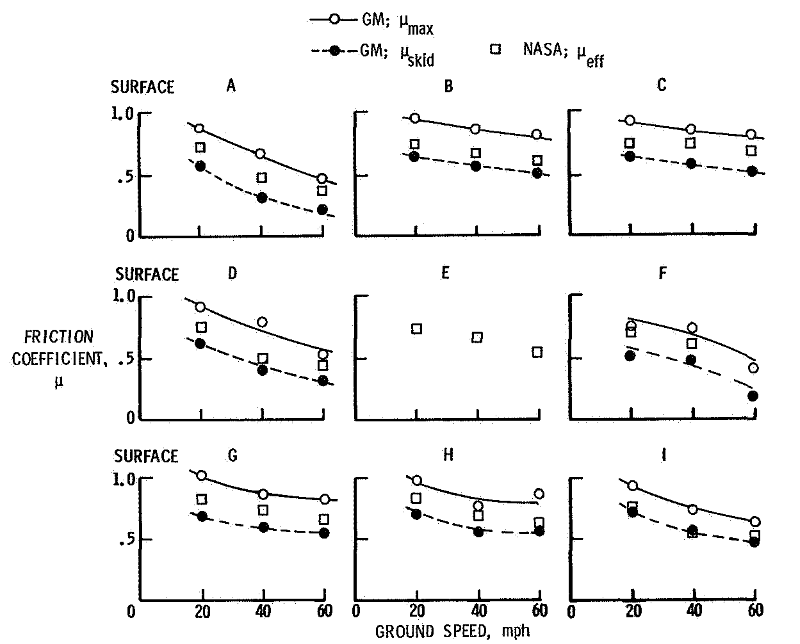
(a) Wet and puddled runway surfaces.

Figure 11.- Comparison of friction coefficients obtained from GM braking trailer and B. F. Goodrich diagonal braking automobile. ASTM rib-tread tires; tire pressure, 24 lb/in^2; GM tire vertical load, 1080 lb; BFG tire vertical load, 1133 lb (front) and 1135 lb (rear).



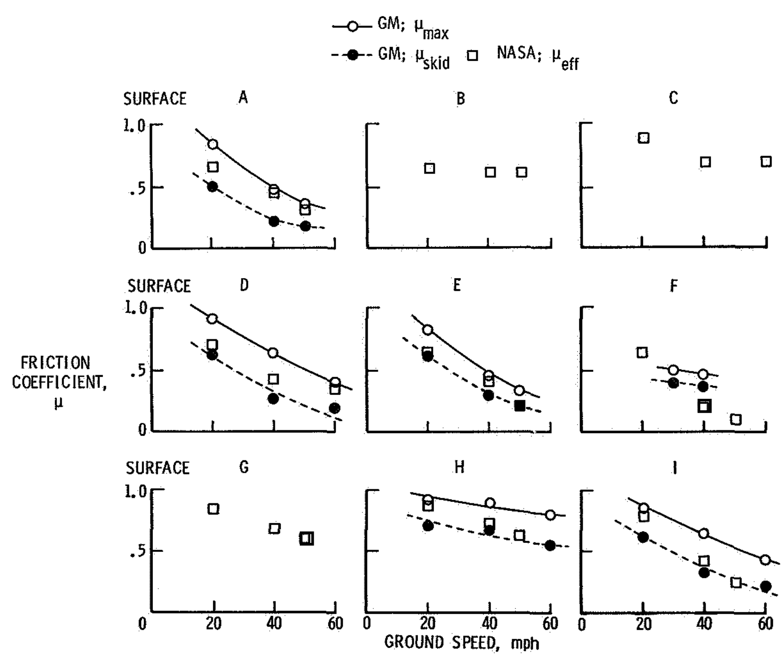
(b) Flooded runway surfaces.

Figure 11.- Concluded.



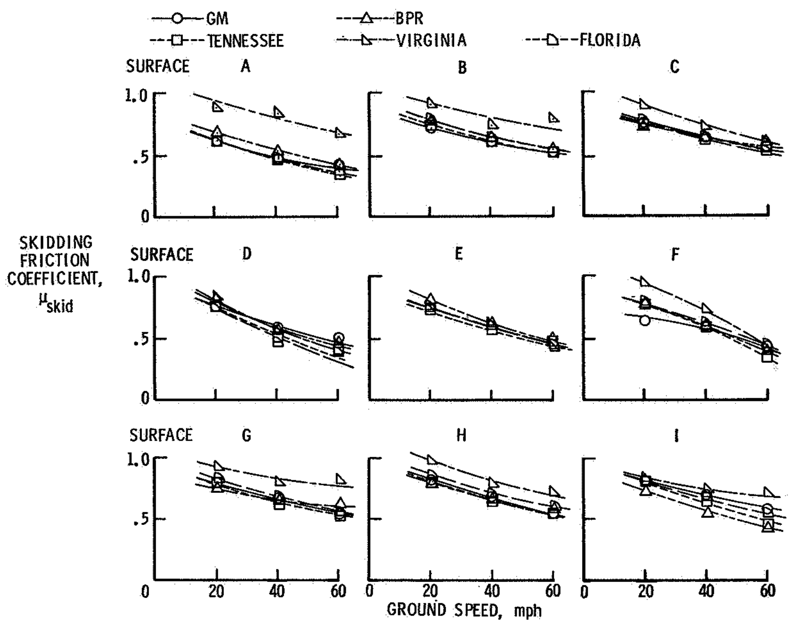
(a) Wet and puddled runway surfaces.

Figure 12.- Comparison of friction coefficients obtained from GM braking trailer and NASA diagonal braking automobile. ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1080 lb (GM) and 1012 lb (NASA).



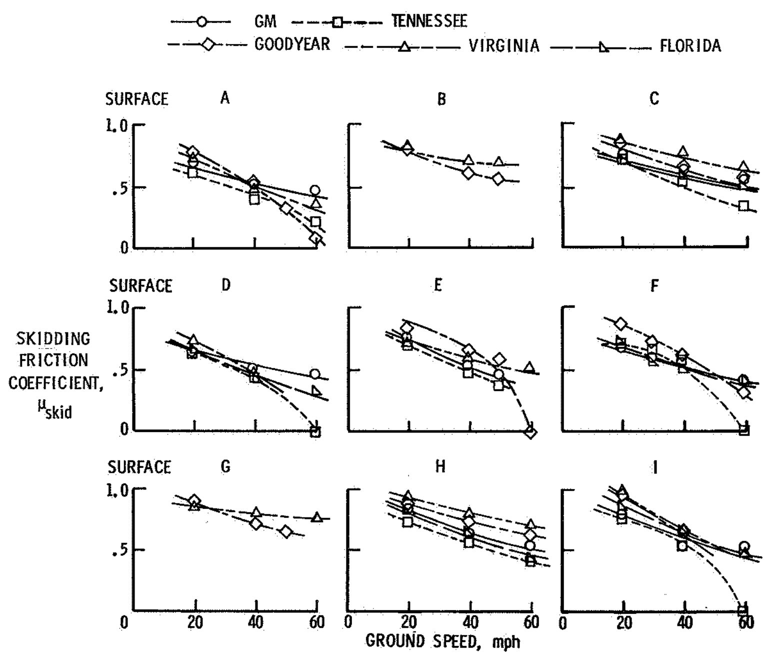
(b) Flooded runway surfaces.

Figure 12.- Concluded.



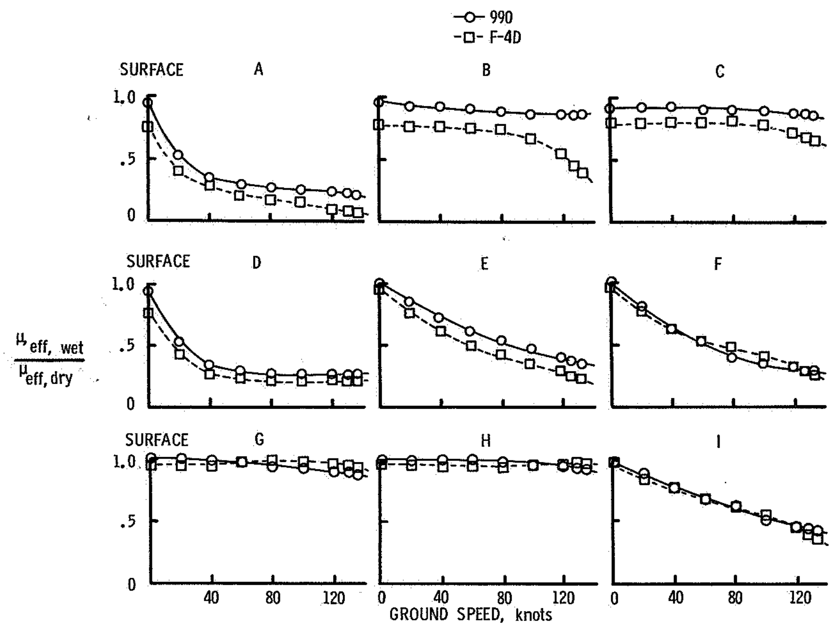
(a) Wet and puddled runway surfaces.

Figure 13.- Comparison of friction coefficients obtained from two-wheel braking trailers. ASTM rib-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1080 lb.



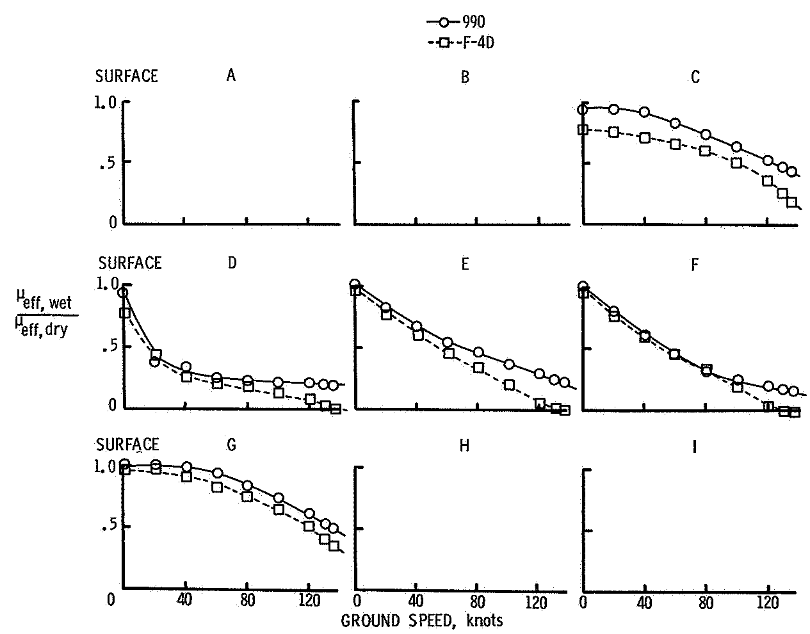
(b) Flooded runway surfaces.

Figure 13.- Concluded.



(a) Wet and puddled runway surfaces.

Figure 14.- Comparison of the ratio of wet to dry effective friction coefficients obtained from 990 aircraft with those obtained from F-4D aircraft. Aircraft rib-tread tires; tire pressure, 160 lb (990 aircraft) and 280 lb (F-4D aircraft).



(b) Flooded runway surfaces.

Figure 14.- Concluded.

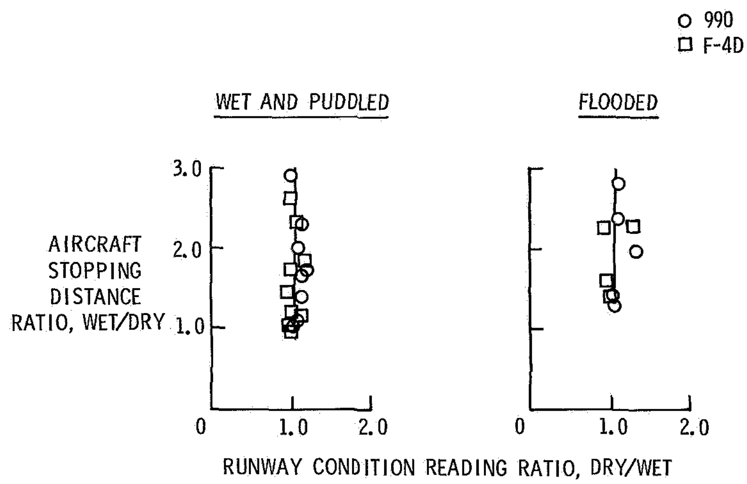
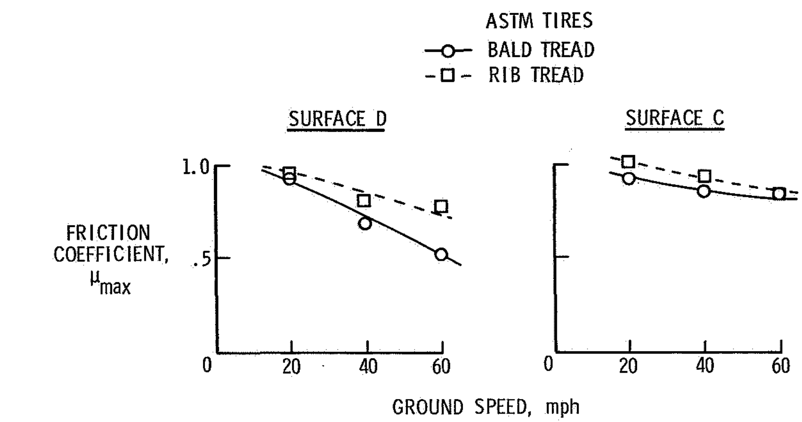
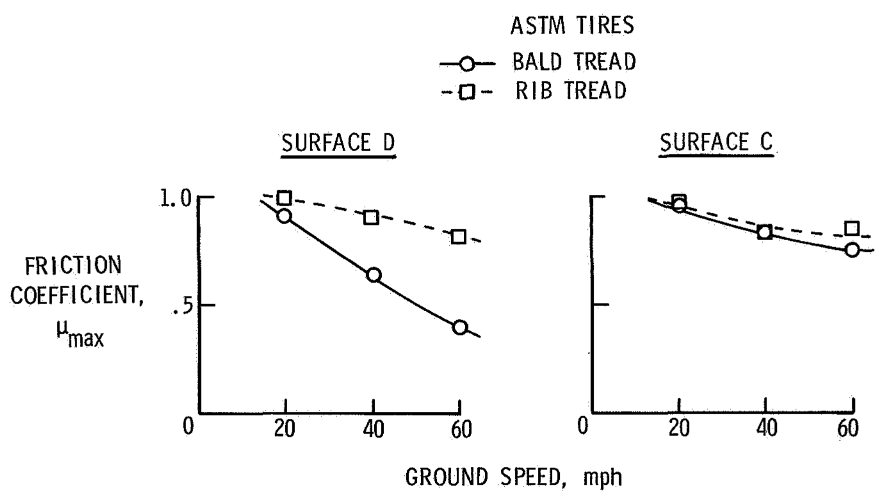


Figure 15.- Comparison of aircraft stopping distance ratios with RCR ratios. Automobile test conditions: velocity, 30 mph; four-wheel skid; typical production tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.



(a) Wet and puddled runway surfaces.

Figure 16.- Effects of tire tread design and vehicle speed on friction coefficients obtained from GM braking trailer. Tire pressure, 24 lb/in^2, tire vertical load, 1080 lb.



(b) Flooded runway surfaces.

Figure 16.- Concluded.

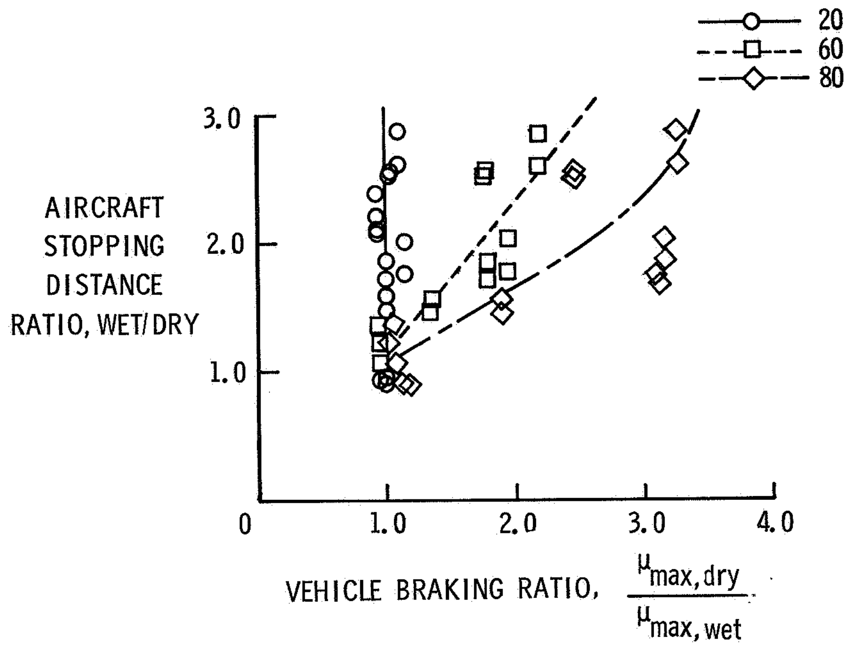


Figure 17.- Comparison of aircraft stopping distance ratios with braking ratios obtained from Swedish Skiddometer on wet and puddled runway surfaces. Skiddometer test condition: ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1080 lb.

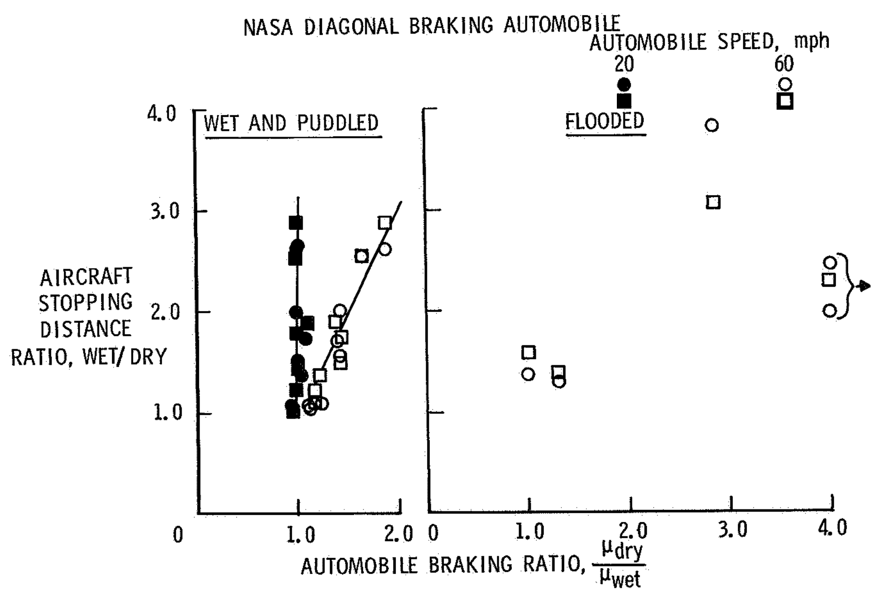


Figure 18.- Use of friction coefficients from NASA diagonal braking automobile to predict aircraft stopping distances. Automobile test conditions: ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.

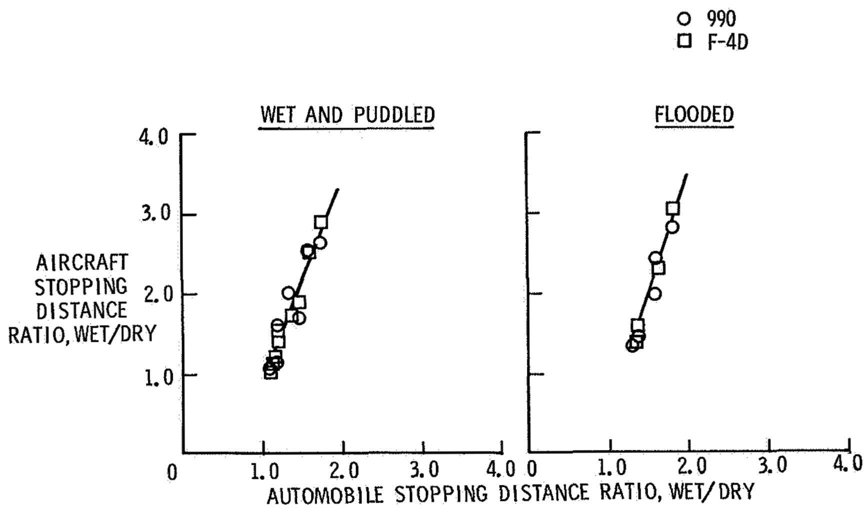


Figure 19.- Use of stopping distances from NASA diagonal braking automobile to predict aircraft stopping distances. Automobile test conditions: velocity, 70 mph; ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.

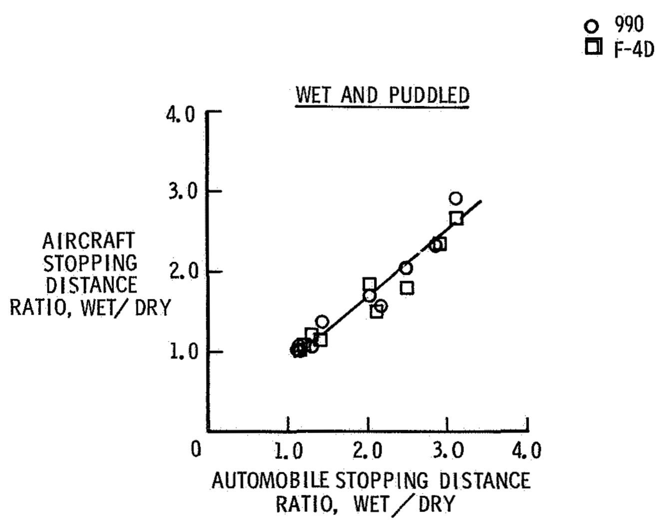


Figure 20.- Use of stopping distances from NASA diagonal braking automobile to predict aircraft stopping distances. Automobile test conditions: velocity, 70 mph; ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.

24. JOINT NASA-BRITISH MINISTRY OF TECHNOLOGY SKID CORRELATION STUDY

RESULTS FROM BRITISH VEHICLES

By R. W. Sugg

Ministry of Technology

SUMMARY

Speed friction results are given from the three British friction vehicles which were engaged in the Joint NASA-Ministry Skid Correlation Trials at NASA Wallops Station. The degree of correlation between the vehicles and aircraft is demonstrated and the ability of the equipment to place the test surfaces in the same friction order as the aircraft is discussed. An investigation is made into the ability of two of the equipments to predict aircraft stopping distances. Braking-force coefficients in the anti-skid, locked-wheel and impending-skid friction conditions are compared, also the effect of changes in tyre pressure. A comparison is made with a standard aircraft tyre prior and subsequent to the introduction of blind pin holes in the tread which were intended to provide an additional way of escape for water in the tyre-ground contact area.

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INTRODUCTION

It was approximately six years ago that the Ministry of Technology first investigated the possibility of correlation between the wet friction of runways as measured by vehicles and aircraft by conducting trials with a fighter aircraft and the Road Research Laboratory Trailer. The trials report indicated that correlation was not close; but since some of the data could have been suspect because of different wetting methods, the Joint Correlation Trials at Wallops Island were most appropriate to our own friction programme and we hoped they would settle this problem.

In addition to our Runway Water Depth Monitor and Slush Drag Meter which were not engaged in the friction trial, we provided two Tapley meters and an Inertia Switch Decelerometer which were used in NASA vehicles. We also brought over the Miles Engineering Company, Ltd., version of the Road Research Laboratory Trailer; another trailer, recently developed for us by the M. L. Aviation Company, Ltd., called the Mu-Meter; and our Heavy Load Friction Vehicle, operated for us by the College of Aeronautics. This paper contains the results of the last three equipments.

The Miles Trailer (fig. 1) was designed with the primary object of producing a small, light test apparatus which could be fitted to most cars with the minimum of modification and the smallest possible effect to their stability, even when testing on extremely slippery runway surfaces. The tyre is 16 inches in diameter and 4 inches wide, and in order to provide good suspension characteristics, a wheel load of 317 lb was chosen to give a high ratio of sprung to unsprung weight. This, with the use of rubber cord springs and a hydraulic shock damper, gives excellent stability in operation throughout the speed range of over 100 mph. The trailer measures the locked-wheel braking-force coefficient and the brake is brought into action by a vacuum servo system controlled by the operator in the towing vehicle. There is no trouble from overheating or brake fade even on high-speed runs. Braking forces are measured by means of a torque arm attached to the brake, operating a strain gauge link which actuates an electronic pen recorder with a moving chart. The calibration of the apparatus is checked at frequent intervals by applying known braking forces to the trailer wheel. In addition to applying the brake the servo system also operates a clamp to prevent the trailer from swinging about the towing point while the wheel is locked because it then has little directional stability, particularly on the more slippery surfaces. To ensure consistency and reproducibility of results, particular attention has been paid to the standardisation of the physical properties of the test tyres such as hardness, resilience, area and perimeter of contact patch, and so forth.

The Mu-Meter (fig. 2) is a trailer comprising three wheels, two of which are mounted at the ends of independently movable arms pivoted to the towing eye and adjusted to a tow out angle of $7\frac{1}{2}^{\circ}$. When towed, the resulting side load imposed on the arms is measured by a pressure capsule mounted between them, the pressure variations being transmitted to a pen recorder which uses pressure-sensitive paper. The third wheel drives the paper chart so that a continuous record of the side load is available, this load being a measure of the surface friction. The equipment incorporates an event marker and a method of averaging friction values over any distance. It is wholly mechanical in its operation requiring no power supply. The total weight is 542 lb of which about 250 lb is removable ballast. It is 4 feet 7 inches long, 2 feet 6 inches wide, and 2 feet 10 inches high; has been towed to a speed of 115 mph; and was designed specifically to meet an ICAO requirement for a machine, which was simple to operate, to provide a continuous measurement of runway friction in a graphic form. The tyre size is 16 inches in diameter and 4 inches wide. A pressure of 10 psi is used with the intention that it should be capable of indicating when aquaplaning conditions exist at its normal towing speed of 40 mph. The tyres have no tread pattern and are rigidly controlled in their manufacture to ensure consistency of results.

The Heavy Load Friction Vehicle (fig. 3), commonly called the "Juggernaut," weighs 11 tons, is powered by a 240 bhp engine, and requires a distance of 4000 feet to reach 60 mph. The test wheel fitted with a 35 × 10-17 aircraft tyre having five circumferential ribs is located by a parallel suspension system and is mounted within the wheel base on the centre line of the vehicle just behind the front axle. This wheel is loaded through a specially developed hydraulic system by adjusting nitrogen pressure in a loading accumulator and the test load can be set to any desired value up to a maximum of 5 tons. With this ability to vary the load, tyre inflation pressures from 24 to 280 psi can be used. Drag and vertical loads are measured by strain gauges and recorded as a continuous trace. The brake is a normal aircraft plate type and can generate sufficient torque to lock on any surface encountered so far. The brake can be operated from an aircraft anti-skid system; alternatively, it can be made to lock the wheel and therefore measure the impending- and locked-wheel skid friction values. During the NASA Wallops Station study, tyre pressures of 24, 100, 160, and 280 psi were used with a normal load of 7840 lb, except that the tyre was at 24 psi when the load was 1750 lb.

RESULTS AND DISCUSSION

The trials results have been analysed to try and answer three questions:

1. Did the Convair 990, McDonnell Douglas F-4D, Miles Trailer, Mu-Meter, and Heavy Load Friction Vehicle all place the surfaces in approximately the same friction order?

2. How closely did the friction values of the ground vehicles correlate with the aircraft throughout their speed ranges?

3. How closely could a friction value at a single speed from the Miles Trailer and Mu-Meter predict aircraft stopping distance?

The answer to the first question is important as we have used the Miles type of trailer for some years to compare our military and some civil runways. This system has worked well. For example, runways complained of as being slippery by pilots were shown to be so by the trailer. There has, however, been some doubt that the aircraft and trailer corresponded except in a general way. The Mu-Meter speed-friction curves for the surfaces on Site 1 are shown in figure 4 and a few others have been added such as those for the dry surface and the Plastolene sheet we put down to simulate an icy surface. (For a description of these surfaces, see ref. 1.) The curves for all the grooved surfaces are close together at the top; there is then a gap and the curves for the low friction surfaces are together at the bottom. The aircraft indicated approximately the same trend but showed the friction of surfaces E and F to be relatively higher. An inspection of the Mu-Meter traces for these two surfaces showed large fluctuations in friction due to ponds forming on an otherwise flat runway.

The results for the Miles Trailer on the same surfaces are in figure 5 where you will notice the upward trend in some of the curves after about 60 mph is reached. The manufacturer has explained this as being a characteristic of the type of tyre used and that it is due to its greater energy absorption on the higher textured surfaces. The phenomenon occurs to a greater or lesser extent on all types of tyre and is made use of by the designers of high-hysteresis tyres. In spite of this, the surfaces are still placed in much the same friction order as with the Mu-Meter and surface E is shown as having the lowest value, possibly for the same reason as with the Mu-Meter, that is, a variation in water depth due to ponding.

Results for the Mu-Meter and Miles Trailer on Site 1 under flooded conditions are shown in figures 6 and 7, respectively, and indicate that grooving increases the speed at which aquaplaning commences.

Curves for the Heavy Load Friction Vehicle on Site 1 using anti-skid are shown in figures 8 to 12 at tyre pressures of 100 and 160 psi and a normal load of 7800 lb. These curves demonstrate that increasing the tyre pressure reduces the friction value and that grooving not only increases the braking-force coefficient but causes it to remain level throughout the speed range. Of particular interest is surface E (Gripstop) which, although fine textured, had about the same friction characteristics as the ungrooved but more open textured asphalt (surface I).

The curves for the locked-wheel condition are in figures 13 to 21, where tyre pressures of 24, 100, 160, and 280 psi were used; the normal load was 1750 lb in the 24 psi case to keep the contact area the same as with 100 psi. The values are all lower than with anti-skid, tyre pressure having the same effect. Here again the Gripstop had similar friction characteristics to the open textured asphalt.

The curves for the impending-skid, or mu maximum, condition are in figures 22 to 30 where the friction readings are shown to be higher than in the anti-skid condition. The usual tendencies of tyre pressure and surface are apparent.

None of the three equipments placed the nine surfaces in exactly the same order as the aircraft; however, as the latter indicated a friction difference of only 0.05 between surfaces B, C, G, and H, that is all the grooved surfaces, the light trailers could not be expected to agree exactly. They did, however, place them well above the other surfaces A, D, E, F, and I. On the lower friction surfaces both trailers showed A, D, F, and E to be close together whilst the aircraft and Heavy Load Friction Vehicle showed E and F to be clearly superior to A and D; this may be due to excess water on the test surfaces. In general, both trailers indicate the good and poor surfaces to a degree which is probably adequate for airfield classification purposes.

We now come to the second question, which is: How closely did the friction values of the ground vehicles correlate with the aircraft? There are a number of ways in which this has been determined in the past and the one chosen here is to plot speed against the ratio of vehicle to aircraft friction at the same speed. Figure 31 shows the variation in this relationship between the anti-skid values of the Heavy Load Friction Vehicle and the Convair 990, both at the same tyre pressure of 160 psi. As any lack in correlation might be thought to be due to the different anti-skid systems in use, that is, Maxaret on the Heavy Load Friction Vehicle and Hytrol on the aircraft, figure 32 uses the vehicle impending-skid values in the ratio. Correlation appears to be worse, but in general, closer agreement was achieved with the higher friction surfaces. It is of interest that the Heavy Load Friction Vehicle gave consistently higher friction values than the aircraft.

The Miles Trailer and Mu-Meter correlations were dealt with in the same way and are shown in figures 33 and 34. As with the Heavy Load Friction Vehicle it was the low friction surfaces which were inconsistent. Although it is well appreciated that the trials did not permit otherwise, it is not entirely fair to compare friction values between two systems unless they were taken under conditions of wetness which were known to be identical and within a few weeks of each other to avoid seasonal changes in friction. Our own trials in the United Kingdom have demonstrated that the amount of water on a surface is of prime importance particularly on the finer textured surfaces. Certainly some of the runs with the Mu-Meter had a trace where the friction value oscillated between 0.1 and 0.3 at 40 mph on a so-called damp runway where ponds at least 1/8 inch deep had formed; whilst during the rain which occurred early in the Wallops trial, a value of 0.8 was obtained on the same surface at the same speed. Limited trials with both trailers indicated that when patterned tyres were used, the effect of overwetting fine textured surfaces was reduced.

The third and last question – How closely could a friction value at a single speed from the Miles Trailer and Mu-Meter predict aircraft stopping distance? – is an attempt to determine if empirical relationships can be established between vehicles and aircraft. If some agreement could be demonstrated on two aircraft it would give some confidence that it was possible on others, but might introduce a system where each type of aircraft had to be tested separately on high and low friction surfaces. Bearing in mind the tyre pressures of these two trailers (Miles Trailer, 20 psi and Mu-Meter, 10 psi), speeds were chosen which were at about the "aquaplaning" velocities on the more slippery surfaces as demonstrated in the flooded trials. The speeds selected were 55 mph for the Miles Trailer and 45 mph for the Mu-Meter.

First a system was tried by making an assumption that the mean friction value for the Convair 990 was at 80 knots when stopping from 125 knots, and this value was plotted against both trailers. There was a general but not sufficiently accurate correlation – surfaces E and F were again inconsistent particularly in the flooded condition – but since the friction value for the aircraft would not necessarily be at 80 knots on all surfaces, it was discarded in favour of plotting the trailer values against aircraft stopping distances calculated from friction-speed curves. The degree of correlation by using this system is shown in figures 35 and 36 for the Mu-Meter and Miles Trailer, respectively; surfaces E and F are once again the exception to the rule and have been ignored.

In another method of predicting aircraft stopping distances by vehicles which has been suggested by NASA researchers, the ratios of wet to dry stopping distances for the aircraft and vehicle are plotted against each other for a series of surfaces. Figures 37 and 38 demonstrate the degree of correlation by calculating the stopping distances wet and dry from the speed-friction graphs for the Miles Trailer and Mu-Meter from a speed of 70 mph and comparing them with the wet-dry ratio for the 990 and F-4D from 140 knots. Surfaces E and F have been ignored for the reasons stated previously. Although some agreement has been obtained, further trials with aircraft are essential before sufficient confidence can be placed in the method.

As mentioned before, to build up sufficient data to produce these correlation curves will require trials on different friction surfaces and perhaps be too expensive. It may be thought more profitable, particularly in the civil field, merely to allocate friction numbers where the meters will denote "good," "medium," or "poor" surfaces, which is a system recommended at the ICAO conference in Montreal about a year ago. Provided different equipments were correlated to give the same word description, then it would not matter what was used and the pilot would come to understand what each description meant to his aircraft. These Wallops Station trials may be instrumental in demonstrating what correlation exists between various friction-measuring equipments.

Figures 39 to 61 show friction curves for the three vehicles on Site 2 (ref. 1); the Heavy Load Friction Vehicle only tested a percentage of these surfaces, all in the locked-wheel and impending-skid condition. The usual trends were apparent: increase in friction with a reduction in tyre pressure at the same normal load, impending values higher than locked wheel, and an increase in friction due to grooves.

At 100 psi the Heavy Load Friction Vehicle showed little difference between longitudinally and transversely grooved concrete. Transverse grooves in asphalt were, however, shown to be superior to longitudinal and an improvement in friction was achieved by reducing the groove pitch from 1 inch to 3/4 inch. The Sinopal gave results which were better than some grooved surfaces, appeared to have good speed characteristics, and was as effective as the transversely grooved and ungrooved concrete.

The Miles Trailer showed the transversely grooved concrete to be superior to longitudinal grooves and the Sinopal to be inferior to grooved concrete. The poor results on the Sinopal may have been due to the trailer measuring the friction of the black filler and not the Sinopal itself. The optimum surface was the original open textured asphalt in Area B of Site 2 although the transversely grooved concrete was marginally superior at 80 mph. The poorest results were obtained from the Eastern Shore sand mix. The curves for asphalt, epoxy, and grooved concrete all showed rising curves at speeds above approximately 40 to 60 mph. The remainder showed a decaying friction. The synthetic surface, Sinopal, gave a decreasing result but was better than epoxy, original concrete, Eastern Shore sand mix, or longitudinally grooved concrete for speeds up to 60 mph.

The Mu-Meter showed little difference between transversely and longitudinally grooved concrete and asphalt. The 1-inch pitch grooved asphalt was inferior to the 3/4-inch pitch and again the open textured asphalt in area D was among the best, being as good as the grooved surfaces at high speed. The epoxy, Carrier Deck Paint, and Sinopal surfaces gave very good values at low speed but appeared to be dropping rather sharply at 80 mph. Again the worst surface was the Eastern Shore sand mix which did not have good high- or low-speed characteristics.

As an entirely separate trial, the Heavy Load Friction Vehicle was used to compare the friction characteristics of a standard aircraft tyre with those of some tyres provided by the Dunlop Rubber Company with blind pin holes drilled in the tread.

The reasoning behind this modification is that in order to develop a retarding force on wet runways, the water film must be excluded from at least a portion of the tyre-runway contact area. The total time that any one point on the tyre takes to go through the contact area is governed by speed and deflection; this can be very short, in the order of 10 milliseconds. Within this time it is suggested that a three-stage process occurs (fig. 62):

1. In the first stage, the bulk of the water has to move sideways outside the path of the tyre or into the tread grooves.

2. The second stage is an intermediate one when the finer asperities constituting the runway microtexture start breaking through the water film.

3. The third and last stage is when the thin water film is squeezed from between the tyre tread and runway surface.

It is in the second and particularly the third stage of this cycle that the drag forces are developed. The speed with which water is removed from the contact area is therefore of prime importance and can be increased by having an open textured surface and a tread pattern with sufficient drainage channels. Unfortunately the high tangential forces with aircraft tyres at the ground-tyre interface would cause tread damage in the form of tearing and chunking if any of the well established types of fragmentated tread patterns were used under dry braking conditions. The addition of a large number of blind pin holes in the tread to provide an additional way of escape for the water in the contact area does not incur any of these disadvantages. (See fig. 62.) Figures 63 to 69 compare the friction of modified and unmodified tyres and it appears that in general on the finer textured surfaces the modified tyre gave an increase in friction particularly at the higher speeds.

It is intended that we will conduct aircraft trials in the United Kingdom to investigate the full capabilities of this type of tyre.

CONCLUSIONS

During the tests with the trailers under so-called damp conditions there was too much water on the surface which formed puddles despite efforts at removal by sweeping. This caused them to record large fluctuations in friction particularly on the lower friction surfaces and possibly resulted in some friction coefficients being lower than under normal wet conditions. The two trailers demonstrated that they were capable of classifying the runway surfaces on Site 1 in the same general order as the Convair 990 and McDonnell Douglas F-4D. The ratio on the Miles Trailer friction readings to those of the 990 on the nine surfaces of Site 1 lay between 1.2 and 2.0 at 20 mph and 0.3 and 1.8 at 80 mph. The ratio of the friction readings of the Mu-Meter to those of the 990 under the same conditions lay between 1.2 and 2.8 at 20 mph and 0.2 and 1.8 at 100 mph. The friction ratio of the Heavy Load Friction Vehicle with impending skid to the 990 on the same surfaces lay between 1.4 and 2.1 at 20 mph and between 1.6 and 3.0 at 60 mph. In the anti-skid braking condition the ratio was between 1.1 and 1.5 at 20 mph and 1.2 and 2.1 at 60 mph.

Except for two of the surfaces, there was a fair degree of correlation between the friction values of the Miles Trailer and Mu-Meter at 55 and 40 mph, respectively, with the 990 and F-4D stopping distances. Tests on the flooded surfaces with the trailers indicate that the speed at which aquaplaning begins increases with the more open textured or grooved surfaces.

All three test vehicles demonstrated that the 1- by 1/4- by 1/4-inch grooving at least doubled the friction coefficient of the surfaces. Longitudinal grooving was less effective than lateral, and reducing the pitch of the grooves from 1 inch to 3/4 inch appeared to make little difference. The open textured asphalt on Site 2 (Section 2, Area B), which consisted of large stones set in a fine aggregate, was as effective as 1/8-inch grooved asphalt or concrete. The epoxy and Sinopal surfaces did not appear to have any friction advantages over the concrete or asphalt and were sometimes less effective when the latter were grooved, particularly at the higher speeds. It was noted that as the trial proceeded, the black filler wore off the Sinopal so that the friction being measured may have been that of the filler and not the aggregate.

With the Heavy Load Friction Vehicle a reduction in tyre pressure with the same normal load increased the friction values. Reducing the normal load to keep the tyre footprint area the same also increased the friction value.

The concrete surfaces, grooved or ungrooved, were in general slightly lower in friction than asphalt. The Carrier Deck Paint had good friction properties at speeds up to 60 mph, but the Eastern Shore sand mix had poor characteristics and was probably the lowest in friction of all the surfaces tested.

The introduction of blind pin holes in the tyre tread appears to increase the friction on the more slippery surfaces and reduce it on grooved surfaces.

REFERENCE

1. Horne, Walter B.: Results From Studies of Highway Grooving and Texturing at NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 26 herein.)

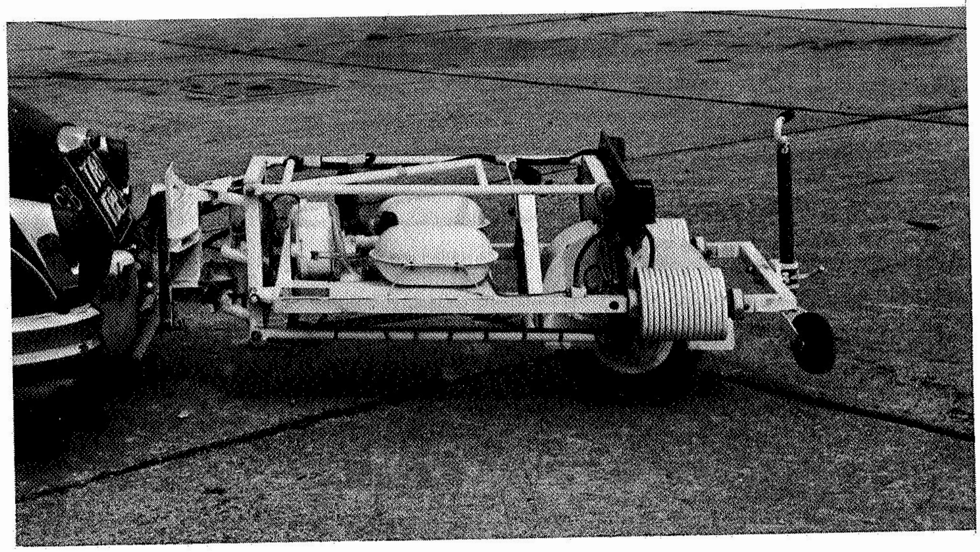


Figure 1.- Miles Trailer.

Figure 2.- Mu-Meter.

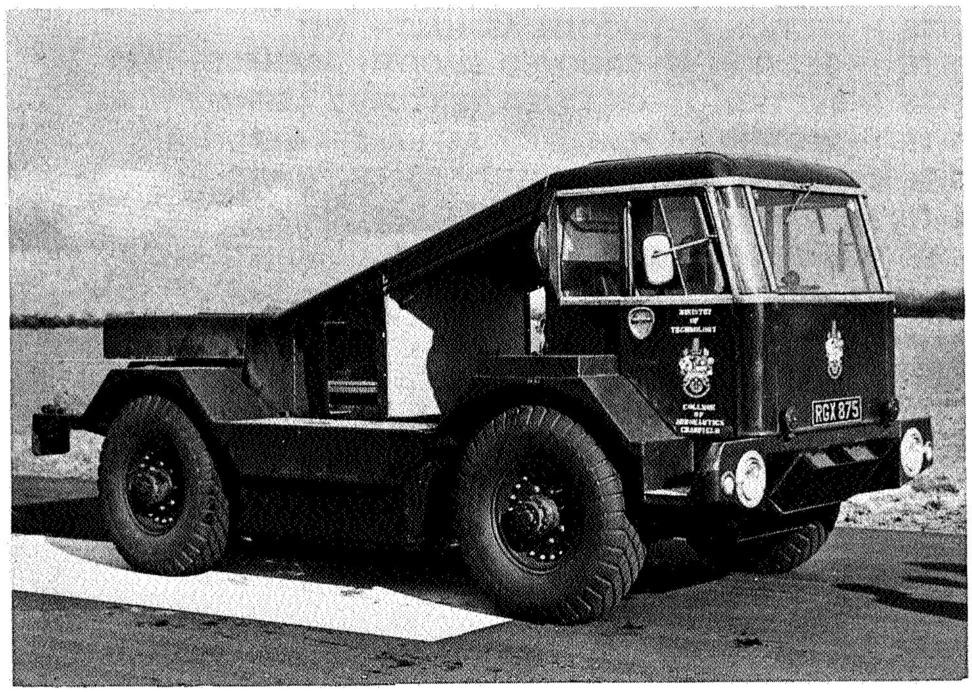


Figure 3.- Heavy Load Friction Vehicle.

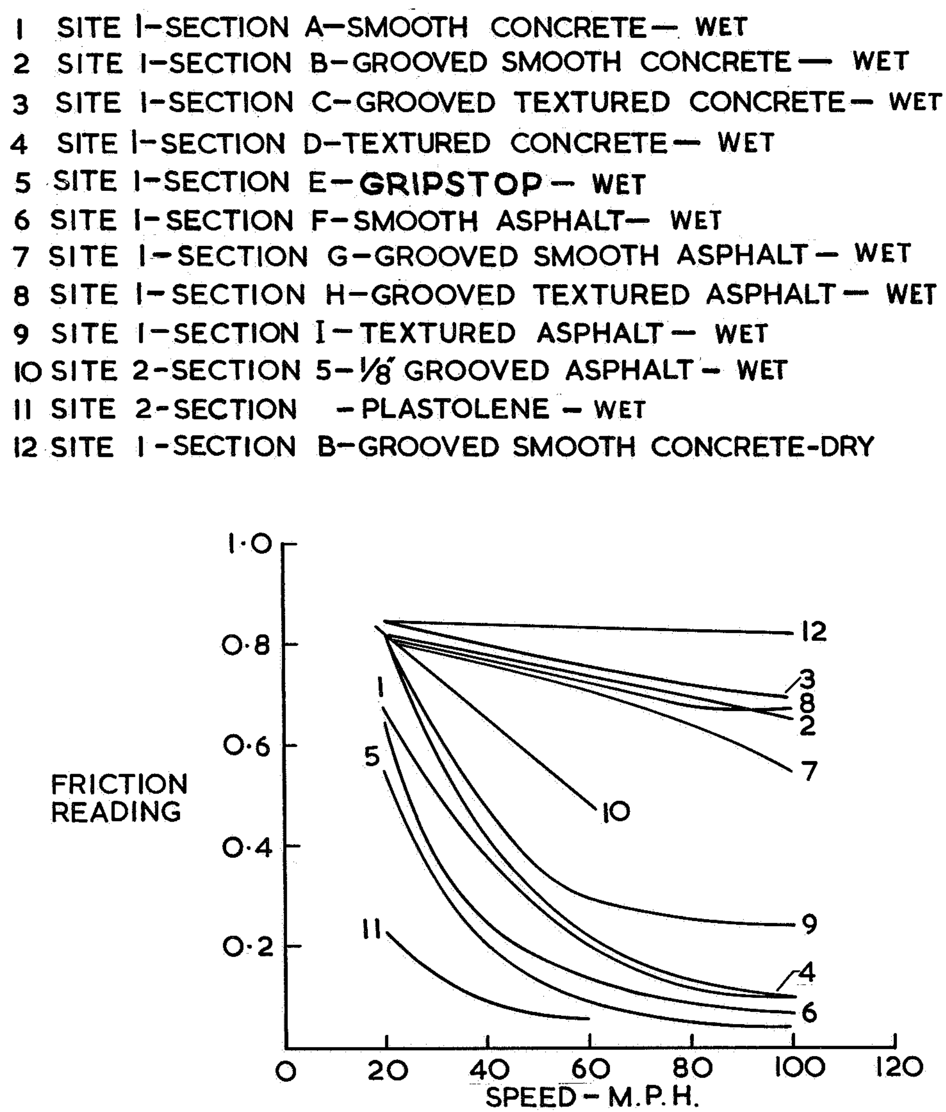


Figure 4.- Mu-Meter comparison of surfaces.

1 SITE 1-SECTION A-SMOOTH CONCRETE— WET
2 SITE 1-SECTION B-GROOVED SMOOTH CONCRETE— WET
3 SITE 1-SECTION C-GROOVED TEXTURED CONCRETE— WET
4 SITE 1-SECTION D-TEXTURED CONCRETE— WET
5 SITE 1-SECTION E-**GRIPSTOP**— WET
6 SITE 1-SECTION F-SMOOTH ASPHALT— WET
7 SITE 1-SECTION G-GROOVED SMOOTH ASPHALT— WET
8 SITE 1-SECTION H-GROOVED TEXTURED ASPHALT— WET
9 SITE 1-SECTION I-TEXTURED ASPHALT— WET
10 SITE 2-SECTION 5-1/8" GROOVED ASPHALT— WET
11 SITE 2-SECTION -PLASTOLENE— WET
12 SITE 1-SECTION B-GROOVED SMOOTH CONCRETE-DRY

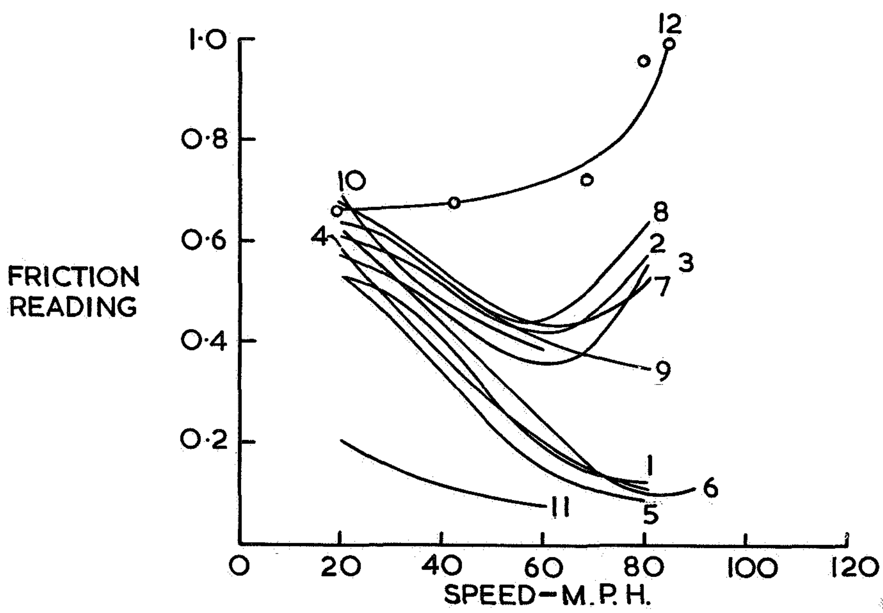


Figure 5.- Miles Trailer comparison of surfaces.

1 SITE 1 - SECTION A — FINE TEXTURED CONCRETE — FLOODED
2 SITE 1 - SECTION B — GROOVED SMOOTH CONCRETE - FLOODED
3 SITE 1 - SECTION C — GROOVED TEXTURED CONCRETE - FLOODED
4 SITE 1 - SECTION D — TEXTURED CONCRETE — FLOODED
5 SITE 1 - SECTION E — GRIPSTOP — FLOODED
6 SITE 1 - SECTION F — SMOOTH TEXTURED ASPHALT — FLOODED
7 SITE 1 - SECTION G — GROOVED SMOOTH ASPHALT — FLOODED
8 SITE 1 - SECTION H — GROOVED TEXTURED ASPHALT - FLOODED
9 SITE 1 - SECTION I — TEXTURED ASPHALT — FLOODED

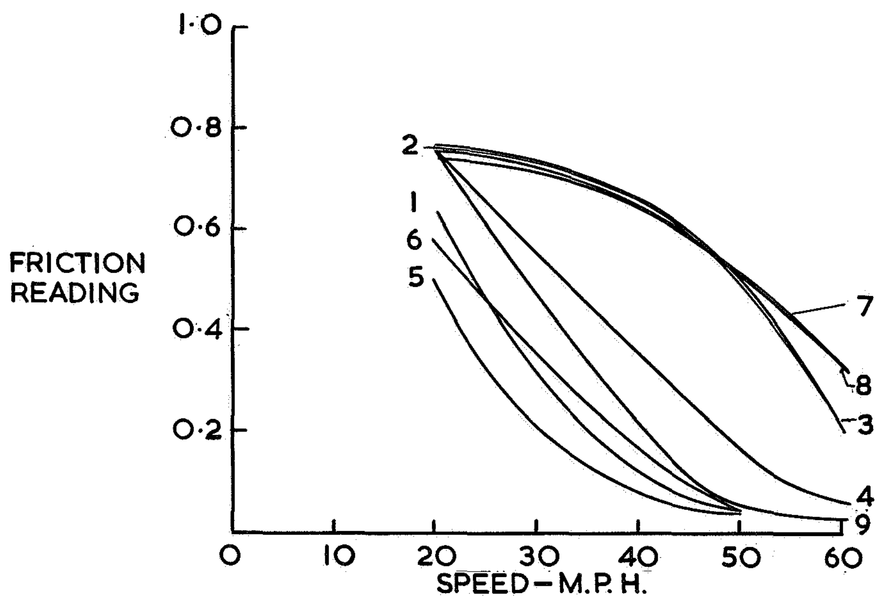


Figure 6.- Comparison of surfaces. Site 1; flooded; Mu-Meter.

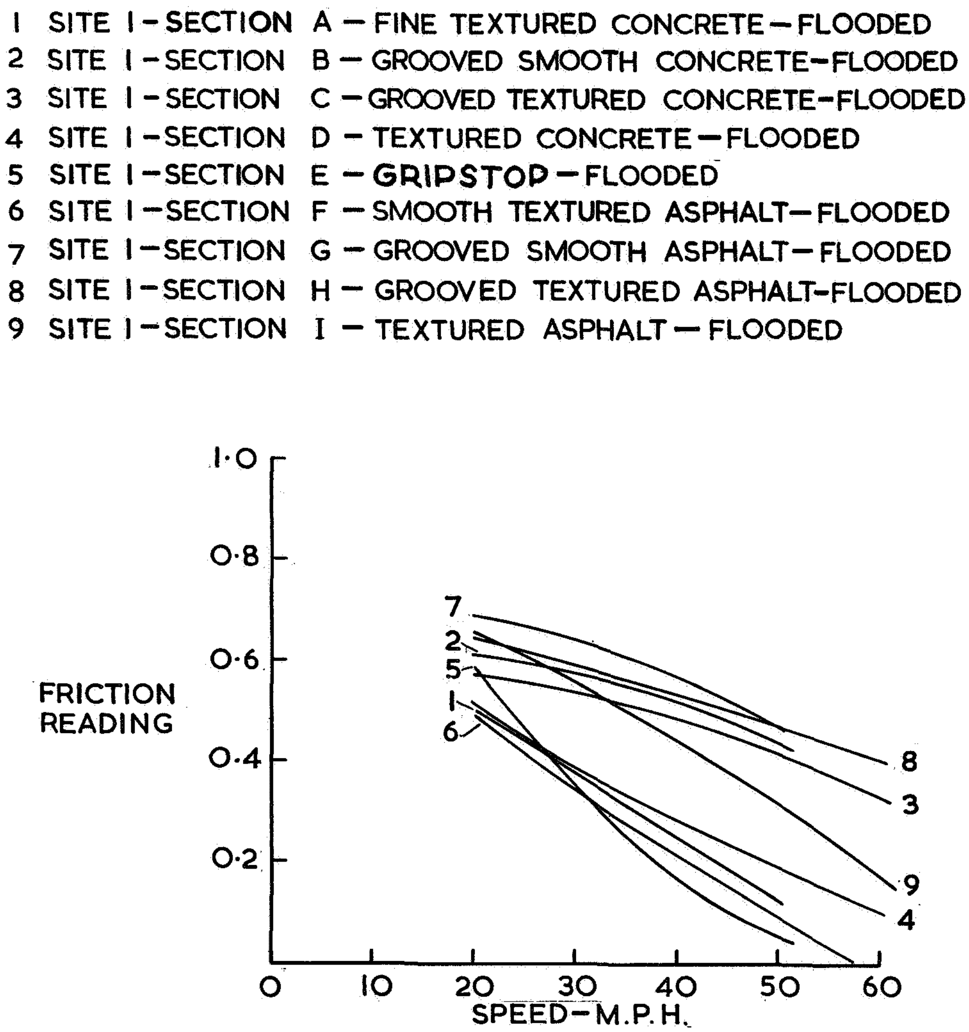


Figure 7.- Comparison of surfaces. Site 1; flooded; Miles Trailer.

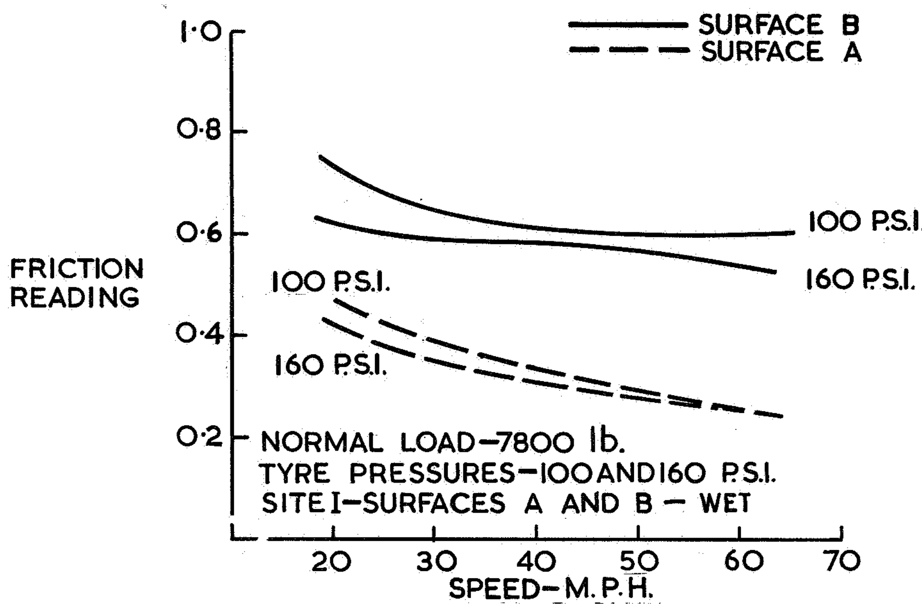


Figure 8.- Relationship between anti-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surfaces A and B.

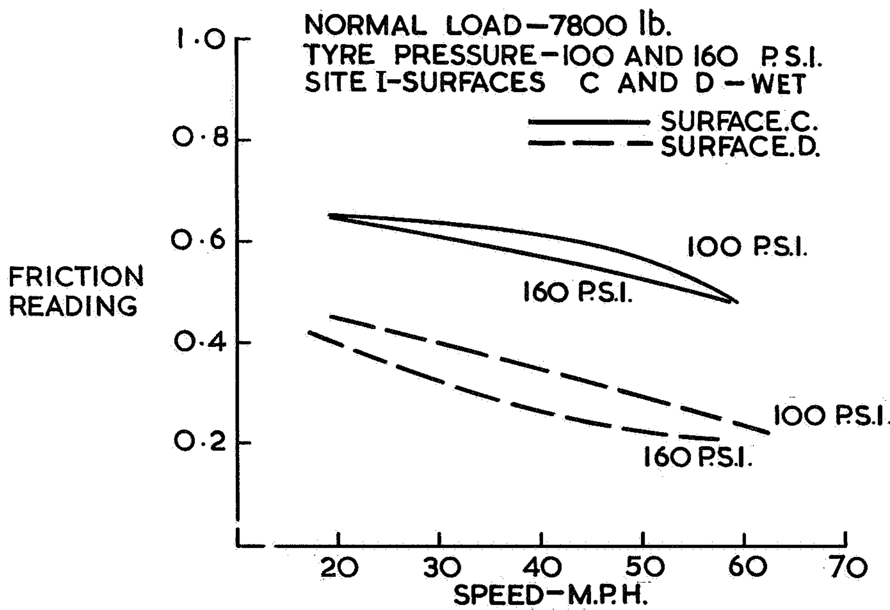


Figure 9.- Relationship between anti-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surfaces C and D.

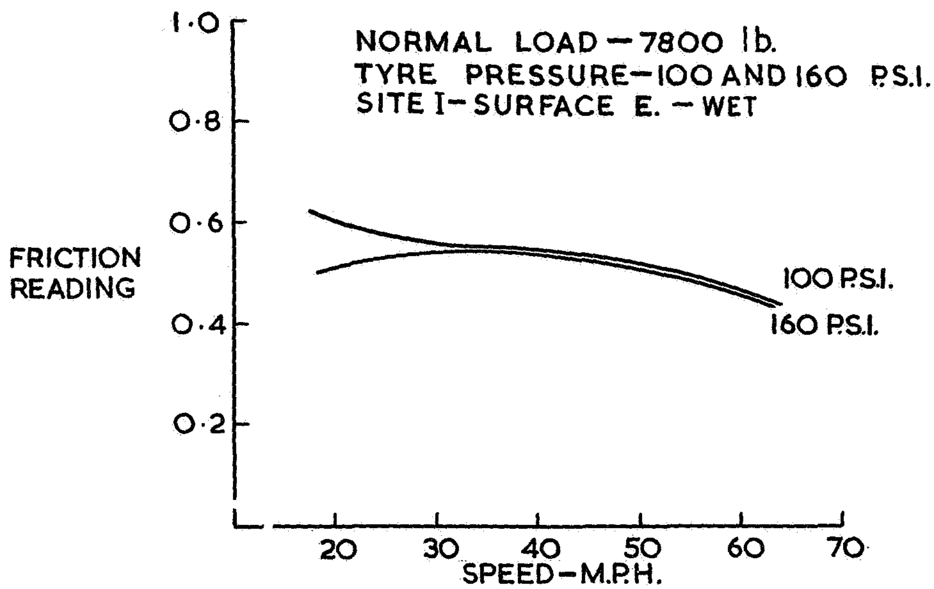


Figure 10.- Relationship between anti-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface E.

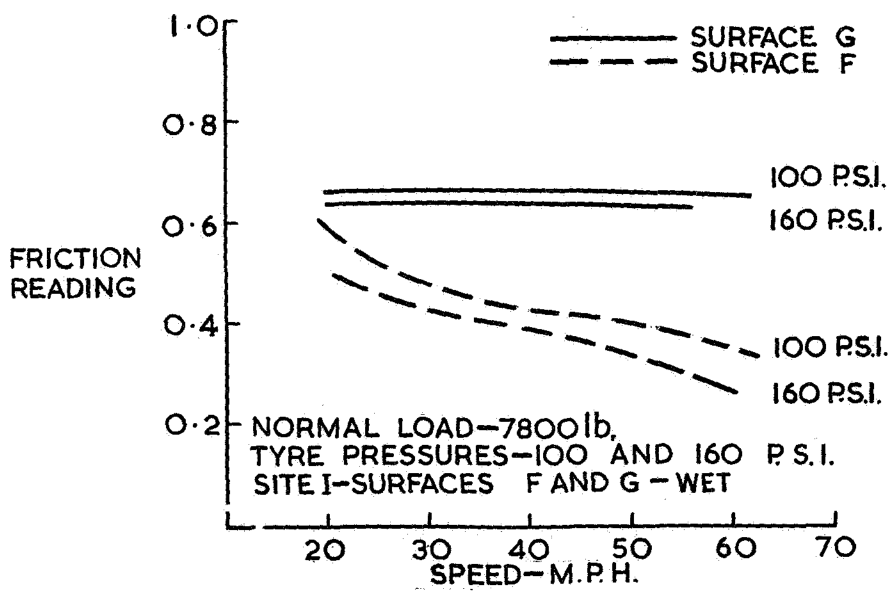


Figure 11.- Relationship between anti-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surfaces F and G.

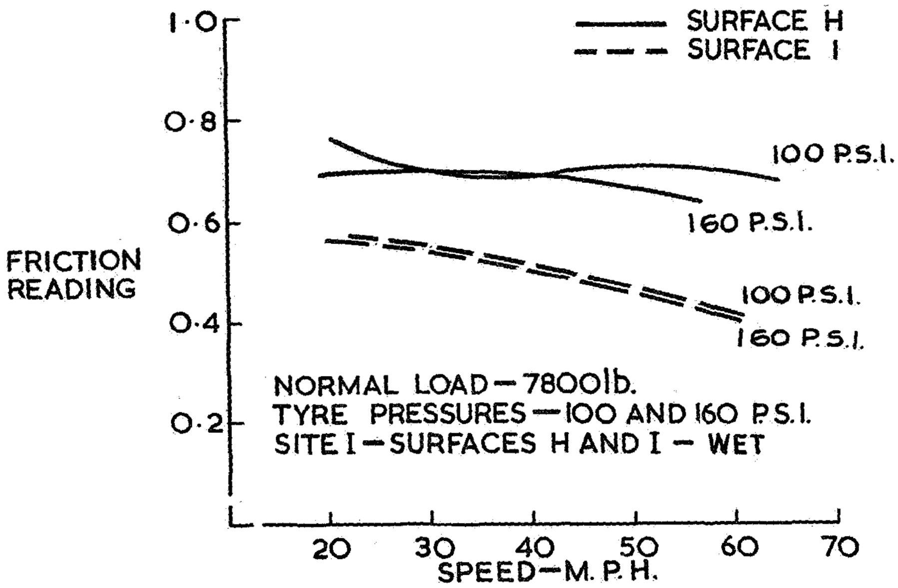


Figure 12.- Relationship between anti-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surfaces H and I.

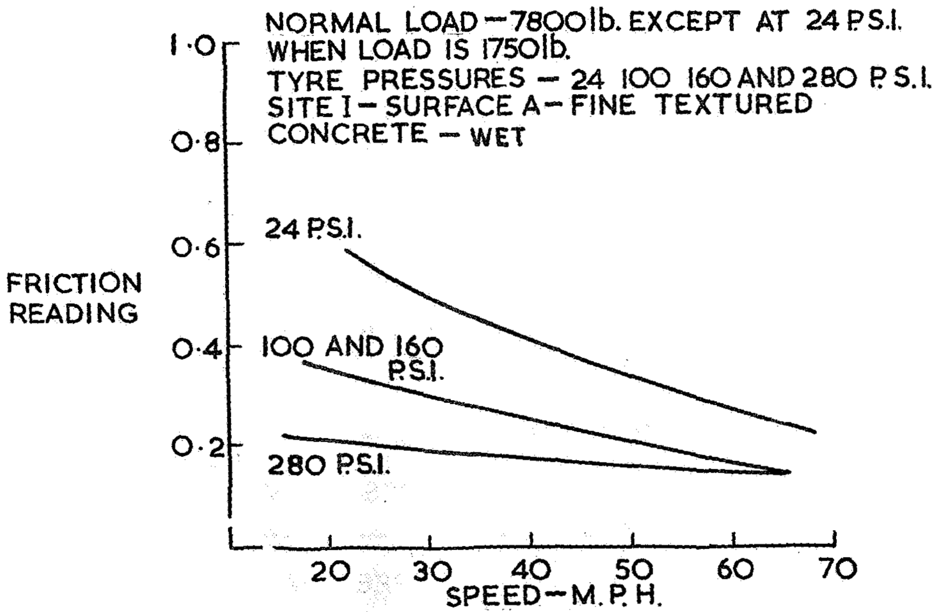


Figure 13.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface A.

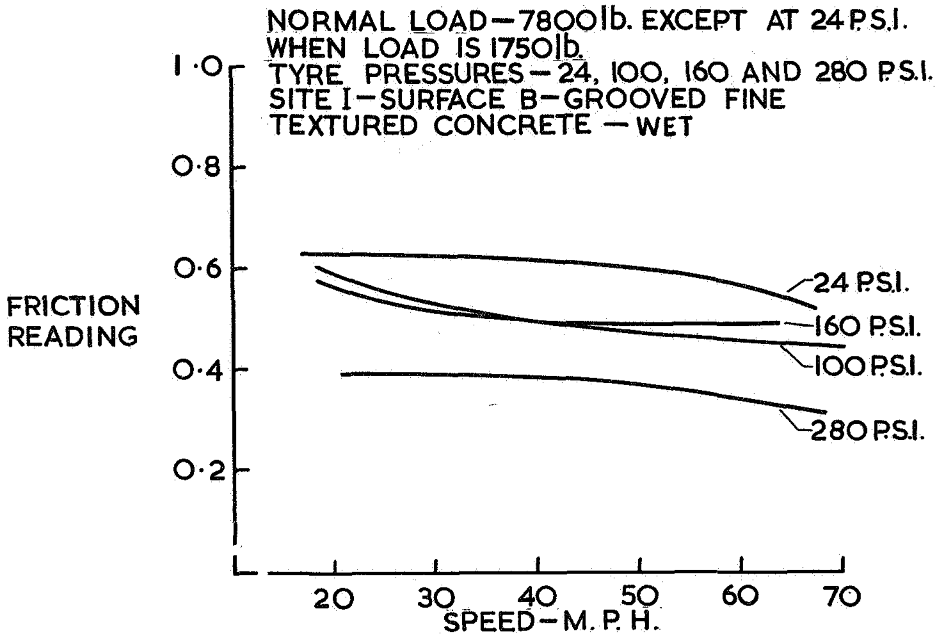


Figure 14.- Relationship between locked-wheel braking-force coefficent and speed with Heavy Load Friction Vehicle. Surface B.

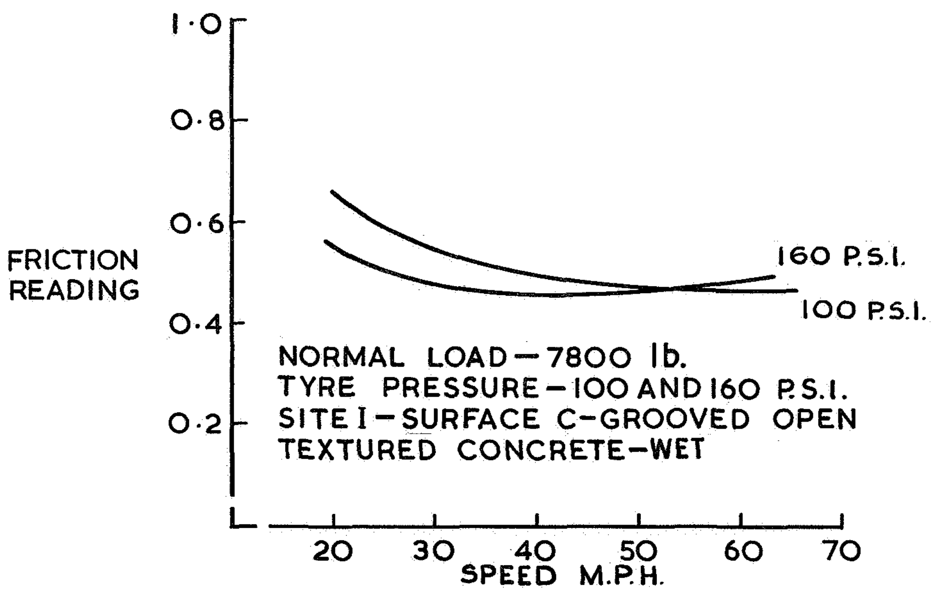


Figure 15.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface C.

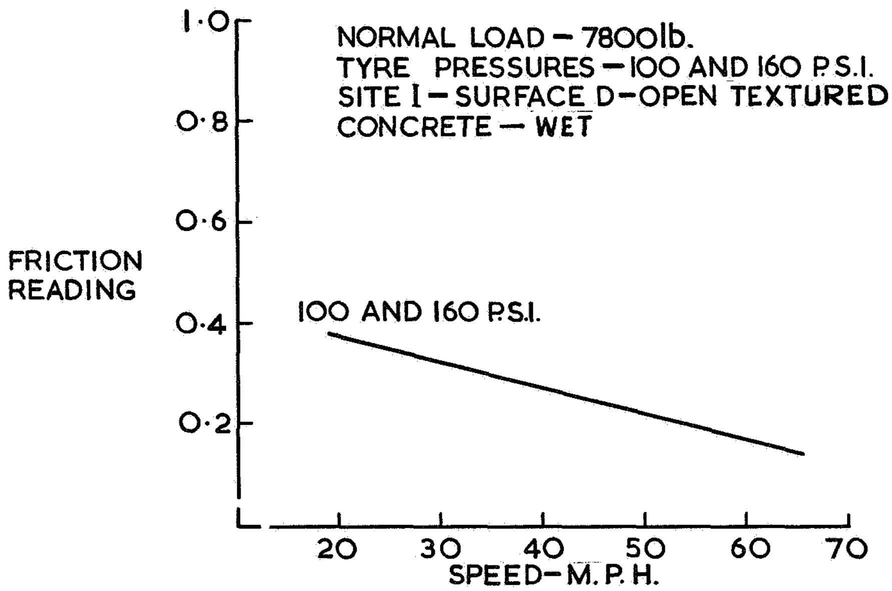


Figure 16.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface D.

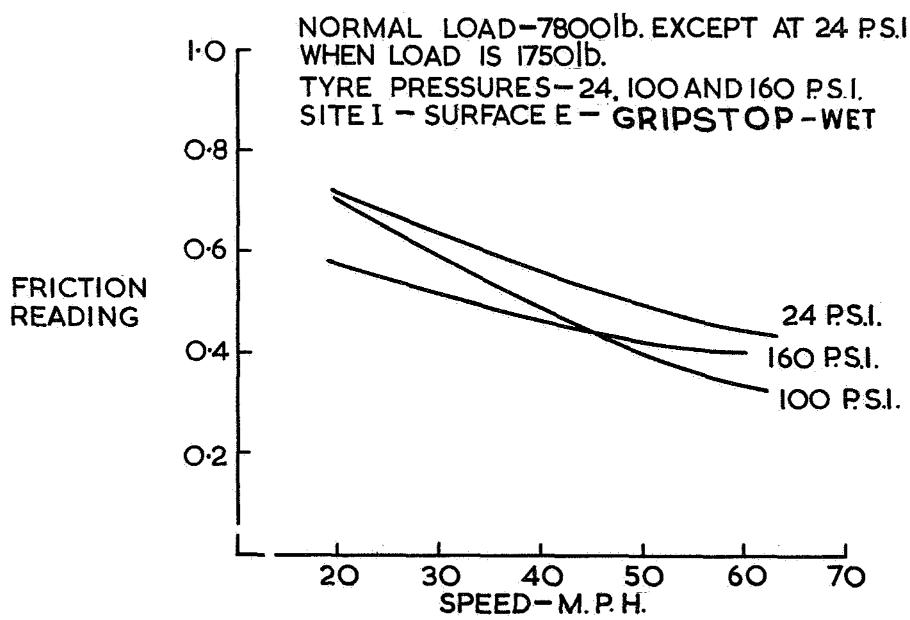


Figure 17.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface E.

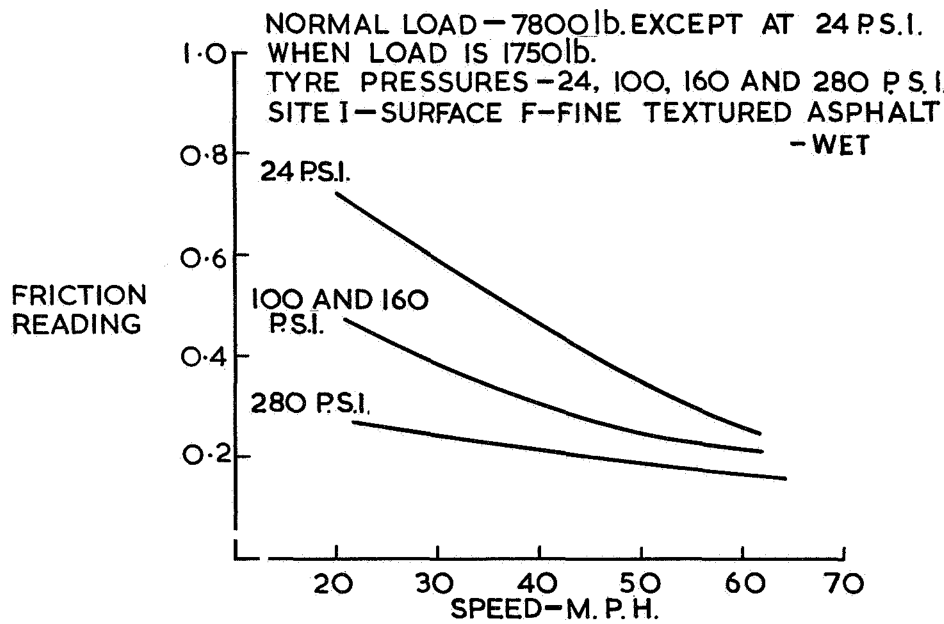


Figure 18.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface F.

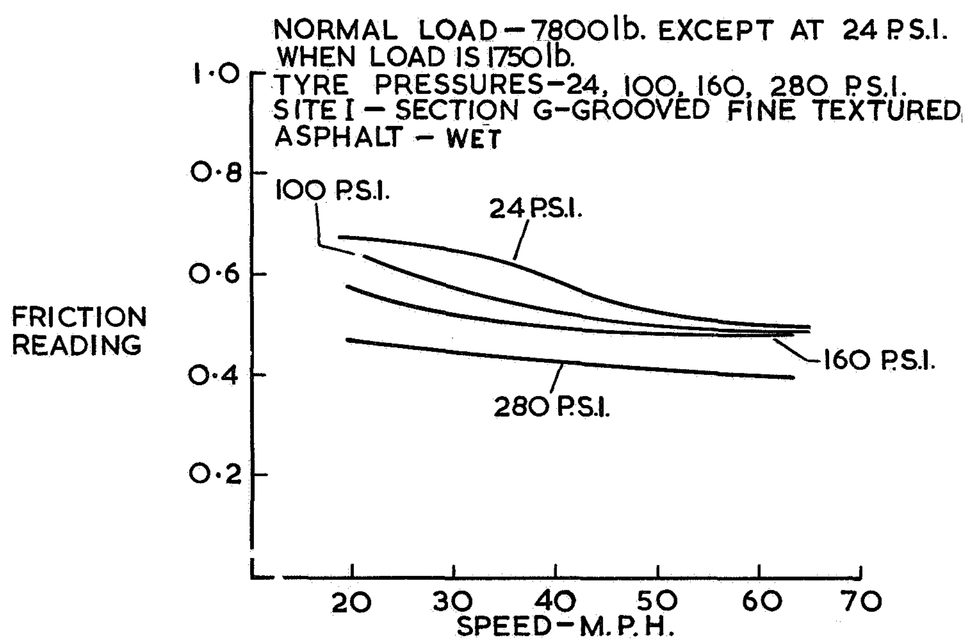


Figure 19.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface G.

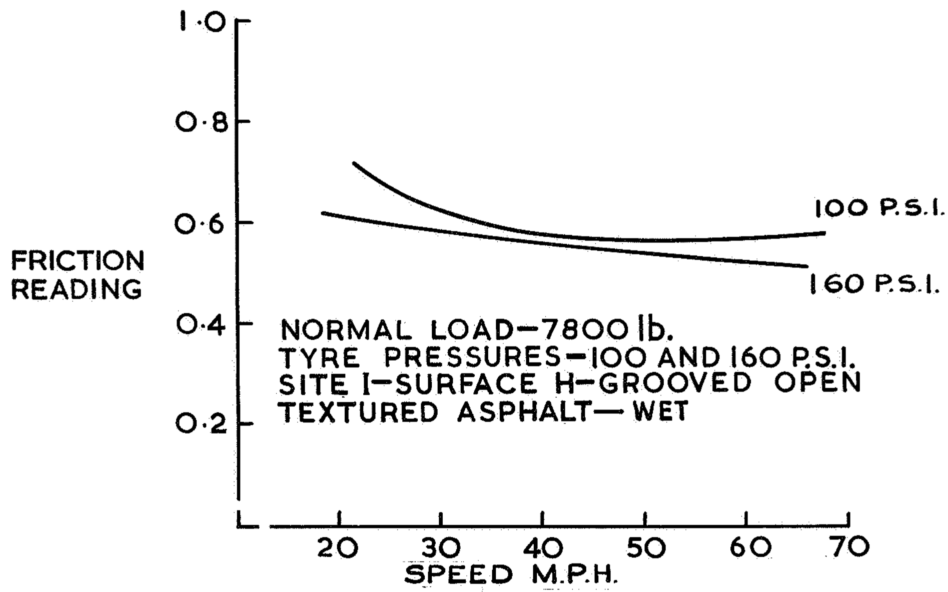


Figure 20.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface H.

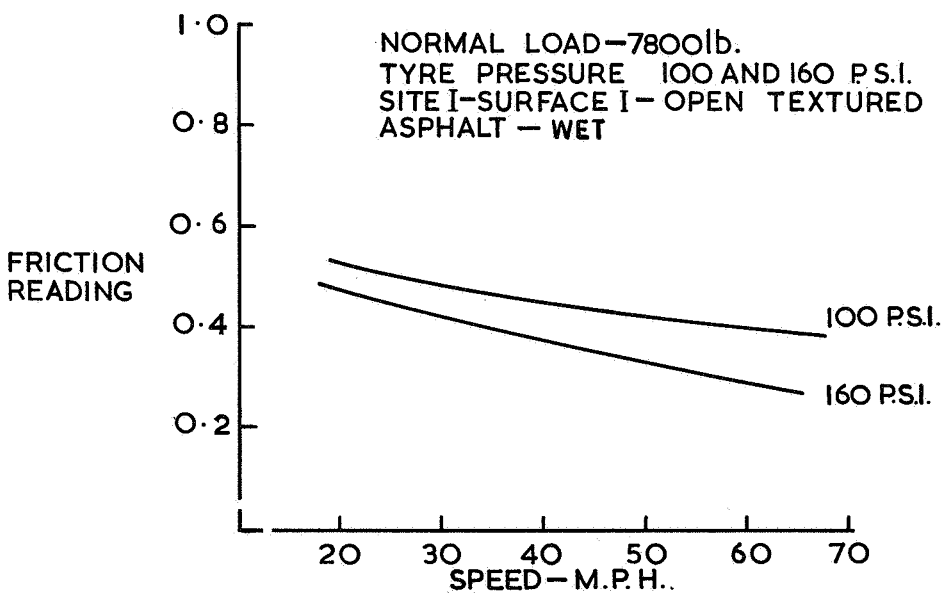


Figure 21.- Relationship between locked-wheel braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface I.

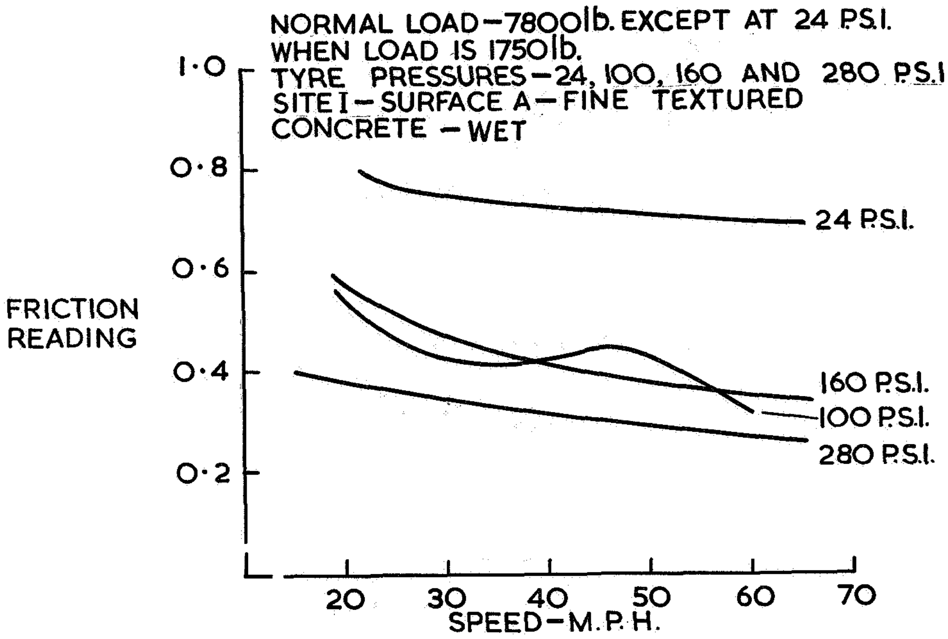


Figure 22.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface A.

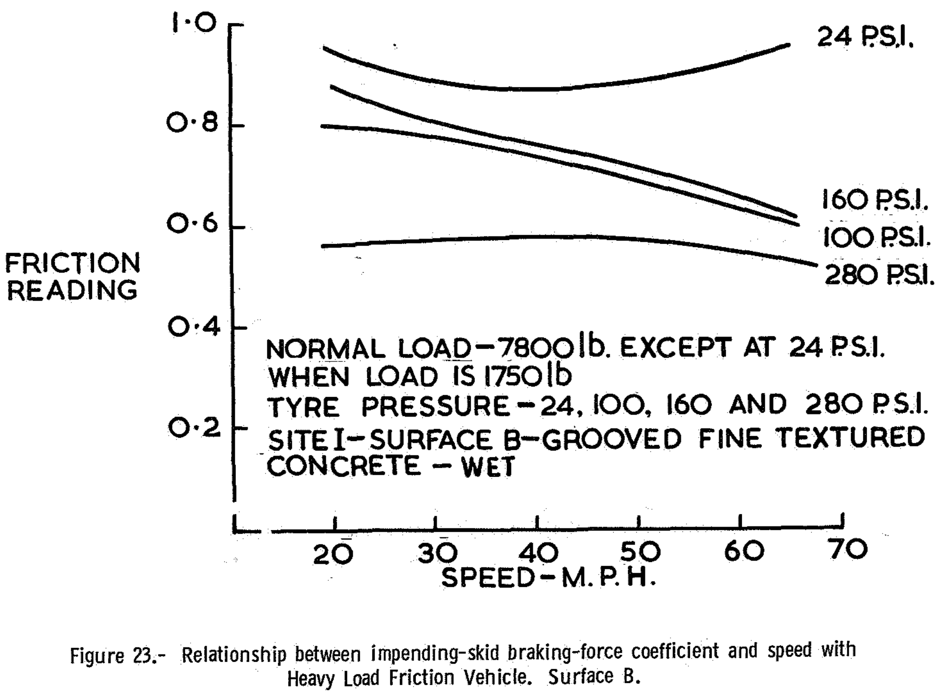


Figure 23.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface B.

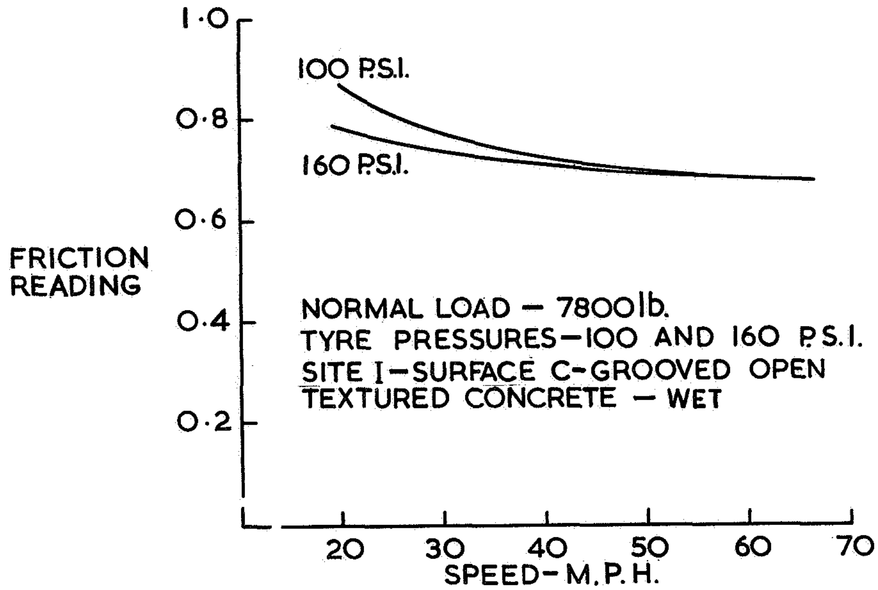


Figure 24.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface C.

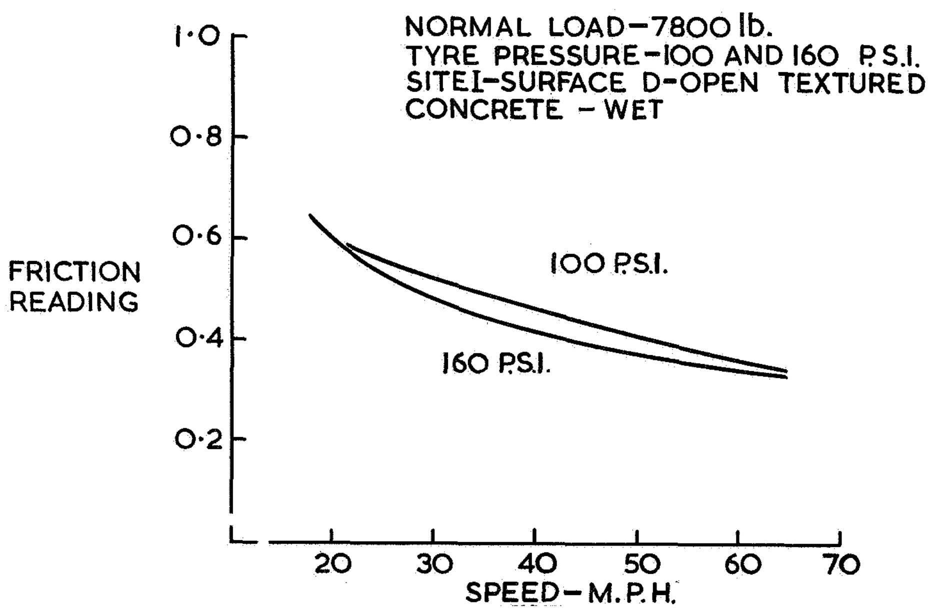


Figure 25.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface D.

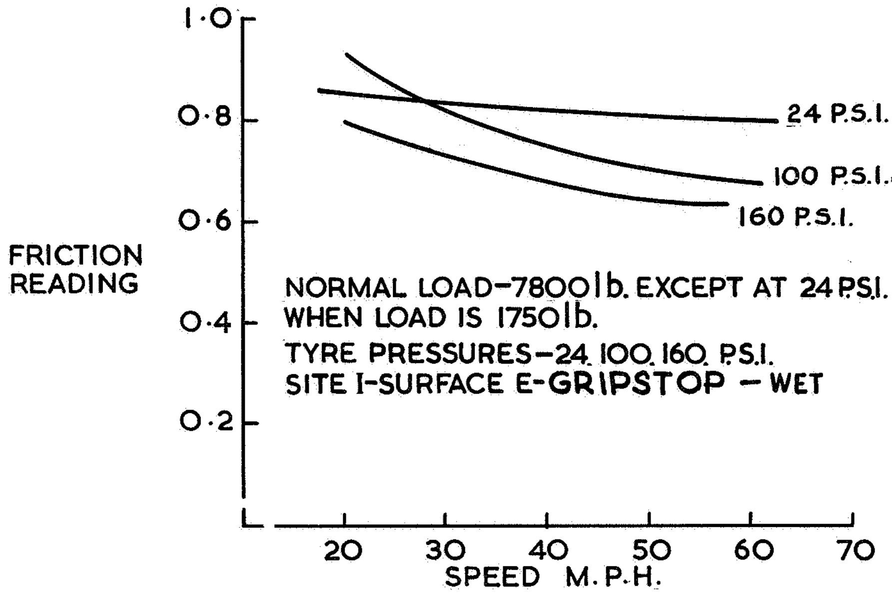


Figure 26.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface E.

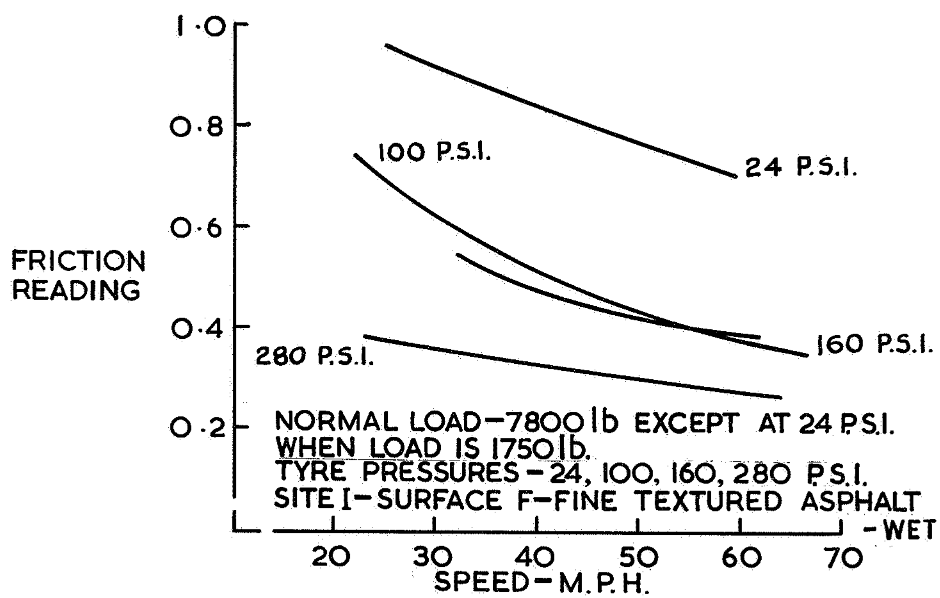


Figure 27.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface F.

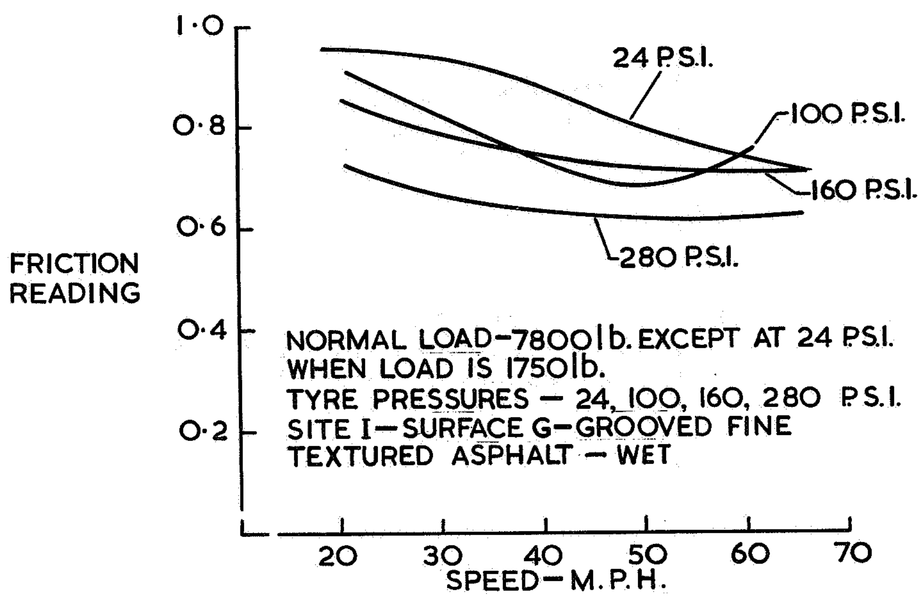


Figure 28.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface G.

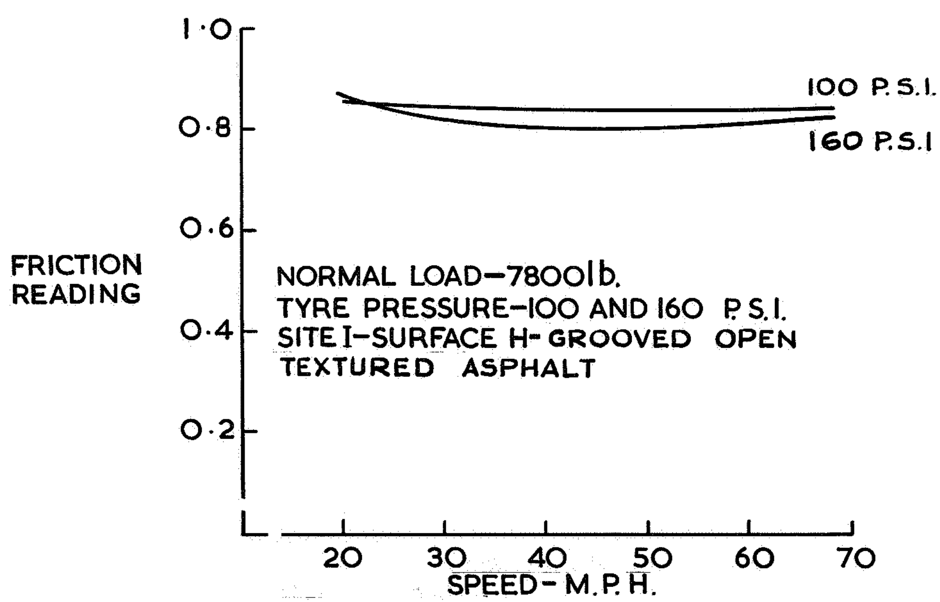


Figure 29.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface H.

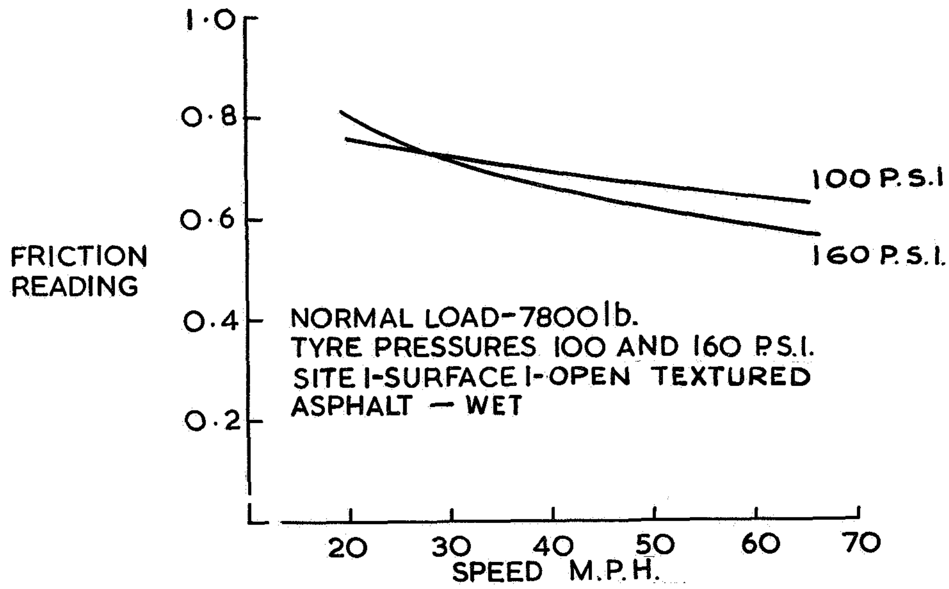


Figure 30.- Relationship between impending-skid braking-force coefficient and speed with Heavy Load Friction Vehicle. Surface I.

1 SITE 1-SECTION A — FINE TEXTURED CONCRETE – WET
2 SITE 1-SECTION B — GROOVED SMOOTH CONCRETE – WET
3 SITE 1-SECTION C — GROOVED TEXTURED CONCRETE-WET
4 SITE 1-SECTION D — TEXTURED CONCRETE – WET
5 SITE 1-SECTION E — GRIPSTOP – WET
6 SITE 1-SECTION F — SMOOTH TEXTURED ASPHALT – WET
7 SITE 1-SECTION G — GROOVED SMOOTH ASPHALT – WET
8 SITE 1-SECTION H — GROOVED TEXTURED ASPHALT – WET
9 SITE 1-SECTION I — TEXTURED ASPHALT – WET
10 SITE 1-SECTION C — GROOVED TEXTURED CONCRETE - DRY

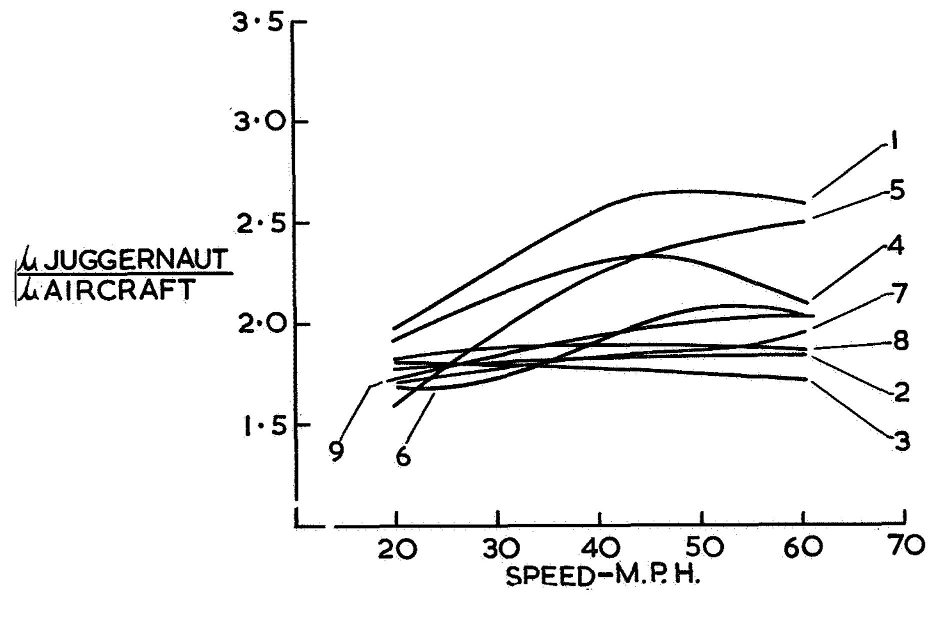


Figure 31.- Correlation between Heavy Load Friction Vehicle and 990 aircraft at 160 psi using anti-skid.

1 SITE I—SECTION A — FINE TEXTURED CONCRETE — WET
2 SITE I—SECTION B — GROOVED SMOOTH CONCRETE — WET
3 SITE I—SECTION C — GROOVED TEXTURED CONCRETE — WET
4 SITE I—SECTION D — TEXTURED CONCRETE — WET
5 SITE I—SECTION E — GRIPSTOP — WET
6 SITE I—SECTION F — SMOOTH TEXTURED ASPHALT — WET
7 SITE I—SECTION G — GROOVED SMOOTH ASPHALT — WET
8 SITE I—SECTION H — GROOVED TEXTURED ASPHALT — WET
9 SITE I—SECTION I — TEXTURED ASPHALT — WET
10 SITE I —SECTION C — GROOVED TEXTURED CONCRETE — DRY

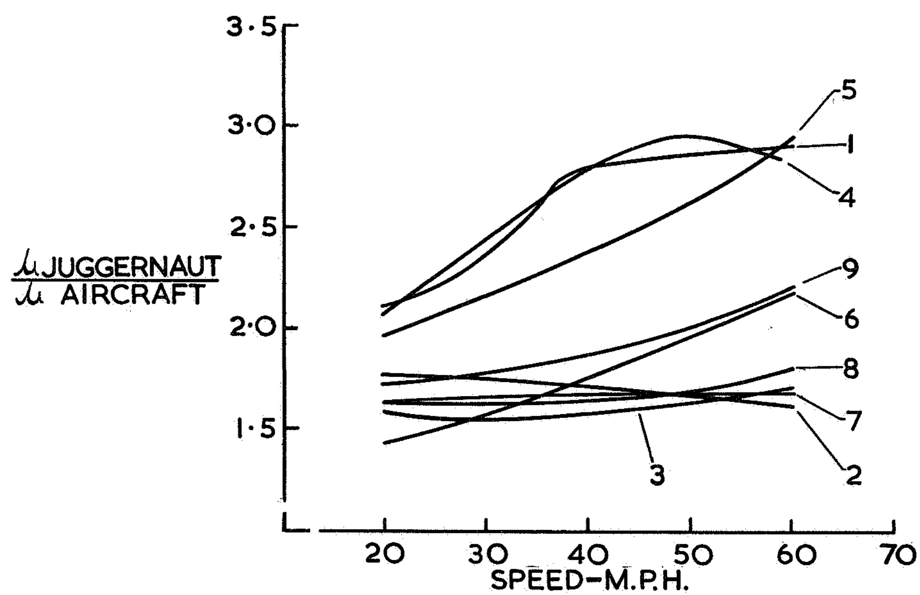


Figure 32.- Correlation between Heavy Load Friction Vehicle at impending skid and 990 aircraft at 160 psi.

1 SITE I–SECTION A – FINE TEXTURED CONCRETE – WET
2 SITE I–SECTION B – GROOVED SMOOTH CONCRETE – WET
3 SITE I–SECTION C – GROOVED TEXTURED CONCRETE – WET
4 SITE I–SECTION D – TEXTURED CONCRETE – WET
5 SITE I–SECTION E – GRIPSTOP – WET
6 SITE I–SECTION F – SMOOTH TEXTURED ASPHALT – WET
7 SITE I–SECTION G – GROOVED SMOOTH ASPHALT – WET
8 SITE I–SECTION H – GROOVED TEXTURED ASPHALT – WET
9 SITE I–SECTION I – TEXTURED ASPHALT – WET
10 SITE I –SECTION C – GROOVED TEXTURED CONCRETE – DRY

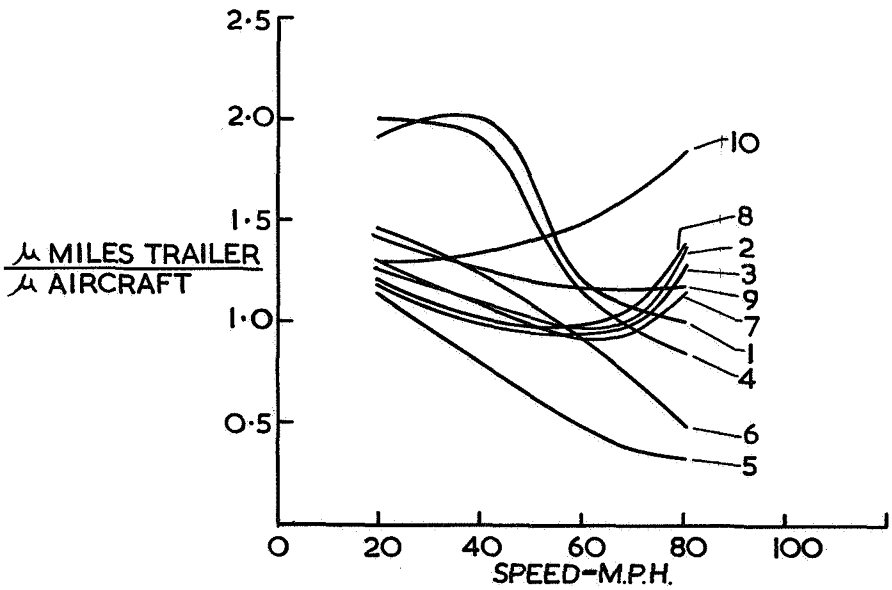


Figure 33.- Correlation between Miles Trailer and 990 aircraft.

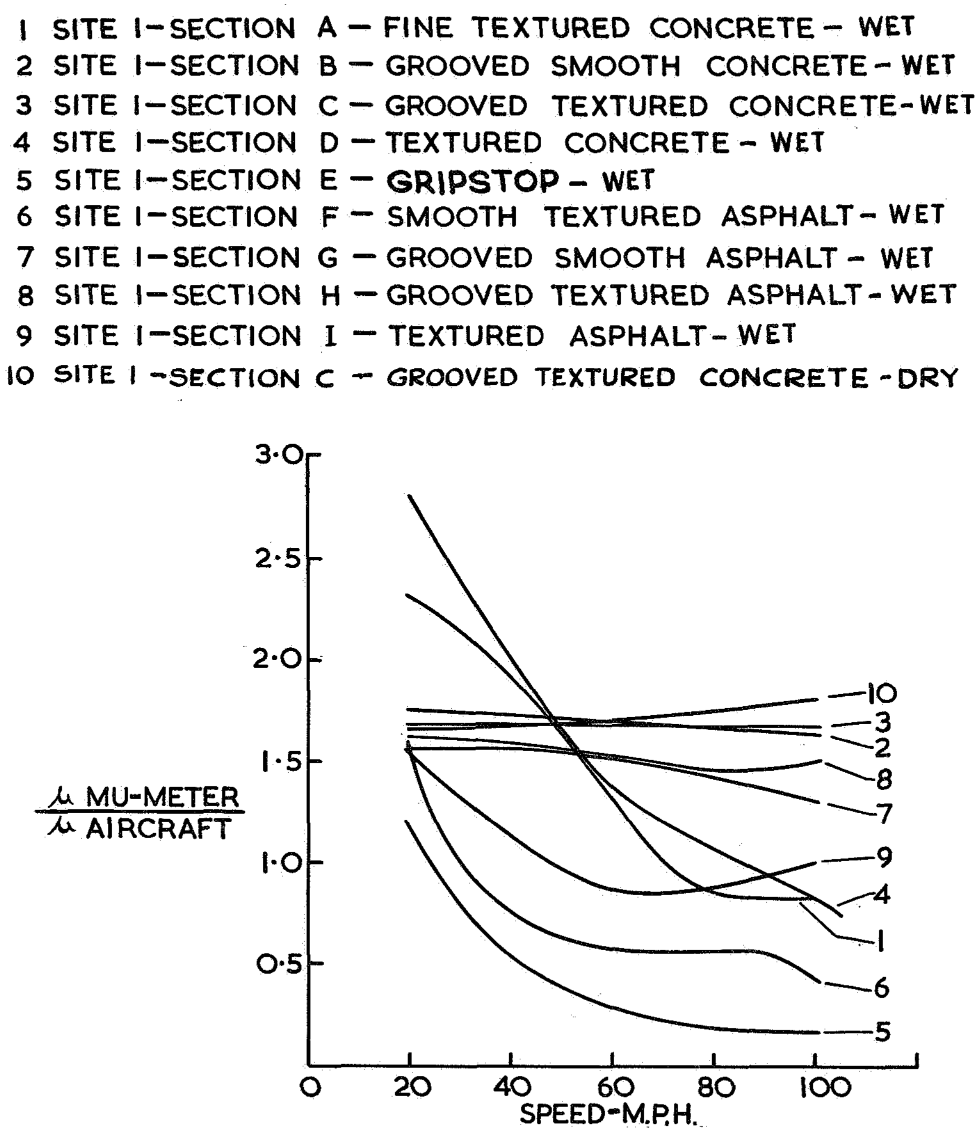


Figure 34.- Correlation between 990 aircraft and Mu-Meter.

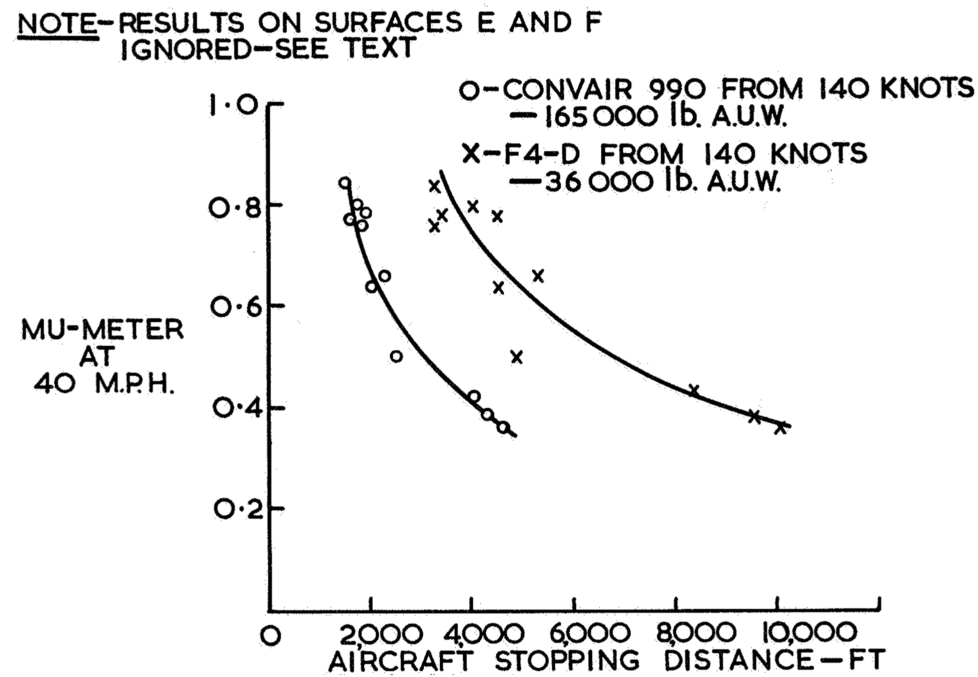


Figure 35.- Mu-Meter correlation with aircraft stopping distances. Site 1.

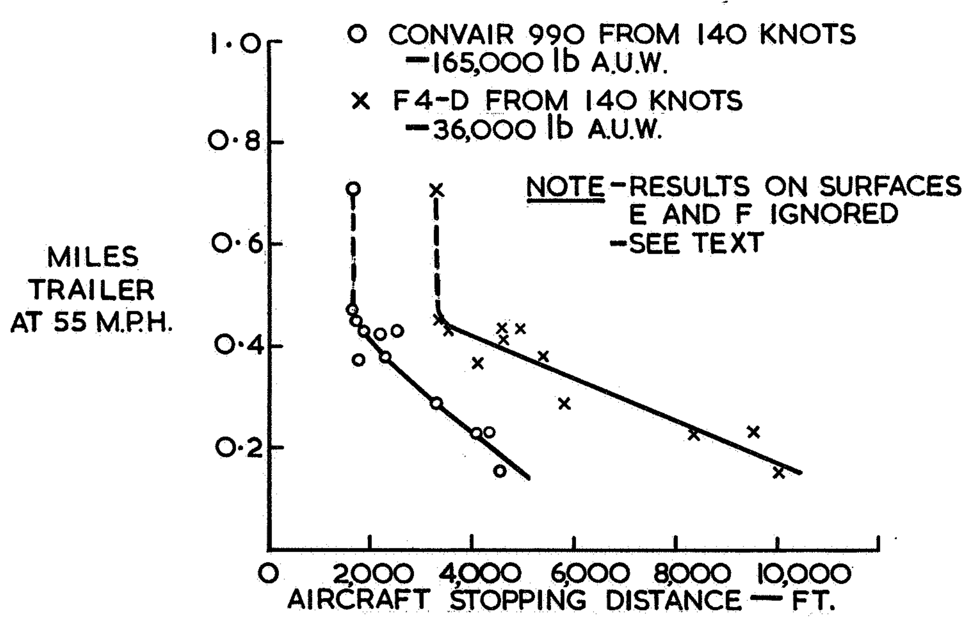


Figure 36.- Miles Trailer correlation with aircraft stopping distances. Site 1.

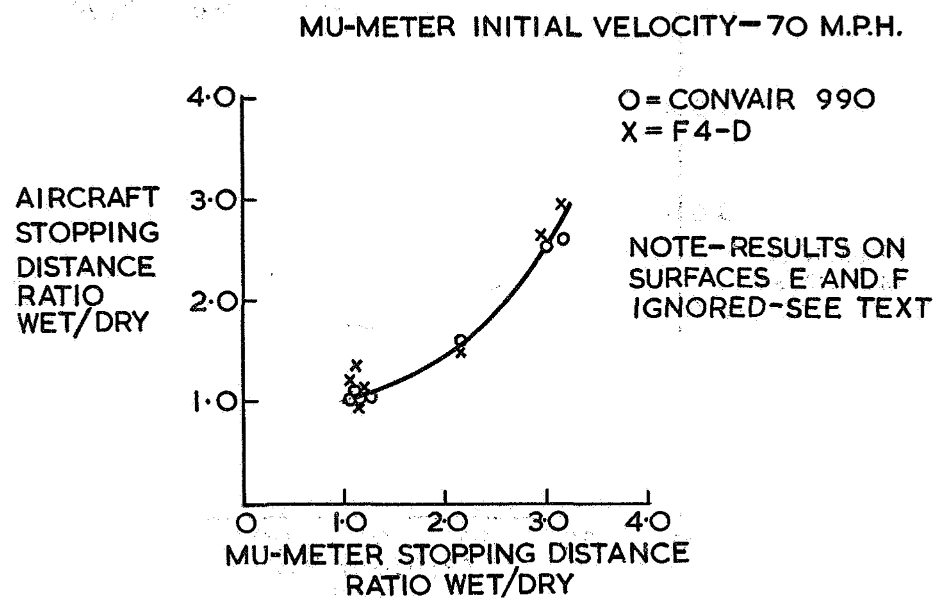


Figure 37.- Use of Mu-Meter stopping distance to indicate aircraft stopping distance.

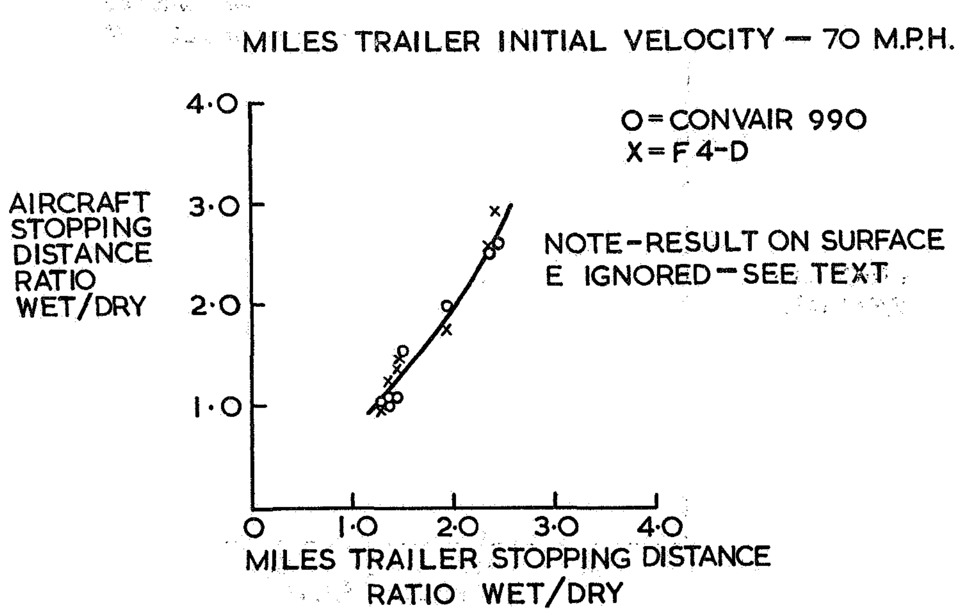


Figure 38.- Use of Miles Trailer stopping distance to indicate aircraft stopping distance.

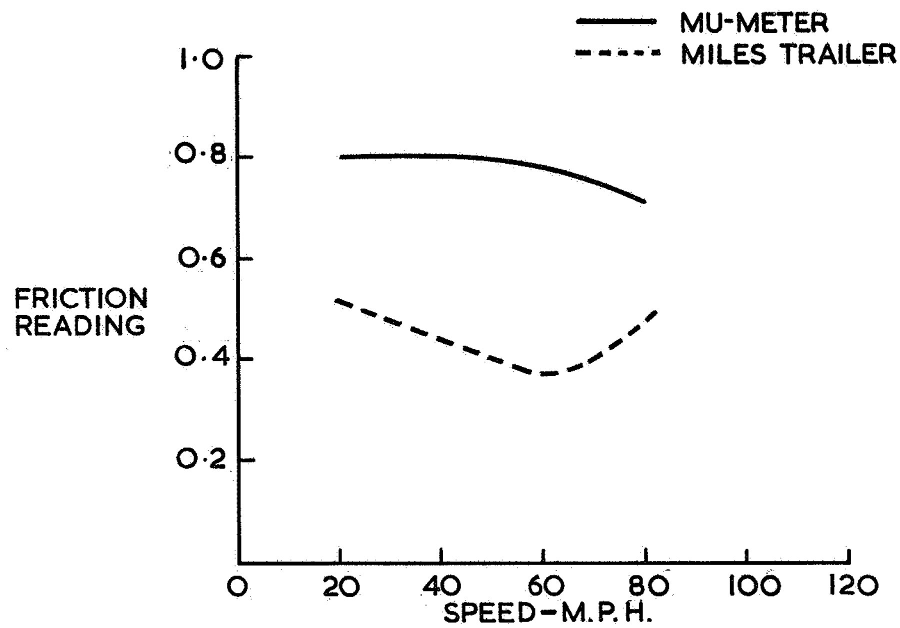


Figure 39.- Site 2, Section 2, Devron epoxy. Grey; wet.

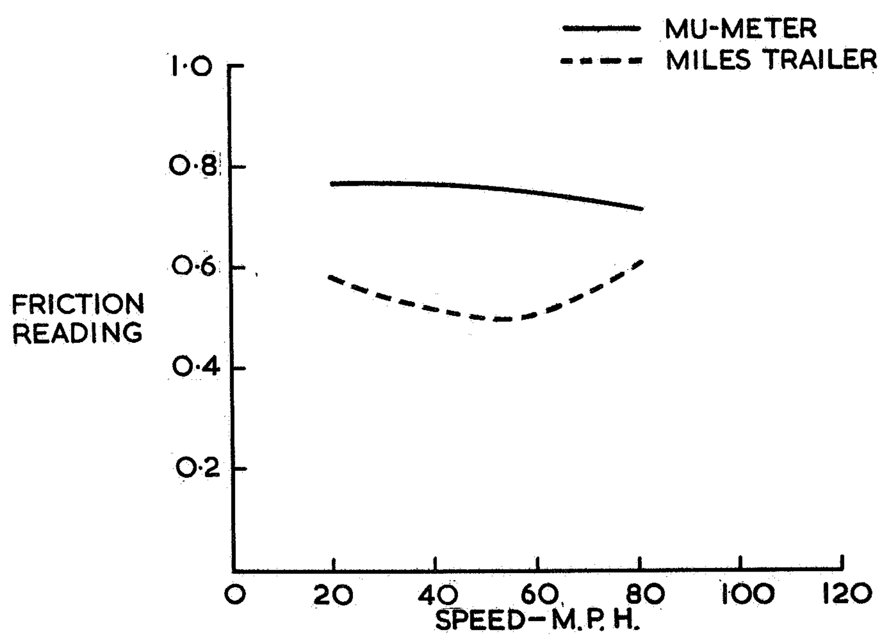


Figure 40.- Site 2, Section 2, original open textured asphalt. Wet.

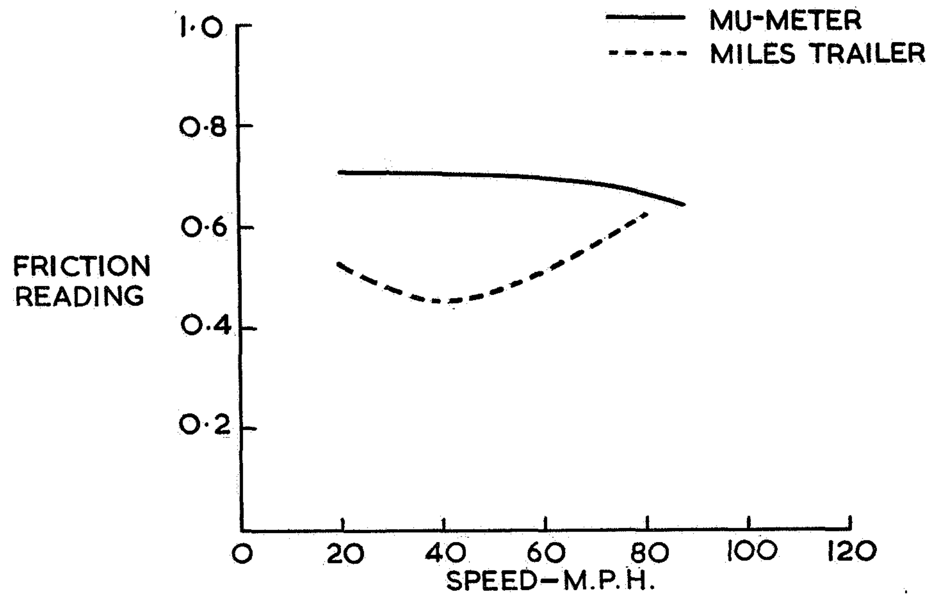


Figure 41.- Site 2, Section 2, transversely grooved concrete, 3/4 by 1/8 by 1/8 inch. Wet.

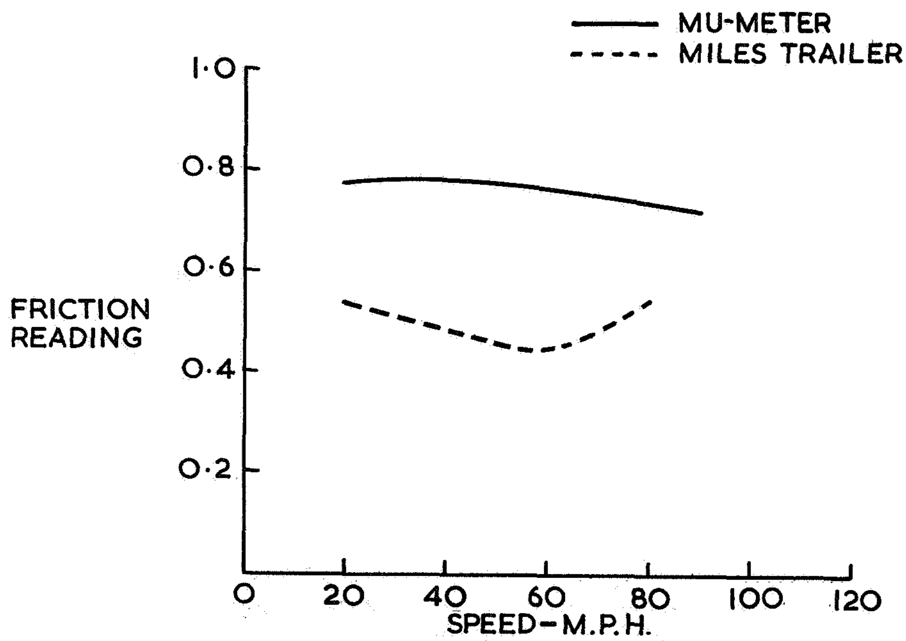


Figure 42.- Site 2, Section 2, transversely grooved asphalt, 3/4 by 1/8 by 1/8 inch. Wet.

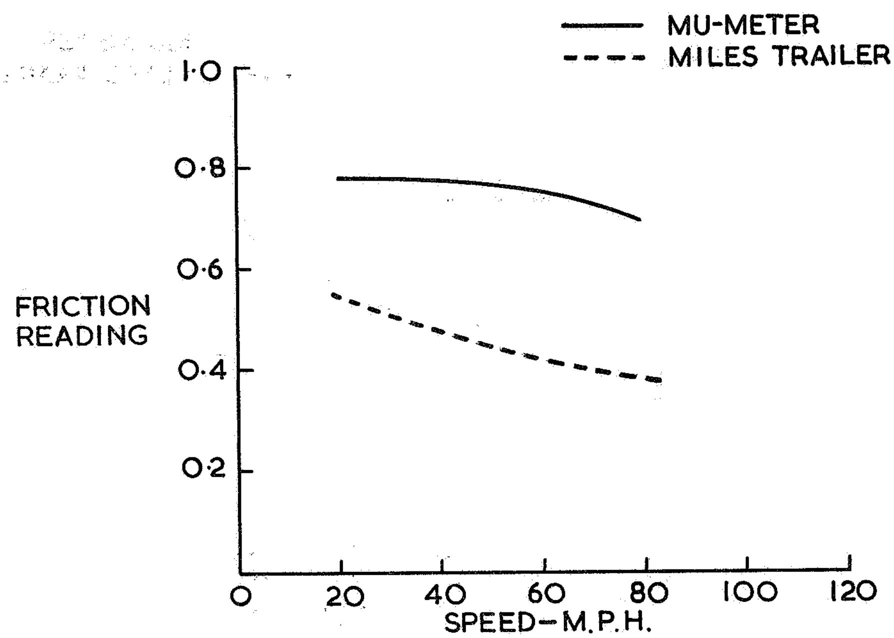


Figure 43.- Site 2, Section 3, epoxy. Wet.

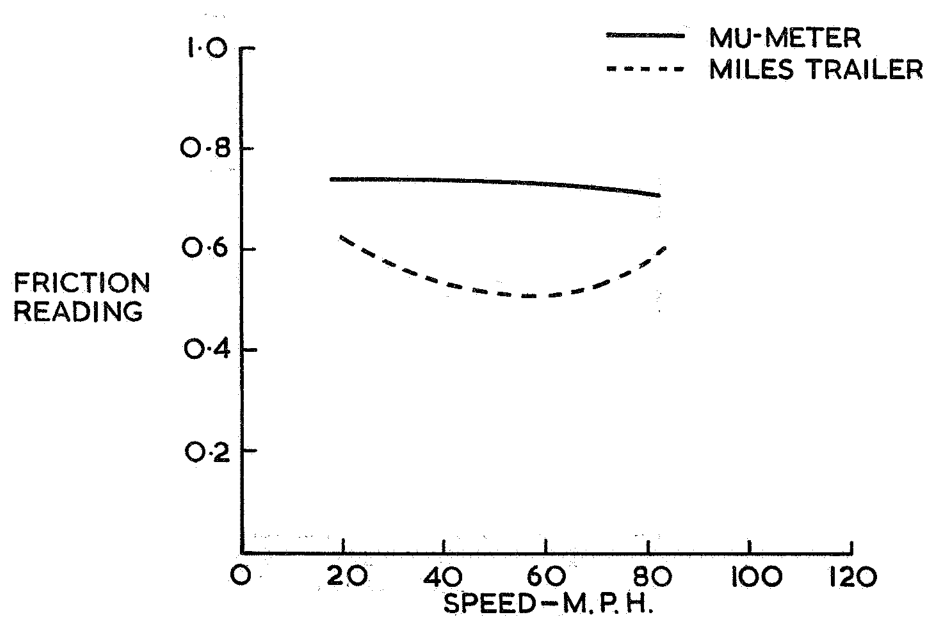


Figure 44.- Site 2, Section 3, original open textured asphalt. Wet.

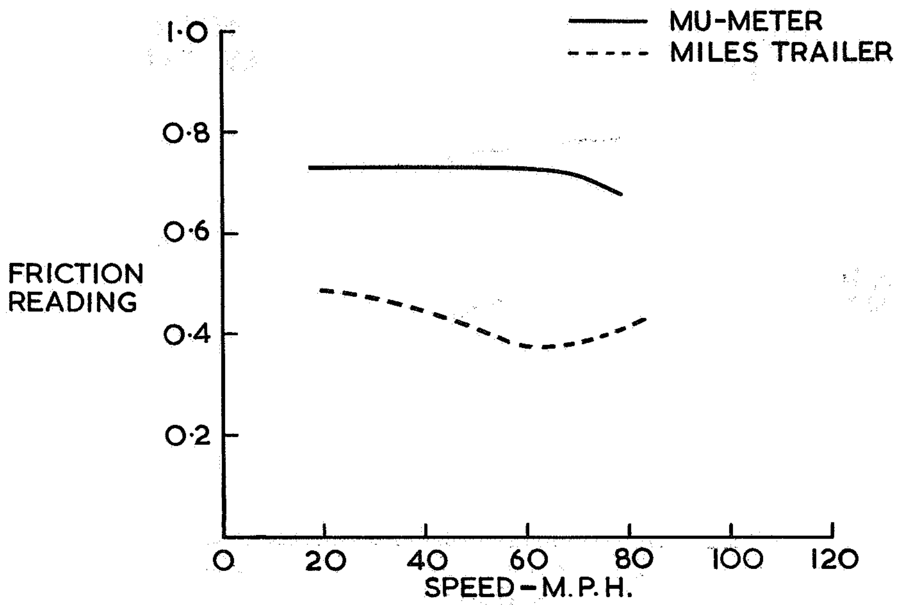


Figure 45.- Site 2, Section 3, concrete with longitudinal grooves, 3/4 by 1/8 by 1/8 inch. Wet.

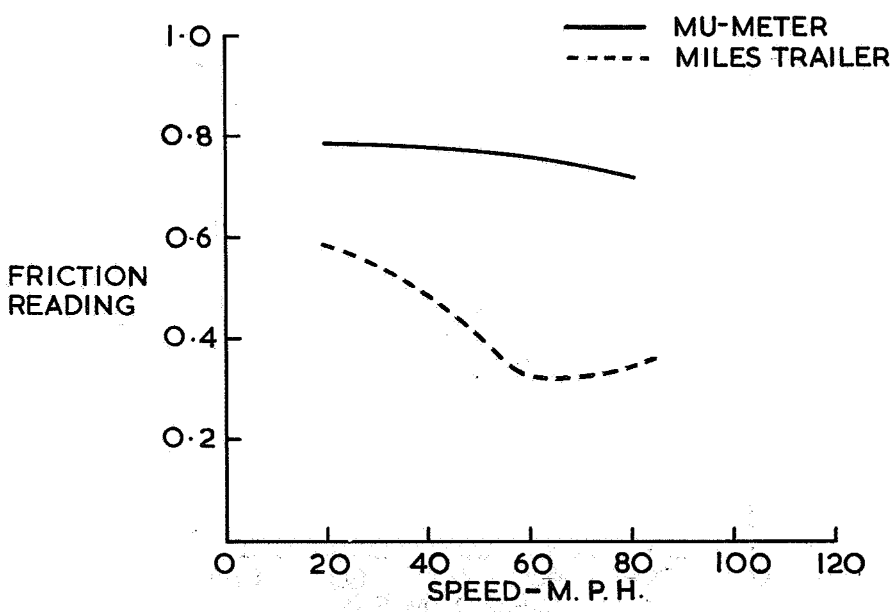


Figure 46.- Site 2, Section 3, asphalt with longitudinal grooves, 3/4 by 1/8 by 1/8 inch. Wet.

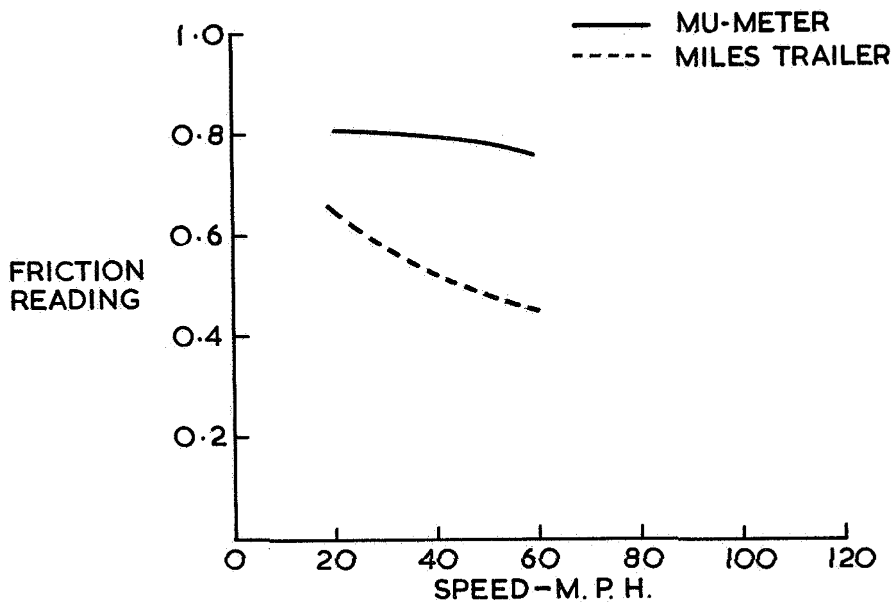


Figure 47.- Site 2, Section 4, Carrier Deck Paint. Wet.

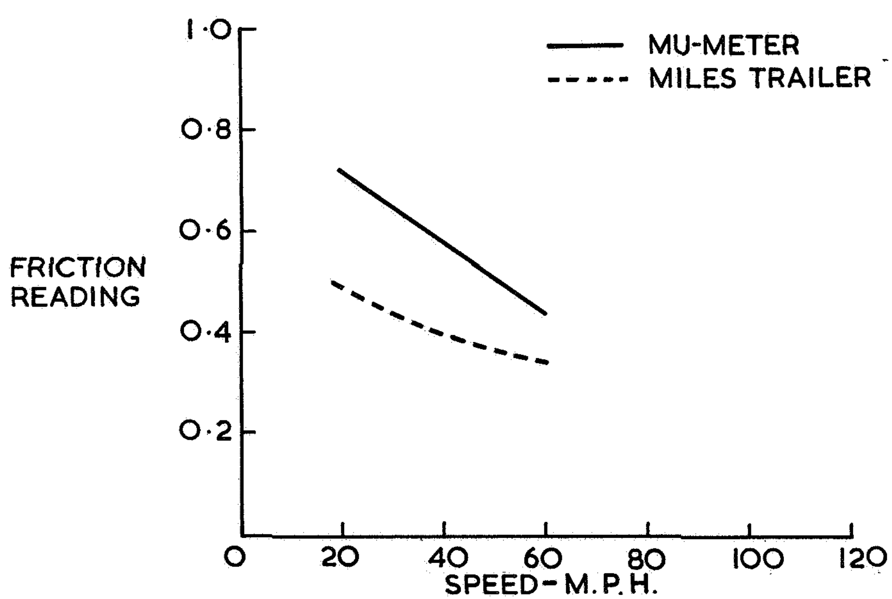


Figure 48.- Site 2, Section 4, fine textured concrete. Wet.

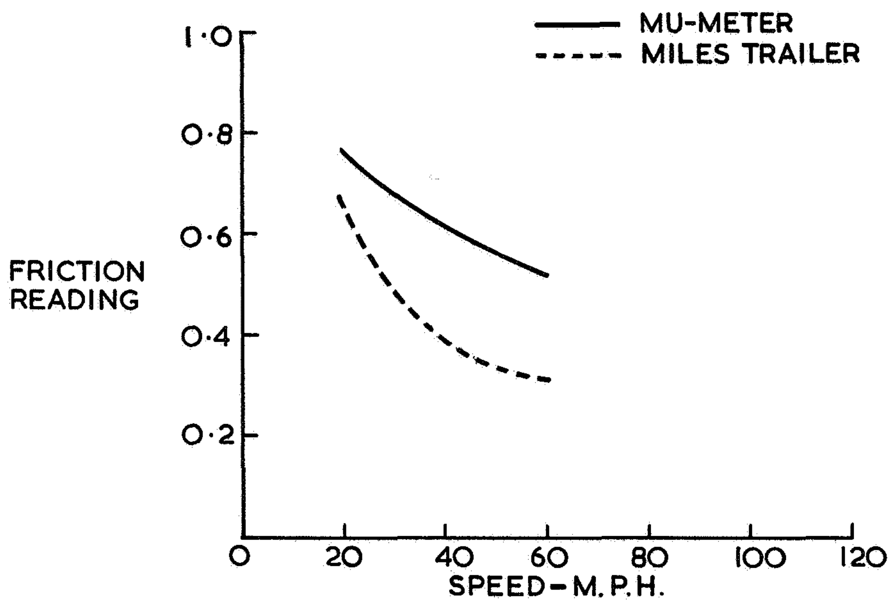


Figure 49.- Site 2, Section 4, longitudinally grooved asphalt, 1 by 1/8 by 1/8 inch. Wet.

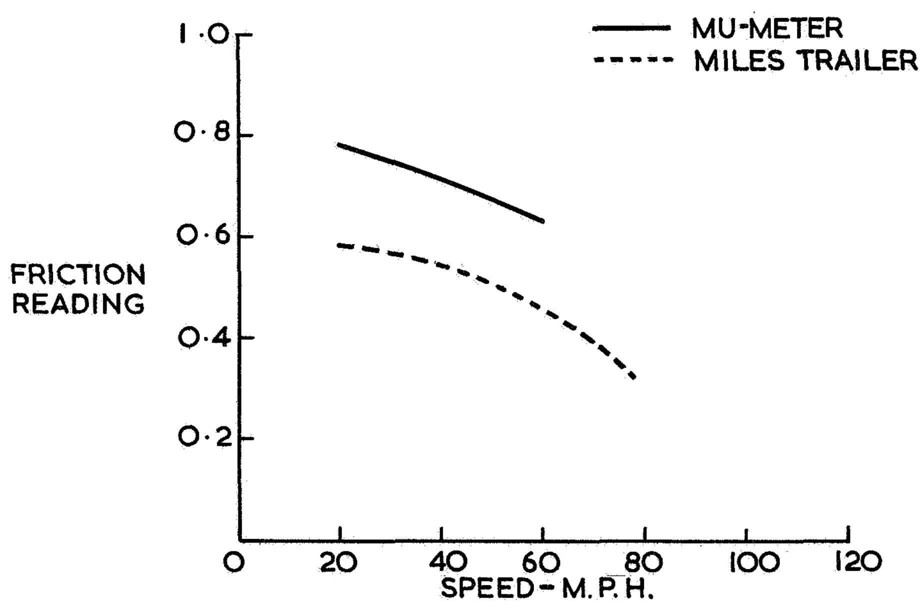


Figure 50.- Site 2, Section 5, Sinopal. Wet.

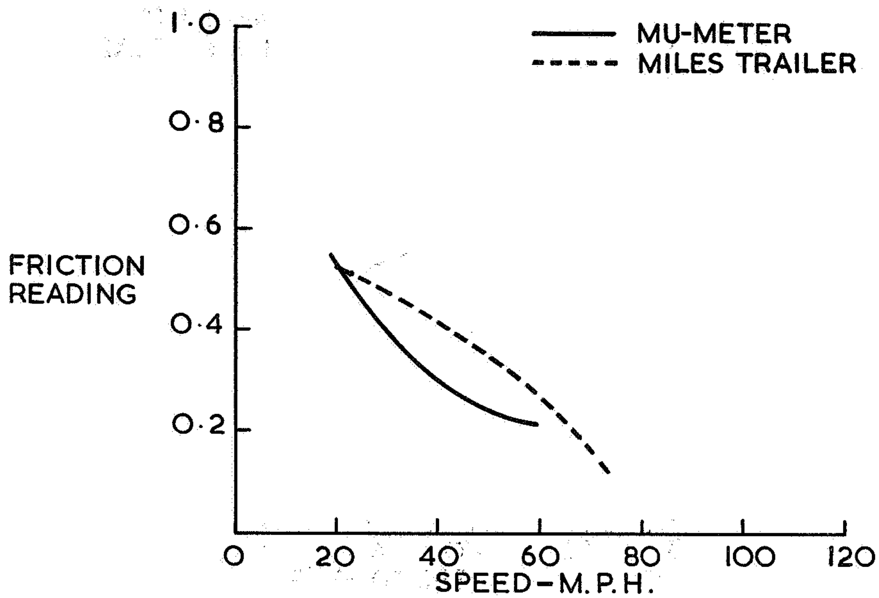


Figure 51.- Site 2, Section 5, Eastern Shore sand mix. Wet.

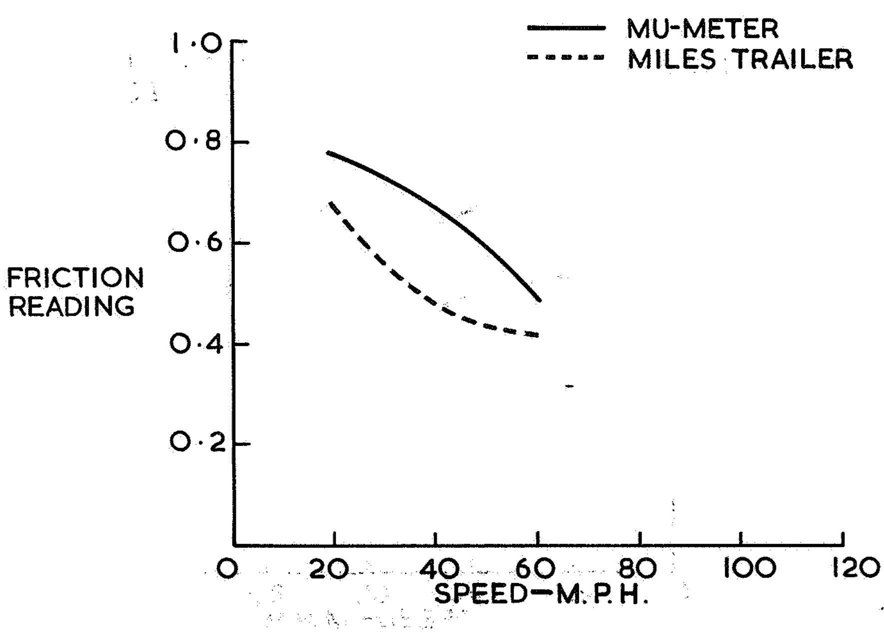


Figure 52.- Site 2, Section 5, transversely grooved asphalt, 1 by 1/8 by 1/8 inch. Wet.

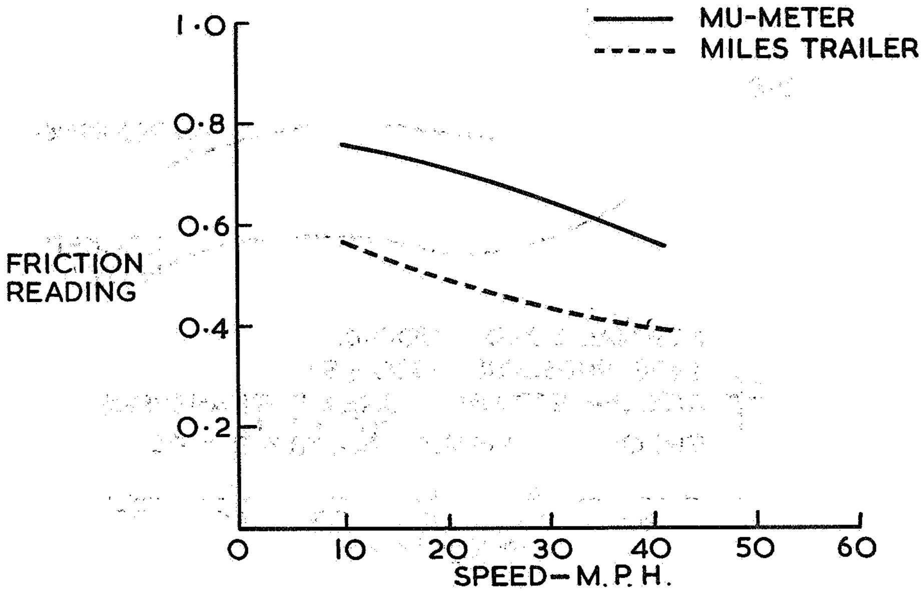


Figure 53.- Site 2, Section 6, fine textured asphalt. Wet.

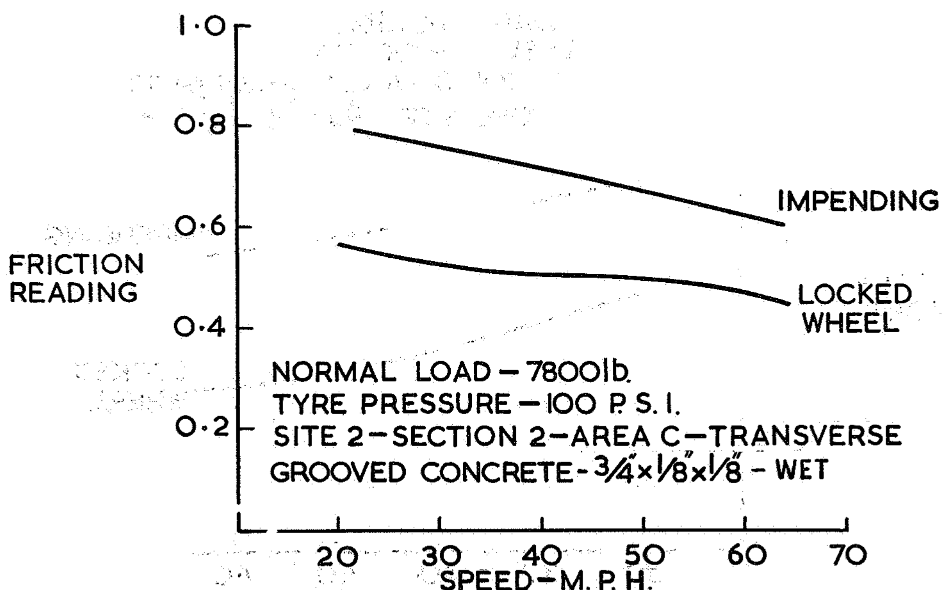


Figure 54.- Relationship between locked-wheel and impending-skid braking-force coefficients and speed with Heavy Load Friction Vehicle. Transversely grooved concrete, 3/4 by 1/8 by 1/8 inch.

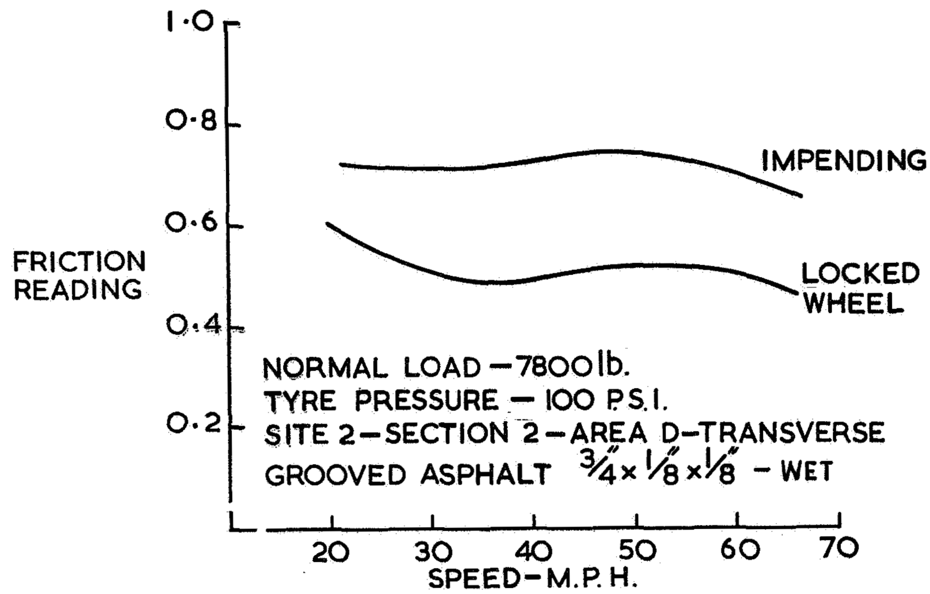


Figure 55.- Relationship between locked-wheel and impending-skid braking-force coefficients with Heavy Load Friction Vehicle. Transversely grooved asphalt, 3/4 by 1/8 by 1/8 inch.

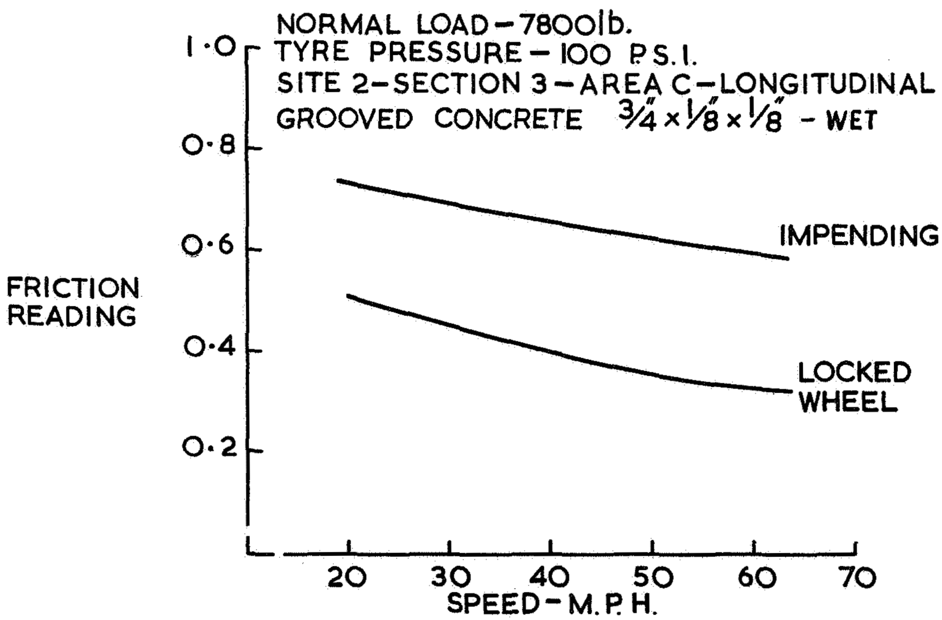


Figure 56.- Relationship between locked-wheel and impending-skid braking-force coefficients with Heavy Load Friction Vehicle. Longitudinally grooved concrete.

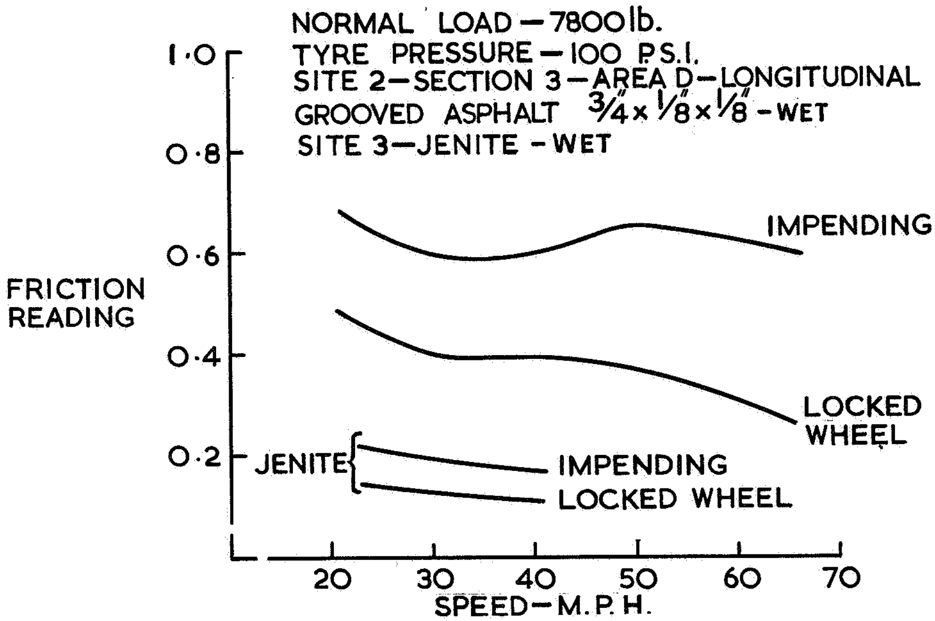


Figure 57.- Relationship between locked-wheel and impending-skid braking-force coefficients with Heavy Load Friction Vehicle. Longitudinally grooved asphalt, 3/4 by 1/8 by 1/8 inch, and Jennite.

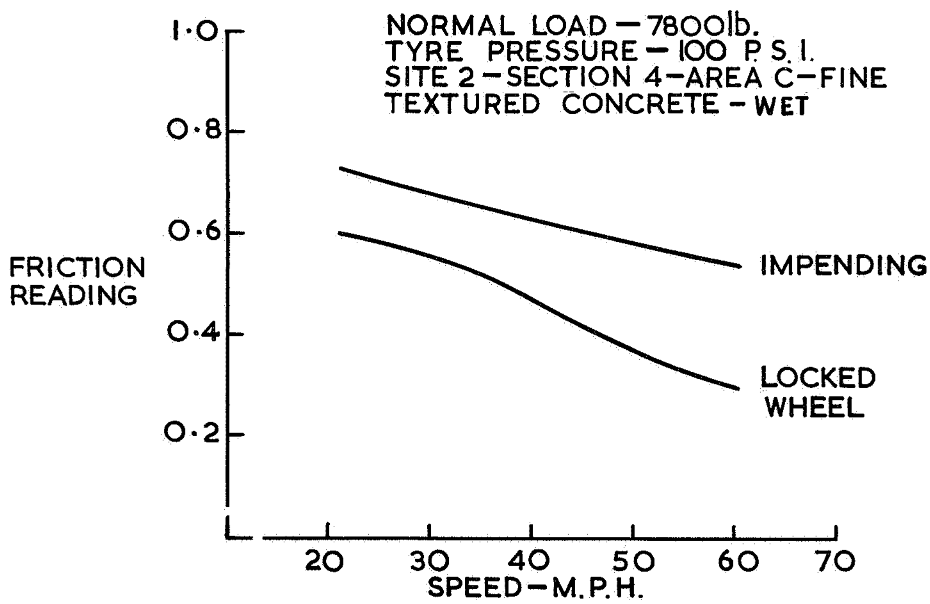


Figure 58.- Relationship between locked-wheel and impending-skid braking-force coefficients with Heavy Load Friction Vehicle. Fine textured concrete.

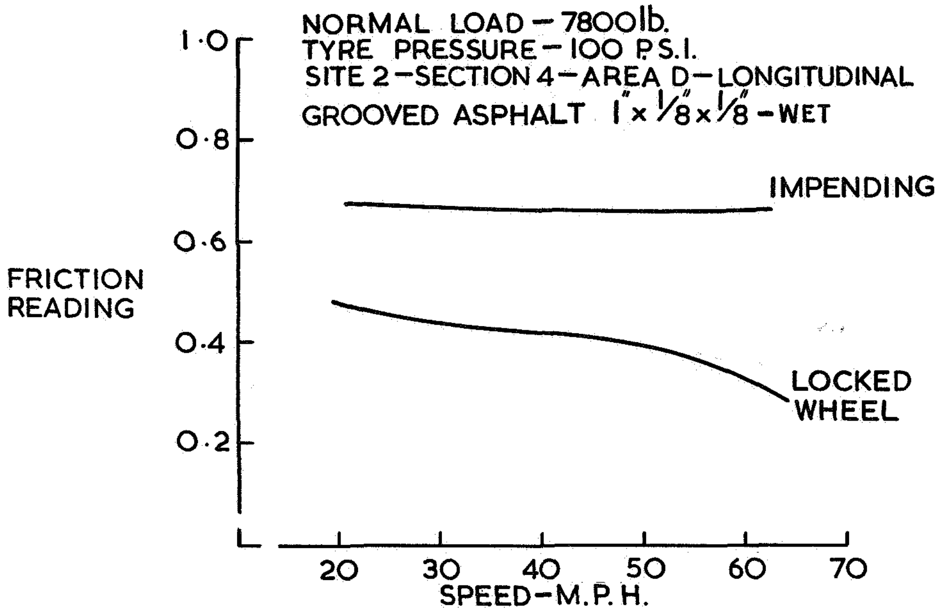


Figure 59.- Relationship between locked-wheel and impending-skid braking-force coefficients with Heavy Load Friction Vehicle. Longitudinally grooved asphalt, 1 by 1/8 by 1/8 inch.

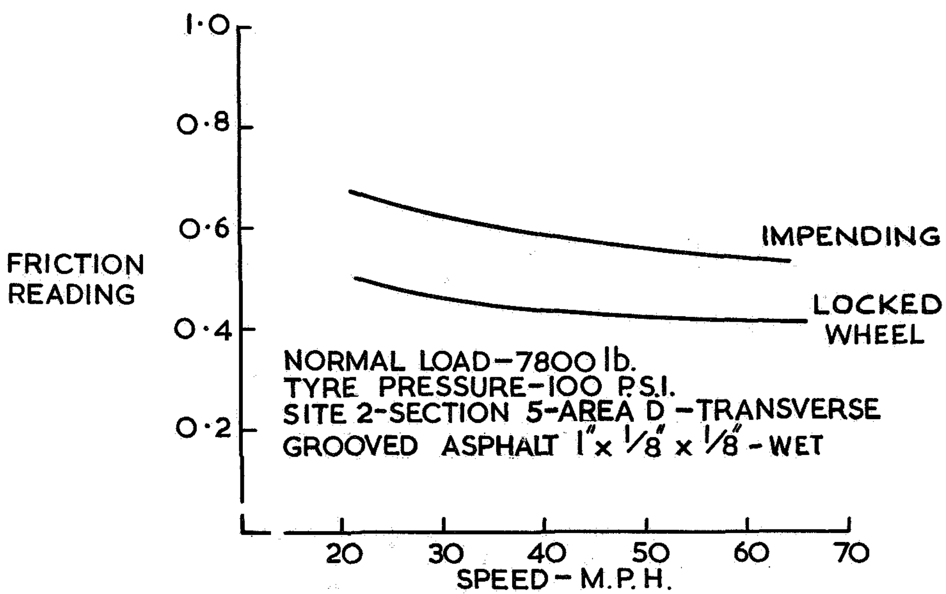


Figure 60.- Relationship between locked-wheel and impending-skid braking-force coefficients with Heavy Load Friction Vehicle. Transversely grooved asphalt, 1 by 1/8 by 1/8 inch.

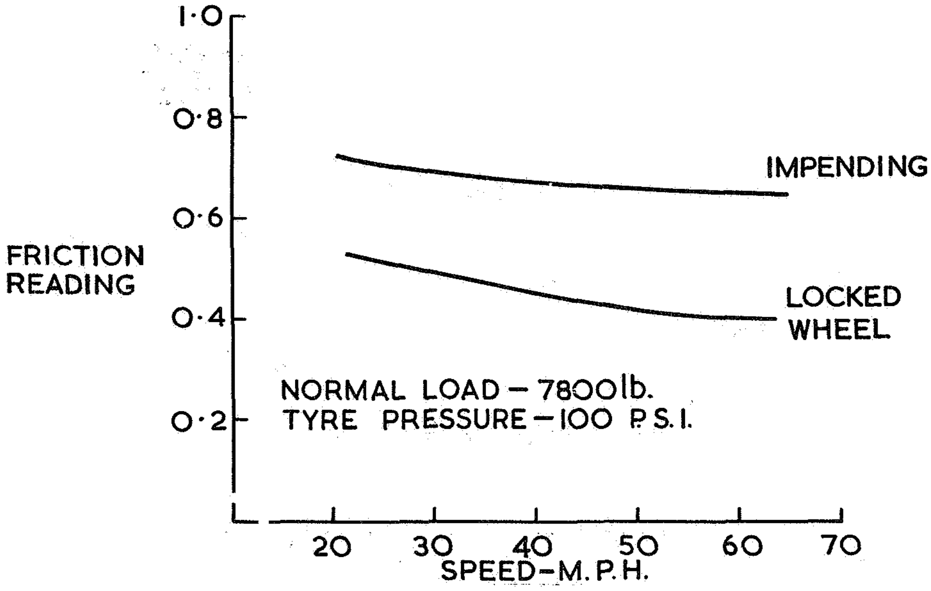


Figure 61.- Relationship between locked-wheel and impending-skid braking-force coefficients with Heavy Load Friction Vehicle. Site 2, Section 5, Sinopal.

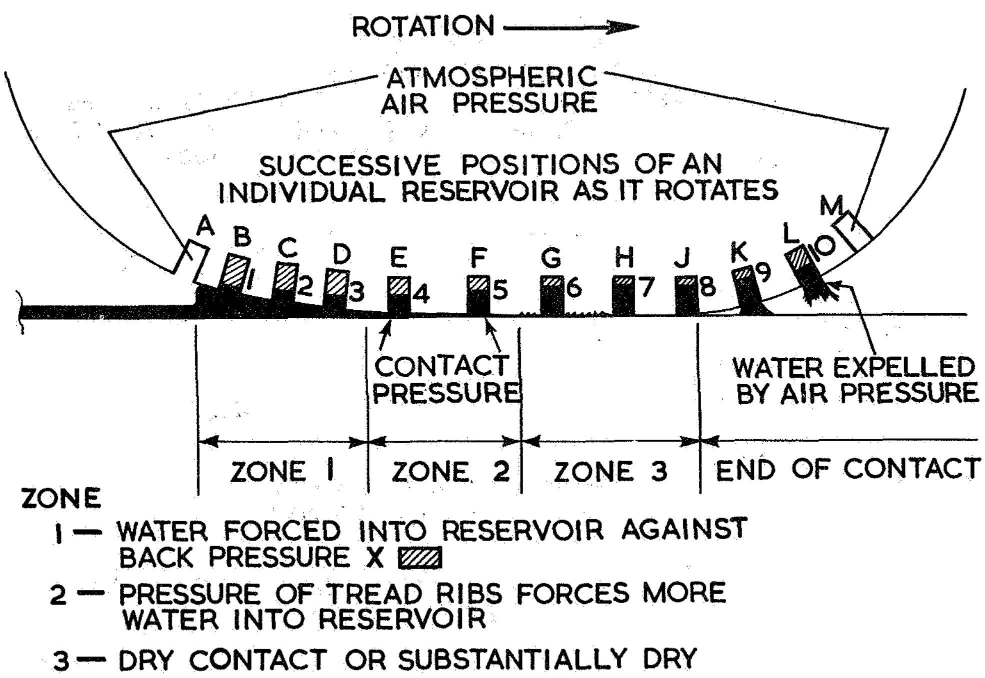


Figure 62.- Dunlop Wet Grip aircraft tyre.

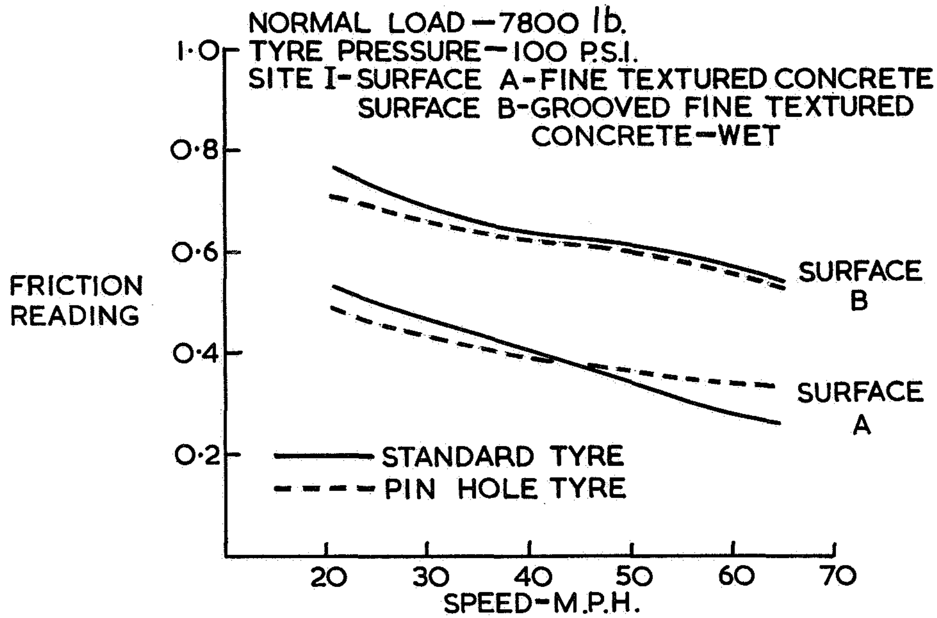


Figure 63.- Relationship between peak value of anti-skid braking-force coefficient and speed with standard and "pin hole" tyres using Heavy Load Friction Vehicle. Surfaces A and B; tyre pressure, 100 psi.

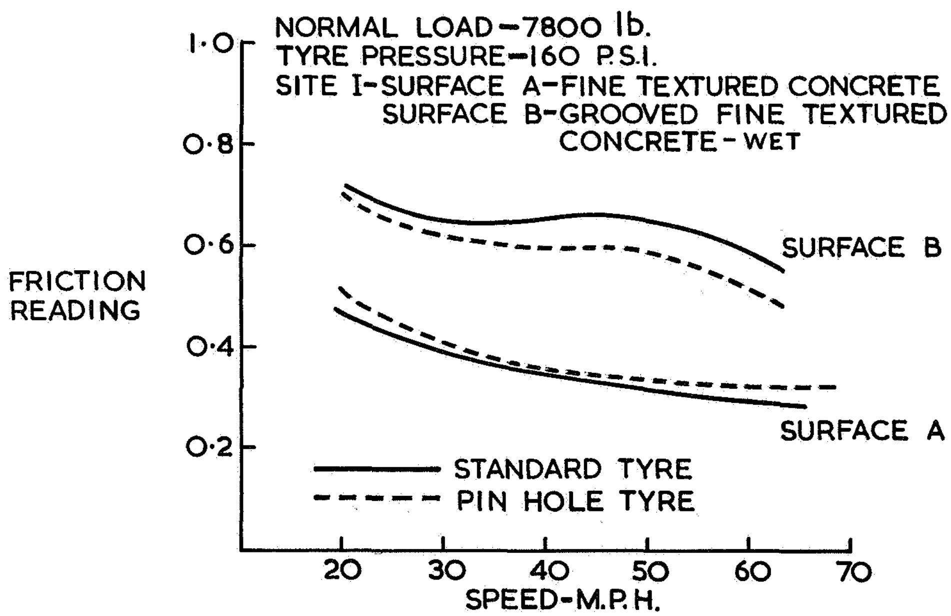


Figure 64.- Relationship between peak value of anti-skid braking-force coefficient and speed with standard and "pin hole" tyres using Heavy Load Friction Vehicle. Surfaces A and B; tyre pressure, 160 psi.

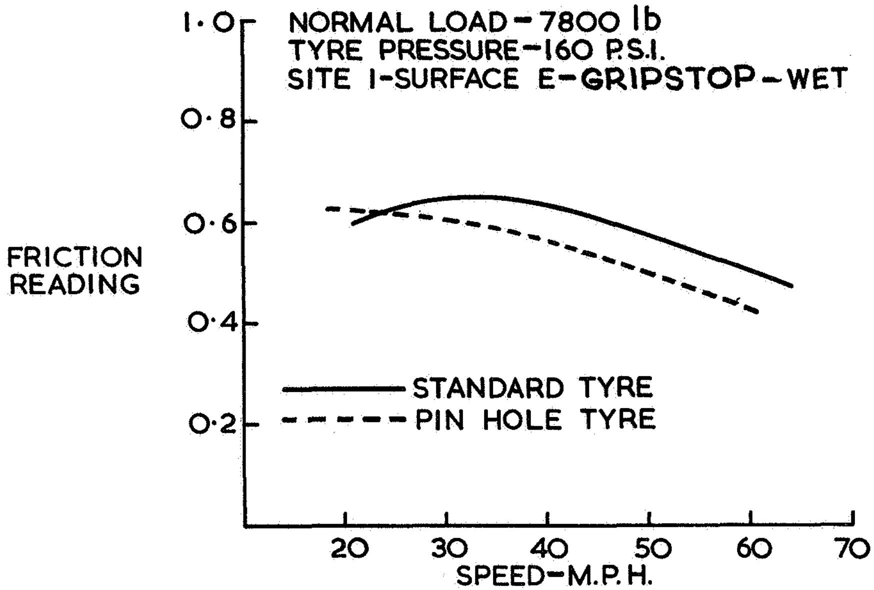


Figure 65.- Relationship between peak value of anti-skid braking-force coefficient and speed with standard and "pin hole" tyres using Heavy Load Friction Vehicle. Surface E.

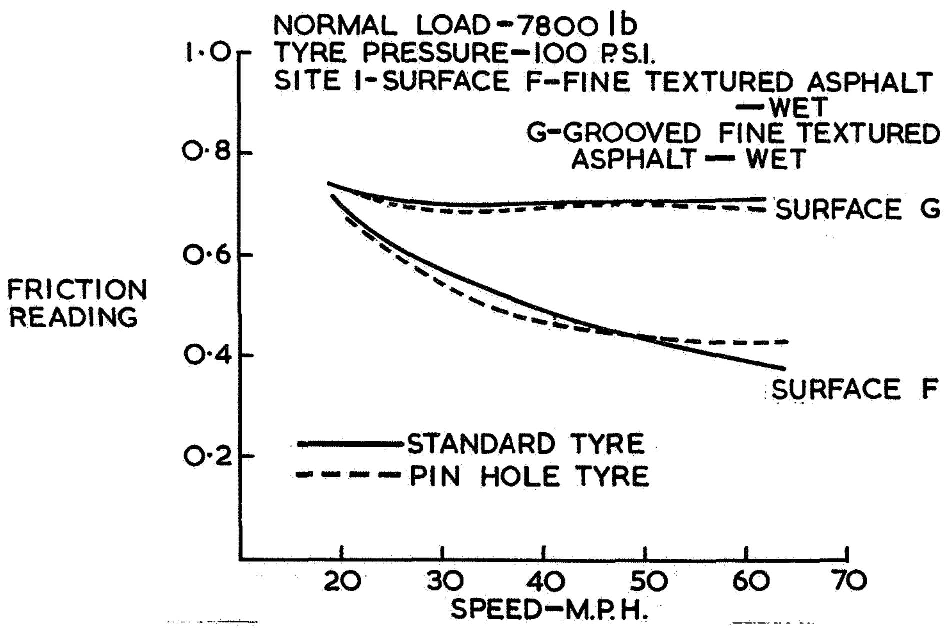


Figure 66.- Relationship between peak value of anti-skid braking-force coefficient and speed with standard and "pin hole" tyres using Heavy Load Friction Vehicle. Surfaces F and G; tyre pressure, 100 psi.

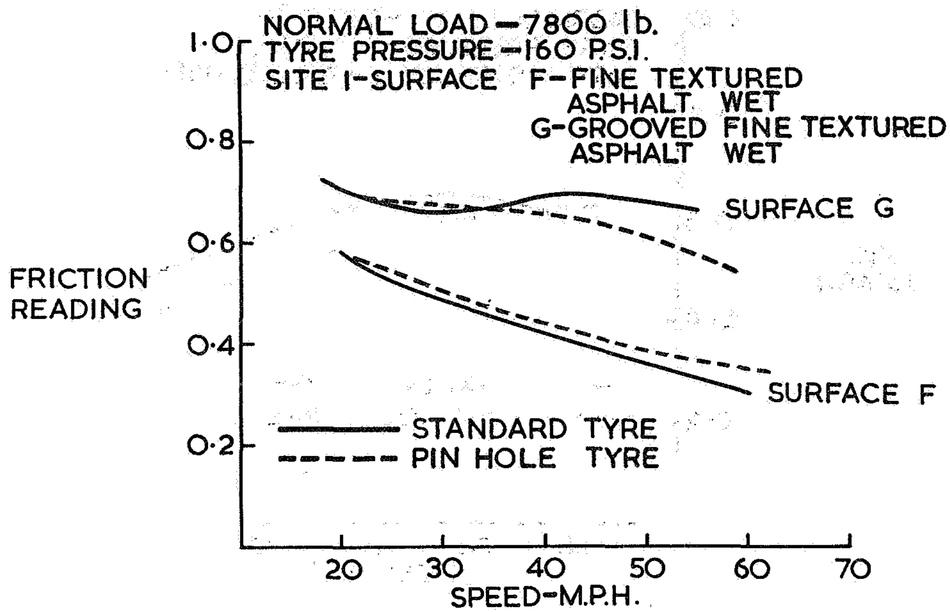


Figure 67.- Relationship between peak value of anti-skid braking-force coefficient and speed with standard and "pin hole" tyres using Heavy Load Friction Vehicle. Surfaces F and G; tyre pressure, 160 psi.

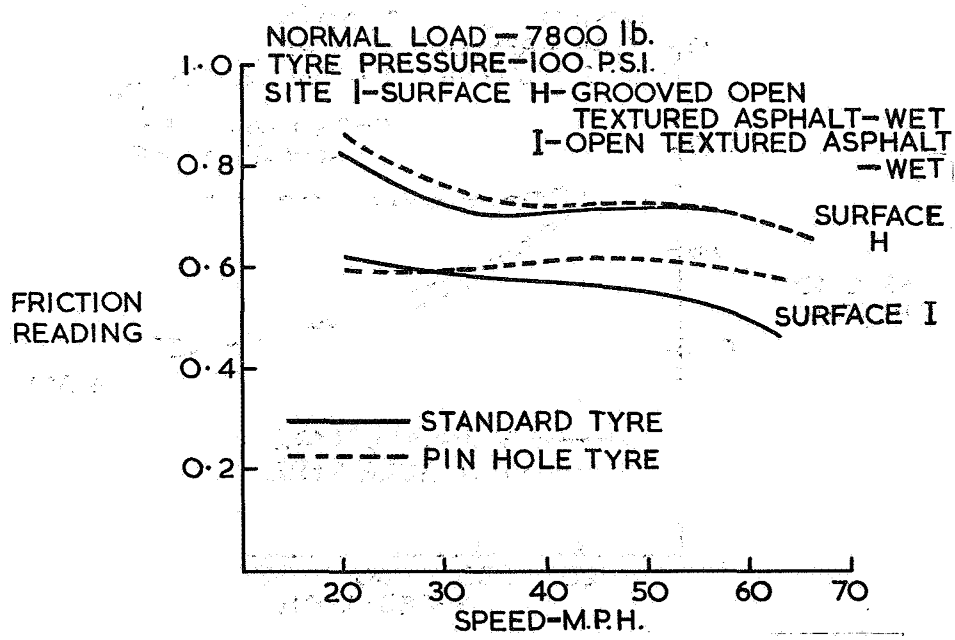


Figure 68.- Relationship between peak value of anti-skid braking-force coefficient and speed with standard and "pin hole" tyres using Heavy Load Friction Vehicle. Surfaces H and I; tyre pressure, 100 psi.

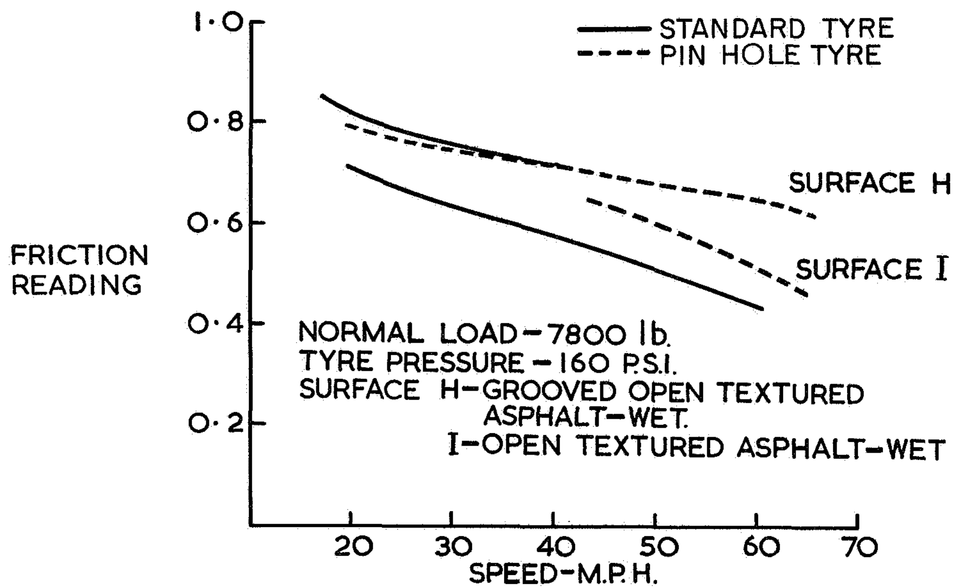


Figure 69.- Relationship between peak value of anti-skid braking-force coefficient and speed with standard and "pin hole" tyres using Heavy Load Friction Vehicle. Surfaces H and I; tyre pressure, 160 psi.

25. PAVEMENT GROOVING ON HIGHWAYS

By Eugene E. Farnsworth

California Division of Highways

INTRODUCTION

Several years ago California Division of Highways accident analysis showed that some sections of concrete highways, especially on curves, were having an unusual number of accidents during rainy weather. Pavement grooving was applied to the surface of the roadway in an attempt to reduce the number of wet-pavement accidents. The project was financed by the U.S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads. The opinions, findings, and conclusions expressed in this paper are those of the author and not necessarily those of the Bureau of Public Roads.

CHARACTERISTICS OF GROOVING

Various grooving patterns have been applied to California highways. Widths and depths of the grooves vary from 1/4 inch to 1/8 inch, and spacing of the cuts varies from 3/8 to 1 inch center to center. All grooving is longitudinal.

The oldest grooving in California (project A) was placed in 1960. The pattern was 1/8 inch by 1/8 inch on 3/8-inch centers. After 8 years of heavy traffic wear there is very little deterioration of the grooves (fig. 1). Figure 2 illustrates the change in friction values of portland cement concrete (PCC) pavement after grooving of various projects in California. At project A the coefficient of friction is increasing with age. The friction values shown are for the California tester, 0.25 being the critical value for remedial action.

California has had very little experience with the freeze-thaw cycle effect on pavement grooving. In a mountainous area, where snow chains are used, the pavement is subjected to considerable wear. A grooving pattern of 1/8 inch by 1/8 inch on 1-inch centers placed in this area shows a tendency to round over between the grooves.

There is no effect on PCC grooving from high temperatures. Much of our grooving has been done in areas with daily summer temperatures in the 90° to 100° F range. High temperatures will affect grooving on asphalt concrete (AC). Only AC pavement with exposed aggregate and aged asphalt is suitable for grooving.

BENEFITS OF GROOVING

The increase in coefficient of friction after grooving changes the friction values from below critical to above critical. The measurements are taken longitudinally. However, the benefit to the vehicle is the ability of the grooves to prevent sideways skidding, which is not being measured by skid testers.

Before-and-after accident studies of grooved areas have clearly shown the benefit of pavement grooving to the motorist. The longitudinal grooves act as "tracks," resisting lateral movement and stabilizing the vehicle. They also serve as quick surface drains to minimize any water buildup on the pavement.

Figure 3 shows the results of grooving on I-5, 50 miles north of Los Angeles. This grooving, 1/8 inch by 1/8 inch on 1/2-inch centers, was completed in 1963. ADT in this area is 17 000. Cost of the work was $2,500. There were nine wet-pavement accidents during the 2 years before the grooving and none during the 5 years after the grooving.

Figure 4 shows the results of grooving on I-5 at Laguna Canyon Road just off the west end of the El Toro Marine Base runway. The grooving was completed in 1966, using a pattern of 1/8 inch by 1/8 inch on 1/2-inch centers. The ADT in this area is 45 000. The radius of curvature is 2000 feet. Before grooving, friction tests averaged 0.25 with a low of 0.17; after grooving, friction tests averaged 0.30 with a low of 0.27. Accident data at this location are as follows:

1963	No wet accidents
1964	8 wet accidents
1965	47 wet accidents
1966	1 wet accident
1967	1 wet accident

This study illustrates how rapidly the wet-pavement accident problem can develop.

Figure 5 shows the before-and-after accident diagram for grooving of 1/8 inch by 1/8 inch on 1-inch centers on I-405 near Bellflower Boulevard in the City of Long Beach. The grooving was done in 1966 and the ADT here is 131 000. Before grooving, friction tests averaged 0.20 with a low of 0.14; after grooving, friction tests averaged 0.24 with a low of 0.17. One and one-half years after, friction tests averaged 0.20 with a low of 0.14. There were 20 wet-pavement accidents during the year before grooving and none for the next 2 years from the grooved section. This is a tangent section of roadway and the skidding started at the sag point where the vehicles started to accelerate as they approached the Bellflower Boulevard overcrossing.

A broader approach to pavement grooving is shown in figure 6, where 1 mile of the southbound I-405, also in Long Beach, was grooved. There were two curves in the mile, one with a radius of 2800 feet and 4 percent superelevation and the other with a radius of 2500 feet and 6 percent superelevation. The ADT at this location is 148 000. The grooving, 1/8 inch by 1/8 inch on 3/4-inch centers, was done in 1966 at a cost of $25 000 for four lanes of freeway. Before grooving, friction tests varied from 0.12 in the right lane to 0.38 in the median lane; after grooving, friction tests varied from 0.26 to 0.44, respectively. There were 61 wet-pavement accidents during the year before grooving (60 percent occurring in the two median lanes) and three in the year following the grooving. A comparative study of accidents was made on the northbound freeway lanes, where there were seven wet-pavement accidents in the year before and five the year after grooving. There was no significant change in the number of dry-weather accidents.

Figure 7 presents a study on a 1000-foot-radius curve on I-10 about 5 miles east of Los Angeles. This curve is on the westbound roadway. It has a superelevation of 5 percent and an ADT of 164 000. The grooving pattern used here was 1/8 inch by 1/8 inch on 3/4-inch centers. Before grooving, friction tests averaged 0.27 with a low of 0.17; no tests were made after grooving. There were 26 wet-pavement accidents the year before grooving and two in each of the next 2 years after. The after-grooving accidents were occurring at the beginning of the curve before reaching the grooved area, which begins at the BC of the curve. On curves to the left, where the crossfall of the roadway is reversed by the superelevation, it is necessary to begin the grooving on the tangent in the supertransition area. There is a concentration of water flow in this area during periods of rainfall which may cause tire hydroplaning to occur.

RECOMMENDED GROOVING PATTERNS

The depth of the grooves varies from 1/8 inch to 1/4 inch. A minimum depth of 1/8 inch seems to be acceptable.

The spacing of the grooves varies from 3/8 inch to 1 inch center to center. The closer the grooves the more spalling of the pavement is likely to occur. Complete spalling occurs in a bump cutting pattern where the blades are very close. Some spalling occurs on PCC pavement with 3/8-inch and 1/2-inch spacings. There is very little spalling between cuts with 3/4-inch spacing and no spalling with 1-inch spacing. On AC pavement there is extensive spalling on 1/2-inch spacing, but 3/4-inch and 1-inch spacings are satisfactory.

Increases in coefficients of friction vary indirectly with spacing. The 3/4-inch spacing produces an increase that is slightly less than that of the 1/2-inch spacing. The increase from 1-inch spacing is considerably less than from the 3/4-inch spacing.

The width of the groove is critical. After grooving of 1/4 inch by 1/4 inch on 1-inch centers was placed in one location, several complaints were received from drivers of light cars and motorcycles. The complaints were that the vehicle tended to "track" and appeared to be caught in a manner resembling being caught in streetcar tracks. The 1/8-inch grooving has been acceptable in almost every location. To further reduce this tracking effect, grooves were made with a 0.095-inch-wide blade. Tests made on this grooving pattern (0.095 inch by 1/8 inch on 3/4-inch centers) indicate that it will be as effective as the 1/8-inch groove and more desirable from a tracking standpoint. Figure 8 is a photographic comparison of the 1/8-inch grooves and the 0.095-inch grooves.

Another pattern, which resembles bump cutting with grooves, has been placed experimentally at several locations. This pattern can be produced by the diamond-studded cylinder type of cutter or by diamond saw blades. This pattern is a series of grooves 0.095 inch wide by 1/8 inch deep on 3/4-inch centers with four grooves 0.095 inch wide by 1/32 inch deep spaced evenly between each pair of the 1/8-inch-deep grooves. Figure 9 shows this pattern as placed on PCC pavement. Use of this pattern is recommended for pavement that is very smooth, where grooving alone will not produce the desired coefficient of friction. This pattern has not been in place long enough to determine its wear characteristics. The coefficients of friction for PCC pavement were 0.22 before and 0.37 after this pattern was placed. On the same pavement, the coefficient of friction was 0.31 for grooves of 1/8 inch by 1/8 inch on 3/4-inch centers.

The cost of grooving 1/8 inch by 1/8 inch on 3/4-inch centers is approximately 10 cents per square foot. The combination pattern is estimated to cost about 25 percent more.

THE FUTURE

The Highway Safety Program Standards issued by the National Highway Safety Bureau, Federal Highway Administration, dated June 27, 1967, call for each State to have a program for improvement of skid resistance of the pavement surfaces.

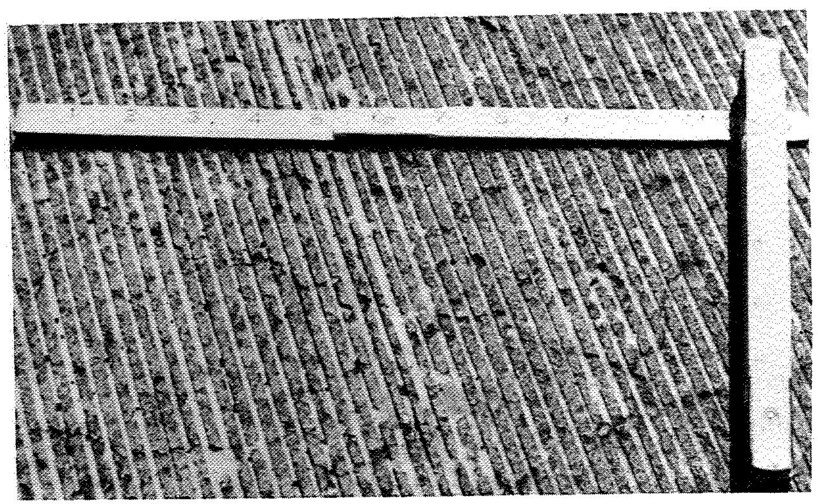
An initial phase of this program is the development of minimum friction requirements and a testing program using the ASTM two-wheel trailer which logs the existing friction values on all highways. The use of this information will be valuable in taking action before an accident problem develops.

BIBLIOGRAPHY

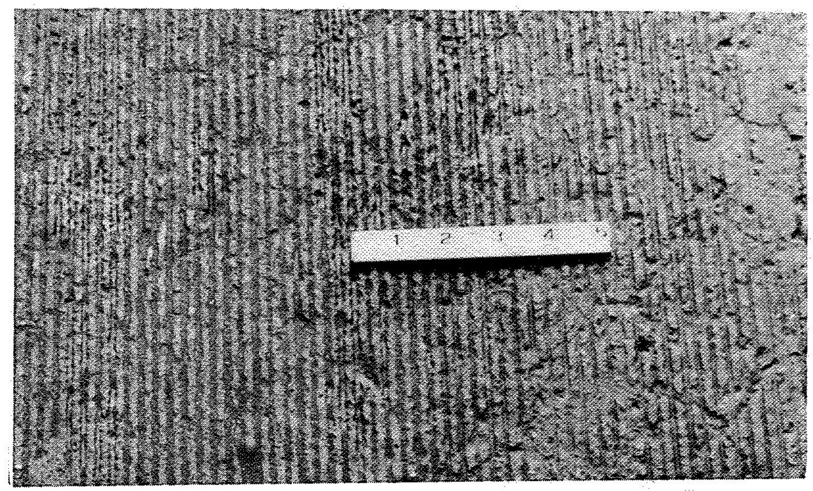
1. Beaton, J. L.; Zube, E.; and Skog, J. B.: Reduction of Accidents by Pavement Grooving. Research Report No. M & R 633126, State of California, Division of Highways, Aug. 1968.

2. Williams, G. M.: Instructional Memorandum, 21-3-68, 32-01, Federal Highway Administration, Apr. 29, 1968.

Portland cement concrete before grooving, 1959



After grooving, 1960



After grooving, 1968

Figure 1.- Grooving Project A, U.S. 99 at Turlock O.H., 1/8-inch by 1/8-inch grooves on 3/8-inch centers.

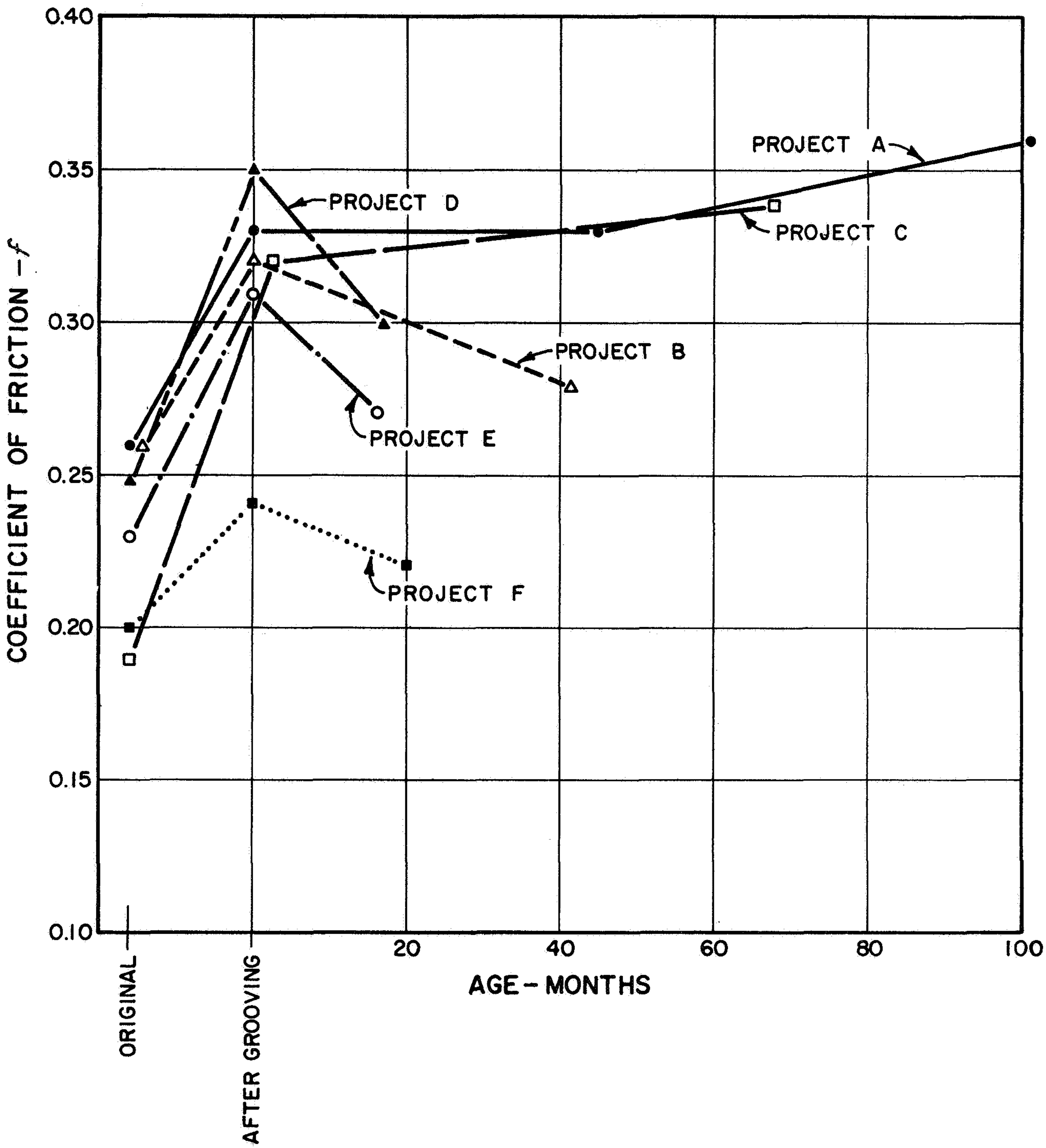
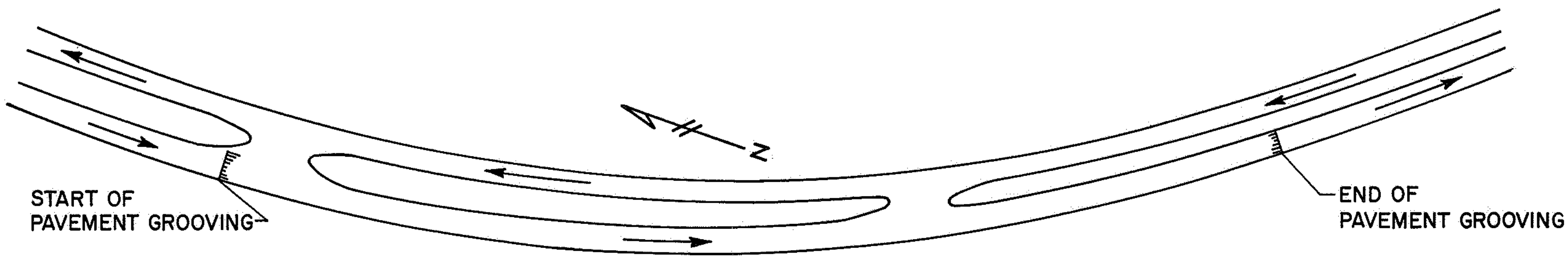


Figure 2.- Friction values before and after grooving of portland cement concrete pavements.

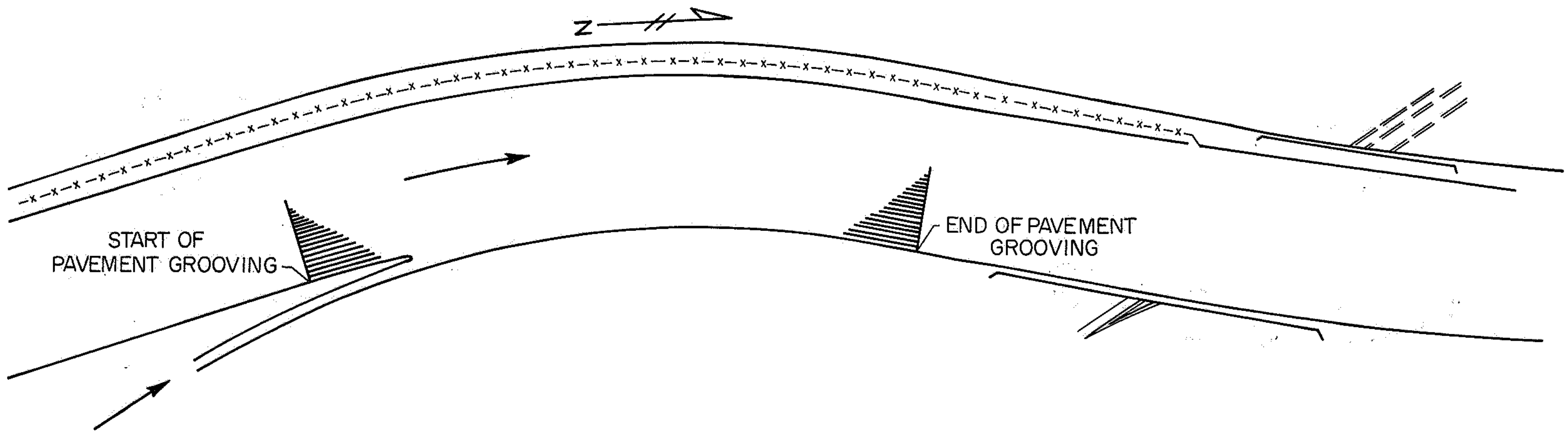


Accident Summary																	
	Year	No. of accidents		Damage class			Elements			Day-light	Dark	Course of vehicle			No. of persons		Rain days
		Total	Wet pavement	Fatal	Injury	Property	Pedes-trian	2 or more vehicles	Single car			Hit object	Ran off road	Over-taking	Killed	Injured	
Before[a]	61-62	15	9	1	7	7	0	7	8	9	6	9	0	6	1	15	29
After[b]	63-64	3	0	0	0	3	0	2	1	3	0	1	0	2	0	0	42
	65	8	0	1	3	4	0	6	2	8	0	2	0	6	5	6	24
	66	8	0	0	2	6	0	4	4	5	3	4	0	4	0	2	12
	67	4	0	0	2	2	0	3	1	2	2	1	0	3	0	3	26

[a]Before grooving: 1-16-61 to 1-15-63.

[b]After grooving: 1-25-63 to 1-26-68.

Figure 3.- Highway I-5, 50 miles north of Los Angeles.

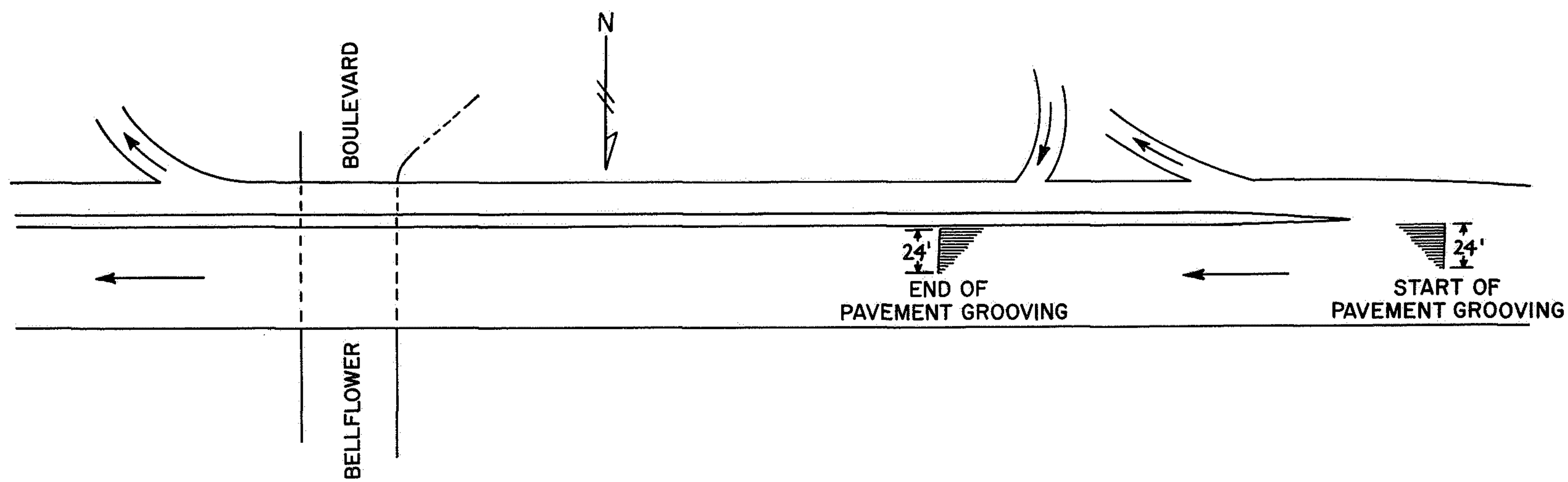


Accident Summary																	
	Year	No. of accidents		Damage class			Elements			Day-light	Dark	Course of vehicle			No. of persons		Rain days
		Total	Wet pavement	Fatal	Injury	Property	Pedes-trian	2 or more vehicles	Single car			Hit object	Ran off road	Over-taking	Killed	Injured	
Before[a]	1963	7	0	0	5	2	0	3	4	4	3	5	0	2	0	12	24
	1964	13	8	0	7	6	0	2	11	6	7	12	0	1	0	9	18
	1965	52	47	0	19	33	0	11	41	36	16	42	0	10	0	35	30
After[b]	1966	8	1	0	5	3	0	4	4	4	4	4	0	4	0	9	15
	1967	4	1	0	2	2	0	3	1	3	1	1	1	2	0	3	20

[a]Before grooving: 1-1-63 to 12-31-65.

[b]After grooving: 2-1-66 to 1-31-68.

Figure 4.- Highway I-5, near El Toro Marine Base.



Accident Summary

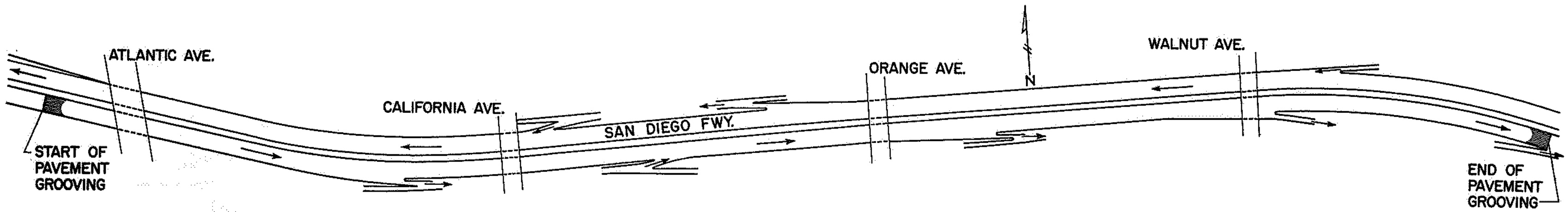
	Year	No. of accidents		Damage class			Elements			Day-light	Dark	Course of vehicle			No. of persons		Rain days
		Total	Wet pavement	Fatal	Injury	Property	Pedes-trian	2 or more vehicles	Single car			Hit object	Ran off road	Over-taking	Killed	Injured	
Before[a]	65-66	30	20	0	13	17	0	10	20	14	16	18	0	12	0	21	29
After[b]	66-67	11	0	0	6	5	0	9	2	5	6	3	0	8	0	10	15
	67-68	10	[c]2	1	5	4	0	3	7	6	4	7	0	3	1	8	27

[a]Before grooving: 2-1-65 to 1-31-66.

[b]First year after grooving: 3-1-66 to 2-28-67; second year after grooving: 3-1-67 to 2-29-68.

[c]In ungrooved lane.

Figure 5.- Highway I-405 (San Diego Freeway), Long Beach at Bellflower Boulevard.



Accident Summary Northbound (Never Grooved)

Year	No. of accidents		Damage class			Elements			Day-light	Dark	Course of vehicle			No. of persons		Rain days
	Total	Wet pavement	Fatal	Injury	Property	Pedes-trian	2 or more vehicles	Single car			Hit object	Ran off road	Over-taking	Killed	Injured	
66-67	21	7	0	10	11	0	10	11	6	15	7	4	10	0	18	20
67-68	22	5	0	10	12	0	10	12	7	15	6	0	16	0	11	17
66-67	Wet pav't	7	0	2	5	0	3	4	3	4	4	0	3	0	2	20
67-68		5	0	2	3	0	5	0	0	5	0	0	5	0	3	17

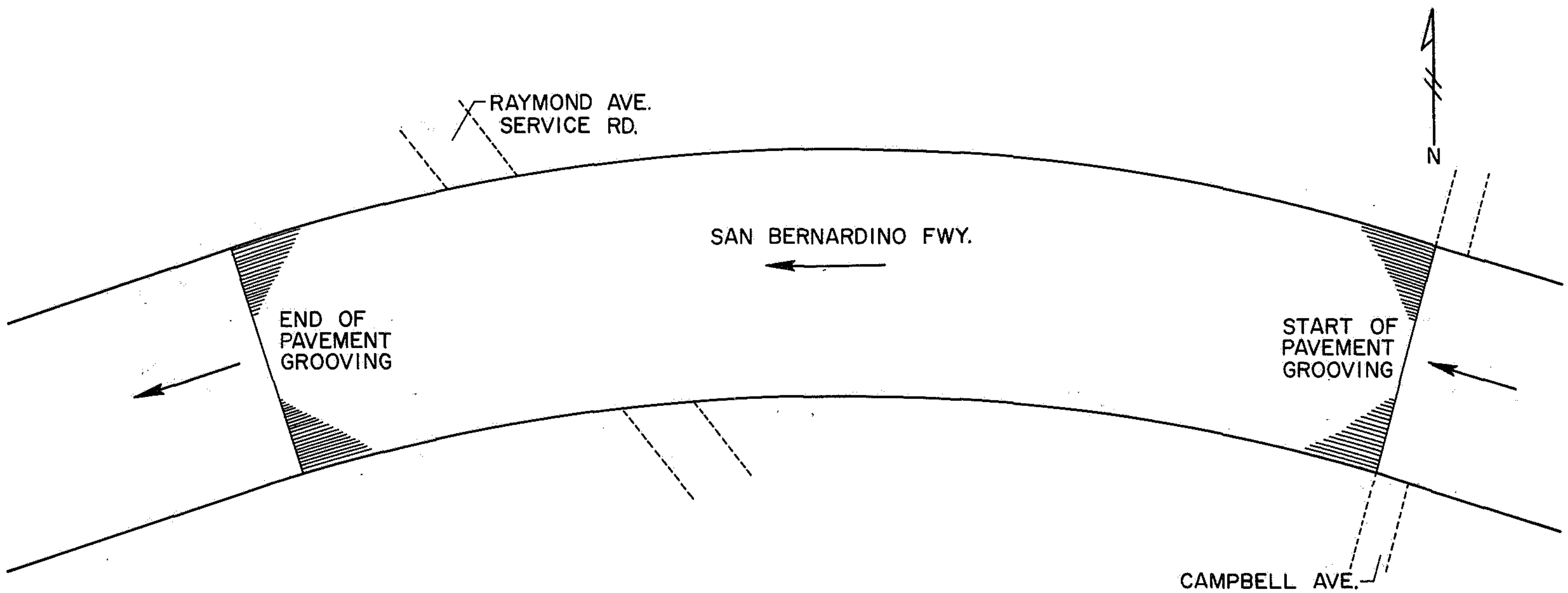
Accident Summary Southbound

	Year	No. of accidents		Damage class			Elements			Day-light	Dark	Course of vehicle			No. of persons		Rain days
		Total	Wet pavement	Fatal	Injury	Property	Pedes-trian	2 or more vehicles	Single car			Hit object	Ran off road	Over-taking	Killed	Injured	
Before[a]	66-67	102	61	0	29	73	0	56	46	62	40	41	8	53	0	58	20
After[b]	67-68	47	3	0	16	31	0	30	17	26	21	16	2	29	0	29	17
Wet before[a]	66-67		61	0	17	44	0	32	29	38	23	29	1	31	0	28	20
Wet after[b]	67-68		3	0	2	1	0	3	0	3	0	0	0	3	0	2	17

[a]Before grooving: 7-1-66 to 6-30-67.

[b]After grooving: 7-1-67 to 7-1-68.

Figure 6.- Highway I-405, Long Beach.



Accident Summary																	
	Year	No. of accidents		Damage class			Elements			Day-light	Dark	Course of vehicle			No. of persons		Rain days
		Total	Wet pavement	Fatal	Injury	Property	Pedes-trian	2 or more vehicles	Single car			Hit object	Ran off road	Over-taking	Killed	Injured	
Before[a]	65-66	43	26	1	14	28	0	15	28	17	26	25	0	18	1	19	29
After[b]	66-67	8	2	0	3	5	0	3	5	2	6	2	2	3	0	2	16
	67-68	10	2	0	3	7	0	4	6	6	4	4	1	5	0	7	28

[a]Before grooving: 1-1-65 to 1-1-66.

[b]After grooving: 1-27-66 to 1-26-68.

Figure 7.- Highway I-10, about 5 miles east of Los Angeles.

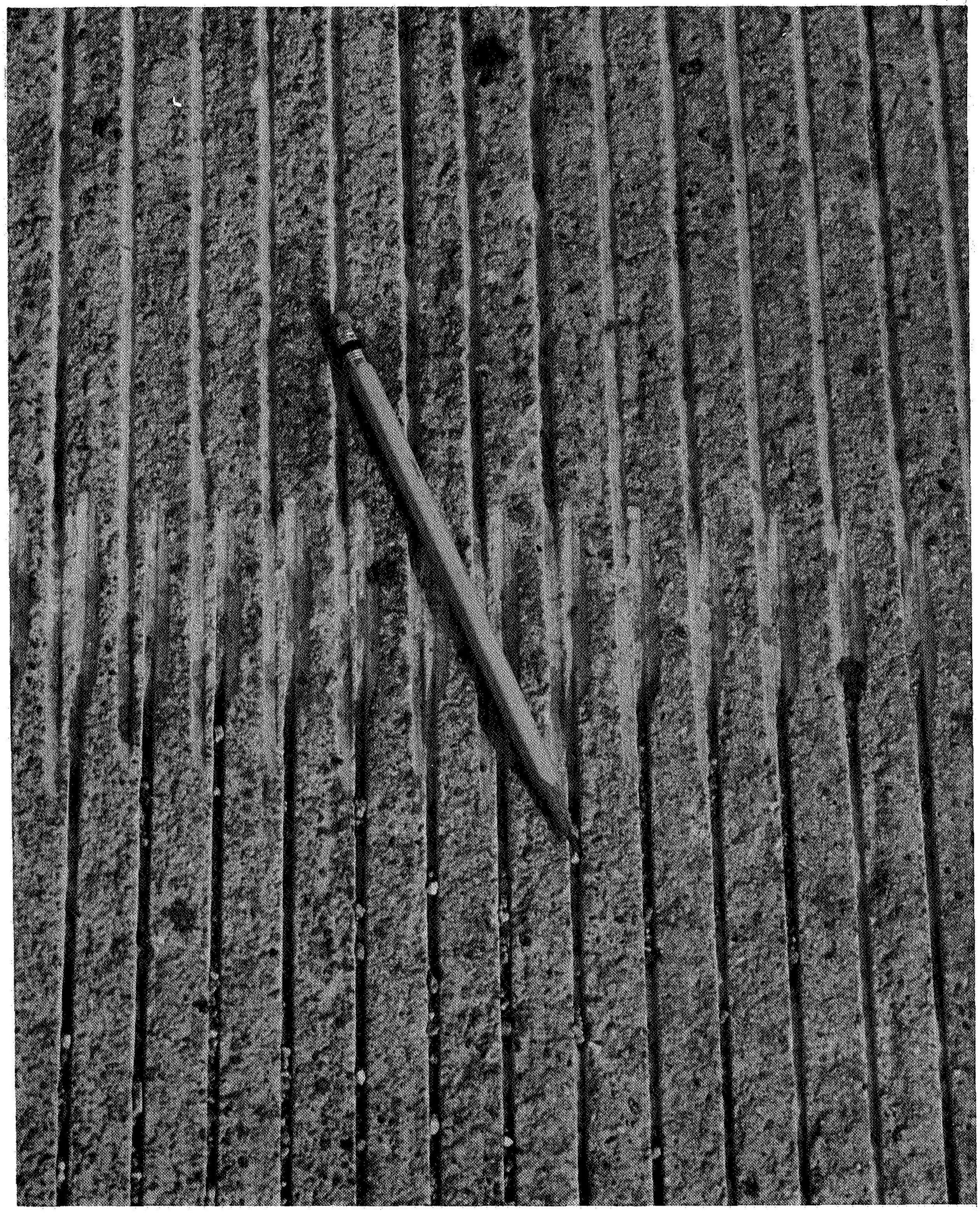


Figure 8.- Pavement with 1/8-inch-wide grooves at top and 0.095-inch-wide grooves at bottom.

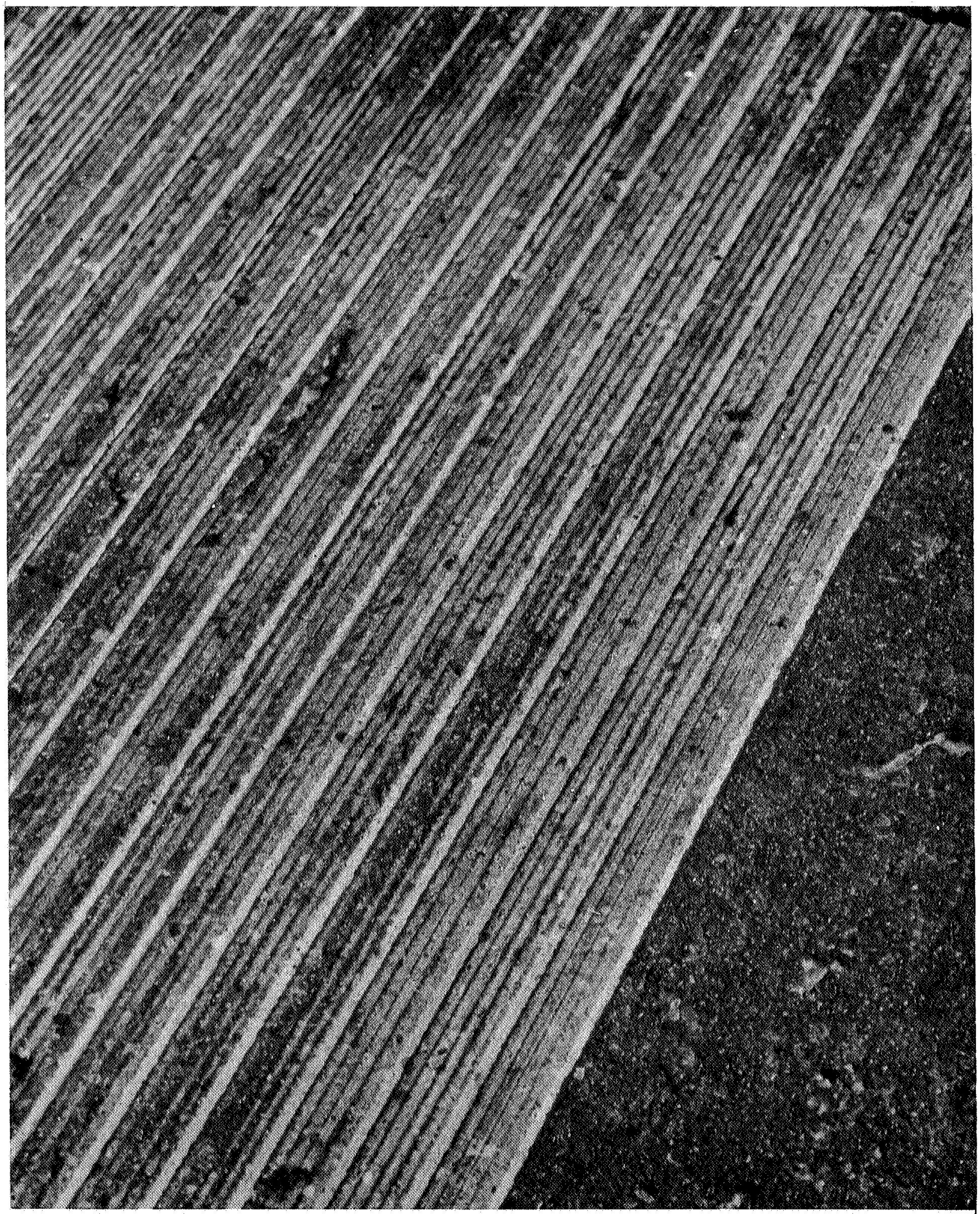


Figure 9.- Combination bump-cutting and grooving pattern.

26. RESULTS FROM STUDIES OF HIGHWAY GROOVING AND TEXTURING AT NASA WALLOPS STATION

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SUMMARY

Results of studies of the skid resistance obtained on 30 different pavement surfaces installed at the NASA Wallops Station airfield are discussed. Presented are transient peak, steady-state peak, and locked-wheel braking coefficients of friction for ASTM rib-tread and ASTM bald-tread tires and for new and worn production tires obtained under dry, wet, and flooded pavement conditions at vehicle speeds ranging from 10 to 80 mph. Results of limited vehicle spin-out tests on a 500-foot-radius highway curve are also included. It was found that the presently used method of making locked-wheel friction measurements to determine pavement skid resistance does not necessarily denote the true skid resistance of pavements under vehicle rolling or maneuvering conditions. Also, the skid resistance of smooth closed-texture pavements tends to be dangerously low under wet conditions when vehicles are operated at high speed with worn tires. However, the more open textured pavements as well as the transverse- and longitudinal-groove pavements exhibited adequate skid resistance for the vehicle speed and tire conditions investigated.

INTRODUCTION

Two factors which have always been present on the American highway scene in varying degree over the years have now reached a stage of growth to cause concern about future safety of the highway system. These factors are vehicle population frequenting the system and the speed which vehicles attain on highways.

The vehicle population using United States highways is growing rapidly and the Bureau of Public Roads estimates that 102 to 103 million vehicles will be in use during 1969. Since the end of World War II, the average speed of vehicles on our main highways has risen approximately 1 mile per hour per year.

The risk of accidents occurring on dry pavements during normal driving maneuvers is also increasing as the number of maneuvers increase due to the larger number of vehicles and the higher speeds involved. This becomes apparent when one notes that the tire-ground friction coefficient required to prevent vehicle spin-out while rounding curves or making lane changes increases as the square of the vehicle speed. The risk of accidents increases even more when pavements become wet or covered with slush, snow, and ice as a result of the reduction in available tire-ground friction coefficient. Limited studies have shown that the average American motorist possesses driving habits which greatly influence highway safety. For example, he reduces his speed significantly under snow- and ice-covered pavement conditions. Thus, the motorist recognizes these hazardous driving conditions by reducing speed. On the other hand, the typical motorist tends to reduce speed only by 1 mile per hour when pavements are wet. Obviously he does not recognize that wet pavements can become equally hazardous under certain conditions. Many motorists also take pride in the number of miles their vehicles can obtain on a set of tires. Significant numbers of vehicles consequently are driven on the highway system with dangerously worn tires. Currently, many states are introducing or have introduced laws to eliminate this practice. Unfortunately, research shows that large differences in wet road grip still exist between a new tire and a tire worn to the legal wear limit, usually 1/16 inch of tread remaining.

With these considerations in mind, the Virginia Highway Research Council requested the assistance of the National Aeronautics and Space Administration in evaluating the skid resistance of different highway surface textures, coatings, and groove patterns under wet conditions at high speed. Several surfaces of each type mentioned were installed on the adjoining taxiway of the landing research runway at NASA Wallops Station in time for a limited evaluation by the highway vehicles and braking trailers participating in the Joint NASA-British Ministry of Technology Skid Correlation Study conducted during June 1968.

It is the purpose of the present paper to describe the changes in skid resistance which occur to these taxiway surfaces, as well as to the test surfaces on the landing research runway, as vehicle speeds increase from low values to as high as 80 miles per hour. This speed seems high by current highway standards, but trends indicate that this speed will be reached in the near future on the interstate highway system. The pavement surfaces were studied under dry, wet, and flooded conditions with ASTM rib- and bald-tread tires. Limited tests were conducted with new production tires and production tires worn to the legal wear limit. Most of the test data were obtained during vehicle braking although some cornering data were obtained on vehicles rounding a 500-foot-radius highway curve at speeds up to 50 miles per hour.

TEST SURFACES

The test surfaces investigated are located on three separate sites at the NASA Wallops Station airfield.

Site I

Site I is the landing research runway which is described in references 1 and 2. The surfaces installed on this runway were selected to cover the range of pavement textures presently in use on airport runways of this country. A short description and a photograph of each test surface on site I are presented in table I and figure 1, respectively.

Site II

Site II is the concrete taxiway of the landing research runway. The surfaces studied on this site were chosen on the basis of their applicability for use on highway pavements. Included in these test surfaces are several currently used highway groove patterns cut in both concrete and asphalt, sprayed and rolled epoxy overlays, a sand asphalt deslicking mix, and an asphalt overlay containing a synthetic aggregate. The layout of the site II test surfaces is shown in figure 2. A short description and a photograph of each test surface on site II are given in table II and figure 3, respectively. The groove patterns were cut into the pavement by using the diamond saw technique. It should be noted that the approaches to and the transitions between some of the site II test surfaces were at different elevations due to pavement overlays either used to seal coat the taxiway some years before the time of this study or installed immediately prior to the study to form test surfaces. The consequence was vehicle pitching or bouncing during the runs especially at the higher test speeds on some of the test surfaces. These vehicle oscillations during tests tended to increase the scatter of test data acquired on site II as compared with the scatter of test data acquired on the more level and uniform test surfaces of sites I and III.

Site III

Site III is a concrete hangar apron which was converted into a large rectangular skid pad as shown in figure 4. Yellow highway marking paint was used to outline both straight and curved traffic lanes on the skid pad. The approaches to the skid pad were such that cornering and braking tests performed on the skid pad had to be limited to a maximum vehicle speed of 50 miles per hour. A special feature of the skid pad was the installation of longitudinal highway grooves along a 500-foot-radius traffic lane. For comparison purposes, several concentric 500-foot-radius ungrooved traffic lanes were also installed on the skid pad (fig. 4). A short description and a photograph of each test surface on site III are presented in table III and figure 5, respectively.

Surface Conditions

It should be pointed out that none of the test surfaces of this study had been subjected to traffic, such as that experienced on highway pavements, before the start of testing. This point should be borne in mind when the test data are analyzed. For example, surface E of site II is an asphalt overlay containing a synthetic aggregate called Sinopal which is very white and purported to be highly skid resistant. The photograph of surface E taken at the conclusion of the tests (fig. 3) shows only a few white stones on the surface. In essence, the braking tests performed on this surface determined the skid resistance of the asphaltic binder adhering to the Sinopal aggregate rather than the skid resistance of the Sinopal surface itself. If, however, this surface had experienced more traffic, much of the surface binder would have worn off; thus, a larger proportion of the Sinopal aggregate would be exposed and, as a result, different traction values would be obtained.

PAVEMENT WETTING TECHNIQUES

Site I

Three-thousand feet of pierced plastic pipe were placed along the edge of the runway test sections. The pipe was connected at 200-foot intervals with a water hydrant system located off the side of the runway. Through intermittent use of the sprinkler system a wet and puddled pavement condition was achieved on the desired test sections for test purposes. Continuous use of the sprinkler system produced a flooded condition on the test sections where the water depth was maintained at an average level of 0.1 inch on the pavement surfaces. Figure 6 illustrates the wet and puddled pavement condition achieved on surface A of site I during braking tests with the British "Juggernaut" test vehicle.

Several runs were made on surfaces A and C of site I under a slush cover. The slush was made by letting crushed ice melt on the runway surface until the desired slush level was reached. The test technique used is described in reference 2.

Site II

The plastic-pipe sprinkler system used on site I was also used on site II to wet the test surfaces. The flooded pavement condition is illustrated in figure 7(a) which shows the NASA diagonal braking car making a run on surface E of site II. The wet and puddled pavement condition used on site I was not used on site II. For the wet condition on site II, the sprinkler system was turned on to wet the pavement and then turned off. A powered rotary broom was then driven over the test surfaces to remove puddled water. This technique left the surface wet for test purposes but without water puddles. When the test surfaces were seen to be drying out, this procedure was repeated to maintain uniform test conditions.

Site III

The concrete apron forming the site III skid pad was a flat tilted slab. Pierced canvas fire hose was placed along the upper edge of the slab. When the sprinkler system was turned on, the water flowed from top to bottom which allowed a fairly uniform water film to be established over the entire skid pad surface. This sprinkler system is shown in operation to produce a flooded pavement condition in figure 7(b). The sprinkler system, along with the powered rotary broom, was intermittently used to obtain a wet pavement condition without puddles for test purposes.

Vehicle spin-out tests were also conducted on the 500-foot-radius curves on the site III skid pad for an extremely slippery condition. This condition was obtained by the use of hydrolube or "instant banana peel." This material which is a white powder was sprinkled uniformly over the wet test surface. The powder immediately mixed with the water to form an extremely slippery film which bonded to the pavement surface. The test surface after a treatment of hydrolube was at least as slippery as wet smooth ice and as difficult to walk upon without slipping.

Test Tires

The tires used to determine the skid resistance of the test pavements are shown in figure 8. Most of the braking data described in this paper were obtained with ASTM bald-tread and rib-tread test tires which are described in reference 3. Limited braking data were obtained with a typical production tire worn to the point that the wear markers of the tread were showing. Highway safety laws currently in effect in some states require that tires be replaced when this stage of wear is reached.

The ASTM bald-tread tire, the worn production tire, and a new production tire of the same tread design as the worn tire were used in unbraked vehicle spin-out tests on site III to determine the skid resistance of curved pavement.

Test Vehicles

It is beyond the scope of this paper to present all the braking data obtained by the different test vehicles that participated in the Joint NASA-British Ministry of Technology Skid Correlation Study. Instead, selected braking data obtained with the General Motors braking trailer, the FAA Swedish Skiddometer, the B. F. Goodrich diagonal braking car, and the NASA diagonal braking car are presented for pavement skid resistance comparisons. Most of the data presented were obtained during the Joint Correlation Study although some data with the NASA diagonal braking car were obtained after the conclusion of the correlation study. These data include, for example, the braking results obtained on site II test surfaces under flooded pavement conditions. The vehicle spin-out tests on site III were also conducted after the conclusion of the skid correlation study. Participating vehicles for this study were the B. F. Goodrich diagonal braking car and a stripped convertible with protective cage operated by NASA.

The operating characteristics of the General Motors braking trailer, FAA Swedish Skiddometer, B. F. Goodrich diagonal braking car, and the NASA diagonal braking car are described in reference 3. The NASA stripped convertible used in the vehicle spin-out tests on site III is shown in figure 9.

SKID RESISTANCE OF TEST SURFACES

Braking and cornering friction data obtained under dry, wet, and flooded conditions on the 30 surfaces of sites I, II, and III are discussed in this section. Also included are braking data on several surfaces of site I under slush-covered and ice-covered pavement conditions. Some vehicle spin-out or cornering data obtained on the 500-foot-radius grooved and ungrooved highway curve test surfaces of site III under an extremely slippery pavement condition effected by using hydrolube and water are also presented.

The maximum skid resistance of a pavement normally occurs under dry conditions. A considerable effort, and quite a few test tires, was expended to obtain dry-surface braking data on all the test surfaces so that a firm base could be established to rate the relative skid resistance of the test surfaces under wet conditions.

Site I Surfaces

Dry conditions.- The dry-surface skid resistance of site I surfaces was rated by the NASA diagonal braking car. A Tapley meter installed in this car measured an effective friction coefficient μ_{eff} which is between transient peak μ_{max} and locked-wheel μ_{skid} friction-coefficient values. These data are presented in figure 10 where effective friction coefficient μ_{eff} is plotted as a function of ground speed. It is interesting to note that no significant differences in dry-surface friction values exist between the ungrooved or grooved surfaces of site I at speeds up to 60 miles per hour. The data in figure 10 indicate that the dry-surface friction values for the ASTM rib-tread tire are somewhat lower than those for the ASTM bald-tread tire, especially at medium test speeds.

A similar presentation of dry-surface braking results for the FAA Swedish Skiddometer on site I surfaces is given in figure 11. It should be noted that the Swedish Skiddometer measures the maximum steady-state braking friction coefficient that occurs at a slip ratio of 0.13. The Skiddometer used the ASTM bald-tread tire for this evaluation. Again, the dry-surface skid-resistance values of the ungrooved surfaces are close together and the grooved surface values are also close together over the speed range from 10 to 80 miles per hour covered in these tests. The peak friction coefficients μ_{max}, however, measured by the Skiddometer indicate slightly higher dry-surface friction values for the grooved surfaces than for the ungrooved surfaces of site I. This is an interesting result in that the 1- × 1/4- × 1/4-inch groove pattern used in site I actually removes 25 percent of the pavement surface and thereby increases the tire-ground bearing pressure by 25 percent. Aeronautical tire research has shown that the dry-surface friction coefficient developed by tires on pavements decreases with increasing bearing pressure between tire and ground (ref. 4). The Skiddometer results as well as the diagonal braking car results infer that tire-groove interlocking effects may account for this benefit.

Wet and puddled conditions.- The skid resistance of site I surfaces for a wet and puddled runway condition was rated with the NASA diagonal braking car and the data are presented in figure 12. Values of μ_{skid} were obtained in this case from a recording accelerometer installed in the car, and these measurements were made during the time that the wheels were in a locked-wheel skid condition. In the figure, μ_{skid} values obtained for the ASTM bald-tread tire and the ASTM rib-tread tire are plotted as a function of ground speed. On the ungrooved pavements, the best surface for the bald-tread tire at 40 miles per hour is surface E (Gripstop), a sand-type asphalt. At a speed of 70 miles per hour this surface is among the worst. At 70 miles per hour, not one of the ungrooved surfaces of site I provides adequate traction for a bald-tread tire in a locked-wheel condition. The results for the ASTM rib-tread tire show much better pavement skid resistance. At 40 miles per hour, all ungrooved surfaces of site I show a μ_{skid} value of 0.37 or better. The value of 0.37 has been proposed as a minimum skid standard for pavements by Kummer and Meyer in reference 5. It is noticed in the figure that at 70 miles per hour all μ_{skid} values of the ungrooved surfaces fall below this value. Placing 1- × 1/4- × 1/4-inch transverse grooves in the pavements raises the skid resistance of site I surfaces so that at 70 miles per hour the skid values for ASTM bald- and rib-tread tires meet this standard on all surfaces with the exception of surface B which has a value of 0.35 for the bald-tread tire.

The FAA Swedish Skiddometer, using a self-watering system, was also employed to rate the relative skid resistance of site I surfaces. The results obtained with the ASTM bald-tread tire are shown in the lower graphs of figure 11. The self-watering technique deposited a continuous water film 0.02 inch thick on the dry pavement immediately ahead of the test tire.

For the ungrooved surfaces, the surfaces having the least skid resistance at 80 miles per hour were surfaces A and E which were canvas belt concrete and Gripstop. The best surface was surface I, the plant mix asphalt with 3/4-inch aggregate. These results tend to conform with NASA grease test measurements of average pavement texture depth made on the surfaces of site I, as shown in the following table:

Site I surface	NASA grease test average texture depth, mm	FAA Skiddometer steady-state braking friction coefficient at 80 mph, μ_{max}
A . . .	0.12	0.19
D . . .	0.20	0.3
E . . .	0.14	0.19
F . . .	0.19	0.23
I . . .	0.32	0.4

The surfaces having the best skid resistance also had the largest average pavement texture depth. These results indicate that for high-speed operations, a pavement should have an open texture to provide external water drainage between tire and ground.

The remarkable effectiveness of 1- × 1/4- × 1/4-inch transverse pavement grooves in improving wet pavement skid resistance is also shown in figure 11. At 80 miles per hour, the wet peak braking values are only slightly lower than the dry values. In fact, over most of the speed range, the wet values are higher than the dry values. This result is attributed to a water cooling effect since the ASTM bald tire tread rubber was found to be extremely hot to the touch when running at peak braking conditions on dry pavements. It should be noted in figure 11 that the transverse-groove pattern on site I restores the wet-surface skid resistance of a bald-tread tire to dry-surface values while rolling under peak braking conditions. Grooving is not as effective on wet pavements when the tire operates in a locked-wheel braking mode. The data in figure 12 indicate that the μ_{skid} values obtained on wet grooved pavements are significantly less than the dry-surface friction values although they are substantially higher than the μ_{skid} values obtained on wet ungrooved pavements at high speed.

The effect of increasing pavement texture depth on pavement skid resistance is shown in figure 13. In this figure μ_{eff} values obtained on concrete surfaces A and B of site I which have a canvas belt drag surface treatment are compared with μ_{eff} values obtained on surfaces A-1 and B-1 which actually are surfaces A and B given a spray coating of epoxy-grit. The average grit size is 3/32 inch. The void areas between the grit particles on the pavement surface provided more external water drainage capacity and improved the skid resistance of both grooved and ungrooved pavements even when a worn tire was used on the test vehicle under flooded pavement conditions.

A most important feature of the pavement grooving used on site I is the restoration of the skid resistance of worn tires on wet pavements to resistance values of new tires. This feature was first noted during the aircraft tests on site I. Figure 12 illustrates this point with ASTM bald- and rib-tread tires. The B. F. Goodrich diagonal braking car also made braking tests with a worn production tire and the ASTM rib-tread tire under flooded pavement conditions on surfaces C and D of site I. These results are compared in figure 14. It can be seen that the worn tire (wear markers showing) at speeds greater than 40 miles per hour on the ungrooved concrete has less than one-half the skid resistance of the ASTM rib-tread tire, yet on the 1- × 1/4- × 1/4-inch transverse-groove pavement both tires have about equal skid resistance.

Slush conditions.- Several tests were made on surfaces A (ungrooved) and C (grooved) of site I where a slush layer ranging from 0.5 to 2 inches covered the pavement. This slush layer quickly became rutted with the passage of vehicles during tests. Figure 15 presents the skid resistance of these pavements under this slush cover in terms of transient peak μ_{max} (ref. 3) and locked-wheel μ_{skid} friction coefficients for both ASTM bald- and rib-tread tires. It can be seen that the ASTM rib-tread tire develops higher friction coefficients than the ASTM bald-tread tire on ungrooved surface A. It is also of interest to note that no significant difference exists between the ASTM rib-tread-tire transient peak μ_{max} and locked-wheel μ_{skid} friction coefficients at 60 miles per hour on the ungrooved surface. This result indicates that some, if not all, of the apparent friction coefficient developed at this speed may be due to slush displacement drag acting on the tire rather than from adhesion forces acting between tire and ground. The friction coefficients for grooved surface C are higher than those for ungrooved surface A at speeds below 60 miles per hour.

Ice conditions.- An icy runway condition developed during testing of the F-4D aircraft on site I. From results of automobile tests presented in table IV, considerable improvement in pavement skid resistance was noted for the grooved pavement over the ungrooved pavement. In fact, during tests where braking was initiated at 50 miles per hour, the average friction coefficient on the grooved surface became nearly double that on the ungrooved surface. Similar improvement in skid resistance on ice was noted during steering tests with another car employing half-worn tires (fig. 16). It should be noted that for this temperature of 31° F, the ice was thin and not firmly bonded to the pavement surface. Another test was made with water sprayed through a fog nozzle on surfaces F and G of site I at an ambient temperature of 18° F. At this temperature, the thin coating of ice that formed on the surface developed a hard bond with the pavement. Locked-wheel tests with the NASA diagonal braking car and ASTM bald-tread tires showed much less skid resistance for both the grooved and ungrooved surfaces for this condition as compared with the results at 31° F. In fact, at 50 miles per hour, the car only developed a μ_{skid} value of 0.08 on grooved surface G and a μ_{skid} value of 0.04 on ungrooved surface F. From these results, it is apparent that pavement grooving improves pavement skid resistance under icy conditions but is of practical benefit in braking vehicles only near temperatures when ice is first formed, that is, near 32° F. Steering tests were not made for the cold icy condition (18° F) and, therefore, the benefit from grooving is not known for this vehicle operating condition.

Site II Surfaces

Dry conditions.- The NASA diagonal braking car equipped with ASTM bald-tread tires and using a Tapley meter to measure vehicle braking was employed to rate the dry-surface skid resistance of the 13 pavement surfaces of site II. The effective friction coefficient is presented as a function of vehicle ground speed for the site II surfaces in figures 17 to 21. Although the scatter of data for the site II surfaces is considerably more than that for the site I surfaces in figure 10, the average values obtained on site II surfaces are in agreement with site I dry-surface friction-coefficient values. As previously mentioned in the section entitled "Test Surfaces," this increase in test-data scatter for site II surfaces is attributed to vehicle pitching and bouncing caused by the more uneven test surfaces of site II.

Wet conditions.- Unfortunately, a poor choice was made on the wetness condition for site II surfaces during the Joint Correlation Study. As was described in the section entitled "Pavement Wetting Techniques," a powered rotary broom was used to remove all puddled water from the test surfaces. This wetness condition was insufficient to create major changes in skid resistance between the different test surfaces, especially if ASTM rib-tread tires were used on the test vehicles. This wetness condition, although classified as wet, was in reality a damp surface such as that which might occur on a highway after a rain had stopped falling and vehicular traffic had removed any puddled water from the pavement.

After the completion of the Joint Correlation Study, the NASA diagonal braking car was rerun over the site II surfaces under a flooded pavement condition described in the section entitled "Pavement Wetting Techniques." ASTM bald-tread tires were used and the Tapley meter was employed to measure vehicle braking. As previously discussed, this vehicle braking technique and measuring system creates an effective friction coefficient which lies between the transient peak μ_{max} and locked-wheel μ_{skid} friction values.

Figure 17 shows the skid-resistance rating by the NASA diagonal braking car of the more conventional test surfaces of site II under the aforementioned dry, wet, and flooded conditions. It can be seen that the skid resistance for all surfaces in figure 17 decreased from dry-surface values as speed increased for this essentially damp pavement condition. Larger losses in skid resistance developed on the surfaces under flooded pavement conditions. All surfaces in figure 17 had a closed texture with a small average texture depth (fig. 3). These results are in agreement with results obtained on site I surfaces which showed the smooth closed-texture-pavement surfaces as having poor skid resistance at high speed under wet conditions.

The improved skid resistance that more open-texture-pavement surfaces provide under wet and flooded conditions is illustrated in figure 18. This figure compares the skid resistance of surfaces C, E, F, and G which, as indicated in figure 3, had higher average texture depths than surfaces A, B, and D. The order of improvement in skid resistance for the surfaces shown in figure 18 apparently follows the degree of texturing provided in the surface.

Figure 19 shows the improvement in skid resistance gained when the 25-year-old concrete surface A of site II is provided with 3/4- × 1/8- × 1/8-inch transverse or longitudinal grooves. This groove pattern is typical of that being used in current highway grooving. Both the transverse and longitudinal groove patterns used improved the pavement skid resistance under the wet and flooded test conditions as is noted by the higher and therefore safer friction values. The transverse-groove pattern also restored more of the dry-surface skid performance of the pavement than did the longitudinal-groove pattern. The improvement in skid resistance for the best groove pattern was about equal to that obtained by the asphalt dressing treatment shown in figure 18 for flooded pavement conditions. Similar results are shown in figure 20 where surface B, the 13-year-old asphalt seal coat of site II, was provided with the same 3/4- × 1/8- × 1/8-inch transverse and longitudinal grooves as the 25-year-old concrete surface A. An interesting result shown in figure 20 for the flooded pavement condition is that the longitudinal-groove pattern is as effective at 70 miles per hour as the transverse-groove pattern in raising the surface skid resistance.

Figure 21 shows the improvement in skid resistance obtained on surface B, the 13-year-old asphalt seal coat, when 1- × 1/8- × 1/8-inch transverse- and longitudinal-groove patterns were cut in the surface. Comparison of these data with the 3/4-inch-groove data presented in figure 20 reveals that the 1-inch grooves (fig. 21) are as effective as the 3/4-inch grooves when the surface is wet. Under flooded conditions, the 3/4-inch groove pattern with its higher water-drainage capacity provides the greater improvement in skid resistance to surface B.

Site III Surfaces

Dry conditions.- Figure 22 presents effective dry-surface friction coefficients measured by the NASA diagonal braking car on the specially prepared skid pad of site III. The skid pad was covered with a liquid coating of Jennite, a coal-tar product, without the sand or aggregate content that is normally used when Jennite is applied to highway surfaces. (See table III.)

It is important to note that the ASTM bald-tread-tire dry-surface friction values obtained on site III surfaces are somewhat less than those obtained on site I surfaces. (Compare figs. 22 and 10.) On the other hand, larger differences in dry-surface friction values exist between site I and site III surfaces for the ASTM rib-tread tire. The reason for the low ASTM rib-tread-tire dry-surface friction values on site III surfaces is not known at the present time.

Wet and flooded conditions.- The NASA convertible test car shown in figure 9 was equipped with a Tapley meter mounted on the floor of the car and sideways to the direction of vehicle motion. The test car was then driven at increasing speeds around the 500-foot-radius grooved and ungrooved curves of site III until vehicle spin-out occurred. The lateral friction coefficients and spin-out speeds obtained with the test vehicle equipped with ASTM bald-tread tires, new production tires, and worn production tires (wear marker showing) are shown in figure 23(a) for a wet pavement condition (surface wet but no puddles). Photographs of these tires are shown in figure 8. The wet pavement condition was achieved by driving a powered rotary broom over the test surface to remove surplus water from the surface after it was initially wetted by the sprinkler system installed at site III. The data shown indicate that longitudinal grooves on a highway curve can improve the skid resistance of a pavement when ASTM bald-tread and worn production tires are used on a vehicle. The maximum test speed for site III of 50 miles per hour was obtained before spin-out conditions occurred for the new production tire tested. This result shows the importance of having and maintaining an effective tread design on road vehicle tires.

The same tire tread configurations were tested on the NASA convertible under flooded pavement conditions and the results are shown in figure 23(b). For the flooded ungrooved curve, all tires regardless of tread design caused the vehicle to spin-out at about 38 miles per hour. The vehicle spin-out speed and skid resistance of the pavement were improved by grooving the highway curve, as also shown in figure 23(b).

Many different opinions have been expressed to explain the improved performance of vehicles operating on grooved wet or flooded pavements as contrasted with vehicle performance obtained under similar conditions on ungrooved pavements. Among these are better water drainage through the low-pressure escape channels provided by grooving and the biting of the sharp edges of groove corners into the tire and displacing the viscous and tenacious fluid film which separates tire from pavement. Also, it has been suggested that the tire tread rubber penetrates into the pavement grooves under operating conditions and it is this interlocking or gear effect plus possibly the groove edge effect which produces the improvement in skid resistance. In an attempt to isolate this interlocking effect, the following experiment was performed. Hydrolube or "instant banana peel" was mixed with water on the test surfaces of site III. This technique produced a slippery pavement condition, at least as slippery as wet ice. It was hoped that such a slippery condition would reduce tire-ground adhesion to minimal values so that any improvement in skid resistance on the grooved pavement must come from the interlocking effect. The results of the experiment are shown in figure 24. On the lubricated ungrooved pavement, the spin-out speeds for the two test vehicles, a sedan and a convertible, were extremely close but very low. In fact, the spin-out speed was only 15 miles per hour regardless of whether a new production tire or an ASTM bald-tread tire was used. The test results on the lubricated grooved surfaces showed a large improvement in skid resistance from longitudinal grooving for both tire designs. These results tend to confirm the presence of a mechanical interlocking effect between a tire and grooved pavement. Further corroboration of the interlocking effect is evident by the audible rumble produced by the tires when the test vehicle starts to slide sideways on a longitudinally grooved pavement. The sideways-mounted recording accelerometer placed in the B. F. Goodrich test car also showed a ripple in its acceleration trace when the car slid sideways on the grooved pavement.

The results from highway grooving in California have provided the researcher a most exasperating paradox. On every highway where grooves were installed, vehicle accident rates under wet pavement conditions fell dramatically. Yet skid resistance tests before and after grooving showed very little difference in friction coefficient, hardly enough to account for the dramatic accident rate reduction due to grooving. Grooving tests have been made by other states with basically similar unrewarding skid resistance results. The vehicle spin-out tests along with vehicle braking tests made on site III have furnished sufficient data to explain this paradox. In figure 22 are presented the vehicle spin-out lateral friction coefficients obtained with the NASA convertible car (fig. 23(b)) and near transient peak braking friction coefficients obtained with the NASA diagonal braking car using a Tapley meter under flooded conditions. It can be seen that, although the agreement between lateral and braking measurements is fair, the braking values are lower than the actual lateral friction-coefficient values occurring at spin-out on the curve. Figure 25 presents transient peak μ_{max} and locked-wheel μ_{skid} friction-coefficient data obtained with the General Motors braking trailer on the grooved and ungrooved curves of the site III skid pad for ASTM bald- and rib-tread tires. Also shown are the lateral friction coefficients obtained at spin-out speeds occurring to the NASA convertible test car (fig. 23(b)) when equipped with ASTM bald- and rib-tread tires. Finally, the steady-state peak μ_{max} braking coefficients obtained with the FAA Swedish Skiddometer equipped with ASTM bald-tread tires are shown.

It first should be pointed out that the μ_{skid} values obtained by the General Motors braking trailer (fig. 25) indicate little improvement in skid resistance between grooved and ungrooved pavement surfaces for either ASTM rib- or bald-tread tires. This result is consistent with the experience of California and other states when testing grooved pavements with braking trailers. On the other hand, the actual vehicle spin-out data on the curves in figures 23, 24, and 25 show an improvement in skid resistance between grooved and ungrooved pavements. It is interesting to note that the transient peak braking coefficients by the General Motors braking trailer show a large improvement in skid resistance when the pavement is grooved. These data are corroborated by the FAA Skiddometer, the steady-state peak braking friction data of which show a similar improvement in skid resistance for the grooved surface. The General Motors data also show that pavement grooving raises ASTM bald-tread-tire peak friction levels to the level attained by the ASTM rib-tread tire.

The NASA research truck, which has the capability of measuring transient peak and locked-wheel braking coefficients of friction as well as steady-state peak lateral coefficient of friction, participated in the Florida Skid Correlation Study. Figure 26 presents some of the data obtained on five of the test surfaces under a wet pavement condition with the ASTM rib-tread tire and a production radial-tread tire. It can be seen that the transient peak braking coefficient was in close agreement with the steady-state peak lateral coefficient of friction. Also, the locked-wheel friction coefficient was considerably less than either peak values, especially on the lowest skid resistance surface (painted concrete).

With these results in mind, it is fairly obvious that when a vehicle spins out on a highway curve or while making a lane change, it must first pass through the incipient skid point of the lateral-force-slip curve. This means that the steady-state peak lateral friction determines the skid resistance of the pavement for this vehicle operating condition. Since the data in figure 26 indicate that transient peak braking measurements are in close agreement with steady-state lateral-friction values, the transient peak braking coefficient may be used for this purpose as well.

Therefore, the skid resistance of a pavement for vehicles undergoing spin-out on highway curves or suffering loss of directional control from other tire cornering deficiencies is determined by incipient skid tire conditions which may be obtained from either steady-state peak lateral or transient peak or steady-state peak braking coefficients of friction. The skid resistance of a pavement for this vehicle operating condition cannot be obtained by locked-wheel skid-friction-coefficient measurements.

Another point can be gained from the data presented in figure 25. It will be noticed that spin-out values of lateral friction coefficient tend to be lower than the transient peak braking values. This fact is attributed to the method of test. For example, the test drivers were told to maintain constant speed through the curve during the spin-out tests by use of throttle. Thus, the rear driving tires of the vehicles had to develop a forward tractive force as well as a lateral force on the curve. It is believed that this factor, and perhaps vehicle suspension effects as well, account for the difference in results.

CONCLUDING REMARKS

Test results have been presented of the skid resistance obtained on 30 different pavement surfaces installed at the NASA Wallops Station airfield. The skid resistance of these pavements was determined by the use of ASTM rib- and bald-tread tires and by new and worn production tires mounted on test vehicles which measured transient peak, steady-state peak, and locked-wheel braking coefficients of friction. Limited vehicle spin-out tests on a 500-foot-radius highway curve were also made to study the skid resistance of pavements under this vehicle operating condition.

On the basis of results of the present highway grooving and texturing studies, some suggestions are included for improving the techniques for measuring skid resistance and for improving the skid resistance of pavements.

Improving the Techniques for Measuring Pavement Skid Resistance

At the present time, some highway agencies employ braking trailers which make locked-wheel skid tests on ASTM rib-tread tires to study pavement skid resistance. Unfortunately, such equipment supplies only a small part of the information required to depict the true skid resistance of a pavement. For example, the typical automobile spends most of its operating hours under rolling conditions on highways and very few hours undergoing panic stop situations where the wheels are inadvertently locked. The data in this paper show extremely large differences in tire traction performance for all pavements and wetness conditions depending upon whether the vehicle-tire operating mode is rolling under transient braking peak, or rolling at steady-state lateral or cornering peak, or undergoing a locked-wheel braking skid. It has also been demonstrated herein that the locked-wheel friction coefficient μ_{skid} considerably underestimates the ability of grooved pavements to improve pavement skid resistance on freeways or the open road under wet conditions.

For the open road driving or maneuvering condition, a vehicle before it skids must first pass through the peak or maximum point of the friction-coefficient slip-ratio curve. Thus, it is the peak friction coefficient rather than the locked-wheel friction coefficient μ_{skid} that depicts the true skid resistance of the pavement for this driving situation. For highway or street intersections where heavy vehicle braking is employed, more consideration should be given to the locked-wheel friction coefficient μ_{skid} rather than to peak friction coefficient in assessing pavement skid resistance for this driving situation. It follows from this discussion that pavement skid resistance measuring equipment must measure peak as well as skidding coefficients of friction to properly assess pavement skid resistance.

If all vehicles using the highway system of this country could be surveyed at one point in time, this survey should show that 25 percent of the vehicles have new tires, 25 percent have bald-tread tires or tires with the wear markers showing, and 50 percent have tires with wear between these two extremes. The results of the present study show that the skid resistance for open-texture and grooved pavement surfaces is insensitive to tire wear, whereas for most other pavement surfaces skid resistance is extremely sensitive to tire wear especially when tires are worn to the point of replacement. It follows therefore that pavement skid resistance measurements should be made on the ASTM bald-tread tire as well as the ASTM rib-tread tire to establish upper and lower bounds of skid resistance values to account for tire wear effects.

The fortunate correlation of steady-state or transient peak braking coefficients with steady-state lateral or cornering peak coefficient of friction shown in this paper means that these peak braking coefficients can be used to determine the lateral skid resistance of a pavement. From the foregoing considerations, it is suggested that second-generation braking trailers be of the two-wheel braking type with an ASTM bald-tread tire on one wheel and an ASTM rib-tread tire on the other wheel. The measuring equipment of the trailer should be capable of measuring both transient peak and locked-wheel braking coefficients for both wheels. The friction-coefficient values obtained during test establish the upper and lower bounds of pavement skid resistance for vehicle directional control and braking modes of operation, respectively, as well as upper and lower bounds for new and worn tire effects. With this information, the highway engineer can consider the pavement – street intersection or open highway – and more accurately determine whether the pavement is safe for continued operation or should be treated before further use. It is also suggested that the second-generation braking trailer and towing vehicle have high-speed testing capability so that the skid resistance of high speed highways can be determined for actual vehicle operating speed conditions.

Improving Pavement Skid Resistance

The present study shows that the skid resistance of most of the pavement surfaces investigated can safely support vehicle operations as high as 80 miles per hour under wet conditions as long as the ASTM rib-tread tire or the production equivalent tire is used on the vehicle. On the other hand, when worn tires or ASTM bald-tread tires are used on vehicles, the skid resistance of the low average texture depth pavements, such as the sand asphalt and canvas belt concrete surfaces, drops to marginal values at this speed. This situation becomes worse as the water-film thickness on the pavement increases. It has been shown in this paper that open-texture pavements provide much better skid resistance than closed-texture pavements at speeds of 70 miles per hour even under flooded conditions. It follows, then, that high speed highways should be provided with a deeper, more open textured surface than is ordinarily used on highways with low speed limits, such as city streets. Highway engineers point out that open-texture pavements polish more than closed-texture pavements under heavy traffic conditions and, therefore, such surface treatment could create a greater pavement slipperiness problem at a future time. The answer to this polishing problem must be in the selection of minimum polishing aggregate for use in the wearing course of such pavements. If such local natural aggregate is not available, consideration should be given to the use of the new synthetic aggregates that are now coming into production and that possess the desired skid and polish resistant properties.

A most promising approach to improve pavement skid resistance is by pavement grooving. Transverse and longitudinal grooving of crowned pavements significantly increases the drainage of water from a pavement during times of precipitation. Consequently, the water-film thickness on the tire-pavement interface is reduced.

Both longitudinal and transverse highway grooves and the larger runway grooves studied demonstrated repeatedly the capability of not only improving new tire performance on wet or flooded pavements but also restoring worn and bald-tread-tire friction levels to new tire performance levels. Thus, grooved pavements tend to have only one set of pavement skid resistance boundaries: one upper boundary for the peak braking or cornering tire operating mode and one lower boundary for the locked-wheel skid tire operating mode. With the exception of very open textured pavements, most other pavement textures have two sets of boundary values for pavement skid resistance to account for tire wear effects.

Pavement skid resistance can be dramatically improved by eliminating the lower boundary due to locked-wheel vehicle operation. This can be accomplished by the mandatory use of antiskid braking systems on ground vehicles when such systems are perfected.

REFERENCES

1. Allen, Curtis R.; and Quillen, James W.: Problem Areas Associated With the Construction and Operation of the Landing Research Runway at NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 8 herein.)
2. Yager, Thomas J.: Comparative Braking Performance of Various Aircraft on Grooved and Ungrooved Pavements at the Landing Research Runway, NASA Wallops Station. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 3 herein.)
3. Horne, Walter B.; and Tanner, John A.: Joint NASA-British Ministry of Technology Skid Correlation Study – Results From American Vehicles. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 23 herein.)
4. Smiley, Robert F.; and Horne, Walter B.: Mechanical Properties of Pneumatic Tires With Special Reference to Modern Aircraft Tires. NASA TR R-64, 1960.
5. Kummer, H. W.; and Meyer, W. E.: Tentative Skid-Resistance Requirements for Main Rural Highways. Rep. 37, Nat. Cooperative Highway Res. Program, Nat. Res. Counc., 1967.

TABLE I.- SITE I (LANDING RESEARCH RUNWAY) TEST SURFACES

Surface	Material	Description
A	Ungrooved concrete	Surfaces A and B were subjected to a canvas belt drag treatment. The goal was to obtain as smooth a surface texture as practically possible. Later, 1- × 1/4- × 1/4-inch transverse grooves were cut in surface B by diamond saws.
B	Grooved concrete	
C	Grooved concrete	Surfaces C and D were subjected to a longitudinal burlap drag treatment. The goal was to obtain a typical currently used runway surface texture. Later, 1- × 1/4- × 1/4-inch transverse grooves were cut in surface C by diamond saws.
D	Ungrooved concrete	
E	Asphalt	The wearing course of surface E was paved with Gripstop, a refined product of Kentucky rock asphalt. The resulting course had a very smooth surface with fine but sharp sand particles exposed.
F	Ungrooved asphalt	Surfaces F and G were paved with asphalt containing 3/8 inch or less aggregate. Later, 1- × 1/4- × 1/4-inch transverse grooves were cut in surface G by diamond saws.
G	Grooved asphalt	
H	Grooved asphalt	Surfaces H and I were paved with asphalt containing 3/4 inch or less aggregate. Later, 1- × 1/4- × 1/4-inch transverse grooves were cut in surface H by diamond saws.
I	Ungrooved asphalt	
A-1	Ungrooved epoxy	Outside lanes of surfaces A and B were given a spray coating of epoxy-grit. (See table II, surface G.)
B-1	Grooved epoxy	

TABLE II.- SITE II (LANDING RESEARCH RUNWAY TAXIWAY) SURFACES

Surface	Treatment	Description
A	Ungrooved	Original concrete taxiway surface with smooth sandy texture. 26-year-old surface
A-1	3/4- × 1/8- × 1/8-inch transverse grooves	
A-2	3/4- × 1/8- × 1/8-inch longitudinal grooves	
B	Ungrooved	Asphalt seal coat overlaying original concrete taxiway surface. 13-year-old surface
B-1	3/4- × 1/8- × 1/8-inch transverse grooves	
B-2	3/4- × 1/8- × 1/8-inch longitudinal grooves	
B-3	1- × 1/8- × 1/8-inch transverse grooves	
B-4	1- × 1/8- × 1/8-inch longitudinal grooves	
D	Asphalt overlay	Local sand mix asphalt, 8% asphalt. New surface
C	Asphalt surface dressing	Asphalt with exposed large aggregate projecting above surface. 13-year-old surface
E	Sinopal asphalt overlay	Plant mix asphalt with 50% aggregate containing Sinopal, a synthetic stone, 25% crushed granite, and 25% silica sand. New surface (furnished by Martin Marietta Corp.)
F	Rolled epoxy coating	Flint abrasive and carborundum with aggregate size of 20-70. Epoxy film thickness was 0.015 to 0.050 inch. Coverage was 40 square feet per gallon using 39.7 grams of aggregate. New surface (furnished by American Abrasive Metals Co.)
G	Sprayed epoxy-grit coating	Grit used was blast furnace slag with average aggregate size of 3/32 inch. Epoxy film thickness was 0.030 inch. New surface (furnished by Devoe & Reynolds Co., Inc.)

TABLE III.- SITE III (SKID PAD) TEST SURFACES

Surface	Treatment	Description
A	3/4- × 1/8- × 1/8-inch transverse grooves on straightaway	The entire concrete surface of the 88- × 450-foot skid pad was covered with liquid Jennite which is a coal-tar emulsion. The usual sand and aggregate content normally used in highway application was omitted in the treatment of the skid pad to obtain as smooth and slippery a skid surface as possible.
B	3/4- × 1/8- × 1/8-inch longitudinal grooves on straightaway	
C	3/4- × 1/8- × 1/8-inch longitudinal grooves on 500-foot-radius-curve lane	
D	Ungrooved 500-foot-radius-curve lane	
E	Ungrooved straightaway	
G	Ungrooved 500-foot-radius-curve lane	

TABLE IV.- AUTOMOBILE STOPPING DISTANCE ON ICE-COVERED SITE I SURFACES AT A GROUND SPEED OF 50 MILES PER HOUR

	Stopping distance, ft	Average friction coefficient
Surface C (1- × 1/4- × 1/4-inch transverse grooved concrete)	146	0.570
Surface D (Ungrooved concrete)	281	0.296

Test conditions: Ice formed on pavement surfaces during flooding operations prior to testing F-4D aircraft. Ambient air temperature was 31° F. Test car was new and equipped with original equipment tires (2000 miles indicated on vehicle odometer). Brakes were applied firmly by driver, locking all four vehicle wheels at entrance onto test surface at speed of 50 mph. Distance to complete stop was measured.

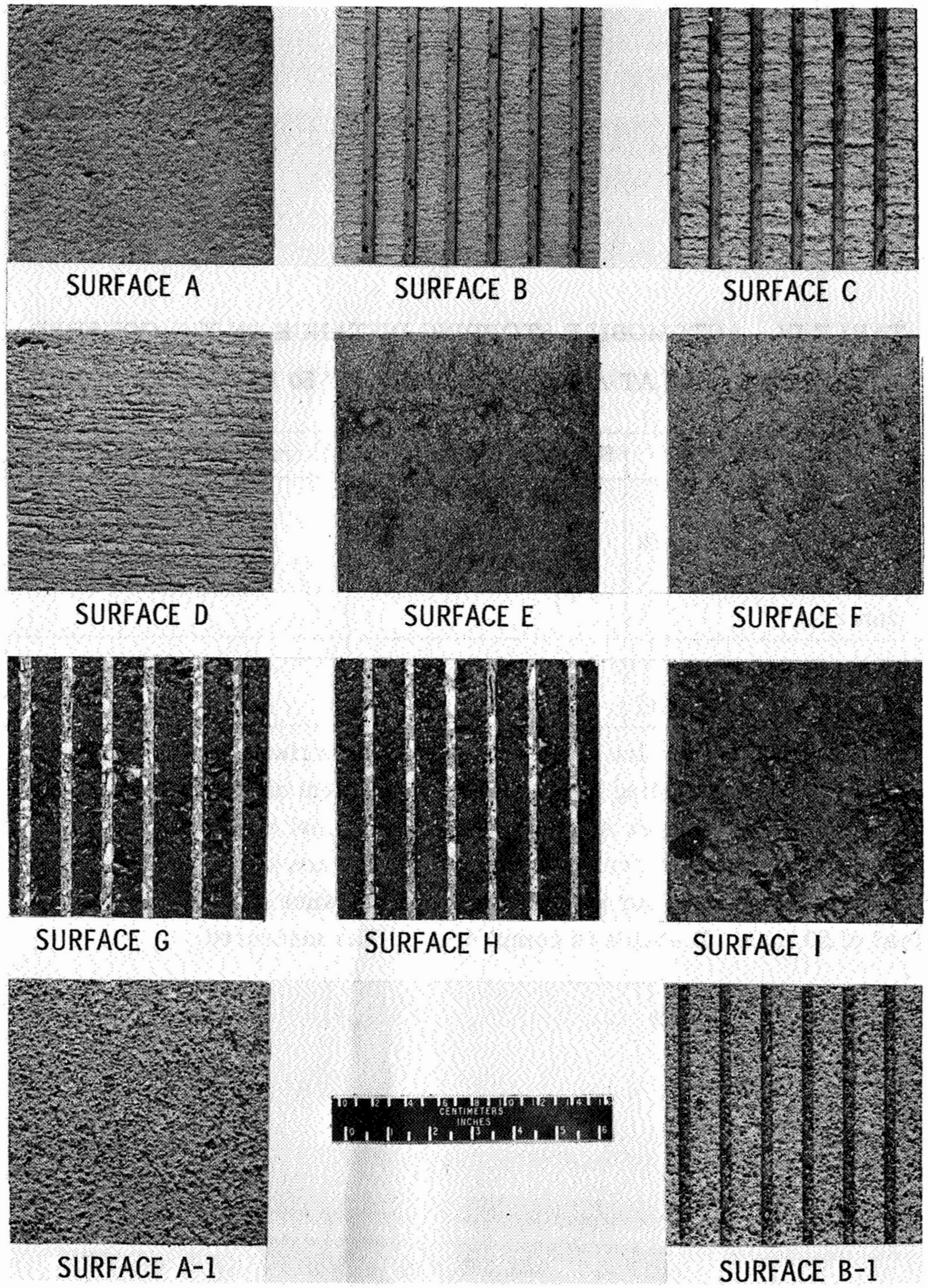


Figure 1.- Test surfaces installed on site I (landing research runway). (See table I for test surface description.)

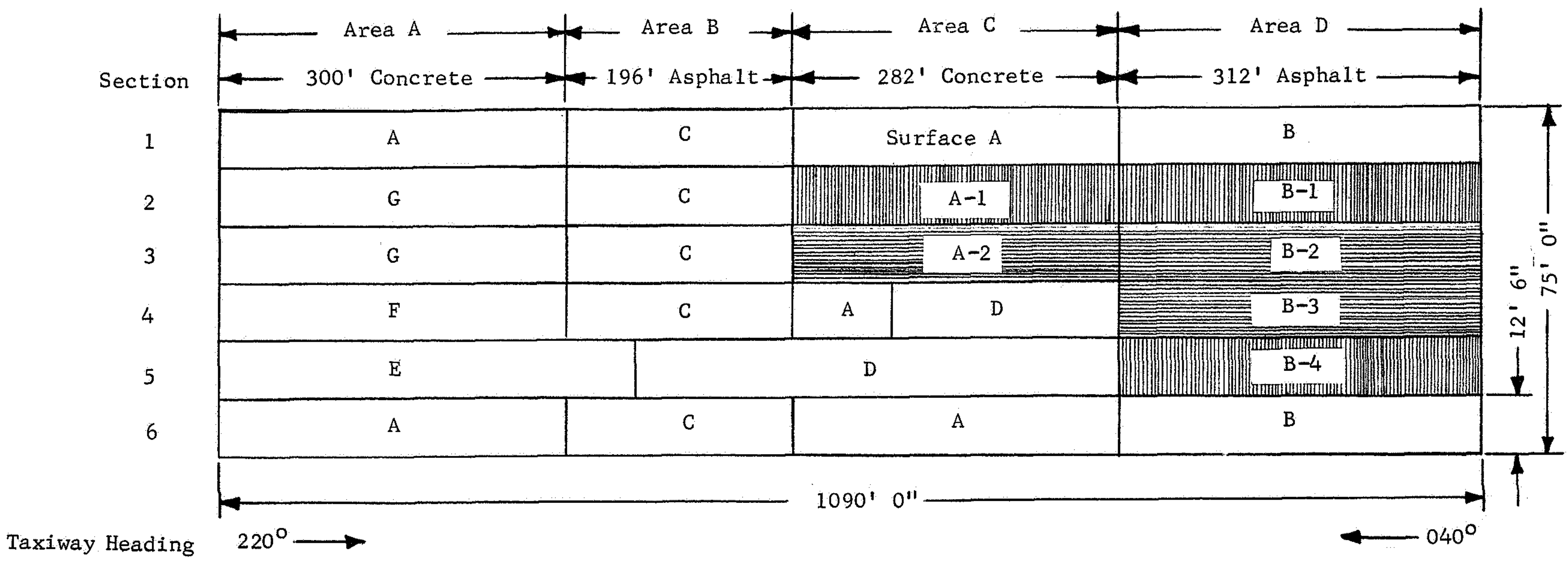


Figure 2.- Layout of test surfaces on site II (taxiway of landing research runway).

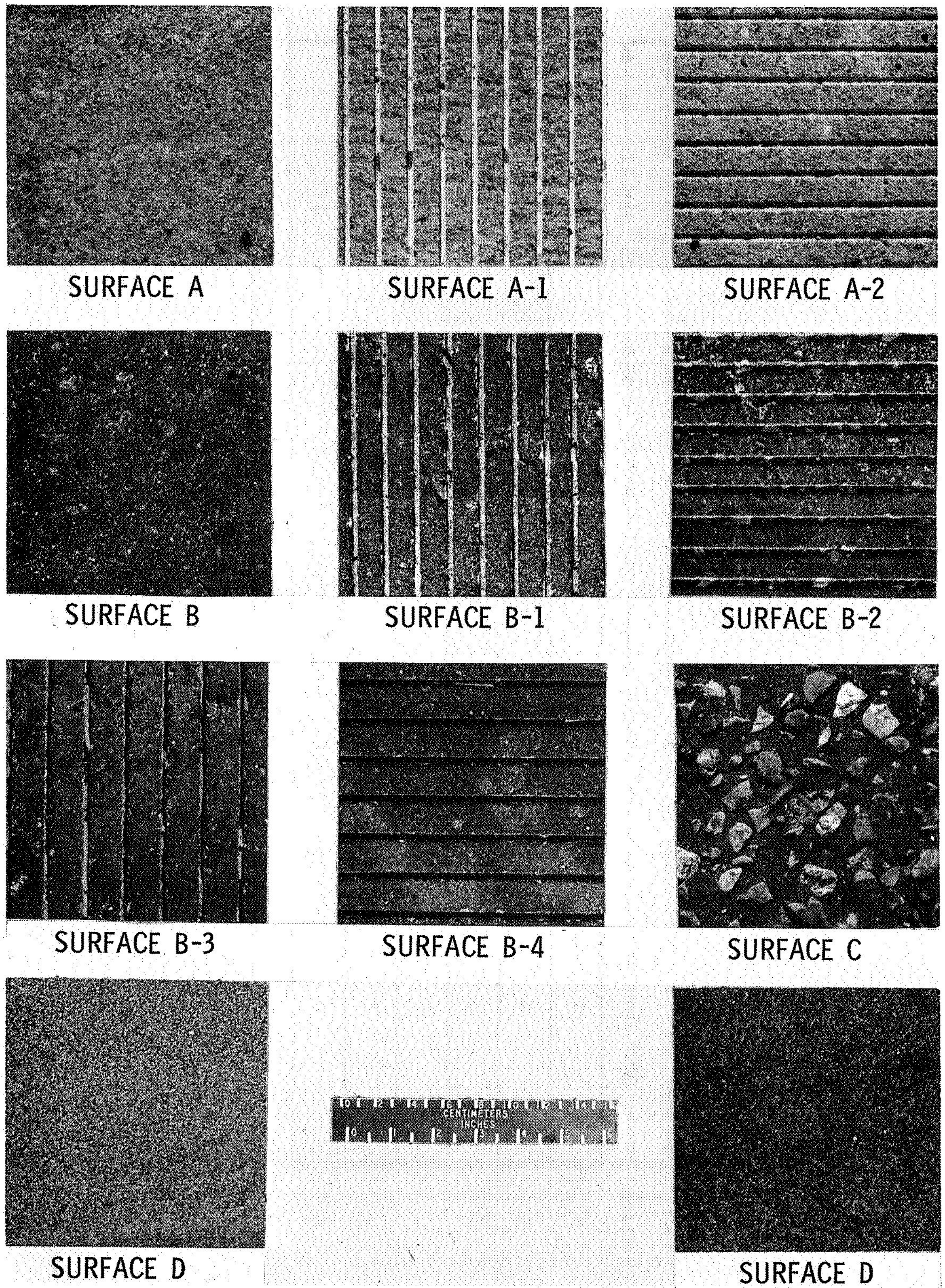


Figure 3.- Test surfaces installed on site II (taxiway of landing research runway).

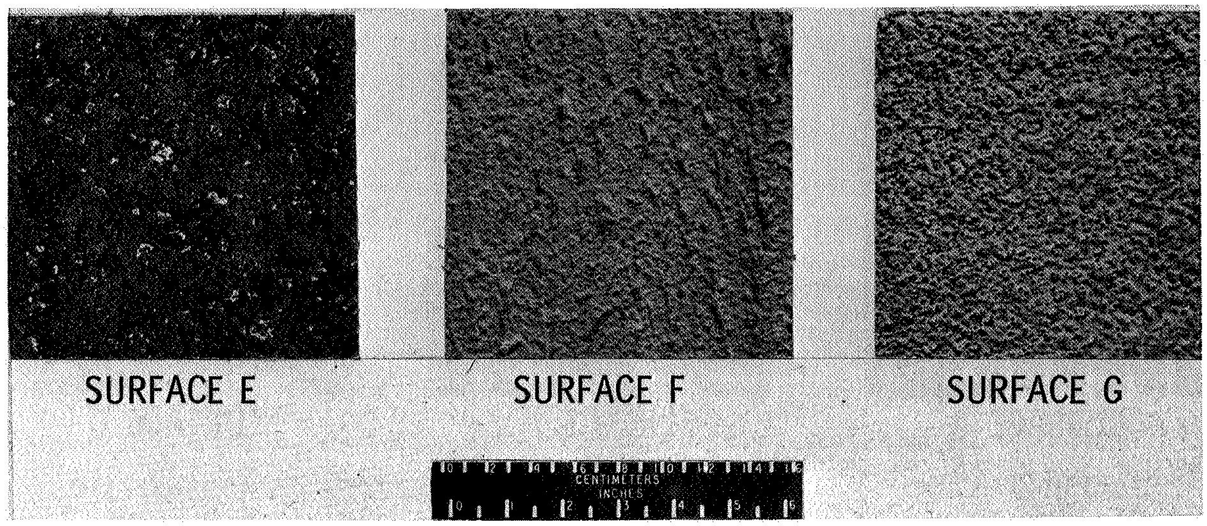


Figure 3.- Concluded.

500-foot radius
Highway curve

Surface
D Ungrooved
G Ungrooved
C Longitudinal grooves; 3/4" x 1/8" x 1/8"

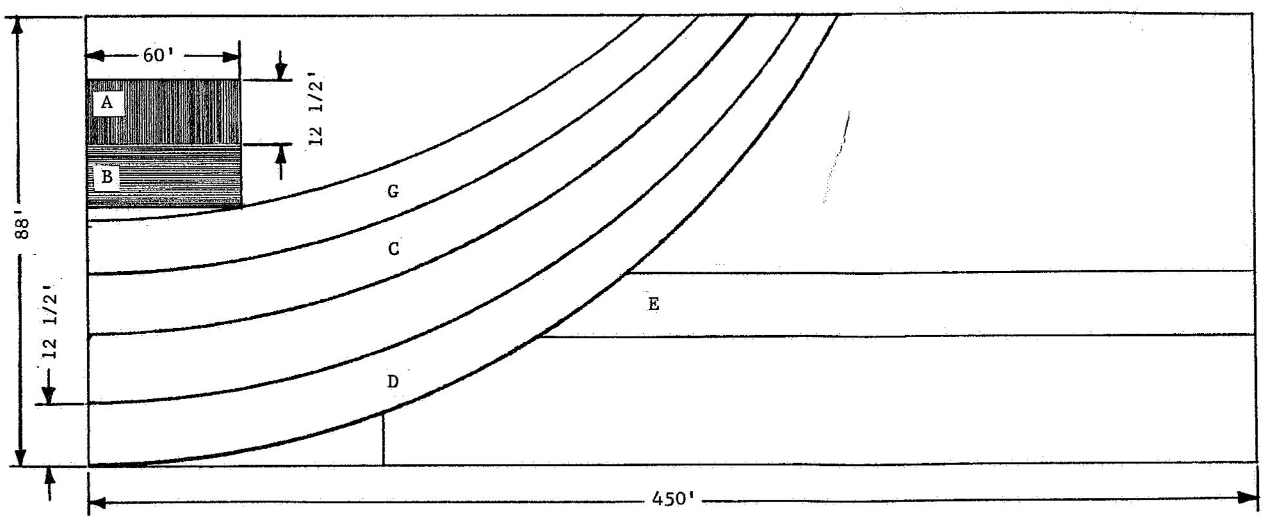


Figure 4.- Layout of test surfaces on site III (skid pad, the hangar apron covered with Jennite, a coal-tar emulsion).

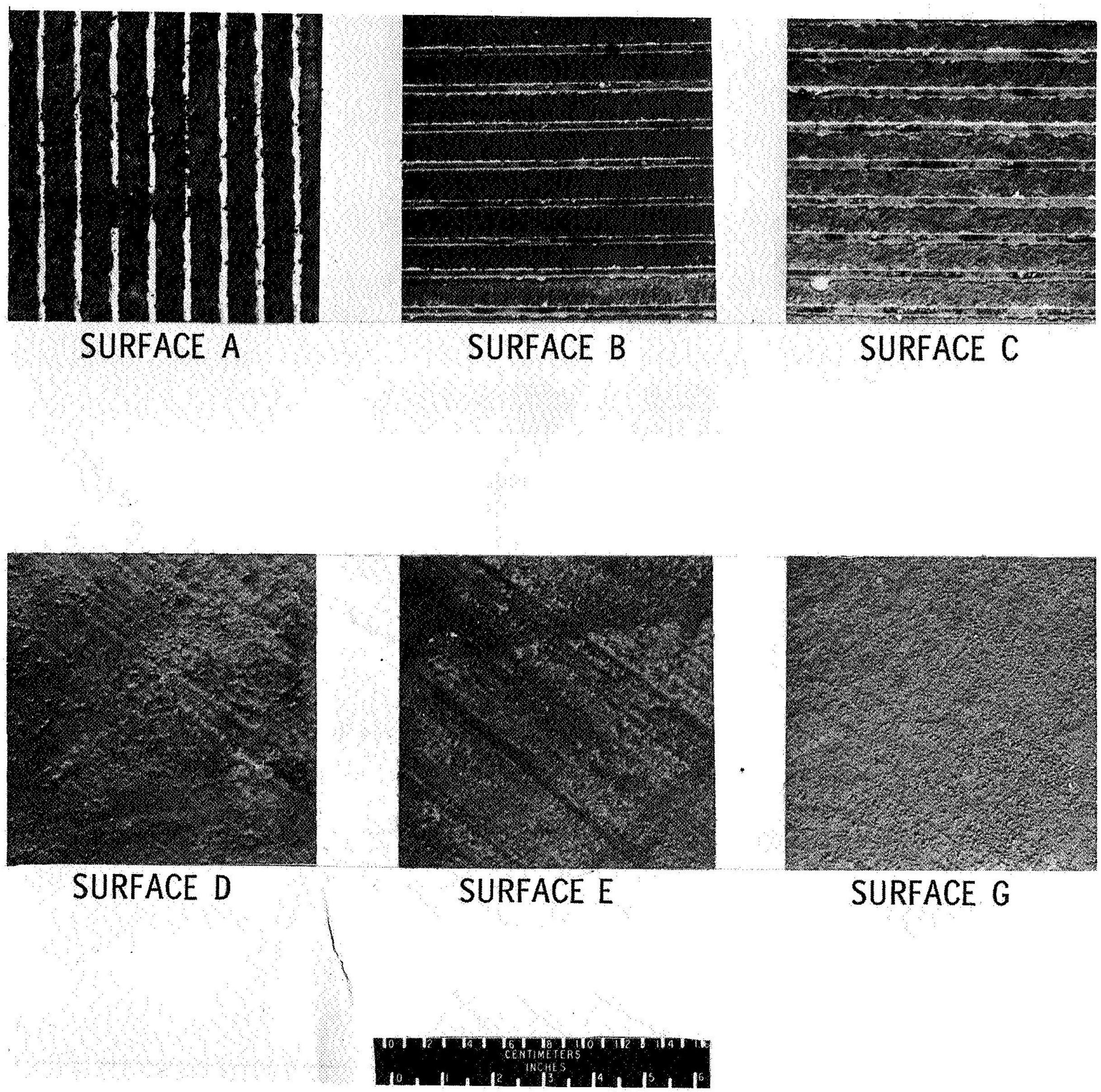
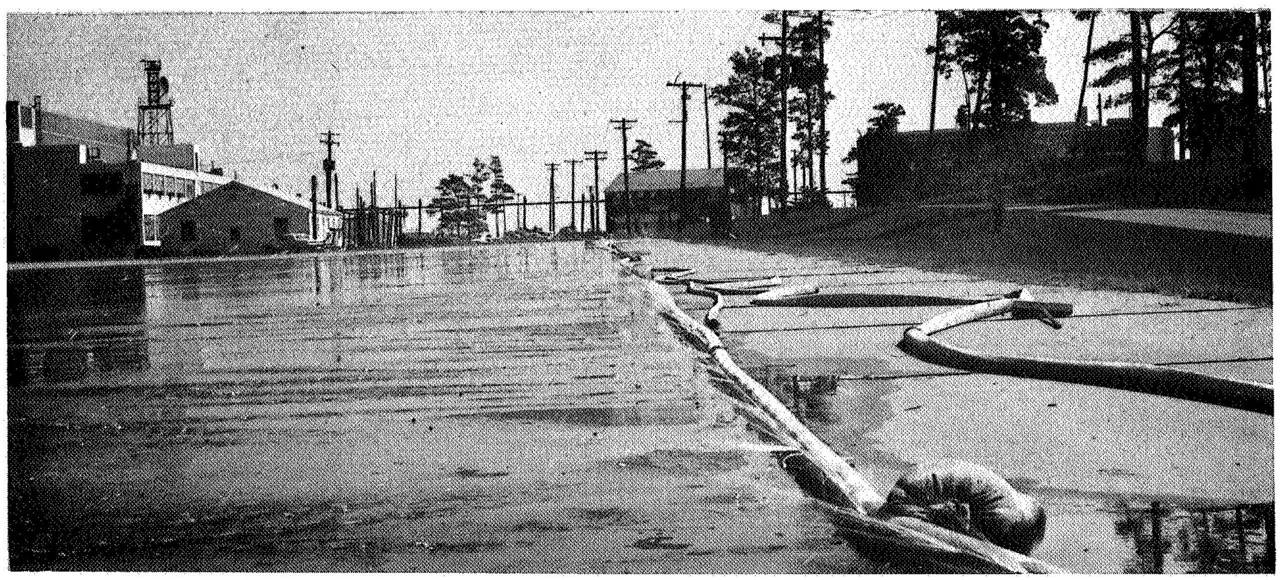


Figure 5.- Test surfaces installed on site III (skid pad). (See table III for test surface description.)

Figure 6.- The British "Juggernaut" test vehicle undergoing a braking test on surface A of site I under a wet and puddled pavement condition.

(a) NASA diagonal braking car undergoing test on surface E of site II under a flooded pavement condition provided by plastic-pipe sprinkler system.



(b) Pierced-canvas-fire-hose sprinkler system used to wet or flood site III skid pad.

Figure 7.- Water sprinkler systems used to wet or flood site II and site III test surfaces.

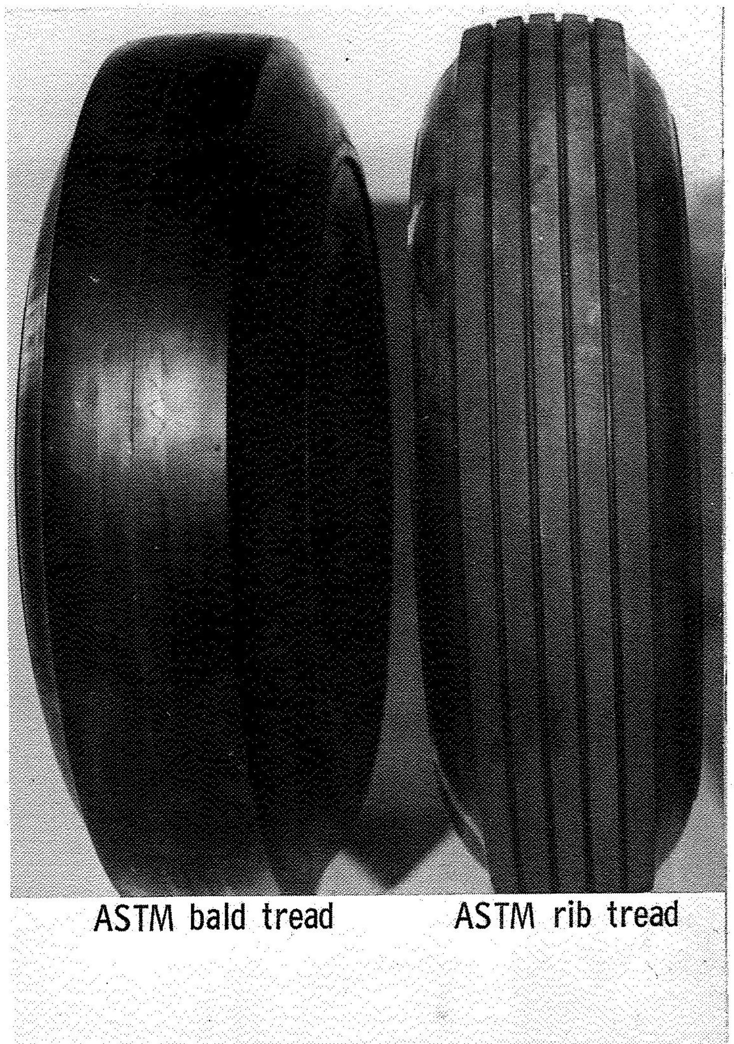


Figure 8.- Tires used on test vehicles to evaluate pavement skid resistance.

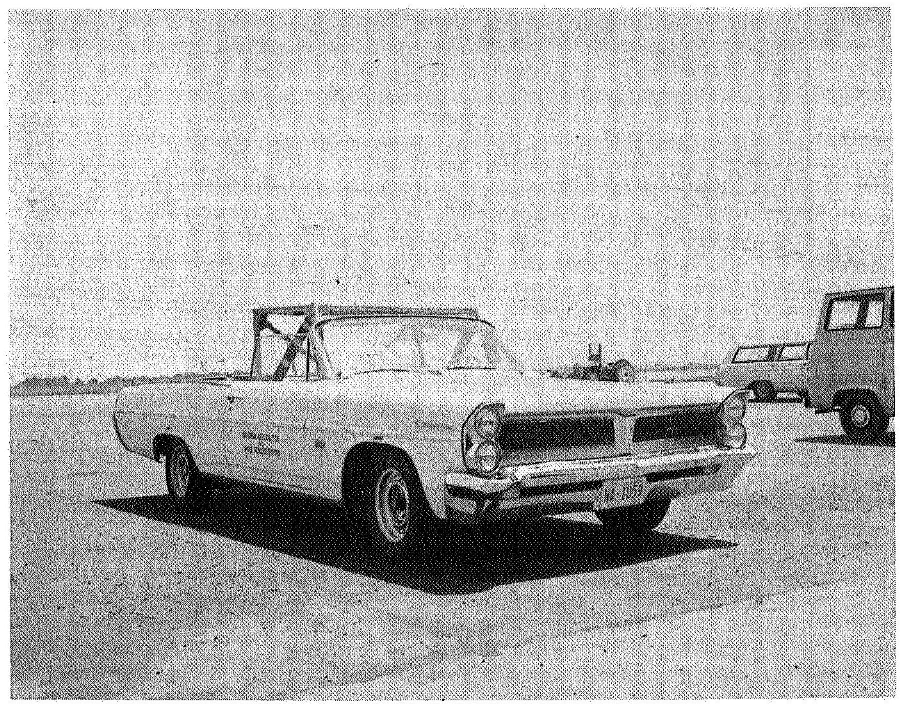


Figure 9.- Stripped convertible with protective cage used by NASA in vehicle spin-out tests on site III skid pad.

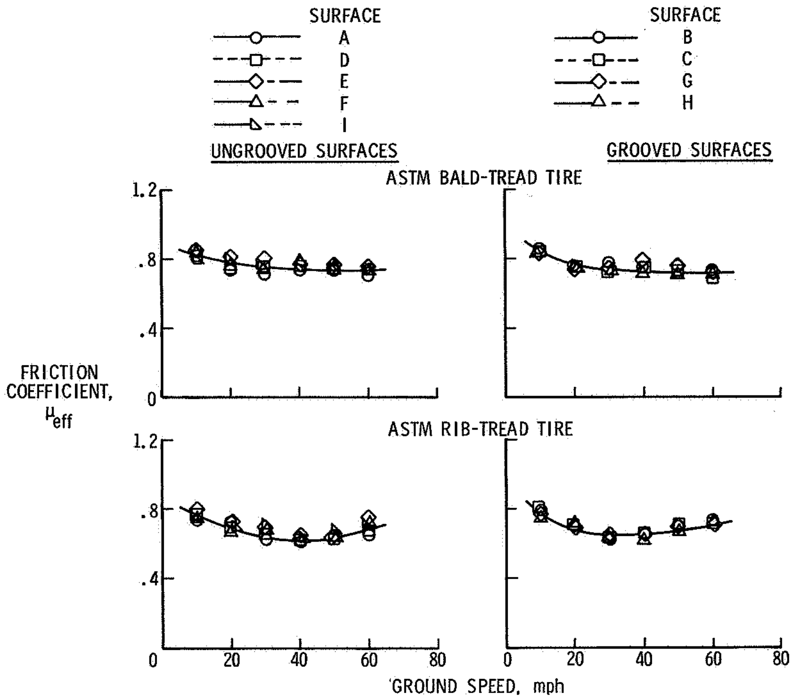


Figure 10.- Skid resistance of site I surfaces rated by NASA diagonal braking car under near transient peak braking conditions. ASTM bald- and rib-tread tires; dry pavement; Tapley meter.

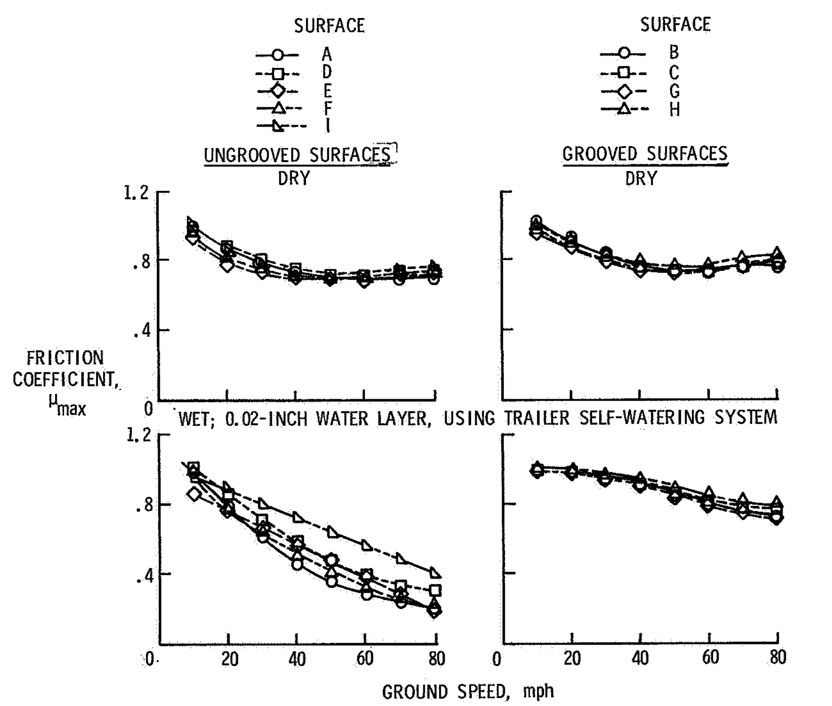


Figure 11.- Skid resistance of site I surfaces rated by FAA Swedish Skiddometer under steady-state peak braking conditions. ASTM bald-tread tire.

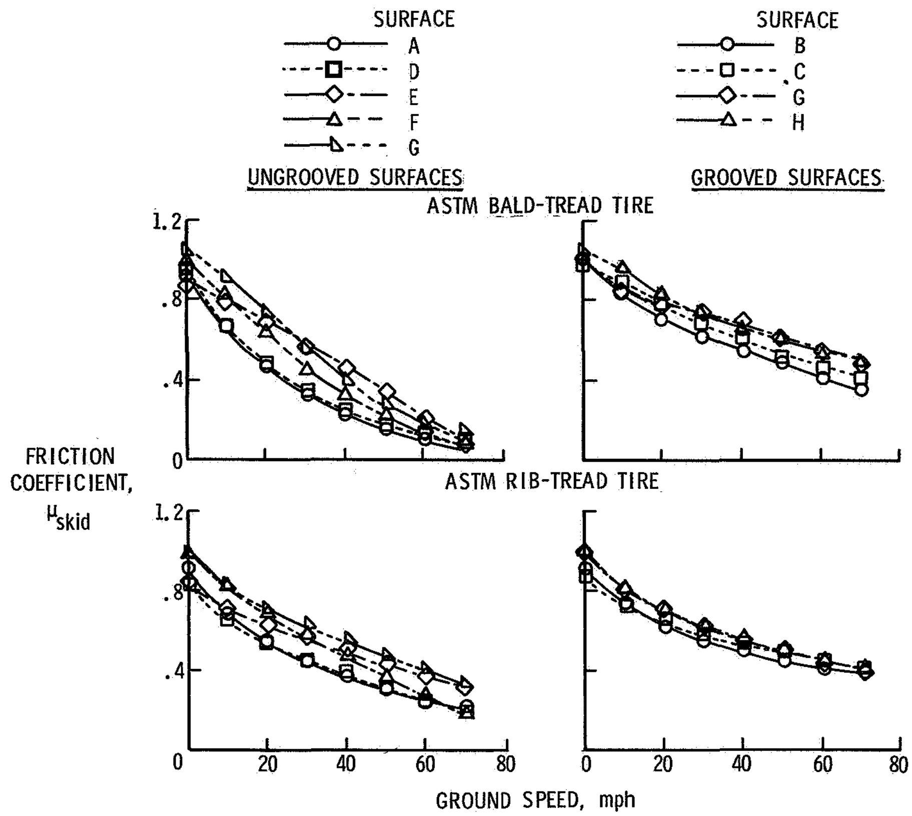


Figure 12.- Skid resistance of site I surfaces rated by NASA diagonal braking car under locked-wheel braking conditions. ASTM bald- and rib-tread tires; wet and puddled surfaces; recording accelerometer.

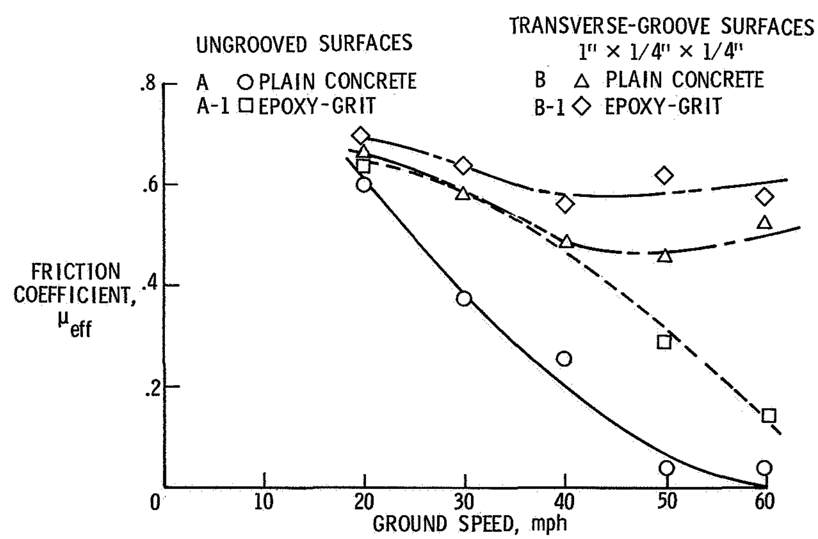


Figure 13.- Improvement in pavement skid resistance by increasing pavement average texture depth by use of epoxy-grit. NASA diagonal braking car; worn tires (wear markers showing); flooded pavement from natural rain; Tapley meter.

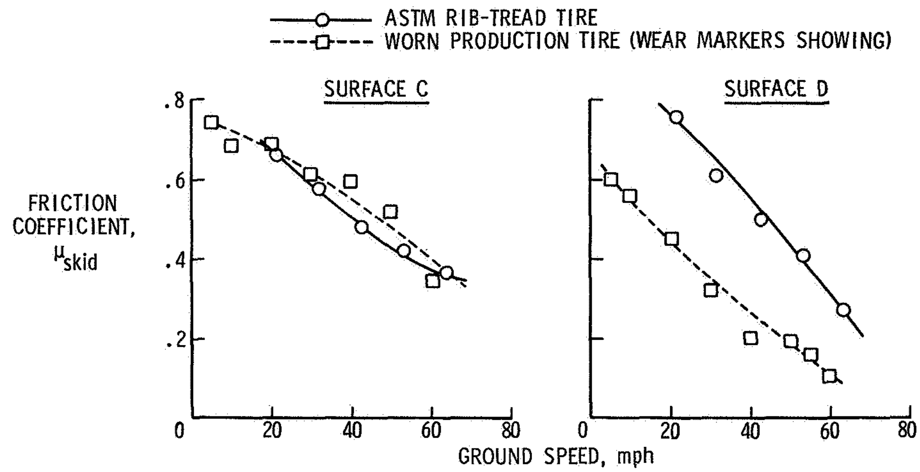


Figure 14.- Comparison of braking performance of ASTM rib-tread and worn production tires on site I surfaces. B. F. Goodrich diagonal braking car; flooded pavement conditions.

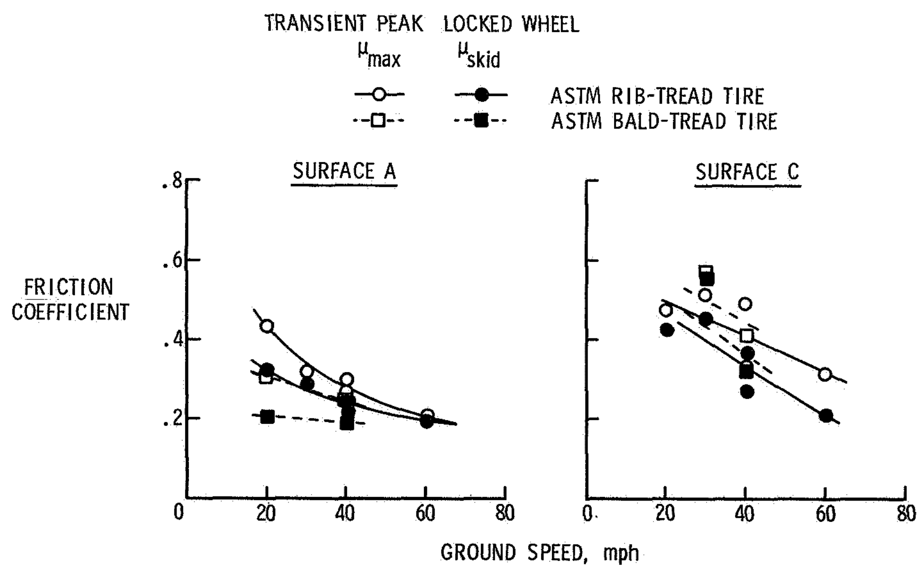
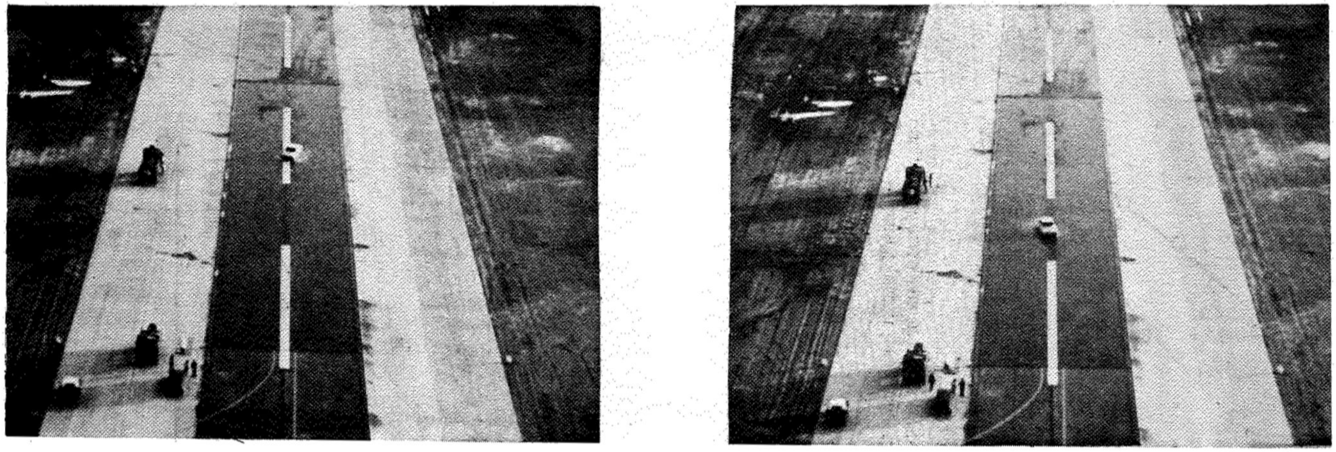


Figure 15.- Skid resistance of site I surfaces under deep slush pavement conditions (0.5 to 2.0 inches). General Motors braking trailer.



(a) Making "S" turns about runway center line on concrete surface C with $1- \times \frac{1}{4}- \times \frac{1}{4}$-inch grooves. Vehicle did not skid.

(b) Making "S" turns about runway center line on ungrooved concrete surface D. Same steering input was used as for part (a). Vehicle lost directional control and skidded sideways.

Figure 16.- Vehicle steering and directional control on ice-covered grooved and ungrooved pavements of site I. Vehicle speed, 30 mph; half-worn tires.

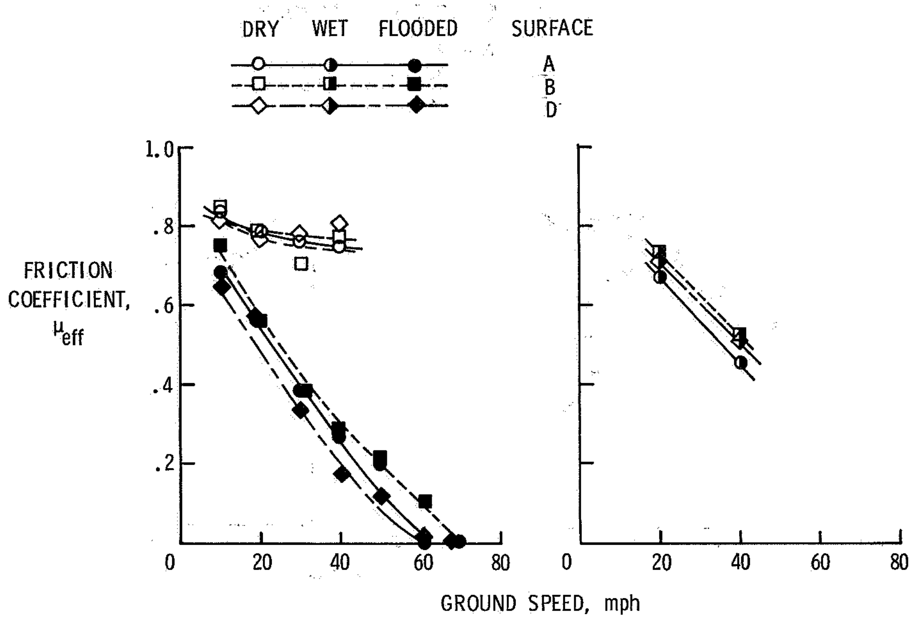


Figure 17.- Skid resistance of conventional site II surfaces. NASA diagonal braking car; Tapley meter; ASTM bald-tread tires.

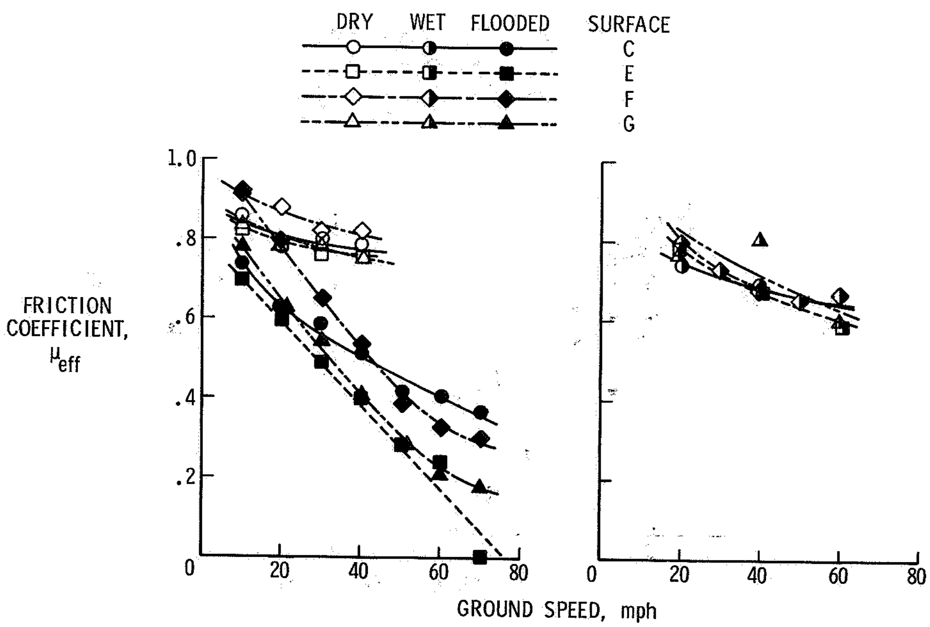


Figure 18.- Skid resistance of treated site II surfaces. NASA diagonal braking car; Tapley meter; ASTM bald-tread tires.

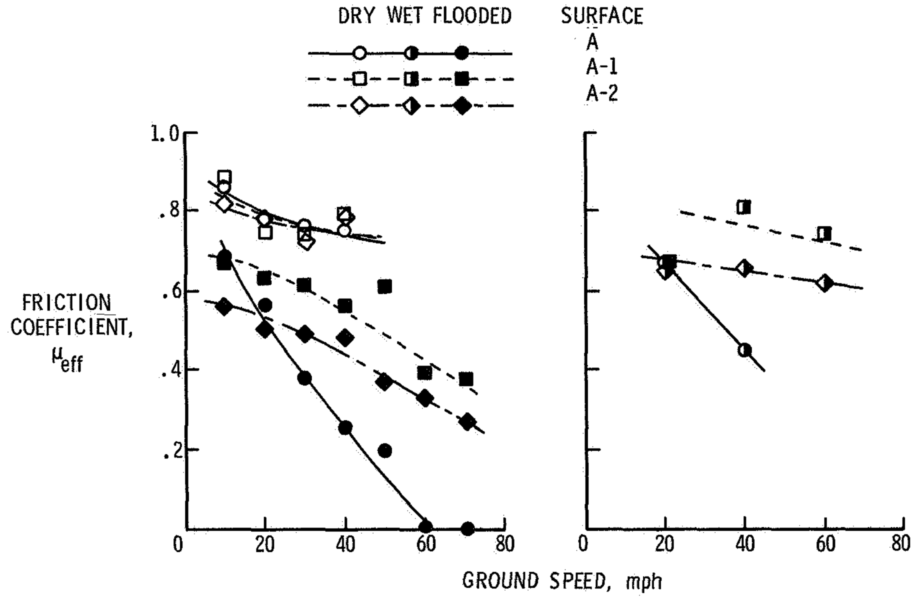


Figure 19.- Improvement in skid resistance of site II concrete pavement by using $\frac{3}{4}$- × $\frac{1}{8}$- × $\frac{1}{8}$-inch groove patterns. NASA diagonal braking car; Tapley meter; ASTM bald-tread tires.

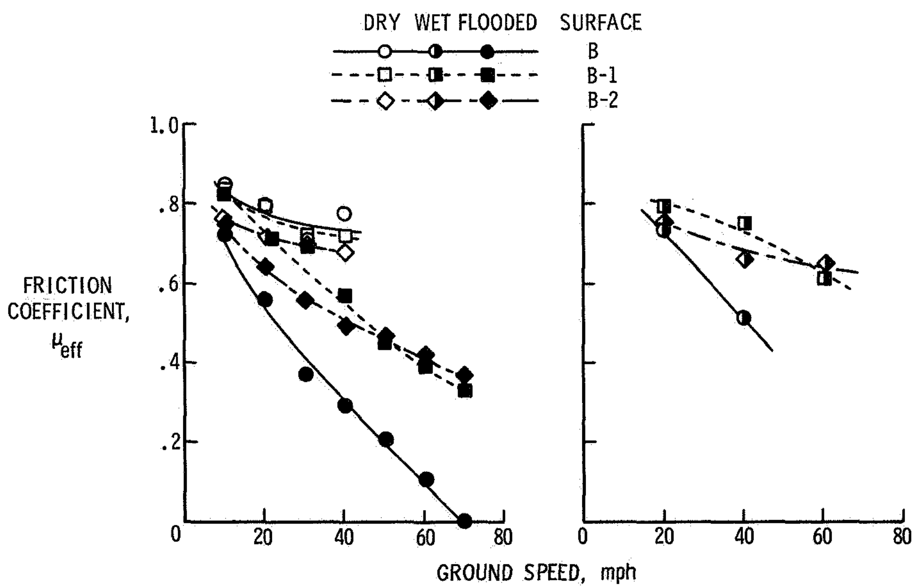


Figure 20.- Improvement in skid resistance of site II asphalt (seal coat) pavement by using $\frac{3}{4}$- × $\frac{1}{8}$- × $\frac{1}{8}$-inch groove patterns. NASA diagonal braking car; Tapley meter; ASTM bald-tread tires.

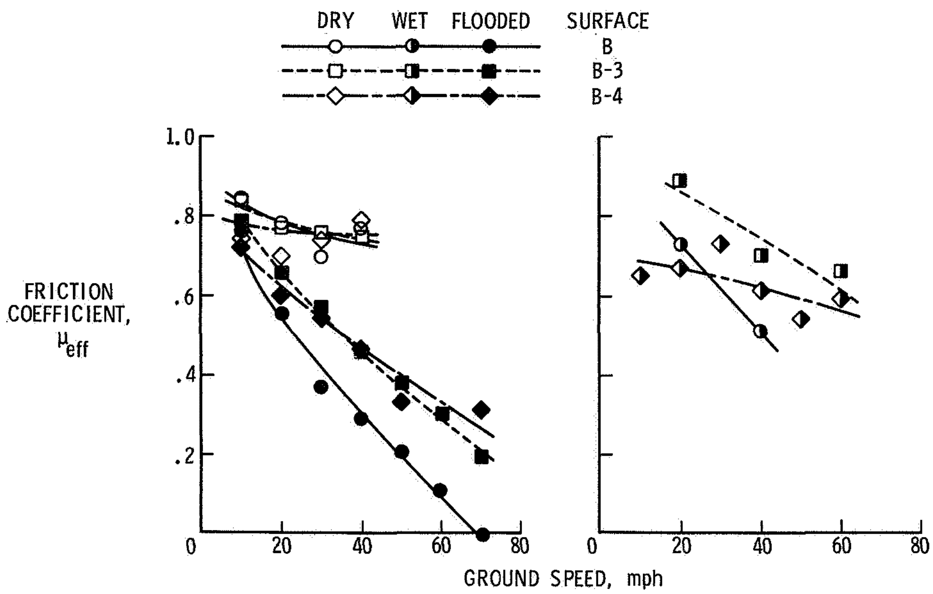


Figure 21.- Improvement in skid resistance of site II asphalt (seal coat) pavement by using 1- × $\frac{1}{8}$- × $\frac{1}{8}$-inch groove patterns. NASA diagonal braking car; Tapley meter; ASTM bald-tread tires.

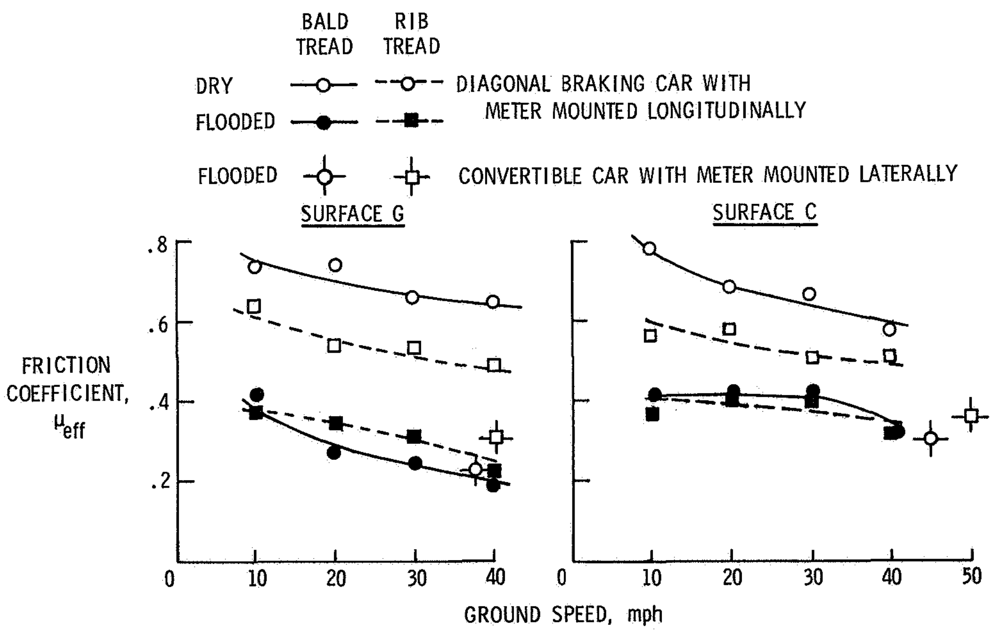
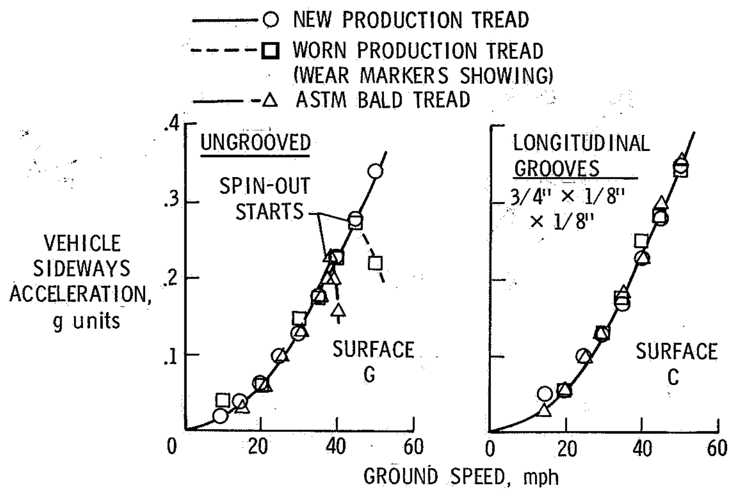
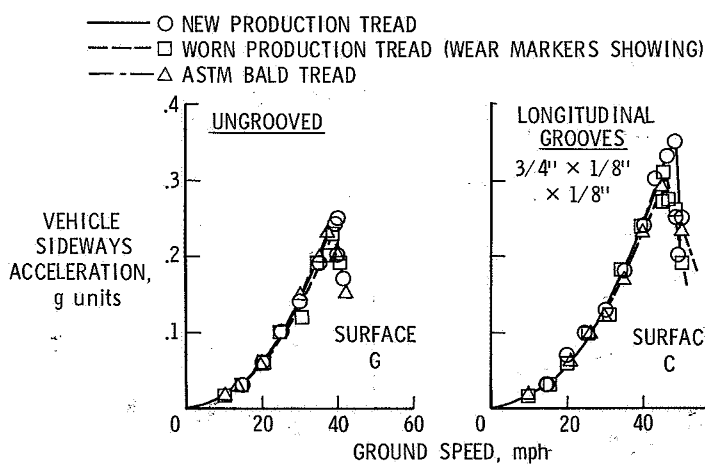


Figure 22.- Comparison of braking and lateral friction coefficients obtained on 500-foot-radius curves of site III skid pad. Jennite surface; NASA diagonal braking and convertible cars; ASTM tires.



(a) Wet pavement conditions.



(b) Flooded pavement conditions (0.05 to 0.1 inch).

Figure 23.- Vehicle spin-out speeds obtained on 500-foot-radius curves of site III skid pad. NASA convertible car; Tapley meter mounted sideways.

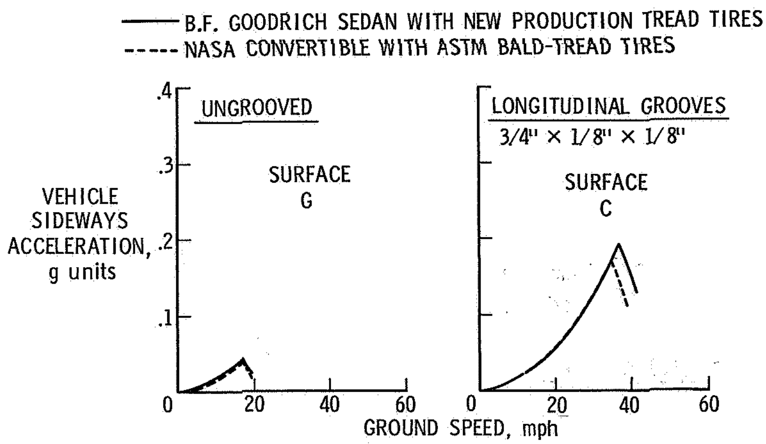


Figure 24.- Vehicle spin-out speeds obtained on 500-foot-radius curves of site III skid pad under slippery pavement conditions (mixture of water and hydrolube).

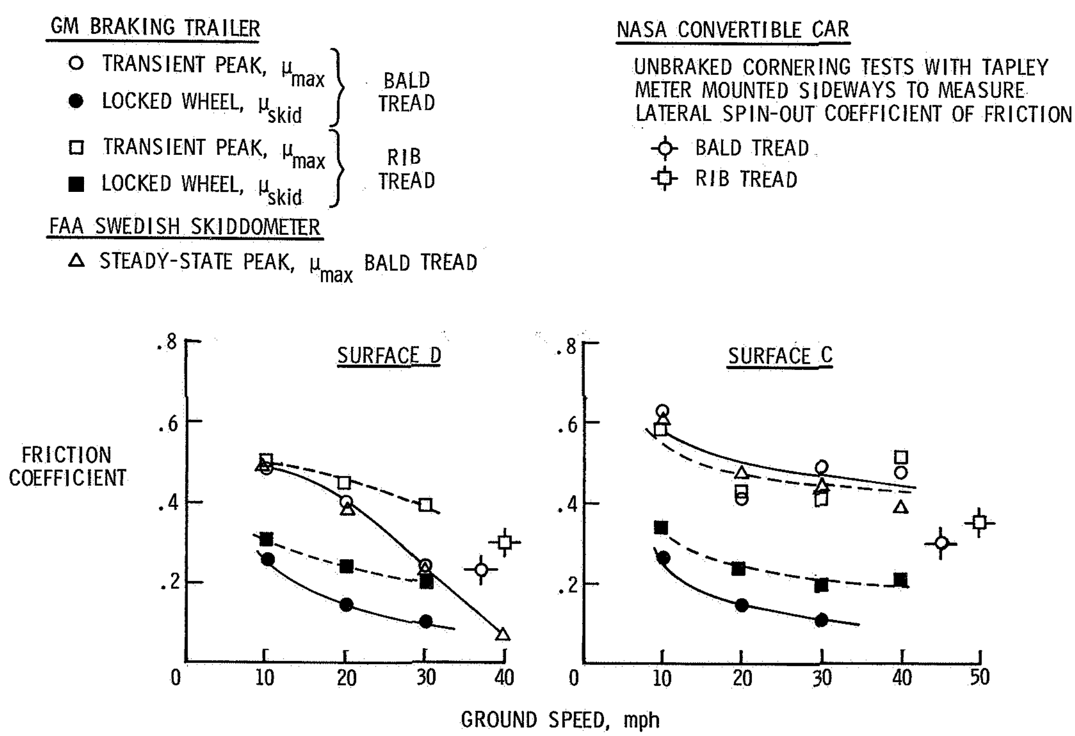


Figure 25.- Comparison of braking and lateral friction coefficients obtained on 500-foot-radius curves of site III skid pad. Flooded pavement conditions; ASTM tires.

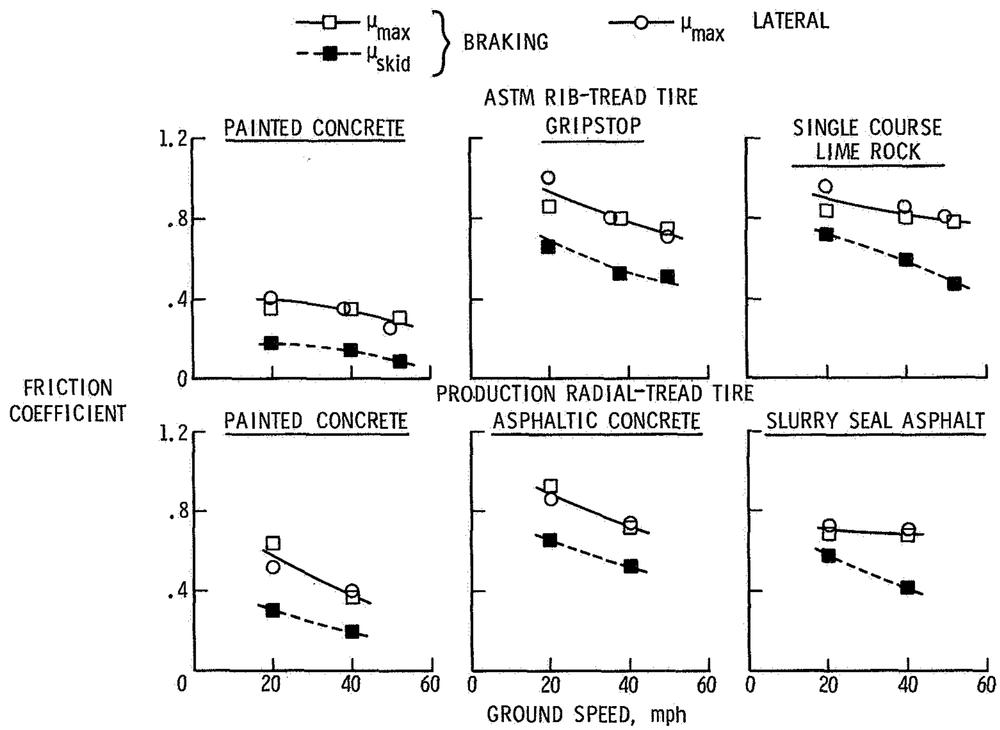


Figure 26.- Comparison of steady-state peak lateral, transient peak, and locked-wheel braking coefficients of friction. NASA research truck; surfaces wetted by sprinkler system; Florida Skid Correlation Study.

27. RESULTS FROM STUDIES OF HIGHWAY GROOVING AND TEXTURING BY SEVERAL STATE HIGHWAY DEPARTMENTS

By Larry G. Mosher

Clipper Manufacturing Company

SUMMARY

In an effort to combat the increasing rate of automobile accidents, several State highway departments have been evaluating the pavement grooving process to increase the safety of their highways. The process and results of pavement grooving being performed at several locations are discussed herein. At locations where accident data are available, this technique appears to be very effective in the prevention of wet-weather accidents; however, for most of the locations, accident data are not available.

INTRODUCTION

The commonly used "Slippery When Wet" sign is merely a temporary expedient for a correctable condition. The Special Traffic Safety Committee of the American Association of State Highway Officials has recommended skid-proofing slippery pavements to correct high-accident-rate locations (ref. 1). Several State highway departments have used pavement grooving for this purpose and it has proven very effective. Major reduction of accident rates immediately followed the grooving operations, as shown in this table:

Location	No. of accidents* and time period		Reduction (prorated), percent
	Before grooving	After grooving	
Georgia	66 (1 year)	46 (1 year)	30
Indiana	8 (1 year)	1 (4 months)	62
Minnesota	50 (1 year)	22 (9 months)	41
St. Louis Co.	8 (1 year)	4 (1 year)	50
Texas	120 (1 year)	(Significant reduction for 5 months; then accident rate increased)	

*For Georgia, number of accidents per 100 000 000 vehicle miles; for all locations, total number of accidents on both wet and dry pavement.

The reduction percentages have been calculated to represent the decrease in accidents for a full year of grooving-performance observation, even though information for

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that length of time was not available for all the locations. The lack of effectiveness of the grooving in Texas was probably attributable to the very soft aggregate used in the concrete mixture. (See ref. 2.) Also, it should be noted that a closer groove pattern was used in Texas than was used in most projects.

It would not have been possible to prepare a paper of this scope without the cooperation of several people. Acknowledgment is hereby given to Christensen Diamond Services, Incorporated; Concut, Incorporated; and the several State highway departments that furnished much of the information.

DESCRIPTION OF PAVEMENT GROOVING PROCESS

Pavement grooving is the process of making several shallow cuts of a uniform depth, width, and shape in the surface of the pavement. For the studies contained in this report, nine different patterns of grooves have been used. (See fig. 1.) These patterns are produced by the use of cutting heads made of several diamond-impregnated saw blades (see fig. 2) or by the use of a diamond-impregnated cutting drum molded in the proper shape to cut the desired pattern. While there has been no definite indication of which pattern is the best suited, the one most commonly used on highway pavement grooving projects to date has been pattern "B" (see fig. 1) in the longitudinal direction. The speed of grooving is generally from 5 to 25 feet of forward progress per minute for a width of grooved pavement from 1 to 3 feet, depending on the type of material being cut and the grooving equipment being used.

Grooves placed in the longitudinal direction or parallel with the roadway have proven most effective in increasing directional control of the vehicle. The rubber tire on the automobile penetrates into the grooves forming a mechanical interlock that helps hold the vehicle in alinement with the roadway, much the same as tiny streetcar tracks. (See fig. 3 and ref. 3.) Longitudinal grooving is particularly effective in preventing hydroplaning accidents on curved sections of roadways, bridges, and tangent sections of roadways subject to high cross winds. During an emergency stop, the longitudinal grooves also help hold the vehicle within its own traffic lane, a factor which is extremely important on multiple-lane roadways. (See fig. 4 and ref. 2.)

Coefficient-of-friction measurements made with skid trailers may help identify dangerous pavements of the type described above, but do not necessarily indicate whether the grooves solve the problem. Pavements sometimes show a high value of coefficient of friction at speeds of 30 to 40 mph due to a good microtexture, but this effect may fall off rapidly with increased speed (ref. 4). Also, worn tires on vehicles may react differently than the tires used on the skid testing vehicle. If the skid trailer is equipped with its own watering device near the tire footprint, it may fail to indicate the improved drainage of the pavement that grooving normally provides. (See fig. 5.)

Most skid trailers today measure only braking coefficient of friction and do not indicate cornering traction. On high-speed roadways where stopping is generally not required, it would be advantageous to be able to measure side force. Tests at Wallops Island by NASA indicate that while longitudinal grooving may only increase the braking coefficient of friction a small amount, the cornering traction around a 500-foot-radius curve may be three to four times that for the ungrooved pavement. (See fig. 6.) The longitudinal grooves also provide low-pressure escape channels for the water, which will minimize or prevent dynamic hydroplaning. (See ref. 3 and fig. 7.)

Transverse grooving on highways has been used to a lesser extent than longitudinal grooving, partially because most grooving equipment available today lends itself more readily to placing grooves parallel to the roadway. Transverse grooving is most effective at high-accident-rate locations where vehicles make frequent stops such as intersections, crosswalks, and toll booths. The stopping distance for vehicles on slippery wet pavement at 30 mph has been reduced by 30 to 40 percent by the use of transverse grooves, as shown in the following table of results based on tests by the Louisiana Department of Highways at Baton Rouge:

Pavement	Pattern	Stopping distance, ft		Decrease, percent
		Before grooving	After grooving	
Concrete	"F"	76	52	31
Asphalt	"B"	74	45.5	40

If the pavement has a low coefficient-of-friction value prior to grooving, the value is generally increased significantly by placing transverse grooves. However, if the pavement shows a high coefficient-of-friction value prior to grooving, there is generally little, if any, increase after transverse grooving. Most of the studies reported herein indicate that the coefficient of friction on pavement with transverse grooves, although generally very high immediately following grooving operations, will tend to drop off as the pavement is subjected to traffic. This effect is apparently caused by a wearing down of the sharp edges of the grooves rather than any decrease in the groove size due to surface wear or deterioration. However, it must be remembered that conventional skid trailers may fail to indicate that transverse grooves provide improved drainage and escape channels for the water, particularly for worn or smooth tires.

Transverse grooves have been proven to reduce the hazards of hydroplaning by increasing the number of escape channels for water on both worn and good tires. (See fig. 7 and ref. 5.) They also greatly facilitate drainage by providing deeper channels for the water to run from the roadway, and as a result a much harder rainfall is required to cause hydroplaning problems. (See fig. 5.) The best pattern for transverse grooves has not yet been determined. Tests at Wallops Island by NASA indicate that a 1 inch by 1/4 inch by 1/4 inch groove pattern gives the highest coefficient of friction of those patterns tested, but this pattern has not been tried on highways.

PROBLEMS ASSOCIATED WITH PAVEMENT GROOVING

There has been much concern about the effect that pavement grooving will have on the durability of the various pavement types in the various climates. The pavement grooving projects summarized in this report consist of various types and climatic conditions. One of the most frequent questions asked by highway engineers from the Northern States is "What will water freezing in the grooves do to the concrete pavement?" Laboratory tests have been made on 1/8-inch-wide grooves to a depth of $1\frac{3}{4}$ inches in concrete pavement, and even at this depth there was no deterioration resulting from a wedge action of ice within the grooves (ref. 6). An examination of grooved pavement in Minnesota, after it had been subjected to one winter of freeze-thaw cycles and studded tires, indicated no deterioration from the freeze-thaw cycles, but did show some wear in the wheel tracks, probably resulting from the use of studded tires. (See fig. 8.)

Much concern has been expressed about grooves in asphalt pavement losing their effectiveness by the flowing back together of this flexible material, particularly during hot weather. This result has been observed under certain conditions when a fairly new asphalt pavement or a pavement with a low aggregate content has been grooved. This condition seems predominant at locations subjected to power steering of the vehicle while it is stopped. Older asphalt pavement with high aggregate content seems to hold up very well. The pavement in St. Louis, Missouri, has been subjected to two summers and one winter of intersection traffic and looks almost as good as it did when the grooves were placed there 18 months ago. (See fig. 9.)

It appears that grooving may lose its effectiveness in 6 months when placed in concrete pavements containing extremely soft, fine and coarse aggregate. However, it must be remembered that in the one location where this loss in effectiveness was very obvious, pattern "D" was used; that pattern calls for a much closer spacing of the 1/8-inch-wide grooves than any other pattern. It is not known whether pattern "A" or "B" would hold up for a longer time in very soft material.

There have been some complaints that longitudinal grooving affects the steering of certain automobiles and motorcycles, but no severe problems have been encountered. However, when grooving pavement longitudinally, care should be taken to prevent any irregularities or "wiggles" in the pavement grooving pattern. Upon observing some early attempts of pavement grooving, it is noted that frequent variations in alinement can be found in the longitudinal grooves. (See fig. 10.) These variations may be attributed to manual steering of the grooving equipment and the tendency for the equipment to slip downhill when working on a superelevation. Recent improvements in grooving equipment assure an alined grooving pattern parallel to the roadway. (See fig. 11.)

Another problem that has been noted, particularly during grooving operations, is the disposal of the water and the fine material cut from the grooves. Approximately 1 gallon of water per square foot of grooving is required to cool the cutting head. The resulting slurry can make the adjacent pavement very slippery, particularly if grooving begins on the high side of a multiple-lane roadway. (See fig. 12.) To avoid this situation and to facilitate cleaning up of the grooved area, a recent improvement in grooving equipment is a slurry pickup device. When a device of this type is used, the pavement is left free of dust or slipperiness and washed clean. (See fig. 13.)

SUMMARY OF PAVEMENT GROOVING PROJECTS IN SEVERAL STATES

The following results represent most of the work performed in the United States, with the exception of the State of California, on highway pavement grooving. The work in California has been reported in reference 7.

For simplification of reporting, the groove patterns have been referred to by letter and have been illustrated in figure 2. The dates given indicate when the work was performed.

Grooving in Concrete Pavement

Longitudinal grooving studies in concrete.- Longitudinal pavement grooving is seen to be very effective in eliminating wet-weather accidents where before and after records are available, even though the coefficient of friction is generally not significantly increased by this process. Longitudinal grooving in concrete pavement seems to hold up very well except in pavement where extremely soft, fine and coarse aggregate is used. A brief summary of projects at various locations follows:

COLORADO

LOCATION:	I-25 southbound on Santa Fe Overpass in Denver	
DATE:	March 1968	
PATTERN OF GROOVES:	"B"	
PURPOSE:	To prevent hydroplaning accidents	
DIMENSIONS:	12 feet wide; 325 feet long	
COEFFICIENT OF FRICTION:	Measurements were made with British Portable Tester.	
	Parallel to roadway	Transverse to roadway
Before grooving:	60	60
After grooving:	60	85
8 months later:	60	80
ACCIDENT DATA:	All accidents reported were on wet pavement.	
	Total no.	No. of injuries
Before (4/1/67 to 10/1/67):	15	4
After (3/15/68 to 11/6/68):	0	0

COMMENTS: A 325-foot-long section of asphalt pavement was also grooved adjacent to this location. The accident data before grooving are for the total area (see data under studies on asphalt pavement).

GEORGIA

LOCATION:	At a curve and tangent on I-20 between Decatur and Atlanta
DATE:	May 1966
PATTERN OF GROOVES:	"G" and another pattern similar to "G" but having grooves that are 3/16 inch wide at top with a 30^{o} taper to a 1/8-inch width at bottom
PURPOSE:	To prevent crossing-the-median accidents
DIMENSIONS:	12 feet wide; 9000 feet long (passing lane)
COEFFICIENT OF FRICTION:	Measurements made with the Pennsylvania State University Drag Tester showed very little difference in skid resistance before and after grooving.
ACCIDENT DATA:	All figures are based on 100 000 000 vehicle miles.

	Total no.	Injury rate	Fatality rate
Before (6 months):	66.0	70.8	14.1
After (6 months):	46.4	9.9	0

COMMENTS: Property damage was reduced 80 percent from the level before grooving. Grooves are holding up very well. Pavement consists of a good granite aggregate. The rectangular grooves of pattern "G" chip off at the edges to form shapes similar to the tapered grooves.

IDAHO

LOCATION:	Twin bridges across the Snake River in Pocatello
DATE:	August 1968
PATTERN OF GROOVES:	"G"
PURPOSE:	To prevent hydroplaning accidents
DIMENSIONS:	Two wheel paths, each 3 feet wide and 800 feet long (on each bridge)
COEFFICIENT OF FRICTION:	The values 32 and 36 were obtained from measurements made with the Bureau of Public Roads skid trailer before grooving, no measurements were made after grooving.

ACCIDENT DATA:

January 1968 to August 1968: 12 total accidents
3 injuries
1 fatality

After-grooving data not yet available

COMMENTS: The grooves appear to help hold the vehicles in line with the roadway.

ILLINOIS

LOCATION:	At intersection of State Route 48 on U.S. 66 south of Springfield
DATE:	August 1966
PATTERN OF GROOVES:	"I"
PURPOSE:	To improve skid resistance
DIMENSIONS:	12 feet wide; 281 feet long (traffic lane)
COEFFICIENT OF FRICTION:	Before grooving: 0.47 After grooving: .42
COMMENTS:	Grooves are holding up very well. Accident data are not available. Grooving lowered the friction factor, but the method of testing was not given.

MINNESOTA – PROJECT #1

LOCATION:	Curve on I-494 at Concord Street in South St. Paul
DATE:	October 1967
PATTERN OF GROOVES:	"B"
PURPOSE:	To prevent wet-weather accidents
DIMENSIONS:	24 feet wide; approximately 1900 feet long; total area of 5000 square yards

ACCIDENT DATA:	Total no.	No. of injuries	No. of fatalities
Before (1/1/67 to 12/31/67):	50	18	5
After (1/1/68 to 9/30/68):	22	5	0

COMMENTS: Grooves seem to be holding up well at this location. They seem to help hold the vehicles in line with the pavement.

MINNESOTA – PROJECT #2

LOCATION:	Curve on I-94 in St. Paul
DATE:	October 1967
PATTERN OF GROOVES:	"B"
PURPOSE:	As a precaution before opening to traffic
DIMENSIONS:	24 feet wide; total area of 3200 square yards
COMMENTS:	This location is a tight curve where the speed limit reduces from 60 to 45 mph. Pavement grooving was done prior to opening the road to traffic in order to prevent spin-out of the vehicles during wet weather.

MINNESOTA – PROJECT #3

LOCATION:	Curve on I-35W south of Minneapolis
DATE:	October 1967
PATTERN OF GROOVES:	"B"
PURPOSE:	To prevent wet-weather accidents
DIMENSIONS:	24 feet wide; total area of 20 000 square yards
COEFFICIENT OF FRICTION:	Portable skid tester indicated no improvements in coefficient of friction after grooving.
COMMENTS:	There was a definite reduction in accident rate at this location after grooving; however, not enough data are available to attribute reduction completely to grooving. There is evidence of wear in the wheel paths, probably caused by the use of studded tires and an average daily traffic of approximately 50 000 vehicles.

MINNESOTA – PROJECT #4

LOCATION:	Curve on I-90 near Austin
DATE:	October 1968
PATTERN OF GROOVES:	Similar to "I" with large grooves on 1-inch centers and only three small ridges between the grooves
PURPOSE:	To prevent wet-weather accidents
DIMENSIONS:	24 feet wide; total area of 6488 square yards
COMMENTS:	There were numerous wet-weather accidents at this location prior to grooving. It is too early to tell the results after grooving.

OHIO – PROJECT #1

LOCATION:	At a curve and tangent on I-71 in Morrow County
DATE:	Summer of 1966
PATTERN OF GROOVES:	"B"
PURPOSE:	To eliminate slippery pavement conditions in traffic lanes
DIMENSIONS:	9 feet wide; 2 miles long
COMMENTS:	The grooving has substantially reduced the number of accidents, but exact data are not available. The grooving has not adversely affected pavement durability, but some wear is noticed in wheel path areas. Some automobile owners have complained about the poor handling of their vehicles over this section of pavement.

OHIO – PROJECT #2

LOCATION:	Curve on I-270 exit ramp in Columbus
DATE:	Summer of 1966
PATTERN OF GROOVES:	"B"
PURPOSE:	To eliminate slippery pavement conditions
DIMENSIONS:	12 feet wide; approximately 1500 feet long
COMMENTS:	The grooving has proven very effective, but accident data are not available. There are no durability problems with the pavement, but some wear in the wheel paths is indicated.

OHIO – PROJECT #3

LOCATION:	Ramp off I-75 at Lima
DATE:	Summer of 1966
PATTERN OF GROOVES:	"B"
PURPOSE:	To eliminate slippery conditions on ramp
DIMENSIONS:	10 feet wide; 500 feet long
COMMENTS:	The grooving has proven very effective, but accident data are not available. There are no durability problems with the pavement, but some wear in the wheel paths is indicated.

OHIO – PROJECT #4

LOCATION:	Curve and tangent near Lima on I-75
DATE:	May 1968
PATTERN OF GROOVES:	"B"
PURPOSE:	To eliminate slippery pavement conditions in traffic lane
DIMENSIONS:	Two wheel paths, each 3 feet wide and 3 miles long
COMMENTS:	It is too early to make any accurate judgment on effectiveness.

PENNSYLVANIA

LOCATION: Curve westbound on Hershey Road near Harrisburg

DATE: April 1967

PATTERN OF GROOVES: "B"

PURPOSE: To evaluate the feasibility of grooving pavement

DIMENSIONS: Two wheel paths, each 3 feet wide and 739 feet long

COEFFICIENT OF FRICTION: Skid numbers were obtained in accordance with ASTM E-274.

Before grooving: 27

After grooving: 30

12 months later: 28

COMMENTS: The Pennsylvania Department of Highways reports that 1/8-inch grooves were too shallow and are now practically nonexistent in some areas. No accident data were reported.

ST. LOUIS COUNTY ROAD DEPARTMENT

LOCATION: On ramp to Ashby Road at Midland Boulevard in St. Louis, Missouri

DATE: April 1967

PATTERN OF GROOVES: "C"

PURPOSE: To realine vehicle after turning on to a ramp

DIMENSIONS: 10 feet wide; 60 feet long

COMMENTS: This was a very polished concrete pavement. The grooves are holding up okay after 18 months. (For accident data at this intersection, see studies on asphalt pavement with transverse grooving.)

TEXAS

LOCATION: Curve and tangent on I-35 in San Antonio

DATE: August 1962

PATTERN OF GROOVES: "D"

PURPOSE: To prevent wet-weather accidents

DIMENSIONS: 48 feet wide; 1.2 miles long

COEFFICIENT OF FRICTION: Tests were made on wet pavement at 30 mph.

	Stopping distance	Coefficient of friction
Before grooving (measured by stopping car):	94 feet	0.32
After grooving (measured by stopping car):	72 feet	.42
6 months later (measured by skid trailer):	------	.28

ACCIDENT DATA:

Before (1/1/61 to 1/1/62): 120 total (60 wet weather)

After: Significant reduction for 5 months; then accident rate increased

COMMENTS: The loss in effectiveness was probably attributable to the very soft, fine and coarse aggregate. Sections of the grooved area were overlaid with type "D" asphaltic concrete in August 1963. In April 1964 the remaining grooved area was overlaid.

UTAH

LOCATION: On foothill overpass at I-80 in Salt Lake City

DATE: January 1967

PATTERN OF GROOVES: "G"

PURPOSE: To improve drainage of bridge deck

DIMENSIONS: 12 feet wide; 99 feet long

COEFFICIENT OF FRICTION: Measurements were made with Bureau of Public Roads skid trailer.

Before grooving (taken on adjacent deck): 0.30

7 months later: .39

COMMENTS: Accident data are not available. The Utah State Department of Highways reports that drainage is improved but grooves are wearing off.

WYOMING – PROJECT #1

LOCATION: Entrances to tunnels at Green River

DATE: April 1968

PATTERN OF GROOVES: "B"

PURPOSE: To prevent wet- and icy-pavement accidents

DIMENSIONS:
- Westbound entrance: 24 feet wide; 300 feet long
- Eastbound entrance: 24 feet wide; 400 feet long

ACCIDENT DATA:
- Before (Nov. 1966 to May 1968): 3 icy; 1 wet
- After (May 1968 to Nov. 1968): 0 icy; 0 wet

COMMENTS: There have been no icy conditions since grooving, but the Wyoming Highway Department believes that this grooving should be an answer to the problem of tracking moisture into the tunnels, which causes the so-called "Black Ice" condition. The pavement is holding up very good.

WYOMING – PROJECT #2

LOCATION: Archer overhead bridge 3 miles east of Cheyenne

DATE: June 1967

PATTERN OF GROOVES: "C"

PURPOSE: To reduce accidents caused by rain and frost on bridge deck

DIMENSIONS: 28 feet wide; 380 feet long

ACCIDENT DATA: Most accidents occurred on frost or wet pavement.
- Before (5 years to June 1967): 20 total
- After (June 1967 to Nov. 1968): 0 total

COMMENTS: Grooves are holding up very well.

WYOMING – PROJECT #3

LOCATION:	I-25 on Central Avenue interchange bridge in Cheyenne
DATE:	June 1967
PATTERN OF GROOVES:	"C"
PURPOSE:	To reduce minor fender-bender accidents during wet weather
DIMENSIONS:	28 feet wide; 300 feet long
COMMENTS:	No specific accident data are available, but the frequency of minor accidents has been reduced sharply. The grooved pavement is holding up very good. The approaches to the structure will be grooved in the near future.

Transverse grooving studies in concrete.- Transverse grooves in concrete highways have been used primarily at intersections. They decrease the stopping distance on slippery pavement by improving drainage and by increasing the coefficient of friction. There is generally a decrease in coefficient of friction of the grooved pavement after a few months of traffic; however, the drainage improvement appears long lasting. A brief summary of several projects follows:

FLORIDA (ST. AUGUSTINE) – PROJECT #1

LOCATION: Intersection of King Street on State Route 5 in St. Augustine

DATE: August 1967

PATTERN OF GROOVES: "E"

PURPOSE: To reduce stopping distance on wet pavement

DIMENSIONS:

48 feet (four lanes) wide; 7-percent textured area 600 feet long
50-percent textured area 300 feet long
100-percent textured area 200 feet long

COEFFICIENT OF FRICTION: Measurements were made with Florida skid trailer with ASTM Test Tires at 40 mph.

	December 5, 1967		August 6, 1968	
	Traffic lane	Passing lane	Traffic lane	Passing lane
Control:	42	45	43	46
7-percent textured:	40	45	43	50
50-percent textured:	46	44	45	50
100-percent textured:	43	51	50	52

COMMENTS: The 7-percent textured area consists of a 3-foot textured area every 40 feet. The 50-percent textured area consists of a 3-foot textured area alternating with a 3-foot untreated area. No accident data are available. This pattern was not effective in increasing tire noise as a warning. (See fig. 14.)

FLORIDA (ST. AUGUSTINE) – PROJECT #2

LOCATION: On southbound lanes of State Route 5 in St. Augustine

DATE: August 1967

PATTERN OF GROOVES: "E"

PURPOSE: To reduce stopping distance on wet pavement

DIMENSIONS: Two lanes wide; 650 feet long

COEFFICIENT OF FRICTION: Measurements were made with Florida skid trailer.

	December 5, 1967		August 6, 1968	
	Traffic lane	Passing lane	Traffic lane	Passing lane
Control:	40	41	42	48
Textured:	43	43	52	54

COMMENTS: No accident information is available. The increase in coefficient of friction between December 1967 and August 1968 was not explained.

FLORIDA (ST. AUGUSTINE) – PROJECT #3

LOCATION: Approach to sharp curve on State Route 5 in St. Augustine

DATE: August 1967

PATTERN OF GROOVES: "I"

PURPOSE: To evaluate grooving

DIMENSIONS: Two lanes wide; 450 feet long

COEFFICIENT OF FRICTION: Measurements were made with Florida skid trailer.

	December 5, 1967		August 6, 1968	
	Traffic lane	Passing lane	Traffic lane	Passing lane
Control:	40	41	42	48
50-percent textured:	42	41	44	49

COMMENTS: The 50-percent textured area consists of a 3-foot grooved area alternating with a 3-foot ungrooved area. No accident data are available.

FLORIDA (MIAMI) – PROJECT #4

LOCATION: Approach to intersection on State Route 5 in Miami

DATE: August 1967

PATTERN OF GROOVES: "E"

PURPOSE: To reduce stopping distance on wet pavement

DIMENSIONS: Two lanes wide; 300 feet long

COEFFICIENT OF FRICTION: Measurements were made with Florida skid trailer.

	January 10, 1968		August 14, 1968	
	Traffic lane	Passing lane	Traffic lane	Passing lane
Control:	43	49	45	48
Textured:	47	50	44	50

COMMENTS: No accident data are available.

ILLINOIS

LOCATION: At intersection of State Route 48 on U.S. 66 south of Springfield

DATE: August 1966

PATTERN OF GROOVES: "I"

PURPOSE: To improve skid resistance at high-accident-rate location

DIMENSIONS: 12 feet wide; 240 feet long (passing lane)

COEFFICIENT OF FRICTION: Test method is not given.

Before grooving (in adjacent lane): 0.47

After grooving: .48

COMMENTS: Grooves are holding up very well. Accident data are not available.

LOUISIANA

LOCATION:	Intersection in Baton Rouge
DATE:	October 1966
PATTERN OF GROOVES:	"F" and "G"
PURPOSE:	To decrease stopping distance
COEFFICIENT OF FRICTION:	Measurements were made by stopping a car at 30 mph on wet pavement.
	Before grooving: 76 feet
	After grooving: 52 feet
COMMENTS:	Accident data are not available.

TEXAS

LOCATION:	I-35 in downtown San Antonio
DATE:	July 1966
PATTERN OF GROOVES:	"F"
PURPOSE:	To test effect of grooving on skid resistance
DIMENSIONS:	48 feet wide; 100 feet long
COEFFICIENT OF FRICTION:	Measurements were made with skid trailer at 40 mph.
	Before grooving: 0.25
	After grooving: .58
	45 days later: .38
	10 months later: .30
COMMENTS:	Accident data are not available. The Texas Highway Department believes the soft aggregate used in the pavement caused the loss of skid resistance after grooving.

UTAH

LOCATION:	On foothill overpass at I-80 in Salt Lake City
DATE:	January 1967
PATTERN OF GROOVES:	"F" and "I"
PURPOSE:	To improve drainage
DIMENSIONS:	12 feet wide; 181 feet long
COEFFICIENT OF FRICTION:	Measurements were made with Bureau of Public Roads skid trailer.
	Before grooving (adjacent structures): 0.33 and 0.29
	After grooving (pattern "F"): .38
	After grooving (pattern "I"): .41
COMMENTS:	No accident data are reported. Drainage of water is improved, but grooves are wearing off.

Grooving In Asphalt Pavement

Longitudinal grooving studies in asphalt.- The initial effectiveness of grooving asphalt pavement longitudinally is the same as for concrete pavement, but the durability is questionable if the pavement is highly flexible or has a low aggregate content. If the pavement is dense and has a high aggregate content, longitudinal grooves hold up well in asphalt pavement. A brief summary of a few projects follows:

COLORADO

LOCATION: I-25 on Santa Fe Overpass in Denver

DATE: March 1968

PATTERN OF GROOVES: "B"

PURPOSE: To prevent hydroplaning accidents

DIMENSIONS: 12 feet wide; 325 feet long

COEFFICIENT OF FRICTION: Measurements were made with British Portable Tester.

	Parallel to roadway	Transverse to roadway
Before grooving:	70	70
After grooving:	70	82
8 months later:	68	68

ACCIDENT DATA: All accidents reported were on wet pavement.

	Total no.	No. of injuries
Before (4/1/67 to 10/1/67):	15	4
After (3/15/68 to 11/6/68):	4	0

COMMENTS: A 325-foot-long section of concrete pavement was also grooved adjacent to this location. The accident data before grooving are for the total area (see data under studies on concrete pavement). The accidents occurred in late summer; the grooves were kneaded over by then. This was a thin asphalt overlay over an existing concrete pavement.

IDAHO

LOCATION: Pocatello

DATE: August 1968

PATTERN OF GROOVES: "I"

PURPOSE: To eliminate slipperiness caused by bleeding asphalt

DIMENSIONS: 9 feet wide; $1\frac{1}{4}$ miles long

COEFFICIENT OF FRICTION: Measurements were made with Bureau of Public Roads skid trailer

Before grooving: 36

After grooving: Not measured

COMMENTS: One fatality was reported for June 1968, but no other accident data were reported. Grooving appears to be standing up well, but more will be known after hot weather next summer.

PENNSYLVANIA

LOCATION: Tangent on Hershey Road near Harrisburg

DATE: April 1967

PATTERN OF GROOVES: "B"

PURPOSE: To evaluate the feasibility of grooving pavement

DIMENSIONS: Two wheel paths, each 3 feet wide and 285 feet long

COEFFICIENT OF FRICTION: Skid numbers were obtained in accordance with ASTM E-274.

Before grooving: Skid number 31

After grooving: Skid number 42

12 months later: Skid number 39

COMMENTS: The Pennsylvania Department of Highways reports that 1/8-inch grooves were too shallow and are practically nonexistent in some areas. No accident data were reported.

WYOMING

LOCATION:	On a slight curve 1 mile east of Cheyenne
DATE:	June 1967
PATTERN OF GROOVES:	"A"
PURPOSE:	To evaluate grooving asphalt pavement
DIMENSIONS:	4 feet wide; 100 feet long
COMMENTS:	Pavement was constructed in 1958. The grooving is holding up very well after about 18 months of service.

Transverse grooving studies in asphalt.- Significant increases in coefficient of friction have been realized by transversely grooving slippery asphalt pavement. If the pavement is dense and has a high aggregate content, the grooves hold up well. Rear-end-collision skidding accidents have been substantially reduced by grooving asphalt pavement transversely at intersections. While some projects report a decrease in coefficient of friction after several months, the drainage is still improved. A brief summary of several projects follows:

FLORIDA (MIAMI) – PROJECT #1

LOCATION: Approach to intersection on State Route 5 near Miami

DATE: July 1967

PATTERN OF GROOVES: "E"

PURPOSE: To improve skid resistance

DIMENSIONS: Two lanes wide; 300 feet long

COEFFICIENT OF FRICTION: Measurements were made with Florida skid trailer.

	January 10, 1968		August 14, 1968	
	Traffic lane	Passing lane	Traffic lane	Passing lane
Control:	32	37	28	34
Textured:	40	46	35	37

COMMENTS: Accident data are not available.

FLORIDA (MIAMI) – PROJECT #2

LOCATION: Intersection on N.W. 27th Avenue at 119th Street in Miami

DATE: June 1967

PATTERN OF GROOVES: "E"

PURPOSE: To improve skid resistance

DIMENSIONS: Two lanes wide; 300 feet long

COEFFICIENT OF FRICTION: Measurements were made with Florida skid trailer.

	January 10, 1968		August 14, 1968	
	Traffic lane	Passing lane	Traffic lane	Passing lane
Control:	30	30	31	31
Textured:	48	45	37	37

COMMENTS: Accident data are not available.

FLORIDA (MIAMI) – PROJECT #3

LOCATION: Intersection on Biscayne Boulevard at N.E. 96th Street in Miami

DATE: June 1967

PATTERN OF GROOVES: "E"

PURPOSE: To improve skid resistance

DIMENSIONS: Two lanes wide; 1300 feet long

COEFFICIENT OF FRICTION: Measurements were made with Florida skid trailer.

	January 10, 1968		August 14, 1968	
	Traffic lane	Passing lane	Traffic lane	Passing lane
Northbound roadway				
Control:	30	33	28	34
Textured:	46	43	38	40
Southbound roadway				
Control:	30	32	28	34
Textured:	42	45	38	40

COMMENTS: Accident data are not available.

ILLINOIS

LOCATION: Intersection approach on U.S. 66, 30 miles south of Springfield

DATE: August 1966

PATTERN OF GROOVES: "I"

PURPOSE: To improve skid resistance

DIMENSIONS: Two lanes wide; 200 feet long

COEFFICIENT OF FRICTION:

	Traffic lane	Passing lane
Before grooving:	0.31	----
After grooving:	.34	0.35

COMMENTS: Accident data are not available. In less than 1 year the grooves were closed.

INDIANA

LOCATION:	State Route 100 approaching intersection with State Route 67 in Indianapolis
DATE:	April 1968
PATTERN OF GROOVES:	"B"
PURPOSE:	To reduce skidding accidents
DIMENSIONS:	Three lanes wide; 310 feet long
ACCIDENT DATA:	
Before (4/24/67 to 4/24/68):	8 total (3 on wet pavement)
After (4/24/68 to 8/23/68):	1 total (0 on wet pavement)
COMMENTS:	Some closing of the grooves is reported.

LOUISIANA

LOCATION:	At traffic light on Flores Road in Baton Rouge
DATE:	September 1967
PATTERN OF GROOVES:	"B"
PURPOSE:	To prevent skidding accidents
DIMENSIONS:	One lane wide; 120 feet long
COEFFICIENT OF FRICTION:	Tests were made on wet pavement at 30 mph.

	Stopping distance	Skid number
Before grooving (measured by stopping car):	74 feet	--
After grooving (measured by stopping car):	45.5 feet	--
12 months later (measured by ASTM skid trailer):	--------	40

COMMENTS:	No accident data are reported. Grooves are holding up very well after 1 year. Skid resistance dropped; however, a different test method was used.

ST. LOUIS COUNTY ROAD DEPARTMENT

LOCATION:	On Midland Boulevard at Ashby Road in St. Louis, Missouri
DATE:	April 1967
PATTERN OF GROOVES:	"C"
PURPOSE:	To reduce skidding accidents
DIMENSIONS:	Two 10-foot-wide lanes; 90 feet long
ACCIDENT DATA:	Year of 1966: 8 rear end Year of 1967: 3 rear end; 1 left turn
COMMENTS:	Shortly after grooving, the County Road Department removed a stop sign at this location. Normally this would have increased major rear-end accidents, but actually they decreased 62.5 percent. Minor accidents are not reported or filed.

Grooving Projects Underway or Recently Completed

Louisiana.- In August 1968 pattern "F" transverse grooves were placed at an intersection in Baton Rouge. For additional information, contact Verdi Adam of the Louisiana Department of Highways in Baton Rouge.

Minnesota.- During 1968 longitudinal grooves were placed at five locations on rural routes in Minnesota. These projects totaled 17 133 square yards of grooved pavement. The sections were 24 feet wide and varied in length from 1333 to 6400 feet. All except one location had a history of wet-weather accidents. One project was grooved before the pavement was open to traffic in an effort to prevent accidents. For additional information, contact C. K. Preus of the Minnesota Department of Highways in St. Paul.

Nebraska.- Pattern "B" grooves are currently being placed in concrete pavement on I-80 westbound near 42nd Street in Omaha. Three lanes are being longitudinally grooved for a distance of approximately 1 mile. For additional information, contact Robert Meyer, Traffic Engineer, Department of Roads, Lincoln, Nebraska.

New York.- In June 1968 longitudinal grooves were placed on Major Deegan Boulevard and Long Island Expressway in New York City. The groove pattern was the same as pattern "I" except that large grooves were 1/4 inch deep. The purpose of grooving was to improve directional control and decrease occurrences of hydroplaning. For additional information, contact Bob Murphy, City of New York, or R. Winton, Parks Department.

In June 1968 longitudinal pattern "B" grooves were placed on the Southern State Parkway at various entrance and exit ramps. The purpose of grooving was to increase traction on ramps to reduce skidding. For more information, contact the Jones Beach State Parkway Authority.

Wisconsin.- In October 1968 longitudinal pattern "B" grooves were placed on a 1200-foot curve on the North-South Freeway at Howard Avenue in Milwaukee. The grooving was done to prevent cars from skidding into the guardrail during wet weather. For more information, contact James E. Meier, District Engineer of Wisconsin State Highway Department at Milwaukee.

RECOMMENDATIONS

According to present indications, test equipment other than skid trailers must be used in order to give a proper evaluation of the effectiveness of pavement grooving. Stopping and cornering tests with a vehicle under artificially wet conditions would probably provide the most accurate information, but these tests are very impractical for use on highways under traffic. There is a need for a friction measuring device that would not only indicate braking coefficient of friction but would also indicate hydroplaning conditions, vehicle cornering ability, pavement drainage, and the reaction to all these factors when contact is made with the pavement by worn or smooth tires.

If a test method could be devised that would indicate all or most factors related to vehicle performance before and after grooving, then it would be easier to determine which pattern of grooves is proper under the various conditions. This test method would indicate what pattern of grooves should be used under various conditions and to what limits the pavement grooving should extend.

Until a complete test procedure is available, accidents should be tabulated and analyzed prior to selecting a location for grooving. These analyzed results should be compared with results for a comparable period of time and traffic after grooving. While this paper indicates that grooves have failed to improve the coefficient of friction under certain conditions, there has been no report that grooving has failed to decrease the number of wet-weather accidents for a period of at least 5 months and in many cases much longer after grooving. Processes used for tabulating and analyzing accidents in most states are currently being updated.

While in most cases the initial effectiveness of pavement grooving is rather consistent, the life of this effectiveness is varied. Thus care must be taken in selecting pavement grooving as a corrective measure to wet-weather accidents. If new, very flexible asphalt pavement with a low aggregate content makes up the existing surface, the grooves are likely to close up after a period of time. If a very soft, fine and coarse aggregate is used in concrete pavement, the top surface may wear away causing a loss of effectiveness of the grooves. To date there has been no report of regrooving pavement after it appears to lose its effectiveness. More study is required to determine which pattern should be used in marginal pavements. Also, it should be determined if the pavement is actually becoming unsafe just because its coefficient of friction decreases from the value realized immediately following the grooving operations.

To date there has been no report of pavement deterioration as a result of grooving. In the one location where an overlay was placed on the grooved area, the grooves provided a good surface for bonding the overlay.

SAFETY FEATURES

Longitudinal grooves will prevent many accidents during wet weather and some accidents during dry weather by providing the pavement with the following safety features:

(1) Directional stability for cornering through mechanical interlock of the rubber tire within the grooves

(2) Low-pressure escape routes for the water beneath the tire to prevent hydroplaning

(3) Directional control and resistance to cross wind through mechanical interlock of the rubber tire within the grooves

(4) Directional stability during locked-wheel skidding through mechanical interlock of the rubber tire within the grooves

(5) Frost or thin-ice interruptions that facilitate the dispersion of these materials from the tire track.

A typical section of pavement improved by longitudinal grooving is illustrated in figure 15. Curves, bridges, ramps, and open road subjected to frequent cross winds all benefit from longitudinal grooving.

Transverse grooves in pavement will reduce skidding accidents during wet weather by providing the pavement with the following safety features:

(1) A desirable coefficient of friction

(2) Reduction of 30 to 40 percent in the stopping distance of vehicles during wet weather at 30 mph on slippery pavements

(3) Facilitation of drainage to allow faster drying of the pavement

(4) Removal of oil, molten rubber, and so forth from the tire footprint to restore normal tire-pavement contact during a locked-wheel skid

(5) Frost or thin-ice interruptions that facilitate the dispersion of these materials from the tire track.

Transverse grooves are usually most beneficial for reducing stopping distance at intersections, crosswalks, and toll booths. Some projects have used interrupted patterns, as illustrated in figure 14.

Sometimes both longitudinal and transverse grooves are used at the same location. (See fig. 16.) Transverse grooves are used to help vehicles stop, while longitudinal grooves are used to assist the vehicle in directional control.

Pavement grooving in either direction (longitudinal or transverse) reduces the hazards of hydroplaning. The grooves provide low-pressure escape routes for the water from the tire footprint area. A much greater water depth is required for hydroplaning to occur on grooved pavement than on smooth or fine textured pavement. A combination of speed and water depth sufficient to cause dynamic hydroplaning on properly grooved pavement is unlikely to occur on modern highways with present-day automobiles.

CONCLUDING REMARKS

In an effort to combat the increasing rate of automobile accidents, several State highway departments have been evaluating the pavement grooving process. At locations where accident data are available, this technique appears to be very effective in the prevention of wet-weather accidents. Curves, bridges, ramps, and open road subjected to frequent cross winds all benefit from longitudinal grooving. Transverse grooves are usually most beneficial for reducing stopping distance at intersections, crosswalks, and toll booths.

REFERENCES

1. Anon.: Highway Design and Operational Practices Related to Highway Safety. Amer. Ass. State Highway Officials, Feb. 1967, p. 62.

2. Nixon, John F.: Report on Concrete Pavement Grooving in Texas. Dep. Res. Rep. No. SS 8.0, Texas Highway Dep., Aug. 1968, pp. 10-11.

3. Horne, Walter B.: Skidding Accidents on Runways and Highways Can Be Reduced. Astronaut. Aeronaut., vol. 5, no. 8, Aug. 1967, pp. 48-55.

4. Sabey, Barbara E.: Road Surface Texture and the Change in Skidding Resistance With Speed. RRL Rep. No. 20, Brit. Min. Transp., 1966, p. 7.

5. Anon.: Hazards of Tire Hydroplaning – A Sequel. NASA Langley Research Center Film Serial No. L-957, 1968.

6. Perenchio, William: Effect of Surface Grinding and Joint Sawing on the Durability of Paving Concrete. J. PCA Res. Develop. Lab., vol. 6, no. 1, Jan. 1964, pp. 16-19.

7. Farnsworth, Eugene E.: Pavement Grooving on Highways. Pavement Grooving and Traction Studies, NASA SP-5073, 1969. (Paper No. 25 herein.)

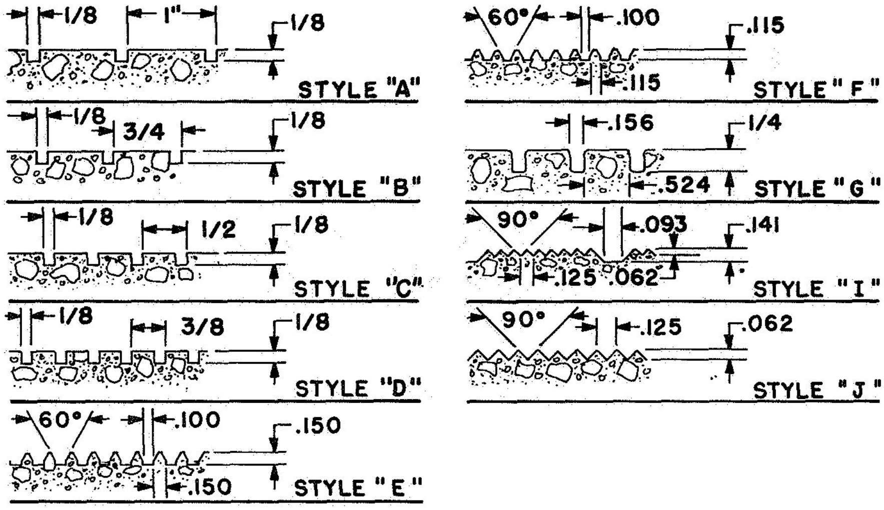

Figure 1.- Groove patterns.

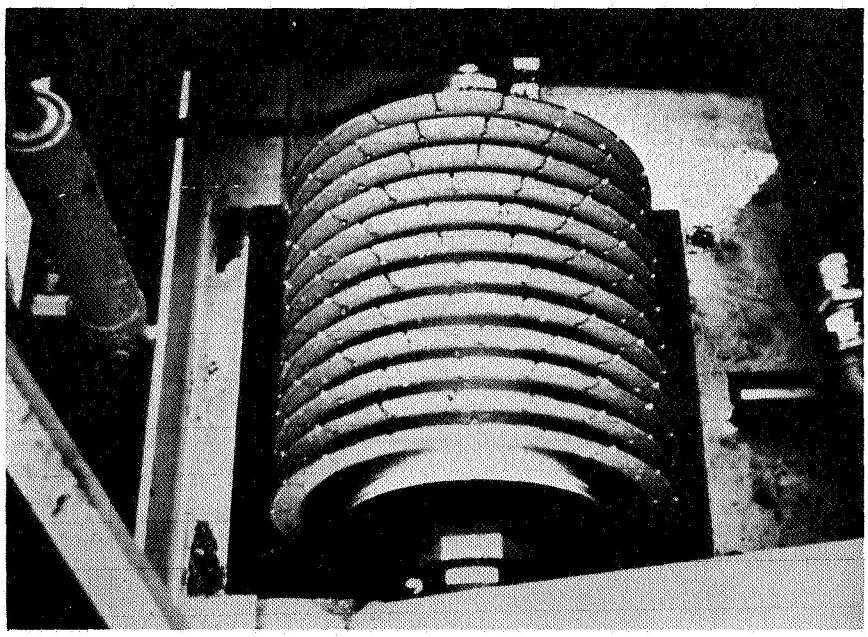

Figure 2.- Cutting head.

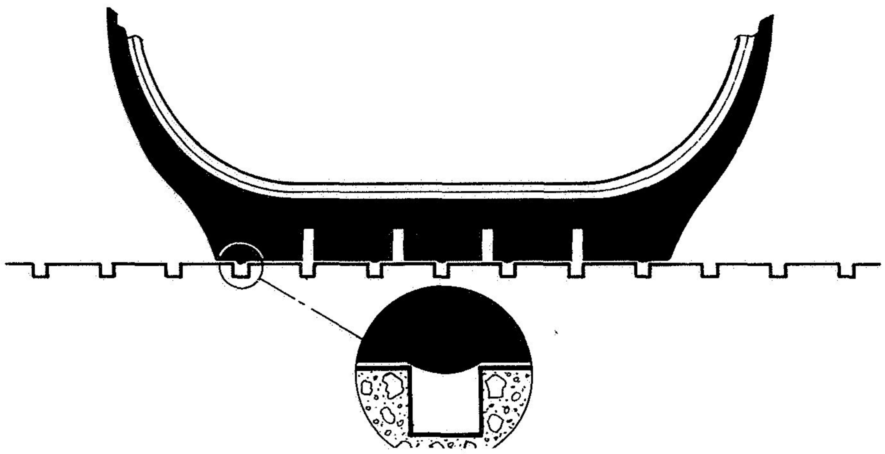

Figure 3.- Profile of a tire on longitudinal groove pattern.

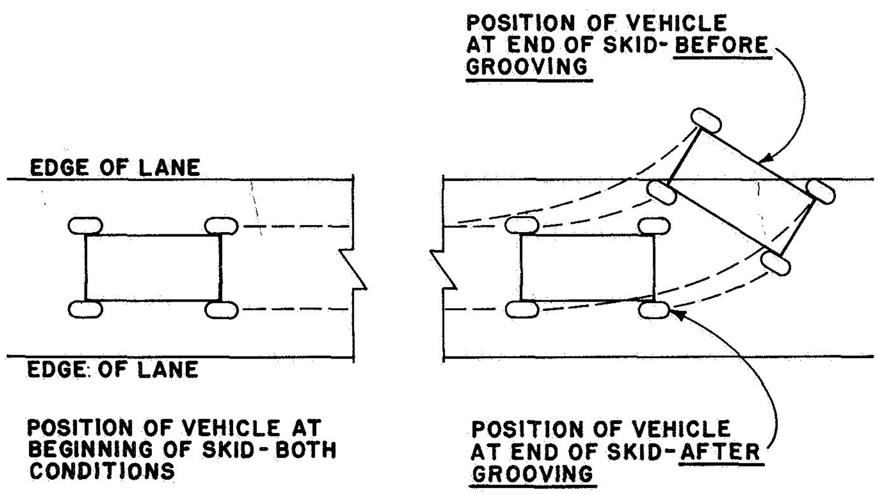

Figure 4.- Skid pattern before and after grooving.

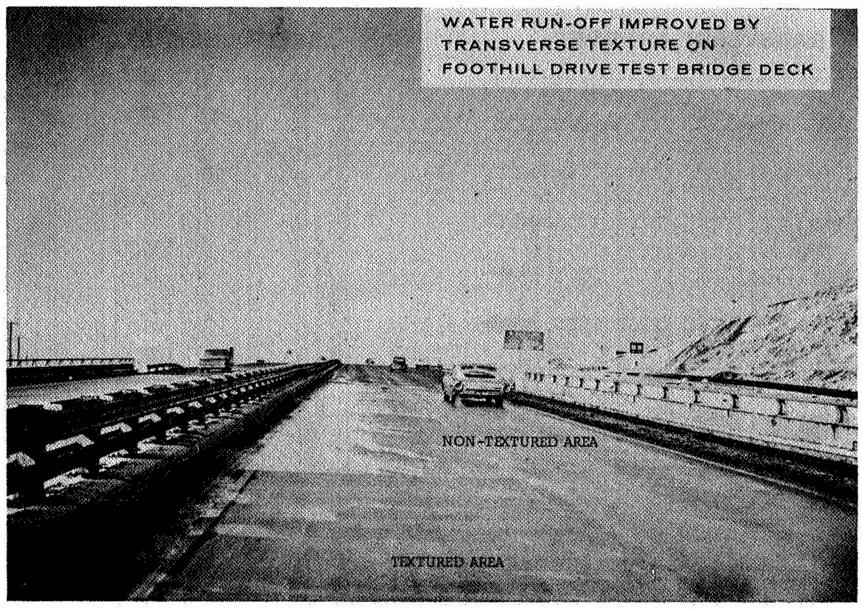

Figure 5.- Pavement drainage.

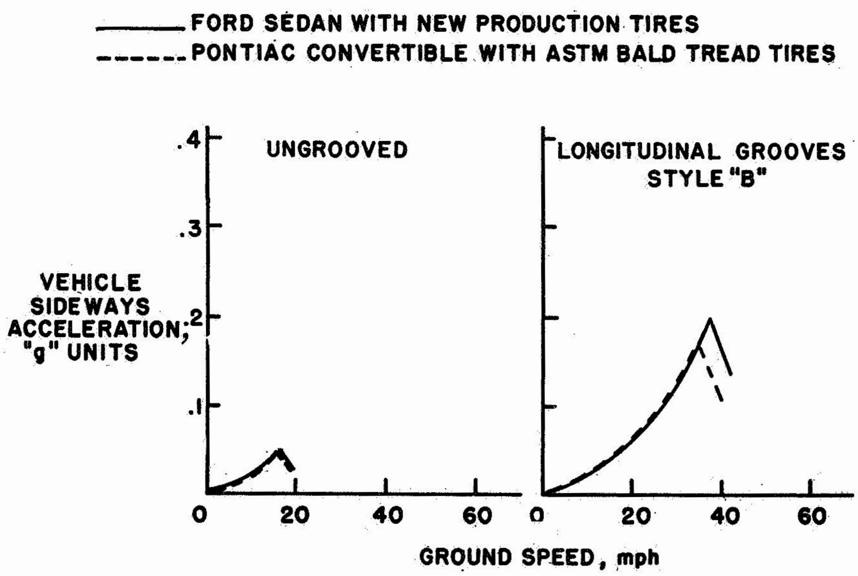

Figure 6.- Vehicle spin-out on 500-foot-radius road curve. Smooth Jennite surface; mixture of water and hydrolube.

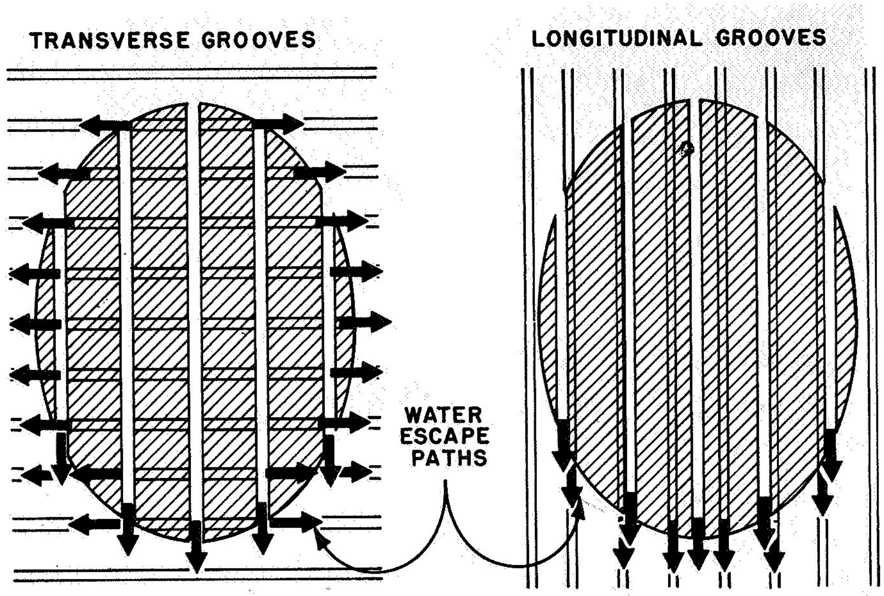

Figure 7.- Treaded footprint.

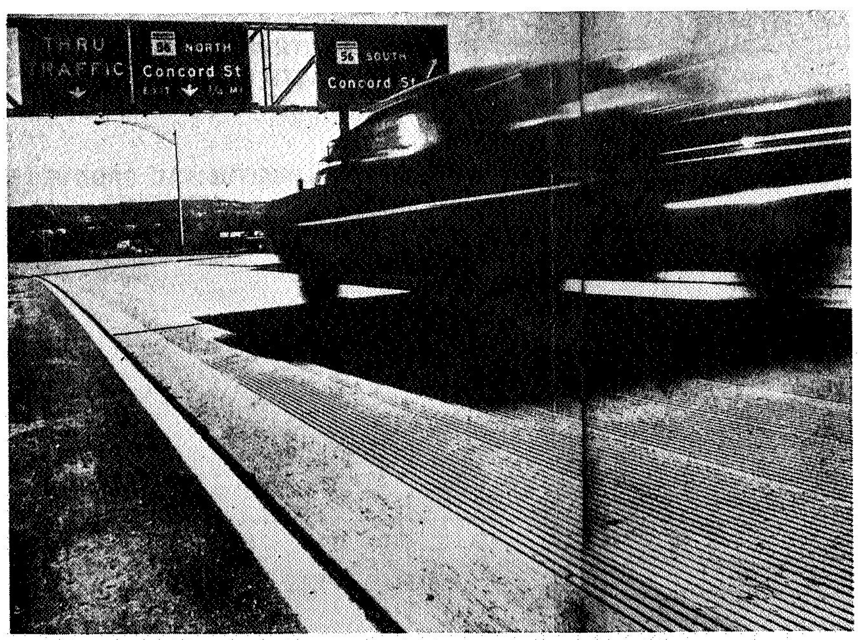

Figure 8.- Grooved pavement in St. Paul, Minnesota.

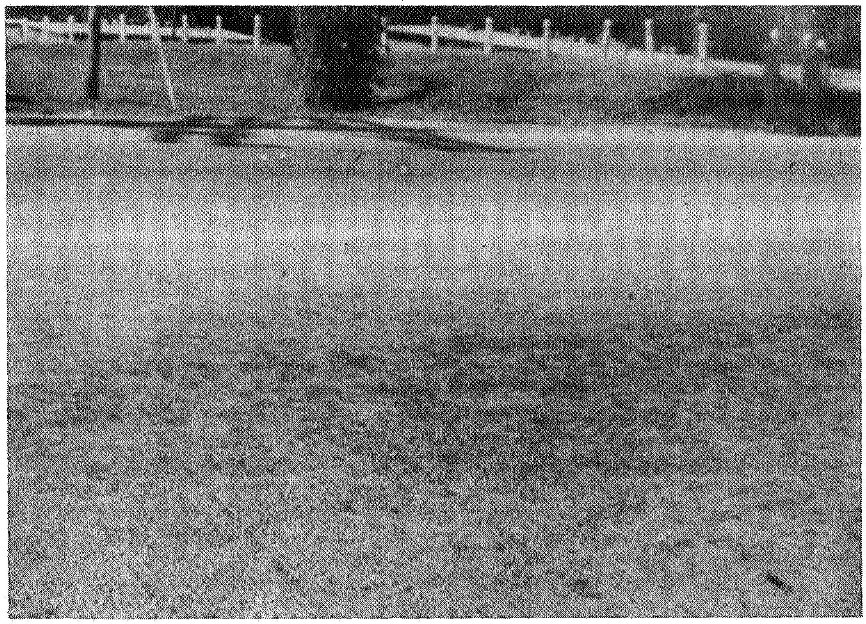

Figure 9.- Grooved pavement in St. Louis, Missouri.

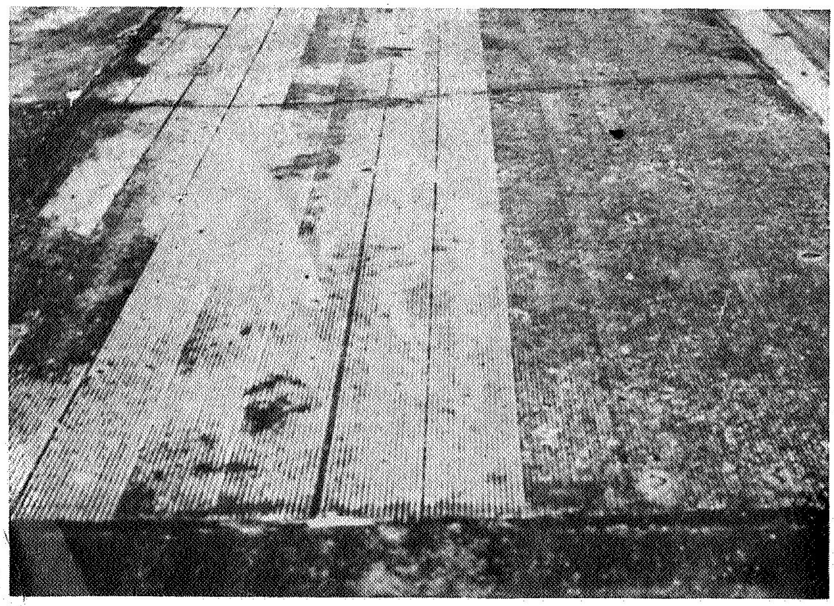

Figure 10.- Irregularities in longitudinal grooves.

Figure 11.- Alined grooving pattern.

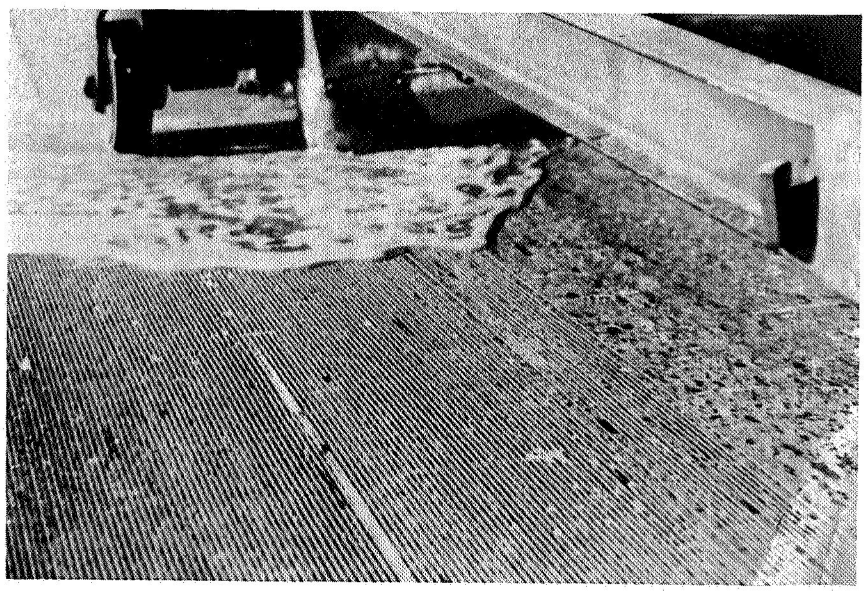

Figure 12.- Slurry.

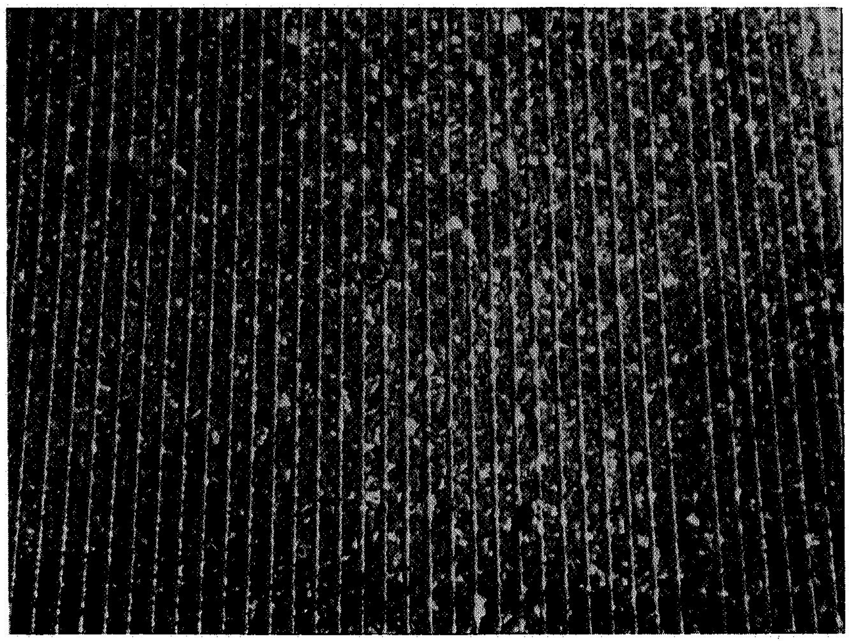

Figure 13.- Clean pavement.

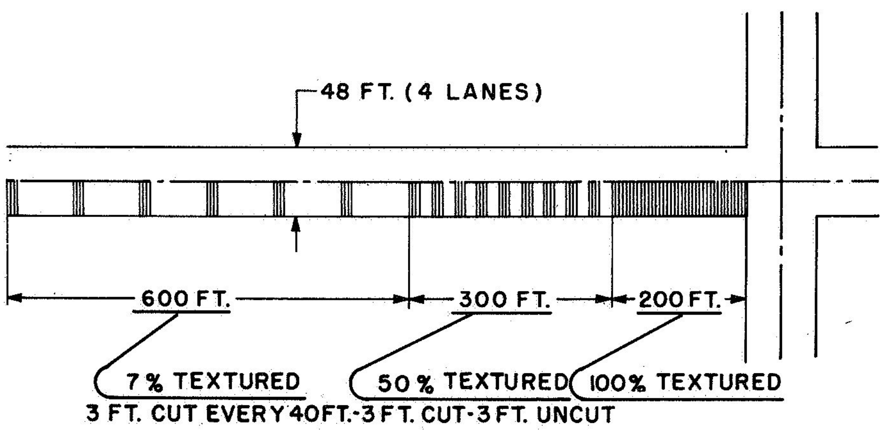

Figure 14.- King Street intersection in St. Augustine, Florida.

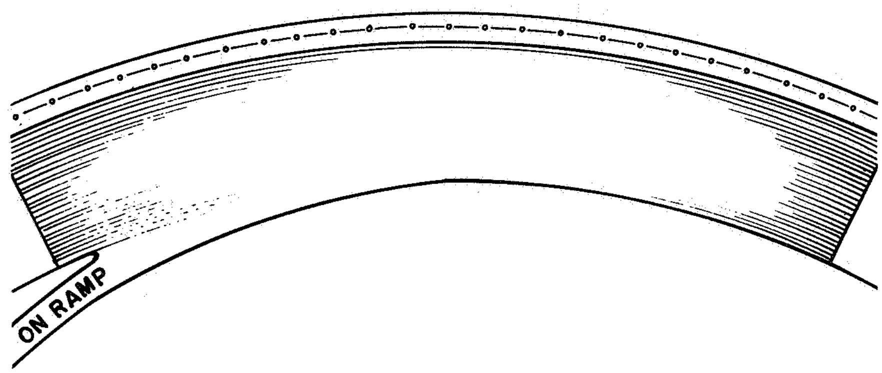

Figure 15.- Longitudinally grooved curve.

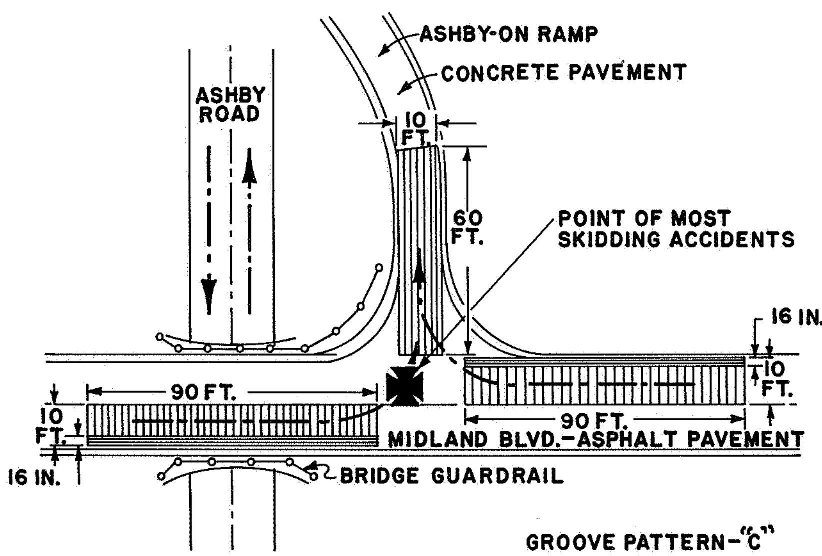

Figure 16.- St. Louis intersection (Midland Boulevard and Ashby Road).

LIST OF ATTENDEES

ABBOTT, Edwin W.	Air Transport Association of America
ALLEN, Curtis R.	NASA Wallops Station
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MARTIN, F. R.	Ministry of Public Building and Works (England)

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ROWE, Kenneth A.	Virginia State Corporation Commission
RUNYAN, Harry L., Jr.	NASA Langley Research Center
RYDER, Jack	Firestone Tire & Rubber Company
SAÍNT-PAÚL, Jean R.	Kleber-Colombes (France)
SALLICK, M. W.	National Guard Bureau
SAMOS, John	NASA Langley Research Center
SANFORD, T. W., Jr.	Federal Aviation Administration
SANTAMARIA, J.	International Civil Aviation Organization (Canada)
SAUNDERS, Rodney V.	Georgia Department of Industry & Trade
SCHAEFER, Edward W.	Federal Aviation Administration
SCHAEVITZ, Ronald N.	The Boeing Company

SCHOEPPEL, John	National Water Lift Company
SCHONFELD, Robert	Department of Highways (Canada)
SCHROCK, Martin O.	Pennsylvania State University
SCHWARTZ, Francis X.	Soiltest, Inc.
SEBAK, Edward C.	The General Tire & Rubber Company
SHAVER, W. C.	Air Treads, Inc.
SHILLING, B.	Royal Aircraft Establishment (England)
SHREVE, R. D.	Federal Aviation Administration
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SIMMS, G. E.	Concut, Inc.
SLAMA, Mr.	Direction Bases Aeriennes (France)
SMITHSON, Fraser D.	General Motors Proving Ground
SPARKS, Howard	Wright-Patterson Air Force Base
STAFFORD, D. L.	American Airlines, Inc.
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STEFANSKY, T. J.	Firestone Tire & Rubber Company
STEWART, Jerry	LTV Corporation
STOCKER, A. James	Texas A & M University
STRATFORD, H. Ralph	York Gears Ltd. (Canada)
SUGG, Robert W.	Ministry of Technology (England)
SVENDSEN, Fugl	Scandinavian Airlines System (Sweden)
TALBERT, John T., Jr.	John Talbert & Assoc. Inc.
TANAKA, Muneo	IRM (U.S.A.) Inc.
TANNER, John A.	NASA Langley Research Center
TEGEN, Robert	Engelhard Hanovia
THARP, Thomas A.	The General Tire & Rubber Company
THOMAS, K. G.	Thompson Aircraft Tire Corporation
THOMPSON, L. E.	Federal Highway Administration
THORN, Ed	Clipper Manufacturing Company
THORPE, Mark C.	McDonnell Douglas Corporation
THORPE, Roy	Falcon Safety Products, Inc.
TIERNEY, E. J.	The Permagile Corporation of America
TIERNEY, W.	The Permagile Corporation of America
TINGLER, Ezra	Peninsula Airport Commission
TOMITA, Hisao	U.S. Naval Civil Engineering Laboratory
TROST, Louis F.	Langley Air Force Base
TWIGHT, F. J.	KLM, Royal Dutch Airlines (Netherlands)
WALKER, F. I. V.	F. G. Miles Engineering, Ltd. (England)

WALLACE, Edward H.	UNIROYAL, Inc.
WALTERS, Harold M.	Concut, Inc.
WALTHER, H.	Scandinavian Airlines System (Sweden)
WARMFLASH, Schuyler	Port of New York Authority
WATSON, J. R.	Federal Highway Administration
WAY, James H.	Ent Air Force Base
WEBSTER, M. Lee	North Carolina State Highway Commission
WHITE, B. G.	Peninsula Airport Commission
WIGNOT, Jack E.	Lockheed-California Company
WILLIAMS, John R.	College of Aeronautics (England)
WILLOUGHBY, Howard	Kansas City Municipal Airport
WILLSE, Sherman S.	U.S. House of Representatives
WILSON, Calvin F.	Kanawha Airport
WILSON, John	Martin Marietta Corporation
WISEMAN, R. R.	The Goodyear Tire & Rubber Company
WOODSON, Dillard D.	The Asphalt Institute
WORNOM, Forest E.	Peninsula Airport Commission
WRIGHT, Harold	Clipper Manufacturing Company
YAGER, Thomas J.	NASA Langley Research Center
YOUNG, Geoff	Ansett Airlines of Australia
YOUNG, Jacques	Wright-Patterson Air Force Base
ZIMMERMAN, T. R.	Schenuit Industries

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