RECENT PROGRESS TOWARDS PREDICTING AIRCRAFT GROUND HANDLING PERFORMANCE

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SUMMARY

The current capability implemented at Langley in simulating aircraft ground handling performance is reviewed and areas for further expansion and improvement are identified. The problem associated with providing necessary simulator input data for adequate modeling of aircraft tire/runway friction behavior is discussed and recent efforts to improve tire/runway friction definition, and hence simulator fidelity, are described. Aircraft braking performance data obtained on several wet runway surfaces are compared to ground vehicle friction measurements and, by use of empirically derived methods, agreement obtained between actual and estimated aircraft braking friction from ground vehicle data is shown. Further research efforts to improve methods of predicting tire friction performance are discussed including use of an instrumented tire test vehicle to expand the tire friction data bank and a study of surface texture measurement techniques. Future development plans directed towards improving the capability and fidelity of the aircraft ground handling simulation program are discussed relative to achieving "total simulation" and providing a valuable research tool for use in solving aircraft ground operational problems.

INTRODUCTION

Flight simulation is as old as powered flight itself if one considers the gliders the Wright brothers built to solve control problems before risking their lives and airplane. Since then we have had a number of simulation devices but it was not until the 1940's that flight simulation provided an electronic equivalent of the airplane, its flight crew input-output cues and indications of all instruments, systems, and flight control units. Over the intervening years, motion cues have been added together with out-of-cockpit visual cues not only to greatly enhance simulation capability, but also to provide impetus for expanded usage of the simulator as a training tool. A 1978 American Airlines survey of 18 scheduled U.S. airlines revealed that more than 70 modern flight simulators were owned and operated for air crew proficiency checks and transition training. Data from this survey also indicated that the annual fuel savings will exceed 380 kL (100 million gal) through the use of flight simulators for recurrent training requirements alone; over 760 kL (200 million gal) of fuel will be saved annually for all simulator applications in lieu of actual airplane flights. In addition to this proven energy conservation and a noticeable increase in quality and effectiveness of crew training, many airlines have identified improved safety in both training and operations as one of the major contributions of the flight simulator.

More recent progress in technology and rapid development of advanced simulator systems have encouraged airline training executives to seriously consider "total simulation" as a near term reality. The Federal Aviation Administration (FAA) has further stimulated this move toward total simulation with a proposed plan involving an incremental program that would lead to providing 100% training in simulators, followed by routine line checks. At present, airline simulator training is supplemented by at least several hours flying in the real thing. It is thus vitally important that simulators reproduce aircraft behavior as accurately as possible and pursuit of total simulation for crew training is generally conceded to require better visual systems and improved, more comprehensive, aircraft data. Significant progress has been achieved in meeting visual system requirements with development of daylight computer-generated image displays; but the paucity of data available for aircraft in ground effect (how an aircraft behaves during the last 90 m (295 ft) or so of a landing approach) and, to a lesser extent, aircraft performance on the ground continues to compromise total simulation fidelity. Flight test programs and research studies using instrumented aircraft have proven helpful in defining airplane braking performance, but because of limitations imposed by safety constraints, rising costs, and the ability to control test parameters, researchers have turned to development of new test techniques, computational methods, and improved simulation capabilities for acquiring complete aircraft ground handling characteristics.

This paper discusses NASA's program effort to expand flight simulator capability to confidently address aircraft ground handling performance, and hence aid in the development of total simulation as well as provide a useful tool for research studies. A description of the development and implementation of Langley's aircraft ground handling simulation facility is given together with an explanation of how the necessary tire/runway friction models were determined. The problems confronting researchers trying to accurately and adequately define the influence of this complex factor on aircraft ground performance are examined, and the need to improve and expand test data sources is identified. The use of empirically derived methods of estimating tire friction capability is explained and recent efforts to improve fidelity and expand usefulness of test methods and procedures to acquire better tire/runway friction models are discussed. The paper concludes with anticipated future developments to improve the simulator capability.

AIRCRAFT GROUND HANDLING SIMULATION FACILITY

Background

The rapid growth of jet-powered, high-performance aircraft usage in the civil and military fleets, coupled with improvements in airport landing aids, has resulted in an increased number of aircraft takeoff and landing operations under adverse weather conditions. Aircraft ground operational safety margins are severely compromised by combinations of such factors as slippery runways, crosswinds, windshears, extended touchdown points, excessive velocity, equipment malfunction, piloting techniques, and reduced visibility. Joint NASA, FAA, and USAF aircraft braking studies (see refs. 1 to 6) have indicated that on many runways, tire traction capability can be significantly degraded in the presence of rain, ice, or other pavement surface contaminants. These studies also provided the stimulus to investigate and improve the equally important directional control aspect of aircraft ground handling performance, particularly under conditions of crosswind and low runway friction. However, safety constraints as well as unpredictability of surface winds preclude full-scale flight testing as a viable means of fully defining aircraft directional control limitations. As a result of this impasse, NASA initiated in 1973 a feasibility study to expand available flight simulation capability to include the complex ground phase of aircraft operations. The feasibility of this approach was verified in a contracted study by McDonnell Aircraft Company using an F-4 fighter aircraft. The implementation of this initial contractor study and the results from piloted validation runs are documented in reference 7 and described in a paper (ref. 8) presented during the 1976 NASA conference on aircraft safety and operating problems.

Subsequent contractor development and expansion efforts, reported in references 9 and 10, resulted in validating a DC-9 aircraft ground handling simulation program in 1977. This simulation program has been implemented at Langley, using existing simulation equipment and computer facilities, and verified through piloted evaluation runs and agreement with available aircraft test data. Aircraft landings, ground maneuvers, takeoffs, and aborted takeoffs have been simulated and the effects of many parameters on aircraft ground performance are being studied, including crosswinds, runway roughness and friction levels, reverse thrust, and antiskid brake system operation. Although development of an adequate simulation of the ground phase of aircraft operations is an essential step in achieving total aircraft simulation, NASA Langley's primary interest is in using this expanded simulator capability as a research tool for study and solution of aircraft ground operational problems.

Motion Base Simulator

The motion simulation is provided to a general-purpose cockpit (adapted to represent a DC-9 aircraft) by a six-degree-of-freedom synergistic motion base as shown in figure 1. The six-axis motion is provided by six hydraulic jacks arranged in a configuration developed by the Franklin Institute, with the performance limits listed as follows:

Degree of Freedom	Position		Velocity	Acceleration
Horizontal X	Forward Aft	1.245 m 1.219 m	±0.610 m/sec	±0.6g
Lateral Y	Left Right	1.219 m 1.219 m	±0.610 m/sec	±0.6g
Vertical Z	Up Down	0.991 m 0.762 m	±0.610 m/sec	±0.6g
Yaw ψ	$\pm 32^{o}$		$\pm 15^{o}$/sec	$\pm 50^{o}/sec^{2}$
Pitch θ	$+30^{o}$ -20^{o}		$\pm 15^{o}$/sec	$\pm 50^{o}/sec^{2}$
Roll ϕ	$\pm 22^{o}$		$\pm 15^{o}$/sec	$\pm 50^{o}/sec^{2}$

The base does not have independent drive systems for each degree of freedom, but achieves motion in all degrees of freedom by a combination of actuator extensions. Software is provided for the actuator extension, inverse transformation, the centroid transformation, and the washout algorithm necessary to return the base to the neutral point once the onset motion cues have been commanded. The washout algorithm is a Langley adapted version (ref. 11) of Schmidt and Conrad's coordinated washout circuitry, with the parameters modified slightly for ground handling. Figure 2 shows the interior of the cockpit with seats provided for the pilot and first officer or observer. The visual display is provided to both seats. Instruments showing airspeed, attitude, glide slope deviation, heading, localizer deviation, altitude, and vertical speed are active for the pilot. The column, wheel, and rudder pedals furnish primary flight inputs to the computer. Throttles with reverse thrust, flap control, and manual or automatic spoilers are available. Engine pressure ratio instruments, reverse thrust bucket indicator lights, and other instrumentation are available.

Visual Landing Display System

The visual landing display system (VLDS) is a camera/model board system designed to generate a six-degree-of-freedom, visual, out-the-window scene for the pilot of a simulated aircraft. The system shown in figure 3 consists of an 18.3x7.3 m (60x24 ft) dual-scaled terrain model, a lamp bank to illuminate the model, a three-degree-of-freedom translation motion system to position the camera, and a three-degree-of-freedom optical/rotational system mated to a color television camera. The terrain model contains two airports sufficiently separated to facilitate a scale factor of 1500:1 at the three-runway airport layout and a scale factor of 750:1 at the two-runway and heliport airport layout. With the minimum camera "look-point" height of the optical probe limited to 0.178 cm (0.070 in.), which equates to 2.74 m (9 ft) at 1500:1 or 1.37 m (4.5 ft) at 750:1, the dual scale provides the capability of simulating both large and small aircraft during landings, ground maneuvers, and takeoffs. The two long runways at the larger airport represent runways which are 3505 m (11 500 ft) in length and 81 m (267 ft) in width, and it is on these two runways that piloted test runs are conducted in the DC-9 aircraft ground handling program. The visual scene, displayed to the pilot by the color television camera signals transmitted to an external cockpit cathode ray tube screen, provides a horizontal and vertical field of view of 48 and 36 degrees, respectively. Figure 3 also shows a typical scene presented to the simulator pilot during approach for landing. Options available for the visual scene display include daytime, dusk, or nighttime conditions as well as limited visibility. Reference 12 contains additional information about the equipment, operation and performance of the Langley VLDS.

Computer Program Capability and Characteristics

The simulation was implemented at Langley as shown in figure 4. The six-degree-of-freedom equations of motion representing the airframe, the aerodynamic and control system, the engines, the environment, landing gear and brake system, and auxiliary equations are all computed on a CDC Cyber 175 computer. The Cyber computer also provides computations for the VLDS drive signals and the motion base washout and drive equations, as well as all cockpit instrument signals. The computer is interfaced with the VLDS, the motion base, and cockpit as shown in the figure. The loop is closed by the pilot providing the control deflections and thrust settings from the cockpit back to the computer.

The implementation of the model on the computer requires approximately 132 000 octal locations of memory and approximately 45% of the available control processor unit (CPU) time. Since the range of the mission is large (an aircraft during landing approach through a complete stop on the ground), and the ground model is complex and extensive (composed of full strut and tire dynamics for individual landing gears as well as a variety of runway slipperiness ranges), some special programing techniques were required. The landing gear dynamics are characterized by a set of lightly damped, high frequency, differential equations. To maintain stability of these solutions in a real-time environment with a reasonable number of iterations/sec to hold down CPU time without compromising the landing gear behavior, a local linearization integration algorithm (ref. 13) was used. The second order Adams-Bashforth algorithm was used for all other equations and the iteration rate for the whole model was 32/sec. Other special implementation techniques were required to accommodate the aircraft reaching zero velocity, crosswind effects on aircraft at zero forward velocity, trimming the aircraft at zero velocity, and a piloting technique of holding "brakes-on" during thrust buildup for takeoff while waiting at the end of the runway.

Validation of ground handling simulators in general is hampered to some degree by lack of flight data, although data does exist for stopping distances and lateral deviations from the centerline of the runway under various conditions. Table I summarizes the extent of the validation effort completed at Langley in the simulation program. The quantity of solutions in different categories and whether they were quantitative (compared to measurable data) or qualitative (subjective opinion from pilot or researchers) are shown. Also indicated is the source of comparison data for each category, whether it be actual flight data or Douglas Aircraft Co. (DAC) simulator results. The first three categories of solutions, longitudinal trim, longitudinal dynamic damping, and lateral direction damping, were "in-flight" checks. The remaining four categories, three of which were piloted, were for validation on the ground. The last category of selected piloted cases covered the majority of runway friction variations, wind conditions, and aircraft ground maneuvers. The results of the Langley validation checks compared favorably with the flight data and the DAC simulation results.

Simulation Models

The aircraft system, which must be defined mathematically and programmed in the computer to provide the simulation capability, consists of five principal models: aerodynamics, engines, landing gear, antiskid brake system, and tire/runway friction. A mathematical description of the aircraft motion is formed by establishing a fixed reference plane representing the earth and equations are written to define the displacements, velocities, and accelerations of the aircraft. The principal force inputs to these equations of motion come from gravity and the aircraft aerodynamics, engines, and landing gear. This aircraft force data, derived from both wind tunnel and flight test data, is compiled in a form suitable for use with the equations of motion. The complete DC-9 airframe mathematical model, based on a combination of these equations of motion with mathematical representations of aircraft control and guidance systems, wind and turbulence, runway roughness, and other pertinent elements, was provided by Douglas Aircraft Company, under contract to Langley, and documented in reference 14. This reference also describes how the digital antiskid brake system performance was derived and modeled from both NASA track test data reported in reference 15 and flight test data documented in reference 5.

Of all the mathematical models developed to implement the aircraft ground handling simulation program, the environmentally sensitive tire/runway friction modeling proved to be the most challenging to define. Available data sources from various flight test studies and track test investigations (see refs. 1 to 6 and 16 to 18) were found insufficient to completely determine the aircraft ground operation envelope of braking and cornering friction performance for the range of runway contamination conditions desired in the simulation. As a result of this lack of experimental data, NASA assisted the contractor in obtaining the desired friction models using analytical methods based on empirically derived tire friction relationships discussed in references 19 and 20. The tire friction curves (see ref. 14) generated from this mix of analytical and experimental test data described the unbraked cornering force friction coefficient variation with yaw angle for both main and nose gear tires, and the combined cornering and braking friction coefficient variation with yaw angle and slip ratio for the main gear tires at ground speeds from 0 to 150 knots on a variety of runway contamination condition

The runway conditions simulated by these tire friction curves included continuous dry, wet, flooded, or icy pavements. Combinations of these conditions, described by the term "patchy", were also modeled to expose the aircraft main gear tires to simulated symmetrical and unsymmetrical variations in friction while traveling down the runway. In general, the 15 line and test pilots that have flown the simulation during checkout, validation, demonstration, and parameter evaluation runs have been favorably impressed with the simulated aircraft ground handling performance but several areas related to the tire/runway friction model have been identified for improvement (see ref. 10). Consequently, NASA has initiated efforts involving new equipment and test techniques directed toward acquiring additional data necessary to enhance the fidelity of the tire/runway friction model and concurrently, to refine and improve the empirically derived methods used for estimating tire friction performance.

SOME RECENT EFFORTS TO IMPROVE TIRE/RUNWAY FRICTION DEFINITION

An adequate ground handling simulation for a particular aircraft type depends substantially on how accurately the tire friction envelope, including free rolling, braking, cornering, and combinations thereof, is defined for meeting demands imposed during ground operations under a wide variety of loading, speed, and environmental conditions. Determination of aircraft tire friction performance, however, is difficult at best considering the varied influence of both tire and runway surface characteristics and the effects of aircraft landing gear geometry and brake system performance. Review of test results from previous studies (including refs. 1-6, 8, 15-19, 21-23) has provided researchers with sufficient friction data on a large number of different-sized pneumatic tires to permit determination of empirically derived equations and relationships for use in estimating a particular tire friction performance. Figure 5 indicates in block diagram form how this methodology is used to transform tire friction-speed gradient data obtained experimentally in one operational mode (e.g. ground vehicle, locked-wheel tire friction) into estimated aircraft tire locked-wheel skidding (μ_{skid}), maximum (μ_{max}), and side (μ_{side}) friction coefficient variations with speed for different surface conditions and tire yaw angles. Using an antiskid brake system efficiency term (η), the estimated aircraft tire effective braking friction coefficient (μ_{eff}) variation with speed can be determined from the derived maximum friction values. Details of the procedures and equations currently used in this methodology are given in reference 20. Further refinements and improvements of these methods are planned based on results obtained from several ongoing tire friction studies (see ref. 24) and antiskid brake system evaluations (see ref. 25) conducted at the Langley Landing-Loads Track, in addition to the aircraft/ground vehicle tests and surface texture measurement study discussed in the following sections.

Aircraft/Ground Vehicle Friction Measurements

A joint NASA/FAA runway friction program was initiated in 1978 with several major objectives: (1) to establish a safe and reliable instrumented aircraft test technique for evaluating runway friction; (2) to obtain comparative friction data with old and new technology ground vehicle friction measurement systems; and (3) to determine the degree of correlation between different ground vehicle friction measurements and between ground vehicle and aircraft friction readings. The aircraft and the three ground vehicles selected for testing in this program are shown in figure 6. The FAA Sabre-liner-80 aircraft is a swept-wing, twin-engined jet airplane equipped with antiskid brake units on the dual main landing gear wheels. A portable accelerometer package coupled to an analog tape recorder was installed in the aircraft to provide continuous time history records of aircraft deceleration during maximum-braking test runs. The mu-meter is a British-developed side-force measuring trailer which was towed with a light truck. The two friction-measuring tires are operated at a 7.5^{o} toe-out angle and the third (rear central) wheel drives a chart recorder for monitoring the variation in side force friction during test runs. The diagonal-braked vehicle (DBV) friction measuring system was developed by NASA to safely obtain locked-wheel friction data at high speeds using smooth ASTM E524 tires on the braked, diagonal pair of wheels. An on-board oscillograph recorder provides time histories of several test parameters including vehicle ground speed, stopping distance, and longitudinal deceleration during braking. Additional details concerning the mu-meter and the DBV are given in references 3, 4, and 5. The friction tester vehicle is a relatively new friction measuring device, and is equipped with front wheel drive and a hydraulically retractable measuring wheel installed behind the rear axle. The measuring wheel, which is designed to operate at a constant 15 percent braking slip ratio, is connected to the axle of the free rolling rear wheels by a chain transmission. The forces acting on this measuring wheel and the distance traveled are fed into a digital computer where the information is converted into friction coefficient form and location on the runway. Friction tests with this device can be conducted at speeds up to 161 km/hr (100 mph) and an on-board wetting system is available for obtaining wet surface friction data.

The NASA Wallops Flight Center was chosen as the test site because of the variety of grooved and ungrooved runway surfaces and the large data bank compiled from other aircraft braking performance tests (see refs. 1 to 5). A series of instrumented aircraft braking runs were made on each surface under dry and artificially wet conditions. Since many of the test surfaces were only 107 m (350 ft) long, several runs were required to obtain friction measurements over the desired speed range. A large water tank truck, equipped with a wide dispersal nozzle, was used to wet the surface before each series of tests. In order to minimize the effects of time-related changes in surface wetness conditions, the time of ground vehicle measurements taken before and after each aircraft test run was noted and later the measurements were corrected, by linear interpolation, to the time of the aircraft test run. These corrected ground vehicle friction measurements reflect the same runway slipperiness condition as encountered by the aircraft.

Table II provides a compilation of the friction readings obtained at speeds of 17, 35, and 52 knots with the test aircraft and the three ground vehicles under artificially wetted conditions on all five types of runway surfaces. Since the friction data obtained with each test vehicle on the two concrete and two asphalt transversely grooved surfaces did not differ significantly, all the grooved surface friction data were faired to determine average friction values at each speed increment. Agreement in ranking the surfaces was obtained by the four test vehicles despite significant differences in the type of friction coefficient measured by the aircraft and each ground vehicle. Friction readings on the well-textured, damp, slurry-seal asphalt surface were the highest (ranking of 1) whereas the poorly textured, wet, canvas belt-finished concrete surface produced the lowest (ranking of 5) friction readings for all vehicles. Friction readings on the grooved surfaces were somewhat less than that measured on the slurry-seal asphalt because of the influence of several isolated puddles which were observed on the grooved surfaces after artificial wetting.

A further comparison of the aircraft and ground vehicle friction measurements obtained on each of these fives types of surfaces with artificial wetting is given in figure 7. The faired friction-speed gradient curves indicate the wide range of friction values determined from the aircraft and ground vehicle tests. The significant differences in the aircraft and ground vehicle tire characteristics, operating test modes, and braking system operations contributed to this friction data dispersion. Further evidence of the effect of tire characteristics is shown by the difference in the friction tester data obtained using both a high pressure, 3-groove tire and a low pressure, patterned tread tire. The data curves in figure 7 also illustrate the complexity of the problem faced in relating ground vehicle friction measurements obtained in one tire operational mode (e.g., locked wheel μ_{skid}) with that developed by an aircraft equipped with an antiskid brake system.

Calculations were made, however, to estimate the effective Sabreliner-80 aircraft braking friction coefficient variation with speed based on the friction measurements obtained by each ground vehicle and using the empirically derived methods discussed earlier in this paper. In general, the actual aircraft braking performance and that estimated from the ground vehicle friction measurements are shown in figure 8 to be in relatively good agreement on each of the five different test surfaces. The friction tester device shows great promise in providing runway friction measurements for use in estimating aircraft friction performance. Further evaluation of the test tires used by each ground vehicle is in progress using an instrumented tire test vehicle (truck), and test results may justify some modifications in the transformation relationships to provide closer agreement with the aircraft friction measurements.

Instrumented Tire Test Vehicle Friction Evaluations

The main features of the instrumented tire test vehicle (ITTV) used in previous tire friction and wear studies (see ref. 26) are identified in figure 9. Vertical load on the test tire up to 22.2 kN (5000 lb) is applied by means of two pneumatic cylinders and this load, together with the drag and side loads developed on the tire during test runs, is measured by strain gage beams centered about the wheel and mounted above the wheel-axle support structure. Continuous time histories of the output from these strain gages are recorded on an oscillograph mounted in the vehicle cab compartment. A pneumatic system to lower or raise the test tire from the surface is controlled in the cab compartment by the vehicle operator. Simulated tire braking at fixed slip ratios is accomplished by driving the test wheel with an adjustable steel shaft connected through a universal coupling (see fig. 9(b)) to interchangeable sprocket gears, which in turn, are chain driven by a sprocket replacing one left rear driving wheel of the vehicle. Changing the slip ratio involves replacement of the sprocket gear positioned at the driving end of the universal coupling. For locked-wheel braking tests, the universal shaft and coupling are removed and a mechanical locking device is installed on the test wheel axle to prevent wheel rotation. For yawed rolling tire tests, the test fixture is rotated manually to the preselected angle and locked in place. The output from the instrumented trailing wheel, providing an accurate measurement of vehicle speed and distance, and a cam-operated microswitch mounted on the test wheel axle, transmitting a signal for each test wheel revolution, is recorded on the oscillograph as well as displayed to the vehicle operator on digital counters in the cab compartment.

Braking and cornering tests have been conducted on several different runway surfaces at NASA Wallops Flight Center using the ITTV equipped with the bias-belted ASTM E501 and E524 test tires used on skiddometer trailers and diagonal-braked vehicles. The E501 tire has a 6-groove rib-tread pattern and the E524 tire has no tread (smooth) pattern. Wet surface tire braking results from these tests indicated that throughout the speed range evaluated, the rib-tread E501 tire developed higher friction compared to the smooth E524 tire. Figure 10 shows similar results that were obtained on an asphalt and a concrete surface at a test track in San Angelo, Texas using a skiddometer trailer device equipped with an on-board wetting system. Several locked-wheel friction (μ_{skid}) measurements were taken at each of six speed increments up to 97 km/hr (60 mph) and the data points shown in the figure indicate numerical averages of the μ_{skid} values obtained at each speed. In general, the locked-wheel friction developed by both tires on the two wet surfaces decreased with increasing speed as expected (see ref. 22) but the higher friction levels developed on the asphalt surface are contrary to previously noted trends of higher friction with higher surface texture depths. Measurements of surface macro-texture depth using the silicone putty sample technique described in reference 27 indicate the asphalt surface has considerably less macro-texture than the concrete surface. Apparently surface micro-texture characteristics as well as aggregate shape and surface finish treatment must significantly contribute to the ability of the test tires to develop friction forces on the wet surfaces.

Surface Texture Measurement Study

It has long been recognized that the friction forces which a pneumatic tire can develop for the purposes of braking, cornering, or driving are greatly influenced by the finish of the runway or road surface. Many different volumetric, profile, topography, and drainage techniques (see ref. 27) have been developed by reseachers to provide quantitative measurements of surface macro-texture (large scale) and to a lesser degree of success, surface micro-texture (small scale). Results from previous tire friction evaluations (e.g., see ref. 28) have indicated that the slope and the magnitude of the friction-speed gradient curve are functions of the surface macro- and micro-texture features, respectively.

A study of surface texture measurement techniques was recently started to determine the correlation between values obtained with several different techniques and to further define the relationship of these measurements with tire friction performance. Figure 11 shows an example of the correlation established between surface macro-texture depth values measured on a variety of concrete and asphalt pavements using the grease sample and sandpatch methods. Both techniques (see photographs in fig. 11) involved spreading a known volume of material (grease or sand) over the surface, measuring the area covered, and calculating an average texture depth. The data points shown in the figure represent average values determined from six measurements on a given surface with each method and the correlation equation was calculated using a least squares linear data fit. The grease sample technique results in a lower (approximately half) texture depth value than that measured by the sandpatch method, probably because of the manner in which the two materials are applied to the surface. The sand is spread by a lightly loaded, hard rubber disc which makes contact with only the high points in the pavement aggregate, whereas the grease is spread by a relatively soft rubber squeegee with a force that tends to wipe the high pavement peaks and fill the voids. Factors influencing this correlation are currently being evaluated, together with several other techniques including static drainage measurements obtained with outflowmeters.

An outflowmeter consists of a transparent cylinder with a rubber ring attached to the bottom face. When placed on a pavement surface, the cylinder is loaded so that the rubber ring will drape over the aggregate particles in a manner similar to that expected of tire tread elements. Water is poured into the open-topped cylinder, and the operator initiates water discharge by raising a rubber stopper at the bottom of the cylinder. The time required for a known volume of water to escape through any pores or channels in the pavement, as well as between the rubber ring and the pavement surface, is then measured. Short drainage times (high rates of flow) are thus associated with high surface macro-textures. The wide variation in outflowmeter water drainage times shown in figure 12 indicates the effect of various surface finishes and treatments on a surface macro-texture. These drainage measurements were taken on a canvas belt-finished concrete runway which was constructed level, both longitudinally and transversely, at NASA Wallops Flight Center. The runway centerline paint markings significantly reduced the ungrooved surface macro-texture (as indicated by the long drainage times) and the saw-cut grooving greatly improved the surface drainage rates. The outflowmeter drainage time measured on the 51 mm (2 in.) spaced groove pattern was approximately twice as long as that measured on the 25 mm (1 in.) spaced groove pattern. The drainage time differences shown between the two groove patterns may be partially due to the placement of the outflowmeter with respect to the groove configuration since the water discharge opening is only 51 mm (2.0 in.) in diameter.

CONCLUDING REMARKS

The significant progress which has been achieved in development of aircraft ground handling simulation capability at Langley is reviewed with additional improvements in software modeling identified. The problem associated with providing necessary simulator input data for adequate modeling of aircraft tire/runway friction behavior is discussed and recent efforts to improve this complex model, and hence simulator fidelity, are described. Aircraft braking performance data obtained on several wet runway surfaces is compared to ground vehicle friction measurements and, by use of empirically derived methods, good agreement between actual and estimated aircraft braking friction from ground vehicle data is shown. The performance of a relatively new friction measuring device, the friction tester, showed great promise in providing data applicable to aircraft friction performance. Additional research efforts to improve methods of predicting tire friction performance are discussed including use of an instrumented tire test vehicle to expand the tire friction data bank and a study of surface texture measurement techniques.

Future plans for the aircraft ground handling simulation program include development of a tire failure model and better antiskid brake system performance through test track investigations. Although attaining the capability to adequately simulate the ground phase of aircraft operations is an essential step in achieving total aircraft simulation, NASA Langley's primary interest is in using this expanded simulator capability as a research tool for study and solution of aircraft ground operational problems.

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TABLE I.- SCOPE OF AIRCRAFT GROUND HANDLING SIMULATOR VALIDATION.

TYPE OF SOLUTION (COMPARISON)	QUANTITY	TYPE OF EVALUATION		SOURCE OF COMPARISON DATA	
		QUANTITATIVE	QUALITATIVE	DAC SIMULATION RESULTS	FLIGHT TEST
LONGITUDINAL TRIM	9	√		√	√
LONGITUDINAL DYNAMIC DAMPING (PHUGOID)	2	√		√	√
LATERAL DIRECTION DAMPING (DUTCH ROLL CHARACTERISTICS)	2	√		√	√
MINIMUM CONTROL SPEED GROUND (V_{MCG}) -- PILOTED	4	√		√	√
STOPPING DISTANCE (BRAKES ONLY) -- PILOTED	4	√		√	√
GEAR DYNAMICS AND OVERALL LANDING AND ROLL OUT CONDITIONS	6	√		√	
SELECTED CASES COVERING MOST IMPORTANT PARAMETERS -- PILOTED	59		√	√	

TABLE II.- RUNWAY SURFACE RANKINGS BASED ON COMPARATIVE TEST AIRCRAFT AND GROUND VEHICLE FRICTION READINGS.
(Artificial wetting condition which differed between surfaces)

TEST DEVICE	TEST SPEED			TEST SURFACE FRICTION READING (RANKING*)				
	KNOTS	km/hr	MPH	SLURRY SEAL ASPHALT	GROOVED**	SMALL AGGREGATE ASPHALT	BURLAP DRAG FINISHED CONCRETE	CANVAS BELT FINISHED CONCRETE
SABRELINER-80 AIRCRAFT, μ_{EFF}	17	32	20	0.41 (1)	0.41 (1)	0.40 (3)	----	0.32 (5)
	35	65	40	0.40 (1)	0.40 (1)	0.35 (3)	0.34 (4)	0.28 (5)
	52	98	60	0.38 (1)	0.38 (1)	0.28 (4)	0.29 (3)	0.24 (5)
MU-METER, μ_{SIDE}	17	32	20	0.82 (1)	0.73 (2)	0.65 (4)	0.66 (3)	0.58 (5)
	35	65	40	0.80 (1)	0.68 (2)	0.38 (4)	0.57 (3)	0.26 (5)
	52	98	60	0.78 (1)	0.64 (2)	0.25 (4)	0.51 (3)	0.12 (5)
FRICTION TESTER,*** μ_{MAX}	17	32	20	0.98 (1)	0.86 (2)	0.71 (3)	0.71 (3)	0.63 (5)
	35	65	40	0.94 (1)	0.80 (2)	0.62 (4)	0.64 (3)	0.48 (5)
	52	98	60	0.86 (1)	0.74 (2)	0.43 (4)	0.56 (3)	0.23 (5)
DIAGONAL BRAKED VEHICLE, μ_{SKID}	17	32	20	0.73 (1)	0.62 (2)	0.56 (3)	0.48 (4)	0.45 (5)
	35	65	40	0.58 (1)	0.54 (2)	0.25 (4)	0.26 (3)	0.17 (5)
	52	98	60	0.51 (1)	0.47 (2)	0.13 (4)	0.18 (3)	0.06 (5)

*RANKING OF (1) INDICATES HIGHEST VALUE, (5) INDICATES LOWEST VALUE
**AVERAGE OF COMPARATIVE DATA OBTAINED ON FOUR DIFFERENT SURFACES TRANSVERSELY GROOVED WITH A 25 × 6 × 6 mm (1 × 1/4 × 1/4 in.) PATTERN
***FRICTION DATA OBTAINED WITH LOW PRESSURE, PATTERNED TEST TIRE

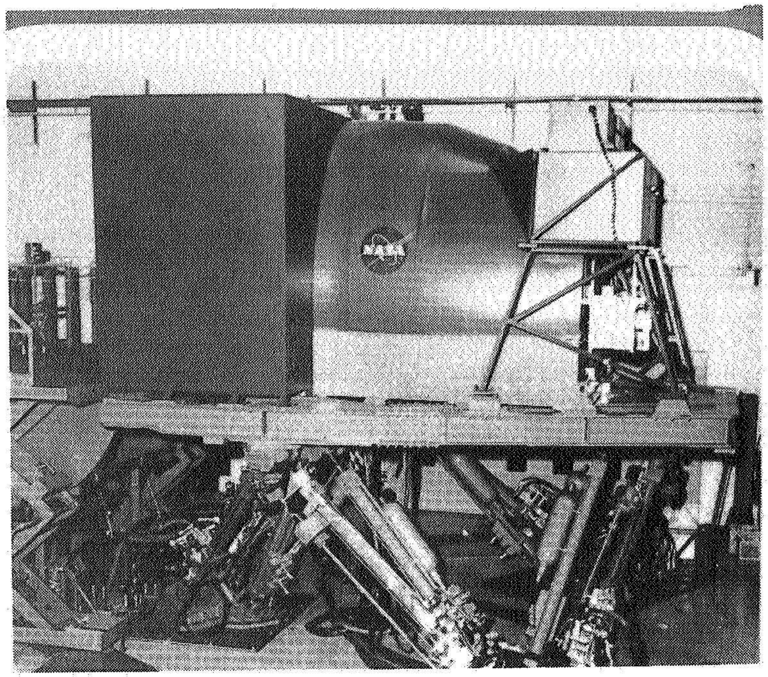


Figure 1.- Motion base simulator.

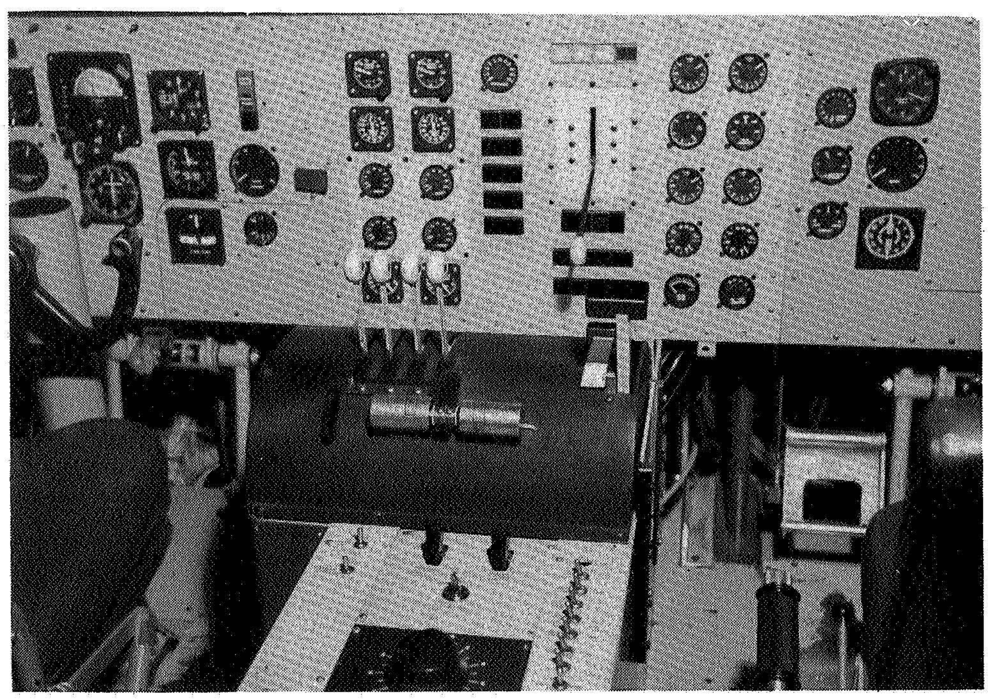


Figure 2.- Motion base cockpit interior.

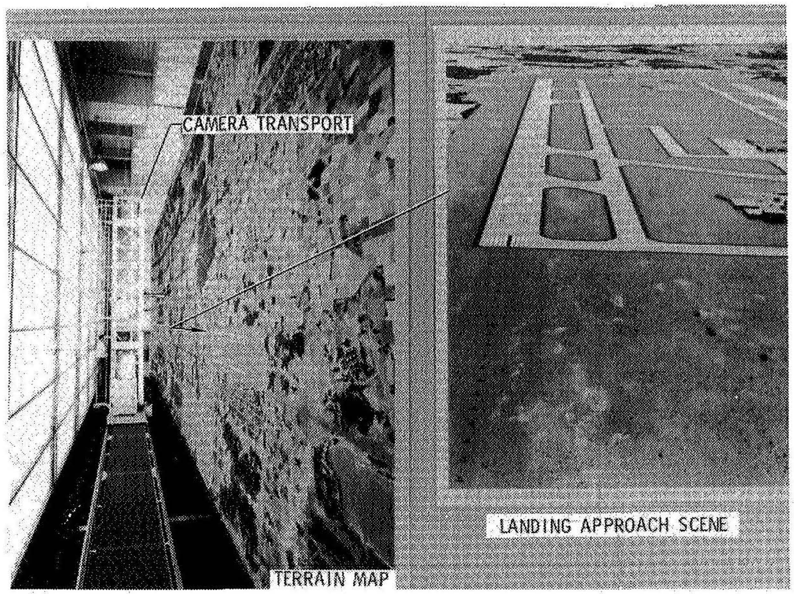


Figure 3.- Visual landing display system.

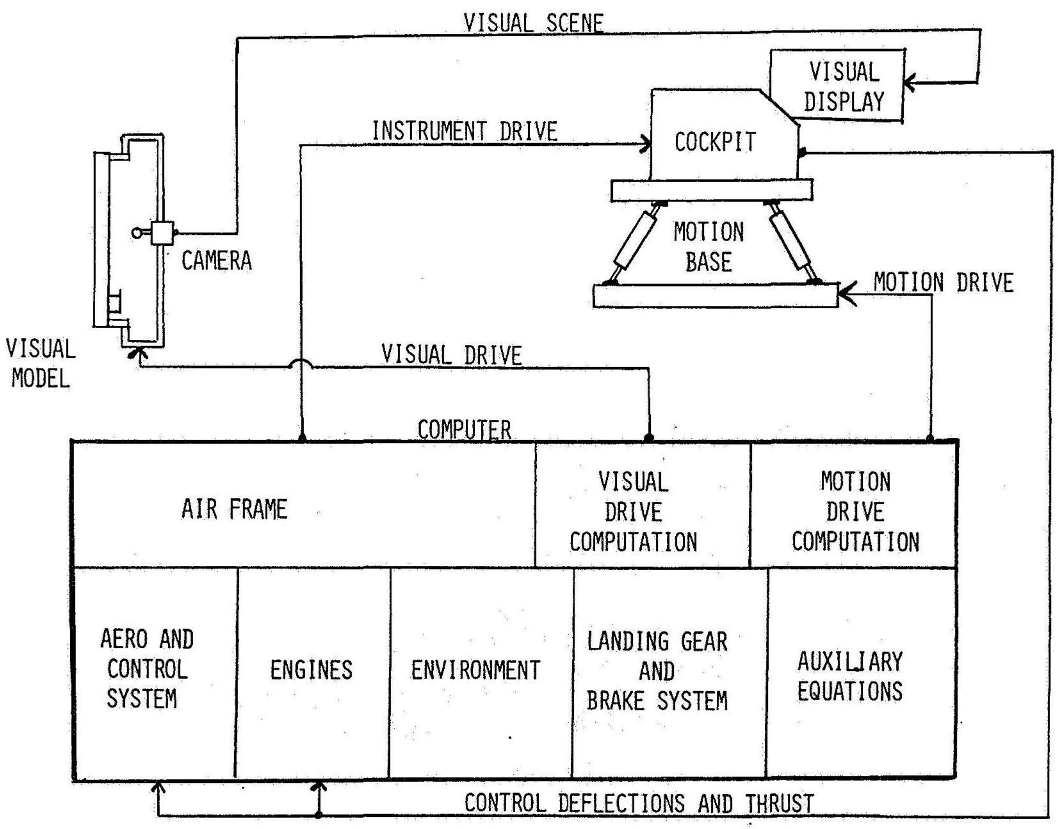


Figure 4.- Block diagram indicating implementation of aircraft ground handling simulation facility.

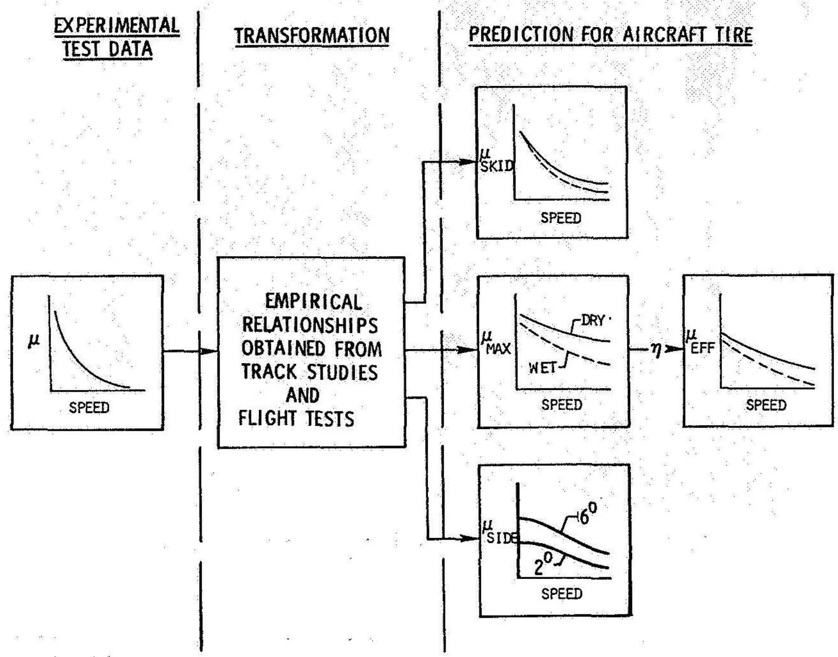
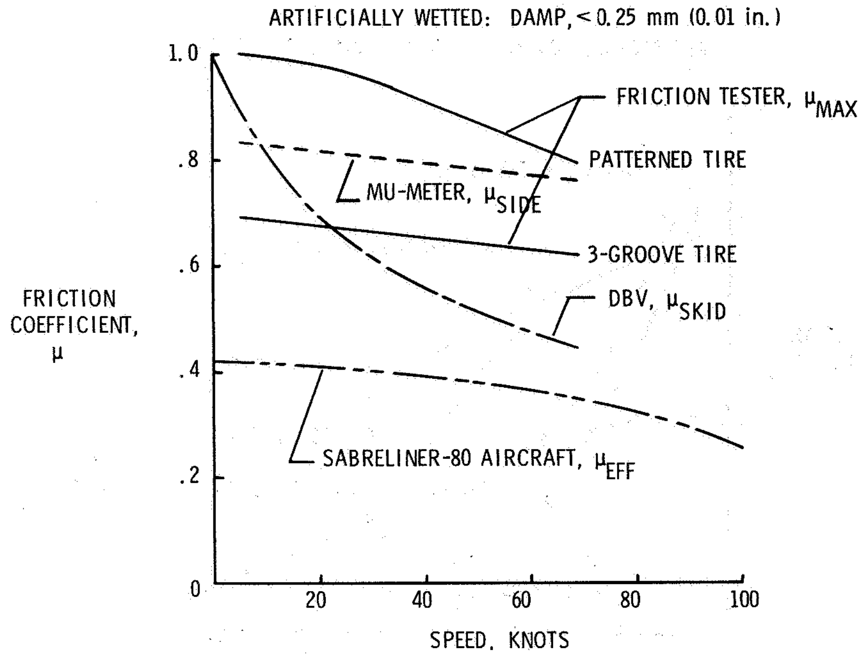
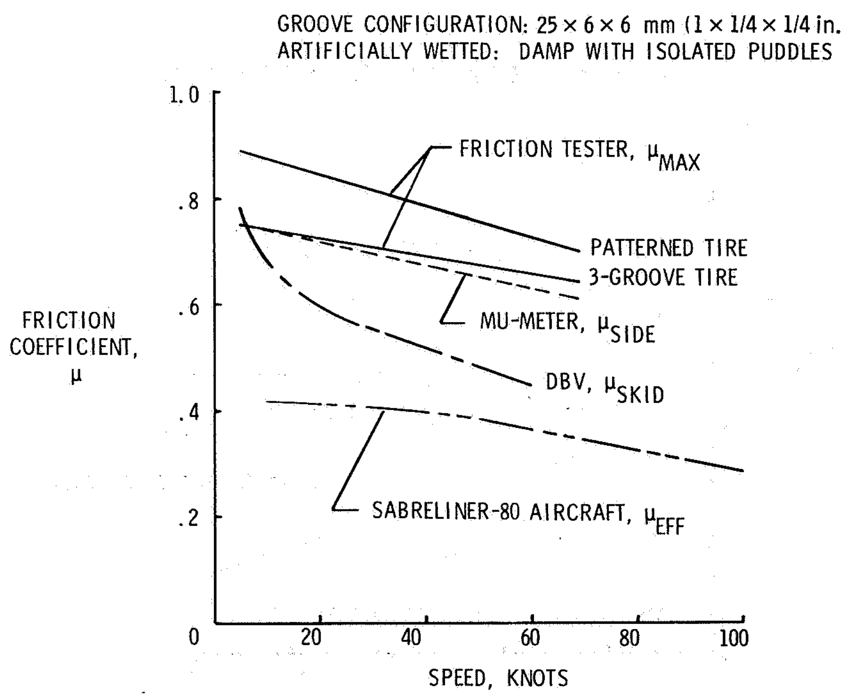


Figure 5.- Methodology used to estimate aircraft tire friction performance.

Figure 6.- Test aircraft and ground friction measuring vehicles used in joint NASA/FAA program.

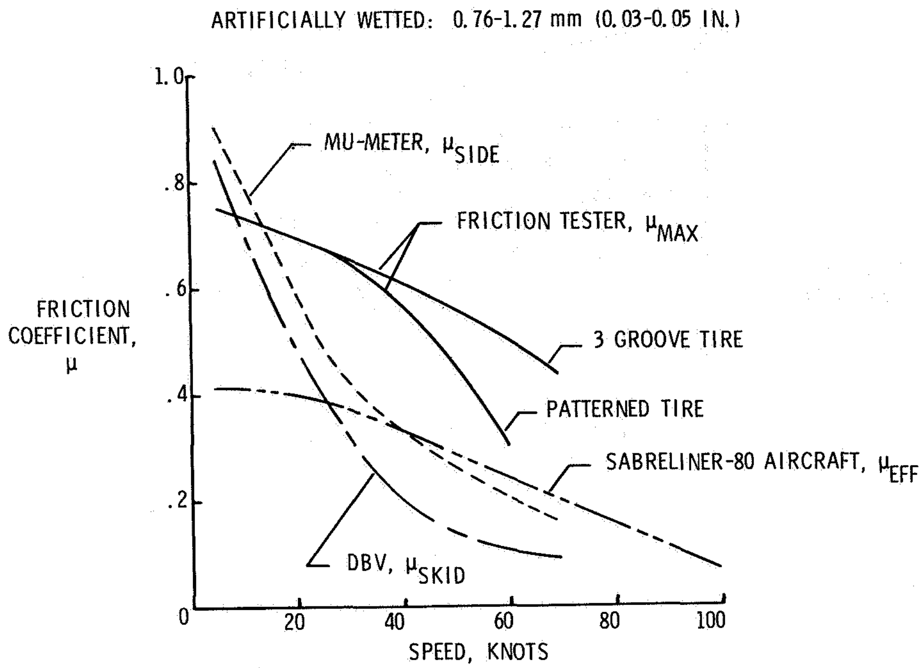


(a) Slurry seal asphalt surface.

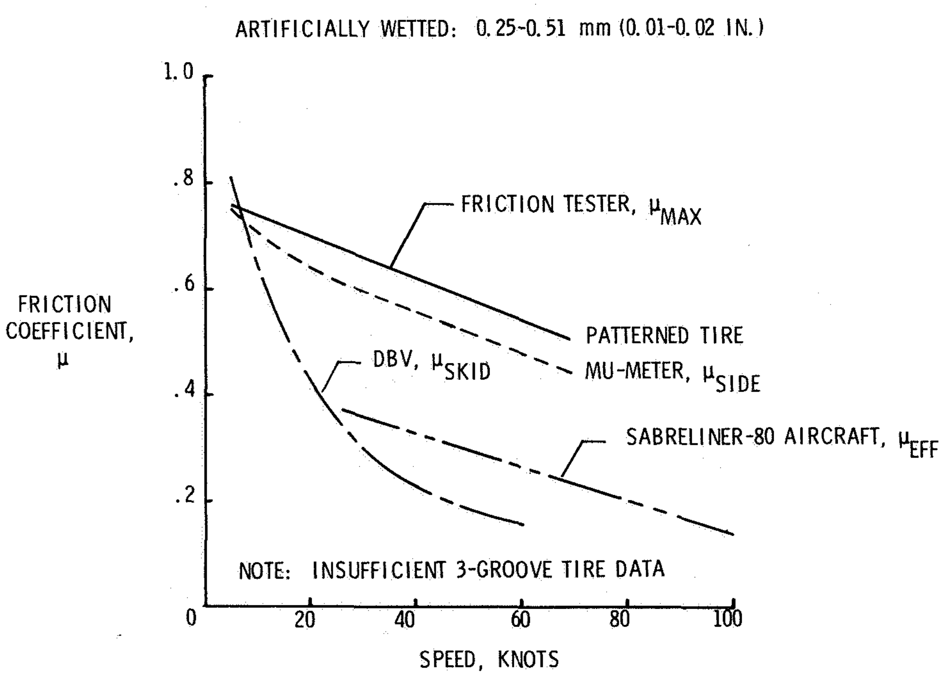


(b) Transverse grooved surfaces.

Figure 7.- Range of aircraft and ground vehicle friction data obtained on different wet runway surfaces at NASA Wallops Flight Center.

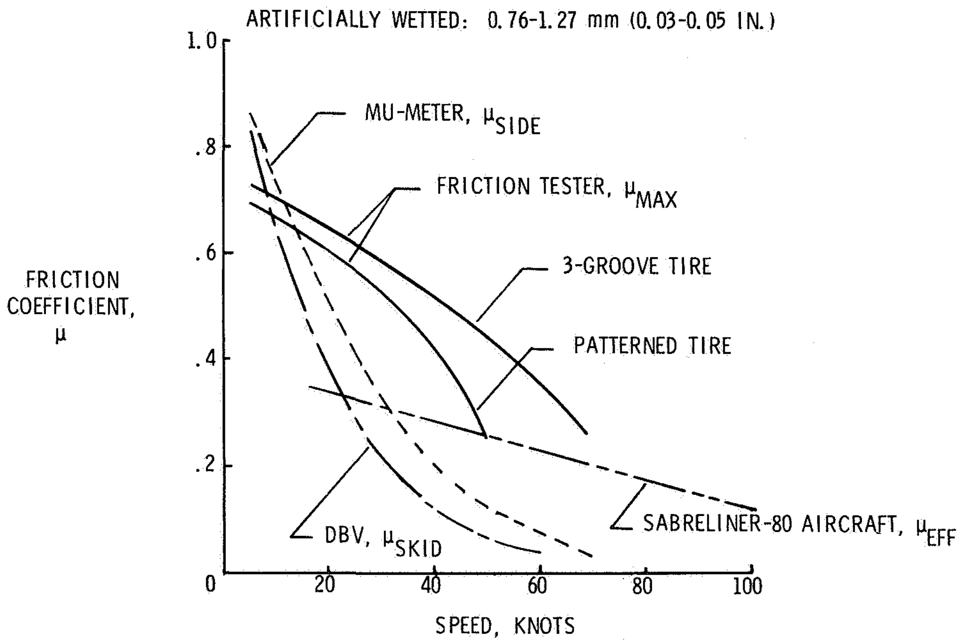


(c) Small aggregate asphalt surface.



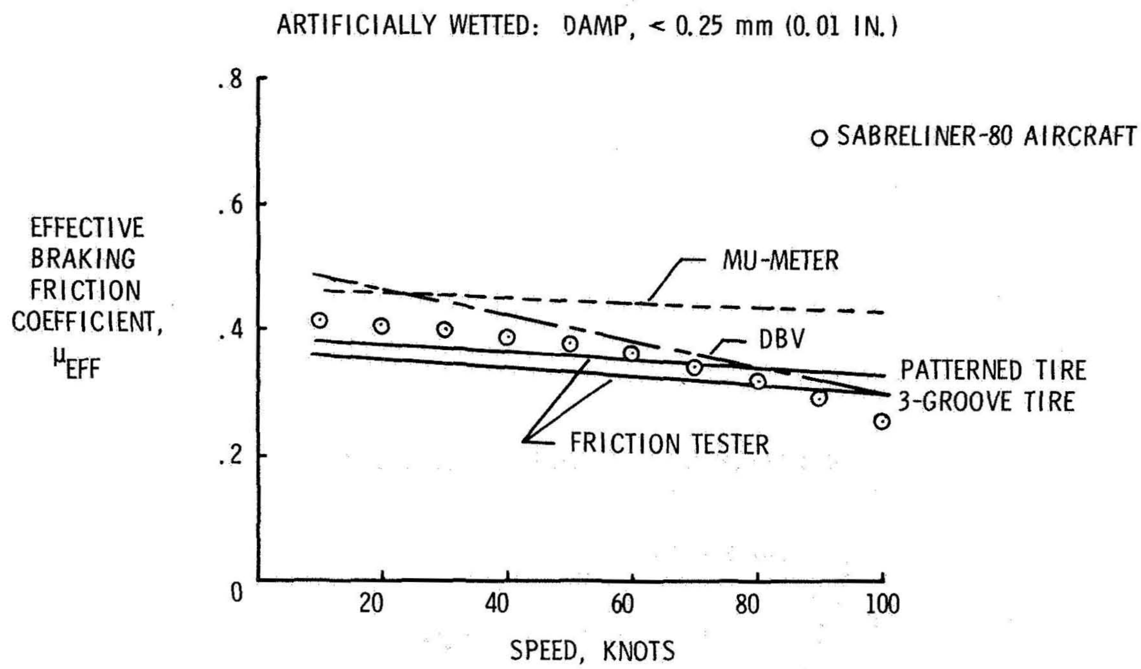
(d) Burlap drag-finished concrete surface.

Figure 7.- Continued.

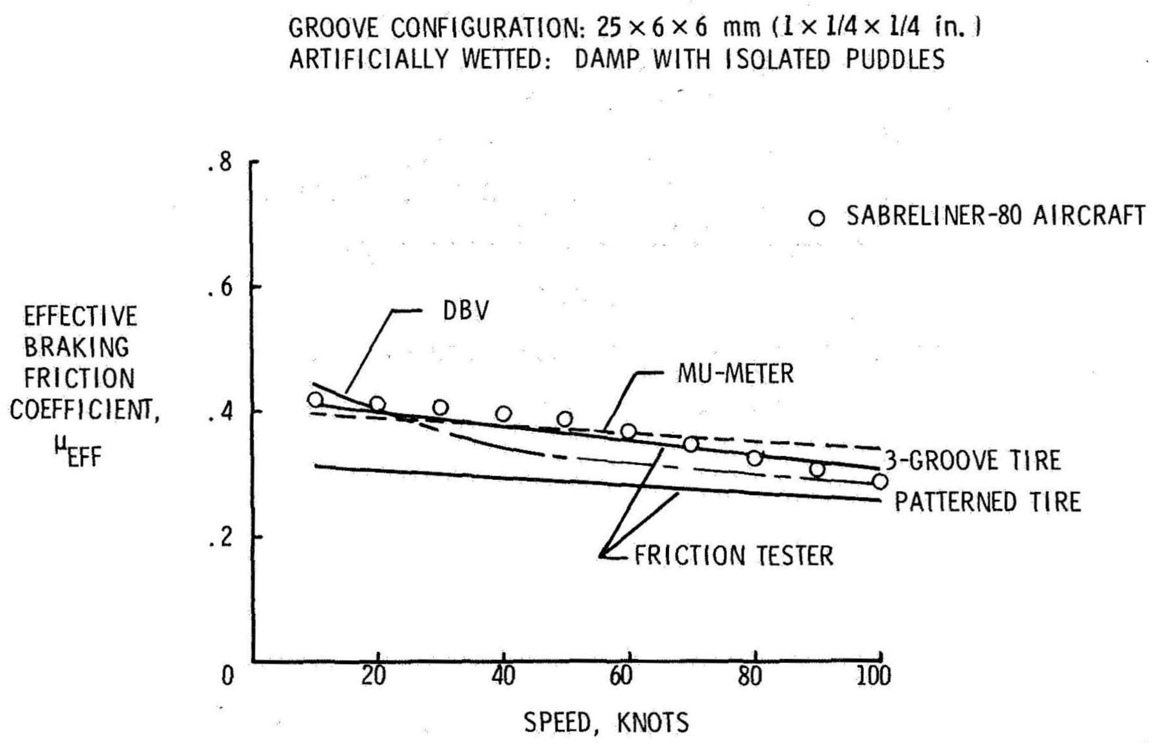


(e) Canvas belt-finished concrete surface.

Figure 7.- Concluded.

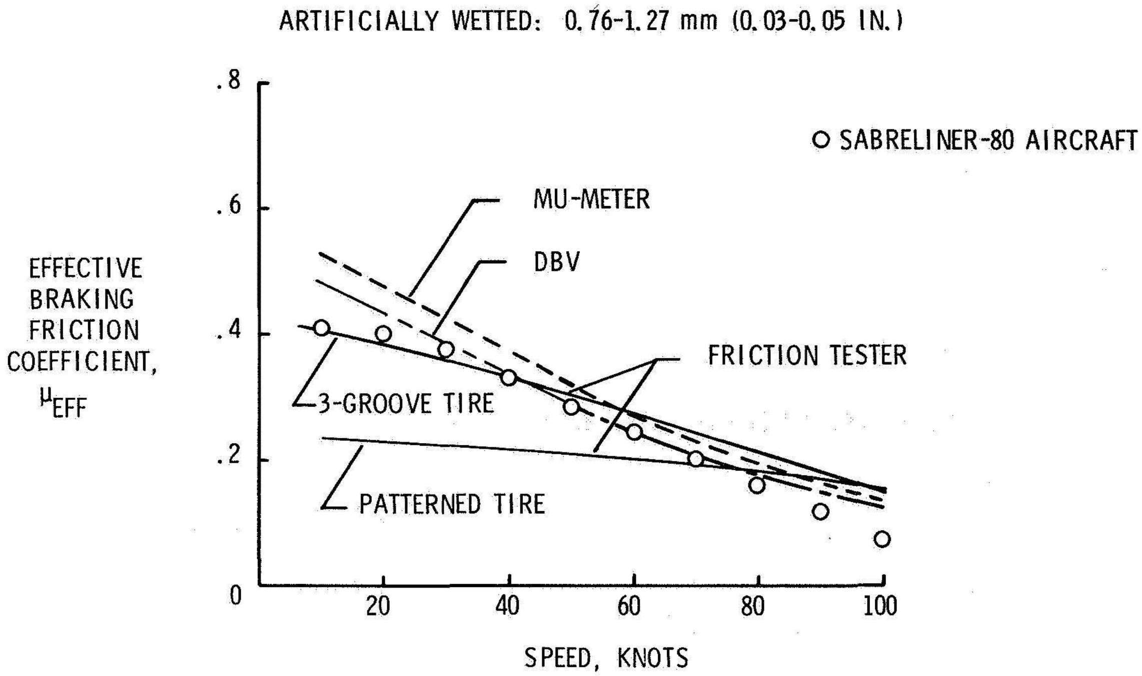


(a) Slurry seal asphalt surface.

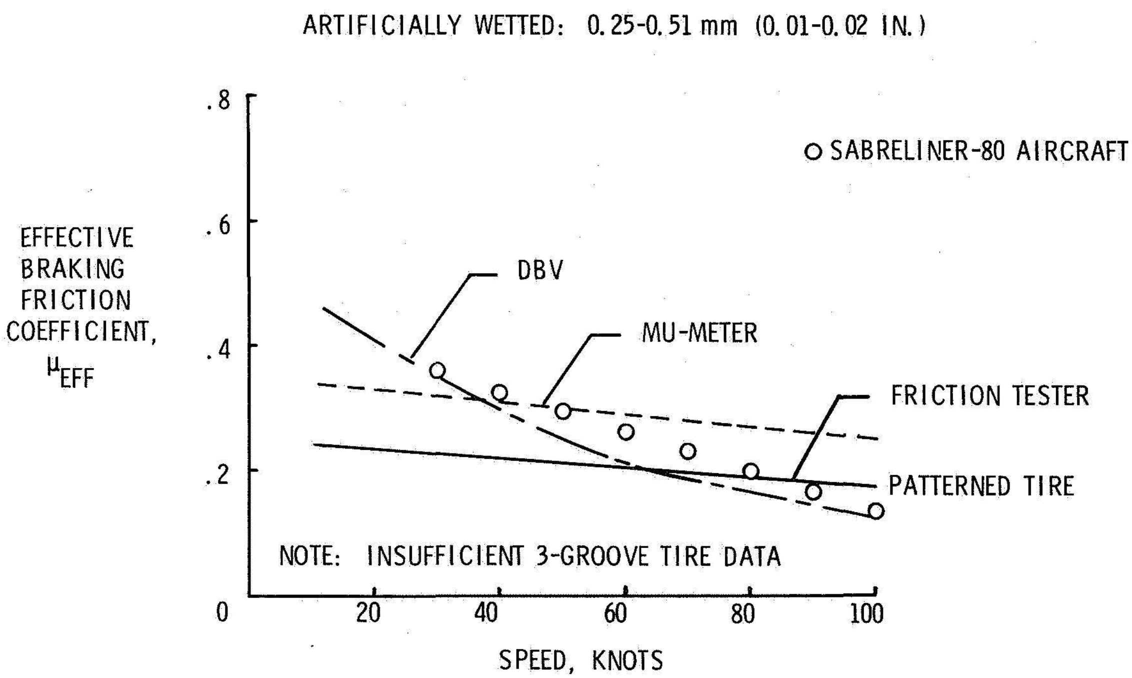


(b) Transverse grooved surfaces.

Figure 8.- Agreement between actual and estimated aircraft braking performance from ground vehicle friction measurements.



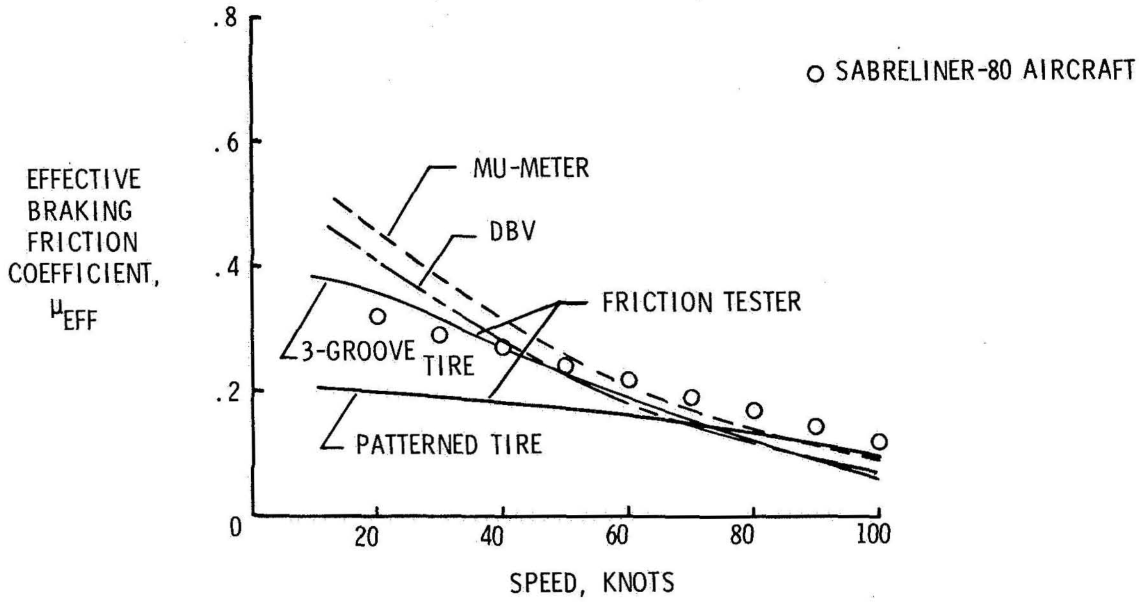
(c) Small aggregate asphalt surface.



(d) Burlap drag-finished concrete surface.

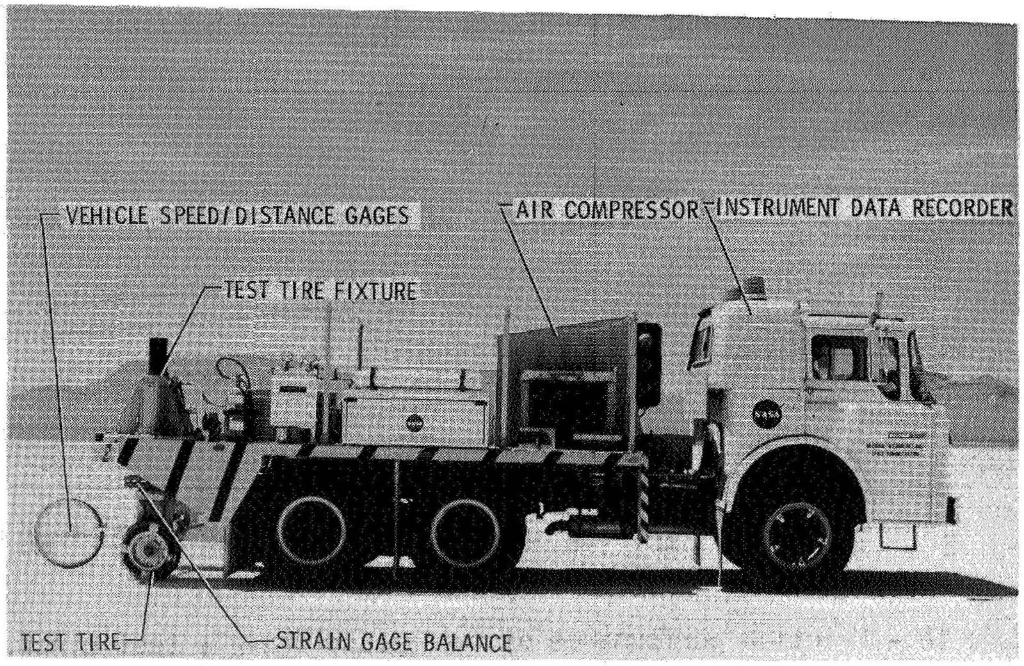
Figure 8.- Continued.

ARTIFICIALLY WETTED: 0.76-1.27 mm (0.03-0.05 IN.)

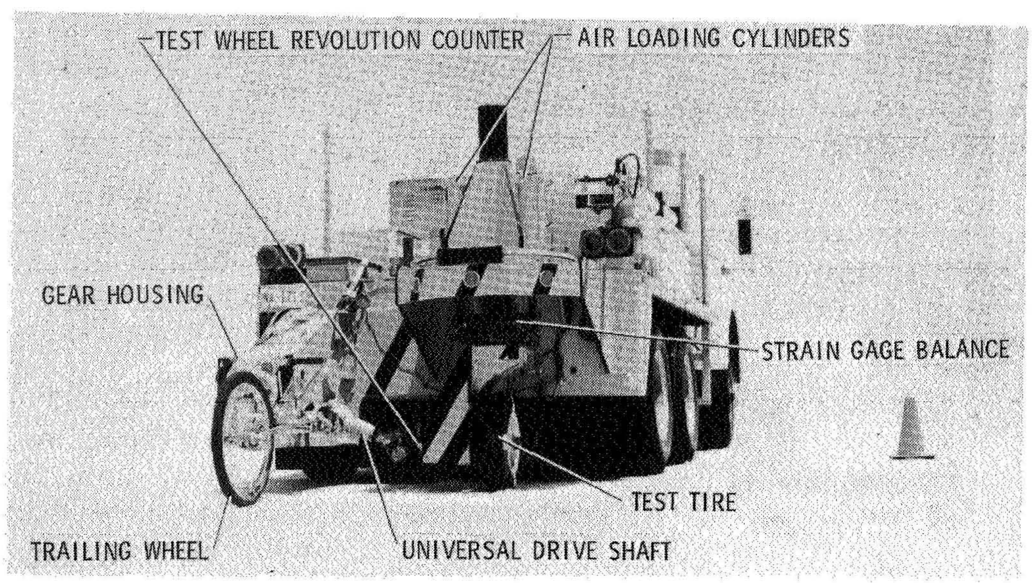


(e) Canvas belt-finished concrete surface.

Figure 8.- Concluded.



(a) Side view.



(b) Rear view.

Figure 9.- Instrumented tire test vehicle.

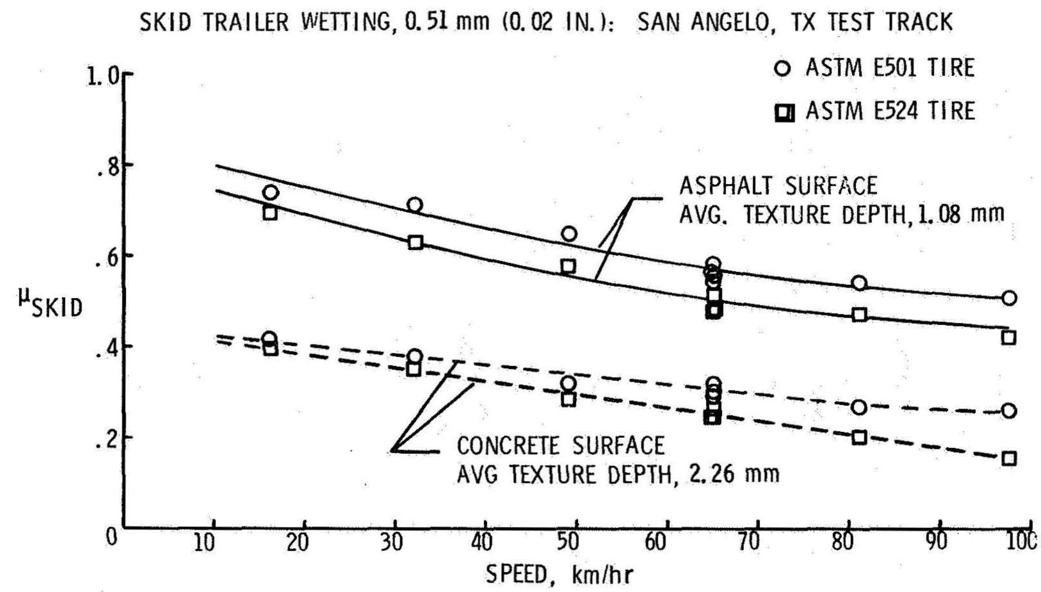


Figure 10.- Friction performance of two ground vehicle test tires.

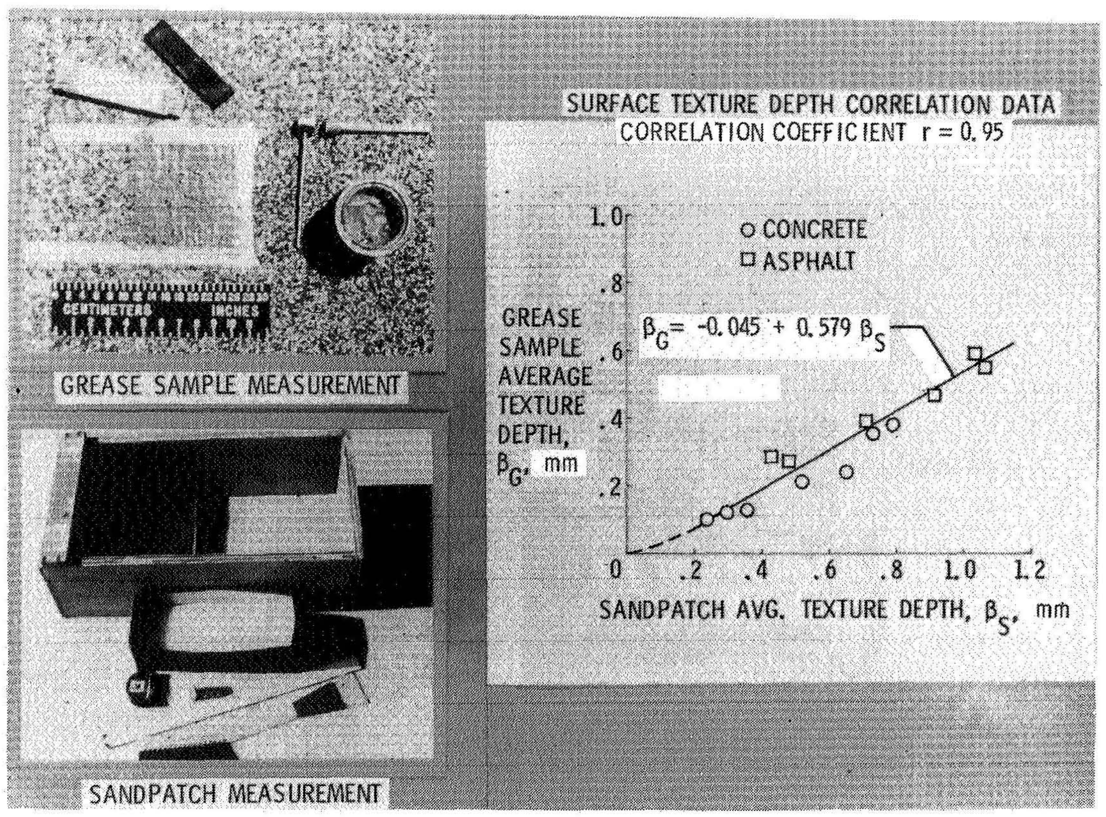


Figure 11.- Example of surface texture measurement correlation.

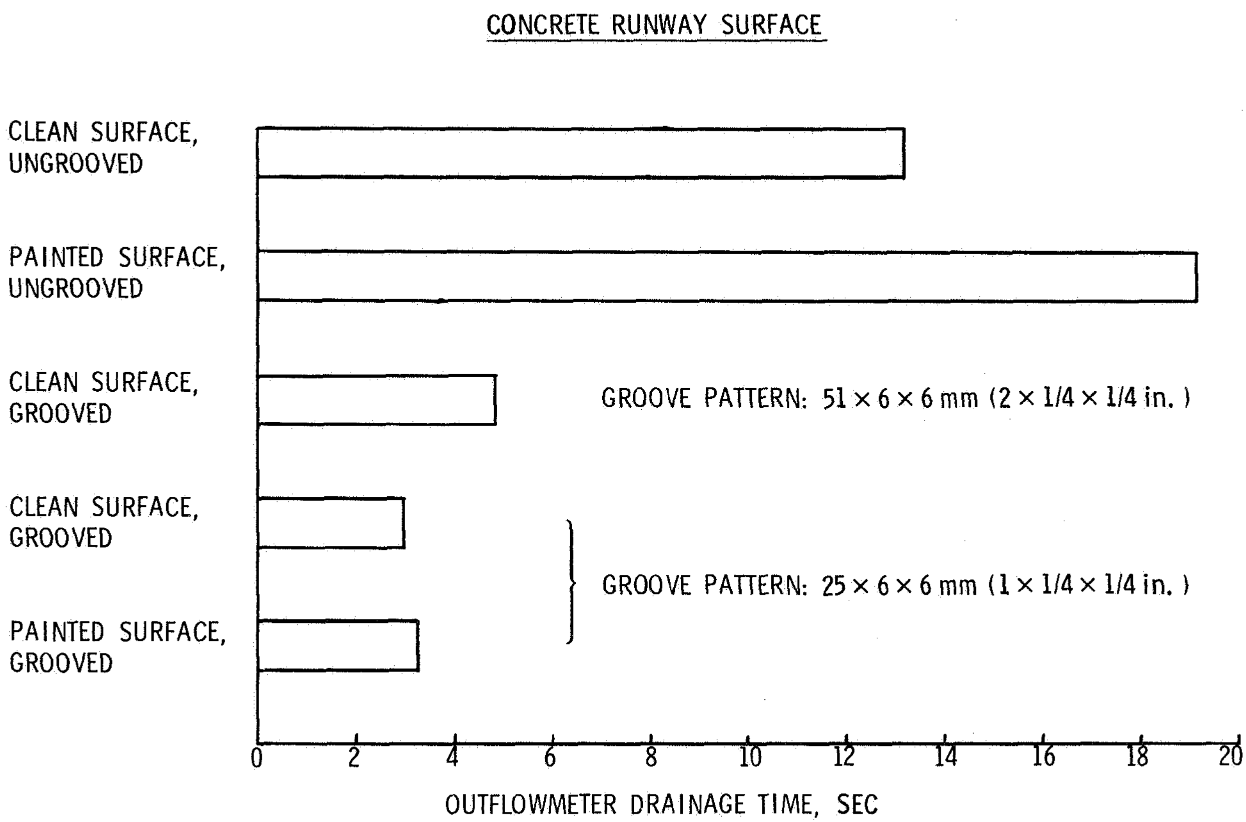


Figure 12.- Effect of surface treatments on outflowmeter drainage measurements.