Reliability and Performance of Friction-Measuring Equipment and Friction Equipment Correlation

THOMAS H. MORROW

The FAA conducted a tire performance evaluation and friction equipment correlation study in August 1989 at NASA Wallops Flight Facility located at Wallops Island, Virginia. The study was performed in response to a request by the ASTM to evaluate the performance of tires manufactured according to specifications ASTM E524 and ASTM E670. Some 1,650 tests were conducted on five types of surfaces using three different brands of tires and four different types of friction-measuring devices. Friction tests were conducted at speeds of 40 and 60 mph (65 and 95 km/hr), using the self-water system of the device on dry test surfaces. The water was applied to a depth of 0.04 in. (1 mm). The analyses conducted involved 156 reliability and performance studies and 31 correlation comparisons. Limits of acceptability were established for the data evaluation. The McCreary tire performed best on the runway friction tester, Saab friction tester, and the skiddometer. The Dico tire performed best on the mu meter. The tire formulation given in the ASTM E524 specification for lock-wheel trailers will be put into a new ASTM standard to describe the characteristics of the McCreary tire. The present E670 specification will contain the specifications for the Dunlop and Dico tires.

During 1978–1980, the FAA awarded a contract to evaluate 491 runways at 268 airports within the contiguous United States. The National Runway Friction Measurement Program (NRFMP) (*1*) used the Mark 3 mu meter, which at the time was a mechanical-hydraulic device (precomputer technology). The specific objectives of the program were to

1. Update, expand, and disseminate improved guidance material contained in Advisory Circular 150/5320-12b, *Methods for the Design, Construction and Maintenance of Skid Resistant Airport Pavement Surfaces* (*2*).
2. Provide airport managers with timely input from the friction and pavement condition surveys to budget their fiscal programs for whatever improvements were necessary as determined from the findings in those surveys.
3. Increase the effectiveness of the 1982 Airport and Airway Improvement Program (AAIP) by identifying the airport construction methods that are most cost effective in providing excellent drainage and friction properties.
4. Enhance safety at airports by reducing hydroplaning potential and improving pavement surface friction characteristics by developing recommendations for improved maintenance and maintenance monitoring practices.

Federal Aviation Administration, U.S. Department of Transportation, 800 Independence Avenue, S.W., Washington, D.C. 20591.

One of the major findings in the study concerned the performance of the tires used on the friction-measuring devices. When changing from one batch of tires to another batch, mu values were noticed to vary by as much as 10 numbers. This variance was realized by comparing the data obtained from one batch with the data of another batch. Friction tests were conducted on the same day over the same pavement surface under the exact same conditions. At this point, the quality control used by the tire manufacturer began to be suspect. Other reports were suggested by airport managers who were operating friction-measuring devices. They also recognized that there were differences in tire performance between batches. The tire performance problem was brought to the attention of the ASTM Subcommittee E17.21.

ASTM REQUEST FOR RESEARCH

On June 17, 1988, the ASTM Subcommittee E17.21 chairman requested the FAA to conduct tests to evaluate tire performance on friction measuring devices. The chairman requested these tests to be performed by the FAA Technical Center at the National Aeronautics and Space Administration (NASA) Wallops Flight Facility (WFF), Wallops Island, Virginia.

PURPOSE OF THE TIRE PERFORMANCE STUDY

The purpose of the tire performance study was twofold:

1. To establish the reliability, performance, and consistency of tires on all types of dry runway pavement surfaces, using continuous friction-measuring devices equipped with self-water systems (*3,4*).
2. To select the best performing tires that will achieve consistent correlation between the various friction-measuring devices and to develop guidelines that would be dependable and useful to airport operators in maintaining runway pavement surfaces for safe aircraft operations during wet weather conditions.

SELECTION OF TIRES TO BE EVALUATED IN THE TEST PROGRAM

Three manufacturers' tires were tested in the program. They were the Dico Tire, Inc., of Clinton, Tennessee; Dunlop Tire

Co. in the United Kingdom; and the McCreary Tire and Rubber Co. of Indiana, Pennsylvania. The Dico and McCreary tires are formulated according to portions of ASTM E501, ASTM E524, and ASTM E670 Specifications. Each tire manufacturer provided two batches of tires with each batch containing 10 tires. Each batch was divided further into two series of five tires each.

LOCATION OF TEST PROGRAM

The tire performance study was conducted in August 1989 at the NASA WFF. This location was selected by FAA because the facility offered several types of pavement surfaces that were constructed over 25 years ago for the purpose of conducting friction tests with ground friction measuring devices and aircraft (*5*). Each type of surface was carefully constructed to ensure consistency throughout the test segment. The test surfaces provide a wide range of mu values. An additional surface was temporarily constructed of aluminum plates to simulate an extremely low mu value to observe the behavior of the friction devices at these low mu values. A complete description of each test segment is presented in Table 1.

Three test sites were used at the facility. One was located on Runway 04–22 and the other two on the taxiway parallel to Runway 04–22. Figure 1 shows the location of the test sites. Segments *D*, *B*, and *A* were selected on Runway 04–22 as shown in Figure 2. The segments on the parallel taxiway were *K* and *P* (*6*).

TYPES OF FRICTION EQUIPMENT USED IN THE PROGRAM

General Description

Four types of friction-measuring devices were used in the test program. They were the mu meter (MUM) trailer, Saab friction tester (SFT) automobile, skiddometer (SKD) trailer, and the runway friction tester (RFT) minivan. All were fixed-slip devices except the mu meter, which is a side-force friction measuring device. The fixed-slip devices use a single smooth

TABLE 1 DESCRIPTION OF PAVEMENT SEGMENTS

SURFACE	MATERIAL	DESCRIPTION
A	Ungrooved Concrete	Surfaces A and B were subjected to a canvas belt drag treatment. The goal was to obtain as smooth a surface texture as possible. Later, 1 x 1/4 x 1/4 inch (25 x 6 x 6 mm) transverse grooves were cut in surface B by diamond saws.
B	Grooved Concrete	
D	Ungrooved Concrete	Surface D was subjected to a longitudinal burlap drag treatment. The goal was to obtain a typical currently used runway surface texture.
K	Ungrooved Asphalt	The skid pad was covered with liquid Jennite, which is a coal-tar emulsion. The usual sand and aggregate content normally used in highway application was omitted in the treatment of the skid pad to obtain as smooth and slippery surface as possible.
P	Aluminum Plates	Aluminum plates were constructed on the taxiway to obtain near zero mu values with the friction measuring devices.

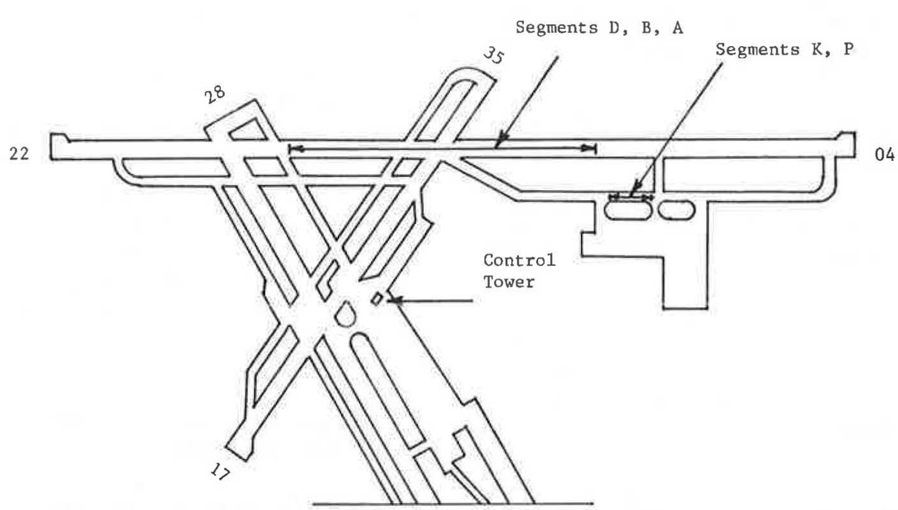

FIGURE 1 Runway schematic for NASA WFF indicating locations of test sections.

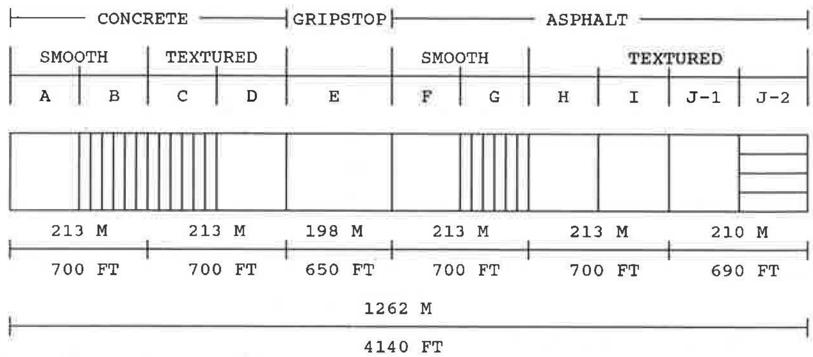

FIGURE 2 Schematic of Runway 04–22 test surfaces at NASA WFF.

tread tire that is inflated to 30 psi. The side-force device uses two friction-measuring tires inflated to 10 psi. Table 2 presents the test tire conditions for the four friction devices. All friction-measuring tires are 16 × 4 size. All devices are equipped with self-water systems and water storage tanks. The two trailer friction devices require a tow vehicle. A computer keyboard is available on all friction devices except the SKD. Instruction manuals are supplied by the manufacturer with all friction testers. FAA Advisory Circular 150/5320-12b, *Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces* (*2*), provides guidance on the operation of these devices.

Mark 4 MUM Trailer

The MUM is a three-wheel trailer. The trailer weighs approximately 540 lb and uses a vertical load of 171 lb on each of the two friction-measuring wheels. It uses two smooth-tread tires for measuring friction, each one in a toed-out position of 7.5 degrees from the direction of travel, resulting in an included angle of 15 degrees. When operated in the test mode, the MUM produces an apparent slip ratio of 13.5 percent. The rear wheel on the trailer, which has conventional tire tread design and is inflated at 30 psi, measures the distance traveled and provides stability during the course of the test run.

Mark 2 SFT Automobile

The SFT is a four-door sedan, equipped with front-wheel drive and a hydraulically retractable friction-measuring wheel located in the trunk of the vehicle, mounted directly behind the rear axle of the sedan. The friction-measuring wheel is oriented in the same direction as the four freely rolling tires on the sedan. The friction-measuring wheel arm consists of a chain drive connected to the vehicle's rear axle and contains the torque gauge used to compute the braking friction values. Depending on the pressure used in the friction-measuring tire (30 or 100 psi), the fixed-slip ratio varies from 10 to 12 percent. A vertical load of 310 lb is applied on the friction-measuring tire. The high-pressure tire has a three-grooved tread pattern.

BV-11 SKD Trailer

The SKD trailer, which weighs about 795 lb, is a welded steel frame supported by three-in-line wheels. The outer two wheels are free rolling and support the weight of the frame. The interior wheel of the trailer is the friction-measuring wheel. The wheels are connected by roller chains and sprockets with differing number of teeth. It has an applied vertical load of 220 lb. Depending on the pressure used in the friction-measuring tire (30 or 100 psi), the fixed-slip ratio varies from 15 to 17 percent. The friction-measuring wheel is oriented in the same direction as the outer two wheels of the trailer. The high-pressure tire has a three-grooved tread pattern.

M 6800 Runway Friction Tester

The M 6800 runway friction tester is a front-wheel drive minivan. The friction-measuring wheel is connected to the rear axle by a gear drive that produces a 13.5 percent fixed-slip ratio. The friction-measuring wheel is oriented in the same

TABLE 2 TEST TIRE CONDITIONS FOR FRICTION-MEASURING EQUIPMENT

FRICTION MEASURING DEVICE	TEST-TIRE MODE	TIRE TYPE	TREAD DESIGN	INFLATION PRESSURE PSI	VERTICAL LOAD LB
MARK 2 SAAB FRICTION TESTER	FIXED SLIP, 10 TO 12%	RL2 AERO	SMOOTH 3-GROOVE	30 100	310
M 6800 RUNWAY FRICTION TESTER	FIXED SLIP, 13%	RL2	SMOOTH	30	300
BV-11 SKIDDOMETER	FIXED SLIP, 15 TO 17%	RL2 AERO	SMOOTH 3-GROOVE	30 100	220
MARK 4 MU METER	7.5 YAWED ROLLING APPARENT SLIP, 13.5%	RL2	SMOOTH	10	171

direction as the four freely rolling wheels of the minivan. It uses only the smooth-tread low-pressure (30-psi) tire. The test tire includes a two-axis force transducer, which measures the vertical and drag forces. The friction measuring tire has an applied vertical load of 300 lb.

TEST PROCEDURES

Tire Identification for Field Tests

To ensure that all tires were properly identified in the field test program, each tire was marked according to the labels presented in Table 3.

An example is given to explain the meaning of the label RFT/DUN/B2S1: Runway Friction Tester/Dunlop Tire/Batch 2, Series 1. Batch numbers for the Dunlop tire were 100/B4C4338 and 100/E4C4338.

Coded Tire Combinations for Statistical Analysis

Because there were 60 tires to be tested in the program, it was imperative that they be properly coded for identification in the statistical analyses. Seven combinations of tires were identified and coded according to the labels presented in Table 4.

Equipment Calibration and Maintenance

All friction equipment used in the program was calibrated according to the manufacturers' instruction manuals. All personnel responsible for the operation of the friction equipment were instructed to maintain the equipment throughout the test program.

Texture Depth Measurements of Selected Pavement Segments

Texture depth measurements were made on pavement segments D, B, A, and K. The aluminum test plates were not measured. The average texture depth was based on three measurements taken in each segment, using the NASA grease-smear method (*7*).

Test Run Sequence Schedule and Data Records

Four test teams were assigned to complete 72 test runs per day for an aggregate total of 288 test runs per day. The program required 6 days to complete. A total of 1,643 runs were completed out of a possible 1,728, which represents 95 percent completion of the planned tests. All data obtained for each test run were logged on a data sheet provided by the program coordinator.

TABLE 3 CATALOG WITH TEST TIRE IDENTIFICATION

BATCH	DUNLOP TIRES	McCREARY TIRES	DICO TIRES
1	RFT/DUN/B1S1 SFT/DUN/B1S1 SKD/DUN/B1S1 MUM/DUN-L/B1S1 MUM/DUN-R/B1S1	RFT/MAC/B1S1 SFT/MAC/B1S1 SKD/MAC/B1S1 MUM/MAC-L/B1S1 MUM/MAC-R/B1S1	RFT/DIK/B1S1 SFT/DIK/B1S1 SKD/DIK/B1S1 MUM/DIK-L/B1S1 MUM/DIK-R/B1S1
	RFT/DUN/B1S2 SFT/DUN/B1S2 SKD/DUN/B1S2 MUM/DUN-L/B1S2 MUM/DUN-R/B1S2	RFT/MAC/B1S2 SFT/MAC/B1S2 SKD/MAC/B1S2 MUM/MAC-L/B1S2 MUM/MAC-R/B1S2	RFT/DIK/B1S2 SFT/DIK/B1S2 SKD/DIK/B1S2 MUM/DIK-L/B1S2 MUM/DIK-R/B1S2
2	RFT/DUN/B2S1 SFT/DUN/B2S1 SKD/DUN/B2S1 MUM/DUN-L/B2S1 MUM/DUN-R/B2S1	RFT/MAC/B2S1 SFT/MAC/B2S1 SKD/MAC/B2S1 MUM/MAC-L/B2S1 MUM/MAC-R/B2S1	RFT/DIK/B2S1 SFT/DIK/B2S1 SKD/DIK/B2S1 MUM/DIK-L/B2S1 MUM/DIK-R/B2S1
	RFT/DUN/B2S2 SFT/DUN/B2S2 SKD/DUN/B2S2 MUM/DUN-L/B2S2 MUM/DUN-R/B2S2	RFT/MAC/B2S2 SFT/MAC/B2S2 SKD/MAC/B2S2 MUM/MAC-L/B2S2 MUM/MAC-R/B2S2	RFT/DIK/B2S2 SFT/DIK/B2S2 SKD/DIK/B2S2 MUM/DIK-L/B2S2 MUM/DIK-R/B2S2

TABLE 4 CODED TIRE COMBINATIONS FOR STATISTICAL STUDY

TIRE CODE	EXPLANATION OF CODED TIRE COMBINATIONS
1.2	Compares Batch 1 with Batch 2
11.12	Compares Batch 1 - Series 1 with Batch 1 - Series 2
21.22	Compares Batch 2 - Series 1 with Batch 2 - Series 2
11.21	Compares Batch 1 - Series 1 with Batch 2 - Series 1
12.22	Compares Batch 1 - Series 2 with Batch 2 - Series 2
11.22	Compares Batch 1 - Series 1 with Batch 2 - Series 2
12.21	Compares Batch 1 - Series 2 with Batch 2 - Series 1

Data Acquisition and Reduction

Three test site locations were used in the program. Six test runs were conducted on each of the five pavement test segments for each of the two series of tires within a batch. This setup was done at two test speeds. A total of 1,643 runs and a total of 2,725 data points were accrued in the program.

The length of the pavement segments at WFF ranged from 200 to 350 ft. The friction devices are automatically set up to record mu averages for each 500-ft section. This meant that the mu averages for each test segment had to be visually interpreted by the test personnel. When traversing from one pavement segment to the adjacent one, it takes the recording instruments time to adjust to the change in mu values from one segment to another on the friction trace. The more the difference in mu values between segments, the more time and distance it takes to stabilize. To ensure that the friction trace has completely stabilized within the individual pavement segment, the test personnel had to carefully review the friction trace, selecting the mu averages from either the central 100-ft portion of the segment or the distance where it becomes obvious to the observer that the friction trace was stabilized. Usually, it takes about the first and last 50 ft of the segment to establish complete stabilization of the friction trace.

Data Analysis

A total of 156 regression analyses were performed to determine the reliability and performance of the tires manufactured by Dunlop, McCreary, and Dico. Another 31 regression analyses were performed to determine correlation between the four friction-measuring devices.

DEVELOPMENT OF LIMITS OF ACCEPTABILITY FOR TIRE PERFORMANCE

Development of Procedure

In order to compare the performance of one tire with that of another, parameters were set in the test program to establish boundary conditions that would satisfy all data needs.

Setting the Limits of Acceptability

There are three basic areas for consideration in setting the parameters for the limits of acceptability. The first and most critical is the slope of the regression line. When there is a one-to-one agreement, then the relationship $Y = X$ exists between the two variables. The second critical element concerns the coefficients of correlation and determination and the third is the standard error of estimate. The parameters set forth in the following paragraphs represent the minimum and maximum values that the calculated regression line can vary from the predicted one-to-one relationship. The slope of the calculated regression line must lie within these limits.

Intercept and Slope Set

The parameters for this set were divided into three elements: intercept at $X = 0$; slope of linear regression line; and intercept at $X = 100$.

Intercept at $X = 0$ The parameter for this set is ± 3 mu numbers for one standard error of estimate.

Slope of Regression Line A perfect correlation line is established when the slope of the regression line equals 1.000. The parameter for the allowable variance from this line was set at ± 0.080, or the slope may range from 0.920 to 1.080.

Intercept at $X = 100$ The parameter for allowable variance at this intercept was set at $X = \pm 5$ mu numbers for one standard error of estimate.

Coefficient Set

The parameters for this set were divided into two elements: the coefficient of correlation and the coefficient of determination.

Coefficient of Correlation The minimum acceptable value for the coefficient of correlation was set at 0.980.

Coefficient of Determination The minimum acceptable value for the coefficient of determination was set at 0.960. The coefficient of determination was calculated by squaring the coefficient of correlation.

Standard Error of Estimate Set

This set consists of only one element, the standard error of estimate. The parameter for this set was ± 3 mu numbers for one standard error of estimate.

RATIONALE FOR EVALUATION METHOD

To emphasize the importance of the slope of the calculated linear regression line and how it compared to the predicted one-to-one regression line, a method was devised to determine how well each tire performed in the program. Each set was weighted to reflect the importance to the whole. The weighting method was set up on the basis of the author's field experience obtained while testing friction-measuring equipment at the NASA WFF. The breakdown of the weighting percentages was based on the author's acquired knowledge in understanding these relationships. The slope-intercept set was weighted at 50 percent; the coefficient set at 20 percent; and the standard error of estimate set at 30 percent, for a total of 100 percent for the three sets.

Each element within the set must meet the parameter for that element; any data that fall outside of the parameter for that element fail the entire set. If the set failed, it received no evaluation points. Point values were assigned to each set.

Tire Combination Categories

There were two tire combination categories: Category A and Category B.

Category A

In this category, one batch of tires was compared with another batch for each of the three manufacturers. This combination was the only tire combination for this category and was worth 50 percent of the total evaluation points.

Category B

This category compared various combinations of tire batches and series. There were six tire combinations in this category and the entire category was worth 50 percent of the total evaluation points.

Evaluation Points Assigned to Each Category

The total evaluation points assigned for both categories was 120.

Evaluation Point Breakdown for Category A

The total number of evaluation points for this category was 60. The point distribution for the three sets within this category is as follows:

Set	*Point Distribution*
Intercept Set	30
Coefficient Set	12
Standard Error of Estimate Set	18

Evaluation Point Breakdown for Category B

The total evaluation points for this category was 60, distributed between six tire combinations. The total evaluation points for any one tire combination was 10 points. The point distribution for the three sets within this category is as follows:

Set	*Point Distribution*
Intercept Set	5
Coefficient Set	2
Standard Error of Estimate Set	3

EVALUATION RESULTS OF TIRE PERFORMANCE

Tables 5–7 indicate the results of the evaluation of tire performance on each of the four friction devices used in the study.

SUMMARY OF OVERALL TIRE PERFORMANCE

Table 8 indicates the final results of the overall tire performance and reliability evaluation. The McCreary tire, which follows ASTM Specification E524, performs best on the nonyawed or fixed-brake slip friction devices, whereas the yawed-mode or side force friction device, the mu meter, performs best when using the Dico tire according to the ASTM Specification E670. The test results obtained in the program vindicate that the tires will perform satisfactorily when manufactured in accordance with the procedures given in the ASTM specifications.

TABLE 5 EVALUATION RESULTS FOR MCCREARY TIRE PERFORMANCE

TIRE CATEGORY	TIRE PERFORMANCE AT 40 MPH		TIRE PERFORMANCE AT 60 MPH		OVERALL TIRE PERFORMANCE	
	ACCRUED POINTS	PERCENTAGE	ACCRUED POINTS	PERCENTAGE	ACCRUED POINTS	PERCENTAGE
McCREARY TIRE PERFORMANCE ON RUNWAY FRICTION TESTER						
A	60	100.0000	60	100.0000	120	100.0000
B	60	100.0000	55	91.6667	115	95.8333
TOTAL	120	100.0000	115	95.8333	235	**97.9167**
McCREARY TIRE PERFORMANCE ON SAAB FRICTION TESTER						
A	60	100.0000	60	100.0000	120	100.0000
B	55	91.6667	60	100.0000	115	95.8333
TOTAL	115	95.8333	120	100.0000	235	**97.9167**
McCREARY TIRE PERFORMANCE ON SKIDDOMETER						
A	60	100.0000	60	100.0000	120	100.0000
B	60	100.0000	55	91.6667	115	95.8333
TOTAL	120	100.0000	115	95.8333	235	**97.9167**
McCREARY TIRE PERFORMANCE ON MU METER						
A	30	50.0000	12	20.0000	42	35.0000
B	32	53.3333	39	65.0000	71	59.1667
TOTAL	62	51.6667	51	42.5000	113	**47.0833**

TABLE 6 EVALUATION RESULTS FOR DICO TIRE PERFORMANCE

TIRE CATEGORY	TIRE PERFORMANCE AT 40 MPH		TIRE PERFORMANCE AT 60 MPH		OVERALL TIRE PERFORMANCE	
	ACCRUED POINTS	PERCENTAGE	ACCRUED POINTS	PERCENTAGE	ACCRUED POINTS	PERCENTAGE
DICO TIRE PERFORMANCE ON RUNWAY FRICTION TESTER						
A	0	0.0000	30	50.0000	30	25.0000
B	24	40.0000	35	58.3333	59	49.1667
TOTAL	24	20.0000	65	54.1667	89	**37.0833**
DICO TIRE PERFORMANCE ON SAAB FRICTION TESTER						
A	0	0.0000	0	0.0000	0	0.0000
B	21	35.0000	16	26.6667	37	30.8333
TOTAL	21	17.5000	16	13.3333	37	**15.4167**
DICO TIRE PERFORMANCE ON SKIDDOMETER						
A	0	0.0000	30	50.0000	30	25.0000
B	16	26.6667	40	66.6667	56	46.6667
TOTAL	16	13.3333	70	58.3333	86	**35.8333**
DICO TIRE PERFORMANCE ON MU METER						
A	60	100.0000	60	100.0000	120	100.0000
B	52	86.6667	60	100.0000	112	93.3333
TOTAL	112	93.3333	120	100.0000	232	**96.6667**

TABLE 7 EVALUATION RESULTS FOR DUNLOP TIRE PERFORMANCE

TIRE CATEGORY	TIRE PERFORMANCE AT 40 MPH		TIRE PERFORMANCE AT 60 MPH		OVERALL TIRE PERFORMANCE	
	ACCRUED POINTS	PERCENTAGE	ACCRUED POINTS	PERCENTAGE	ACCRUED POINTS	PERCENTAGE
DUNLOP TIRE PERFORMANCE ON RUNWAY FRICTION TESTER * Batch 2 was not completed due to accidental damage to vehicle						
A	NA *		NA *		NA *	
B	NA *		NA *		NA *	
TOTAL						
DUNLOP TIRE PERFORMANCE ON SAAB FRICTION TESTER						
A	12	20.0000	30	50.0000	42	35.0000
B	12	20.0000	40	66.6667	52	43.3333
TOTAL	24	20.0000	70	58.3333	94	**39.1667**
DUNLOP TIRE PERFORMANCE ON SKIDDOMETER						
A	12	20.0000	12	20.0000	24	20.0000
B	29	48.3333	45	75.0000	74	61.6667
TOTAL	41	34.1667	57	47.5000	98	**40.8333**
DUNLOP TIRE PERFORMANCE ON MU METER						
A	0	0.0000	0	0.0000	0	0.0000
B	26	43.3333	27	45.0000	53	44.1667
TOTAL	26	21.6667	27	22.5000	53	**22.0833**

TABLE 8 OVERALL SUMMARY OF TIRE PERFORMANCE ON FRICTION EQUIPMENT

FRICTION EQUIPMENT	TEST TIRE		
	McCREARY	DICO	DUNLOP
RUNWAY FRICTION TESTER	98%	37%	INCOMPLETE
SAAB FRICTION TESTER	98%	15%	39%
SKIDDOMETER	98%	36%	41%
MU METER	47%	97%	22%

CORRELATION OF FRICTION EQUIPMENT AND DEVELOPMENT OF CORRELATION PARAMETERS

Background

The parameters used in this study for correlation between two friction devices that operate in different friction modes was established during many years of experience of testing friction equipment at the NASA WFF. The two most important parameters for correlation are the coefficient of correlation and the standard error of estimate. However, the slope is no longer in the one-to-one relationship realized in the criteria developed for the tire evaluation study. Therefore, it will not apply to the correlation analysis evaluation. The slope of the calculated regression line exhibiting correlation between the two friction devices is shifted from the one-to-one relationship. This shift is attributed to the physical characteristics of each friction device. They are not designed to operate in the same friction mode and thus record different mu numbers for the same pavement surface conditions in portions of the friction range. The precision of the correlation is determined by the data scatter pattern relative to the calculated regression line and how well the line is established throughout the friction range.

Setting the Evaluation Parameters

Correlation between two friction devices is acceptable when the correlation coefficient exceeds 0.9800, the coefficient of determination exceeds 0.9604, and the standard error of estimate is less than ±3.5 mu numbers. The slope of the regression line must be well established throughout the friction range.

Evaluation Method

This method is divided into two sets: the coefficient set and the standard error of estimate set.

Point Breakdown for the Coefficient Set

The coefficient set includes the coefficients of correlation and determination. The set is worth 5 points, and if either of the parameters is not acceptable, the entire set fails and gets zero points.

Point Breakdown for the Standard Error of Estimate Set

The standard error of estimate set includes only the standard error of estimate. The set is worth 5 points.

OVERALL SUMMARY OF TIRE PERFORMANCE

Table 9 presents the overall tire performance on friction equipment correlation. The McCreary tire, mounted on all four friction devices, was given a 13 percent performance rating. The combinations of the McCreary tire mounted on the RFT, SFT, and SKD and the Dico tire mounted on the MUM were given a performance rating of 88 percent. The Dunlop tire, mounted on all four devices, was given a 20 percent performance rating.

SELECTION OF BEST-PERFORMING TIRES FOR CORRELATION

The McCreary tire did not perform well on the MUM and that is why the correlation between the MUM and the other devices using the McCreary tire did not meet the performance criteria. The Dunlop tire had variations between series within the same batch as well as between batches and as a result did not meet the performance criteria as set forth in this report. The best-performing tire combinations were the McCreary tire mounted on the RFT, SFT, and SKD and the Dico tire mounted on the MUM. The tires mounted on the friction equipment presented in Tables 10 and 11 are the recommended correlation standard for vehicle speeds of 40 and 60 mph and will be included in the next revision of Advisory Circular 150/5320-12b (*2*).

DEVELOPMENT OF CORRELATION BETWEEN FRICTION EQUIPMENT

Tests have been conducted at NASA WFF for the past 8 years. The MUM was the first friction device used in this country

TABLE 9 OVERALL SUMMARY OF TIRE PERFORMANCE ON FRICTION EQUIPMENT CORRELATION

OVERALL TIRE PERFORMANCE		
McCREARY TIRE	McCREARY/DICO TIRE	DUNLOP TIRE
13 %	88 %	20 %

TABLE 10 CORRELATION OF MU VALUES FOR FRICTION-MEASURING EQUIPMENT USING SELF-WATER SYSTEM AT SPEED OF 40 mph

CODED FRICTION PARAMETER	MARK 4 MU METER WITH DICO TIRE	M 6800 RUNWAY FRICTION TESTER BV-11 SKIDDOMETER MARK 2 SAAB FRICTION TESTER WITH THE McCREARY TIRE
	CORRESPONDING MU VALUES	
A	42	50
B	52	60
C	72	82

TABLE 11 CORRELATION OF MU VALUES FOR FRICTION-MEASURING EQUIPMENT USING SELF-WATER SYSTEM AT SPEED OF 60 mph

CODED FRICTION PARAMETER	MARK 4 MU METER WITH DICO TIRE	M 6800 RUNWAY FRICTION TESTER WITH McCREARY TIRE	MARK 2 SAAB FRICTION TESTER, BV-11 SKIDDOMETER WITH McCREARY TIRE
	CORRESPONDING MU VALUES		
A	26	41	34
B	38	54	47
C	66	72	74

for many years before the other testers were introduced on the market. As a result, an extensive data base was established, and, when the other devices were available on the market, the MUM was used as the base for correlation between the various friction devices. Tests conducted by NASA in the early 1970s, using a B-727 and a MUM, established the criteria for determining a satisfactory level of friction for aircraft operations. The mu value of 50 that was adopted from the study has been used up to the present time as the maintenance level for an acceptable pavement surface condition. Tables 12 through 14 present the results of the statistical analyses; the values in the bold print exceed the evaluation parameters.

CONCLUSIONS

It is recommended that Tables 10 and 11 be included in the next revision of AC 150/5320-12b, *Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces* (*2*). The coded friction parameters presented in the tables determine the corresponding mu values for the friction device used at the airport. It is used in conjunction with the paragraphs concerned with friction survey measurement parameters, which provide the airport operator with guidelines for determining whether or not corrective action may be required to improve the surface friction characteristics of a wet runway.

TABLE 12 CORRELATION SUMMARY BETWEEN FRICTION EQUIPMENT USING MCCREARY TIRE

FILENAME	TEST SPEED (MPH)	COEFFICIENTS A	B	C	* CC	* CD	* SEE	NUMBER OF DATA PAIRS IN ANALYSIS
40MUMMAC.DUN	40	+3.8726	+0.0779	+0.0131	0.9810	0.9623	**4.1356**	111
40MUM60.MAC	40/60	+4.3028	-0.1120	+0.0139	**0.9772**	**0.9549**	**4.0162**	120
40MUMRFT.MAC	40	-1.0198	+0.8186	-	**0.9752**	**0.9510**	**3.6612**	120
60MUMRFT.MAC	60	-0.0008	+0.9653	-0.0021	**0.9762**	**0.9529**	3.4449	120
40MUMSFT.MAC	40	-9.1162	+1.1797	-	**0.9679**	**0.9368**	**6.0374**	120
60MUMSFT.MAC	60	-2.6108	+0.8164	+0.0039	**0.9799**	**0.9603**	**4.1933**	120
40MUMSKD.MAC	40	-8.5669	+1.1586	-	**0.9594**	**0.9204**	**6.7166**	120
60MUMSKD.MAC	60	-1.3518	+0.9504	+0.0022	**0.9693**	**0.9396**	**5.2838**	120

* NOTE: The values shown in **bold** print fell outside of the Limits of Acceptability.

TABLE 13 CORRELATION SUMMARY BETWEEN FRICTION EQUIPMENT USING MCCREARY AND DICO TIRE COMBINATION

FILENAME	TEST SPEED (MPH)	COEFFICIENTS						NUMBER OF DATA PAIRS IN ANALYSIS
		A	B	C	CC	CD	* SEE	
40DUNMUM.DIK	40	-0.6210	+1.0095	-	0.9908	0.9818	2.8666	51
40MUM60.DIK	40/60	+2.1717	+0.0878	+0.0107	0.9929	0.9859	2.2521	120
MUDKRFMC.40	40	+5.1043	+0.7721	-	0.9881	0.9763	2.5462	120
MUDKRFMC.60	60	+0.7518	+1.3431	-0.0080	0.9894	0.9789	2.3055	120
MUDKSFMC.40	40	-0.6109	+1.1213	-	0.9883	0.9767	**3.6674**	120
MUDKSFMC.60	60	-1.8676	+1.2369	-0.0022	0.9889	0.9779	3.1262	120
MUDKSKMC.40	40	-0.5894	+1.1136	-	0.9918	0.9837	3.0321	120
MUDKSKMC.60	60	-0.9254	+1.4294	-0.0049	0.9830	0.9662	**3.9503**	120

* NOTE: The values shown in **bold** print fell outside of the Limits of Acceptability.

TABLE 14 CORRELATION SUMMARY BETWEEN FRICTION EQUIPMENT USING DUNLOP TIRE

FILENAME	TEST SPEED (MPH)	COEFFICIENTS						NUMBER OF DATA PAIRS IN ANALYSIS
		A	B	C	* CC	* CD	* SEE	
40MUM60.DUN	40/60	-0.2885	+0.4105	+0.0066	0.9916	0.9832	2.5355	108
40MUMSFT.DUN	40	+0.4883	+1.2891	-	**0.9468**	**0.8964**	**9.3393**	111
60MUMSFT.DUN	60	-1.1043	+1.5292	-0.0053	**0.9463**	**0.8955**	**8.0194**	108
40MUMSKD.DUN	40	+0.1000	+1.2373	-	**0.9575**	**0.9168**	**7.9419**	111
60MUMSKD.DUN	60	+0.5361	+1.2123	-0.0006	**0.9590**	**0.9197**	**6.7917**	108

* NOTE: The values shown in **bold** print fell outside of the Limits of Acceptability.

It is recommended that the tire composition given in ASTM Specification E524 for the McCreary tire be developed into a new ASTM specification that has the same tire dimensions given in the ASTM E670 specification. The Dico tire specification will be included in the present ASTM E670 specification.

Complete details of this study can be found in Report DOT/FAA/AS-90-1, *Reliability and Performance of Friction Measuring Tires and Friction Equipment Correlation* (*8*).

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