23. JOINT NASA-BRITISH MINISTRY OF TECHNOLOGY SKID CORRELATION STUDY

RESULTS FROM AMERICAN VEHICLES

By Walter B. Horne and John A. Tanner

NASA Langley Research Center

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 $\mathrm{lb/in^2}$ 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 $\mathrm{lb/in^2}$ 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° 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:

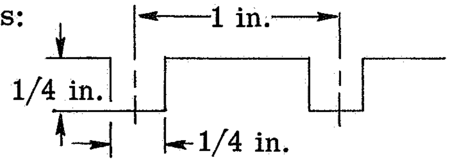


TABLE II.- TWO-WHEEL TRAILER SPECIFICATIONS

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

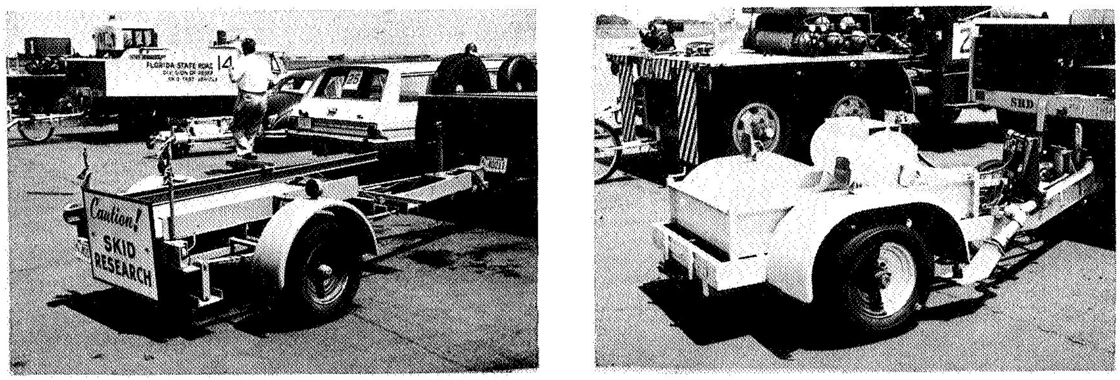
	Penn State	FAA
Vertical load on test tire, lb	800	1080
Brake system	Shoe type, activated by air over hydraulic	Driven wheel at constant slip ratio of 0.13
Watering system		
Pump	Centrifugal	Positive displacement
Water trace	Constant film thickness	Constant film thickness
Speed measuring system	Fifth 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.

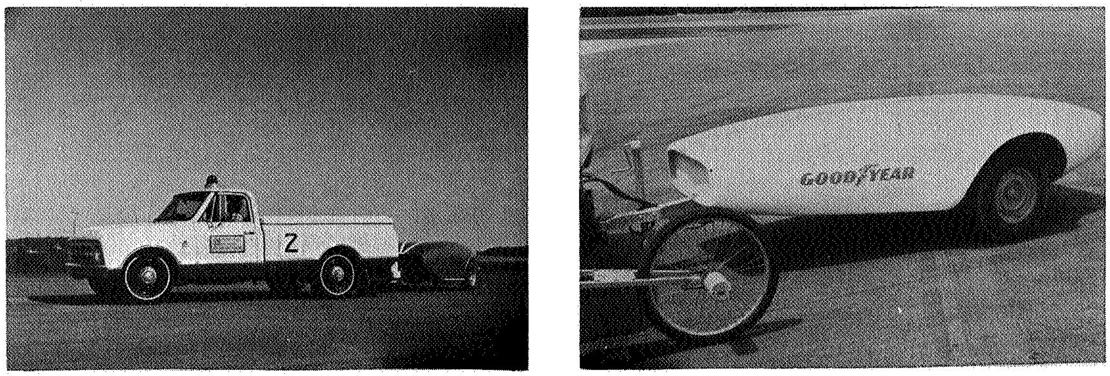
Figure 1.- Watering system of the landing research runway.



(a) Bureau of Public Roads.

(b) Florida State Road Department.

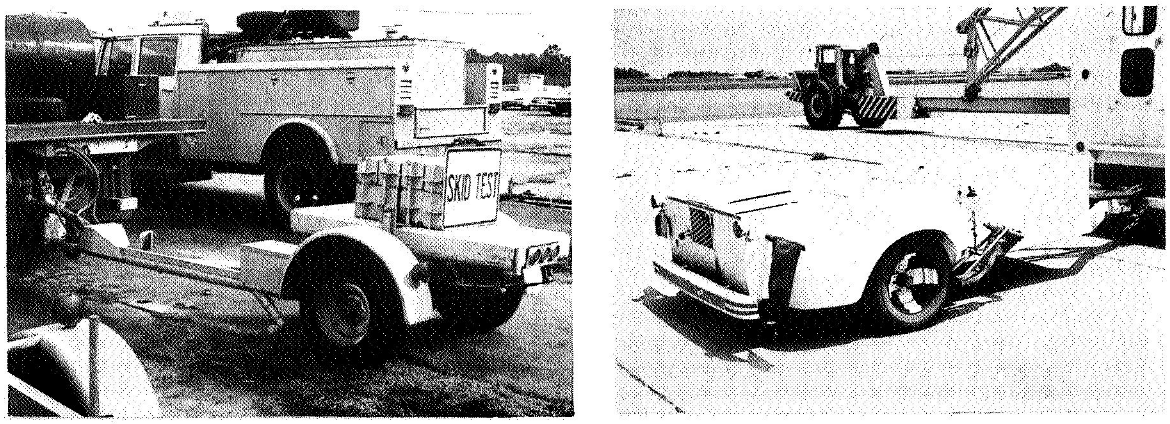
Figure 2.- Two-wheel braking trailers.



(c) General Motors Corporation.

(d) Goodyear Tire and Rubber Company.

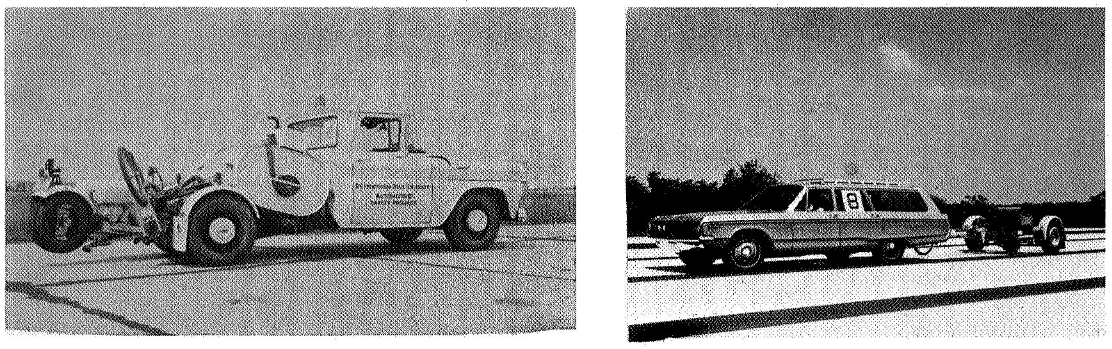
Figure 2.- Continued.



(e) Tennessee Highway Research Program.

(f) Virginia Highway Research Council.

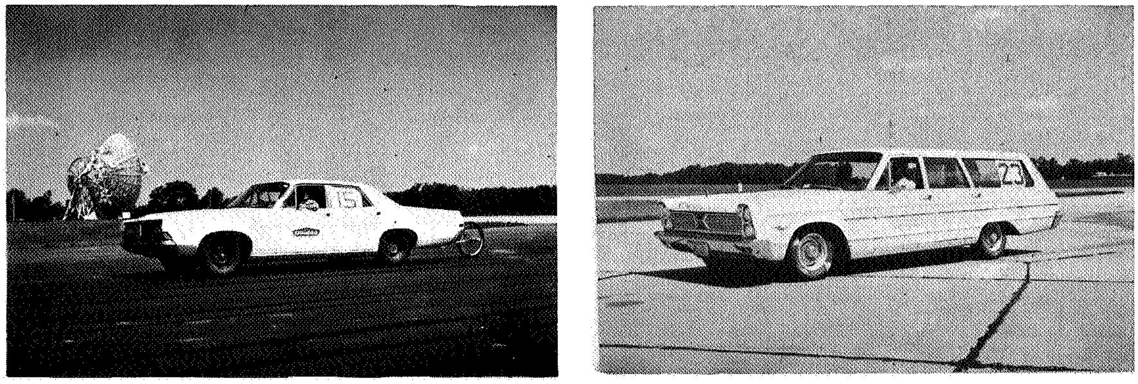
Figure 2.- Concluded.



(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.

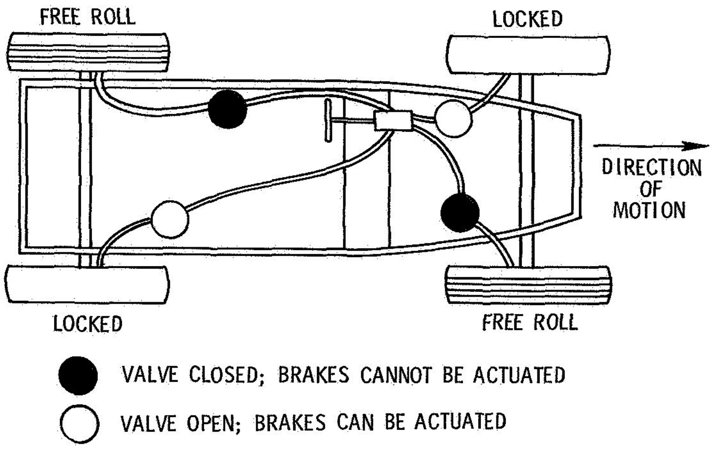


Figure 5.- Braking system for the diagonal braking vehicles.

Figure 6.- Four-wheel braking automobile.

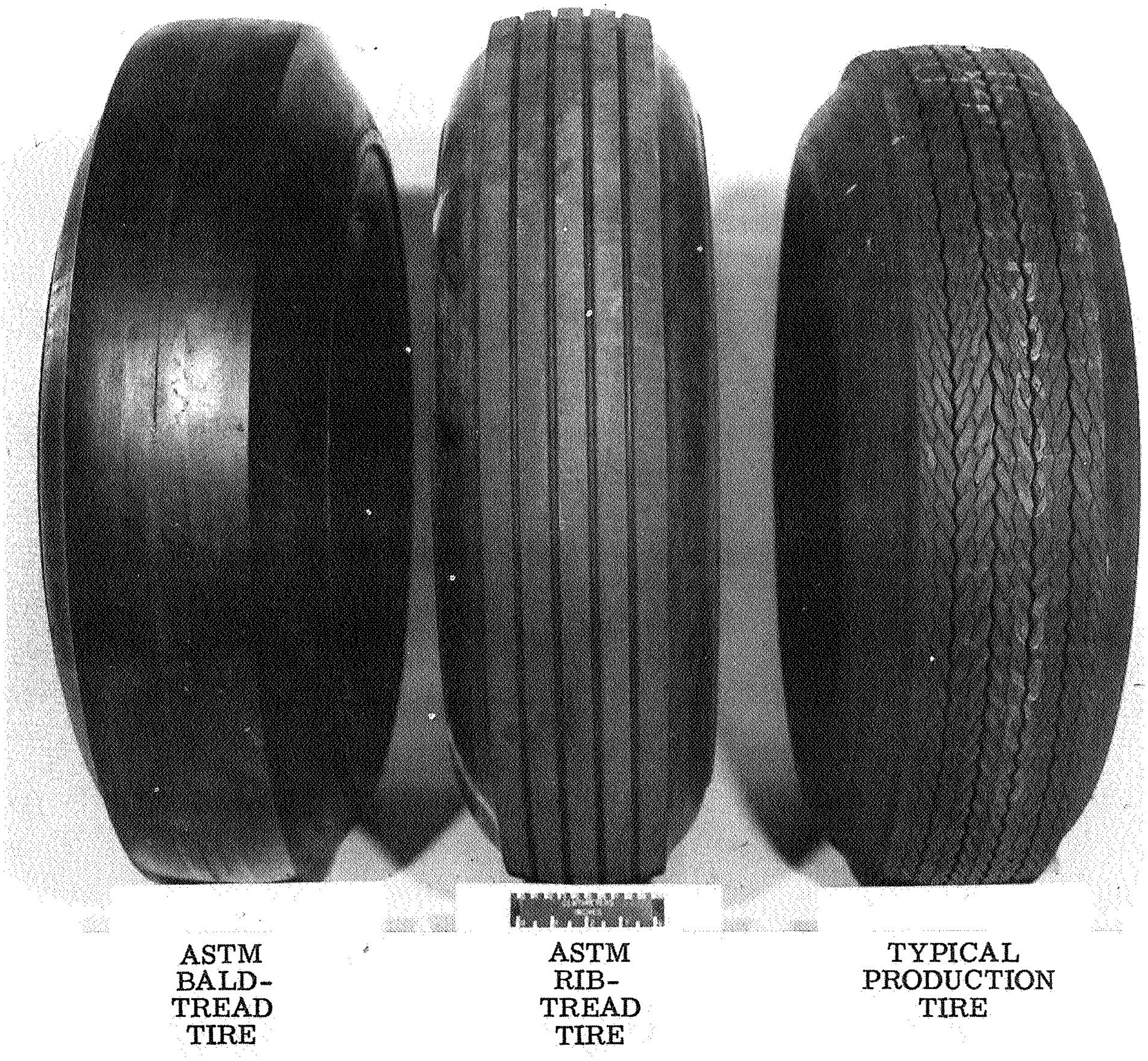
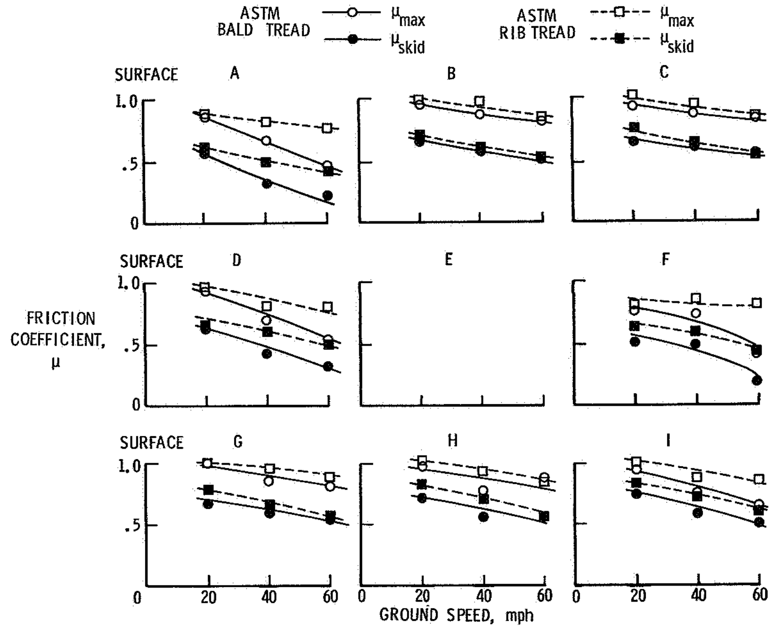
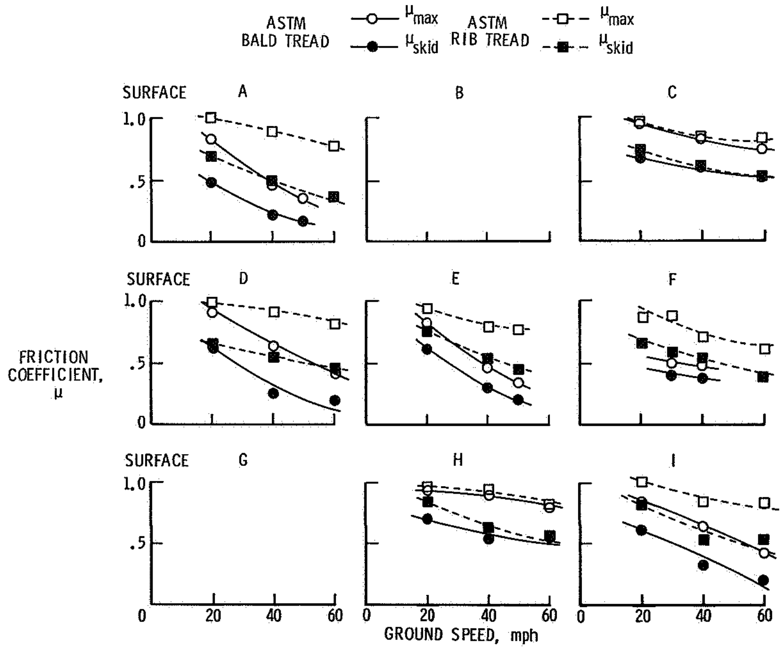


Figure 7.- Ground-vehicle tires.



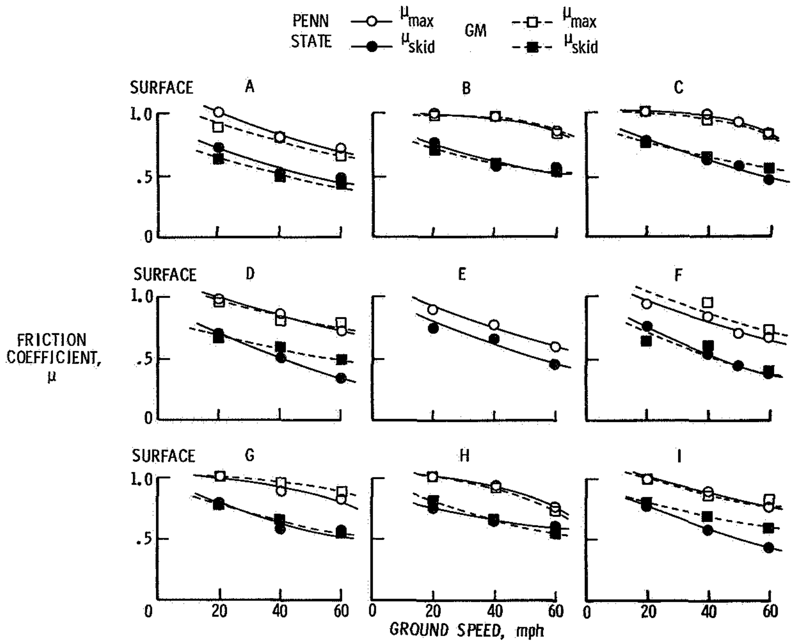
(a) Wet and puddled runway surfaces.

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.



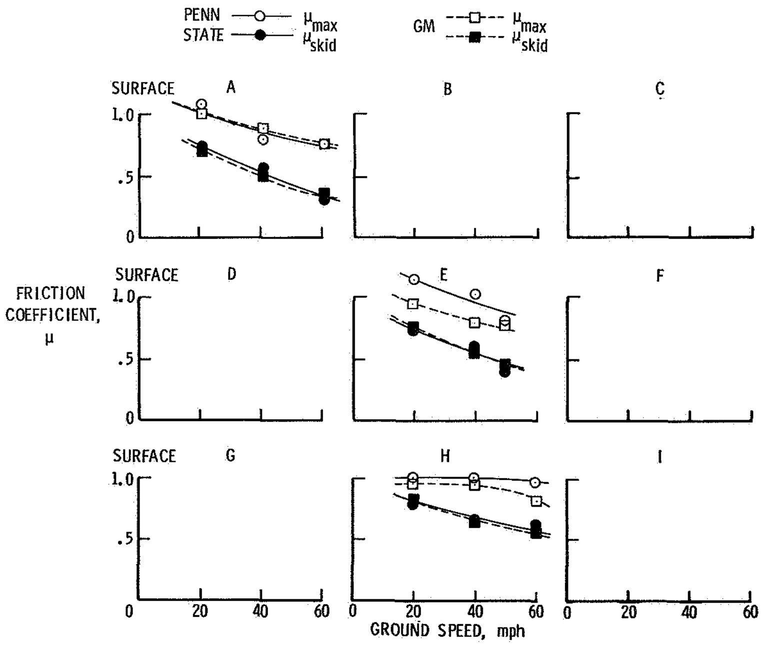
(b) Flooded runway surfaces.

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.

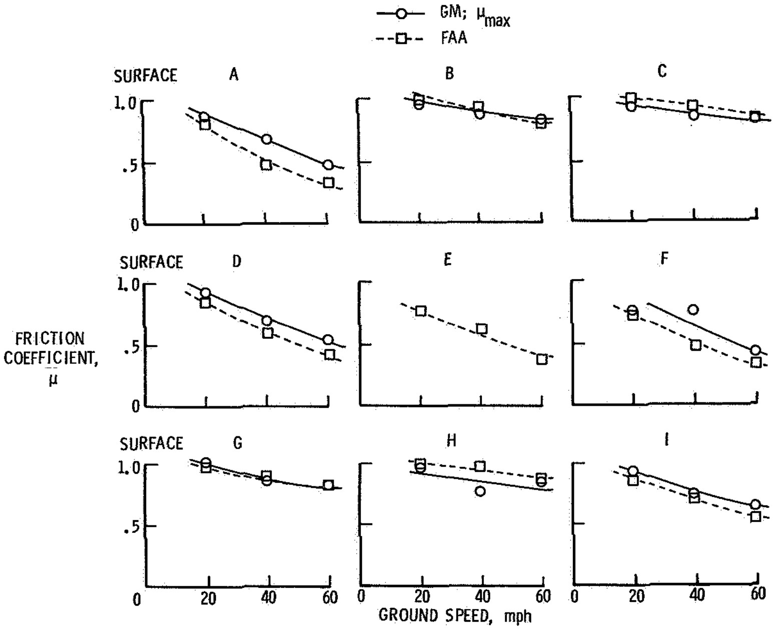
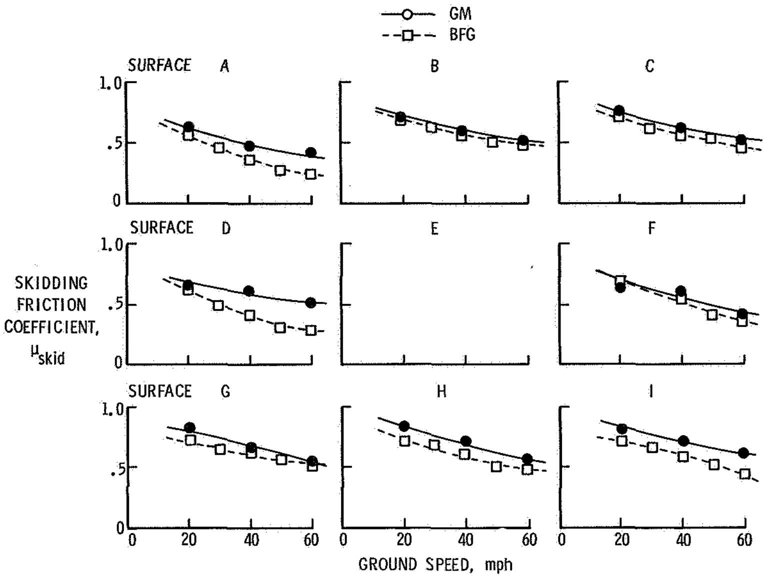
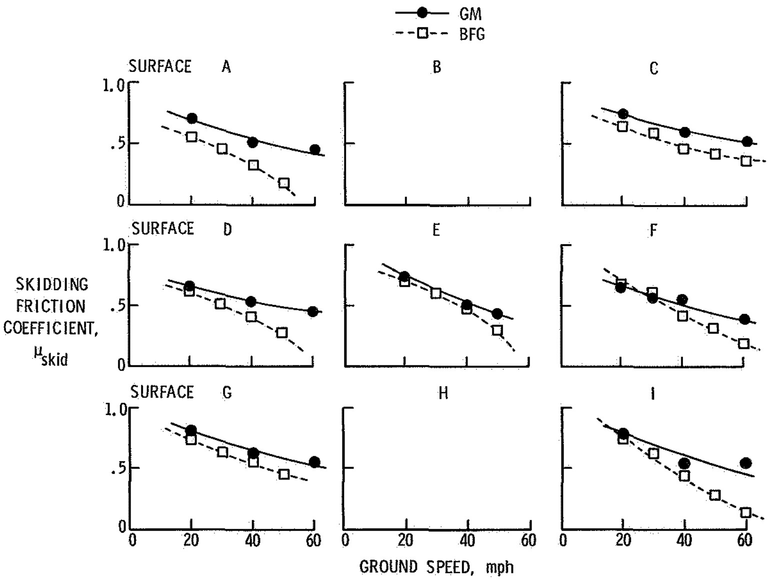


Figure 10.- Comparison of friction coefficients obtained from GM braking trailer and Swedish Skiddometer (slip ratio ≈ 0.13) on wet and puddled runway surfaces. ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1080 lb.



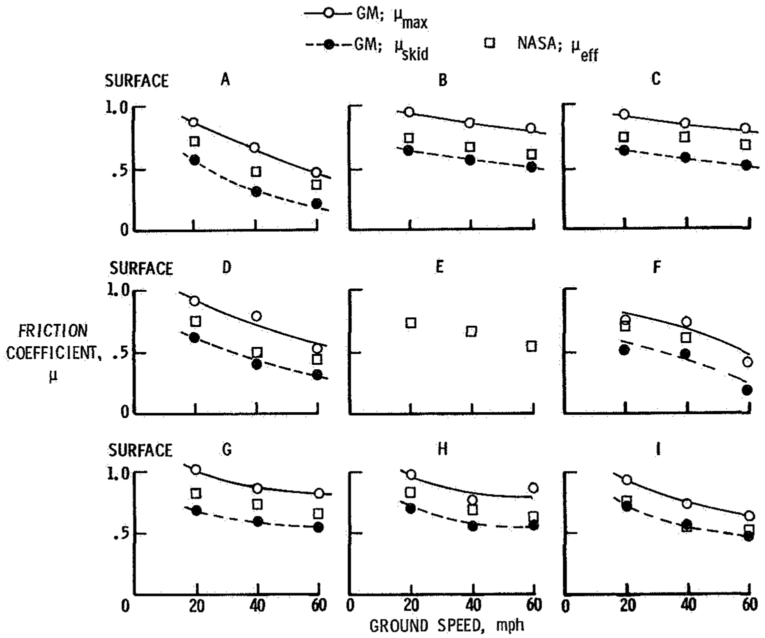
(a) Wet and puddled runway surfaces.

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).



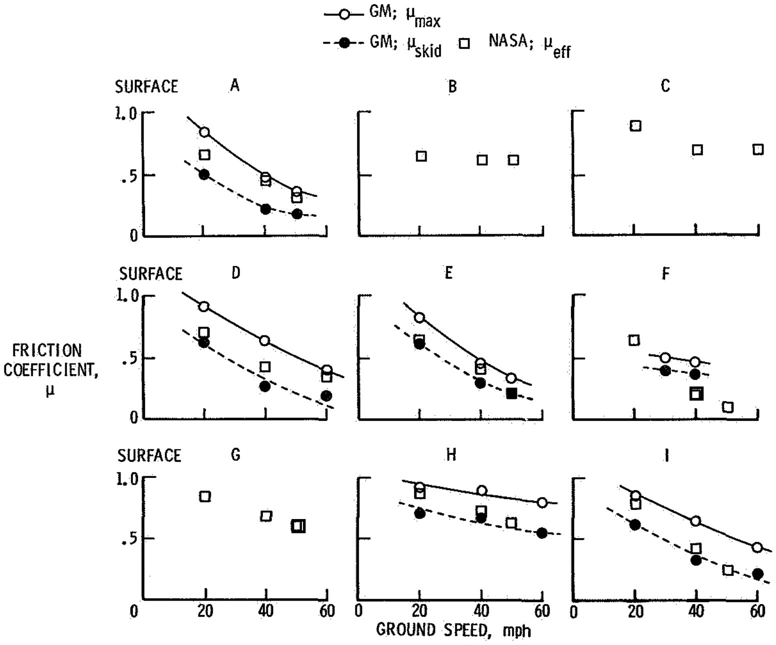
(b) Flooded runway surfaces.

Figure 11.- Concluded.



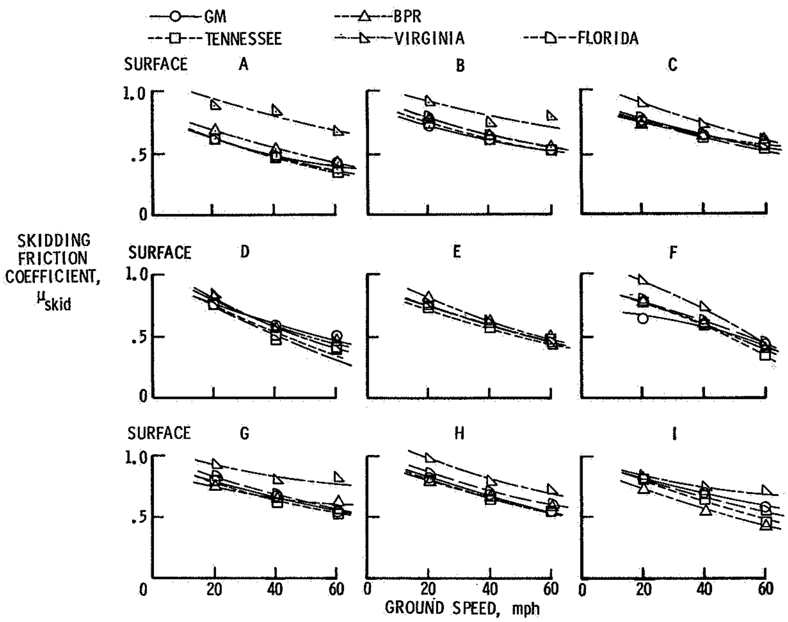
(a) Wet and puddled runway surfaces.

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).



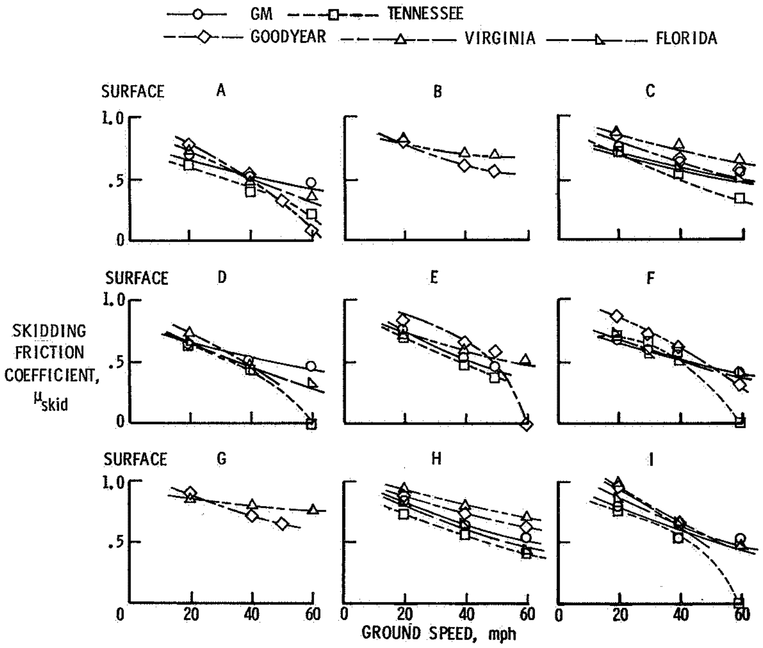
(b) Flooded runway surfaces.

Figure 12.- Concluded.



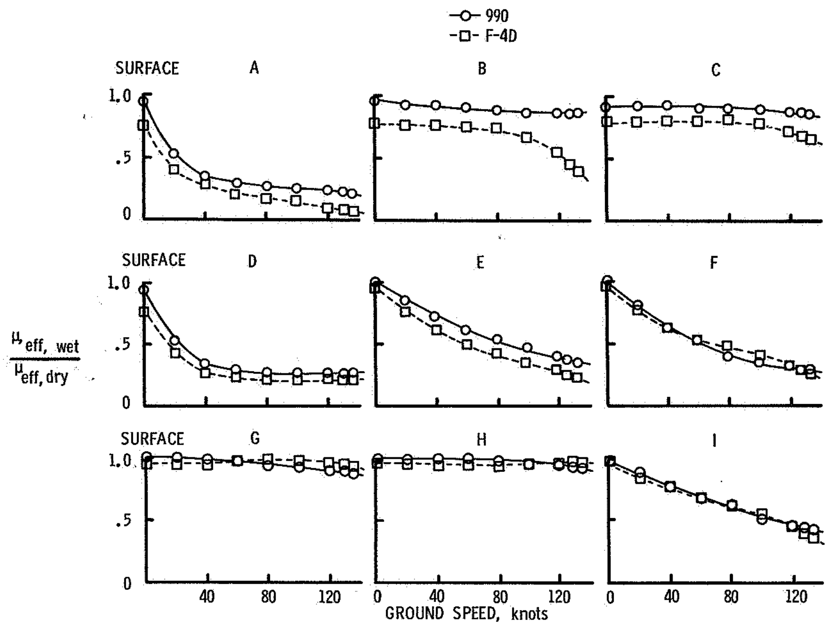
(a) Wet and puddled runway surfaces.

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.



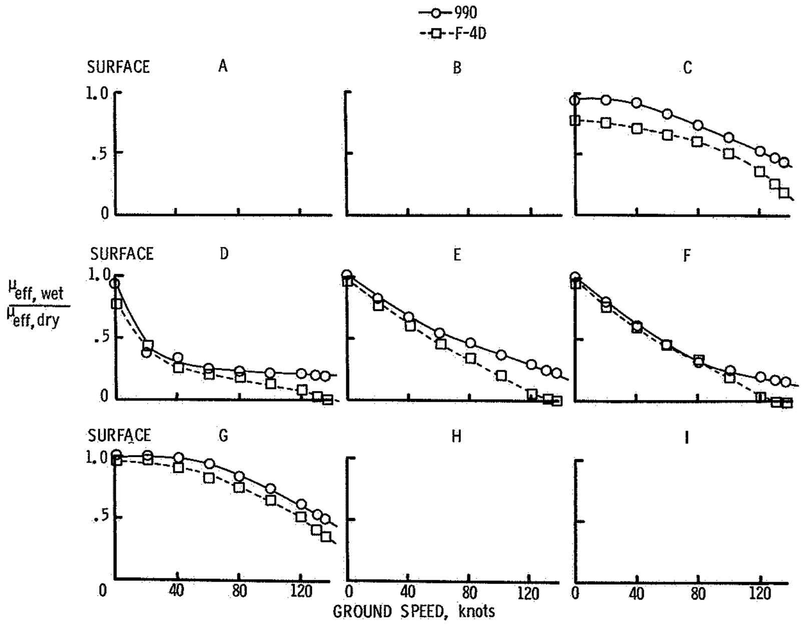
(b) Flooded runway surfaces.

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.

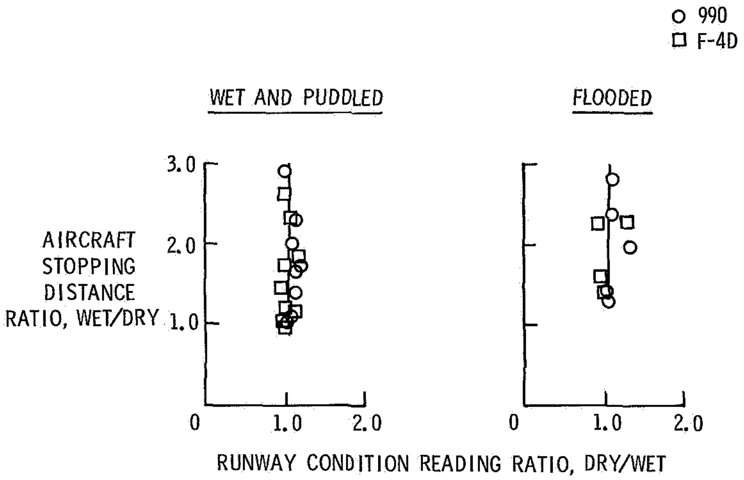
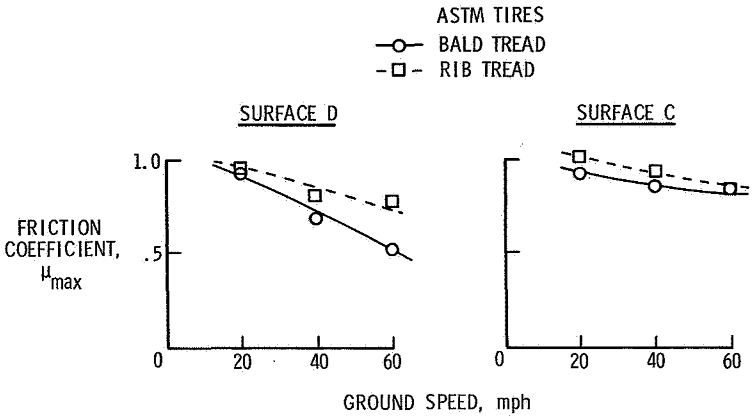
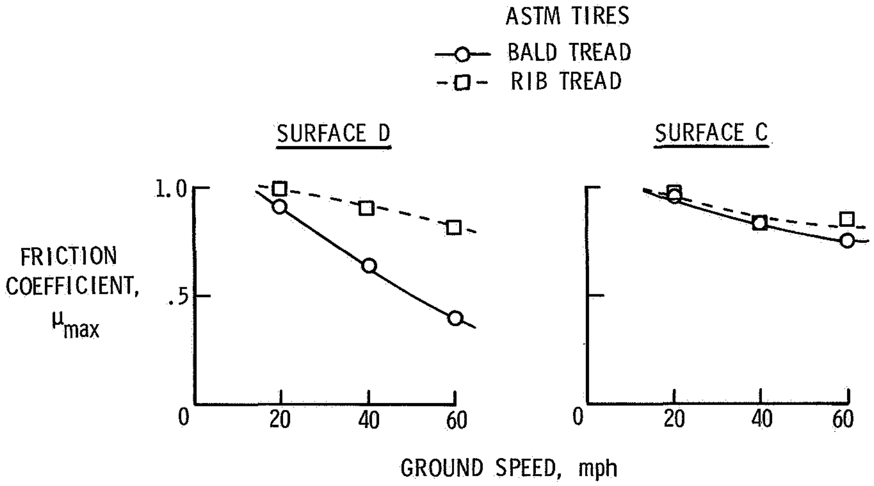


Figure 15.- Comparison of aircraft stopping distance ratios with RCR ratios. Automobile test conditions: velocity, 30 mph; four-wheel skid; typical production tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.



(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.

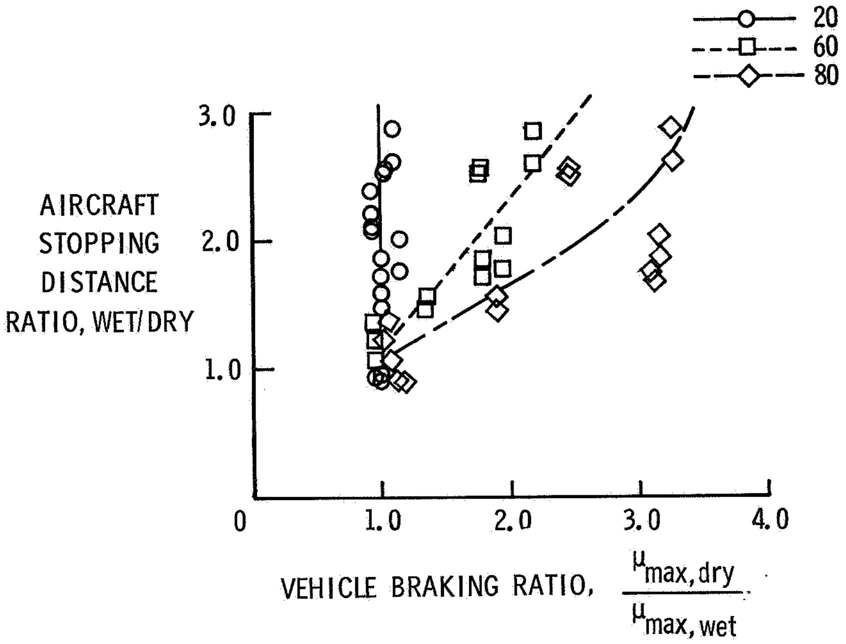


Figure 17.- Comparison of aircraft stopping distance ratios with braking ratios obtained from Swedish Skiddometer on wet and puddled runway surfaces. Skiddometer test condition: ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1080 lb.

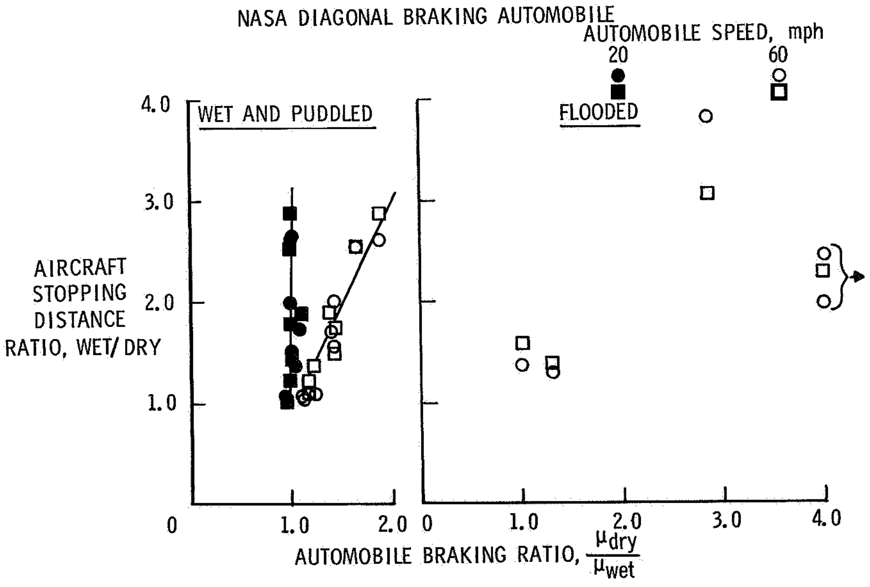


Figure 18.- Use of friction coefficients from NASA diagonal braking automobile to predict aircraft stopping distances. Automobile test conditions: ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.

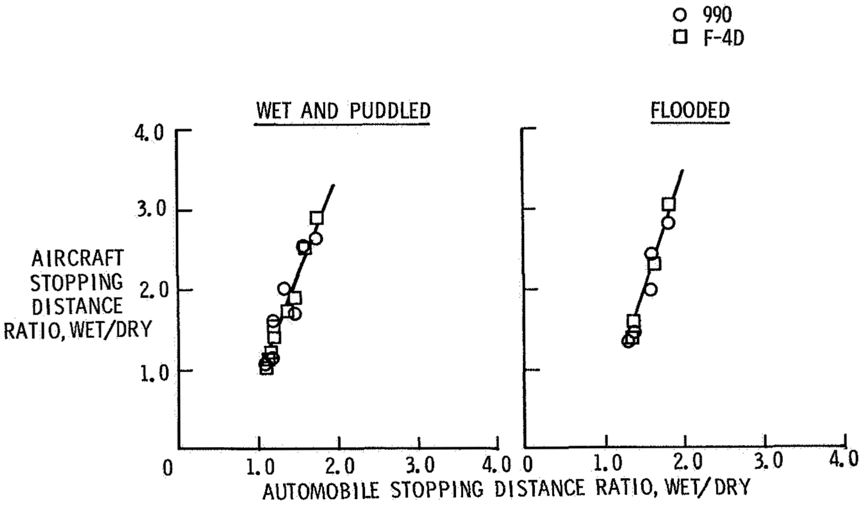


Figure 19.- Use of stopping distances from NASA diagonal braking automobile to predict aircraft stopping distances. Automobile test conditions: velocity, 70 mph; ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.

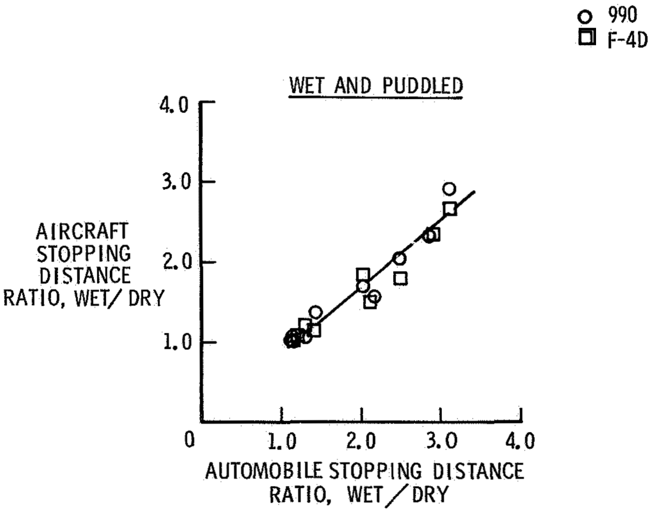


Figure 20.- Use of stopping distances from NASA diagonal braking automobile to predict aircraft stopping distances. Automobile test conditions: velocity, 70 mph; ASTM bald-tread tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb.