



ESDU 00018

Issued October 1999
Re-issued September 2010

Example of statistical analysis of wet runway friction: ground-test machine data

Endorsed by
The Royal Aeronautical Society

AVA Documents
Document Sharing Hub

ESDU DATA ITEMS

Data Items provide validated information in engineering design and analysis for use by, or under the supervision of, professionally qualified engineers. The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants. The whole process is subject to independent review for which crucial support is provided by industrial companies, government research laboratories, universities and others from around the world through the participation of some of their leading experts on ESDU Technical Committees. This process ensures that the results of much valuable work (theoretical, experimental and operational), which may not be widely available or in a readily usable form, can be communicated concisely and accurately to the engineering community.

We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Performance Committee. This Committee first met in 1946 and now has the following membership:

Chairman	
Mr K J Balkwill	— Independent
Members	
Mr P V Aidala*	— Northrop Grumman ESID, Bethpage, New York, USA
Dr J.D. Avery	— Defence Evaluation and Research Agency, Boscombe Down
Mr T Bartup	— Avro International Aerospace, Woodford
Mr M Broad	— Independent
Mr N J Herniman	— Airbus Industrie, Toulouse, France
Mr R G Humpston	— Rolls-Royce plc, Aero Division, Derby
Mr T S R Jordan	— Independent
Mr R J Orlowski*	— Boeing Commercial Airplane Company, Seattle, Washington, USA
Dr P Render	— University of Loughborough
Mr D N Sinton	— Independent
Mr G J R Skillen	— Civil Aviation Authority, Safety Regulation Group, Gatwick
Mr G E Smith	— Independent
Mr A Stanbrook	— Independent
Mr R Storey	— British Aerospace, Military Aircraft and Aerostructures, Brough
Prof. E Torenbeek*	— Delft University of Technology, The Netherlands
Mr S. Tsachr*	— Israel Aircraft Industries, Jerusalem, Israel
Mr C J Turner*	— Boeing, Douglas Products Group, Long Beach, Calif., USA
Mr M Wilson	— Britten-Norman Ltd, Isle of Wight.

* Corresponding Member

The construction and subsequent development of the Data Item was undertaken by the Chairman of the Performance Committee,

Mr K J Balkwill — under contract to ESDU.

The person with overall responsibility for the work in this subject area is Mr D.J. Mitchell, Head of Performance Group.

EXAMPLE OF STATISTICAL ANALYSIS OF WET RUNWAY FRICTION: GROUND-TEST MACHINE DATA

CONTENTS

	Page
1. NOTATION, UNITS AND DEFINITIONS	1
1.1 Notation	1
1.2 Definitions	2
1.2.1 Ground-test machine	2
1.2.2 Coefficient of friction	2
2. INTRODUCTION	3
3. DESCRIPTION OF MU-METER, TESTS AND AVAILABLE DATA	3
4. ANALYSIS	4
4.1 Dry Runway Data	5
4.2 Wet Runway Data	6
4.3 Friction Data Bases for the Example Ground-Test Machine (Mu-Meter)	6
4.3.1 Graphical representation of Friction Data Base	8
4.4 Concluding Remarks	8
5. REFERENCES	9
6. TABLES	10
FIGURES 1 to 3	11 to 12
APPENDIX A	13
A.1 Distributions of Values of μ_{dry} and κ from Mu-Meter Test Data	13
FIGURES A1 to A12	14 to 16

EXAMPLE OF STATISTICAL ANALYSIS OF WET RUNWAY FRICTION: GROUND-TEST MACHINE DATA

1. NOTATION, UNITS AND DEFINITIONS

The units given in this section are coherent sets – as are required for equations throughout the Data Item. However, where numerical values are quoted, customary British units are used for d_{tex} , d_W , p , q and V_G .

1.1 Notation

A^*	modified Anderson-Darling goodness-of-fit statistic, see Reference 8	–	–
d_{tex}	runway surface macro-texture depth	m	ft
d_W	depth of water on runway	m	ft
$E[]$	expected or calculated value of quantity in square brackets, i.e. corresponds to $P_E = 0.5$	–	–
G_B	tangential force on tyre due to braking	N	lbf
n	size of sample	–	–
$P[]$	probability of occurrence of quantity in []	–	–
P_E	probability of exceedence	–	–
p	tyre inflation pressure	N/m ²	lbf/ft ²
q	kinetic pressure of runway surface water ($= \rho_W V_G^2 / 2$)	N/m ²	lbf/ft ²
V_G	ground speed	m/s	ft/s
Z	normal (to runway) load on wheel	N	lbf
z	percentage point in Standard Normal Distribution	–	–
β	parameter defined in Equation (4.1)	–	–
$\Delta[]$	residual about correlation of quantity in square brackets	–	–
κ	tyre-to-wet-runway interaction parameter, $(\beta d_{tex})^{1/2}$	m ^{1/2}	ft ^{1/2}
$\bar{\kappa}$	mean value of κ	m ^{1/2}	ft ^{1/2}
μ	coefficient of friction, G_B/Z	–	–
μ_{datum}	datum value of μ at $V_G = 0$ on dry runway	–	–

Issued October 2000 – 16 pages
Re-issued September 2010 – 16 pages

μ_m	coefficient of friction for ground-test machine	—	—
ρ_w	density of water (taken as 1000 kg/m ³ or 1.94 slug/ft ³)	kg/m ³	slug/ft ³
$\sigma[\]$	standard deviation of quantity in square brackets	—	—
Φ	Standardised Normal Cumulative Distribution Function, see Reference 7 for numerical values	—	—
χ^2	“Chi-squared” test statistic, see Section 5.1 of Reference 7	—	—

Superscript

—	denotes mean value
---	--------------------

Subscripts

<i>dry</i>	denotes value for dry conditions
<i>wet</i>	denotes value for wet conditions

1.2 Definitions

1.2.1 Ground-test machine

Any device giving a measure of runway friction conditions for subsequent use in predicting aircraft stopping performance. The definition may include towed devices or those that are integral with the vehicle.

1.2.2 Coefficient of friction

For ground-test machines, μ ($\equiv \mu_m$) represents whatever coefficient of friction is recorded by any particular machine. In general, μ_m can be expected to be one of

- locked-wheel coefficient of friction,
- coefficient of friction at prescribed tyre “slip” condition,
- maximum coefficient of friction at optimum tyre “slip” condition,
- yawed rolling coefficient of friction at prescribed tyre yaw angle.

2. INTRODUCTION

This Data Item is the third of a series of examples of the application of a method for representing – and, if necessary, relating – the braking performances of aircraft and ground-test machines in wet conditions. The method, which is given in Reference 11, is essentially statistical and implies that there is a clearly-defined level of probability that can be deduced from test runs of a ground-test machine (or an aircraft) in a given set of wetness conditions on a particular runway. If the runway macro-texture depth is known, then the parameter that defines the variation of coefficient of braking friction in the given conditions can be readily calculated from a pre-determined *Friction Data Base*. The concept of a Friction Data Base is explained in Reference 11.

This example uses data for the “Mu-Meter” ground-test machine operating both on wetted runways and in *self-wetting mode*. The background to the tests is described in Section 3. The method of analysis is summarised and results are presented in Section 4. Mu-Meter friction measurements are available from widely differing test series – to the extent that the suitability of the various results for use in predicting aircraft stopping performance can be assessed – see Table 4.1 – as a function of the ranges of runway wetness conditions used.

Two examples of the derivation of Friction Data Bases for individual aircraft are given in ESDU 99016 and ESDU 99017 (References 12 and 13). The former of these considers an aircraft for which an extensive set of test data is available; the latter considers an aircraft for which a limited set of test data is available.

If the method of Reference 11 is to be used to relate the braking performances of a given combination of aircraft and ground-test machine, the procedure comprises two distinct phases. The first is the establishment of separate *Friction Data Bases* for the aircraft and for the ground-test machine. The second is the prediction of operational braking performance of the aircraft using day-to-day measurements from the ground-test machine.

3. DESCRIPTION OF MU-METER, TESTS AND AVAILABLE DATA

The Mu-Meter is a ground-test machine which infers a value of braking coefficient of friction from measurements of sideforce at the axles of two *friction wheels* on a towed trailer. Generally, the friction wheels are toed inwards at 7.5 degrees to the direction of motion; this produces an apparent slip ratio close to 0.13. A third (rear) wheel provides distance data and stabilises the motion of the trailer. A constant vertical load of 171 lbf is applied to each friction wheel by ballasting the shock absorbers. The tyres on all three wheels are 16 × 4, 6ply RL2: those on the friction wheels have a smooth tread and are inflated to 10 lbf/in², whilst that on the rear wheel has a tread of conventional design and is inflated to 30 lbf/in². The “standard” test speed of the machine is 40 mph although many tests have used other speeds as well.

There are two modes of operation: the machine can be used either directly on a wet runway or in *self-wetting mode*. In the latter case a jet of water is sprayed, through a pair of rectangular nozzles, into the paths of the friction wheels. In this mode, the effective depth of water is controlled by the mass flow through the nozzles.

Data for Mu-Meter operations on wet runways are taken from References 3, 4, 5 and 6, as follows.

- (i) For the survey carried out by the Pavements Surface Effects Team (PSET) of the United States Air Force, and reported in Reference 4, the Mu-Meter was towed at 40 mph on runways wetted artificially, as follows. “Application of water is always made in two passes, each applying 0.1 inch of water. The total application of 0.2 inch of water within a 15 minute period simulates a heavy rainfall rate of 0.8 inch per hour.”

- (ii) For two sets of experiments conducted by the FAA and reported in References 3 and 5, the runway wetness conditions were closely controlled and a detailed record was kept of the water depth for each test run. For Reference 3 the mean water depth, $\bar{d}_W = 0.0209$ inch, with a range $0 \leq d_W \leq 0.06$ inch. For Reference 5, the mean water depth, $\bar{d}_W = 0.0726$ inch; for most tests, $0 \leq d_W \leq 0.06$ inch but for a few tests, $0 \leq d_W \leq 0.2$ inch.
- (iii) For the Joint NASA and FAA study reported in Reference 6, “water depths of approximately 0.02 to 0.03 inch were noted for most *wet* runway tests. For *flooded* runway tests, water depths between 0.1 and 0.2 inch were maintained”. In these tests the machine was towed at a variety of speeds so that it is possible to determine a value of the tyre-runway interaction parameter over a range of speeds.

Data for Mu-Meter operations in self-wetting mode are available from a number of sources but only those provided in Reference 14 have been used here. Most of those results are for a speed of 40 mph and a water depth of 0.04 inch but some results for a water depth of 0.02 inch have also been used.

For all the tests considered in this example, the average depth of the macro-texture of the runways was obtained using the *grease patch* method (see Section 5.2.1 of Reference 1 for a description, Section 3.3.1 of Reference 2 for examples and Reference 9 for statistical distributions of d_{tex} for runways).

4. ANALYSIS

In this Section, the method derived in Reference 11 is summarised and the variables that are used to create the *Friction Data Base* for the “example” machine are calculated. The statistical distributions of the variables in the model are also given.

For a single braked run on a wet runway with braking force *limited solely by friction*, it is shown in Reference 11 that the variation of μ with speed can be represented by the simple expression

$$\mu = \frac{\mu_{datum}}{1 + \beta \frac{q}{p}} \quad (4.1)$$

Provided that a sufficiently comprehensive test[†] series is available, it is shown further in Reference 11 that each value of the parameter β can be combined with the macro-texture depth, d_{tex} , of the wetted runway to define a variable κ such that

$$\kappa = (\beta d_{tex})^{1/2} \quad (4.2)$$

conforms to the Normal Distribution, with expected (or mean) value $E[\kappa]$ (or $\bar{\kappa}$) and standard deviation $\sigma[\kappa]$. This variable is characteristic of the design of the machine and its tyres. The parameter κ , together with μ_{datum} , is used to create the *Friction Data Base* for the machine. The objective of the analysis is, therefore, to establish a value for μ_{datum} from tests on dry runways and to determine the distribution of κ from tests on wet runways or when the machine is in self-wetting mode.

[†] The criterion for sufficiency is related to the range of wetting conditions and to the number of tests in the series. It is advisable to consult Reference 11 to find advice on test planning. For the present Example, the effects of different ranges of water depths on the Friction Data Base are assessed in Table 4.1.