TECHNICAL NOTE

BOEING

DOCUMENT NO. D6-58384-18TN

USE OF RUNWAY CONDITION METHOD TO PREDICT BRAKING PERFORMANCE.

MODEL General

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THE BOEING COMPANY
COMMERCIAL AIRPLANE DIVISION
RENTON, WASHINGTON

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(DATE)

BRAKE
RUNWAY
OPERATIONS

REV SYM

NOTICE TO USERS

TABLE OF CONTENTS

FOREWARD

The following paper was prepared by N. S. Attri for presentation at SAE A5 Committee (Aerospace Landing Gear Systems) Meeting. The paper was presented on October 23, 1969.

USE OF RUNWAY CONDITION READING METHOD TO PREDICT BRAKING PERFORMANCE

By N. S. Attri

The Boeing Company
Seattle, Washington

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ABSTRACT

Both the U. S. Air Force and FAA currently use James Brake Decelerometer to measure the runway condition ~~(RCR)~~ and to enable the prediction of braking performance. A new method has been recently developed ~~(Anderson method)~~ which also can be used to predict braking performance and uses runway condition reading ~~(RCR)~~ as a measure of ground mu. This paper discusses both ~~the RCR~~ methods ~~and the Anderson method~~ of predicting the braking performance. It is felt that both RCR and Anderson's method lack the ingredients necessary for useful prediction of braking performance in adverse weather. Further studies are urged to develop means of monitoring mu as well as predicting airplane performance.

SUMMARY

Runway condition plays a vital role in adverse weather braking performance. Several methods of measuring runway condition are currently in use by the various agencies in USA and abroad. For example, the U. S. Air Force and FAA use a James Brake Decelerometer (JBD) to measure runway condition (RCR). An FAA working paper "On Runway Surface Condition Measuring, Recording, and Reporting" (Appendix I) proposes the use of the RCR method for assessing airport runway condition for use by the Airlines. The U. S. Air Force has also developed a method of assessing the ground roll using the JBD assessed condition (RCR) of runway. During a recent ANTISKID FORUM a new method of predicting braking performance using RCR as a measure of ground mu was proposed (Anderson method). (See Appendix II). This paper briefly describes both methods. Boeing test data from icy and wet runway tests is used to assess RCR as well as Anderson's method.

Use of James Brake Decelerometer can be satisfactory for dry runways as well as hard packed snow and ice. Under slush and flooded conditions the RCR readings do not correlate too well. The RCR readings are masked by test vehicle speed, surface texture, tire design and condition and vehicle suspension characteristics. The test driver's notes based on visual observation, therefore, become very important supplementary information to assure proper accounting of this RCR information. The Anderson method uses RCR as a measure of ground mu. Due to lack of proper correlation between RCR and ground mu, this is unsatisfactory information. The method further applies a graduated correction to these assessed ground mu values to account for antiskid efficiency. This correction is somewhat arbitrary and ignores the recent advances in antiskid technology. The application of the method to a few Boeing test results shows that this method lacks the necessary ingredients for predicting braking performance.

It is urged that the Industry develop more meaningful means of predicting ground mu. Further work is also needed to improve the adverse runway performance of antiskid systems. The methods of predicting braking performance require meaningful values of ground mu and antiskid efficiency.

INTRODUCTION

With the increasing number of jet transport aircraft operating in areas where runways are either wet or slush covered, the FAA and the Airlines are becoming increasingly concerned about airplane braking performance under such conditions. The necessary prerequisite to determination of braking performance is the assessment of runway surface characteristics. As would be expected the braking performance is dependent on a large number of variables. Most of these variables can, however, be predicted with reasonable degrees of accuracy. The one variable which does not lend itself to easy determination is the tire-runway friction coefficient. This coefficient (which is often termed ground mu) is dependent on speed, pressure, tire design, properties of tread material, tire dynamic properties, tire temperature and many other variables. This clearly is a complex problem in tire dynamics. Studies are presently underway to explore this aspect. The results of these studies would materially enhance the antiskid performance, as well as improve ground mu measurement and landing roll prediction.

While the industry is engaged in developing means of improving brake control systems and braking performance the means of assessing performance under adverse runway conditions are desperately needed. The Federal Aviation Administration (FAA) has proposed the adoption of a system of recording and reporting individual runway conditions using a James Brake Inspection Decelerometer (more commonly termed JBD). A similar system has been used by the United States Air Force since 1960. Under the proposed system (see Appendix I) the runway surface condition would be measured periodically and the data disseminated to air crews by the various radio facilities connected with that airport. The air crew would then use the two digit number to compute a corrected landing distance.

An evaluation of the JBD as a means of measuring consistently the runway surface conditions was conducted concurrently with 737 Air Registration Board (ARB) wet runway refused take-off performance testing. An evaluation was also conducted, at the request of Alaska Airlines, on an ice and snow covered runway at Nome Air Field (Alaska).

These tests and the data obtained will be discussed along with the data obtained using ground vehicles.

DESCRIPTION OF JAMES BRAKE DECELEROMETER AND RCR METHOD

The instrument is basically an air damped pendulum which drives an indicator needle through a linkage. The needle reading, in feet per second squared (ft/sec^2), is directly related to the inertial displacement of the pendulum during the deceleration of the vehicle in which it is carried. Some error is introduced into the reading of the JBD due to pitch down of the front of the vehicle as brakes are applied.

The procedure used in determining the runway condition is to drive a suitable vehicle along the runway in question at about 20-30 miles per hour, apply the brakes firmly to the point of skidding and read the maximum deceleration value recorded on the JBD. This is done at 500 foot intervals (or other suitable interval depending upon the logistics of a particular situation) along the length of the runway about 20 ft either side of the centerline.

The average of all these recorded values becomes the Runway Condition Reading Index (RCR).

It is readily apparent that choice of vehicle, proper suspension system, careful choice of location for installation of JBD and manner of sampling the runway all influence the data obtained.

Having selected a vehicle with the desired characteristics and established the location for mounting the JBD the most critical part of performing the test is establishing the calibration for the system.

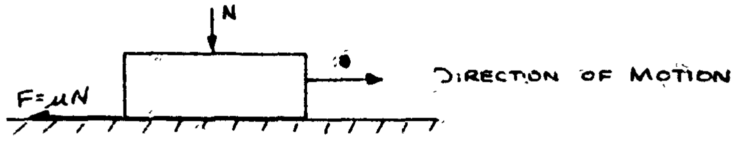
Figure 1 shows a James Brake Decelerometer. Prior to any evaluation a calibration is generally conducted. During 737 wet runway tests, calibration was conducted using a tilt table. The instrument was placed in a tilt table and indicated deceleration for chosen tilt angles was recorded. The ideal values of tilt angle and deceleration should be as follows:

Tilt Angle	Scale Reading Ft/sec^2
0	0
10	5.7
15	8.6
20	11.7
25	15.0
30	18.6
35	22.6
40	27.1
45	32.2

The deviation of the instrument from the ideal was obtained and plotted (see figure 2). The instrument was mounted on a piece of aluminum plate to provide a firm base and then placed on the floor of the test car. The JBD readings taken during the tests were corrected using the instrument calibration. The corrected deceleration was then converted to an equivalent friction coefficient (μ). The FAA working paper which proposes the use of RCR method is included in Appendix I for the convenience of the reader.

The basis for obtaining this value of μ is next discussed.

For a body moving on a rough surface the opposing force of friction can be expressed as $F = \mu N$



The dynamics of the moving body can be expressed using Newton's Second Law of motion.

$$F = MA$$

where M = mass of moving body
A = acceleration or deceleration of the body in the direction
$M = W/g$ = test vehicle of motion mass

Thus $F = \mu \cdot N = \mu \cdot W = MA = \frac{W}{g} A$

or $\mu = \frac{A}{g}$

The foregoing thus enables the determination of ground mu for a moving vehicle using JBD. Since all wheels of the test vehicle must be skidding and because the JBD reads the maximum deceleration encountered, the braking coefficient is ideally that at incipient skid. If the vehicle does not possess sufficient braking, realistic values of RCR cannot be obtained. This was apparent when an Alaska Air Line bus with torque limited brakes was used as a test vehicle. Several other vehicles were used to correlate the vehicle test results and acceptable agreement was found.

Wet Runway Testing with Ground Vehicles and Results.

The calibration of Boeing Field International (BFI) Runway 13/31 was conducted primarily for wet runway refused takeoff performance testing. Thus the JBD evaluation was limited in the scope of its testing. The actual calibration was carried out using a Miles Engineering Laboratories Friction Trailer.

Three 200-yard long test sections, representative of the runway, were located at the 7000 feet, 5000 feet and 3000 "feet remaining" stations of runway 13 and immediately to the west of the centerline. The 7000 feet and 5000 feet remaining stations were paved with concrete while the 3000 feet remaining station was paved with asphalt. These three test stations were artificially wetted using a single water truck.

Because of landing traffic on the runway the test runs were conducted at uneven intervals behind the water truck; then the JBD readings were inconsistent. The data obtained is shown in Table I.

The JBD was again evaluated during wet runway refused takeoff performance testing conducted on a model 737-200 airplane. The test sequence was begun with the artificial wetting of BFI runway 13 with eight water trucks. The runway was wetted from the 9000 feet remaining station to the 3000 feet remaining stations of runway 13. Immediately following the water trucks was the JBD test car. Then, after the airplane had completed the RTO, another JBD test run was conducted. A plot of JBD readings versus the distance remaining stations is presented in figure [illegible].

Icy Runway Tests with Ground Vehicles and Airplane.

The procedure used in determining runway condition was the same as discussed earlier. Readings were taken at 500 feet intervals along the entire length of the runway, about 25 feet either side of the centerline. The average value was treated as the runway condition reading index (RCR). When a minimum RCR reading of 10 is obtained the airfield is bypassed. Alaska Airline assumes that deceleration rates experienced by the truck are the same as those experienced by the airplane. The data obtained on airplane (Boeing 727) and the Alaska Airline panel truck are shown in Table II. The results clearly show reasonable agreement, during the test conditions (on hard packed snow).

As a result of discussion thus far, it may be concluded that JBD provides a reasonable means of predicting surface condition on surfaces such as dry runway, dry compact ice and slightly wet runways. When the runway is slippery due to presence of slush, presence of puddles of water or a generally flooded condition, the readings can often be misleading.

ANDERSON'S METHOD TO PREDICT BRAKE SYSTEM PERFORMANCE

Anderson's method uses RCR information as a measure of ground mu. Using an empirical correction for anti skid efficiency it obtains a corrected value of ground mu. The antiskid correction accounts for individual or paired wheel control, wet or dry runway, modulated or off/on system etc. The method as proposed by Mr. Anderson of General Dynamics, is included in Appendix II.

Having obtained the corrected values of ground mu for the speed range of interest, the braking performance is calculated by the usual methods. These calculations account for the various airplane parameters such as lift drag weight wing area etc. An Airplane braking test is made to make sure that calculated numbers are conservative.

Boeing wet as well as icy runway tests were used to assess the accuracy of this method. The results of applying Anderson's method to these runway conditions are shown in Appendix III.

The end result of Anderson method is to provide ground mu versus velocity data for wet runway and an effective ground mu for dry or icy runway which can be used to calculate stopping distance. The comparison between airplane and calculated ground mu values (See Appendix III) clearly shows that the Anderson method penalizes the ground mu, on wet runways, at high speeds. At low speeds, the resulting mu's are unrealistic. The suppression of mu values at high speeds can have serious pay load implications. The success of the method depends on proper determination of mu and valid information on the antiskid efficiency. These ingredients are missing from this method.

NASA studies (ref. 1) have shown poor correlation between RCR readings and the runway surface. The reasons for this are tire design and test speed. The tire design is so efficient at low speeds that it can completely mask the pavement slipperiness for wet and puddled or flooded runway conditions. The surface texture can also influence the readings. Figure 4 shows the influence of these variable on ground mu. Antiskid efficiencies vary from airplane to airplane. Even for a particular airplane the antiskid efficiency is dependent on a large number of variables. Surface roughness is the predominant variable. Other variables include system component conditions, tolerances, temperature during operation, influence of erosion and contamination and brake wear. A measure of antiskid efficiency for the various available mu conditions can be obtained from the laboratory tests. This data along with available mu data may serve as a guide for the various airlines. It must be recognized that ideal runways do not exist and mu values vary over a wide range on the same runway. The runway may be dry, wet, flooded and icy or all at the same time. It could be wet and flooded or just flooded. The above information could, of course, be applied more easily to a uniform runway. The non-uniform runway conditions impose a severe penalty on antiskid operation and have to be recognized.

It is realized that a need does exist to make airplane ground handling safer. Further industry investigations are needed, however, to develop means of measuring surface traction or available ground mu more realistically. In the meantime further work is also necessary to improve antiskid systems. The available mu as well as the antiskid efficiency data could serve as a useful tool for airlines in planning their route structure.

CONCLUSIONS

1. As a result of a review of literature, vehicle and airplane test data, it can be concluded that RCR provides a reasonable means of predicting surface condition of surfaces such as dry runway, dry compact ice and slightly wet runways.

2. When the runway is slippery due to presence of slush, presence of puddles of water or a generally flooded condition, the readings can be misleading.

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3. In view of the foregoing, RCR as a measure of ground mu is presently of limited value.

4. The Anderson method utilizes the RCR as well as empirical corrections which are not accurate enough to predict realistic braking performance.

RECOMMENDATIONS

It is recommended that industry explore better means of measuring ground mu. The methods of predicting performance that account for known system performance are also needed. In this respect airframe manufacturers must provide continuing support.

REFERENCE:

(1) "Pavement Grooving and Traction Studies" NASA SP-5073 (Nov. 1968)

APPENDIX I

FAA WORKING PAPER ON

RUNWAY SURFACE CONDITION MEASURING, RECORDING, AND REPORTING

1. PURPOSE. This discussion paper provides information and guidance on a standard method of runway surface condition measurement, recording, and reporting. The ultimate goal of the agency is the establishment of an industry-wide integrated system of measuring and assessing a numerical value for runway surface conditions and reporting and disseminating this information to all users.

2. BACKGROUND. The operation of an airplane on a runway surface condition, other than the certification referenced dry surface, has been of significant concern to both the FAA and industry for many years. Operational factors have been applied to dry performance values to afford safety margins to operation on other than dry surfaces. The tangible identification of varying runway surface conditions to the airplane's operational performance, has initiated a research and development program for this purpose. The FAA program is based on the decelerometer system which has been adopted and is being successfully used by the Air Force.

   a. In 1960 the Air Force officially adopted a system of measuring and reporting runway slickness using the James Brake Decelerometer (JBD). At the same time they instituted a method whereby aircrews corrected their normally required ground roll distance for the JBD assessed condition of the runway taken just prior to their landing. This system has been tested, evaluated, and proven.

   b. The Air Force type decelerometer has a dial face marked from 0 to 26 and referenced to feet per second squared. The production civil model of the decelerometer has a dial face marked from 0 to 32.2 feet per second squared. It was recently discovered that the Air Force dial face was incorrectly marked and calibrated and that they will change their entire system to conform to the 0 to 32.2 scale. Many interested parties throughout the conterminous United States and Alaska have heard about the Air Force system and the FAA proposes to adopt a similar system.

3. RECOMMENDATIONS. In order to encourage consistency in data acquisition and dissemination, a vital key in the success of the JBD concept, this circular is being recommended to all interested parties as a standard method of data acquisition and reporting. For those already having a JBD or those about to obtain such a device, it is recommended that a standard method of data acquisition, recording, and reporting be adopted.

   a. Calibration. A stable-state instrument calibration check should be made prior to initial testing with continuing periodic calibration checks to insure the validity of the instrument and its recording capability. The instrument's inherent design affords a relatively simple procedure for the stable-state calibration:

      (1) Adjust the instrument to a zero reading on a known level surface (example: bench, table top, or design mount).

      (2) Raise or tilt the instrument in the direction of car motion pointing downslope, holding the reset button in and tapping lightly to some

predetermined angle (example: 15, 30, or 45 degrees).

(3) Read the feet/second/second scaling. The desired angle may be established by means of a protractor or more simply by a draftsman's triangle. A civil instrument (0 - 32.2 feet/second^2 scaling) is in proper calibration if the following readings are observed:

Angle	Scale Reading Feet/Second^2
0	0.0
10	5.7
15	8.6
20	11.7
25	15.0
30	18.6
35	22.6
40	27.1
45	32.2

Acceptable operational tolerance to the above readings should be no greater than ±1.5 feet/second^2. Instruments not meeting the calibration tolerance should be returned to the manufacturer for adjustment.

(4) For those who have and will continue to use the Air Force instrument scaling (of 0 to approximately 28), conversion readings to civil scaling (of 0 to 32.2 feet/second^2) are included in section (d).

(5) Users of the JBD system should make runs on clean, dry pavement to check vehicle/decelerometer readings. A reading of 26 or above on the civil meter (23 or above on the AF model) indicates that the brakes are in satisfactory condition to give accurate data.

b. Operation

(1) For most reliable results, place the decelerometer on a level mount in the vehicle so that the arrow containing the words "Direction of the Car Motion" is pointing toward the front of the vehicle.

(2) Level the decelerometer by means of the screw in its base, and tap it with a finger to remove static friction. When level, the pointer will coincide exactly with the left horizontal line on the dial. If the pointer is above this line, the instrument is tilted too far backward.

(3) Prior to recording a test run data point, be sure the pointer has been returned to the starting (zero) position. This is done by pressing the reset button located on the side of the case.

(4) Drive the vehicle at a steady speed of 20 miles per hour (steady speeds up to 30 miles per hour may be used if runway conditions permit) down the preselected portion of the runway to be assessed. Apply the vehicle's brakes smoothly and firmly to induce a full skid. The pointer will record the maximum - rate of deceleration in feet per second per second occurring just prior to the skid. The braking technique used is most important; and while a smooth and firm application is required after a full skid has been recognized, the release of braking should be immediate so as to

prevent a full stop. Wherein a full stop is experienced, the test should be rerun.

(5) The pointers position should be read and recorded upon brake release along with the observation and recording of visual runway conditions such as location, contaminents, painted areas, uniform or patchy, etc.

(6) Repeat procedures outlined above at approximately 1,000-foot intervals for the length of the runway. Under patchy contaminated conditions, tests should be made on the most representative surface encountered within each 1,000-foot interval.

(7) To insure that the values obtained are meaningful to the airplane's operation, the preselected longitudinal portions of the runway to be evaluated should be sufficient in number to be representative of the various types of airplanes using the runway, i.e., down the center, 20 feet to right of center, 20 feet left on center, etc. Special attention should be given to areas of known contaminents, such as painted or heavy rubber deposit areas, and appropriate notification made.

(8) Add the decelerometer readings for each 1,000 feet and divide the sum by the total number of readings. This average will be known as the James Brake Index (JBI).

(9) Driver training is the key to successful operation. An inexperienced or careless driver can negate any benefits which may be derived from this system. Several persons should be trained in the use of the JBD. Two persons should be in the vehicle -- one drives and the other reads, records, and resets the instrument. The driver should be cautioned to be alert for premature wheel lockups. If only one wheel skids, the driver may believe he has fulfilled the test requirement; however, the other wheels have not developed maximum stopping power and the reading will be low.

(10) Experience can only be gained from practice, paying particular attention to the following:

- (a) A full skid must be developed.
- (b) The vehicle must not stop or come to the "shuddering" approach to a stop.
- (c) The skid must be entered quickly but smoothly; "jamming" brakes must be avoided. The time between applying brakes and a stop is very short so it takes practice to perform this operation smoothly.

Reporting. In the interim preceeding the official adoption of a complete workable system, it is suggested that average JBI readings and the associated runway surface condition be disseminated as widely as possible to all pilots so that they may become familiar with the terminology. Regard JBI and RSC's (Runway Surface Condition) as an appendage to an hourly weather sequence and any specials. In the future they may be as much a part of the weather observations as wind, ceiling, visibility, etc. JBI's and RSC's should be reported to airport weather stations, control towers, approach control facilities, centers and flight service stations which serve the airport. When runway conditions change, the conditions previously reported to these agencies will be revised or cancelled as appropriate. The JBI should be reported in two digit numbers between 0 and 30 based on the 0-32.2 scale and should be followed by the RSC code which should be reported in the following manner.

(1) WR - Wet Runway

(2) SLR - Slush on Runway

(3) LSR - Loose Snow on Runway

(4) PSR - Packed Snow on Runway

(5) IR - Ice on Runway

(6) P - Patchy (to be used in conjunction with (1) through (5) above.

(7) Sanded - Indicate sanded runways in clear text at the end of sequence. "P" may be used as a prefix to the RSC code to denote a patchy condition which may adversely affect lateral control during braking of some aircraft. An example of a sequence is: R/W 35, JBI 16, PIR Sanded.

d. Recording. Information should be recorded on a form similar to the sample on the following page, based on the 0-32.2 scale. For those operators with an Air Force meter, conversion readings are listed so that Air Force dial readings may be converted to the 0-32.2 basis.

CONVERSION READINGS FOR AIR FORCE AND CIVIL DECELEROMETERS

Air Force Device	Civil Device
2	4.25
3	5.3
4	6.4
6	8.4
8	10.5
10	12.5
12	14.6
14	16.8
16	18.9
18	21.0
20	23.2
22	25.3
24	27.6
26	29.8

MEASUREMENT OF RUNWAY BRAKING TESTS
(using James Brake Decelerometer)
0-32 FT/SEC^2

AIRPORT ______________________ LOCATION ______________________

TEMPERATURE ________________ TIME ______________ DATE ______________

RUNWAY SURFACE CONDITION: ( ) Dry, ( ) Wet, ( ) Ponding Water, ( ) Frost,
( ) Ice, ( ) Loose Snow, ( ) Slush, ( ) Patchy

DEPTH OF MEASURABLE CONDITIONS ____________________ (estimated to nearest 1/10 inch)

RUNWAY ______		RUNWAY ______		RUNWAY ______	
TYPE OF SURFACE ______		TYPE OF SURFACE ______		TYPE OF SURFACE ______	
APPROX. DIST. FROM THRESHOLD	READING	APPROX. DIST. FROM THRESHOLD	READING	APPROX. DIST. FROM THRESHOLD	READING
	Avg. ______		Avg. ______		Avg. ______

REMARKS: ____

____

____

RUNWAY SURFACE HISTORIES: ____

____

____

RECORDED BY: ______________________

DRIVEN BY: ______________________

APPENDIX II

ANDERSON'S METHOD FOR EVALUATING AIRCRAFT SKID CONTROL PERFORMANCE

1. Dry Runway:

A. Establish Braking Friction Coefficient:

(1) Measure Runway RCR

(2) Compute braking friction coefficient using aircraft tire pressure and skid control characteristics as shown by the following example:

Assume RCR = 23, Then the friction coefficient actually achieved by the RCR measuring vehicle is $\frac{23}{32.2}$ = .715 at low speed (approximately 15 knots).

Assume aircraft tire pressure = 150 psi and RCR measuring vehicle tire pressure = 30 psi.

From Figure 52 of NASA Report No. R-64
@ 30 psi = .89
@ 150 psi = .75

Therefore, $\frac{.75}{.89}$ = .844 is the fraction of RCR measuring vehicle friction which is achievable on the aircraft.

(.715) (.844) = .603 = Low speed friction potential for aircraft.

Since almost all test data shows that the achievable friction coefficient decreases with speed (NASA TN D-2770 for example) such that the friction coefficient at about 100 knots is approximately 85 percent of the low speed (0-5 knot) value and since for most of the distance traversed by the aircraft while stopping its velocity is in the high speed range: reduce the friction coefficient to 85 percent of its low speed value for high speed.

(.603) (.85) = .512 = High speed friction potential for aircraft.

(If desired, a friction coefficient vs. velocity relationship could be established.)

$$\mu_A = \mu_p (\eta_{sc})$$

Skid Control Performance Efficiency

Friction Potential for Aircraft

Friction Achievable by Aircraft

η_{sc} is a function of:

(a) Type of skid control system, "Modulated" or "Adaptive," or ON-OFF.

(b) Number of wheels controlled by each brake torque controlling circuit.

(c) Possible pitch control requirements on aircraft with bicycle landing gear or on some types of bogie arrangement landing gears.

For usual configurations without special pitch or frequency control provisions, the following values for η_{sc} are recommended for dry runway.

Number of Wheels Controlled Per Circuit	(Fc)	ON-OFF Skid Control	"Modulated" or "Adaptive" Skid Control
1	1.0	.8	.9
2	.85	.68	.765
3	.78	.625	.702
4	.75	.60	.675

For example, assume modulated skid control with individual wheel control: $\eta_{sc} = .9$

$$\mu_A = (.512)(.9) = .46$$

B. Using the braking friction coefficient established along with the aircraft's aerodynamic and dimensional characteristics, compute stopping distance for land-plane landing design gross weight with brakes applied at power off stall speed. Consider appropriate control surface positions and pilot technique.

C. Perform aircraft test to verify that actual stopping distance is not greater than the above computed value.

2. Wet Runway:

A. Establish Braking Friction Coefficient

(1) Measure Runway RCR

(2) Compute braking coefficient using aircraft tire pressure and skid control characteristics as shown by the following example:

Assume RCR = 17, then the friction coefficient actual achieved by the RCR measuring vehicle is $\frac{17}{32.2} = .528$ at low speed (approximately 19 knots).

For 150 psi aircraft tire pressure and 30 psi RCR measuring vehicle tire pressure, and using NASA Report R64, same as for dry runway, .844 is the fraction of RCR measuring vehicle friction which is achievable on the aircraft.

(.528) (.844) = .445 = Low speed friction potential for aircraft

Compute hydroplaning speed,

$$V_p = 9\sqrt{P} \text{ KNOTS}$$

$$V_p = 9\sqrt{150}$$

$$V_p = 110 \text{ knots}$$

Assume

$$\mu_{PW} = (\mu_o - .05)\, K\, (V_p - V)^2 + .05$$

Friction potential at velocity V, wet

Establish K such that $\mu_{PW} = \mu_o$ at V = 15 knots

$$\mu_o = (\mu_o - .05)\, k\, (V_p - 15)^2 + .05$$

$$k = \frac{1}{(V_p - 15)^2} = \frac{1}{(110-15)^2} = \frac{1}{(95)^2}$$

Therefore

$$\mu_{PW} = (.445 - .05)\frac{1}{(95)^2}(110 - V)^2 + .05$$

$$\mu_{PW} = .395 \left(\frac{110 - V}{95}\right)^2 + .05$$

Using this equation for μ_{PW}, compute μ_A (Friction Achievable by Aircraft) as a function of velocity with the following expression:

$$\mu_A = \mu_{PW}\,(\eta_{SC})$$

Skid Control Performance Efficiency

Where $\eta_{SC} = (\eta_{SC_b})(F_C)$

Control Configuration Factor

Skid Control Performance Efficiency from the attached curve as a function of μ_{PW}/μ_{PD} for individual wheel control.

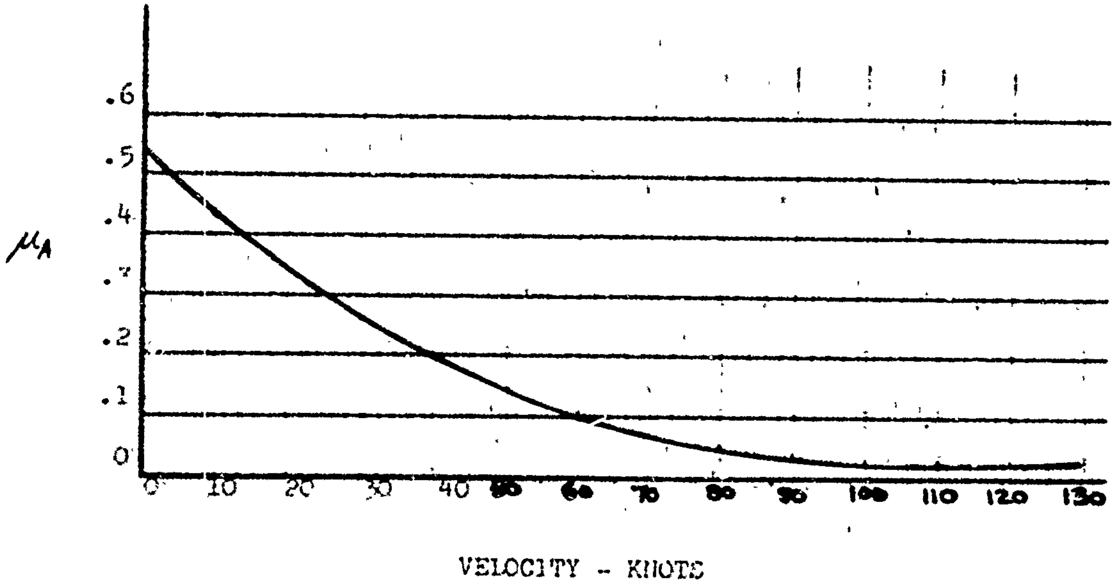
Recommended Values for Control Configuration Factor

Number of Wheels Controlled Per Circuit	F_C
1	1.00
2	.85
3	.78
4	.75

For individual wheel control, μ_{PW} as a function of velocity is computed and presented graphically on the following page.

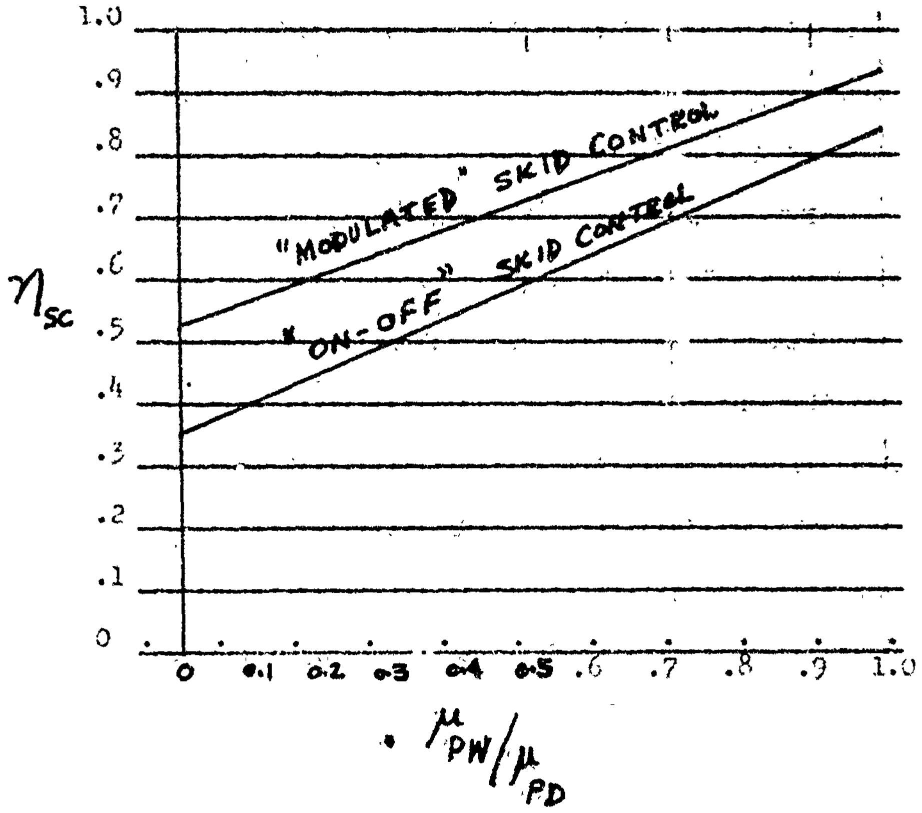
CALCULATION OF μ_A VERSUS VELOCITY

KNOTS	110-V	$\left(\frac{110-V}{95}\right)$	$\left(\frac{110-V}{95}\right)^2$	$\left[\left(\frac{110-V}{95}\right)^2 .395\right]$	$\left[.395\left(\frac{110-V}{95}\right)^2+.05\right]$	$\frac{\mu_{PW}}{\mu_{PD}}$ $\mu_{PD}=.512$	η_{sc}	F_c	η_{sc} $(\eta_{sc} \cdot F_c)$	$\mu_A = (\mu_{PW})(\eta_{sc})$
0	110	1.16	1.29	.509	.559	1.092	.95	1.0	.95	.53
15	95	1.0	1.0	.395	.445	.87	.88	1.0	.88	.491
30	80	.842	.708	.280	.330	.645	.78	1.0	.73	.2575
45	65	.685	.469	.185	.235	.460	.71	1.0	.71	.167
60	50	.526	.277	.1175	.1675	.32	.65	1.0	.65	.106
75	35	.716	[illegible]	.0795	.0895	.175	.58	1.0	.58	.052
95	15	.158	.025	.010	.06	.117	.56	1.0	.56	.0336
110	0	0	0	0	.05	.098	.55	1.0	.55	.0275



Use .0275 at all
speeds above 110 knots

SKID CONTROL PERFORMANCE EFFICIENCY
FOR INDIVIDUAL WHEEL CONTROL



B. Using the braking friction coefficient established for wet runway along with the aircraft's aerodynamic and dimensional characteristics, compute stopping distance for landplane landing design gross weight with brakes applied at power off stall speed. Consider appropriate control surface positions and pilot technique.

C. Perform aircraft test to verify that actual stopping distance is not greater than the above computed value.

APPENDIX III

CORRELATION OF ANDERSON'S METHOD WITH ACTUAL AIRCRAFT TESTS

The method proposed by Mr. Anderson was evaluated for application to dry and wet runways. Its use was extended to icy runways in view of the characteristics of ground mu. (The variation of mu with speed is reasonably small for both dry as well as icy runways). The results are only meaningful in the context of the tests considered here and should not be generalized.

CORRELATION OF ICY RUNWAY TESTS

The RCR readings were recorded as discussed earlier in the main body of the paper. The average value was 12.7.

The friction coefficient actually achieved by RCR measuring vehicle is $\frac{12.7}{32.2} = 0.395$

Aircraft tire pressure = 170 psi.
RCR measuring vehicle tire pressure = 30 psi

From fig. 52 of NASA report no R64.

At 30 psi mu = 0.89
At 170 psi mu = 0.72.

Thus using first step of Anderson method

$\frac{0.72}{0.89} = 0.811$ is the fraction of RCR measuring vehicle friction which is available on aircraft $\cdot 0.395 \times 0.811 = 0.320$. This is the low speed friction potential. Since on an icy runway the mu does not vary significantly with speed, an 85% reduction used for dry runway may provide a measure for runway mu available.

i.e. $0.320 \times 0.85 = 0.272$.

The actual flight test distance for the test airplane on this runway condition was 2800 ft. Using a realistic value of antiskid efficiency under these mu conditions and other airplane parameters an estimated stopping distance can be calculated. To obtain the above stopping distance, however, requires an antiskid efficiency of 43%. This is very unrealistic, especially when actual measured values of antiskid efficiency (using SAE ARP 86[illegible] criterion) suggest much higher numbers (74%).

This simply means that the RCR reading results in too high a mu value. Even after use of conservative correction factors the resulting values are not realistic. The test conditions used here all have the same trend. For the runway conditions where runway surface is not consistent the numbers could easily be more or less conservative. The message is clear that the Anderson method, using RCR as a message of ground mu, does not appear to be a suitable technique for predicting braking performance on icy runways.

CORRELATION OF WET RUNWAY TESTS

The wet runway data offers a real challenge for the RCR method. For this condition mu varies with speed. However, the condition of tire, surface texture and speed of the test vehicle can all mask the slipperiness. NASA studies showed that on moist and slightly wet runways, where there is no standing water, such as a well drained runway, the correlation among the various friction monitoring vehicles was pretty good. The capability of the RCR method was not judged to be particularly good.

The Boeing 737 ARB tests are used here to assess the value of RCR for predicting stopping distance using Anderson's method.

The average RCR reading for two tests considered here was 22.5 which results in a mu value of $\frac{22.5}{32.2} = 0.70$.

From figure 52 of NASA report no R64

At 30 psi mu = 0.89
At 150 psi mu = 0.75

Therefore using the first step of Anderson's method $\frac{0.75}{0.89} = 0.8444$ is the fraction of RCR measuring vehicle friction which is available to the aircraft.

Thus mu available = 0.844 x 0.70 = 0.59.

Now hydroplaning speed $V_p = 9\sqrt{P}$ in knots

Where P = tire inflation pressure $= 9 \times \sqrt{150}$ 110 knots

$$\mu_{PW} = (\mu_0 - .05)\, K\, (V_P - V)^2 + 0.05$$

If K is so established that $\mu_{PW} = \mu_0$ at V = 15 knots

then K = $\frac{1}{(V_P - 15)^2} = \frac{1}{(110-15)^2} = \frac{1}{95^2}$

Therefore

$$\mu_{PW} = (0.59 - 0.05)\,\frac{1}{95^2}\,(110-V)^2 + .05$$

$$\mu_{PW} = .54\left(\frac{110-V}{95}\right)^2 + .05$$

THESE CALCULATED VALUES ARE SHOWN IN FIG. 5.

Using these values of corrected mu and airplane parameters the stopping distance was calculated to be 3760 ft. The airplane stopping distance for these tests was 3402 ft. For these tests it seems that mu values obtained by using Anderson's method are highly suppressed at high speeds. This, however, does not correlate with data obtained from the airplane test results. The mu value determined from flight test results in a stopping distance of 2515. (assuming an antiskid efficiency of 100%).

The overall efficiency for this test seemed to be close to 74%. The stopping distance was also calculated using the mu from airplane test and applying antiskid corrections as outlined in Anderson's method. These results in a distance of 3125. This turns out better than actual airplane stopping distance.

The discrepancy between actual and predicted values of distance has serious payload penalties. For example, if the predictions of this method were to be applied then the airline operator for this airplane may have to unload more than 7500 lbs to meet the stopping distance actually demonstrated, in the test considered above.

The results of this analysis, therefore, indicate that the Anderson method does not permit the prediction of stopping distances with a reasonable degree of accuracy.

Whereas the RCR readings are of questionable value to assess ground mu, these do provide some measure of runway condition, especially when accompanied by notes on the visual condition of the runway. It may be noted that RCR readings do reproduce reasonably well when surface is dry concrete, dry packed snow, et cetera. Its reduction to absolute ground mu, however, presents some problems. Careful control of variables may improve this situation.

TABLE I

BFI RUNWAY 13/31 CALIBRATION (WET RUNWAY)

RUN	JBD DECEL TEST	INST CORR	JBD DECEL CORR	$\frac{a}{g}$	CAR SPEED
1	25.5	1.6	27.1	.841	27
2	25	1.6	26.6	.826	28
3	25	1.6	26.6	.826	25
4	23	1.5	24.5	.761	26
5	25	1.6	26.6	.826	26
6	27.5	1.7	29.2	.908	27
7	24.5	1.6	26.1	.811	26
8	24	1.5	25.5	.792	25
9	31	1.6	32.6	1.0	24
10	25	1.6	26.6	.826	--
11	24	1.5	25.5	.792	--
12	24	1.5	25.5	.792	26
13	22	1.4	23.4	.728	26
14	23.5	1.5	25.0	.778	27
15	21.5	1.4	22.9	.712	24
16	31.0	1.6	32.6	1.0	26
17	30	1.6	31.6	.982	24

TABLE II

ICY RUNWAY TESTS - NOME, ALASKA

AIRPLANE - BOEING 727-100

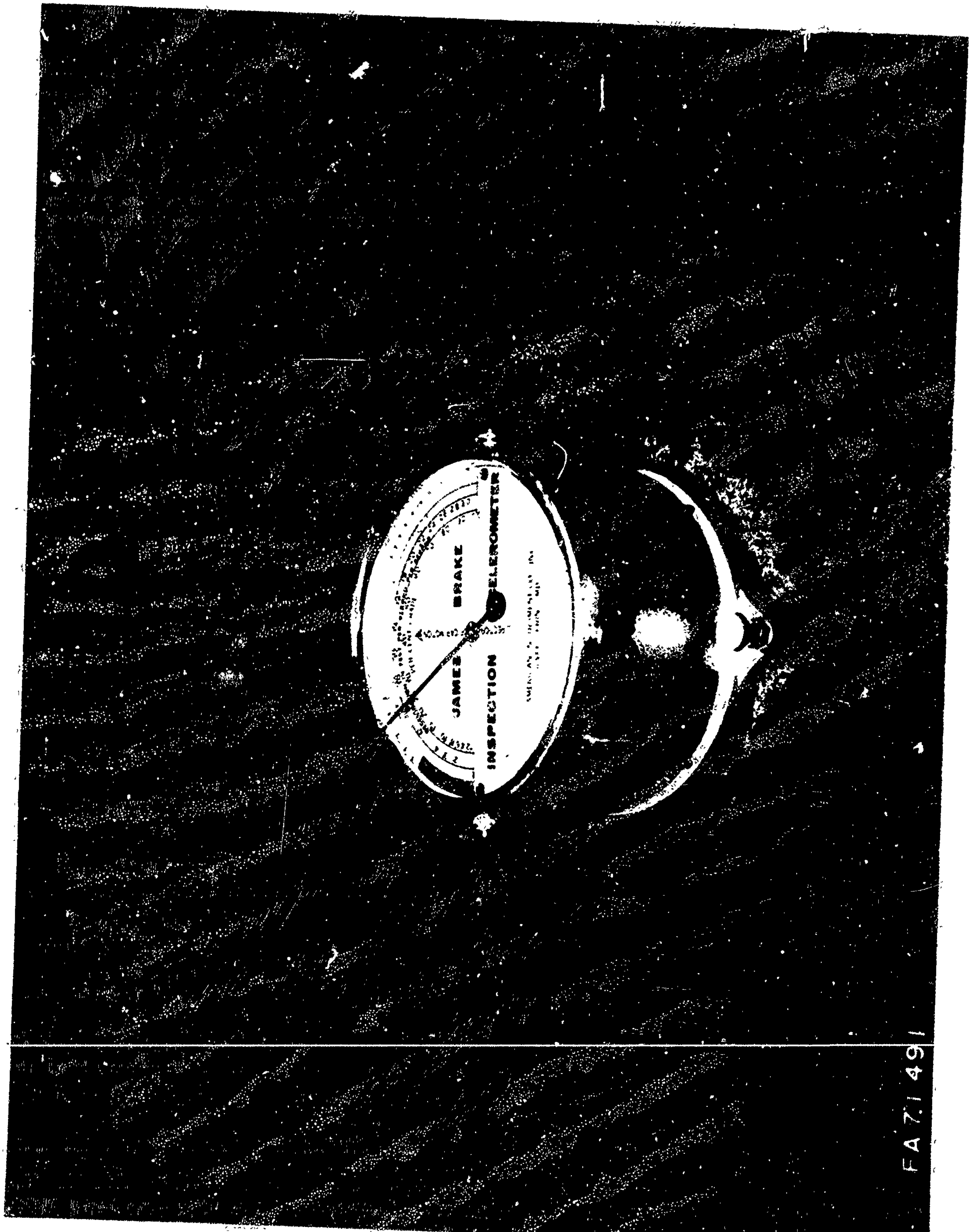
	Airplane Weight (lbs)	Windspeed Knots	Alaska Airlines RCR Ft/sec²	MAX RCR Measured on Airplane	Touchdown Speed Ft/sec	Brake Application Speed Ft/sec.
1.	128500	05	12	11	190	172
2.	126900	05	12	11	192	176
3.	121500	04	12	15	188	171
4.	119200	04	12	14	182	170
5.	115100	10	12	14.5	--	166
6.	111500	09	12	11.5	187	173
7.	110000	08	12	12.5	159	140

TEMPERATURE -2°F

* Nosewheel brakes on for Run 1 through 5.

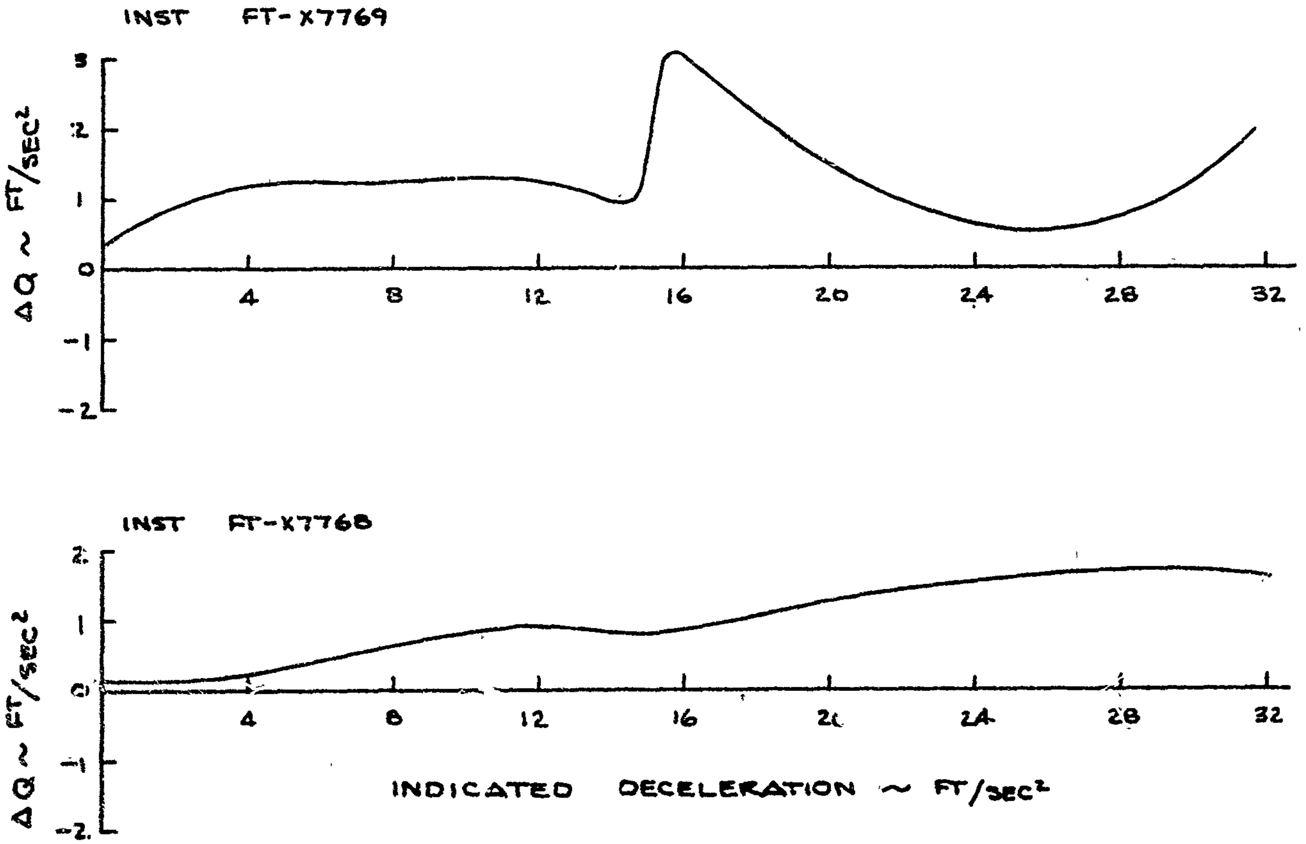
ACKNOWLEDGEMENTS

This author is grateful to Herbert Domandl and G. H. Herndor for their generous assistance in the reading of proof and for their valuable suggestions during the preparation of this paper.



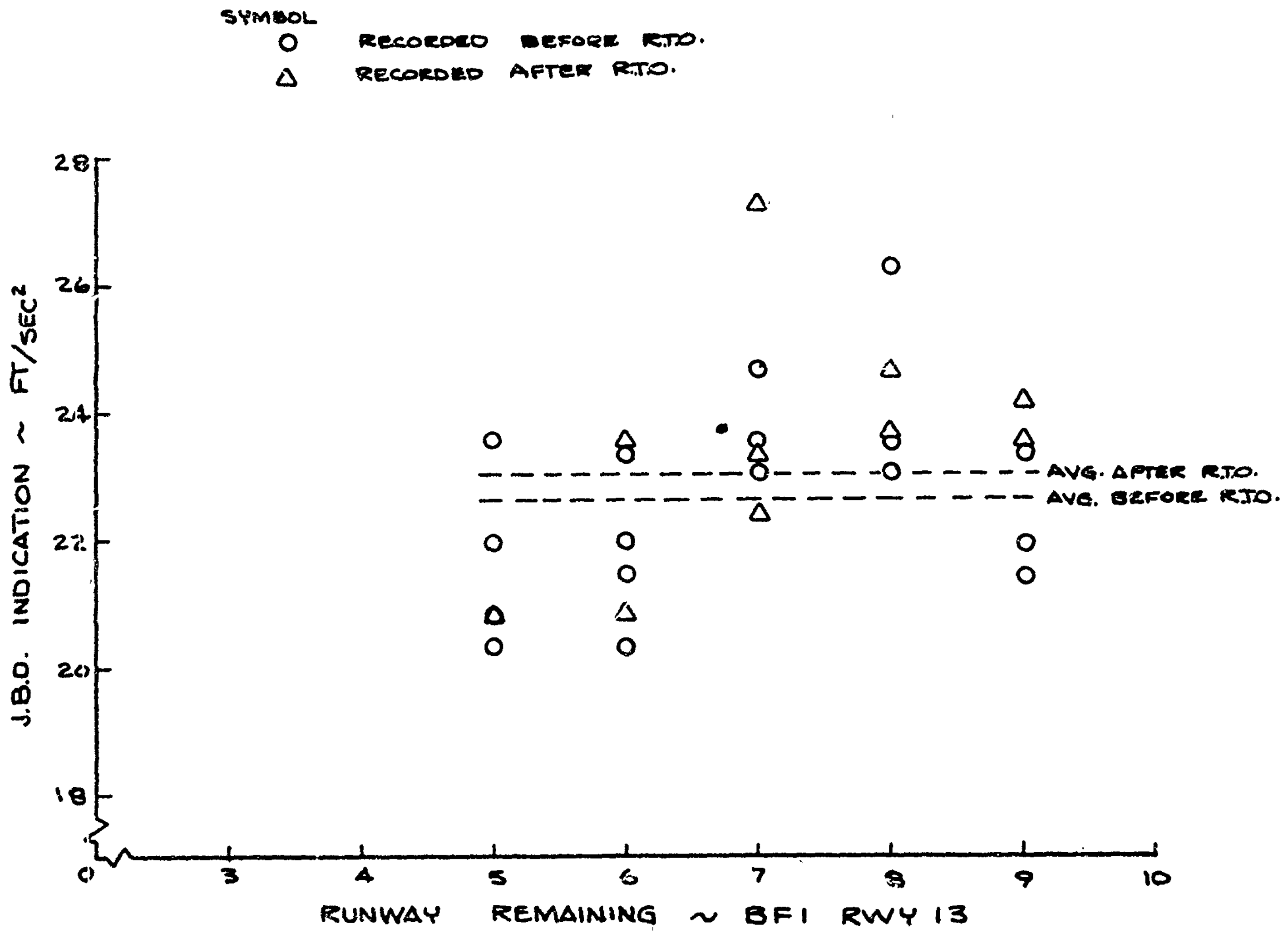
JAMES BRAKE DECELEROMETER

FIG. 1



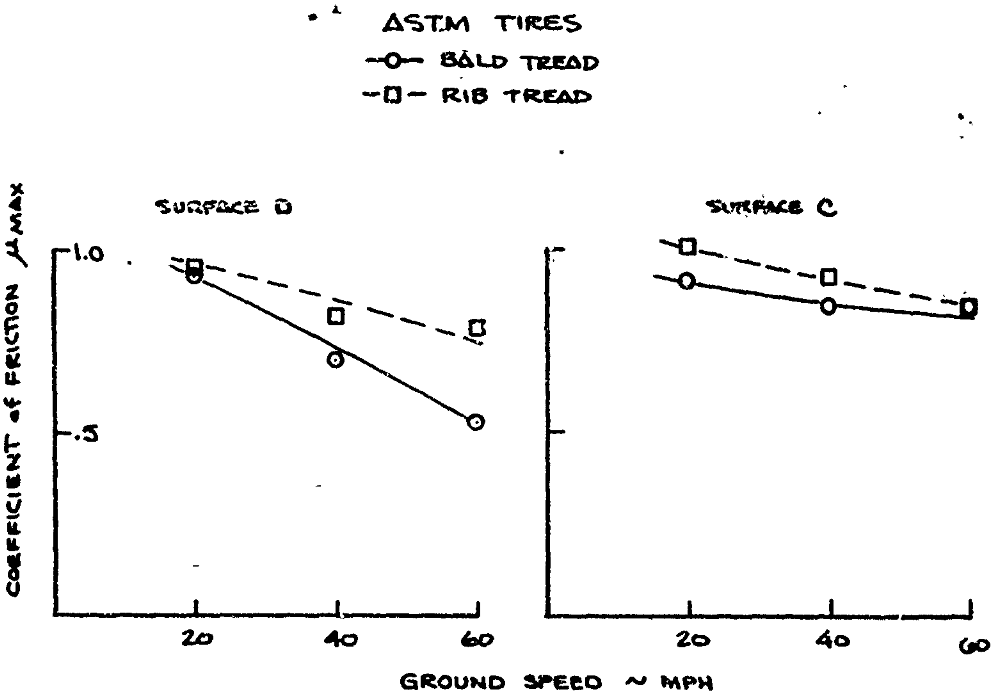
JAMES BRAKE DECELEROMETER CALIBRATION

FIG. 2

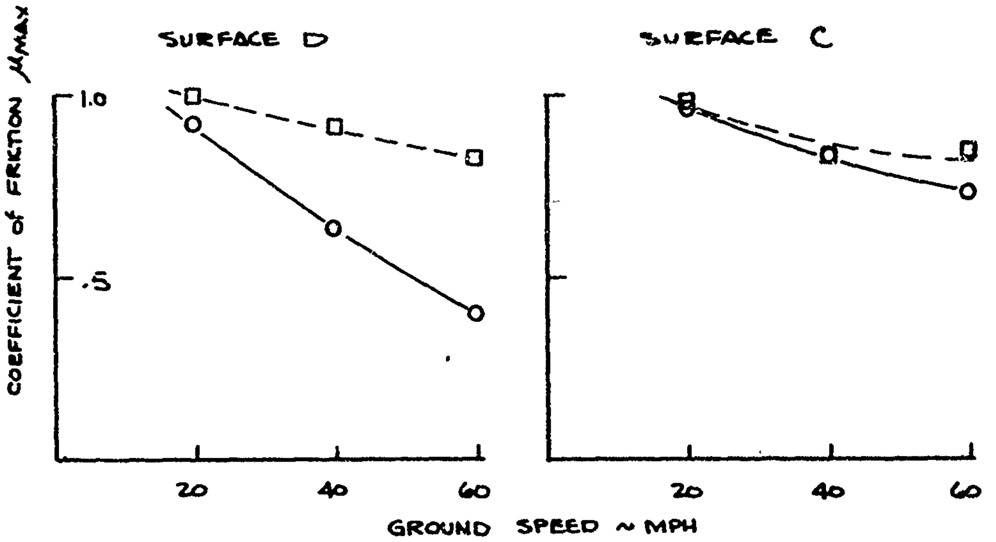


JAMES BRAKE DECELEROMETER WET
RUNWAY PERFORMANCE

FIG. 3



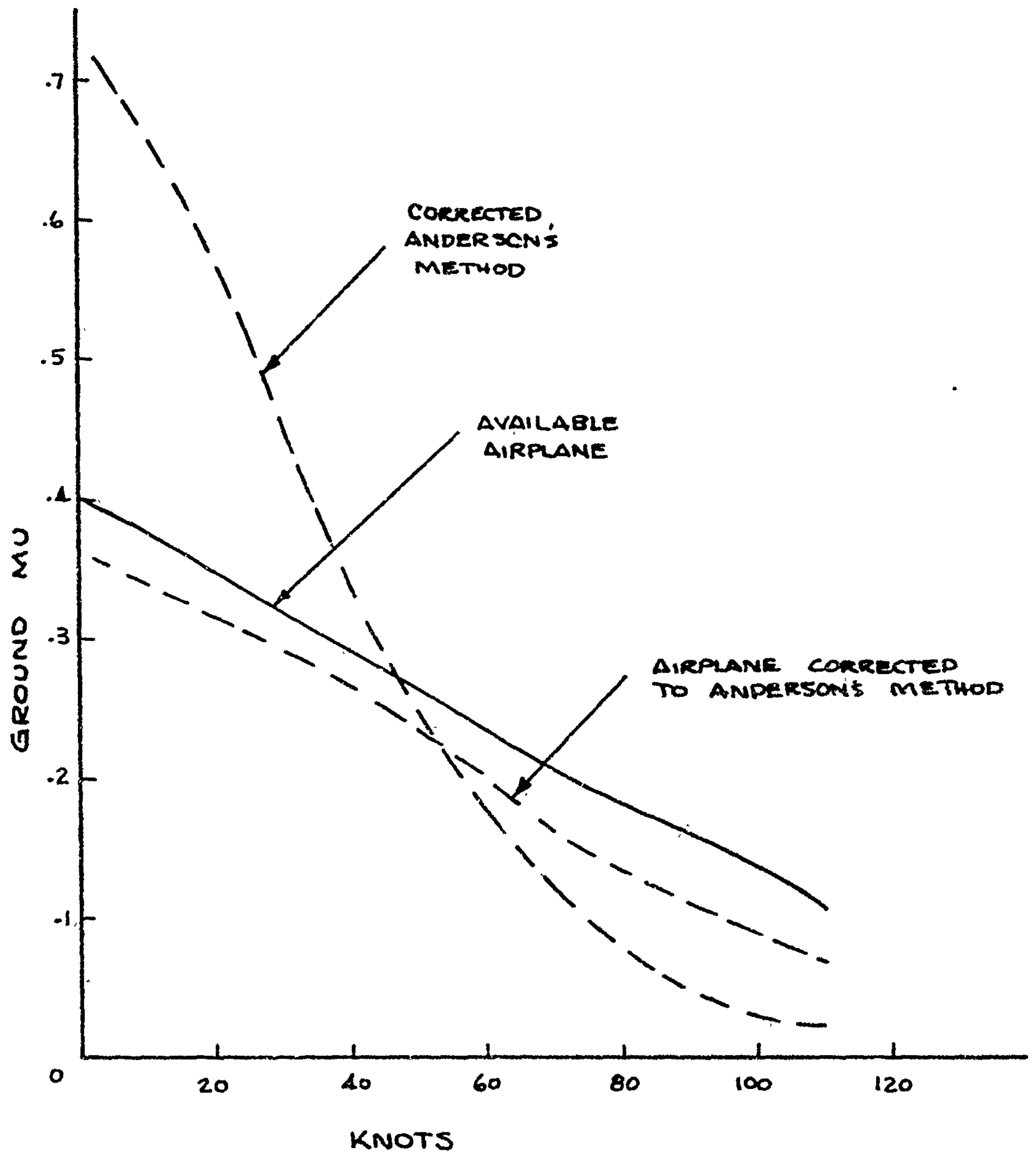
a) WET AND PUDDLED RUNWAY SURFACES



b) FLOODED RUNWAY SURFACES

EFFECTS OF TIRE TREAD DESIGN AND VEHICLE SPEED AND SURFACE TEXTURE ON FRICTION COEFFICIENTS

FIG. 4



GRAPH SHOWING DIFFERENCE BETWEEN AIRPLANE MU AND ESTIMATED MU BY ANDERSON METHOD

FIG. 5

LIST OF ACTIVE PAGES

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AD 1546 D

REV SYM

REVISIONS

REV SYM	DESCRIPTION	DATE	APPROVAL

AD 1546 C

REV SYM