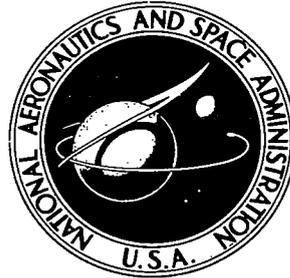


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**PERFORMANCE OF AN AIRCRAFT TIRE
UNDER CYCLIC BRAKING
AND OF A CURRENTLY OPERATIONAL
ANTISKID BRAKING SYSTEM**

by John A. Tanner

Langley Research Center

Hampton, Va. 23365





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SUMMARY

An experimental investigation was conducted at Langley Research Center to study the performance of an aircraft tire under cyclic braking conditions and to study the performance of a currently operational aircraft antiskid braking system. Dry, damp, and flooded runway surface conditions were used in the investigation. The results indicated that under cyclic braking conditions the braking and cornering-force friction coefficients may be influenced by fluctuations in the vertical load, flexibility in the wheel support, and the spring coupling between the wheel and the tire-pavement interface. The cornering capability was shown to be negligible at wheel slip ratios well below a locked-wheel skid under all test surface conditions. The maximum available brake-force friction coefficient was shown to be dependent upon the runway surface condition, upon velocity, and, for wet runways, upon tire differences. Moderate reductions in vertical load and brake system pressure did not significantly affect the overall wet-runway performance of the tire.

Effective brake system performance was observed on dry runways with only minor tire skidding; however, on damp and flooded runways, the braking effectiveness was reduced and the tire was subjected to more severe skidding. The transition from a low- to a high-friction surface required a finite time for the brake system to develop maximum braking upon reaching the high-friction surface, whereas the transition from a high- to a very-low-friction surface (dry to ice-covered) resulted in locked-wheel skids and the formation of reverted rubber in the tire tread.

INTRODUCTION

Over the years the number and variety of aircraft using antiskid systems has steadily increased, with most present-day commercial and military jet airplanes being equipped with skid-control devices. The purpose of the early devices was to avoid tire failures resulting from locked-wheel skids on dry pavements, but modern skid-control

systems are more sophisticated and are designed to provide a maximum braking effort with full antiskid protection under all weather conditions. This stringent design requirement for current systems is generally met by forcing the braking effort to be cyclic about the maximum friction level being developed instantaneously in the tire-pavement interface. However, the fact that a number of skidding incidents and accidents still occur with aircraft equipped with these modern devices suggests that they are not always able to provide sufficient braking or full antiskid protection, particularly under wet or icy runway conditions. Significantly, of the reported skidding accidents, more aircraft leave the side than the end of the runway, and this indicates that a substantial loss in lateral traction occurs during the braking effort.

The design of a skid-control device is largely based upon knowledge of the behavior of the tire during braking operations. Up to the present time, this knowledge is almost exclusively limited either to steady-state braking (testing under a constant preselected brake pressure, for example) or to one braking cycle where the brake pressure is gradually increased to a maximum and released. The data derived from such tests do not necessarily describe the ground reactions of a tire undergoing cyclic brake applications since such effects as tire elasticity and other tire properties are not included. Thus, information on tire performance under cyclic braking conditions is needed in order to permit the design of safer and more efficient skid-control devices.

Reference 1 presents the results of flight tests to evaluate the wet-runway braking performance of a jet fighter aircraft equipped with a modern skid-control system. Although the results are useful in evaluating the aircraft wet-runway braking performance, the lack of knowledge of the uncontrolled variables associated with flight tests preclude the detailed analysis necessary to isolate parameters which affect the efficiency of the braking system. Tire response to an early "on-off" type of automatic braking device is presented in reference 2, which points out some of the deficiencies of that system, particularly on contaminated runway surfaces. References 3 and 4 present the results of analog studies of simple models of aircraft braking systems. However, these analytical results have not been corroborated by experimental data. Furthermore, no meaningful data exist on the loss of lateral traction under cyclic braking conditions.

The purpose of this paper is to present the results of an experimental investigation performed at the Langley landing-loads track to study the performance of a tire under cyclic braking conditions and to study the performance of a currently operational aircraft antiskid braking system. Braking tests were conducted with size $30 \times 11.50-14.50$, type VIII, aircraft tires on dry and wet runway surfaces and on runway surfaces of sharply different character (wet to dry and wet to ice-covered) for speeds from 50 to approximately 100 knots and at yaw angles of 0° and 4° . In addition to variations in the amount of water on the surface to change the runway frictional characteristics, other test param-

eters included tire tread design, brake system supply pressure, and variations in the vertical load to simulate wing lift. The data are presented in terms of the maximum and average friction coefficients developed by the braking system.

APPARATUS AND TEST PROCEDURE

Test Facility

The braking and cornering tests were conducted on the research runway of the Langley landing-loads track. The tires were mounted in the test fixture of the large carriage which provided the appropriate tire loading. Since the weight of the carriage was in excess of 445 kN (100 000 lb), its deceleration due to the braking effort was small enough to allow each test to be conducted at essentially constant speed. A more detailed description of the landing-loads track and its operation is presented in references 2 and 5.

The wheel, tire, and brake assembly were mounted in an instrumented dynamometer, described in reference 6, which was equipped with load beams to measure the vertical, drag, and lateral loads and the brake torque at the axle. Additional instrumentation was provided to measure the brake pressure, the skid signal at the antiskid control valve, and the wheel angular displacement and velocity. The outputs from these instruments and the load beams, together with signals which described the carriage position and ground speed, were transmitted to an oscillograph recorder installed in the carriage.

Tires and Test Surfaces

The tests were conducted with new and worn $30 \times 11.50-14.50$, type VIII, 26-ply-rating aircraft tires from three different manufacturers. Photographs of the various tires used in the study are shown in figure 1. Tires A and C have three-groove treads; tire B has a four-groove tread; and tire D is similar to tire C (same manufacturer) but with a tread worn smooth as a result of normal flight operations. Tire A was photographed after dry-runway testing whereas the other tires were photographed prior to testing. Except for the tests with tire D, tires were replaced when approximately 60 percent of the original tread had been worn off. The test inflation pressure for all tires was maintained at 193 N/cm^2 (280 lb/in^2). Tests were conducted on representative surfaces under dry and damp conditions with no standing water, on flooded surfaces with approximately 2.5 mm (0.1 in.) of water, and on surfaces of sharply different character (wet to dry and wet to ice-covered runways).

Skid-Control Device

A pressure-bias modulated skid-control device typical of those used on many jet transport and fighter aircraft was selected to provide the cyclic braking inputs. This

device was configured to simulate the electronic and hydraulic components of the braking system installed on a current jet fighter aircraft which uses the same tires as described in the previous section. A schematic diagram of the braking system is presented in figure 2, and typical time histories of four fundamental parameters which describe the operation of the braking system on both dry and wet runways are presented in figure 3. The time histories of the braking friction coefficients indicate typical friction levels developed by the braking system on dry and wet runway surfaces. The braking system is activated by brake application at the pilot-operated metering valve which supplies system pressure, nominally 2070 N/cm^2 (3000 lb/in^2), to the brake through the normally open antiskid control valve. If the resulting brake torque is sufficient to overcome the spin-up torque generated by the ground reaction at the tire-pavement interface, the wheel will rapidly decelerate toward a locked-wheel skid (more pronounced in fig. 3(b), for example). When the skid sensor detects this large increase in the wheel angular deceleration, a skid signal is generated by the electronic control box; this signal causes the anti-skid control valve to close and, in so doing, relieves pressure to the brake. When the tire is no longer in danger of skidding, the pressure-bias modulation system governs the reapplication of brake pressure by allowing a residual skid signal voltage, which is proportional to the time integral of the previous skid signal, to remain on the valve after the wheel has regained synchronous speed (full spin-up). This residual voltage acts to restrict the hydraulic pressure applied to the brake. The residual signal voltage is then reduced at a constant rate to allow a more gradual brake-pressure buildup for the next braking cycle.

Test Procedure

The testing technique involved propelling the carriage to the desired ground speed, activating the braking system when the loaded tire reached synchronous speed on the selected test surface, and recording the response of the wheel and brake system. The tests were conducted at nominal speeds of 50, 75, and 100 knots with the wheel positioned at yaw angles of 0° and 4° . In general, the tests were conducted with a vertical load of 66.7 kN (15 000 lb) applied to the tire, which approximated a landing gross weight for this aircraft; however, one series of tests was conducted wherein this loading was decreased with increased speed to simulate wing lift effects. All tests were conducted with the pilot-operated metering valve fully open to simulate full brake pedal deflection, and hence maximum braking, except for several tests which were run at a reduced system supply pressure to simulate partial pedal deflection.

DISCUSSION OF RESULTS

A typical tire frictional response to antiskid controlled cyclic braking on a dry and a flooded runway surface is presented in figure 4. Braking- and cornering-force friction

coefficients developed at a yaw angle of 4° are plotted as a function of the wheel slip ratio. The wheel slip ratio is defined by the following expression:

$$\text{Slip ratio} = 1 - \frac{\text{Instantaneous wheel angular velocity}}{\text{Synchronous wheel angular velocity}}$$

where the synchronous velocity was taken as the maximum wheel speed within a given time interval over which the slip ratio was computed. The presence of any braking forces at the instant that the synchronous wheel speed is determined and any decay of the carriage velocity over the time interval will, of course, result in small errors in the computation of slip ratio. However, these errors should have no significant effect on the data presented in figure 4. The data in the figure were obtained from portions of test oscillograph records. The figure shows that the variation of the friction coefficients with slip ratio is not described by a smooth curve as was observed during steady-state braking (constant brake torque) in reference 7 or during single-cycle braking (free rolling to wheel lockup) in reference 8, for example. The perturbations in the data are ascribed to the small fluctuations in the vertical load due to runway unevenness, the flexibility in the wheel support which is reflected in the measured drag and cornering forces, and the spring coupling between the wheel and the tire-pavement interface.

Figure 4 clearly shows that the level of friction on the flooded surface is considerably less than that developed on the dry surface. This result corresponds to trends previously noted under noncyclic conditions. The maximum braking friction coefficient on a dry surface is approximately 0.5 whereas that on a flooded surface is reduced to about 0.2. The peak cornering friction coefficient is reduced from a maximum value of about 0.3 on a dry runway to roughly 0.15 on a flooded runway. The figure also emphasizes the rapid deterioration in cornering capability with increased braking effort. On both the dry and flooded surfaces, cornering is shown to become negligible at a slip ratio of approximately 0.3 instead of at a slip ratio of 1.0 (locked-wheel skid), which is the value customarily assumed for noncyclic braking.

Effects of Key Test Parameters on Cyclic Braking Friction Coefficient

General considerations. - The influence of several key test parameters on tire cyclic braking performance was determined from a comparison of the maximum friction coefficient available to the braking system with the average friction coefficient developed by the antiskid braking system over the test runway surfaces. These coefficients were determined from the time histories of the braking friction coefficient as developed by the braking system. (See bottom plots in fig. 3(a) and fig. 3(b).) Those peaks in the friction curve accompanied by a corresponding skid signal are considered to represent the maximum friction profile of the surface as seen by the braking system, since it is assumed that the brake torque has exceeded the torque necessary to produce maximum friction. The

arithmetic average of these peaks is defined as the maximum friction coefficient available to the tire for a given runway surface condition. The average friction coefficient developed by the braking system was determined by dividing the area under the braking friction curve for a given time interval by the duration of that interval. These friction coefficients were computed for various test conditions to permit the evaluation of effects attributed to tire differences, simulated wing lift, and reduced brake system pressure. Since the objective was to study cyclic braking behavior, the free-rolling friction coefficients, which varied from 0.044 to 0.049 at speeds between 50 and 100 knots, were subtracted out.

Tire differences. - The maximum available friction coefficients and the average coefficients developed by the antiskid braking system on damp and flooded runways with the test tires of this study are presented as a function of ground speed in figure 5. Also included for comparison are the data from similar tests with tire A on a dry surface. The other tires were not tested on a dry surface; however, on the basis of previous observations (ref. 2, for example), the effect of tread pattern on the dry braking characteristics is relatively insignificant. Thus, these dry-surface data should be representative of all four tires. Figure 5 shows that both the damp and the flooded runway caused a substantial reduction in the maximum available friction coefficients from the dry-runway values. This trend was also reflected in the average friction coefficients developed by the braking system. These reductions are more pronounced at higher speeds, as predicted by current hydroplaning theory. The fact that very little difference exists between the damp- and flooded-runway friction levels at the low test velocities may be attributed to the water depth on the flooded runway (2.54 mm, or 0.1 in.) being less than the average groove depth of the tires (6.35 mm, or 0.25 in.). The results indicate that when tire A was replaced by either tire B or tire C, a significant increase was noted in the available friction level, particularly at the lower test velocities, with tire C showing the greater improvement. The average friction levels developed by the braking system, however, appeared to be much less sensitive to tire differences although, in general, the friction level developed with tire C is higher than that of the other tires. The friction levels associated with a smooth tire (tire D) on the flooded surface were lower than those developed by the grooved tires, as expected, since only a small amount of water on the runway is sufficient to cause this tire to hydroplane. However, the high friction coefficients of tire C cannot be attributed to tread design since tires A and C have identical tread patterns. One possible explanation for the difference in the cyclic friction coefficients between tires A and C may lie in the differences in the elastic and other material properties of the two tires, inasmuch as they were not made by the same manufacturer, and these differences could affect the efficiency of the braking system.

In summary, the results indicate that the maximum available brake-force friction coefficient is dependent upon the runway surface condition (dry, damp, or flooded) and, for

the wet conditions at least, upon tire and tread differences. The average friction coefficient developed by the automatic braking system appears to be less sensitive to tire differences.

Simulated wing lift. - A series of tests was conducted with tire A on damp and flooded surfaces wherein wing-lift effects were simulated by varying the vertical load on the tire with ground speed. For these tests the loading was 65 kN (14 600 lb) at 50 knots, 62.6 kN (14 075 lb) at 75 knots, and 58.7 kN (13 200 lb) at 100 knots. The purpose of these tests was to determine whether a reduction in the vertical load, and hence a reduction in the amount of brake torque necessary to produce a locked-wheel skid, would adversely affect the friction coefficient developed by the brake system. The results presented in figure 6 show that the inclusion of simulated wing lift produced no significant difference in either the maximum available friction coefficient or the average friction coefficient developed by the braking system on both damp and flooded surfaces.

Reduced brake system pressure. - Figure 7 presents the results of tests conducted to evaluate the effects of reduced brake system pressure on the friction coefficients. The data were obtained from tests with tire A on damp and flooded surfaces at a nominal brake system pressure of 2070 N/cm² (3000 lb/in²) and at a reduced pressure of 1035 N/cm² (1500 lb/in²) which simulated partial brake pedal deflection. This reduction in brake pressure produced insignificant differences in the braking coefficients from those measured at the nominal pressure. This result is not surprising since, according to the data of figure 3(b), a brake pressure of only 1035 N/cm² (1500 lb/in²) is more than sufficient to develop maximum braking on the flooded runway test surfaces.

Brake System Performance

Uniform runway conditions. - A measure of the braking efficiency of a system is provided by the ratio of the average friction coefficient developed by the braking system to the maximum friction coefficient available to that system. This ratio, which indicates the ability of the system to utilize the available friction, is plotted as a function of ground speed on uniformly dry, damp, and flooded runway surfaces for tire A in figure 8. The figure shows that the brake system performance on a dry surface exceeds that on the damp and flooded surfaces at ground speeds above approximately 60 knots and improves with increasing ground speed. The lower friction-coefficient ratios at slow speeds for dry conditions are not considered a serious problem since 55 to 60 percent of the available friction on a dry runway represents a sizable braking effort. However, the decrease in friction-coefficient ratios noted on the damp and flooded surfaces at high speeds does constitute a potential hazard since the available friction coefficient has been reduced considerably by hydroplaning effects. The trends associated with all three surface conditions

corroborate braking effectiveness as noted in flight test programs conducted with aircraft using this type of antiskid system. (See ref. 9.)

Transient runway condition: wet to dry concrete. - Figure 9 presents a time history of wheel angular velocity, skid signal, brake pressure, and braking friction coefficient. This history describes the typical operational behavior of the braking system as tire B traverses from a wet to a dry concrete surface. The figure shows that the pressure-bias modulation system prevents locked-wheel skids on the low-friction surface (wet concrete) by maintaining a substantial residual skid signal bias to restrict brake-pressure buildup. This skid-signal-bias level decreases at a predetermined rate to allow steady brake reapplication; hence, each brake cycle is influenced by the preceding cycles. Upon encountering the high-friction surface (dry concrete), the braking system is unable to make full use of the higher available friction, as shown in the figure, until the pressure-bias modulation system relieves the skid-signal-bias level accumulated over the low-friction surface. Thus, transition from a low- to a high-friction surface requires a finite time (at least a second in the example of fig. 9) for this brake system to develop maximum braking capability.

Transient runway condition: dry to ice-covered concrete. - Six tests were conducted with the brake system to study the response of the antiskid device during operations on a runway surface which abruptly changed from a high-friction surface (dry concrete) to a very-low-friction surface of solid ice. Figure 10 typifies this response and shows that, upon encountering the ice-covered concrete surface, the braking system was not capable of relieving the high brake pressures associated with the large braking forces on the dry concrete in sufficient time to avoid a locked-wheel skid. For these tests, the skids extended from about 7.6 m (25 ft) to 30.5 m (100 ft) before the wheel commenced to rotate. Inspection of the tire tread after each test showed evidence of reverted rubber. (See fig. 11 for typical photograph.)

CONCLUDING REMARKS

An experimental investigation was conducted at the Langley landing-loads track to study the performance of several 30 × 11.50-14.50 aircraft tires under cyclic braking conditions and to study the performance of a currently operational aircraft antiskid braking system under dry, damp, and flooded surface conditions. The results indicated that under cyclic braking conditions the braking and cornering-force friction coefficients may be influenced by the small fluctuations in the vertical load, the flexibility in the wheel support, and the spring coupling between the wheel and the tire-pavement interface. The cornering capability was shown to be negligible at wheel slip ratios greater than 0.3 for all test surface conditions, and the maximum available brake-force friction coefficient was shown to be dependent upon the runway surface condition, upon velocity, and, for wet

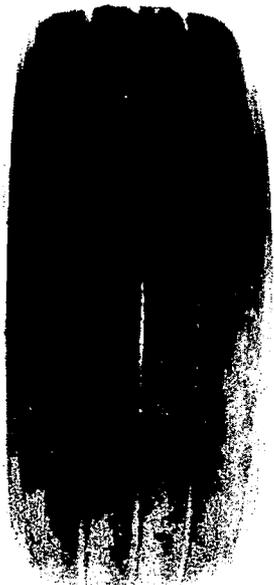
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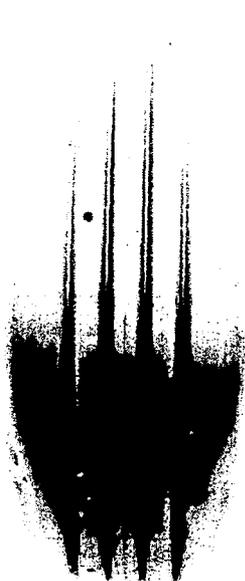
Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., April 24, 1972.

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Tire A



Tire B



Tire C



Tire D

Figure 1.- Aircraft tires used in the investigation.

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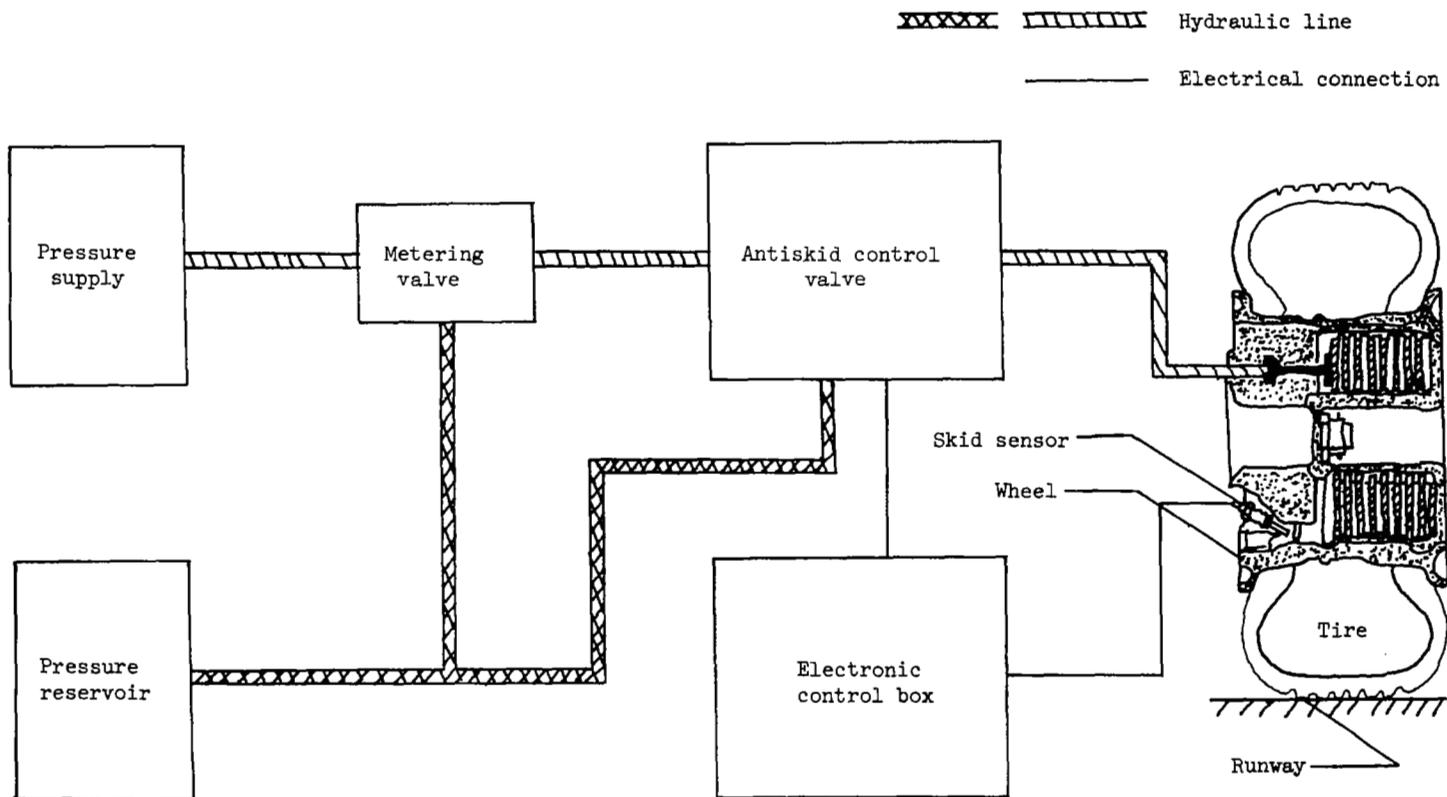
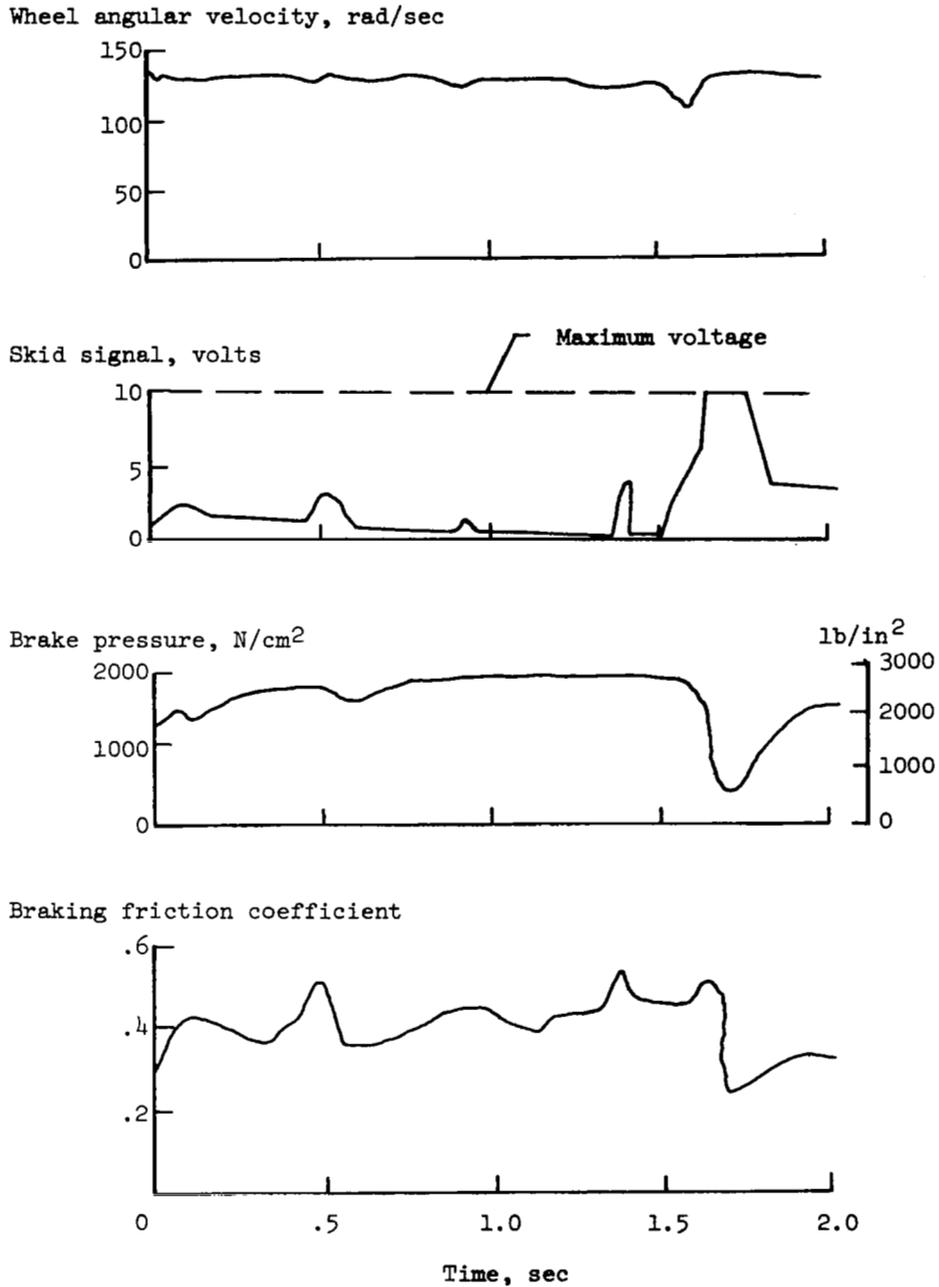
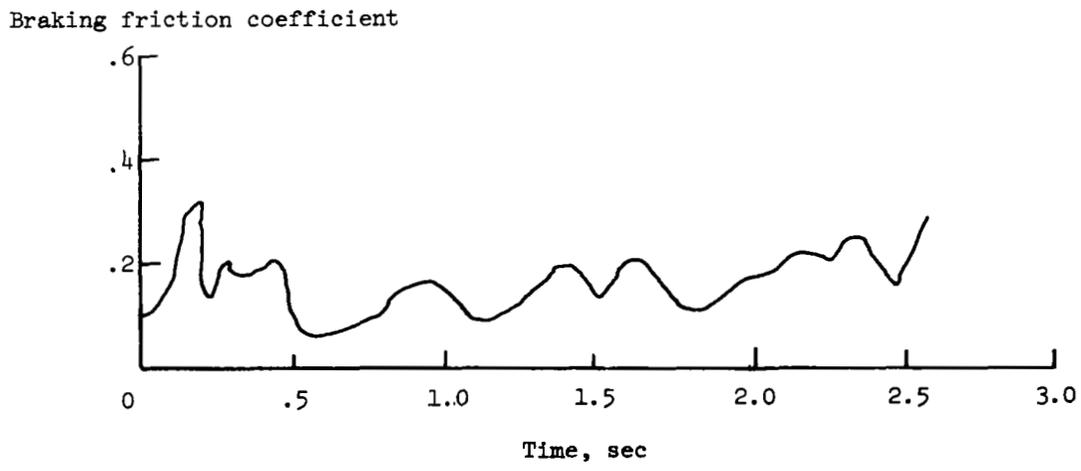
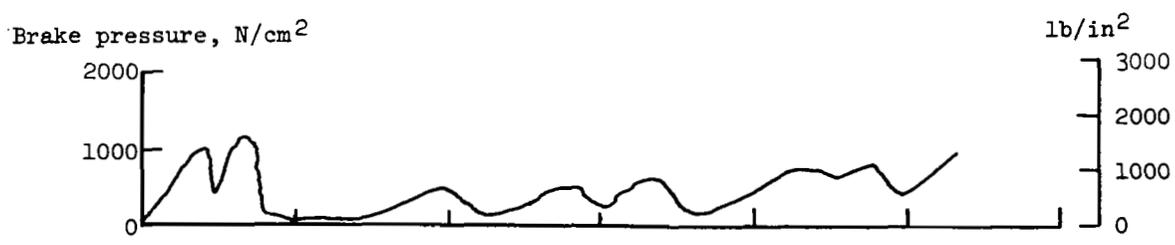
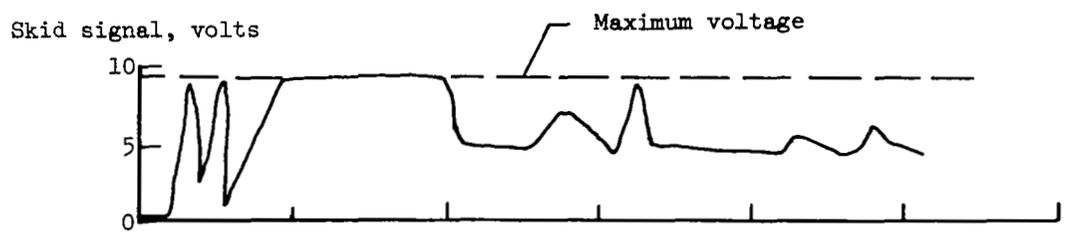
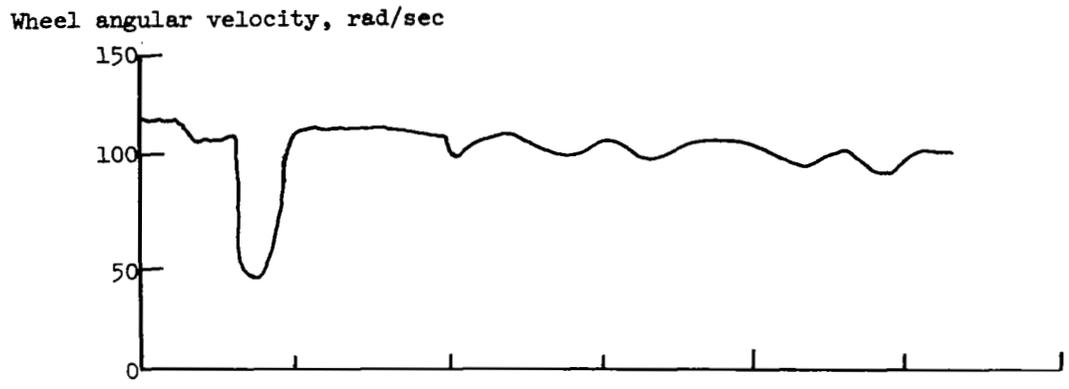


Figure 2. - Schematic diagram of the aircraft antiskid braking system used in the investigation.

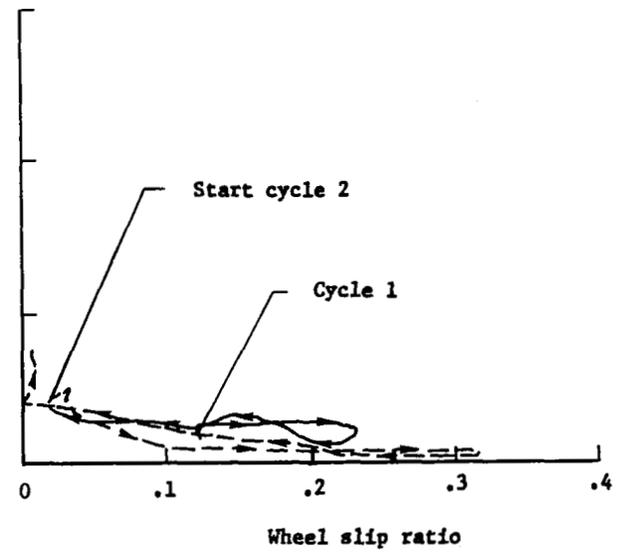
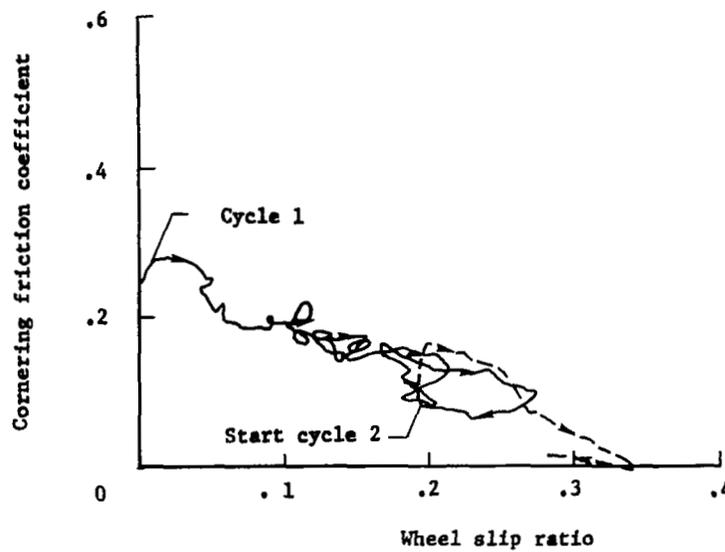
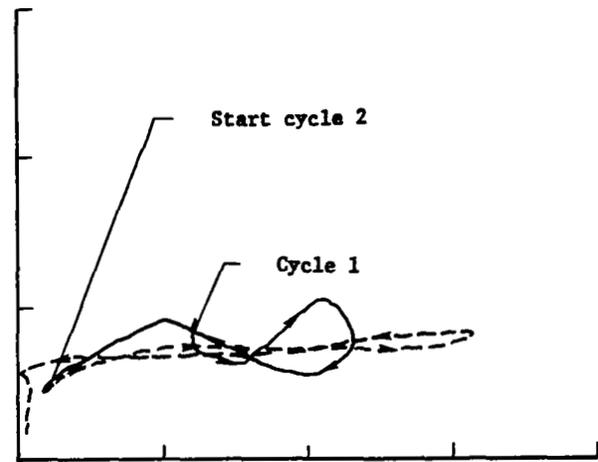
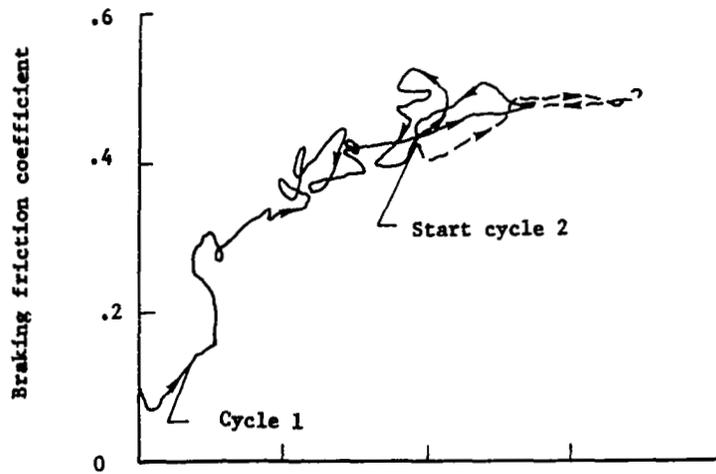


(a) Dry runway; tire A.

Figure 3.- Typical time histories showing the response of the braking system under dry and flooded runway conditions. Yaw angle = 0°.



(b) Flooded runway; tire B.
 Figure 3.- Concluded.

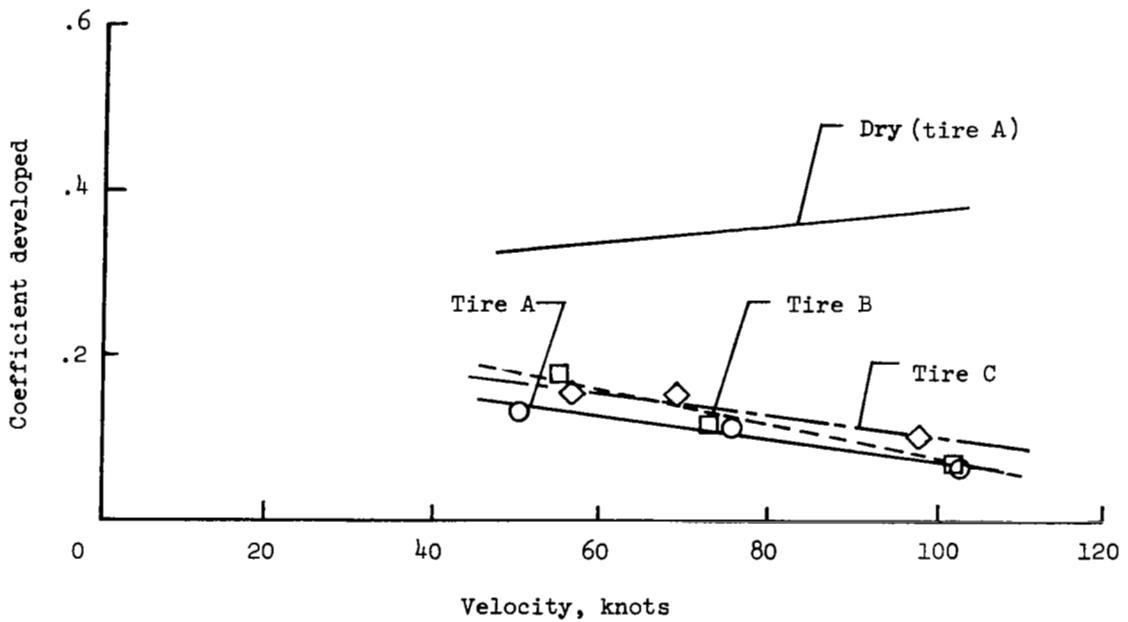
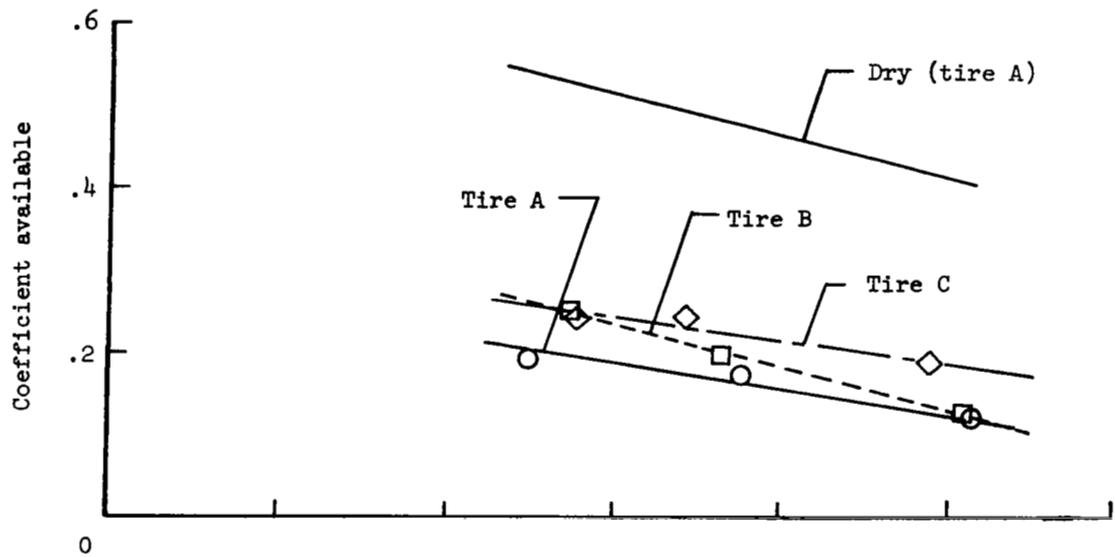


(a) Dry runway.

(b) Flooded runway.

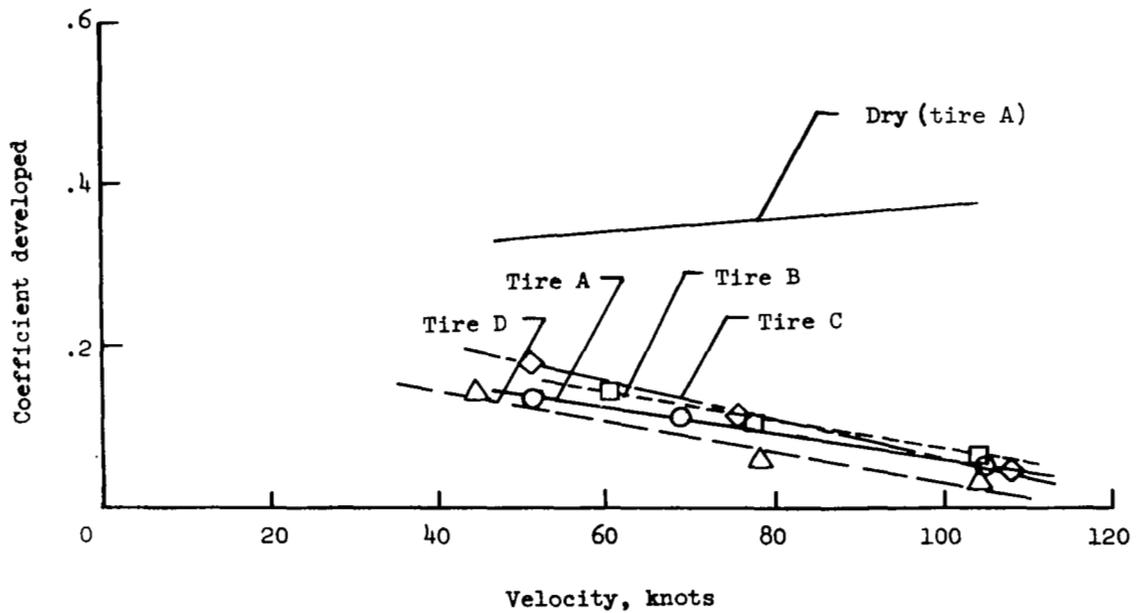
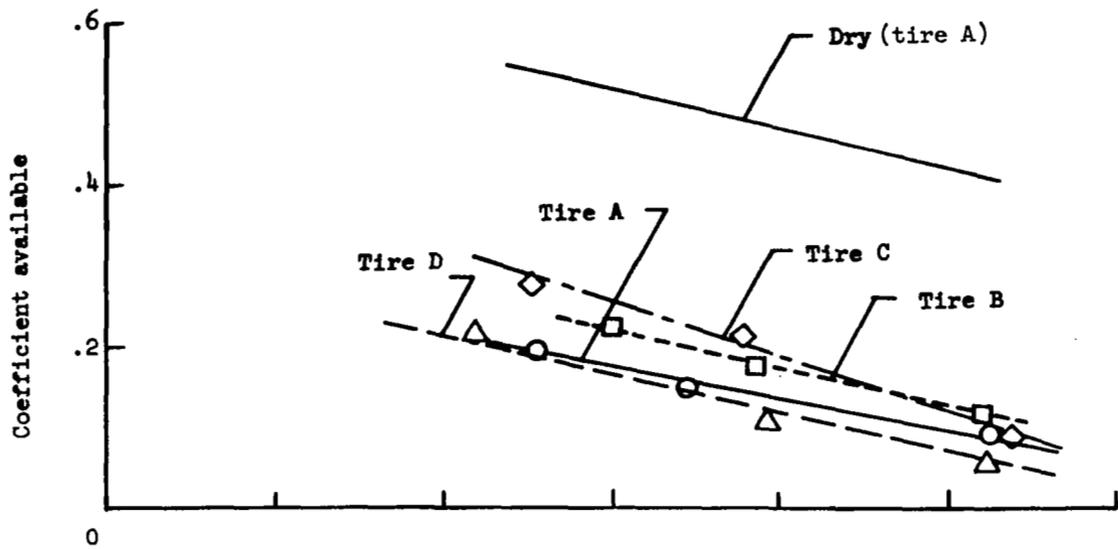
Figure 4. - Variation in friction coefficient with wheel slip ratio under cyclic braking conditions.

Yaw angle = 4°; tire A.



(a) Damp runway.

Figure 5.- Effects of tire differences on average developed and maximum available friction coefficients. Yaw angle = 0° .



(b) Flooded runway.

Figure 5.- Concluded.

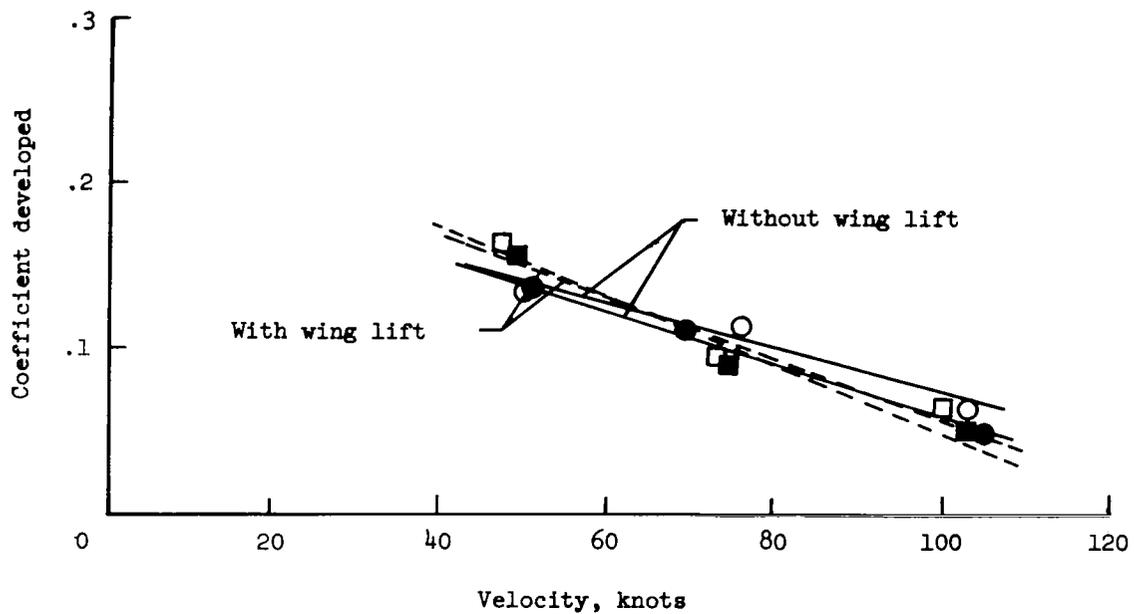
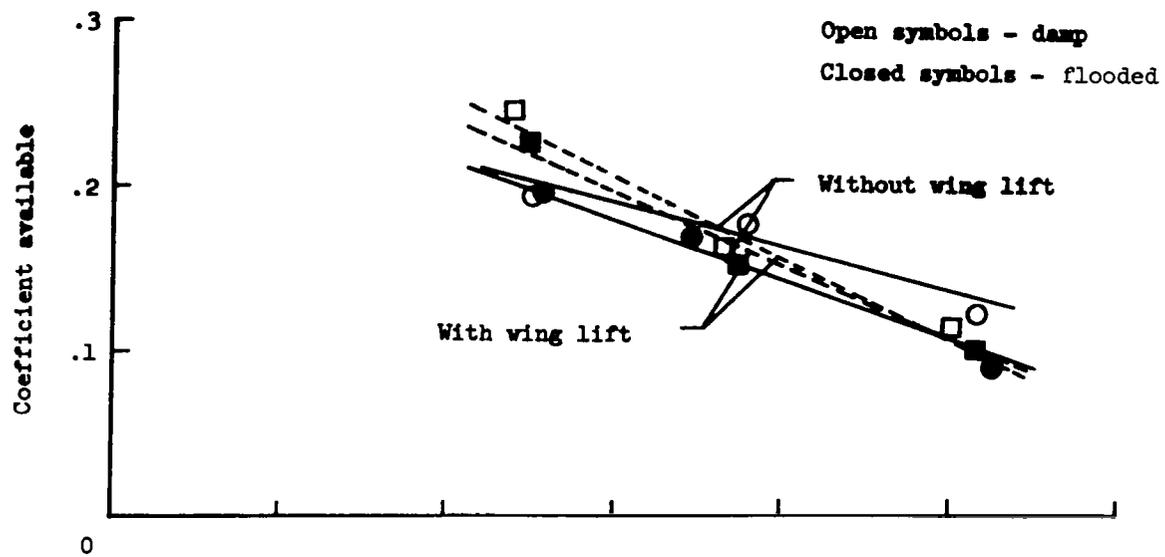
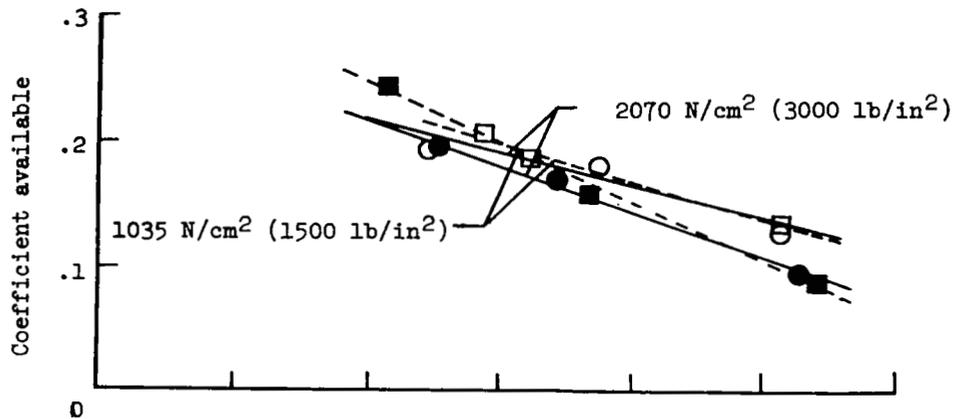


Figure 6.- Effect of wing lift on average developed and maximum available friction coefficients. Tire A; Yaw angle = 0°.



Open symbols - damp
 Closed symbols - flooded

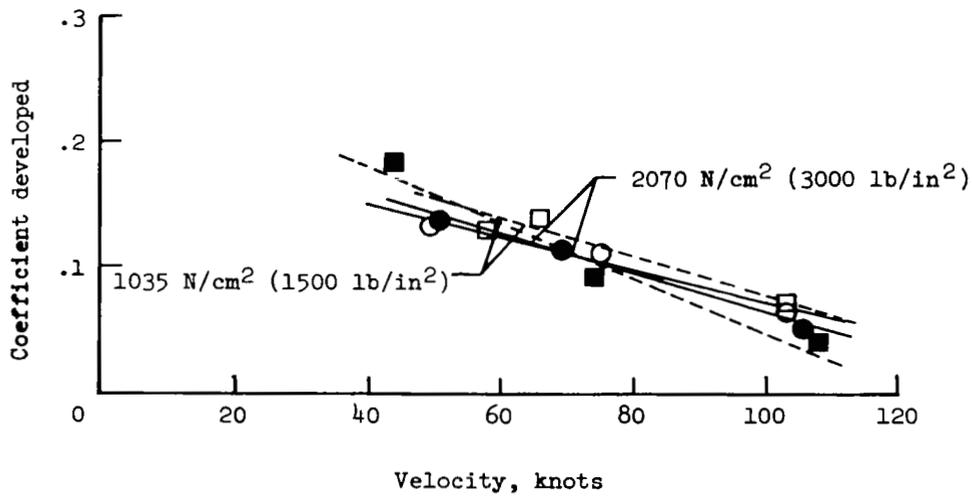


Figure 7.- Effects of reduced brake system pressure on average developed and maximum available friction coefficients. Tire A; Yaw angle = 0°.

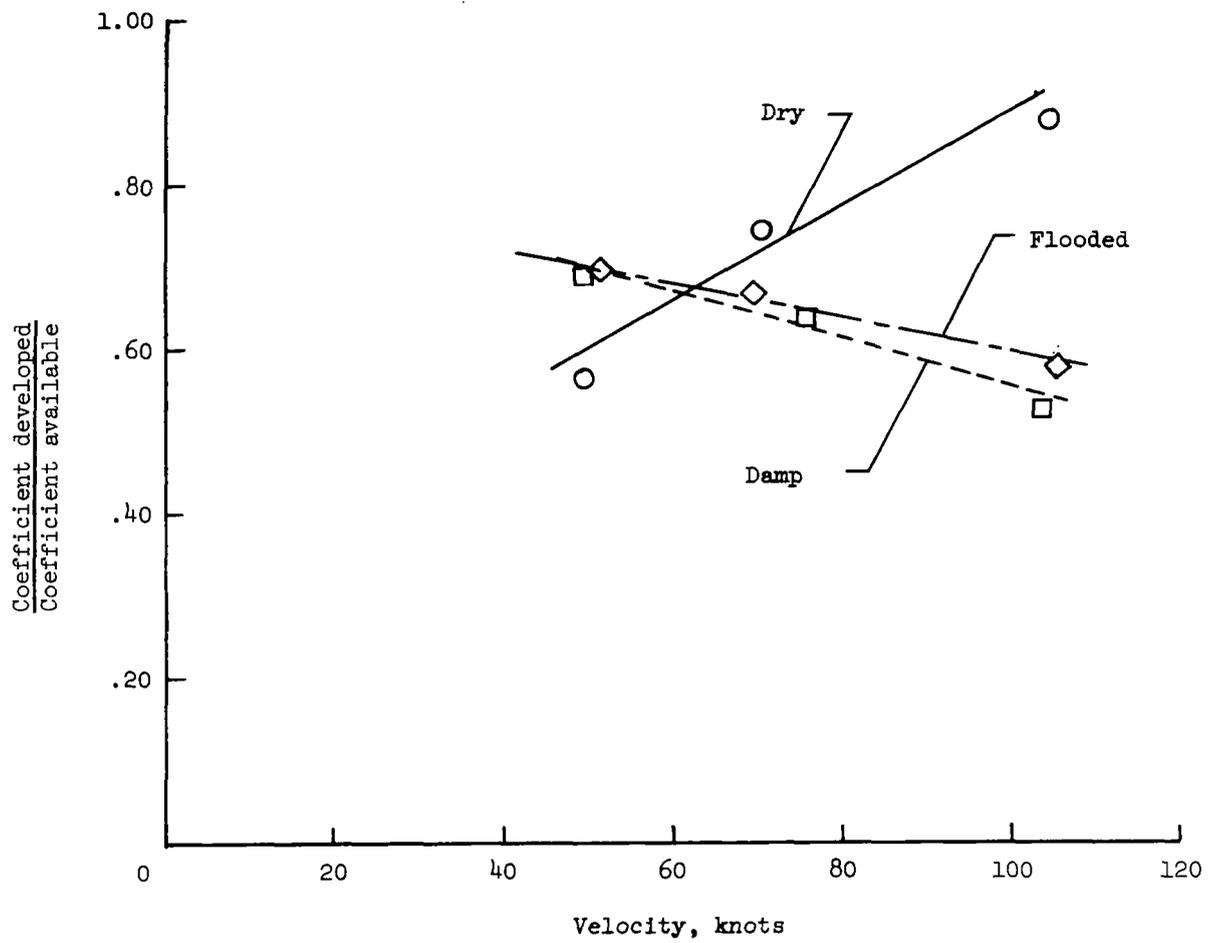


Figure 8.- Variation in the ratio of average developed friction coefficient to maximum available friction coefficient with velocity. Tire A; Yaw angle = 0°.

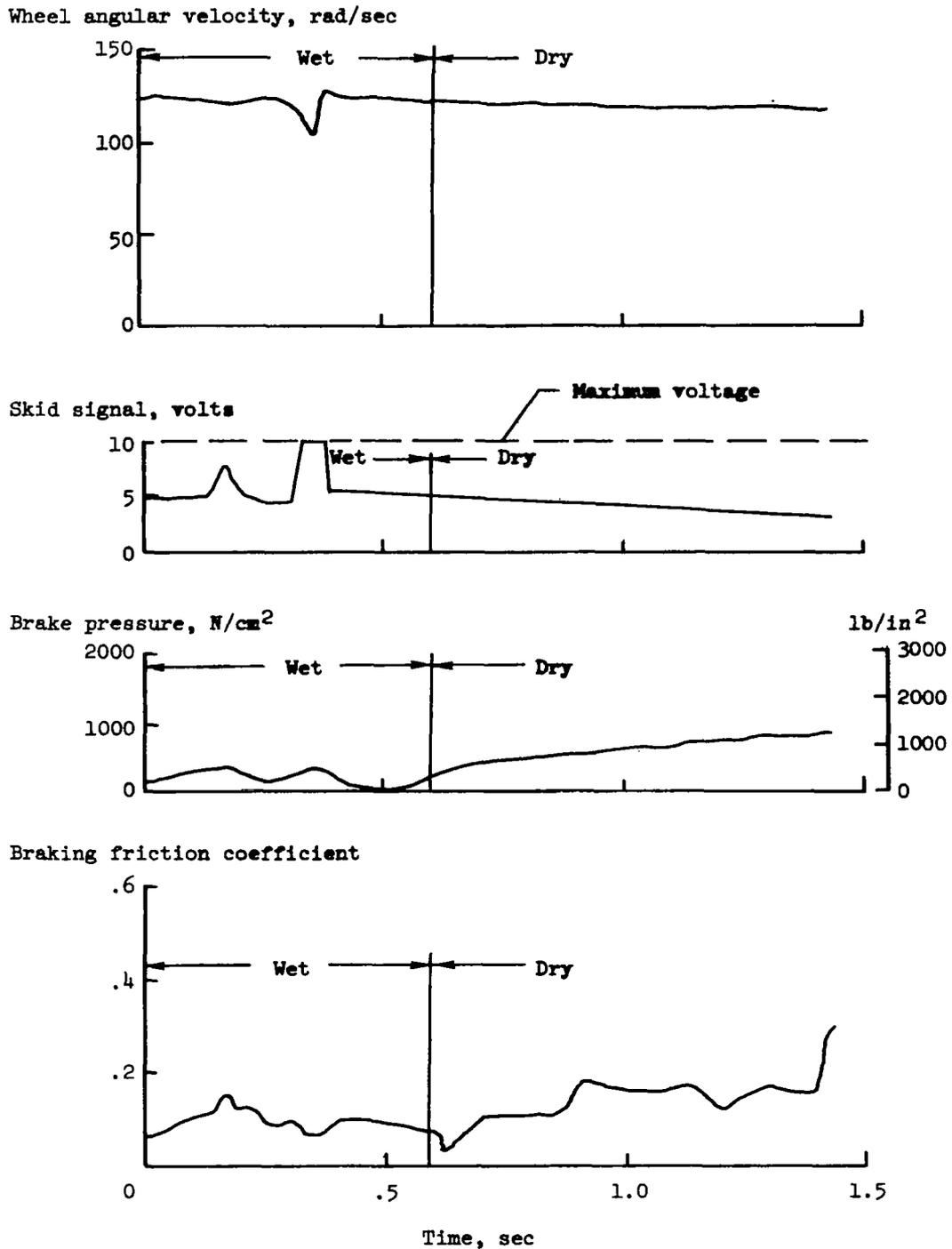


Figure 9.- Time history of brake system response during transition from wet to dry concrete. Tire B; Yaw angle = 0°.

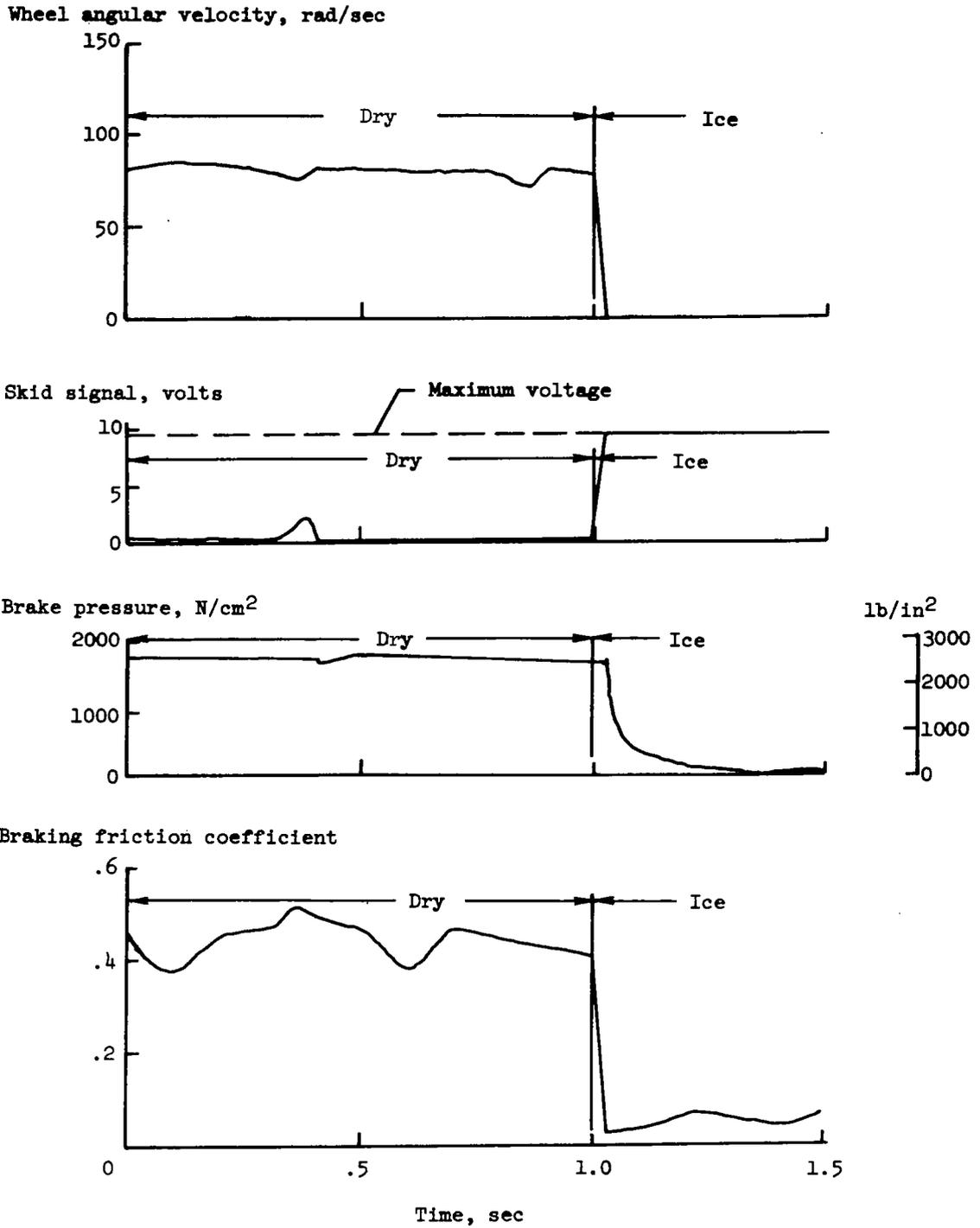


Figure 10.- Time history of brake system response during transition from dry to ice-covered concrete. Tire A; Yaw angle = 0°.



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Figure 11.- Reverted rubber in tread of tire A following locked-wheel skid on ice-covered concrete.