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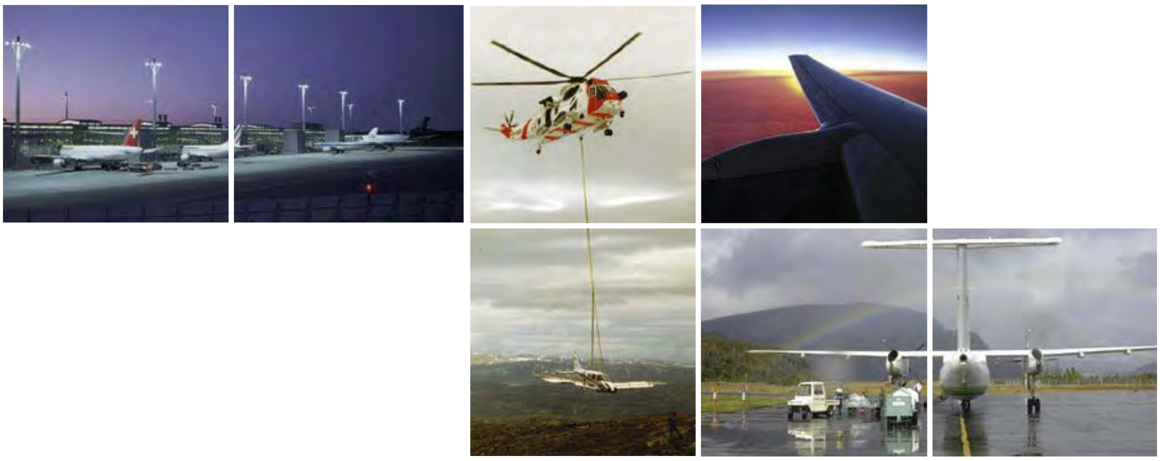

WINTER OPERATIONS, FRICTION MEASUREMENTS AND CONDITIONS FOR FRICTION PREDICTIONS

VOLUME III - APPENDICES A-Z

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WINTER OPERATIONS, FRICTION MEASUREMENTS AND CONDITIONS FOR FRICTION PREDICTIONS

The report is divided into three volumes. Volume I Executive Summary, Volume II Main Report and Volume III Appendices A-Z.

VOLUME III

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APPENDIX A

RELEVANT ACRONYMS AND ABBREVIATIONS

ABC	Airplane Braking Coefficient
AFM	Aircraft Flight Manual
AIBN	Accident Investigation Board of Norway
AIC	Aeronautical Information Circular
AIP	Aeronautical Information Publication
AMJ	JAA Advisory Material
ATM	Aircrew Training Manual
CAR	Civil Aviation Regulations
CPC	Cockpit Performance Computer
CRFI	Canadian Runway Friction Index
CS	Certification Specification
EASA	European Aviation Safety Agency
ENDU	Bardufoss Airport
ENEV	Harstad/Narvik Airport Evenes
ENGM	Oslo Airport Gardermoen
ENKR	Kirkenes Airport Høybuktmoen
ENSB	Svalbard Airport Longyear
ENTC	Tromsø Airport Langnes
ENTO	Sandefjord Airport Torp
ENVD	Vadsø Airport
ERD	Electronic Recording Decelerometer
FAA	Federal Aviation Administration
FC	Friction Coefficient
FFA	Flygtekniska ForsøksAnstalten
GWT	Gross Weight Tables

ICAO	International Civil Aviation Organisation
IRFI	International Runway Friction Index
IRIS	Integrated Runway Information System
JAA	Joint Aviation Authorities
JAR	Joint Aviation Regulations
JAR OPS	Joint Aviation Regulations Operations
JWRFMP	Joint Winter Runway Friction Measurement Program
METAR	Meteorological Aerodrome Report
Mu	Friction coefficient (μ)
MyT	MyTravel Airways Scandinavia
NAS	Norwegian Air Shuttle
NCAA	Norwegian Civil Aviation Authority
NTSB	National Transportation Safety Board
PSI	Pound per Square Inch
REP	Report
SAFO	Safety Alert for Operators
SAS	Scandinavian Airlines System
SASBRA	SAS Braathens
SNOWTAM	Snow Notice to Airmen
SUP	Flight Manual Supplement
SWOP	Safe Winter Operation Project
TAF	Terminal Area Forecast
TC	Transport Canada
UK CAA	United Kingdom Civil Aviation Authority
WIF	Widerøes Flyveselskap

APPENDIX B

Extract from ICAO Annex 14/15

ICAO Annex 14, Attachment 1, Guidance material ch. 6.

The following is an extract from the above-mentioned document:

> *Determining and expressing the friction characteristics of snow- and ice-covered paved surfaces*
>
> *6.1 There is an operational need for reliable and uniform information concerning the friction characteristics of ice- and snow-covered runways. Accurate and reliable indications of surface friction characteristics can be obtained by friction measuring devices; however, further experience is required to correlate the results obtained by such equipment with aircraft performance, owing to the many variables involved, such as: aircraft mass, speed, braking mechanism, tire and undercarriage characteristics.*
>
> *6.2 The friction coefficient should be measured if a runway is covered wholly or partly by snow or ice and repeated as conditions change. Friction measurements and/or braking action assessments on surfaces other than runways should be made when an unsatisfactory friction condition can be expected on such surfaces.*
>
> *6.3 The measurement of the friction coefficient provides the best basis for determining surface friction conditions. The value of surface friction should be the maximum value which occurs when a wheel is slipping but still rolling. Various friction measuring devices may be used. As there is an operational need for uniformity in the method of assessing and reporting runway friction conditions, the measurements should preferably be made with equipment which provides continuous measuring of the maximum friction along the entire runway. Measuring techniques and information on limitations of the various friction measuring devices and precautions to be observed are given in the Airport Services Manual, Part 2.*
>
> *6.4 A chart, based on results of tests conducted on selected ice- or snow-covered surfaces, showing the correlation between certain friction measuring devices on ice- or snow-covered surfaces is presented in the Airport Services Manual, Part 2.*
>
> *6.5 The friction conditions of a runway should be expressed as "braking action information" in terms of the measured friction coefficient* μ *or estimated braking action. Specific numerical* μ *values are necessarily related to the design and construction of each friction measuring device as well as to the surface being measured and the speed employed.*
>
> ***6.6 The table below with associated descriptive terms was developed from friction data collected only in compacted snow and ice and should not therefore be taken to be absolute values applicable in all conditions. If the surface is affected by snow or ice and the braking action is reported as "good", pilots should not expect to find conditions as good as on a clean dry runway (where the available friction may well be greater than that needed in any case). The value "good" is a comparative value and is***

intended to mean that aeroplanes should not experience directional control or braking difficulties, especially when landing.

Estimated Measured braking coefficient	*action*	*Code*
0.40 and above	*Good*	*5*
0.39 to 0.36	*Medium to good*	*4*
0.35 to 0.30	*Medium*	*3*
0.29 to 0.26	*Medium to poor*	*2*
0.25 and below	*Poor*	*1*

ICAO Annex 15

Chapter 5, 5.2.3

5.2.3 Information concerning snow, slush, ice and standing water on aerodrome/heliport pavements shall, when reported by means of a SNOWTAM, contain the information in the order shown in the SNOWTAM Format[1] *in Appendix 2.*

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[1] SNOWTAM Format in Appendix 2 is similar to table above.

APPENDIX C

Relevant JAR OPS 1/EU OPS regulations

OPS 1.400 Approach and Landing Conditions

Before commencing an approach to land, the commander must satisfy himself / herself that, according to the information available to him / her, the weather at the aerodrome and the condition of the runway intended to be used should not prevent a safe approach, landing or missed approach, having regard to the performance information contained in the Operations Manual.

IEM OPS 1.400 Approach and Landing Conditions

The in-flight determination of the landing distance should be based on the latest available report, preferably not more than 30 minutes before the expected landing time.

OPS 1.485 General

(a) An operator shall ensure that, for determining compliance with the requirements of this Subpart, the approved performance data in the Aeroplane Flight manual is supplemented as necessary with other data acceptable to the Authority if the approved performance data in the Aeroplane Flight manual is insufficient in respect of items such as:

1. *Accounting for reasonably expected adverse operating conditions such as take-off and landing on contaminated runways; and*
2. *Consideration of engine failure in all flight phases.*

(b) An operator shall ensure that, for the wet and contaminated runway case, performance data determined in accordance with applicable requirements on certification of large aeroplanes or equivalent acceptable to the Authority is used.

IEM OPS 1.485(b)

General – Wet and Contaminated Runway data

(See JAR-OPS 1.485(b))

If the performance data has been determined on the basis of measured runway friction coefficient, the operator should use a procedure correlating the measured runway friction coefficient and the effective braking coefficient of friction of the aeroplane type over the required speed range for the existing runway conditions.

OPS 1.490 Take-off

(a) An operator shall ensure that the take-off mass does not exceed the maximum take-off mass specified in the Aeroplane Flight Manual for the pressure altitude and the ambient temperature at the aerodrome at which the take-off is to be made.

(b) An operator must meet the following requirements when determining the maximum permitted take-off mass:

…

5. *on a wet or contaminated runway, the take-off mass must not exceed that permitted for a take-off on a dry runway under the same conditions.*

(c) When showing compliance with subparagraph (b) above, an operator must take account of the following:

---

3. *the runway surface condition and the type of runway surface*

(see IEM OPS 1.490(c)(3))

IEM OPS 1.490(c)(3)

Takeoff – Runway surface condition

See JAR-OPS 1.490(c)(3)

1. Operation on runways contaminated with water, slush, snow or ice implies uncertainties with regard to runway friction and contaminant drag and therefore to the achievable performance and control of the aeroplane during take-off, since the actual conditions may not completely match the assumptions on which the performance information is based. ***In the case of a contaminated runway, the first option for the commander is to wait until the runway is cleared.*** *If this is impracticable, he may consider a take-off, provided that he has applied the applicable performance adjustments, and any further safety measures he considers justified under the prevailing conditions.*

2. An adequate overall level of safety will only be maintained if operations in accordance with JAR-25 AMJ 25X1591[1] are limited to rare occasions. ***Where the frequency of such operations on contaminated runways is not limited to rare occasions, operators should provide additional measures ensuring an equivalent level of safety. Such measures could include special crew training, additional distance factoring and more restrictive wind limitations prohibiting operation(s) on the contaminated surface(s) for which information is not supplied.***

Additional information covering operation on contaminated surfaces other than the above may be provided at the discretion of the applicant.

(b) Performance information furnished by the applicant must be contained in the AFM. The information may be used to assist operators in producing operational data and instructions for use by their flight crews when operating with contaminated runway surface conditions. The information may be established by calculation or by testing.

(c) The AFM must clearly indicate the conditions and the extent of applicability for each contaminant used in establishing the contaminated runway performance information. It must also state that actual conditions that are different from those used for establishing the contaminated runway performance information may lead to different performance.

[Amdt. No.:25/2]

OPS 1.515 Landing – Dry runways

(a) An operator shall ensure that the landing mass of the aeroplane determined in accordance with OPS 1.475(a) for the estimated time of landing at the destination

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[1] AMJ 25X1591 er erstattet av CS 25.1591 og AMC 25.1591.

aerodrome and at any alternate aerodrome allows a full stop landing from 50 ft above the threshold:

1. *For turbo-jet powered aeroplanes, within 60 % of the landing distance available; or*

2. *For turbo-propeller powered aeroplanes, within 70 % of the landing distance available;*

3. For steep approach procedures the Authority may approve the use of landing distance data factored in accordance with subparagraphs (a)1 and (a)2 above as appropriate, based on a screen height of less than 50 ft, but not less than 35 ft. (See Appendix 1 to OPS 1.515(a)3);

4. When showing compliance with subparagraphs (a)1 and (a)2 above, the Authority may exceptionally approve, when satisfied that there is a need (see Appendix 1), the use of short landing operations in accordance with Appendices 1 and 2 together with any other supplementary conditions that the Authority considers necessary in order to ensure an acceptable level of safety in the particular case.

(b) When showing compliance with subparagraph (a) above, an operator must take account of the following:

1. the altitude at the aerodrome;
2. not more than 50 % of the head-wind component or not less than 150 % of the tailwind component; and
3. the runway slope in the direction of landing if greater than +/-2 %.

(c) When showing compliance with subparagraph (a) above, it must be assumed that:

1. the aeroplane will land on the most favourable runway, in still air; and
2. the aeroplane will land on the runway most likely to be assigned considering the probable wind speed and direction and the ground handling characteristics of the aeroplane, and considering other conditions such as landing aids and terrain.

(d) If an operator is unable to comply with subparagraph (c)1 above for a destination aerodrome having a single runway where a landing depends upon a specified wind component, an aeroplane may be despatched if 2 alternate aerodromes are designated which permit full compliance with subparagraphs (a), (b) and (c). Before commencing an approach to
land at the destination aerodrome the commander mustsatisfyhimself/herself that a landing can be made in full compliance with OPS 1.510 and subparagraphs (a) and (b) above.

> *(d) If an operator is unable to comply with subparagraph (c)2 above for the destination aerodrome, the aeroplane may be despatched if an alternate aerodrome is designated which permits full compliance with subparagraphs (a), (b) and (c).*

(see AMC OPS 1.515)

OPS 1.520 Landing – Wet and contaminated runways

(a) An operator shall ensure that when the appropriate weather reports or forecasts, or a combination thereof, indicate that the runway at the estimated time of arrival may be wet, the landing distance available is at least 115 % of the required landing distance, determined in accordance with OPS 1.515.

(b) An operator shall ensure that when the appropriate weather reports or forecasts, or a combination thereof, indicate that the runway at the estimated time of arrival may be contaminated, the landing distance available must be at least the landing distance determined in accordance with subparagraph (a) above, or at least 115 % of the landing distance determined in accordance with approved contaminated landing distance data or equivalent, accepted by the Authority, whichever is greater.

(c) A landing distance on a wet runway shorter than that required by subparagraph (a) above, but not less than that required by OPS 1.515 (a), may be used if the Aeroplane Flight Manual includes specific additional information about landing distances on wet runways.

(d) A landing distance on a specially prepared contaminated runway shorter than that required by subparagraph (b) above, but not less than that required by OPS 1.515 (a), may be used if the Aeroplane Flight Manual includes specific additional information about landing distances on contaminated runways.

(e) When showing compliance with subparagraph (b), (c) and (d) above, the criteria of OPS 1.515 shall be applied accordingly except that OPS 1.515 (a) 1 and 2 shall not be applied to subparagraph (b) above.

APPENDIX D

Extract of JAR 25/EASA Certification Specification/CS-25

CS 25.125 Landing

(a) The horizontal distance necessary to land and to come to a complete stop from a point 15 m (50 ft) above the landing surface must be determined (for standard temperatures, at each weight, altitude and wind within the operational limits established by the applicant for the aeroplane) as follows:

(c) The landing distance must be on a level, smooth, dry, hard surfaced runway. (See AMC 25.125(c).)

(g) If any device is used that depends on the operation of any engine, and if the landing distance would be noticeably increased when a landing is made with that engine inoperative, the landing distance must be determined with that engine inoperative unless the use of compensating means will result in a landing distance not more than that with each engine operating.

[Amdt. No.:25/3]

CS 25.1591 Performance Information for Operations with Contaminated Runway Surface Conditions (See AMC 25.1591).

(a) Supplementary performance information applicable to aeroplanes operated on runways contaminated with standing water, slush, snow or ice may be furnished at the discretion of the applicant. If supplied, this information must include the expected performance of the aeroplane during take-off and landing on hard-surfaced runways covered by these contaminants. If information on any one or more of the above contaminated surfaces is not supplied, the AFM must contain a statement prohibiting operation(s) on the contaminated surface(s) for which information is not supplied. Additional information covering operation on contaminated surfaces other than the above may be provided at the discretion of the applicant.

(b) Performance information furnished by the applicant must be contained in the AFM. The information may be used to assist operators in producing operational data and instructions for use by their flight crews when operating with contaminated runway surface conditions. The information may be established by calculation or by testing.

(c) The AFM must clearly indicate the conditions and the extent of applicability for each contaminant used in establishing the contaminated runway performance information. It must also state that actual conditions that are different from those used for establishing the contaminated runway performance information may lead to different performance.

[Amdt. No.:25/2]

AMC 25.1591 The derivation and methodology of performance information for use when taking-off and landing with contaminated runway surface conditions.

1.0 Purpose

This AMC provides information, guidelines, recommendations and acceptable means of compliance for use by applicants in the production of performance information for aeroplanes when operated on runways that are contaminated by standing water, slush, snow, ice or other contaminants.

2.0 Technical Limitations of Data

The methodology specified in this AMC provides one acceptable means of compliance with the provisions of CS 25.1591. In general it does not require aeroplane testing on contaminated runway surfaces, although such testing if carried out at the discretion of the applicant may significantly improve the quality of the result or reduce the quantity of analytical work required.

Due to the nature of naturally occurring runway contaminants and difficulties associated with measuring aeroplane performance on such surfaces, any data that is either calculated or measured is subject to limitations with regard to validity. *Consequently the extent of applicability should be clearly stated.*

The properties specified in this AMC for various contaminants are derived from a review of the available test and research data and are considered to be acceptable for use by applicants. This is not an implied prohibition of data for other conditions or that other conditions do not exist.

It has been recently determined that the assumption to use wet runway surface field length performance data for operations on runway surfaces contaminated with dry snow (depths below 10 mm) and wet snow (depths below 5 mm) may be inappropriate. Flight test evidence together with estimations have indicated *some measure of relatively low gear displacement drag and* ***a measurable reduction in surface friction in comparison to the assumptions associated with wet runway field performance data.*** *As a consequence it has been agreed that additional work is required to further develop the associated methodology. As an interim measure it has been concluded that it is reasonable to consider these surfaces by recommending that they be addressed by using the data for the lowest depth of the contaminant provided.*

It is intended that the use of aeroplane performance data for contaminated runway conditions produced in accordance with CS 25.1591 should include recommendations associated with the operational use of the data. Where possible, this operational guidance should be provided by the applicant or its production co-ordinated with the applicant to ensure that its use remains valid.

Operators are expected to make careful and conservative judgments in selecting the appropriate performance data to use for operations on contaminated runways. Particular attention should be paid to the presence of any contaminant in the critical high speed portion of the runway. For takeoff, it may be appropriate to use different contaminant types or depths for the takeoff and the accelerate-stop portions. For example, it may be appropriate to use a greater contaminant depth or a contaminant type that has a more detrimental effect on acceleration for the takeoff portion than for the accelerate-stop portion of the takeoff analysis.

In considering the maximum depth of runway contaminants it may be necessary to take account of the maximum depth for which the engine air intakes have been shown to be free of ingesting hazardous quantities of water in accordance with CS 25.1091(d)(2).

3.0 Standard Assumptions

Due to the wide variation in possible conditions when operating on contaminated runways and the limitations inherent in representing the effects of these conditions analytically, it is not possible to produce performance data that will precisely correlate with each specific operation on a contaminated surface. Instead, the performance data should be determined for a standardised set of conditions that will generally and conservatively represent the variety of contaminated runway conditions occurring in service.

It should be assumed that:

- the contaminant is spread over the entire runway surface to an even depth (although rutting, for example, may have taken place).

- the contaminant is of a uniform specific gravity.

- where the contaminant has been sanded, graded (mechanically levelled) or otherwise treated before use, that it has been done in accordance with agreed national procedures.

4.0 Definitions

These definitions may be different to those used by other sources but are considered appropriate for producing acceptable performance data, suitable for use in aeroplane operations.

4.1 Standing Water

Water of a depth greater than 3mm. A surface condition where there is a layer of water of 3mm or less is considered wet for which AMC 25.1591 is not applicable.

4.2 Slush

Partly melted snow or ice with a high water content, from which water can readily flow, with an assumed specific gravity of 0.85. Slush is normally a transient condition found only at temperatures close to 0°C.

4.3 Wet Snow

Snow that will stick together when compressed, but will not readily allow water to flow from it when squeezed, with an assumed specific gravity of 0.5.

4.4 Dry Snow

Fresh snow that can be blown, or, if compacted by hand, will fall apart upon release (also commonly referred to as loose snow), with an assumed specific gravity of 0.2. The assumption with respect to specific gravity is not applicable to snow which has been subjected to the natural ageing process.

4.5 Compacted Snow

Snow which has been compressed into a solid mass such that the aeroplane wheels, at representative operating pressures and loadings, will run on the surface without causing significant rutting.

4.6 Ice

Water which has frozen on the runway surface, including the condition where compacted snow transitions to a polished ice surface.

4.7 Specially Prepared Winter Runway

A runway, with a dry frozen surface of compacted snow and/or ice which has been treated with sand or grit or has been mechanically or chemically treated to improve runway friction. The runway friction is measured and reported on a regular basis in accordance with national procedures.

4.8 Specific Gravity

The density of the contaminant divided by the density of water.

5.0 Contaminant Properties to be Considered

5.1 Range of Contaminants

The following general range of conditions or properties may by used. The list given in Table 1[1] *is not necessarily comprehensive and other contaminants may be considered, provided account is taken of their specific properties.*

Data should assume the contaminant to be uniform in properties and uniformly spread over the complete runway.

Contaminants can be classified as being:-

(i) Drag producing, for example by contaminant displacement or impingement,

(ii) Braking friction reducing, or

(iii) A combination of (i) and (ii).

Data to be produced should use the classification and assumptions of Table 1 and then the appropriate sections of the AMC as indicated.

5.2 Other Contaminants

Table 1 lists the contaminants commonly found. It can be seen that the complete range of conditions or specific gravities has not been covered. Applicants may wish to consider other, less likely, contaminants in which case such contaminants should be defined in a manner suitable for using the resulting performance data in aeroplane operations.

6.0 Derivation of Performance Information

6.1 General Conditions

Take-off and landing performance information for contaminated runways should be determined in accordance with the assumptions given in paragraph 7.0. Where performance information for different contaminants are similar, the most critical may be used to represent all conditions. This AMC does not set out to provide a complete technical analytical process but rather to indicate the elements that should be addressed. Where doubt exists with regard to the accuracy of the methodology or the penalties derived, consideration should be given to validation by the use of actual aeroplane tests or other direct experimental measurements.

6.2 Take-off on a Contaminated Runway

6.2.1 Except as modified by the effects of contaminant as derived below, performance assumptions remain unchanged from those used for a wet runway, in accordance with the agreed certification standard. These include accelerate-stop distance definition, time delays,

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[1] The table is not included in the AIBN report.

take-off distance definition, engine failure accountability and stopping means other than by wheel brakes (but see paragraph 7.4.3).

6.2.2 Where airworthiness or operational standards permit operations on contaminated runways without engine failure accountability, or using a V_{STOP} *and a* V_{GO} *instead of a single* V_1*, these performance assumptions may be retained. In this case, a simple method to derive a single* V_1 *and associated data consistent with the performance assumptions of paragraph 6.2.1 must also be provided in the AFM.*

NOTE: V_{STOP} *is the highest decision speed from which the aeroplane can stop within the accelerate-stop distance available.* V_{GO} *is the lowest decision speed from which a continued take-off is possible within the take-off distance available.*

6.3 Landing on a Contaminated Runway

6.3.1 Airborne distance

Assumptions regarding the airborne distance for landing on a contaminated runway are addressed in paragraph 7.4.2.

6.3.2 Ground Distance

Except as modified by the effects of contaminant as derived below, performance assumptions for ground distance determination remain unchanged from those used for a dry runway. These assumptions include:

- Touchdown time delays.

- Stopping means other than wheel brakes (but see paragraph 7.4.3)."

7.0 Effects of Contaminant

7.1 Contaminant Drag - Standing Water, Slush, Wet Snow

General advice and acceptable calculation methods are given for estimating the drag force due to fluid contaminants on runways:

Total drag Drag due to Drag due to airframe due to fluid = fluid displacement + impingement of fluid contaminant by tyres spray from tyres The essence of these simple calculation methods is the provision of appropriate values of drag coefficients below, at, and above tyre aquaplaning speed, VP (see paragraph 7.1.1):

• Paragraphs 7.1.2.a and 7.1.2.b give tyre displacement drag coefficient values for speeds below VP.

• Paragraph 7.1.3.b.2 gives tyre equivalent displacement drag coefficient values to represent the skin friction component of impingement drag for speeds below VP.

• Paragraph 7.1.4 gives the variation with speed, at and above VP, of drag coefficients representing both fluid displacement and impingement.

7.1.1 Aquaplaning Speed

An aeroplane will aquaplane at high speed on a surface contaminated by standing water, slush or wet snow. For the purposes of estimating the effect of aquaplaning on contaminant drag, the aquaplaning speed, VP, is given by - $VP = 9 \sqrt{P}$ *where VP is the ground speed in knots and* $\sqrt{P}$ *is the tyre pressure in lb/in2.*

Predictions (Reference 5) indicate that the effect of running a wheel over a low density liquid contaminant containing air, such as slush, is to compress it such that it essentially acts as high density contaminant.[2] *This means that there is essentially no increase in aquaplaning speed to be expected with such a lower density contaminant.*

For this reason, the aquaplaning speed given here is not a function of the density of the contaminant.

(See References 1, 5 and 10)

7.1.2 Displacement Drag

This is drag due to the wheel(s) running through the contaminant and doing work by displacing the contaminant sideways and forwards.

a. Single wheel.

The drag on the tyre is given by −

$D = CD\tfrac{1}{2}\rho V2S$

Where ρ *is the density of the contamination, S is the frontal area of the tyre in the contaminant and V is the groundspeed, in consistent units.*

S = b x d where d is the depth of contamination and b is the effective tyre width at the contaminant surface and may be found from –

$b = 2w\{(\delta+d)/w-(\delta+d)^2/w\}\tfrac{1}{2}$

Where W is the maximum width of the tyre and δ is the tyre deflection, which may be obtained from tyre manufacturers" load-deflection curves.
The value of CD may be taken as 0.75 for an isolated tyre below the aquaplaning speed, VP.

(See Reference 3)

b. Multiple wheels

A typical dual wheel undercarriage shows a drag 2.0 times the single wheel drag, including interference. For a typical four-wheel bogie layout the drag is 4 times the single wheel drag (again including interference). For a six-wheel bogie layout a reasonable conservative estimate suggests a figure of 4.2 times the single wheel drag.

The drag of spray striking the landing gear structure above wheel height may also be important and should be included in the analysis for paragraph 7.1.3.b.1 but for multiple wheel bogies the factors above include centre spray impingement drag on gear structure below wheel height.

(See Reference 3)

7.1.3 Spray Impingement Drag

a. Determination of spray geometry

The sprays produced by aeroplane tyres running in a liquid contaminant such as slush or water are complex and depend on aeroplane speed, the shape and dimensions of the loaded tyre and the contaminant depth. The spray envelope should be defined, that is the height, width, shape and location of the sideways spray plumes and, in the case of a dual wheel

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[2] This implies an approximately constant μ value and is in conflict with 7.3.1 Default Friction Values for Slush in Table 2.

undercarriage, the centre spray plumes. Additionally, a forward bow-wave spray will be present which may be significant in drag terms should it impinge on the aeroplane.

In order to assess the drag it is necessary to know the angles of the spray plumes so that they can be compared with the geometry of the aeroplane. The angle at which the plumes rise is generally between 10° and 20° but it varies considerably with speed and depth of precipitation and to a small extent with tyre geometry. A method for estimating the plume angles in the horizontal and vertical directions is given in References 1 and 7 and may be used in the absence of experimental evidence. This information may be used to indicate those parts of the airframe which will be struck by spray, in particular whether the nose-wheel plume will strike the main landing gear or open wheel-wells, the wing leading edges or the engine nacelles, and whether the main-wheel plumes will strike the rear fuselage or flaps.

b. Determination of the retarding forces

Following definition of the spray envelopes, the areas of contact between the spray and the airframe can be defined and hence the spray impingement drag determined.

This will be in two parts, direct interaction of the spray with the aeroplane structure and skin friction.

For smaller jet aeroplanes, typically those where the wing-to-ground height is less than 2 metres (6 feet), the methods contained in this document may not be conservative. Drag estimates should be correlated with performance measurements taken, for example, during water trough tests for engine ingestion.

b.1. Drag caused by direct impact of the spray

For aeroplane designs where surface areas are exposed to direct spray impact, the resulting drag forces should be taken into account. These forces exist where a significant part of the spray flow is directed at part of the aeroplane structure at a normal or non-oblique angle. The drag, or momentum loss of the mass of fluid, so caused should be accounted for.

(See Reference 6)

b.2. Drag caused by skin friction

Reference 2 explains that the relative velocity between spray from the landing gear and wetted aeroplane components causes drag due to skin friction and provides a method for its calculation. Where more than one spray acts on the same wing or fuselage surface the skin friction forces are not cumulative and the single, higher calculated value should be used.

An alternative, simple, conservative empirical estimate of skin friction drag, which converts the skin friction drag into an equivalent displacement drag coefficient based on nose-wheel alone drag measurements, is given by

C_D *spray = 8 x L x 0.0025*

where C_D *spray is to be applied to the total nose-wheel displacement area (b x d x number of wheels) and L is the wetted fuselage length in feet behind the point at which the top of the spray plume reaches the height of the bottom of the fuselage.*

This relation can also be used in the case of a main-wheel spray striking the rear fuselage. In the case of any one main wheel unit only the inner plume from the innermost leading wheel is involved so the relevant displacement area is half that of one main wheel.

7.1.4 Effect of Speed on Displacement and Impingement Drag Coefficients at and above Aquaplaning Speed

The drag above VP reduces to zero at lift off and one acceptable method is to reduce C_D as shown in the curve in Figure 1[3]*. This relationship applies to both displacement and spray impingement drag coefficients.*

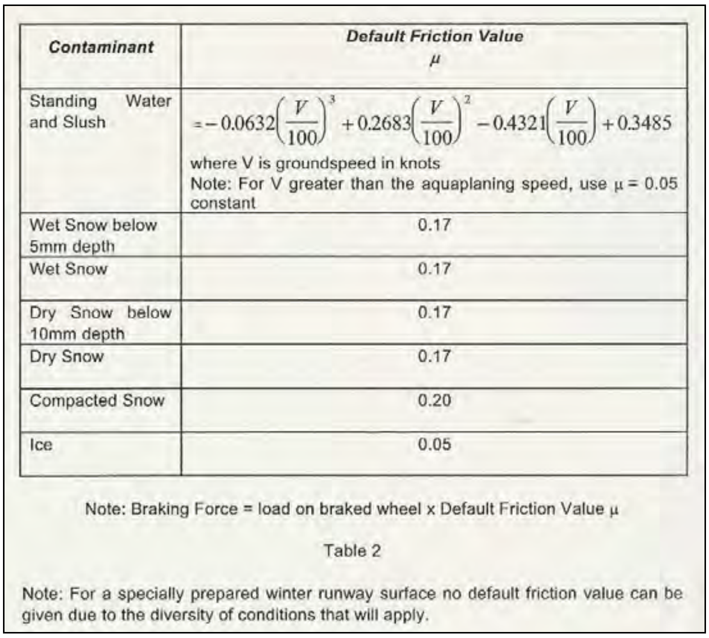
……………………………………………………

"7.3 Braking Friction (All Contaminants)

On most contaminant surfaces the braking action of the aeroplane will be impaired. Performance data showing these effects can be based on either the minimum conservative ‚default" values, given in Table 2 or test evidence and assumed values (see paragraph 7.3.2). In addition the applicant may optionally provide performance data as a function of aeroplane braking coefficient or wheel braking coefficient.

7.3.1 Default Values

To enable aeroplane performance to be calculated conservatively in the absence of any direct test evidence, default friction values as defined in Table 2 may be used. These friction values represent the effective braking coefficient of an anti-skid controlled braked wheel/tyre.



Contaminant	Default Friction Value μ
Standing Water and Slush	$= -0.0632\left(\frac{V}{100}\right)^3 + 0.2683\left(\frac{V}{100}\right)^2 - 0.4321\left(\frac{V}{100}\right) + 0.3485$ where V is groundspeed in knots Note: For V greater than the aquaplaning speed, use $\mu = 0.05$ constant
Wet Snow below 5mm depth	0.17
Wet Snow	0.17
Dry Snow below 10mm depth	0.17
Dry Snow	0.17
Compacted Snow	0.20
Ice	0.05

Note: Braking Force = load on braked wheel x Default Friction Value μ

Table 2

Note: For a specially prepared winter runway surface no default friction value can be given due to the diversity of conditions that will apply.

Table 2. EASA Contaminant Default Friction Values[4]

(See Reference 10)

7.3.2 Other Than Default Values

In developing aeroplane braking performance using either test evidence or assumed friction values other than the default values provided in Table 2, a number of other brake related aspects should be considered. Brake efficiency should be assumed to be appropriate to the

---

[3] Figure 1 is not included in the AIBN report.

[4] AIBN remark: Standing water and slush formula gives at 100 kt $\mu_b = 0.12$, 50 kt $\mu_b = 0.26$, 10 kt $\mu_b = 0.31$. These results are in conflict with the AIBN findings which show that wet types of contaminations frequently indicate Medium to Poor (0.15 – 0.05), and does not vary that much with ground speed.

brake and anti-skid system behaviour on the contaminant under consideration or a conservative assumption can be used. It can be assumed that wheel brake torque capability and brake energy characteristics are unaffected. Where the tyre wear state significantly affects the braking performance on the contaminated surface, it should be assumed that there is 20% of the permitted wear range remaining. Where limited test evidence is available for a model predecessor or derivative this may be used given appropriate conservative assumptions.

7.3.3 Use of Ground Friction Measurement Devices

Ideally it would be preferable to relate aeroplane braking performance to a friction index measured by a ground friction device that would be reported as part of a Surface Condition Report. However, there is not, at present, a common friction index for all ground friction measuring devices. Hence it is not practicable at the present time to determine aeroplane performance on the basis of an internationally accepted friction index measured by ground friction devices. Notwithstanding this lack of a common index, the applicant may optionally choose to present take-off and landing performance data as a function of an aeroplane braking coefficient or wheel braking coefficient constant with ground speed for runways contaminated with wet snow, dry snow, compacted snow or ice. The responsibility for relating this data to a friction index measured by a ground friction device will fall on the operator and the operating authority.

7.4 Additional Considerations

7.4.1 Minimum V_1

For the purpose of take-off distance determination, it has been accepted that the minimum V_1 speed may be established using the V_{MCG} value established in accordance with CS 25.149(g). As implied in paragraph 8.1.3, this may not ensure that the lateral deviation after engine failure will not exceed 30 ft on a contaminated runway.

7.4.2 Landing Air Distance

For contaminated surfaces, the airborne distance should be calculated by assuming that 7 seconds elapse between passing through the 50 ft screen height and touching down on the runway. In the absence of flight test data to substantiate a lower value, the touchdown speed should be assumed to be 93% of the threshold speed.

7.4.3 Reverse Thrust

Performance information may include credit for reverse thrust where available and controllable.

8.0 Presentation of Supplementary Performance Information

8.1 General

Performance information for contaminated runways, derived in accordance with the provisions of paragraphs 5.0 to 7.0, should be accompanied by appropriate statements such as:

8.1.1 Operation on runways contaminated with water, slush, snow, ice or other contaminants implies uncertainties with regard to runway friction and contaminant drag and therefore to the achievable performance and control of the aeroplane during take-off, since the actual conditions may not completely match the assumptions on which the performance information is based. ***Where possible, every effort should be made to ensure that the runway surface is cleared of any significant contamination.***

8.1.2 The performance information assumes any runway contaminant to be of uniform depth.

8.1.3. The provision of performance information for contaminated runways should not be taken as implying that ground handling characteristics on these surfaces will be as good as can be achieved on dry or wet runways, in particular following engine failure, in crosswinds or when using reverse thrust.

8.1.4 The contaminated runway performance information does not in any way replace or amend the Operating Limitations and Performance Information listed in the AFM, unless otherwise stated.

8.2 Procedures

In addition to performance information appropriate to operating on a contaminated runway, the AFM should also include recommended procedures associated with this performance information. ***Differences in other procedures for operation of the aeroplane on a contaminated surface should also be presented, e.g., reference to crosswinds or the use of high engine powers or derates.***

8.3 Take-off and Landing Data

This should be presented either as separate data appropriate to a defined runway contaminant or as incremental data based on the AFM normal dry or wet runway information. Information relating to the use of speeds higher than V_{REF} on landing, that is speeds up to the maximum recommended approach speed additive to V_{REF}, and the associated distances should also be included.

The landing distance must be presented either directly or with the factors required by the operating manuals, with clear explanation where appropriate.

Where data is provided for a range of contaminant depths, for example 3, 6, 9, 12, 15 mm, then the AFM should clearly indicate how to define data for contaminant depths within the range of contaminant depths provided.

Where the AFM presents data using V_{STOP} and V_{GO}, it must be stated in the AFM that use of this concept is acceptable only where operation under this standard is permitted.

9 References

Reference sources containing worked methods for the processes outlined in 7.1 to 7.3.3 are identified below:

1. ESDU Data Item 83042, December 1983, with Amendment A, May 1998. "Estimation of Spray Patterns Generated from the Side of Aircraft Tyres Running in Water or Slush".

2. ESDU Data Item 98001, May 1998. "Estimation of Airframe Skin-Friction Drag due to Impingement of Tyre Spray".

3. ESDU Data Item 90035, November 1990, with Amendment A, October 1992. "Frictional and Retarding Forces on Aircraft Tyres. Part V: Estimation of Fluid Drag Forces".

*4. ESDU Memorandum No.97, July 1998. "The Order of Magnitude of Drag due to Forward Spray from Aircraft Tyres"***.**

5. ESDU Memorandum No. 96, February 1998. "Operations on Surfaces Covered with Slush".and density.

6. ESDU Memorandum No. 95, March 1997, "Impact Forces Resulting From Wheel

Generated Spray: Re-Assessment Of Existing Data".

7. NASA Report TP-2718 "Measurement of Flow Rate and Trajectory of Aircraft Tire-Generated Water Spray".

8. Van Es, G.W.H., "Method for Predicting the Rolling Resistance of Aircraft Tires in Dry Snow". AIAA Journal of Aircraft, Volume 36, No.5, September-October 1999.

9. Van Es, G.W.H., "Rolling Resistance of Aircraft Tires in Dry Snow", National Aerospace Laboratory NLR, Technical Report TR-98165, Amsterdam, 1998.

10. ESDU Data Item 72008, May 1972. 'Frictional and retarding forces on aircraft tyres. Part III: planning.

[Amdt. No.:25/2]"

APPENDIX E

Extract from Airbus Industrie's document *"Getting to Grips with Cold Weather Operations", Airbus Industrie, Flight Operations Support, Customer Services Directorate, 1999* (Reference 7):

> ***"C3.4.2 Difficulties in assessing the effective µ***
>
> *The two major problems introduced by the airport authorities' evaluation of the runway characteristics are:*
>
> *-The correlation between test devices, even though some correlation charts have been established.*
>
> *-The correlation between measurements made with test devices or friction measuring vehicles and aircraft performance.*
>
> *-These measurements are made with a great variety of measuring vehicles, such as:Skiddometer, Saab Friction Tester (SFT), MU-Meter, James Brake Decelerometer (JDB),Tapley meter, Diagonal Braked Vehicle (DBV).*
>
> ***Refer to ICAO, Airport Services Manual, Part 2 for further information on these measuring vehicles.***
>
> *The main difficulty in assessing the braking action on a contaminated runway is that it does not depend solely on runway surface adherence characteristics.*
>
> *What must be found is the resulting loss of friction due to the interaction tire/runway.*
>
> *Moreover, the resulting friction forces depend on the load, i.e. the aircraft weight, tire wear, tire pressure and anti-skid system efficiency.*
>
> ***In other words, to get a good assessment of the braking action of an A340 landing at150,000 kg, 140 kt with tire pressure 240 PSI, the airport should use a similar spare A340... Quite difficult and pretty costly!***
>
> *The only way out is to use some smaller vehicles. These vehicles operate at much lower speeds and weights than an aircraft. Then comes the problem of correlating the figures obtained from these measuring vehicles and the actual braking performance of an aircraft. The adopted method was to conduct some tests with real aircraft and to compare the results with those obtained from measuring vehicles.*
>
> ***Results demonstrated poor correlation. For instance, when a Tapley meter reads 0.36, a MU-meter reads 0.4, a SFT reads 0.43, a JBD 12...***
>
> ***To date, scientists have been unsuccessful in providing the industry with reliable and universal values. Tests and studies are still in progress.***
>
> *As it is quite difficult to correlate the measured µ with the actual µ, termed as effective µ, the measured µ is termed as «reported µ«.*
>
> ***In other words, one should not get confused between:***
>
> ***1/ Effective µ:*** *The actual friction coefficient induced from the tire/runway surface interaction between a given aircraft and a given runway, for the conditions of the day.*

2/ Reported μ: *Friction coefficient measured by the measuring vehicle.*

Particularities of fluid contaminants

Moreover, the aircraft braking performance on a runway covered by a fluid contaminant (water, slush and loose snow) does not depend only on the friction coefficient μ.

As presented in chapters C2.2 and C2.3, the model of the aircraft braking performance (takeoff and landing) on a contaminated runway takes into account not only the reduction of a friction coefficient but also:

- The displacement drag

- The impingement drag

These two additional drags (required to be taken into account by regulations) require knowing ***the type and depth of the contaminant.***

In other words, even assuming the advent of a new measuring friction device providing a reported μ equal to the effective μ, it would be impossible to provide takeoff and landing performance only as a function of the reported μ. Airbus Industrie would still require information regarding the depth of fluid contaminants.

C3.4.3 Data provided by Airbus Industrie

Please refer to § C6 for further details on contaminated runway performance provided by Airbus Industrie.

Hard contaminants

For hard contaminants, namely compacted snow and ice, Airbus Industrie provides the aircraft performance independently of the amount of contaminants on the runway. Behind these terms are some effective μ. These two sets of data are certified.

Fluid contaminants

Airbus Industrie provides takeoff and landing performance on a runway contaminated by a fluid contaminant (water, slush and loose snow) as a function of the depth of contaminants on the runway.

For instance, takeoff or landing charts are published for «1/4 inch slush», «1/2 inch slush», «1/4 inch water» and «1/2 inch water». For loose snow, a linear variation has been established with slush.

In other words, pilots cannot get the performance from reported μ or Braking

Action. Pilots need the type and depth of contaminant on the runway.

CORRELATION BETWEEN REPORTED μ AND BRAKING PERFORMANCE

Please, bear in mind:

Airports release a friction coefficient derived from a measuring vehicle. This friction coefficient is termed as ***«reported μ»****.*

The actual friction coefficient, termed as ***«effective μ»*** *is the result of the interaction tire/runway and depends on the tire pressure, tire wear, aircraft speed, aircraft weight and anti-skid system efficiency.*

To date, ***there is no way to establish a clear correlation between the «reported µ» and the «effective µ». There is even a poor correlation between the «reported µ» of the different measuring vehicles.***

It is then very difficult to link the published performance on a contaminated runway to a «reported µ« only. The presence of ***fluid contaminants*** *(water, slush and loose snow) on the runway surface* ***reduces the friction coefficient****, may lead to* ***aquaplaning*** *(also called hydroplaning) and creates an* ***additional drag.*** *This additional drag is due to the precipitation of the contaminant onto the landing gear and the airframe, and to the displacement of the fluid from the path of the tire. Consequently, braking and accelerating performance are affected. The impact on the accelerating performance leads to a limitation in the depth of the contaminant for takeoff.* ***Hard contaminants*** *(compacted snow and ice) only affect the braking performance of the aircraft by a reduction of the* ***friction coefficient.*** *Airbus Industrie publishes the takeoff and landing performance according to the* ***type of contaminant****, and to the* ***depth*** *of fluid contaminants."*

APPENDIX F

Extract from Norwegian regulations for runway winter maintenance

Aeronautical Information Publication Norway (AIP Norway[1]) AD 1.2, items 2.4 and 2.5 describe Norwegian requirements for runway preparation and reporting.

Preparation and reporting

> *2.4 Preparation*
>
> *The surface of the movement area shall be prepared in order to achieve optimum friction, and particular attention shall be paid to the runway. Mechanical treatment, sand and/or chemicals are used to improve friction. The aerodrome operator and the flight operators are required to collaborate closely to avoid chemicals that may harm aircraft.*
>
> *2.5 Reporting*
>
> *2.5.1 The international ICAO SNOWTAM format will be used for reporting conditions in the movement area. The format is described in ICAO Annex 15, Appendix 2.*
>
> *2.5.2 Conditions in the movement areas shall be reported to the Air Traffic Service in the form of runway reports that form the basis for the Air Traffic Service's SNOWTAM notices.*
>
> *The following must be observed in particular:*
>
> *G – Average depth*
>
> *Average depth of loose snow and slush reported in column F, shall be reported for each third of the runway seen from the threshold with the lowest runway number. The depth shall be reported in millimetres to an accuracy of 20 mm for dry snow, 10 mm for wet snow and 3 mm for slush, and the result shall be rounded up so that wet snow with a depth of between 10 and 20 mm is reported as 20 mm deep etc. If the depth of snow or slush is considered to be of no consequence to flight operations, the letter code XX may be used. This is conditional on the aircraft operators having provided the aerodrome operator with the basis required to use XX.*
>
> *H – Friction levels*
>
> *The runway friction level can be reported as measured or estimated. If the aerodrome operator cannot vouch for the friction level or if the conditions are outside the valid range of the friction measuring device, the figure 9 shall be reported. The measured friction level can only be reported when the conditions are within the valid range of the friction measuring device. The measured friction level is reported for each third of the runway seen from the threshold with the lowest runway number and reported using two digits (leaving out zero and the decimal divider) followed by the abbreviation for the friction measuring device. See sections 2.6 and 2.7 below for more information. The friction level can be estimated by qualified personnel. The estimated friction level shall be reported for each third of the runway seen from the threshold with the lowest runway number and stated using one digit in accordance with the following table:*
>
> *5 Good – corresponds to friction level 0.40 or higher*

---

[1] AIP Norway rev. 27 October 2005.

4 Medium good – corresponds to friction level 0.36-0.39

3 Medium – corresponds to friction level 0.30-0.35

2 Medium poor– corresponds to friction level 0.26-0.29

1 Poor – corresponds to friction level 0.25 or lower

9 Cannot be estimated

Norwegian definitions of snow types (CAR/BSL E 4-2 section 3. Definitions)[2]

Slush is water-saturated snow which with a heel-and-toe slap-down motion against the ground will be displaced with a splatter, specific gravity: 0.5 up to 0.8.

Snow (on the ground):

1. *Dry snow: Snow that can be blown away when it is loose or that dissolves when compacted in the hand; specific gravity of less than 0.35.*
2. *Wet snow: Snow that binds together when compacted in the hand and takes the form or verges on taking the form of a snowball; specific gravity of 0.35 or more, but less than 0.5.*
3. *Compacted snow: Snow that has been compacted to a solid mass and resists further compaction and remains together or divides into lumps when lifted up; specific gravity of 0.5 or more".*

Validity range for friction measuring devices (AIP Norway, AD 1.2, item 2.6)[3]

2.6 Friction measuring devices and validity ranges

2.6.1 The following friction measuring devices are accepted for use at Norwegian aerodromes:

– GRT Grip Tester

– SFH Surface Friction Tester, High pressure tyre

– SKH Skiddometer BV 11, High pressure tyre

– RUN Runar

– VIN Vertec Inspector

– TAP Tapley meter

2.6.2 In general, there is a great deal of uncertainty when carrying out measurements on contaminated runways and especially in wet conditions – so-called 'zero degrees' conditions. Snow and ice are then at melting point.

---

[2] Based on definitions in ICAO Airport Services Manual, Part 2, Pavement Surface Conditions, Chapter 4.

[3] AIP Norway rev. 27 October 2005.

The use of TAPs, for example, is not permitted in wet conditions. See section 2.7 below for more information.

2.6.3 A measured friction level will depend on the device that is used to measure it, and cannot be used as an independent value. The validity range of the various friction measuring devices are:

SKH/SFH:

– Dry snow up to 25 mm

– Dry compacted snow irrespective of depth

– Dry ice irrespective of thickness

– Slush up to 3 mm

– Wet snow up to 3 mm

– Wet ice.

GRT/RUN/VIN:

– Dry snow up to 25 mm

– Dry compacted snow irrespective of depth

– Dry ice irrespective of thickness

– Slush up to 3 mm

– Wet snow up to 3 mm

TAP:

– Dry snow up to 5 mm

– Dry compacted snow irrespective of depth

– Dry ice irrespective of thickness

General uncertainty attached to the use of friction values (AIP Norway, AD 1.2, item 2.7)

2.7 The SNOWTAM format section H

The table is section H, with pertaining descriptive text, was developed in the early 1950s on the basis of data collected on compacted snow and ice only. The friction levels cannot be regarded as absolute values and in general are not valid for surfaces other than compacted snow and ice. It is, however, accepted that friction levels can be reported for conditions of up to 3 mm wet snow or slush provided a continuous friction measuring device is used. A numerical expression cannot be acquired for the quality of the friction levels reported in SNOWTAM. Tests show that the accuracy indicated by the table cannot be acquired with today's friction measuring equipment. While the table states values to an accuracy of one part per hundred, tests show that only values to an accuracy of one part per ten can be of operational value. Therefore, great care must be taken when using reported friction levels, and use of the table must be based on the aircraft operators' own experience.

APPENDIX G

AIBN summary: Use of Friction Data

Uncertainty

Table 1 shows documented uncertainty, as established by ICAO and NASA, for friction measuring devices under various conditions. It has long been recognised that the SNOWTAM table is based on dry compacted snow or dry compact ice. Nevertheless, the use of friction measuring devices for wet snow or ice is permitted. Table 1 show that the uncertainty attached to compacted snow and ice (dry) is, at best, in the order of ± 0.10, and may be in the order of ± 0.20 in wet conditions.

Table 1. Various documented uncertainties in friction measurements – various types of friction measuring devices

YEAR	Organisation	Uncertainty	Remark
1962	ICAO[1]	± 0.01	Reported by a State
1974	ICAO[2]	± 0.15 - 0.20	Wet surfaces
1974	ICAO[3]	± 0.10 - 0.15	Compacted snow and ice surfaces
1990	NASA[4]	± 0.10	Aircraft/FC contaminated
2005	ASTM[5]	± 0.05 → ± 0.20	Use of ASTM standard E2100-04

Figures 1 and 2 show friction values measured at Avinor's test runway at Oslo Airport Gardermoen in which a Grip Tester (GRT) and a Skiddometer (SKH) were compared on different test surfaces (wet friction).

The results show an uncertainty in the order of ± 0.15 and are based upon an average comprising three to six individual measurements.

---

[1] ICAO Doc 8298-AGA/593, Aerodromes Air Routes and ground Aids Division, Report of the Seventh Session, Montreal, 13 November - 14 December 1962.

[2] ICAO, Programme for Correlating Equipment Used in Measuring Runway Braking Action, Final Report, 22 February 1974.

[3] ICAO, Programme for Correlating Equipment Used in Measuring Runway Braking Action, Final Report, 22 February 1974.

[4] Thomas J. Yager, William A. Vogler, and Paul Baldasare, Evaluation of Two Transport Aircraft and Several Ground Test Vehicle Friction Measurements Obtained for Various Runway surface Types and Conditions, A Summary of Test Results From Joint FAA/NASA Runway Friction Program., NASA Technical Paper 2917, February 1990.

[5] CDRM Inc., International Runway Friction Index (IRFI): Development technique and methodology (TP 14061e), Transport Canada, 2001.

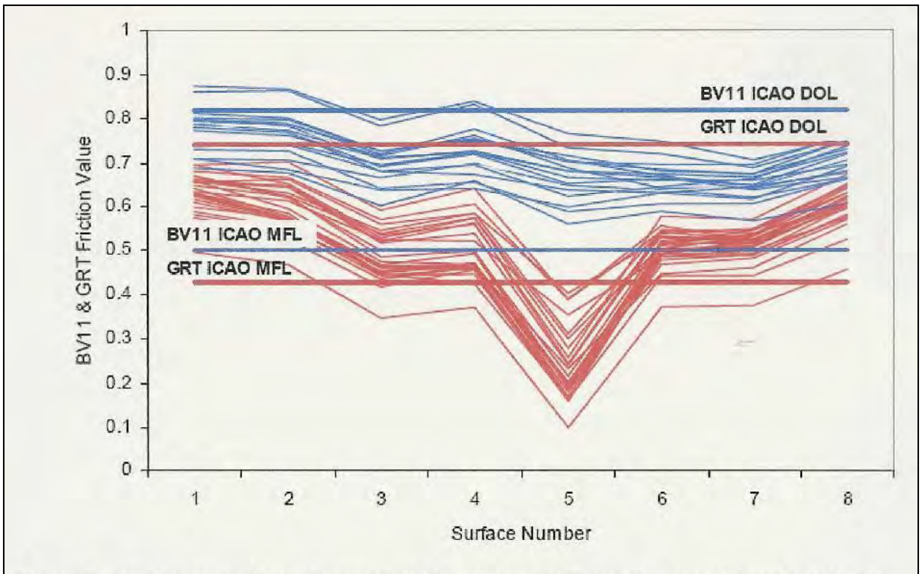


Figure 2 - Summary results from reproducibility study in 1998 of NATAM operated BV11 and GripTester units. DOL= Design Objective Level og MFL = Minimum Friction Level.

Figure 1. Norwegian wet runway FC measurement results with SKH and GRT on different MTD surfaces (Avinor 2003)[6].

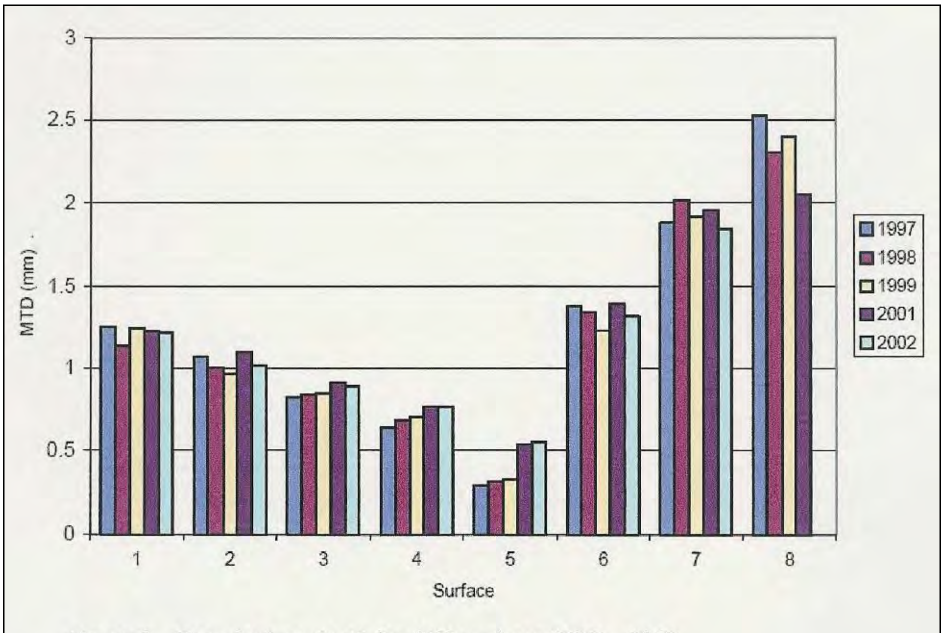


Figure 3 - Mean texture depth for OKK surfaces 1997 – 2002

Figure 2. Norwegian Avinor MTD runway friction test surfaces (Avinor 2003).

Correlation between measured friction and the aircraft effective μ /ABC

Figure 3 shows test data from the Joint Winter Runway Friction Measurement Program (JWRFMP) in Canada. The figure shows the airplane braking coefficient (ABC) versus the Canadian Runway Friction Index (CRFI)[7]. The lowermost red line on the chart is approved by Transport Canada for use by all types of aircraft (95 %). The chart indicates the extent of scatter in the measurement data. $R^2 = 0.89$ shows that 89 % of the variation in the one variable (ABC) is conditional on the variation/scatter of the individual observations of the other

---

[6] G. Lange. Avinor Notice 5-2003.

[7] CFRI is a friction coefficient measured using an electronic recording decelerometer (ERD), TC 2004.

variable (CRFI). The correlation coefficient R= 0.94 is surprisingly high, but its significance is not stated. The findings of AIBN's investigations and the physical processes that form the basis for measured friction coefficients (FC), on the one hand, and the airplane effective µ /ABC, on the other, makes the general applicability of the reported high correlation somewhat doubtful.

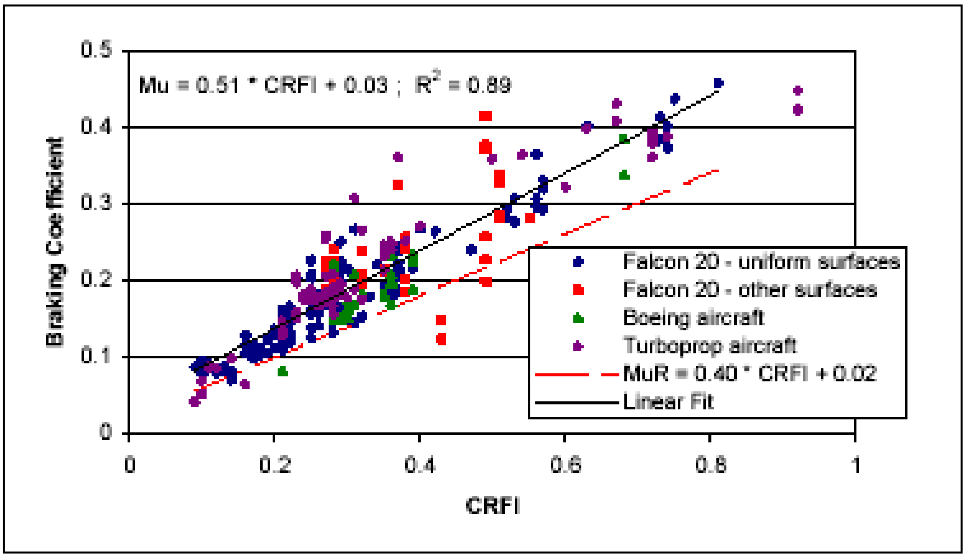


Figure 3. Test data from JWRFMP (2004).

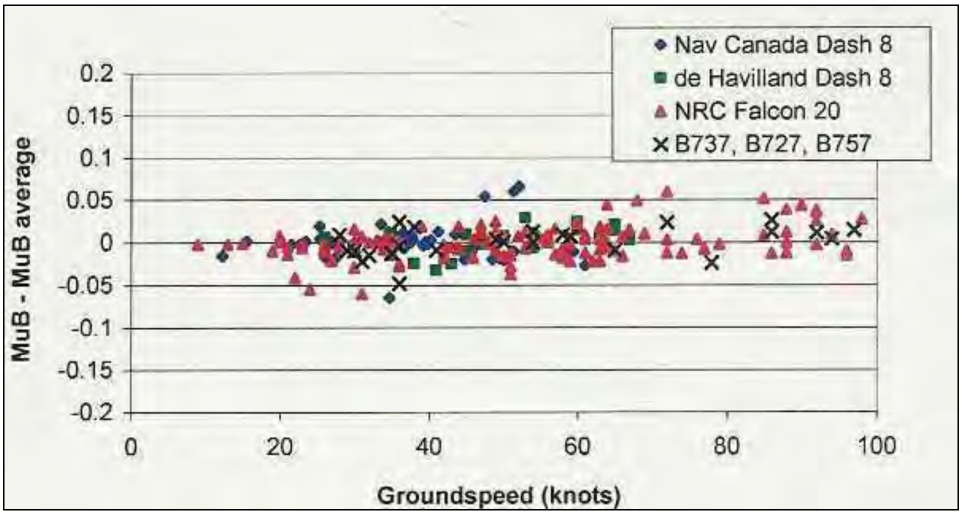
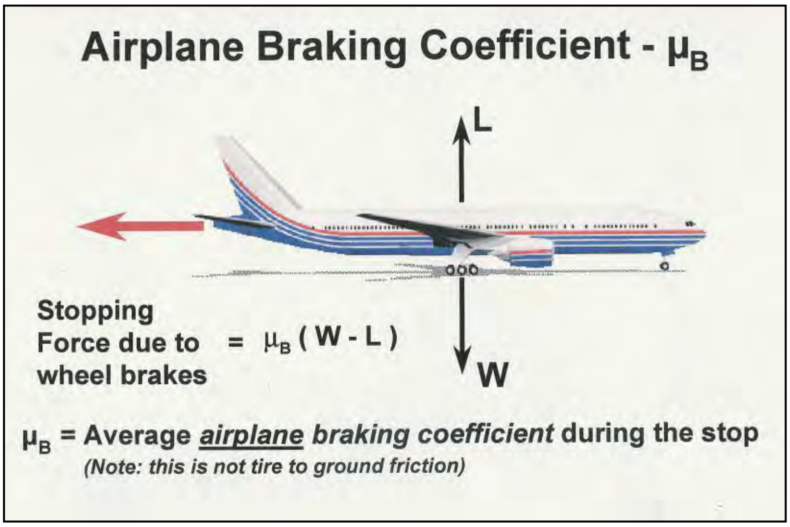


Figure 4. Test data from JWRFMP (2004).

Figure 4 is quite interesting as it is commonly assumed that the 'aircraft µ'/ABC is varying with ground speed. This is true for tire friction on hard surfaces, but the data in Figure 4 show how the aircraft 'aircraft µ' /ABC (Mu – Braking) varied with the planes' ground speed as registered during the JWRFMP tests in Canada. The results show that, in practice, the Mu - Braking is approximately constant at different groundspeeds. Hence, these test results deviate from the theoretical formulas used to determine friction on 'fluid contaminants', and test friction data on hard surfaces.

Boeing does not correlate its defined ABC with correlation curves, but has defined the airplane braking coefficient as shown in Figures 5 and 6.



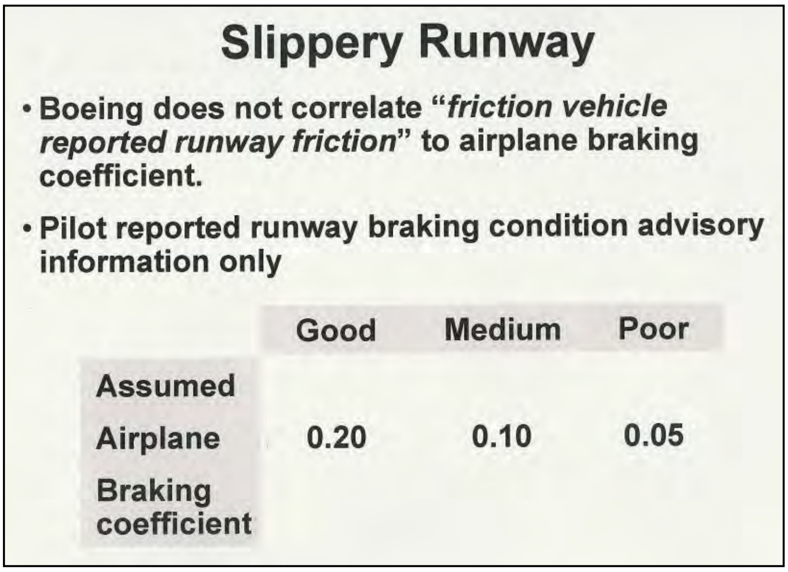
Airplane Braking Coefficient - μ_B

Stopping Force due to wheel brakes $= \mu_B (W - L)$

μ_B = Average *airplane braking coefficient* during the stop

(Note: this is not tire to ground friction)

Figure 5. Boeing's definition of airplane braking coefficient (ABC) (Boeing, 2006).



Slippery Runway

- Boeing does not correlate "*friction vehicle reported runway friction*" to airplane braking coefficient.
- Pilot reported runway braking condition advisory information only

	Good	Medium	Poor
Assumed Airplane Braking coefficient	0.20	0.10	0.05

Figure 6. Boeing's fixed values for "assumed airplane braking coefficient" (Boeing, 2006).

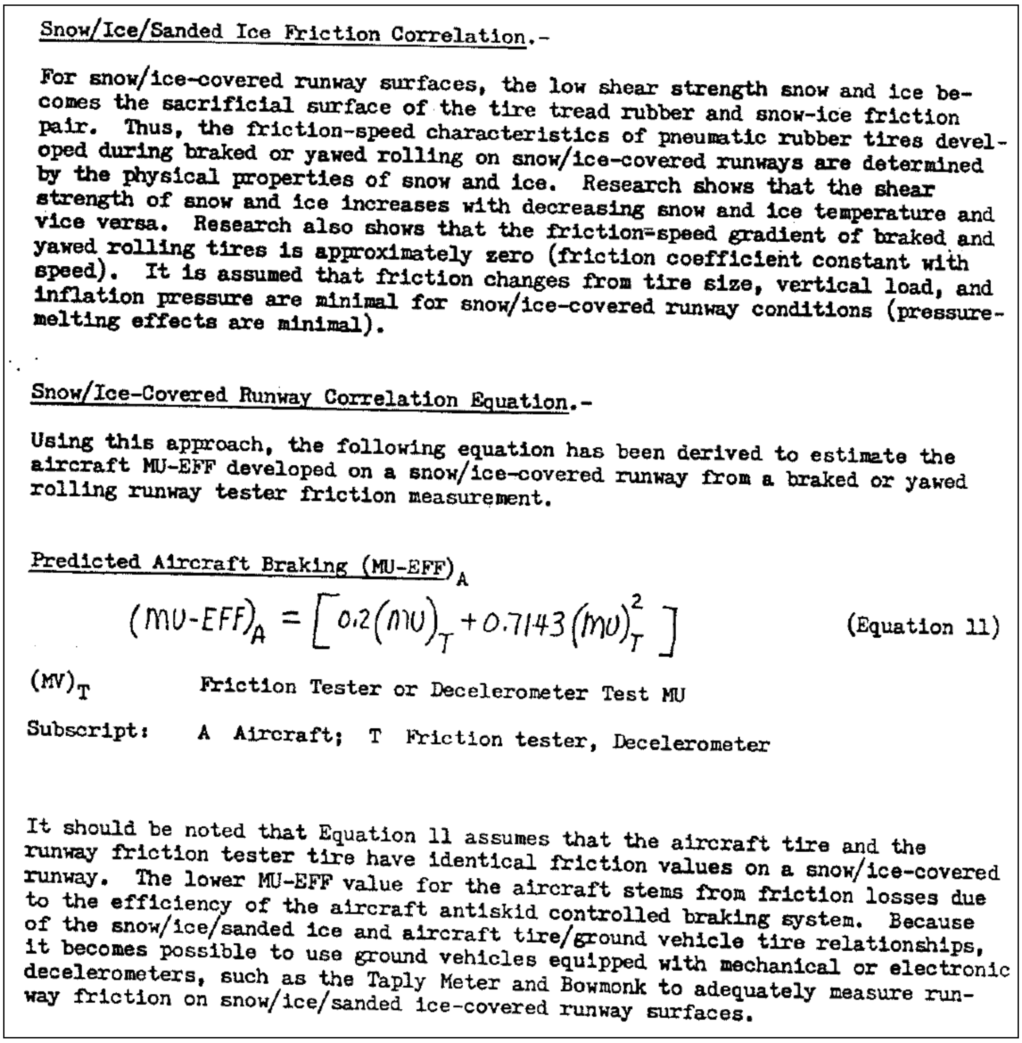
Braathens[8], in its time, received approval from the Norwegian Civil Aviation Administration of its own definition of a correlation curve based on a combination of the SNOWTAM table and Boeing's ABC for Good, Medium and Poor as shown in Table 2. This curve is shown in Figure 8 together with other available correlation curves. This figure indicates the range in Aircraft μ depending on the selected correlation curve.

---

[8] Braathens Airlines, a Norwegian domestic airline bought by SAS in 2004.

Table 2. Boeing's defined ABC versus Different types of contamination (Boeing, 2006).

Airplane Braking Coefficient	Pilot Reported Braking Action	Runway Description
0.4	Approximates dry runway	Friction limited certification values
0.2	Good	Wet Runway, Jar certification for compact snow
0.1	Medium/Fair	Ice, Compacted Snow
0.05	Poor/Nil	Wet Ice, Slush, Melting Compacted Snow, Standing Water



Snow/Ice/Sanded Ice Friction Correlation.-

For snow/ice-covered runway surfaces, the low shear strength snow and ice becomes the sacrificial surface of the tire tread rubber and snow-ice friction pair. Thus, the friction-speed characteristics of pneumatic rubber tires developed during braked or yawed rolling on snow/ice-covered runways are determined by the physical properties of snow and ice. Research shows that the shear strength of snow and ice increases with decreasing snow and ice temperature and vice versa. Research also shows that the friction-speed gradient of braked and yawed rolling tires is approximately zero (friction coefficient constant with speed). It is assumed that friction changes from tire size, vertical load, and inflation pressure are minimal for snow/ice-covered runway conditions (pressure-melting effects are minimal).

Snow/Ice-Covered Runway Correlation Equation.-

Using this approach, the following equation has been derived to estimate the aircraft MU-EFF developed on a snow/ice-covered runway from a braked or yawed rolling runway tester friction measurement.

Predicted Aircraft Braking $(MU\text{-}EFF)_A$

$$(MU\text{-}EFF)_A = \left[0.2(MU)_T + 0.7143(MU)_T^2\right] \qquad \text{(Equation 11)}$$

$(MV)_T$ Friction Tester or Decelerometer Test MU

Subscript: A Aircraft; T Friction tester, Decelerometer

It should be noted that Equation 11 assumes that the aircraft tire and the runway friction tester tire have identical friction values on a snow/ice-covered runway. The lower MU-EFF value for the aircraft stems from friction losses due to the efficiency of the aircraft antiskid controlled braking system. Because of the snow/ice/sanded ice and aircraft tire/ground vehicle tire relationships, it becomes possible to use ground vehicles equipped with mechanical or electronic decelerometers, such as the Taply Meter and Bowmonk to adequately measure runway friction on snow/ice/sanded ice-covered runway surfaces.

Figure 7. NASA formulas for Predicted Aircraft Braking Coefficient (Mu eff) (W. Horne 1990)[9].

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[9] Correlation between aircraft/ground vehicle runway friction measurements. Prepared for the Airline Pilots Association International by Walter B. Horne, Consultant. 1990.

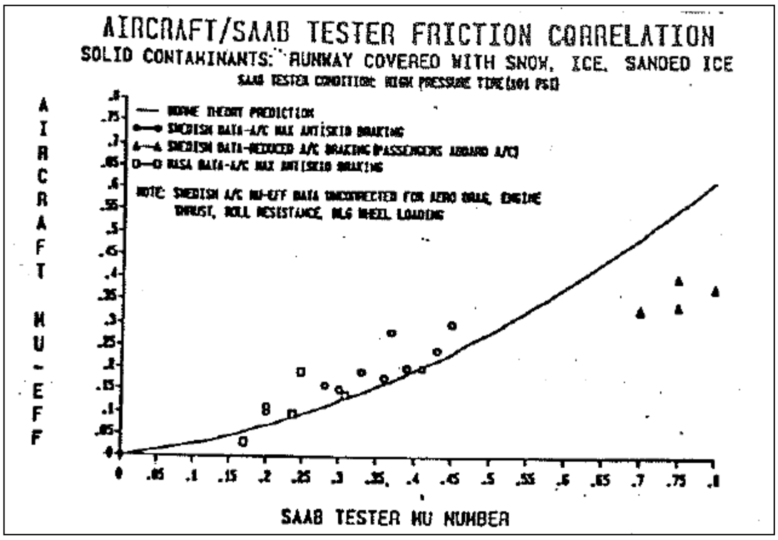

Figure 8. NASA Aircraft/SAAB Tester Friction Correlation (W. Horne, 1990)[10].

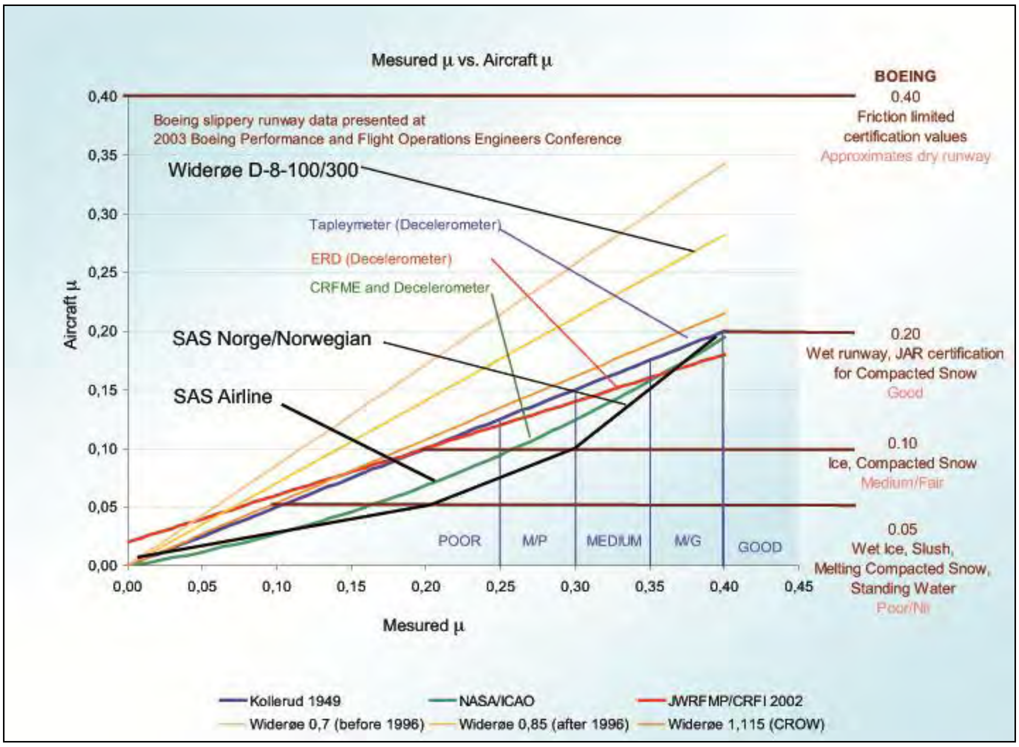

Figure 9. Braathens/SAS Norway, CAA-approved correlation curve (black line)(A. Norheim, 2005).

AIP Norway includes a warning about the use of measured friction coefficients with an accuracy in parts per hundred. AIP EN AD 1.2 item 2.7[11] (revision date 23. January 2003) states:

> *"2.7 SNOWTAM format section H*
>
> *The table in section H, with pertaining descriptive text, was developed in the early 1950s on the basis of data collected on compacted snow and ice only. The friction*

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[10] Correlation between aircraft/ground vehicle runway friction measurements. Prepared for the Airline Pilots Association International.

[11] Aeronautical Information Publication (AIP) Norway, published by Avinor.

levels cannot be regarded as absolute values and are not generally valid for surfaces other than compacted snow and ice. It is, however, accepted that friction levels can be reported for conditions of up to 3 mm wet snow or slush provided a continuous friction measuring device is used. A numerical expression cannot be obtained for the quality of the friction levels reported in SNOWTAM. Tests show that the accuracy indicated by the table cannot be obtained with today's friction-measuring equipment. While the table states values to an accuracy of parts per hundred, tests show that only values to an accuracy of parts per ten can be of operational value. Hence, great care must be taken when using reported friction levels, and use of the table must be based on the aircraft operators' own experience.

Surface temperature

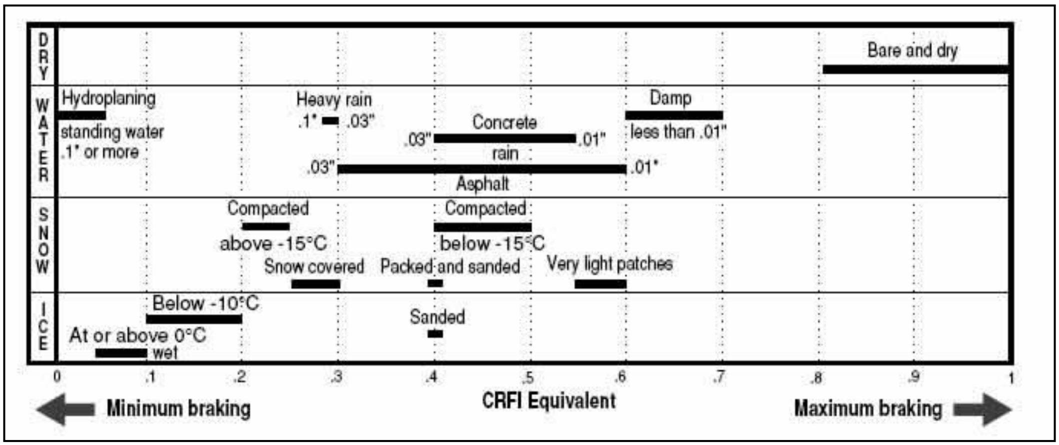

Figure 10. Friction measurements on contaminated surface at different temperatures and humidity[12]

As can be seen in Figure 10, a surface of liquid or frozen water can produce great variations in friction. Research shows us that lower temperatures result in better friction on contaminated surfaces. This is also universally known among pilots who have experienced good friction on frozen surfaces. This can be seen in the figure. We see that dry ice with a surface temperature below minus 10 °C can give an FC of between 0.10 and 0.20, while wet ice at temperatures higher than 0 °C give an FC lower than 0.10. There is therefore a need to measure the surface temperature of contaminated surfaces. This can be done using an infrared temperature meter.

Practical use of friction values

The large differences between measured friction values have become increasingly significant during the past 10 years in that the airlines have started using operational performance computers (OPC). Pilots use FC as a variable to calculate optimal takeoff and landing weights for the runway distance available. When we know that an FC of 0.30 in reality can be 0.20 or lower, the required stopping distance for a speed of 50-60 knots (with reverse thrust shut off) can be up to 50% longer ($S = V^2/2g\mu$, where S = stopping distance, V = landing speed, g = gravitational acceleration and μ = effective μ/ABC). At speeds below 50 knots the contribution of air resistance to the braking action is negligible.

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[12] Transport Canada, 2005.

A friction coefficient (FC) in the order of 0.20 corresponds to an airplane braking coefficient (ABC) of 0.05 as defined by Boeing (Figure 6). A conservative use of the SNOWTAM table may be as shown in Table 3.

Table 3. Possible conservative application of the SNOWTAM table.

0.40 (max. usable)	Good	5
0.30 and above	Medium	3
0.20 (min. usable) and above	Poor	1
Ref. AIP EN AD 1.2 item 2.7		

Table 4. Possible conservative application use of FCs.

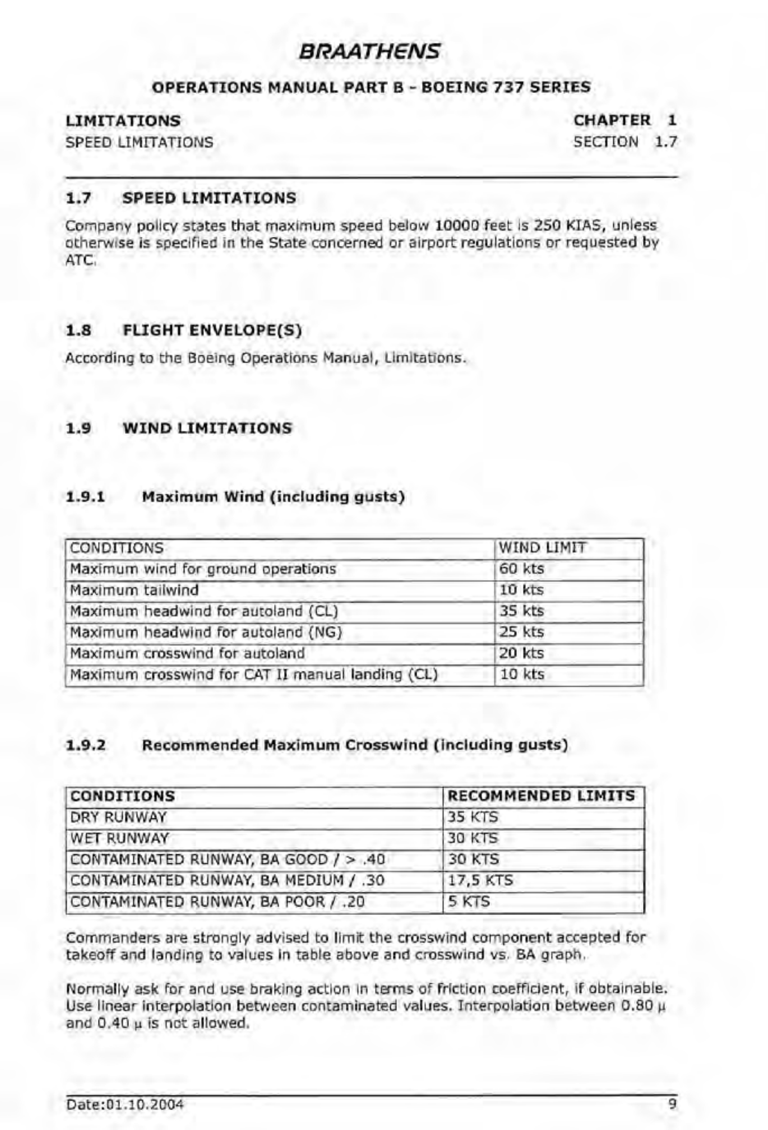
RWY status	Jet ABC	Prop ABC	SNOWTAM	ICAO Code	
Dry	0.40	0.40			
Wet	0.20 or TBD	0.20 or TBD			
Cont FC					
0.40	0.20	0.20	Good	5	
0.30	0.10	0.15-0.17	Medium	3	
0.20	0.05	0.10-0.12	Poor	1	Wet/Moist conditions

Based on empirical data conservative application of FCs may be limited to the values listed in Table 4.

The first column in the table describes the runway conditions. The AIBN believes that the runway status should be limited to the categories dry, wet and contaminated. A contaminated runway may be limited to three friction categories: GOOD, MEDIUM and POOR, which may be used together with ICAO SNOWTAM FC values (0.40, 0.30 and 0.20), which can be entered in the OPC. Columns 2 (jet) and 3 (prop) show airplane braking coefficients (ABC) that may be used in the calculation model in the CPC.

APPENDIX H

Typical airline crosswind limits in combination with contaminated runways



BRAATHENS

OPERATIONS MANUAL PART B - BOEING 737 SERIES

LIMITATIONS **CHAPTER 1**
SPEED LIMITATIONS SECTION 1.7

1.7 SPEED LIMITATIONS

Company policy states that maximum speed below 10000 feet is 250 KIAS, unless otherwise is specified in the State concerned or airport regulations or requested by ATC.

1.8 FLIGHT ENVELOPE(S)

According to the Boeing Operations Manual, Limitations.

1.9 WIND LIMITATIONS

1.9.1 Maximum Wind (including gusts)

CONDITIONS	WIND LIMIT
Maximum wind for ground operations	60 kts
Maximum tailwind	10 kts
Maximum headwind for autoland (CL)	35 kts
Maximum headwind for autoland (NG)	25 kts
Maximum crosswind for autoland	20 kts
Maximum crosswind for CAT II manual landing (CL)	10 kts

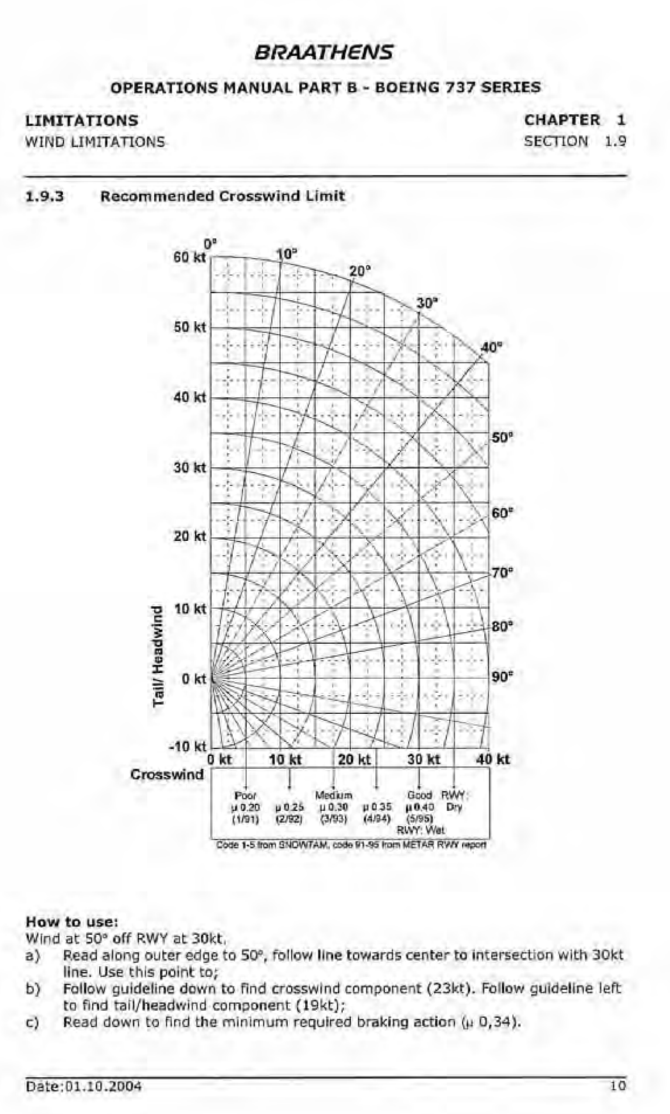
1.9.2 Recommended Maximum Crosswind (including gusts)

CONDITIONS	RECOMMENDED LIMITS
DRY RUNWAY	35 KTS
WET RUNWAY	30 KTS
CONTAMINATED RUNWAY, BA GOOD / > .40	30 KTS
CONTAMINATED RUNWAY, BA MEDIUM / .30	17,5 KTS
CONTAMINATED RUNWAY, BA POOR / .20	5 KTS

Commanders are strongly advised to limit the crosswind component accepted for takeoff and landing to values in table above and crosswind vs. BA graph.

Normally ask for and use braking action in terms of friction coefficient, if obtainable. Use linear interpolation between contaminated values. Interpolation between 0.80 μ and 0.40 μ is not allowed.

Date:01.10.2004 9



BRAATHENS

OPERATIONS MANUAL PART B - BOEING 737 SERIES

LIMITATIONS **CHAPTER 1**
WIND LIMITATIONS SECTION 1.9

1.9.3 Recommended Crosswind Limit

Code 1-5 from SNOWTAM, code 91-95 from METAR RWY report

How to use:
Wind at 50° off RWY at 30kt.

a) Read along outer edge to 50°, follow line towards center to intersection with 30kt line. Use this point to;
b) Follow guideline down to find crosswind component (23kt). Follow guideline left to find tail/headwind component (19kt);
c) Read down to find the minimum required braking action (μ 0,34).

Date:01.10.2004 10

BOEING

Landing on Slippery Runways

Article 6

Paul Giesman
Boeing

Background Information

Each year there are a number of landing overruns where slippery runways or crew procedural deviations are contributing factors. Often, these occurrences are due to a combination of issues such as weather, runway conditions, the airplane's weight, braking systems to be used, improper flight crew technique, or lower than expected runway friction.

As a result of a landing overrun accident and FAA investigation of how slippery runway landing operations have been carried out, the FAA released *Safety Alert for Operations* (SAFO) 06012 at the end of August 2006 (app. 1). SAFO 06012 has the following stated purpose:

> "This SAFO urgently recommends that operators of turbojet airplanes develop procedures for flightcrews to assess landing performance based on conditions actually existing at time of arrival, as distinct from conditions presumed at time of dispatch. Those conditions include weather, runway conditions, the airplane's weight, and braking systems to be used. Once the actual landing distance is determined an additional safety margin of at least 15% should be added to that distance. Except under emergency conditions flightcrews should not attempt to land on runways that do not meet the assessment criteria and safety margins as specified in this SAFO."

This paper is intended to remind flight crews, flight operations engineers, and performance engineers of the factors that affect an airplane's ability to stop on a slippery runway, the runway condition information that is available to flight crews, and the Boeing Flight Crew Training Manual (FCTM) recommended landing

This article is presented as part of the 2007 Boeing Performance and Flight Operations Engineering Conference, providing continuing support for safe and efficient flight operations.

procedures and techniques.

The words "contaminated" and "slippery" are commonly used in the aviation industry to describe the precipitation on a runway. Although there are specific differences between a contaminated and a slippery runway (as described later), for the purposes of this bulletin, the word "slippery" will be used to mean either "slippery" or "contaminated."

> **Note:** The specific information in this bulletin covers the FCTM and/or the Boeing Flight Crew Operations Manual (FCOM) information for the 717/737/747-400/ 757/767/777 model airplanes. In general, the information in this bulletin is also applicable for the 707/727/747/DC-8/DC-9/MD-80/ MD-90/DC-10/MD-10/MD-11 models. Primary areas where the information will vary are reverse thrust procedures, data presentation, and document location for slippery runway landing distances. Operators should review their operating material (and applicable Boeing documents) used for these models. Boeing Flight Operations Engineering can be contacted with questions on the specifics for these airplanes. The 787 performance information is also expected to be consistent with this paper.

Introduction

Boeing provides two different landing distance data sets to operators: Dispatch data and Operational data.

- Dispatch landing data are used during flight planning to determine the maximum takeoff weight at which the airplane can land within the available landing distance at the destination or alternate airport. The data are based on specific regulatory requirements that address dry runway and wet or slippery runway conditions. These data are also referred to as "certified data." The data do not provide distance requirements to cover all operational landing situations. The effect of thrust reversers are not included in the dispatch landing distance data. Wet or slippery conditions are accounted for by factoring the dry runway dispatch landing data.
- Operational landing data are provided by Boeing as Advisory-Normal Configuration Landing Distance data in the Performance Inflight (PI) section of the Quick Reference Handbook (QRH). These data are also referred to as "operational data," "enroute data," or "advisory data." The data provided by Boeing as advisory landing distance data have always been based on the use of reverse thrust.

  Boeing QRH advisory landing distance data are provided as unfactored data. There is no margin applied to the landing distance for operators who use FAA requirements. This may change in the future to include a 1.15 factor as a result of FAA and industry activity.

To accurately determine the operational landing distance required, it is important that flight crews review the information available regarding weather and runway conditions and make appropriate allowances to their calculations for any conditions or landing techniques that are different from those used to calculate the advisory data.

An important factor in the determination of landing distance is the condition of the runway. Information about runway condition is often available through three main sources:

- Pilot information report (PIREP)
  - Qualitative terms of braking action such as "good, medium, poor" or "good, fair, poor, nil."
- Runway surface description
  - Physical description of runway surface and contaminant (e.g., 6 mm of wet snow, patches of ice, compact snow).
- Runway friction reports
  - Measured by friction-reporting vehicles designed for this purpose, using the Greek letter μ (mu), and can be reported as either a whole number or a decimal (e.g., 40, 0.40).

In the summer of 2006 braking action guidelines were developed by a FAA working group that included U.S. airline technical pilots and other interested parties. This is a voluntary operational guide for flight crews and is expected to be the starting point for future FAA guidance for winter operations. These FAA working group guidelines have been used by airlines in creating their own policies and pilot information. These guidelines are attached in *appendix 2* of this paper.

Definitions

The terminology in this bulletin is defined as follows:

Slippery runway–A runway that is not equivalent to dry.

Contaminated runway–A runway that is not dry or wet but with contaminates that have a measurable depth. Examples include ice, loose snow, compact snow, slush, or standing water. Boeing advisory landing distance data are conservative and do not take credit for the deceleration impingement effects of a contaminate with a measurable depth. Therefore, the term "contaminated runway" can be used interchangeably with "slippery runway" for the purposes of this paper.

Enroute–Any phase of flight after takeoff but before landing. For the purposes of this bulletin, enroute refers to the period of time during which the pilot is evaluating the upcoming landing operation.

Pilot information report–Report by flight crews from previous operations. For the purposes of this bulletin, PIREPs are limited to descriptions of the runway surface condition or braking action.

Braking action–A subjective description of airplane stopping capability on a slippery runway. The terminology in ICAO Annex 14 is good, good to medium, medium, medium to poor, and poor. The terminology in the FAA *Airman's Information Manual* (AIM) and AC 150/5200-30A is good, fair, poor, and nil. See *appendix 2* for further explanation.

Runway friction–The capability of the runway surface to convert the vertical load on the braked wheels into a horizontal force to stop the airplane. The Greek letter μ (mu) is typically the symbol for friction and represents the percentage of the vertical load converted into a horizontal force.

Airplane braking coefficient (μ_B)–The ratio of the stopping force contribution of the wheel brakes to the average airplane weight on wheels ($W\text{-}L_{ave}$). Airplane braking coefficient is a different parameter than runway friction.

QRH Advisory-Normal Configuration Landing Distance–Advisory data contained in the PI section of the QRH. The data is provided as a function of braking action and is referred to as "QRH landing advisory data" in this bulletin.

Landing Performance Data

Landing performance data can be separated into two types of data: dispatch data and operational data. Dispatch data is used to meet the specific requirements as set forth in the Code of Federal Requirements (CFRs, same as Federal Aviation Regulations, FARs). The data to satisfy these dispatch requirements can be found in the Airplane Flight Manual (AFM).

Operational data can be used to determine the best course of action for the specific conditions at the destination airport.

Dispatch Requirements

CFR Part 121.195(b) sets the dispatch requirement for dry runway landing distance (fig. 1). This landing distance is based on certification flight testing, which determines an air distance from a 50-ft threshold crossing altitude to touchdown of 800 to 1100 ft.

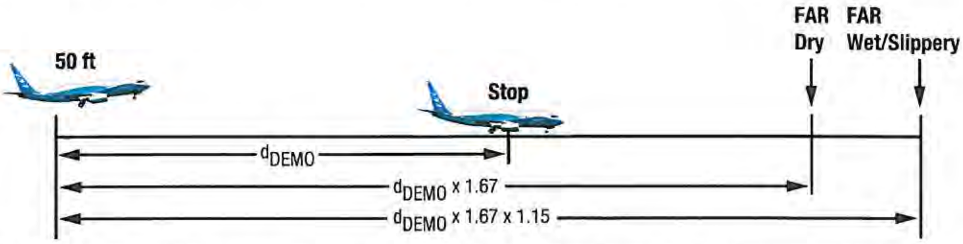


Figure 1. Certified FAR wet or slippery basis used for dispatch requirements

Following touchdown, maximum manual braking and spoiler deployment is initiated as soon as possible to minimize the landing distance. Reverse thrust is not used; therefore, no credit is taken for reverse thrust in the dispatch landing data.

The flight test demonstrated landing distances represent the shortest landing distances for a given airplane weight and the best performance the airplane is capable of (without reversers) for the conditions. To account for operational variances from the flight test demonstrations, the minimum legal dry runway landing field length is increased by a factor of 1.67; this will be called "FAR dry" in this paper.

CFR Part 121.195(d) sets the dispatch requirement for a wet or slippery runway and is based on the distance computed to meet the FAR dry requirement of CFR Part 121.195(b) increased by a factor of 1.15. No specific wet or slippery runway flight testing is required to determine the wet or slippery distance as defined in CFR Part 121.195(d); this will be called "FAR wet or slippery" in this paper.

The AFM wet or slippery runway calculation is not based on the airplane's actual stopping performance on a wet or slippery runway. In fact, slippery runway conditions exist that would result in longer landing distances than the dispatch requirement. To address this, Boeing has supplied Advisory-Normal Configuration Landing Distance information in the QRH. This data can be used for decision making for landings on slippery runways.

Operational (or Enroute) Landing Data

Boeing includes slippery runway landing distance advisory information in the PI section of the QRH (fig. 2). Specifically, these data are labeled Normal Configuration Landing Distance and are for advisory information only.

Advisory Information

Normal Configuration Landing Distance
Flaps 30
Dry Runway

	Landing distance and adjustments, ft											
	Ref dist*	Weight adj	Alt adj	Wind adj per 10 kt		Slope adj per 1%		Temp adj per 10°C		V_{REF} adj	Reverse thrust adj	
Braking configuration	450,000-lb landing wt	Per 10,000-lb above/below 450,000 lb	Per 1000 ft above S.L.	Head wind	Tail wind	Dwn hill	Up hill	Abv ISA	BLW ISA	Per 10 kt above V_{REF30}	One rev	No rev
Max manual	2940	+70/-40	60	-120	440	40	-30	60	-60	230	50	100
Max auto	3980	+60/-40	90	-170	610	0	0	90	-100	410	0	0
Autobrake 4	4940	+80/-60	130	-240	850	20	-20	130	-130	520	0	0
Autobrake 3	5970	+100/-80	160	-290	1060	40	-60	160	-160	590	10	20
Autobrake 2	2940	+120/-4100	190	-340	1220	90	-130	180	-180	540	140	140
Autobrake 1	2940	+140/-120	220	-380	1370	150	-190	200	-200	540	410	500

Good Reported Braking Action

Max manual	4060	+70/-70	110	-200	750	110	-90	100	-100	330	200	450
Max auto	4460	+70/-70	110	-210	780	80	-60	110	-100	410	210	480
Autobrake 4	4960	+80/-80	130	-240	880	40	-30	130	-130	520	20	70
Autobrake 3	5970	+100/-100	160	-290	1060	40	-60	160	-160	590	10	20

Medium Reported Braking Action

Max manual	5470	+100/-100	170	-320	1260	270	-200	150	-140	420	540	1320
Max auto	5730	+100/-100	160	-310	1250	240	-160	150	-140	490	520	1290
Autobrake 4	5730	+100/-100	170	-320	1260	250	-150	150	-150	510	520	1350
Autobrake 3	6280	+110/-110	180	-340	1340	190	-130	170	-170	590	270	900

Poor Reported Braking Action

Max manual	7050	+150/-140	230	-470	2010	680	-390	200	-190	480	1160	3110
Max auto	7400	+150/-140	230	-470	1990	680	-390	200	-190	490	1170	3140
Autobrake 4	7400	+150/-140	230	-470	2000	680	-400	200	-190	490	1190	3180
Autobrake 3	7430	+150/-140	230	-480	2020	650	-340	200	-200	590	1070	3070

* Reference distance is for sea level, standard day, no wind or slope, V_{REF30} approach speed, and two-engine reverse thrust.

Max manual braking data valid for auto speedbrakes. For manual speedbrakes, increase reference landing distance by 200 ft.

Autobrake data valid for both auto and manual speedbrakes.

Actual (unfactored) distances are shown.

Includes distance from 50 ft above threshold (1000 ft of air distance).

Figure 2. Operational (or enroute) landing data (777 data used as an example)

Note: Nomenclature–on other Boeing models, the term "spoilers" is used instead of speedbrakes as presented in Figure 2. This paper uses the term spoilers, as this is the term used in the majority of Boeing FCOMs.

Boeing supplies the slippery runway data in the QRH as a function of reported braking action. The braking deceleration used to calculate the "good" braking action data in the QRH is consistent with wet runway testing done on early Boeing airplane models. The lowest performance level calculated is consistent with braking on wet ice (defined as "nil" in *app. 2*). This is conservatively used by Boeing to define the "poor" braking action data in the QRH.

The Boeing supplied operational slippery runway landing data are based on a mixture of flight test parameters for the specific airplane (e.g., lift, drag, reverse thrust effect) and an engineering analysis of the effect of a slippery runway on the ability of the wheel brakes to stop the airplane.

These operational slippery runway landing data are based on prompt application of all stopping devices and take into account maximum manual braking or the use of the autobrake system.

The advisory data provided in the QRH for operators who use JAA requirements include an additional 15% for added safety margin as required by JAR-OPS 1 rules. The advisory data provided in the QRH for operators who use FAA requirements are unfactored, which means that no additional distance is added to ensure an adequate margin of safety. Operators are encouraged to add additional margins appropriate to their operations. The FAA has released SAFO 06012, which requests U.S. operators to voluntarily add at least a 15% margin as an interim measure until their final rulemaking is completed.

Figure 2 presents a 777 QRH chart as an example of advisory data provided by Boeing. Advisory data for other models will be presented in a similar format. Data are presented at reference conditions (REF DIST) with adjustments supplied for the operator or flight crew to account for the effects of variables such as weight, altitude, wind, slope, temperature, approach speed, reverse thrust, and spoilers.

The reference distance is calculated under the following conditions:

- Prompt initiation of reverse thrust (within 2 seconds of touchdown).
- Autobrake use or prompt application of manual wheel braking. (In general, maximum manual braking data is only valid for auto speed brakes. Autobrake data are valid for both auto and manual speed brakes. Review the notes for your specific airplane to ensure correct accounting if manual speed brakes are required.)
- Includes 1000 ft of distance from threshold to touchdown.
- Threshold crossing speed of $V_{REF.}$

The conditions and assumptions for other models are generally similar to the above; however some variations do exist and operators are encouraged to check the notes on the normal configuration landing distance charts.

Adjustments are supplied for the operator or flight crew to account for the effects of variables such as weight, altitude, wind, slope, temperature, approach speed, and configuration deviations (reverse thrust and spoiler).

The conditions and assumptions for other models are generally similar to the above; however some variations do exist and operators are encouraged to check the notes on the Normal Configuration Landing Distance charts.

Adjustments are supplied for the operator or flight crew to account for the effects of variables such as weight, altitude, wind, slope, temperature, approach speed, and configuration deviations (reverse thrust and spoiler).

Operators and flight crews should ensure that they are familiar with factors that affect the landing distance and with the flight crew techniques that are used to calculate the advisory data (fig. 3). Items include:

- The assumed touchdown point in the data.
- How quickly wheel braking and reverse thrust are applied.
- The level of reverse thrust used.
- What runway surface or braking action is assumed?
- Whether the data include an additional distance margin (For example, is the data factored?).

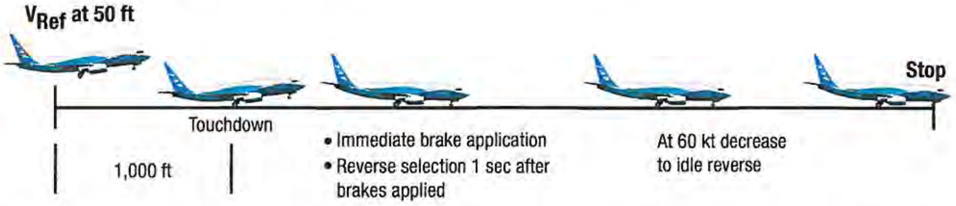


Figure 3. QRH landing advisory data assumptions

Flight crews need to make an appropriate allowance in their calculations of landing distance if their landing differs from the conditions and assumptions used to generate the advisory data.

Comparison of Dispatch and Operational Data

Figure 4 compares the certified data used to meet the requirements of CFR Part 121.195(d) with the operational advisory data at a condition of sea level on a standard day with no slope or wind. The operational advisory data used for this comparison are based on a 1000-ft touchdown point, an approach speed of $V_{Ref} + 5$, auto spoilers, maximum manual braking, and reverse thrust. The operational data used is unfactored.

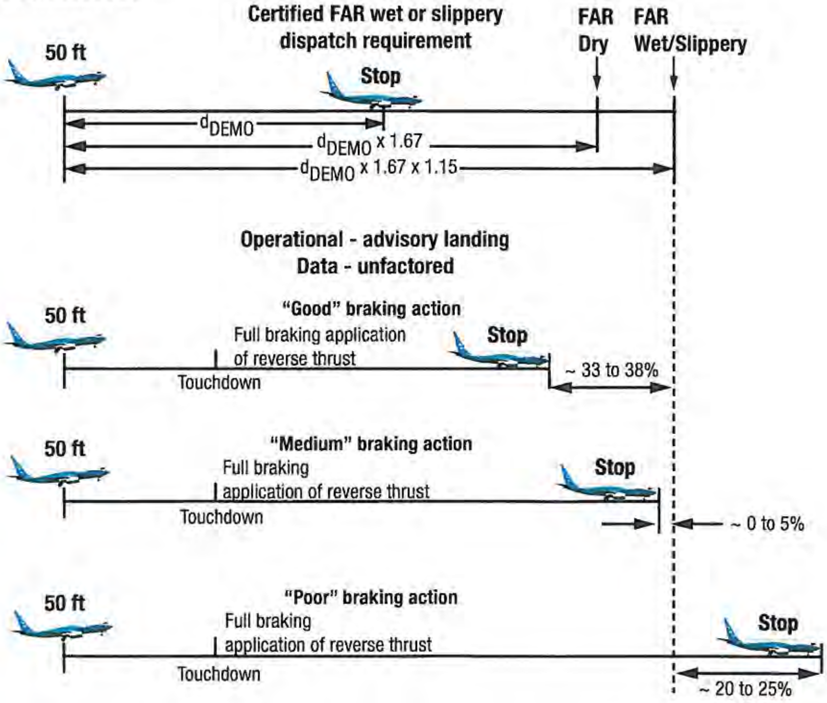


Figure 4. Comparison of FAR wet or slippery to unfactored landing performance on slippery runways

Figure 4 shows that the unfactored advisory data labeled "good" will typically be less than the FAR wet or slippery requirement by a significant margin. The unfactored data labeled "medium" is approximately the same distance as the FAR wet or slippery requirements. The unfactored data labeled "poor" results in a distance required in excess of the FAR wet or slippery requirement.

How is Braking Action Related to Airplane Performance?

Boeing has chosen to supply slippery landing data as a function of braking action. The parameter used by Boeing to represent the contribution of the wheel brakes to stopping the airplane is airplane braking coefficient (μ_B). Airplane braking coefficient (μ_B) is the ratio of the stopping force contribution of the wheel brakes to the average airplane weight on wheels ($W\text{-}L_{ave}$).

At a lower airplane weight on wheels ($W\text{-}L_{ave}$) the airplane wheel brakes are powerful enough that wheel skid would occur if the antiskid did not modulate the hydraulic pressure going to the wheel brakes. This is not desirable, so the antiskid system restricts the hydraulic pressure to the wheel brakes, thereby maximizing the wheel brake effectiveness for that surface. On a *dry runway* this occurs at an airplane braking coefficient (μ_B) of approximately 0.37 to 0.42. That is, 37% to 42% of the average airplane weight on wheels ($W\text{-}L_{ave}$) is converted into an effective stopping force.

Historical Boeing testing on a wet runway has demonstrated an airplane braking coefficient (μ_B) of approximately 0.2 to 0.22. When creating the slippery runway data, it was felt that braking action of good was a reasonable description of the stopping performance on a wet runway. Therefore, an airplane braking coefficient (μ_B) of 0.2 was assigned to a braking action of good, an airplane braking coefficient (μ_B) of 0.1 was assigned to a braking action of medium, and 0.05 was assigned to a braking action of poor. For landing operations, Boeing recommends the use of the data labeled poor for computing performance when landing on runways with reported standing water and slush (fig. 5).

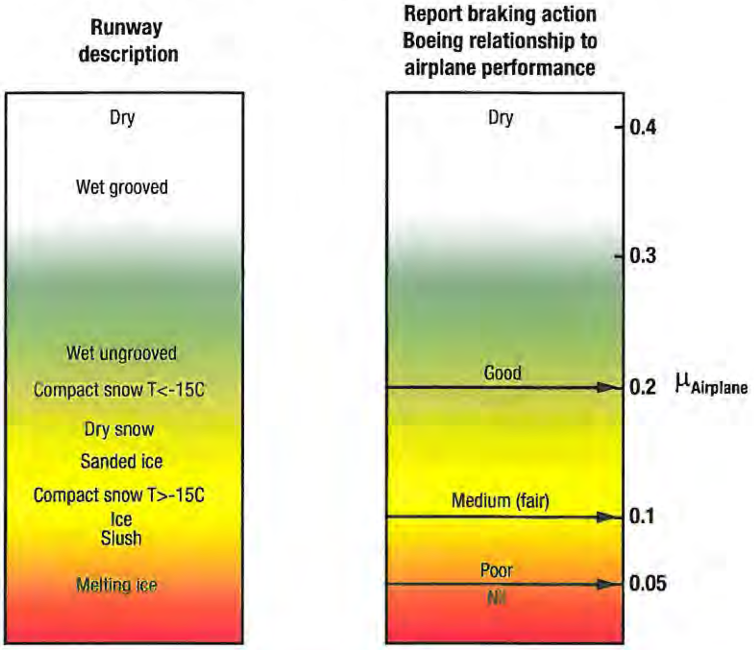


Figure 5. Methods of describing the runway condition and the airplane's performance

There is no universally accepted relationship between runway description, reported braking action, and airplane performance. The airplane's actual performance may well be different for the same description of the runway surface or the pilot-reported braking action. Boeing chose a relationship (discussed above) of reported braking action to airplane braking coefficient; this relationship has been used to create the data published in the QRH for slippery runway operation.

While Boeing uses the aforementioned relationship between the airplane braking coefficient and reported braking action for publishing data in the QRH, in the absence of specific regulatory recommendations the airline is not bound by this choice of relating the performance. Boeing does provide data in the Performance Engineer's Manual and in most of the operational computer programs as a function of airplane braking coefficient. The airline may choose to relate the airplane braking coefficient to the terms as appropriate to its operating environment, flight crew training, and company procedures and polices.

Factors Affecting Landing Distance

Touchdown Point

The QRH data is based on a touchdown point 1000 ft from the runway threshold. The touchdown speed is assumed to be approximately 98% of the approach speed at the runway threshold.

In operation, the airplane flies a glide slope; the typical glide slope is 3 deg. A 3-deg guide slope intersects the runway at approximately 1000 ft from the threshold. The actual airplane height (bottom of the main gear) at the threshold may be less or more than 50 ft depending on the approach guidance. Table 1 provides information based on a two- or three-bar VASI approach for the 737 and 747 airplanes.

Airplane	Approach	Aim point, ft	Pilot eye height, ft	Main gear height at threshold, ft	No flare touchdown point, ft
737 all models, flaps 30 and 40	Two-bar VASI 3° GS	1000	49–50	34–36	650–690
747-400 flaps 30	Two-bar VASI 3° GS	1000	47	12	233
747-400 flaps 30	Three-bar VASI (upper glide path) 3.25° GS	1800	97	62	1091

Reference: Boeing FCTM

Table 1. Airplane threshold height for VASI approach guidance systems

The actual touchdown point is a function of the type of approach flown and pilot technique in the flare. The actual touchdown point can vary from operation to operation. (See the FCTM for individual models to obtain the appropriate data for your model.) The FCTM states that the flare distance (air distance) is approximately 1000 to 2000 ft beyond the threshold.

The 1000-ft touchdown point in the QRH landing advisory data is provided as a reference; this value may be adjusted as required. Reasons for adjusting this value include

- Landing aids at specific airports.
- Operator training programs.
- Operating conditions that may affect pilotage (e.g., tailwind, crosswind, gusting winds, and visibility).
- Any specifics about the airport that would affect the touchdown point.
- Airplane equipage and use (e.g., autoland, HUDs, ILS, and GPS).

Boeing obtains autoland certification and as such must determine an average touchdown point and a statistical 3σ touchdown dispersion point based on flight test and simulations. On average the autoland touchdown point is approximately 1500 ft from the threshold. If a 3σ touchdown dispersion is included, this approximate touchdown point is approximately 2100 ft from the runway threshold. This 3σ touchdown dispersion point means that, statistically, 99.7% of the touchdowns will occur within 2100 ft of the runway threshold. Thus, on average, autolands may require an additional 500 ft of landing distance, but could require as much as an additional 1100 ft in the 3σ statistical case.

HUD systems have demonstrated that they may result in better performance than the pilot flying with no additional guidance. However, HUD systems may still result in longer touchdown points than the 1000 ft accounted for in the FCOM data.

When computing operational landing data, the airline should evaluate its operations and determine an air distance that represents its operation. The airline may choose to use one simple conservative distance that will cover all the airports it flies to or it may choose to use air distances that reflect the different methods of flying the approach based on the guidance available at individual airports and runways.

Maximum Manual Braking

The operational data supplied for normal configuration slippery runway operations are based on either maximum manual braking or use of the auto brake. Data based on maximum manual braking assumes that the pilot is manually applying the wheel brakes to achieve maximum hydraulic pressure to the antiskid system within 1 second after touchdown. The antiskid system will then determine how much of this pressure will be used based on the friction capability of the runway. If the runway is dry, then the antiskid system will use most, if not all, of the hydraulic pressure. This will result in the wheel brakes providing a very large stopping force.

If the runway is slippery, the antiskid system will restrict the amount of hydraulic pressure applied to the wheel brakes in an attempt to prevent tire skid and minimize the landing distance. The stopping force available from the wheel brakes will be reduced. This reduction in stopping force due to the wheel brakes will result in lower deceleration capability and therefore increased stopping distances.

As the runway condition deteriorates, the available deceleration due to the wheel brakes reduces dramatically (fig. 6).

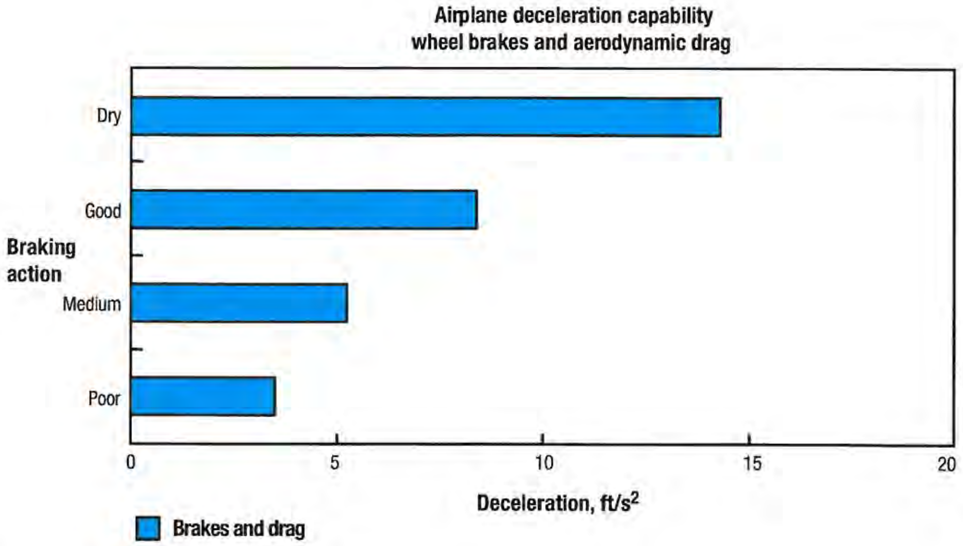


Figure 6. Maximum deceleration available from brakes and drag as a function of braking conditions

Reverse Thrust

Boeing recommends deployment of reverse thrust on every landing when the reversers are available. This recommendation is valid for dry, wet, or slippery runways.

The QRH landing advisory data supplied for landing on slippery runways is based on the prompt application of reverse thrust as called out in the FCTM procedures. For example, according to the 777 FCTM (fig. 7),

> "After touchdown, with the thrust levers at idle, rapidly raise the reverse thrust levers up and aft to the interlock position, then apply reverse thrust as required. The PM should monitor engine operating limits and call out any engine operational limits being approached or exceeded, any thrust reverser failure, or any other abnormalities."

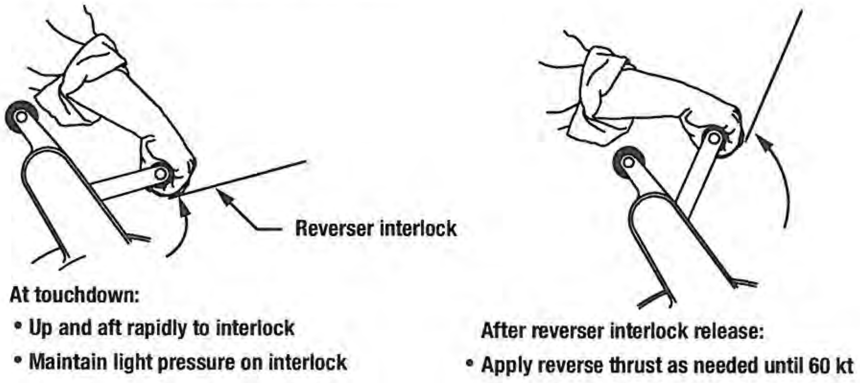


Figure 7. Reverse thrust lever positions

Figure 8 shows time allowances used in the calculation of the QRH landing advisory data. These time allowances account for the selection of reverse, clearing the interlock, deployment of the reverser, and the time for the engine to spin up to the selected reverse thrust level.

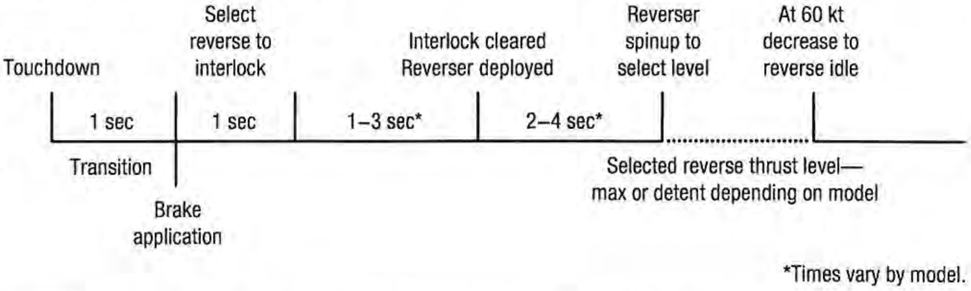


Figure 8. Time used in advisory data for brake application and reverse initiation

In order to achieve the stopping distances stated in QRH advisory data, the reverser must be selected to the interlock position within 2 seconds after main gear touchdown and prior to nose gear touchdown. If selection is delayed until nose gear touchdown (typically 3 to 5 seconds after main gear touchdown), the distance required to stop will be increased.

The QRH landing advisory data are based on prompt application of maximum reverse thrust after landing. The QRH landing advisory data are based on the assumption that the reverse thrust is reduced to reverse idle at 60 knots as recommended in the FCTM. However, reverse thrust should not be reduced until the stop is ensured. (The 737 data are based on No. 2 detent, but maximum reverse is available at all times. Some airplanes, such as the MD-80, have operational limitations on how much reverse thrust is used to ensure adequate directional control during rollout.)

The importance of reverse thrust increases significantly as the runway friction decreases. Figure 9 shows the increase in airplane deceleration capability when thrust reversers are used with maximum manual wheel braking.

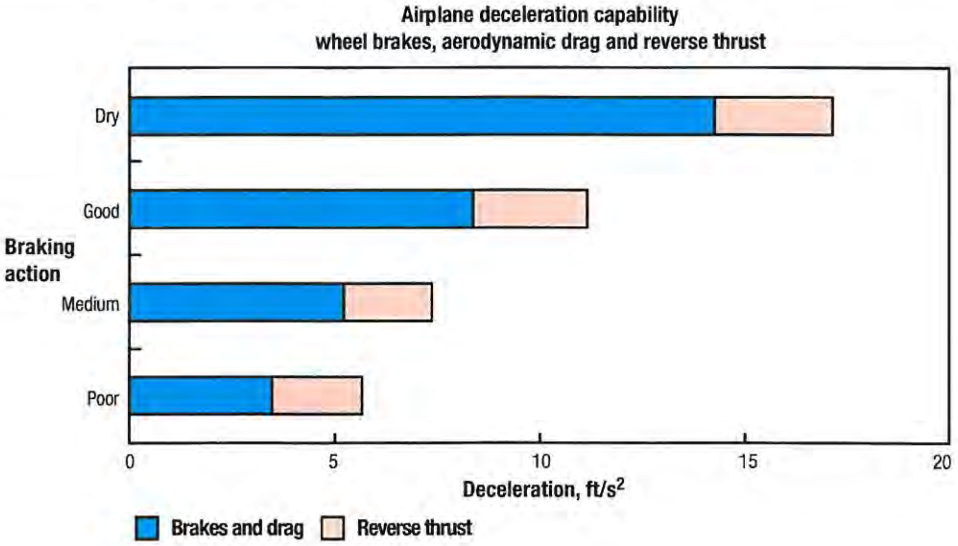


Figure 9. Deceleration capability on a slippery runway including the effect of reverse thrust

Auto Brake Performance

The auto brake system is designed to only use the amount of wheel braking required to achieve the target deceleration commanded for the selected auto brake setting. Figure10 shows a typical 737 auto brake selector.

Figure 10. Typical 737 auto brake selector

Upon touchdown, automatic wheel braking is initiated with main gear spin up. Brake pressure increases until the deceleration rate commanded by the selected auto brake setting is attained. Brake pressure will modulate to maintain the selected deceleration rate until the auto brake is disconnected or the airplane is stopped. The system will respond to changes in reverse thrust, aerodynamic forces, and runway slope and attempt to maintain the selected deceleration rate.

When the available stopping force from the wheel brakes and other deceleration devices results in a deceleration rate that equals or exceeds the commanded auto brake deceleration rates, the airplane stopping distance will be a result of auto brake commanded deceleration rate. This is always the case on a dry runway.

However, as runway friction deteriorates, it is less likely that the airplane will achieve the auto brake-commanded deceleration rates. If the auto brake-commanded deceleration rate cannot be achieved, the airplane stopping distance will be determined by the runway friction capability, not the commanded auto brake deceleration rate.

Figure 11 shows a comparison of the available deceleration as a function of braking action and the required deceleration associated with auto brake (AB) 3 and AB Max.

Consider the following scenarios:

1. Dry runway, AB 3. Auto brake deceleration rates can be achieved without use of reverse thrust. Therefore, the distance required to stop with AB 3 will be the same with and without reverse thrust and will be determined by the programmed deceleration rate in the auto brake system.
2. Medium braking action, AB Max. The AB Max-commanded deceleration rate **cannot** be achieved. The distance required to stop will be determined by the runway friction capability. Reverse thrust will reduce the distance required to stop.
3. Medium braking action, AB 3. The AB 3 deceleration rate can be achieved

only with the use of reverse thrust. Reverse thrust will reduce the distance required to stop, as the AB 3 deceleration rate **cannot** be achieved with brakes alone. The distance required to stop will be determined by the programmed deceleration rate in the auto brake system as long as the combined effect of aerodynamic drag, wheel braking, and reverse thrust can achieve the deceleration rate commanded by the auto brake.

4. Poor braking action, AB 3 or Max. Auto brake deceleration rates **cannot** be achieved. The distance required to stop will be determined by the runway friction capability. Reverse thrust will reduce the distance required to stop.

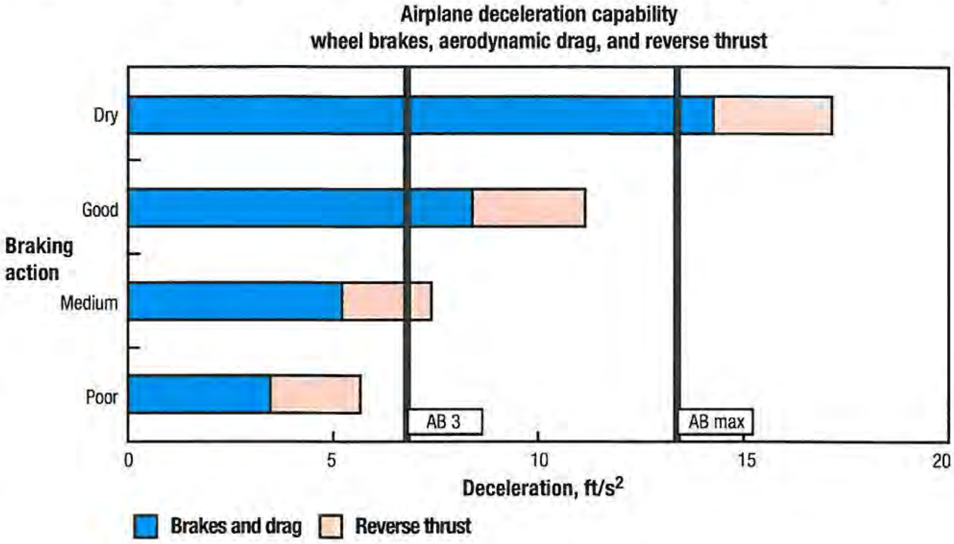


Figure 11. Airplane deceleration capability for different braking actions and auto brake-commanded deceleration rates

The QRH landing advisory data cover the above scenarios. If the auto brake deceleration rates cannot be obtained, the calculated landing distances in the QRH are based on the assumed braking action and will be longer than if the autobrake deceleration levels were achievable.

Spoilers

The advisory performance data are based on auto spoilers with corrections when the use of manual spoilers is necessary. The spoilers increase the drag, which then assists the stop, but more importantly, they increase the weight on the wheels; greatly improving the wheel brake effectiveness.

On a slippery runway, the benefit of both drag and additional load on the gear to increase brake effectiveness is very important.

Runway Condition Reporting

An important part of the slippery runway landing is the prelanding evaluation of the situation. Prior to landing, the flight crew may receive information that will assist in planning for the upcoming landing operation.

Runway condition is typically provided in one or more of three methods: PIREPs of braking action, the physical description of runway conditions, or friction measurements.

Pilot Reports

The PIREPs of braking action are flight crew reports from previous landings that provide the available braking action as perceived by the flight crew. These reports can be affected by the reporting crew's experience and the equipment being operated. The terminology in ICAO Annex 14 is good, good to medium, medium, medium to poor, and poor. The terminology in the FAA *Airman's Information Manual* (AIM) and AC 150/5200-30A is good, fair, poor, and nil. Boeing provides operational data in the FCOMs as a function of pilot reports using the terminology good, medium, and poor.

PIREPs are generally reported at a time closer to the landing operation and therefore inform the flight crew of changing runway conditions. However, PIREPs have the disadvantage of being subjective. A pilot of a small airplane may perceive different braking conditions than a pilot of a large airplane at the same airfield. The flight crew evaluation can also be influenced by the airplane's weight, approach speed, amount of wheel braking applied, and runway location where the highest amount of wheel braking is used.

Physical Description of Runway Condition

The airport authority provides a physical description of the runway surface condition such as wet, flooded, patches of ice, 5 mm of slush, compact snow, 10 mm of dry snow or standing water. These surface conditions provide an idea of the braking action available, but they can also provide misleading information if not all the appropriate information is known. For example, a very cold compact snow or ice surface may have relatively good friction capability, but with a change of a few degrees in temperature or additional precipitation, the available runway friction may deteriorate.

Friction Measurement

Runway friction is reported numerically (e.g., 30 or 0.30). These reports come from a friction measuring vehicle, of which there are many types and manufacturers. The vehicles use different methods for measuring friction. For example, some use decelerometers mounted in vehicles and measure the deceleration available for the test vehicle during a maximum effort stop. This deceleration is then converted to a friction reading.

Another method is a device (typically towed) that continuously measures the force on a braked wheel. Friction is then calculated from the forces on this wheel.

Friction measurement reports have the advantage of being objective. However, there are concerns about the use of friction reports.

As described above, different friction measuring devices measure friction differently; this leads to different answers from different devices for the same conditions.

Ground friction measuring vehicles have reliability issues in depths of standing water and slush as low as 1 to 3 mm. FAA AC 150.5200-30A states that ground friction vehicle reports are not considered reliable when the depth of the contaminant exceeds:

- 1 mm (0.04 in) of water.
- 3 mm (0.125 in) of slush or wet snow.
- 2.5 cm (1 in) of dry snow.

ICAO Annex 14 Att, A-5 provides a similar warning:

> "A decelerometer should not be used in loose snow or slush, as it can give misleading friction values. Other friction measuring devices can also give misleading friction values under certain combinations of contaminants and air/pavement temperature."

Friction measurement reports are taken at a specific time; thus, as time after the measurement increases, the runway condition may change. More precipitation may fall, the temperature may change, or other traffic may cause changes in the runway condition. These changes may increase or decrease the runway friction capability compared to when the friction reading was taken.

In August 2006, an FAA workshop was held to discuss issues with runway condition reporting. A table of braking action terms, definitions, and estimated relationships to runway surface condition and runway μ, mu was created by representatives of the FAA, airlines, and the Airline Pilots Association and is intended for guidance. Airline use of this table is voluntary. This information is presented in *appendix 2*.

Hydroplaning

Hydroplaning is a possibility any time slush or standing water is reported. Hydroplaning leads to a large reduction in friction available at high speeds, greatly reducing the effectiveness of the wheel brakes and increasing the stopping distance.

The type of hydroplaning of concern for slush and standing water is dynamic hydroplaning. During dynamic hydroplaning, the tire lifts off the runway surface and planes on top of the slush or standing water. Important factors affecting dynamic hydroplaning are tire pressure and tire speed. Note that friction measuring vehicles are not reliable sources of aircraft hydroplaning potential because they use different tire pressure and operate at lower speeds; hence, the 1-mm water depth and 3-mm slush depth limitations in the FAA AC mentioned above.

Boeing recommends using QRH landing advisory data associated with poor braking action when landing on slush or standing water due to the potential for hydroplaning.

Example of Runway Condition Reporting

Two examples follow of the difficulty of evaluating the runway condition based on the information available to the flight crew. Both of these examples show where the measured friction would indicate good to very good braking action but the final airplane stopping performance was poor. They illustrate the difficulty when operating during changing conditions because of falling snow or freezing rain and at temperatures near zero and with slush and ice on the runway in mixed reports.

Example 1: Heavy snowfall

This example shows an operation during heavy snowfall. It demonstrates how the friction available from the runway changes with time, the variability in reported braking action, and, in general, the problems facing the flight crew during an active snow event.

Table 2 shows a summary of the reported runway friction, pilot-reported braking action, and the airplane braking coefficient (μ_B) over a period of time. The airplane braking coefficient is based on Boeing analysis of the flight data recorder (FDR) information available.

Time, min	Event	Friction Measured during operations	Reported braking action	Airplane braking coefficient (μ_B)*
0	Runway cleaned			
2	Friction measured	72/59/68		
7	A320 landed/report		Fair	
10	737-700 landed		Fair/poor at the end	0.13
16	737-700 landed			0.12
18	737-700 landed		Good first and second thirds, poor last third	0.08
20	737-700 landed			0.10
26	Citation landed		Poor	
28	Gulfstream landed		Fair to poor	
30	737-700 landed			0.08
37	Friction measured	41/40/38		

* Based on Boeing analysis of FDR data.

Table 2. Information from an operation during an active snow storm

Note: The results of the initial friction test were not supplied as it exceeded the friction level at which a report is required to be issued. A friction report is not issued unless the measurement is 40 or below.

This example shows the complexity of the issues involved in reporting runway condition:

- Time–The runway condition may be changing with time. Friction is taken at a specific time and cannot be redone with out interrupting operations. In this example the friction deteriorated as snow fall continued.
- Effect of snow and slush on accuracy of friction measurement–Earlier in the paper, FAA and ICAO guidance was presented that warns against the use of friction measurements when the runway is covered with snow or slush. This is demonstrated by the second friction test. The braking action reports and the FDR data analysis do not agree with the friction measured.
- Braking action–The braking action reports do confirm that the runway was becoming slippery. However, they aren't always consistent.
  - Analysis of the FDR data also pointed out that during the report of "good first and second thirds, poor last third," the flight crew used light braking during the first two thirds of the stop. In the last third of the stop, the flight crew used heavy braking. The analysis of the FDR data did not show an appreciable change in the capability of the wheel brakes to stop the airplane during the stop.

    A possible reason for this report is that because the flight crew used moderate braking during the first part of the stop, and the reversers were deployed and aerodynamic drag was high, that the deceleration rate was what the flight crew expected for the amount of braking used. However, later in the stop, the pilot applied much heavier braking, but now being at lower speed (less drag) and at lower reverse thrust, the perception was that the runway had gotten slipperier and hence the report of poor for the last third.

Example 2: Operation at 0°C with mixed reports of slush, ice, and wet runway.

In a separate incident an airline requested Boeing analyze FDR data on an airplane that they felt took longer to stop than the runway condition as reported prior to the landing would have indicated.

The runway condition:

- Center of the runway for 100% of the length was 50% bare and wet and 50% trace slush.
- Center of the runway for 100% of the length has been chemically deiced and treated with heated sand.
- Outside the center of the runway, the conditions were ice.
- Canadian Runway Friction Index (CRFI) 0.43. Information from the Canadian AIP indicates that a CRFI of 0.43 would occur on a runway that was
  - Concrete or asphalt with rain between 0.01 and 0.03 inches in depth.
  - Compacted snow below -15 °C.
  - Packed and sanded snow.
  - Sanded ice.

A CRFI of 0.43 should result in an airplane braking coefficient (μ_B) of 0.2 to 0.25 based on the fairing of data collected in the Joint Winter Runway Friction Measuring Program and used in creating CRFI distance tables (TP 13579, "Proceedings of the 3rd International Meeting on Aircraft Performance on Contaminated Runways, IMAPCR 2004").

The temperature was 0°C and the crew reported freezing rain during the approach.

The airplane braking coefficient (μ_B) computed from the FDR during the ground roll indicates the airplane braking coefficient (μ_B) above 70 knots was approximately 0.05 to 0.08. Below 70 knots the airplane braking coefficient (μ_B) started at 0.05 and increased to 0.16 as the airplane slowed down. These values are much lower than the values that would have been expected for a CRFI of 0.43.

Following the landing, the flight crew reported the braking action as poor.

These two examples demonstrate the difficulty of evaluating the information provided to the flight crew on the runway condition and the difficulty they face in making the decision to land or divert.

These examples also demonstrate the difficulty in using measured friction as a lone source of information. Conditions change with time. Additional precipitation may occur that may invalidate the friction measurement; when operating near 0°C, small changes in temperature may cause a large change in the airplane's stopping capability.

Operating Margins

Unfactored data as presented in the QRH landing advisory data represent the airplane's capability assuming that the airplane has been flown in a manner consistent with the assumptions used to create the data. The end of the unfactored distance represents the point at which the airplane's nose wheel will come to a stop. Deviation from these assumptions can result in longer distances. Boeing encourages operators to evaluate their procedures and operations and add margin to the unfactored data as appropriate for their operations.

Many operators add an operational margin to the unfactored data. The chosen margin will be different based on the operator's specific knowledge of its operation. Items such as operator philosophy and regulatory environment, operator training programs, specific airports that the operator serves, experience of the operator's flight crew in operations on slippery runways, and many other considerations may affect the decision of how much margin is the correct amount for the specific operator.

Operators who are subject to JAR OPS-1 requirements must use a minimum factor of 1.15 when computing slippery runway requirements.

Safety Alert for Operators (SAFO) 06012
In August 2006, the FAA released SAFO 06012 recommending that operators perform a landing performance evaluation based on conditions that exist at the time of arrival. Part of this recommendation is that a minimum safety margin of 15% be used when performing this evaluation.

SAFO 06012 is attached as *appendix 1*.

Flying the Airplane

The Boeing FCTM and FCOM have complete sections discussing adverse runway condition operations and techniques. These recommendations and procedures are consistent with the Boeing Advisory - Normal Configuration Landing Distance information. Flight crews are reminded that if they deviate from these recommendations and procedures, they may need to include an appropriate allowance in their landing distance calculations.

In August 2007 Boeing released a Flight Operations Technical Bulletin, which addresses the issues of landing on slippery runways. This bulletin is attached as *appendix 3*.

Conclusion

Safe and successful landings, particularly on slippery runways, are the result of proper planning and flight crew adherence to proper procedures and techniques. The flight crew's familiarity with the performance effect of runway conditions, the possibility of conflicting runway condition reports, the assumptions in the performance data, and the recommended pilot techniques required to achieve the best airplane stopping performance are important in ensuring safe and successful landings on slippery runways.

Boeing recommends that operators have procedures in place to ensure that a full stop landing can be made on the runway to be used, in the conditions existing at the time of arrival, and with the deceleration means and airplane configuration that will be used. This procedure needs to include a determination of whether conditions exist that may affect the safety of the flight and whether operations should be restricted or suspended. Pilots should stay informed, as applicable, of conditions such as airport and meteorological conditions that may affect the safety of the flight.

The Boeing QRH advisory data provided to FAA operators is unfactored. The Boeing QRH advisory data provided to operators who use JAA requirements includes an additional 15% distance margin. Operators are encouraged to add additional margin appropriate to their operations to ensure that an acceptable landing distance is available.

Finally, Boeing encourages additional and more comprehensive dissemination of information to flight crews about aircraft characteristics and capabilities. Boeing supports industry efforts to improve training of airline flight crews involving performance limited landings.

SAFO

Safety Alert for Operators

U.S. Department
of Transportation
Federal Aviation
Administration

SAFO 06012
DATE: 8/31/06

Flight Standards Service
Washington, DC

http://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/safo

A SAFO contains important safety information and may include recommended action. SAFO content should be especially valuable to air carriers in meeting their statutory duty to provide service with the highest possible degree of safety in the public interest.

Subject: Landing Performance Assessments at Time of Arrival (Turbojets)

1. Purpose. This SAFO urgently recommends that operators of turbojet airplanes develop procedures for flightcrews to assess landing performance based on conditions actually existing at time of arrival, as distinct from conditions presumed at time of dispatch. Those conditions include weather, runway conditions, the airplane's weight, and braking systems to be used. Once the actual landing distance is determined an additional safety margin of at least 15% should be added to that distance. Except under emergency conditions flightcrews should not attempt to land on runways that do not meet the assessment criteria and safety margins as specified in this SAFO.

2. Discussion: This SAFO is based on the FAA's policy statement published in the Federal Register on June 7, 2006, and incorporates revisions based on public comments received by the FAA. Accordingly, the FAA has undertaken rulemaking that would explicitly require the practice described above. Operators may use Operation/Management Specification paragraph C382 to record their voluntary commitment to this practice, pending rulemaking.

> **Operators engaged in air transportation have a statutory obligation to operate with the highest possible degree of safety in the public interest.**

3. Applicability:

a. This SAFO applies to all turbojet operators under Title 14 of the Code of Federal Regulations (14 CFR) parts 121, 135, 125, and 91 subpart K. The intent of providing this information is to assist operators in developing methods of ensuring that sufficient landing distance exists to safely make a full stop landing with an acceptable safety margin on the runway to be used, in the conditions existing at the time of arrival, and with the deceleration means and airplane configuration that will be used. The FAA considers a 15% margin between the expected actual airplane landing distance and the landing distance available at the time of arrival as the minimum acceptable safety margin for normal operations.

b. The FAA acknowledges that there are situations where the flightcrew needs to know the absolute performance capability of the airplane. These situations include emergencies or abnormal and irregular configurations of the airplane such as engine failure or flight control malfunctions. In these circumstances, the pilot must consider whether it is safer to remain in the air or to land immediately and must know the actual landing performance capability (without an added safety margin) when making these evaluations. This guidance is not intended to curtail such evaluations from being made for these situations.

c. This guidance is independent of the preflight landing distance planning requirements of part 121, section 121.195, part 135, section 135.385, and part 91, section 91.1037.

d. This 15% safety margin should not be applied to the landing distance determined for compliance with any other OpSpec/MSpec requirement. The landing distance assessment of this guidance is independent of any other OpSpec/MSpec landing distance requirement. The minimum landing distance should comply with all applicable landing distance requirements. Hence, the minimum landing distance at the time of arrival should be the longer of the landing distance in this guidance and that determined to be in compliance with any other applicable OpSpec/MSpec.

e. This guidance does not apply to Land and Hold Short Operations (LAHSO).

4. Definitions: The following definitions are specific to this guidance and may differ with those definitions contained in other published references.

a. Actual Landing Distance. The landing distance for the reported meteorological and runway surface conditions, runway slope, airplane weight, airplane configuration, approach speed, use of autoland or a Head-up Guidance System, and ground deceleration devices planned to be used for the landing. It does not include any safety margin and represents the best performance the airplane is capable of for the conditions.

b. Airplane Ground Deceleration Devices. Any device used to aid in the onset or rate of airplane deceleration on the ground during the landing roll out. These would include, but not be limited to: brakes (either manual braking or the use of autobrakes), spoilers, and thrust reversers.

c. At Time of Arrival. For the purpose of this guidance means a point in time as close to the airport as possible consistent with the ability to obtain the most current meteorological and runway surface conditions considering pilot workload and traffic surveillance, but no later than the commencement of the approach procedures or visual approach pattern.

d. Braking Action Reports. The following braking action reports are widely used in the aviation industry and are furnished by air traffic controllers when available. The definitions provided below are consistent with how these terms are used in this guidance.

Good – More braking capability is available than is used in typical deceleration on a non-limiting runway (i.e., a runway with additional stopping distance available). However, the landing distance will be longer than the certified (unfactored) dry runway landing distance, even with a well executed landing and maximum effort braking.

Fair/Medium – Noticeably degraded braking conditions. Expect and plan for a longer stopping distance such as might be expected on a packed or compacted snow-covered runway.

Poor – Very degraded braking conditions with a potential for hydroplaning. Expect and plan for a significantly longer stopping distance such as might be expected on an ice-covered runway.

Nil – No braking action and poor directional control can be expected.

NOTE: Conditions specified as "nil" braking action are not considered safe, therefore operations under conditions specified as such should not be conducted. Do not attempt to operate on surfaces reported or expected to have nil braking action.

e. **Factored Landing Distance.** The landing distance required by 14 CFR part 25, section 25.125 increased by the preflight planning safety margin additives required by the applicable operating rules. (Some manufacturers supply factored landing distance information in the Airplane Flight Manual (AFM) as a service to the user.)

f. **Landing Distance Available.** The length of the runway declared available for landing. This distance may be shorter than the full length of the runway.

g. **Meteorological Conditions.** Any meteorological condition that may affect either the air or ground portions of the landing distance. Examples may include wind direction and velocity, pressure altitude, and temperature. An example of a possible effect that must be considered includes crosswinds affecting the amount of reverse thrust that can be used on airplanes with tail mounted engines due to rudder blanking effects.

h. **Reliable Braking Action Report.** For the purpose of this guidance, means a braking action report submitted from a turbojet airplane with landing performance capabilities similar to those of the airplane being operated.

i. **Runway Surface Conditions.** The state of the surface of the runway: either dry, wet, or contaminated. A dry runway is one that is clear of contaminants and visible moisture within the required length and the width being used. A wet runway is one that is neither dry nor contaminated. For a contaminated runway, the runway surface conditions include the type and depth (if applicable) of the substance on the runway surface, e.g., standing water, dry snow, wet snow, slush, ice, sanded, or chemically treated.

j. **Runway Friction or Runway Friction Coefficient**. The resistance to movement of an object moving on the runway surface as measured by a runway friction measuring device. The resistive force resulting from the runway friction coefficient is the product of the runway friction coefficient and the weight of the object.

k. **Runway Friction Enhancing Substance.** Any substance that increases the runway friction value.

l. **Safety Margin.** The length of runway available beyond the actual landing distance. Safety margin can be expressed in a fixed distance increment or a percentage increase beyond the actual landing distance required.

m. **Unfactored Certified Landing Distance.** The landing distance required by section 25.125 without any safety margin additives. The unfactored certified landing distance may be different from the actual landing distance because not all factors affecting landing distance are required to be accounted for by section 25.125. For example, the unfactored certified landing distances are based on a dry, level (zero slope) runway at standard day temperatures, and do not take into account the use of autobrakes, autoland systems, head-up guidance systems, or thrust reversers.

5. Background: After any serious aircraft accident or incident, the FAA typically performs an internal audit to evaluate the adequacy of current regulations and guidance information in areas that come under scrutiny during the course of the accident investigation. The Southwest Airlines landing overrun accident involving a Boeing 737-700 at Chicago Midway Airport in December 2005 initiated such an audit. The types of information that were evaluated in addition to the regulations were FAA orders, notices, advisory circulars, ICAO and foreign country requirements, airplane manufacturer-developed material, independent source material, and the current practices of air carrier operators. This internal FAA review revealed the following issues:

a. A survey of operators' manuals indicated that approximately fifty percent of the operators surveyed do not have policies in place for assessing whether sufficient landing distance exists at the time of arrival, even when conditions (including runway, meteorological, surface, airplane weight, airplane configuration, and planned usage of decelerating devices) are different and worse than those planned at the time the flight was released.

b. Not all operators who perform landing distance assessments at the time of arrival have procedures that account for runway surface conditions or reduced braking action reports.

c. Many operators who perform landing distance assessments at the time of arrival do not apply a safety margin to the expected actual landing distance. Those that do are inconsistent in applying an increasing safety margin as the expected actual landing distance increased (i.e., as a percentage of the expected actual landing distance).

d. Some operators have developed their own contaminated runway landing performance data or are using data developed by third party vendors. In some cases, these data indicate shorter landing distances than the airplane manufacturer's data for the same conditions. In other cases, an autobrake landing distance chart has been misused to generate landing performance data for contaminated runway conditions. Also, some operators' data have not been kept up to date with the manufacturer's current data.

e. Credit for the use of thrust reversers in the landing performance data is not uniformly applied and pilots may be unaware of these differences. In one case, there were differences found within the same operator from one series of airplane to another within the same make and model. The operator's understanding of the data with respect to reverse thrust credit, and the information conveyed to pilots, were both incorrect.

f. Airplane flight manual (AFM) landing performance data are determined during flight-testing using flight test and analysis criteria that are not representative of everyday operational practices. Landing distances determined in compliance with 14 CFR part 25, section 25.125 and published in the FAA-approved AFM do not reflect operational landing distances (Note: some manufacturers provide factored landing distance data that addresses operational requirements.) Landing distances determined during certification tests are aimed at demonstrating the shortest landing distances for a given airplane weight with a test pilot at the controls and are established with full awareness that operational rules for normal operations require additional factors to be added for determining minimum operational field lengths. Flight test and data analysis techniques for determining landing distances can result in the use of high touchdown sink rates (as high as 8 feet per second) and approach angles of -3.5 degrees to minimize the airborne portion of the landing distance. Maximum manual braking, initiated as soon as possible after landing, is used in order to minimize the braking portion of the landing distance. Therefore, the landing distances determined under section 25.125 are shorter than the landing distances achieved in normal operations.

g. Wet and contaminated runway landing distance data are usually an analytical computation using the dry, smooth, hard surface runway data collected during certification. Therefore, the wet and contaminated runway data may not represent performance that would be achieved in normal operations. This lack of operational landing performance repeatability from the flight test data, along with many other variables affecting landing distance, are taken into consideration in the preflight landing performance calculations by requiring a significant safety margin in excess of the certified (unfactored) landing distance that would be required under those conditions. However, the regulations do not specify a particular safety margin for a landing distance assessment at the time of arrival. This safety margin has been left largely to the operator and/or the flightcrew to determine.

h. Manufacturers do not provide advisory landing distance information in a standardized manner. However, most turbojet manufacturers make landing distance performance information available for a range of runway or braking action conditions using various airplane deceleration devices and settings under a variety of meteorological conditions. This information is made available in a wide variety of informational documents, dependent upon the manufacturer.

i. Manufacturer-supplied landing performance data for conditions worse than a dry, smooth runway is normally an analytical computation based on the dry runway landing performance data, adjusted for a reduced airplane braking coefficient of friction available for the specific runway surface condition. Most of the data for runways contaminated by snow, slush, standing water, or ice were developed to show compliance with European Aviation Safety Agency and Joint Aviation Authority airworthiness certification and operating requirements. The FAA considers the data developed for showing compliance with the European contaminated runway certification or operating requirements, as applicable, to be acceptable for making landing distance assessments for contaminated runways at the time of arrival.

6. Recommended Action:

a. A review of the current applicable regulations indicates that the regulations do not specify the type of landing distance assessment that must be performed at the time of arrival, but operators are required to restrict or suspend operations when conditions are hazardous.

b. 14 CFR part 121, section 121.195(b), part 135, section 135.385(b), and part 91, section 91.1037(b) and (c) require operators to comply with certain landing distance requirements at the time of takeoff. (14 CFR part 125, section 125.49 requires operators to use airports that are adequate for the proposed operation). These requirements limit the allowable takeoff weight to that which would allow the airplane to land within a specified percentage of the landing distance available on: (1) the most favorable runway at the destination airport under still air conditions;

and (2) the most suitable runway in the expected wind conditions. Sections 121.195(d), 135.385(d), and 91.1037(e) further require an additional 15 percent to be added to the landing distance required when the runway is wet or slippery, unless a shorter distance can be shown using operational landing techniques on wet runways. Although an airplane can be legally dispatched under these conditions, compliance with these requirements alone does not ensure that the airplane can safely land within the distance available on the runway actually used for landing in the conditions that exist at the time of arrival, particularly if the runway, runway surface condition, meteorological conditions, airplane configuration, airplane weight, or use of airplane ground deceleration devices is different than that used in the preflight calculation. Part 121, sections 121.533, 121.535, 121.537, part 135, section 135.77, part 125, section 125.351, and part 91, sections 91.3, and 91.1009 place the responsibility for the safe operation of the flight jointly with the operator, pilot in command, and dispatcher as appropriate to the type of operation being conducted.

c. Sections 121.195(e) and 135.385(e), allow an airplane to depart even when it is unable to comply with the conditions referred to in item (2) of paragraph 5b above if an alternate airport is specified where the airplane can comply with conditions referred to in items (1) and (2) of paragraph 5b. This implies that a landing distance assessment is accomplished before landing to determine if it is safe to land at the destination, or if a diversion to an alternate airport is required.

d. Part 121, sections 121.601 and 121.603, require dispatchers to keep pilots informed, or for pilots to stay informed as applicable, of conditions, such as airport and meteorological conditions, that may affect the safety of the flight. Thus, the operator and flightcrew use this information in their safety of flight decision making. Part 121, sections 121.551, 121.553, and part 135, section 135.69, require an operator, and/or the pilot in command as applicable, to restrict or suspend operations to an airport if the conditions, including airport or runway surface conditions, are hazardous to safe operations. Part 125 section 125.371 prohibits a pilot in command (PIC) from continuing toward any airport to which it was released unless the flight can be completed safely. A landing distance assessment should be made under the conditions existing at the time of arrival in order to support a determination of whether conditions exist that may affect the safety of the flight and whether operations should be restricted or suspended.

e. Runway surface conditions may be reported using several types of descriptive terms including: type and depth of contamination, a reading from a runway friction measuring device, an airplane braking action report, or an airport vehicle braking condition report. Unfortunately, joint industry and multi-national government tests have not established a reliable correlation between runway friction under varying conditions, type of runway contaminants, braking action reports, and airplane braking capability. Extensive testing has been conducted in an effort to find a direct correlation between runway friction measurement device readings and airplane braking friction capability. However, these tests have not produced conclusive results that indicate a repeatable correlation exists through the full spectrum of runway contaminant conditions. Therefore, operators and flightcrews cannot base the calculation of landing distance solely on runway friction meter readings. Likewise, because pilot braking action reports are subjective, flightcrews must use sound judgment in using them to predict the stopping capability of their airplane. For example, the pilots of two identical aircraft landing in the same conditions, on the same runway could give different braking action reports. These differing reports could be the result of differences between the specific aircraft, aircraft weight, pilot technique, pilot experience in similar conditions, pilot total experience, and pilot expectations. Also, runway surface conditions can degrade or improve significantly in very short periods of time dependent on precipitation, temperature, usage, and runway treatment and could be significantly different than indicated by the last report. Flightcrews must consider all available information, including runway surface condition reports, braking action reports, and friction measurements.

(1) Operators and pilots should use the most adverse reliable braking action report, if available, or the most adverse expected conditions for the runway, or portion of the runway, that will be used for landing when assessing the required landing distance prior to landing. Operators and pilots should consider the following factors in determining the actual landing distance: the age of the report, meteorological conditions present since the report was issued, type of airplane or device used to obtain the report, whether the runway surface was treated since the report, and the methods used for that treatment. Operators and pilots are expected to use sound judgment in determining the applicability of this information to their airplane's landing performance.

(2) Table 1 provides an example of a correlation between braking action reports and runway surface conditions:

Braking Action	Dry (not reported)	Good	Fair/Medium	Poor	Nil
Contaminant	Dry	Wet Dry Snow (< 20mm)	Packed or Compacted Snow	Wet Snow Slush Standing Water Ice	Wet ice

Table 1. Relationship between braking action reports and runway surface condition (contaminant type)

NOTE: Under extremely cold temperatures, these relationships may be less reliable and braking capabilities may be better than represented. This table does not include any information pertaining to a runway that has been chemically treated or where a runway friction enhancing substance has been applied.

f. Some advisory landing distance information uses a standard air distance of 1000 feet from 50 feet above the runway threshold to the touchdown point. Unfactored dry runway landing distances in AFMs reflect the distances demonstrated during certification flight testing. These unfactored AFM landing distance data include air distances that vary with airplane weight, but are also nominally around 1000 feet. A 1000 foot air distance is not consistently achievable in normal flight operations. Additionally, the use of automatic landing systems (autoland) and other landing guidance systems (e.g., head-up guidance systems) typically result in longer air distances. Operators are expected to apply adjustments to this air distances to reflect their specific operations, operational practices, procedures, training, and experience.

g. To ensure that an acceptable landing distance safety margin exists at the time of arrival, the FAA recommends that at least a 15% safety margin be provided. This safety margin represents the minimum distance margin that must exist between the expected actual landing distance at the time of arrival and the landing distance available, considering the meteorological and runway surface conditions, airplane configuration and weight, and the intended use of airplane ground deceleration devices. In other words, the landing distance available on the runway to be used for landing must allow a full stop landing, in the actual conditions and airplane configuration at the time of landing, and at least an additional 15% safety margin.

h. Operator compliance can be accomplished by a variety of methods and procedurally should be accomplished by the method that best suits the operator's current procedures. The operator's procedures should be clearly articulated in the operations manual system for affected personnel. The following list of methods is not all inclusive, or an endorsement of any particular methods, but provided as only some examples of methods of compliance.

- Establishment of a minimum runway length required under the worst case meteorological and runway surface conditions for operator's total fleet or fleet type that will provide runway lengths that comply with this guidance.

- The requirements of this paragraph could be considered along with the other applicable preflight landing distance calculation requirements and the takeoff weight adjusted to provide for compliance at the time of arrival under the conditions and configurations factored in the calculation. This information, including the conditions/configurations/etc. used in the calculation, would be provided to the flightcrew as part of the release/dispatch documents. (However, this method may not be sufficient if conditions/configurations/etc. at the time of arrival are different than those taken into account in the preflight calculations; therefore, the flightcrew would need to have access to the landing performance data applicable to the conditions present upon arrival.

- Tab or graphical data accounting for the applicable variables provided to the flightcrew and/or dispatcher as appropriate to the operator's procedures.

- Electronic Flight Bag equipment that has methods for accounting for the appropriate variables.

NOTE: These are only some examples of methods of compliance. There are many others that would be acceptable.

7. Summary of Recommendation.

a. Turbojet operators have procedures to ensure that a full stop landing, with at least a 15% safety margin beyond the actual landing distance, can be made on the runway to be used, in the conditions existing at the time of arrival, and with the deceleration means and airplane configuration that will be used. This assessment should take into account the meteorological conditions affecting landing performance (airport pressure altitude, wind velocity, wind direction, etc.), surface condition of the runway to be used for landing, the approach speed, airplane weight and configuration, and planned use of airplane ground deceleration devices. The airborne portion of the actual landing distance (distance from runway threshold to touchdown point) should reflect the operator's specific operations, operational practices, procedures, training, and experience. Operators should have procedures for compliance with this guidance, absent an emergency, after the flightcrew makes this assessment using the air carrier's procedures, if at least the 15% safety margin is not available, the pilot should not land the aircraft.

(1) This assessment does not mean that a specific calculation must be made before every landing. In many cases, the before takeoff criteria, with their large safety margins, will be adequate to ensure that there is sufficient landing distance with at least a 15% safety margin at the time of arrival. Only when the conditions at the destination airport deteriorate while en route (e.g., runway surface condition, runway to be used, winds, airplane landing weight/configuration/speed/deceleration devices) or the takeoff was conducted under the provisions described in paragraph 5 (c) of this guidance, would a calculation or other method of determining the actual landing distance capability normally be needed. The operator should develop procedures to determine when such a calculation or other method of determining the expected actual landing distance is necessary to ensure that at least a 15% safety margin will exist at the time of arrival.

(2) Operators may require flight crews to perform this assessment, or may establish other procedures to conduct this assessment. Whatever method(s) the operator develops, its procedures should account for all factors upon which the preflight planning was based and the actual conditions existing at time of arrival.

b. Confirm that the procedures and data used to comply with paragraph 6 (a) above for actual landing performance assessments yield results that are at least as conservative as the manufacturer's approved or advisory information for the associated conditions provided therein. Although the European contaminated runway operations requirements are applied differently than the requirements of this guidance, the operator may choose to use data developed for showing compliance with the European contaminated runway operating requirements for making these landing distance assessments for contaminated runways at the time of arrival.

c. A safety margin of 15% should be added to the actual landing distance and require that the resulting distance be within the landing distance available of the runway used for landing. Note that the FAA considers a 15% margin to be the minimum acceptable safety margin.

d. If wet or contaminated runway landing distance data are unavailable, the factors in Table 2 should be applied to the pre-flight planning (factored) dry runway landing distances determined in accordance with the applicable operating rule (e.g., sections 91.1037, 121.195(b) or 135.385(b). Table 2 should only apply when no such data are available. The factors in Table 2 include the 15% safety margin recommended by this guidance, and are considered to include an air distance representative of normal operational practices. Therefore, operators do not need to apply further adjustments to the resulting distances to comply with the recommendations of this guidance.

Runway Condition	Reported Braking Action	Factor to apply to (factored) dry runway landing distance*
Wet Runway, Dry Snow	Good	0.9
Packed or Compacted Snow	Fair/Medium	1.2
Wet snow, slush, standing water, ice	Poor	1.6
Wet ice	Nil	Landing is prohibited

Table 2. Multiplication factors to apply to the factored dry runway landing distances when the data for the specified runway condition are unavailable.

* The factored dry runway landing distances for use with Table 2 must be based on landing within a distance of 60% of the effective length of the runway, even for operations where the preflight planning (factored) dry runway landing distances are based on landing within a distance other than 60% of the effective length of the runway (e.g., certain operations under part 135 and subpart K of par t91). To use unfactored dry runway landing distances, first multiply the unfactored dry runway landing distance by 1.667 to get the factored dry runway landing distance before entering Table 2 above.

> **NOTE: These factors assume maximum manual braking, autospoilers (if so equipped), and reverse thrust will be used. For operations without reverse thrust (or without credit for the use of reverse thrust) multiply the results of the factors in Table 2 by 1.2. These factors cannot be used to assess landing distance requirements with autobrakes.**

e. The landing distance assessment should be accomplished as close to the time of arrival as practicable, taking into account workload considerations during critical phases of flight, using the most up-to-date information available at that time. The most adverse braking condition, based on reliable braking reports or runway contaminant reports (or expected runway surface conditions if no reports are available) for the portion of the runway that will be used for the landing should be used in the actual landing performance assessment. For example, if the runway surface condition is reported as fair to poor, or fair in the middle, but poor at the ends, the runway surface condition should be assumed to be poor for the assessment of the actual landing distance. (This example assumes the entire runway will be used for the landing). If conditions change between the time that the assessment is made and the time of landing, the flightcrew should consider whether it would be safer to continue the landing or reassess the landing distance.

f. The operator's flightcrew and dispatcher training programs should include elements that provide knowledge in all aspects and assumptions used in landing distance performance determinations. This training should emphasize the airplane ground deceleration devices, settings, and piloting methods (e.g., air distance) used in determining landing distances for each make, model, and series of airplane. Elements such as braking action reports, airplane configuration, optimal stopping performance techniques, stopping margin, the effects of excess speed, delays in activating deceleration devices, and other pilot performance techniques should be covered. All dispatchers and flightcrew members should be trained on these elements prior to operations on contaminated runway surfaces. This training should be accomplished in a manner consistent with the operator's methods for conveying similar knowledge to flight operations personnel. It may be conducted via operations/training bulletins or extended learning systems, if applicable to the operator's current methods of training.

g. Procedures for obtaining optimal stopping performance on contaminated runways should be included in flight training programs. All flight crewmembers should be made aware of these procedures for the make/model/series of airplane they operate. This training should be accomplished in a manner consistent with the operator's methods for conveying similar knowledge to flight operations personnel. It may be conducted via operations/training bulletins or extended learning systems, if applicable to the operator's current methods of training. In addition, if not already included, these procedures should be incorporated into each airplane or simulator training curriculum for initial qualification on the make/model/series airplane, or differences training as appropriate. All flight crewmembers should have hands on training and validate proficiency in these procedures during their next flight training event, unless previously demonstrated with their current employer in that make/model/series of airplane.

Appendix 2

FAA Working Group Guidelines on Braking Action

The following page is advisory information as developed by a team of US airline technical pilots and other interested parties. The creation of the table was initiated by a FAA workshop on runway condition reporting in held in August of 2006.

The guidelines from the working group have been used by some airlines to create their own operational policies and publications.

BRAKING ACTION*

PIREPS

When braking action conditions less than Good are encountered, pilots are expected to provide a PIREP based on the definitions provided in the table below. Until FAA guidance materials are revised to replace the term Fair with Medium, these two terms may be used interchangeably. The terms "Good to Medium" and "Medium to Poor" represent an intermediate level of braking action, not a braking action that varies along the runway length. If braking action varies along the runway length, such as the first half of the runway is Medium and the second half is Poor, clearly report that in the PIREP (*e.g., "first half Medium, last half Poor"*).

Correlating Expected Runway Conditions

The correlation between different sources of runway conditions (e.g., PIREPs, runway surface conditions and MU values) ***are estimates***. Under extremely cold temperatures or for runways that have been chemically treated, the braking capabilities may be better than the runway surface conditions estimated below. When multiple sources are provided (e.g., braking action medium, runway covered with ice and runway MU is 27/30/28) conflicts are possible. If such conflicts occur, consider all factors including data currency and the type of airplane a PIREP was given from. A valid PIREP or runway surface condition report are more reliable indicators of what to expect than reported runway MU values.

Runway Friction MU Reports

MU values in the U.S. are typically shown as whole numbers (40) and are equivalent to the ICAO standard decimal values (.40). Zero is the lowest friction and 100 is the highest MU friction. When the MU value for any one-third zone of an active runway is 40 or less, a report should be given to ATC by airport management for dissemination to pilots. The report will identify the runway, the time of measurement, the type of friction measuring device used, MU values for each zone and the contaminant conditions (e.g., wet snow, dry snow, slush, deicing chemicals). While the table below includes information published by ICAO correlating runway friction measurements to estimated braking actions, the FAA cautions that ***no reliable correlation exists***. Runway MU values ***can vary significantly*** for the same contaminant condition due to measuring techniques, equipment calibration, the effects of contamination on the friction measuring device and the time passage since the measurement. ***Do not*** base landing distance assessments solely on runway MU friction reports. If MU is the only information provided, attempt to ascertain the depth and type of runway contaminants to make a better assessment of actual conditions.

BRAKING ACTION

Braking Action		**Estimated Correlations**		
Term	Definition	Runway Surface Condition	ICAO	
			Code	Mu
Good	Braking deceleration is normal for the wheel braking effort applied. Directional control is normal.	• Water depth of 1/8" or less • Dry snow less than ¾" in depth • Compacted snow with OAT at or below -15°C	5	40 & above
Good to Medium	-		4	39 - 36
Medium (Fair)	Braking deceleration is noticeably reduced for the wheel braking effort applied. Directional control may be slightly reduced.	• Dry snow ¾" or greater in depth • Sanded snow • Sanded ice • Compacted snow with OAT above -15°C	3	35 –30
Medium to Poor	-		2	29 - 26
Poor	Braking deceleration is significantly reduced for the wheel braking effort applied. Potential for hydroplaning exists. Directional control may be significantly reduced.	• Wet snow • Slush • Water depth more than 1/8" • Ice (not melting)	1	25 - 21
Nil	Braking deceleration is minimal to non-existent for the wheel braking effort applied. Directional control may be uncertain. **Note:** *Taxi, takeoff, and landing operations in Nil conditions are prohibited.*	• Ice (melting) • Wet Ice	-	20 & below

Note: The ICAO term **Unreliable** and SNOTAM code of "9" indicates contamination is outside the approved operational range for the friction measuring equipment in use and therefore Mu values are not provided. This typically occurs in Poor or worse conditions (greater than 1/8" of wet snow, slush or standing water) whereby a potential for hydroplaning should be expected. *Use PIREPs and the depth and type of runway contaminants to assess actual braking conditions.*

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*This page is advisory information as developed by a team of US airline technical pilots and other interested parties. The creation of the table was initiated by a FAA workshop on runway condition reporting in held in August of 2006.

Appendix 3 – Landing on Slippery Runways

BOEING COMMERCIAL AIRPLANE GROUP

FLIGHT OPERATIONS TECHNICAL BULLETIN

NUMBER:

707	727	737	747
07-1	07-1	07-2	17
747-400	757	767	777
57	77	77	24

DATE: August 23, 2007

These bulletins provide information which may prove useful in airline operations or airline training. This information will remain in effect depending on production changes, customer-originated modifications, and Service Bulletin incorporation. Information in these bulletins is supplied by the Boeing Company and may not be approved or endorsed by the FAA at the time of writing. Appropriate formal documentation will be revised, as necessary to reflect the information contained in these bulletins. For further information, contact Boeing Commercial Airplane Group, Chief Pilot, Training, Technical & Standards, P.O. Box 3707, Mail Stop 14-HA, Seattle, WA, USA 98124-2207, Phone (206) 655-1400, Fax (206) 655-3694, SITA: SEABO7X Station 627.

SUBJECT: Landing on Slippery Runways

ATA NO:

APPLIES TO: All 707, 727, 737, 747, 757, 767, and 777

Background Information

The FAA is recommending operators of turbojet airplanes further develop procedures for flight crews to assess landing performance based on actual weather and runway conditions existing at time of arrival rather than based on conditions presumed at time of dispatch.

The words "contaminated" and "slippery" are commonly used in the aviation industry to describe the precipitation on a runway. Although there are specific differences between a contaminated and a slippery runway (as described later), for the purposes of this bulletin, the word "slippery" will be used to mean either "slippery" or "contaminated."

Each year there are a number of landing overruns where slippery runways or crew procedural deviations are contributing factors. Often, these occurrences are due to a combination of issues such as weather, runway conditions, the airplane's weight, braking systems to be used, improper flight crew technique, or lower than expected runway friction.

Appendix 3 – Landing on Slippery Runways

Flight crew and airline operational personnel should ensure they are familiar with factors that may affect an aircraft's stopping distance so they may make appropriate allowances in calculating the distance required to stop when landing on a slippery runway.

This bulletin is intended to remind flight crews and operators of the factors that affect an airplane's ability to stop on a slippery runway, the runway condition information that is available to flight crews, and the Boeing *Flight Crew Training Manual* (FCTM) recommended landing procedures and techniques.

Note: The specific information in this bulletin covers the FCTM and/or the Boeing *Flight Crew Operations Manual* (FCOM) information for the 737, 747-400, 757, 767, and 777 model airplanes. In general, the information in this bulletin is also applicable for the 707, 727, and 747 models. Operators should review their operating material (and applicable Boeing documents) used for these models. Boeing Flight Operations Engineering can be contacted with questions on the specifics for these airplanes. The 787 performance information is also expected to be consistent with this bulletin.

Note: A corresponding Flight Operations Bulletin (FOB) addresses the 717, DC-8, DC-9, DC-10, MD-80, MD-90, MD-10 and MD-11 models and will be released in October 2007.

Introduction

Boeing provides two different landing distance data sets to operators - Dispatch data and Operational data.

- Dispatch landing data is used during flight planning to determine the maximum takeoff weight at which the airplane can land within the available landing distance at the destination/alternate airport. The data is based on specific regulatory requirements that address dry, wet and slippery runway conditions. This data is also referred to as "certified data." The data does not provide distance requirements to cover all operational landing situations. The effect of thrust reversers is not included in the dispatch landing distance data. Wet/slippery conditions are accounted for by factoring the dry runway dispatch landing data (see FAA Code of Federal Regulations, CFR 121.195 (d)).
- Operational data is provided by Boeing as Advisory-Normal Configuration Landing Distance data in the Performance Inflight (PI) section of the Quick Reference Handbook (QRH). This data is also referred to as "operational data," "enroute data," or "advisory data." The data provided by Boeing as advisory landing distance data has always been based on the use of reverse thrust.

  Boeing QRH advisory landing distance data is provided as unfactored data, i.e., there is no margin applied to the landing distance, for operators who use FAA

> requirements. This may change in the future to include a 1.15 factor as a result of FAA and industry activity.
>
> The advisory data provided in the QRH for operators who use JAA requirements includes a 1.15 factor as required by JAR Ops rules.

To accurately determine the operational landing distance required, it is important that flight crews review the information available regarding weather and runway conditions, and make appropriate allowances to their calculations for any conditions or landing techniques that are different from those used to calculate the advisory data.

An important consideration in the determination of landing distance is the condition of the runway. Information about runway condition is often available through three main sources:

- Pilot reports (PIREPS)
  - Qualitative terms of braking action such as "good, medium, poor" or "good, fair, poor, nil"
- Runway surface description
  - Physical description of runway surface and contaminant, e.g., 6 mm of wet snow, patches of ice, compact snow
- Runway friction reports
  - Measured by friction reporting vehicles designed for this purpose, using the Greek letter, μ, (mu) and can be reported as either a whole number or a decimal (e.g., 40, 0.40)

In August, 2006 the FAA hosted a workshop to address braking action terms and their correlation with varied runway surface conditions. The workshop included U.S. airline technical pilots and other interested parties. The results of the FAA workshop are presented on pages 4 and 5 of this paper. The content is reproduced here without modification although the format has been revised to present the information on two pages. Table 1 (page 5) is a voluntary operational guide for flight crews and is expected to be the starting point for future FAA guidance to be developed for winter operations.

Appendix 3 – Landing on Slippery Runways

Braking Action Terms & Correlation with Runway Surface Conditions (Part 1 of 2)

Boeing Note: This page is advisory information as developed by a team of US airline technical pilots and other interested parties. The creation of the table was initiated by a FAA workshop on runway condition reporting held in August of 2006.

BRAKING ACTION

PIREPS

When braking action conditions less than "good" are encountered, pilots are expected to provide a PIREP based on the definitions provided in the table below. Until FAA guidance materials are revised to replace the term "fair" with "medium," these two terms may be used interchangeably. The terms "good to medium" and "medium to poor" represent an intermediate level of braking action, not a braking action that varies along the runway length. If braking action varies along the runway length, such as the first half of the runway is "medium" and the second half is "poor," clearly report that in the PIREP (*e.g., "first half medium, last half poor"*).

Correlating Expected Runway Conditions

The correlation between different sources of runway conditions (e.g., PIREPs, runway surface conditions and mu values) ***are estimates***. Under extremely cold temperatures or for runways that have been chemically treated, the braking capabilities may be better than the runway surface conditions estimated below. When multiple sources are provided (e.g., braking action "medium," runway covered with ice and runway mu is 27/30/28) conflicts are possible. If such conflicts occur, consider all factors including data currency and the type of airplane from which a PIREP was given. A valid PIREP or runway surface condition report is a more reliable indicator of what to expect than reported runway mu values.

Runway Friction Mu Reports

Mu values in the U.S. are typically shown as whole numbers (40) and are equivalent to the ICAO standard decimal values (.40). Zero is the lowest friction and 100 is the highest mu friction. When the mu value for any one-third zone of an active runway is 40 or less, a report should be given to ATC by airport management for dissemination to pilots. The report will identify the runway, the time of measurement, the type of friction measuring device used, mu values for each zone and the contaminant conditions (e.g., wet snow, dry snow, slush, deicing chemicals). While the table below includes information published by ICAO correlating runway friction measurements to estimated braking actions, the FAA cautions that ***no reliable correlation exists***. Runway mu values ***can vary significantly*** for the same contaminant condition due to measuring techniques, equipment calibration, the effects of contamination on the friction measuring device and the time passage since the measurement. ***Do not*** base landing distance assessments solely on runway mu friction reports. If mu is the only information provided, attempt to ascertain the depth and type of runway contaminants to make a better assessment of actual conditions.

Appendix 3 – Landing on Slippery Runways

Braking Action Terms & Correlation with Runway Surface Conditions (Part 2 of 2)

Table 1

BRAKING ACTION

Braking Action		**Estimated Correlations**		
Term	Definition	Runway Surface Condition	ICAO	
			Code	Mu
Good	Braking deceleration is normal for the wheel braking effort applied. Directional control is normal.	• Water depth of 1/8" or less • Dry snow less than 3/4" in depth • Compacted snow with OAT at or below -15°C	5	40 & above
Good to Medium	-		4	39 - 36
Medium (Fair)	Braking deceleration is noticeably reduced for the wheel braking effort applied. Directional control may be slightly reduced.	• Dry snow 3/4" or greater in depth • Sanded snow • Sanded ice • Compacted snow with OAT above -15°C	3	35 –30
Medium to Poor	-		2	29 - 26
Poor	Braking deceleration is significantly reduced for the wheel braking effort applied. Potential for hydroplaning exists. Directional control may be significantly reduced.	• Wet snow • Slush • Water depth more than 1/8" • Ice (not melting)	1	25 - 21
Nil	Braking deceleration is minimal to non-existent for the wheel braking effort applied. Directional control may be uncertain. **Note:** *Taxi, takeoff, and landing operations in nil conditions are prohibited.*	• Ice (melting) • Wet Ice	-	20 & below

Note: The ICAO term **Unreliable** and SNOTAM code of "9" indicates contamination is outside the approved operational range for the friction measuring equipment in use and therefore mu values are not provided. This typically occurs in poor or worse conditions (greater than 1/8" of wet snow, slush or standing water) whereby a potential for hydroplaning should be expected. *Use PIREPs and the depth and type of runway contaminants to assess actual braking conditions.*

Boeing Note: This page is advisory information as developed by a team of US airline technical pilots and other interested parties. The creation of the table was initiated by a FAA workshop on runway condition reporting held in August of 2006.

Appendix 3 – Landing on Slippery Runways

Definitions:

Slippery Runway — A runway that does not provide the equivalent braking performance of a dry runway.

Contaminated Runway — A runway that is not dry or wet but with contaminants that have a measurable depth; examples include ice, loose snow, compact snow, slush, or standing water. Boeing advisory landing distance data is conservative and does not take credit for the deceleration effects of a contaminant with a measurable depth. Therefore, the term "Contaminated Runway" can be used interchangeably with "Slippery Runway" for the purposes of this bulletin.

Dispatch — Requirements that must be met before takeoff.

Enroute — Any phase of flight after takeoff but before landing. For the purposes of this bulletin, enroute refers to the period of time during which the pilot is evaluating the upcoming landing operation.

Pilot Information Report (PIREP) — Report by flight crews from previous operations. For the purposes of this bulletin, PIREPs are limited to descriptions of the runway surface condition or braking action.

Braking Action — A subjective description of airplane stopping capability on a slippery runway. The terminology in ICAO Annex 14 is "good," "good to medium," "medium," "medium to poor," and "poor." The terminology in the FAA *Airman's Information Manual* (AIM) and AC 150/5200-30A is "good," "fair," "poor," and "nil." Please see the Table 1 for further explanation.

Runway Friction — Runway friction is the capability of the runway surface to convert the vertical load on the braked wheels into a horizontal force to stop the airplane. The Greek letter μ (mu) is typically the symbol for friction and represents the percentage of the vertical load converted into a horizontal force.

QRH Advisory — Normal Configuration Landing Distance—Advisory data contained in the "Performance Inflight" section of the QRH. The data is provided as a function of braking action and is referred to as "QRH landing advisory data" in this bulletin.

Dispatch Landing Data

CFR Part 121.195(b) sets the dispatch requirement for dry runway landing distance (Figure 1). This landing distance is based on certification flight testing which includes an air distance from a 50 foot threshold crossing altitude to touchdown of 800 to 1100 feet.

Following touchdown, maximum manual braking and speed brake deployment is initiated as soon as possible in order to minimize the landing distance. However, reverse thrust is not used; therefore, no credit is taken for reverse thrust in the dispatch landing data.

Appendix 3 – Landing on Slippery Runways

The flight test demonstrated landing distances represent the shortest landing distances for a given airplane weight and represents the best performance the airplane is capable of (without reversers) for the conditions. In order to account for operational variances from the flight test demonstrations, the minimum legal dry runway landing field length is increased by a factor of 1.67.

The dispatch requirement for a wet or slippery runway, CFR 121.195 (d), is based on the distance computed to meet the dry requirement and then increased by a factor of 1.15.

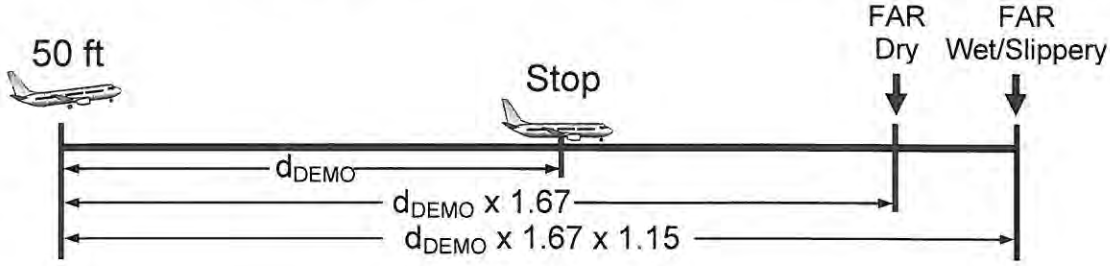


Figure 1 - Dispatch Landing Data

Operational (or Enroute) Landing Data

Boeing includes slippery runway landing distance advisory information in the PI section of the QRH (Figure 2). Specifically, this data is labeled Normal Configuration Landing Distance and is advisory information only.

Boeing supplies the slippery runway data in the QRH as a function of reported braking action. The braking deceleration used to calculate the "good" braking action data in the QRH is consistent with wet runway testing done on early Boeing airplane models. The lowest performance level calculated is consistent with braking on wet ice (defined as "nil" in Table 1 on page 5). This is conservatively used by Boeing to define the "poor" braking action data in the QRH.

The most adverse braking condition, based on reliable expected or actual braking reports, or runway contaminant reports for the portion of the runway that will be used for the landing, should be used in the actual landing performance assessment. For example, if the runway surface condition is reported as "fair to poor," or "fair in the middle, but poor at the ends," the runway surface condition should be assumed to be "poor" for the assessment of the actual landing distance. Pilot braking action reports are subjective; therefore flight crews must use sound judgment in using them to predict the stopping capability of their airplanes.

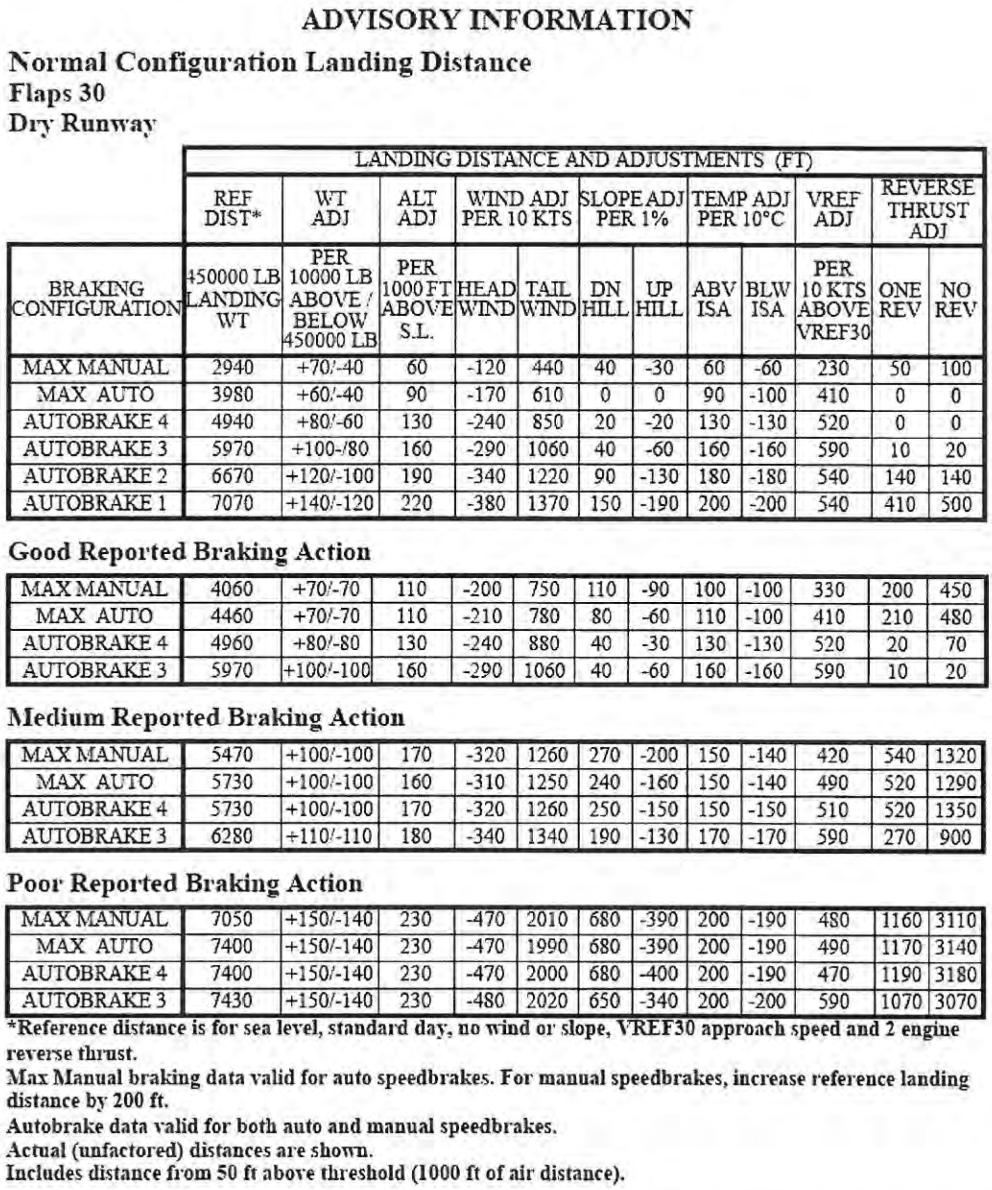
The Boeing supplied operational slippery runway landing data is based on flight test parameters for the specific airplane (lift, drag, reverse thrust effect, etc.) and an engineering analysis of the effect of a slippery runway on the ability of the wheel brakes to stop the airplane.

Appendix 3 – Landing on Slippery Runways

This operational slippery runway landing data is based on prompt application of all stopping devices (speed brakes, wheel brakes, thrust reversers) and takes into account maximum manual braking or use of the autobrake system.

The advisory data provided in the QRH for operators who use FAA requirements is unfactored, meaning no additional distance margin is added. The advisory data provided in the QRH for operators who use JAA requirements includes an additional 15% distance margin as required by JAR Ops 1.520(b). Operators are encouraged to add additional margins appropriate to their operations. Note that the FAA has released Safety Alert for Operators (SAFO) 06012 which requests US operators to voluntarily add at least 15% margin to their operational landing distance calculations. The FAA is currently considering rulemaking on this subject.

Appendix 3 – Landing on Slippery Runways



ADVISORY INFORMATION

Normal Configuration Landing Distance
Flaps 30
Dry Runway

	LANDING DISTANCE AND ADJUSTMENTS (FT)											
	REF DIST*	WT ADJ	ALT ADJ	WIND ADJ PER 10 KTS		SLOPE ADJ PER 1%		TEMP ADJ PER 10°C		VREF ADJ	REVERSE THRUST ADJ	
BRAKING CONFIGURATION	450000 LB LANDING WT	PER 10000 LB ABOVE / BELOW 450000 LB	PER 1000 FT ABOVE S.L.	HEAD WIND	TAIL WIND	DN HILL	UP HILL	ABV ISA	BLW ISA	PER 10 KTS ABOVE VREF30	ONE REV	NO REV
MAX MANUAL	2940	+70/-40	60	-120	440	40	-30	60	-60	230	50	100
MAX AUTO	3980	+60/-40	90	-170	610	0	0	90	-100	410	0	0
AUTOBRAKE 4	4940	+80/-60	130	-240	850	20	-20	130	-130	520	0	0
AUTOBRAKE 3	5970	+100-/80	160	-290	1060	40	-60	160	-160	590	10	20
AUTOBRAKE 2	6670	+120/-100	190	-340	1220	90	-130	180	-180	540	140	140
AUTOBRAKE 1	7070	+140/-120	220	-380	1370	150	-190	200	-200	540	410	500

Good Reported Braking Action

MAX MANUAL	4060	+70/-70	110	-200	750	110	-90	100	-100	330	200	450
MAX AUTO	4460	+70/-70	110	-210	780	80	-60	110	-100	410	210	480
AUTOBRAKE 4	4960	+80/-80	130	-240	880	40	-30	130	-130	520	20	70
AUTOBRAKE 3	5970	+100/-100	160	-290	1060	40	-60	160	-160	590	10	20

Medium Reported Braking Action

MAX MANUAL	5470	+100/-100	170	-320	1260	270	-200	150	-140	420	540	1320
MAX AUTO	5730	+100/-100	160	-310	1250	240	-160	150	-140	490	520	1290
AUTOBRAKE 4	5730	+100/-100	170	-320	1260	250	-150	150	-150	510	520	1350
AUTOBRAKE 3	6280	+110/-110	180	-340	1340	190	-130	170	-170	590	270	900

Poor Reported Braking Action

MAX MANUAL	7050	+150/-140	230	-470	2010	680	-390	200	-190	480	1160	3110
MAX AUTO	7400	+150/-140	230	-470	1990	680	-390	200	-190	490	1170	3140
AUTOBRAKE 4	7400	+150/-140	230	-470	2000	680	-400	200	-190	470	1190	3180
AUTOBRAKE 3	7430	+150/-140	230	-480	2020	650	-340	200	-200	590	1070	3070

***Reference distance is for sea level, standard day, no wind or slope, VREF30 approach speed and 2 engine reverse thrust.**
Max Manual braking data valid for auto speedbrakes. For manual speedbrakes, increase reference landing distance by 200 ft.
Autobrake data valid for both auto and manual speedbrakes.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above threshold (1000 ft of air distance).

Figure 2 - Operational (or Enroute) Landing Data (777 data used as an example)

Figure 2 presents a 777 QRH chart as an example of advisory data provided by Boeing. Advisory data for other models is presented in a similar format. Data is presented at reference conditions (REF DIST) with adjustments supplied for the operator and/or flight crew to account for the effects of variables such as weight, altitude, wind, slope, temperature, approach speed and the usage of reverse thrust and/or manual speed brakes.

The reference distance is calculated under the following conditions:

- Threshold crossing speed of V_{REF}

- Includes distance from 50 foot above threshold to a 1000 foot touchdown point (1000 foot of air distance)
- Automatic speed brake deployment
- Autobrake usage or prompt application of manual wheel braking (Maximum manual braking data is only valid for automatic speed brakes. Autobrake data is valid for both automatic and manual speed brakes)
- Prompt initiation of reverse thrust (within 2 seconds of touchdown).

The conditions/assumptions for other models are generally similar to the above, however some variations do exist and operators are encouraged to check the notes on the Normal Configuration Landing Distance charts.

Flying the Airplane

The Boeing FCTM and FCOM have complete sections discussing adverse runway condition operations and techniques. These recommendations and procedures are consistent with the Normal Configuration Landing Distance information found in the QRH. Flight crews are reminded that if they deviate from these recommendations and procedures, they may need to include an appropriate allowance in their landing distance calculations.

The following provide Boeing recommended procedures.

Approach, Flare and Touchdown

On final approach, maintain a stable speed, descent rate and vertical/lateral flight path in the landing configuration. This is commonly referred to as the stabilized approach concept. Use the maximum landing flap available to minimize landing speed and landing distance.

After the flare is initiated, smoothly retard the thrust levers to idle and make small pitch attitude adjustments to maintain the desired descent rate to the runway. Ideally, main gear touchdown should occur simultaneously with thrust levers reaching idle. A smooth power reduction to idle also assists in controlling the natural nose-down pitch change associated with thrust reduction.

After main gear touchdown, initiate the landing roll procedure. Any delay increases the stopping distance.

Note: Make a normal landing; do not strive for a "smooth" touchdown. Floating above the runway before touchdown must be avoided because it uses a large portion of the available runway. The airplane should be landed as near the normal touchdown point as possible. Deceleration rate on the runway is approximately three times greater than in the air. Do not attempt to hold the nose wheels off the runway.

Autoland may lead to longer touchdowns than that assumed in the Boeing QRH performance data. Boeing autoland testing has shown an average touchdown point of 1500 feet from the threshold, with the possibility of the touchdown occurring as much as

2100 to 2500 feet from the threshold depending on the model. High threshold height will likely result in longer touchdowns. Heads-Up-Display (HUD) landing flare guidance (AIII) may reduce the average touchdown distance and dispersion; however these types of landings may still result in a touchdown point longer than the 1,000 foot touchdown point assumed in the Boeing QRH performance data. As such, operators are encouraged to monitor their touchdown statistics to determine if any adjustments for their operations are appropriate.

Speed Brake Operation

It is important for flight crews to remember that prompt deployment of speed brakes is extremely important to the effectiveness of the wheel brakes. Normally, speed brakes are armed to extend automatically. Both pilots should monitor speed brake extension after touchdown. In the event automatic extension fails, the speed brakes should be manually extended immediately. Boeing QRH landing advisory data is based on the use of automatic speed brakes. If manual speed brakes are used they should be deployed within 2 seconds after touchdown and the additional distance required should be considered.

Braking During Landing Roll

Use an appropriate autobrake setting or manually apply wheel brakes smoothly with steadily increasing pedal pressure as required for runway condition and runway length available. Maintain brake pressure until stopped or until desired taxi speed is reached.

Boeing recommends the autobrake system be used whenever the runway distance is limited, and when landing on a slippery runway. Use of autobrake will ensure prompt application of the wheel brakes following touchdown.

Autobrake

For normal operation of the autobrake system, select a deceleration setting. Settings include:

- MAX - Used when minimum stopping distance is required. Deceleration rate is less than that produced by full manual braking on a dry runway
- 3 or 4 - Should be used for wet or slippery runways or when landing rollout distance is limited
- 1 or 2 - These settings provide a moderate deceleration effect suitable for all routine (i.e., not slippery or contaminated runway) operations

On a slippery runway the autobrake deceleration rate of 3, 4, or maximum (Max), although selectable, may not be achievable. The deceleration rate will be limited by the runway friction available

Note: Available autobrake settings are airplane dependant. The FCTM for the specific airplane should be consulted.

After touchdown, crewmembers should be alert for autobrake disengagement annunciations. The pilot monitoring (PM) should notify the pilot flying (PF) anytime the autobrakes disengage.

If stopping distance is not assured with autobrakes engaged, the PF should immediately apply manual braking sufficient to ensure the maximum deceleration available within the remaining runway.

Manual Braking

Immediately after main gear touchdown, smoothly apply a constant brake pedal pressure for the desired braking. For short or slippery runways, use full brake pedal pressure.

- Do not attempt to modulate, pump or improve the braking by any other special techniques.
- Do not release the brake pedal pressure until the airplane speed has been reduced to a safe taxi speed.
- The antiskid system stops the airplane for all runway conditions in a shorter distance than is possible with either antiskid off or brake pedal modulation.

The antiskid system adapts pilot applied brake pressure to runway conditions by sensing an impending skid condition and adjusting the brake pressure to each individual wheel for maximum braking effort. When brakes are applied on a slippery runway, several skid cycles occur before the antiskid system establishes the right amount of brake pressure for the most effective braking.

If the pilot modulates the brake pedals, the antiskid system is forced to readjust the brake pressure to establish optimum braking. During this readjustment time, braking efficiency is lost.

Pilots may misinterpret the low available friction on extremely slippery runways at high speeds as an antiskid system failure. Pumping the brakes or turning off the antiskid system degrades braking effectiveness. Maintain steadily increasing brake pressure, allowing the antiskid system to function at its optimum.

Note: Although immediate braking is demonstrated in flight test and is the basis for the performance data, experience has shown manual braking techniques commonly seen in line operations involve a four to five second delay between main gear touchdown and brake pedal application. This delay may result in the addition of 800 to 1,000 feet of stopping distance. For this reason, autobrakes are highly recommended.

To achieve the QRH landing distances, the wheel brakes must be applied within 1 second after touchdown.

Reverse Thrust Operation

Awareness of the position of the forward and reverse thrust levers must be maintained during the landing phase. Improper seat position as well as the wearing of long jacket or shirt sleeves may cause inadvertent advancement of the forward thrust levers, preventing movement of the reverse thrust levers.

The position of the hand should be comfortable, permit easy access to the autothrottle disconnect switch, and allow control of all thrust levers, forward and reverse, through full range of motion.

Appendix 3 – Landing on Slippery Runways

Note: On a slippery runway, reverse thrust always reduces the "brake only" stopping distance. Reverse thrust is most effective at high speeds.

After touchdown, with the thrust levers at idle, raise the reverse thrust levers up and aft to the interlock position. As the thrust reversers reach the deployed position, apply reverse thrust as required. It is important to promptly apply reverse thrust. This reduces stopping distance on slippery runways.

Maintain reverse thrust as required, up to maximum, until the airspeed approaches 60 knots. At this point start reducing the reverse thrust so that the reverse thrust levers are moving down at a rate commensurate with the deceleration rate of the airplane. The thrust levers should be positioned to reverse idle by taxi speed, then to full down after the engines have decelerated to idle.

Note: If the stop is in question, maximum reverse thrust should be used until the stop is ensured.

The following should be noted:

- Boeing QRH landing advisory data is based on selection of reverse thrust within 2 seconds after touchdown.
- Waiting to apply reverse thrust until nose gear touchdown will increase the distance required to stop.
- The flight crew should always verify deployment of thrust reversers.
- Boeing advisory QRH "Normal" Configuration Landing Distance is based on all engine reverse thrust with corrections for reverser inoperative and no reverse thrust configurations:
    - 727, 757, 767, and 777 – all engine maximum reverse thrust as baseline
    - 737 – two engine No. 2 detent reverse thrust position as baseline
    - 707 and 747 – four engine maximum reverse thrust is baseline with corrections for two engine symmetrical reverse configuration and no reverse thrust.
- Boeing advisory QRH "Non-Normal" Configuration Landing Distance is based on maximum reverse thrust when available on operating engines.
- Reverse thrust will always reduce the distance required to stop the airplane on a slippery runway.
- Reverse thrust is required to achieve the Boeing QRH reference landing distance on a slippery runway.

Appendix 3 – Landing on Slippery Runways

Conclusion

Safe and successful landings, particularly on slippery runways, are the result of proper planning and flight crew adherence to proper procedures and techniques. The flight crew familiarity with the performance effect of runway conditions, the possibility of conflicting runway condition reports, the assumptions in the performance data, and the recommended pilot techniques required to achieve the best airplane stopping performance are important in ensuring safe and successful landings on slippery runways.

Boeing recommends operators have procedures to ensure that a full stop landing can be made on the runway to be used, in the conditions existing at the time of arrival and with the deceleration means and airplane configuration that will be used. This procedure needs to include a determination of whether conditions exist that may affect the safety of the flight and whether operations should be restricted or suspended. Pilots should stay informed, as applicable, of conditions such as airport and meteorological conditions that may affect the safety of the flight.

The Boeing QRH advisory data provided to FAA operators is unfactored (no additional distance margin). The Boeing QRH advisory data provided to operators who use JAA requirements includes an additional 15% distance margin. Operators are encouraged to add additional margin appropriate to their operations to ensure an acceptable landing distance is available. The FAA has released SAFO 06012 which requests US operators voluntarily add at least a 15% margin as an interim measure until their final rulemaking is completed.

Finally, Boeing encourages additional and more comprehensive dissemination of information to flight crews about aircraft characteristics and capabilities. Boeing supports industry efforts to improve training of airline flight crew involving performance limited landings.

APPENDIX J

AIRCRAFT BRAKING ON RUNWAYS CONTAMINATED BY FROZEN WATER

By Dr. Reinhard Mook, University of Tromsø, Norway[1].

Contents

00 Preface

The chapters presented in this paper are intended to support the work carried out by the Accident Investigation Board Norway (AIBN). Apart from common knowledge in applied physics, especially in micrometeorology, the conclusions are based on my own studies,

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[1] PhD in geophysics, Professor Emeritus reinhard.mook@uit.no

especially at Svalbard Airport Longyear. The presentation is primarily intended for personnel responsible for winter operations on runways contaminated by ice and snow. The cases referred to are biased in respect of climate, as they all concern Norway.

The author is gratefully indebted to Knut Lande, expert consultant to AIBN, for clarifying discussions, essential proposals and assistance with the manuscript. Director Kåre Halvorsen, AIBN, has all the way contributed in that process. However, the responsibility is my own. Yngvild Ytrehus, MSc, at AIBN, kindly designed figures 2 and 3.

01 About Forces

Main points: Review of mechanics that define the coefficient of friction; Longitudinal and lateral forces (cornering).

Force F is generally the product of mass m and acceleration a,

$$F = m \cdot a$$

Acceleration also includes deceleration or retardation, usually designated by –a (minus a). In the following, this distinction is omitted. Force is no subject that exits by itself, but is introduced in order to „explain" the acceleration of a mass.

The friction force F_f between two bodies at different velocities is directly proportional to the normal force F_n (vertical to the earth"s surface, usually given as „weight"). By convention, the coefficient of proportionality is symbolised by the Greek letter μ. Thus, the relationship may be written as

$$F_f = \mu \cdot F_n$$

where

$$F_f = m \cdot a$$

and, writing g for acceleration of gravity (mean value $g = 9.81\ m/s^2$),

$$F_n = m \cdot g$$

Therefore, the coefficient of friction

$$\mu = (m \cdot a)/(m \cdot g) = a/g$$

In the literature, the friction coefficient of a rolling wheel is stated as being approximately 0.3 for rubber against asphalt and 0.003 for steel against a rail. These coefficients are the result of different forces, some at the molecular level. To date, coefficients have had to be derived empirically, since frictional theory falls short. The phenomenon of friction is not only a product of the physical material, but of physical processes induced by the exchange of forces.

In the case of an airborne aircraft, g is more than compensated for by aerodynamic lift. At low speeds (less than 60 kt) the lifting force can be assumed to be zero.

Acceleration (or retardation) of mass implies physical work W to the benefit of, or at the expense of, the momentum P, which describes a motion by the combination of mass and its velocity, not by the velocity alone.

$P = m \cdot v$

where v is velocity of the mass m. Slowing down entails reducing momentum, force F entails transferring momentum. Inside a closed system, for example the braking power unit on board an aircraft together with a runway, the sum of internal forces is zero, as any force provokes an equal but opposite directed force. According to Newton"s Third axiom (action equals reaction), the internal forces between to bodies A and B are $F_A = - F_B$. One of these may be understood as force of inertia related to the other. As a consequence, even the sum of momentum inside a closed system is zero. When a system relative to another system shows a momentum (due to the exchange of external forces), the sum of momentum in the closed system is constant (except for further impacts between systems). As the braking force released on board an aircraft is associated with the equal but opposite force in the runway, no braking would occur. It is due to an external triggered force, the frictional force in the pavement-tyre interface, that braking occurs. Incidents discussed in the present paper are cases when the latter force is weak due to a contaminated runway. Hence insufficient reduced momentum may result in a runway excursion.

Work W is defined as the force acting along a defined distance d:

$W = F \cdot d$

Hence, the work done by friction through the distance d, when F_f is the frictional force (see above) is:

$W_f = F_f \cdot d = \mu \cdot F_n$

where F_n means the weight (normal force).

Momentum means that the mass has the potential to do physical work, which is the same as saying that the momentum of a mass m moving with velocity v represents the energy of motion E_m (kinetic energy). This can be presented thus:

$E_m = m \cdot a \cdot d = ½ (m \cdot v^2)$

The latter relationship is valid even for a force that is dependent on place such as acceleration that changes along a path. (The factor ½ refers to the distance d, not time).

It can be seen that:

$v^2 = 2 \cdot a \cdot d$

and the braking distance is therefore:

$d = v^2 / 2 \cdot a$

The work W_a done for acceleration or braking (-a) from velocity v_2 to velocity v_1 is, referring to the kinetic energy (see above),

$$W_{-a} = \frac{1}{2} [m \cdot (v_2^2 - v_1^2)]$$

When braking, the tangential force of the wheel as part of the braking unit is transferred to a partner (usually the runway) as a shear force. According to Newton‟s Third axiom (see above) an opposite tangential force is released in the runway related to the braking unit (not the wheel). However, in addition, the external force of friction is released. When vertical accelerations are neglected, then no external force is considered. The weight of an aircraft (normal force) and the bearing force of a runway result in the sum zero vertical force, in accordance with Newton.

The exchange of forces between frictional partners can be due to shape, as in the case of toothed wheels, or take place by adhesion as a result of the attraction between molecular forces. The latter mode is applied in braking on asphalt or concrete. When the speed of an aircraft decreases, wheel braking will dominate when the speed drops to less than 60 kt (Boeing 737s). At that point, the micro texture of the adhesive material in the runway surface (less than the range of 0.1 to 0.5 millimetres) becomes important.

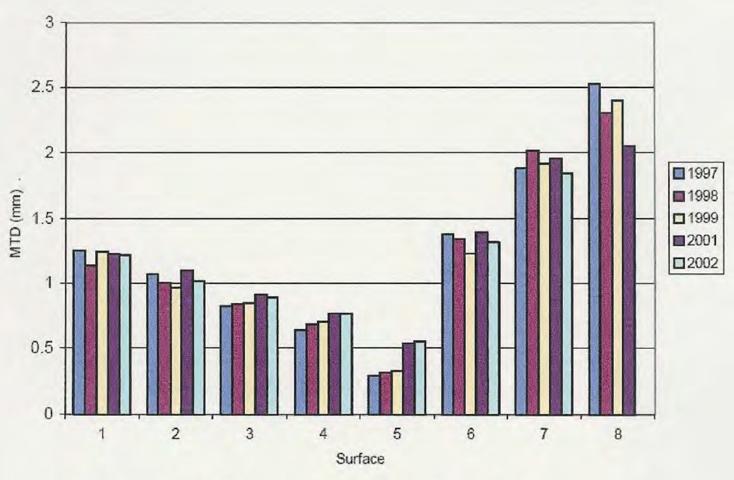

Figure 3 - Mean texture depth for OKK surfaces 1997 – 2002

Figure 1. Mean Texture Depth on Runway Surfaces (ref. Avinor Notice 5:2003, Geir Lange, 2003).

The macro texture at the scale of 0.5 to 2.5 millimetres is relevant to hysteresis (deformations in rubber), especially at higher speeds. Runway macro texture is measured in millimetres (see Figure 1).

The properties of rubber lead to cyclical reversible deformations (hysteresis) that contribute to friction, whereas cohesion, i.e. different forces acting on the rubber and polishing the runway surface, in sum reduce the outcome of braking. Taking all effects into account, the important result is that rubber is very sensitive to liquid water in the context of braking friction. The rolling resistance is due to the wheel carving into a material on the runway, for example slush. Some braking effect may result from kinematic impurity, forces that trigger vibrations, for example due to gusty crosswinds, frozen tracks or patches of ice on the runway. Deceleration is normally not constant but varies with time, and the changes are felt as impact.

An important force when braking on a runway may be the crosswind force vector (cornering effect). The additional force on the aircraft has to be transferred to the runway in order to hold the aircraft on a steady course or return it to the centreline. An aircraft‟s reaction to crosswind depends *inter alia* on the respective positions of the points of gravity and the force of the wind (centripetal force) in relation to the axes, in addition to other aerodynamic properties. Figure 2 shows the main forces acting on the aircraft in the simplified case of a constant crosswind (an abstraction, as wind is always variable).

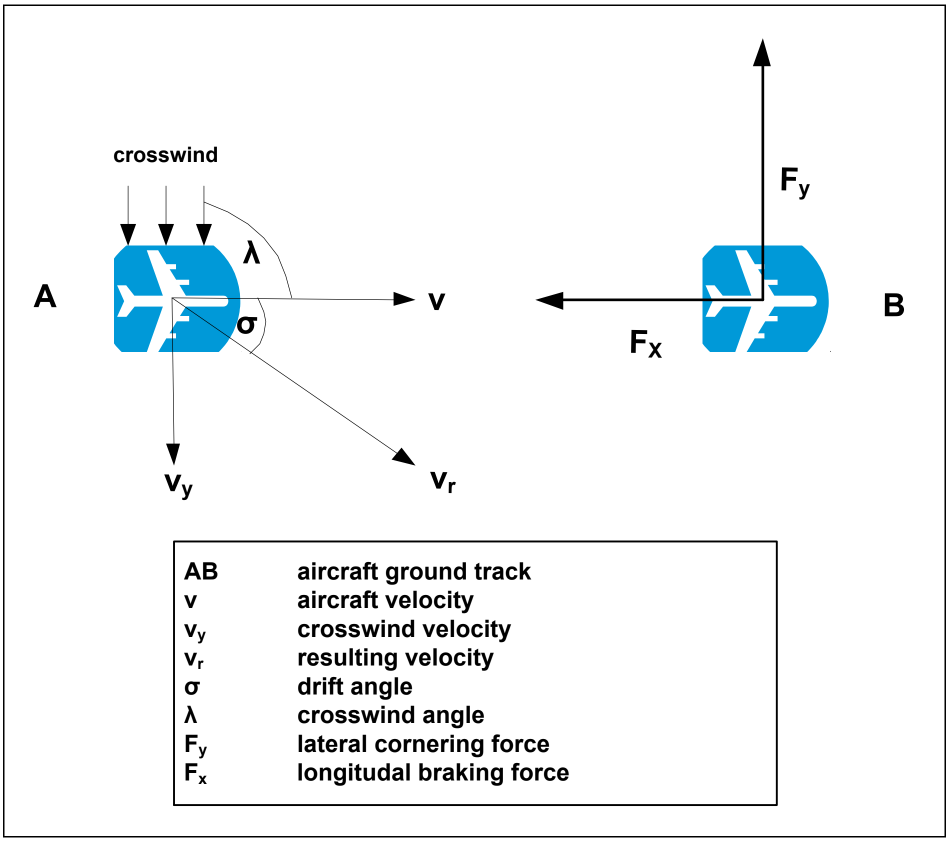

Figure 2. Crosswind effect on an aircraft on ground.

In Figure 2 an aircraft is assumed to be rolling along the runway centreline from A to B in a crosswind velocity v_y. The vector v is the instantaneous speed of the rolling aircraft, and v_r the resulting velocity vector of the aircraft without any friction (longitudinal braking or lateral cornering force). The angle λ represents the crosswind angle, and the angle ζ represents the drift angle. The lateral crosswind force must be balanced by the opposite cornering force F_y represented by the „cornering friction coefficient‟, in combination with the longitudinal braking force F_x represented by the „braking friction coefficient‟, i.e. the vector sum of these two forces (see Figure 3).

As the centre of wind pressure on an aircraft is situated closer to its tail than the centre of gravity, an aircraft exposed to lateral wind tends to turn into the wind. The directional deviation may be counteracted by use of the nose wheel steering. The forces involved are proportional to the pressure of an air stream, $\rho \cdot v^2 / 2$. Here, ρ means the density of the air and v the speed of air resulting from the aircraft‟s rolling motion and the (meteorological) wind. When the aircraft has returned to the centre line, the nose wheel has to maintain deflected for a certain angle in order to balance the force of the wind and to continue along the centre line. The simple abstract model of constant crosswind is complicated by the oscillations of the always turbulent wind, analytically composed by different amplitudes and frequencies.

The centripetal and centrifugal forces now need to be considered. These occur when a braking aircraft follows any curvature. In addition to the tangential force changing the velocity v_t along the path due to the tangential acceleration a_t, a centripetal force F_n acts at right angles to the path and is oriented towards the centre of a curvature with radius r, thus diverting the path from a straight line. The centripetal force F for a mass 1 (unity) is:

$F_n = m \cdot a_t$

or, when mass is defined as m = 1 (unity),

$F_n = a_t = v_t^2 / r$

The centripetal force is balanced by centrifugal force acting in the opposite direction, a force of inertia. The essential point is that F_n increases with the square of v_t and is proportional to the reduction of r when the curvature increases. The force F_n is constant when there is no tangential acceleration.

Provided that the coefficient of friction μ at a point on the runway is valid (effective) in all horizontal directions, the coefficient needed to allow for maximum centripetal acceleration without skidding is given by:

$\mu = (v_t^2 / r)_{max}/g$

where g is the acceleration of gravity. If, for example, an aircraft‟s braking coefficient $\mu = 0.05$ on ice (it could be less), and g is assumed to be approximately 10 m/s^2, then the centripetal force must not exceed 0.5 (kg m)/s^2 (= 0.5 Newton), as the above equation shows. {The unit follows from the product of mass (kg) and acceleration (m/s^2). It describes the force that imparts an acceleration of 1 metre / $second^2$ to a mass of 1 kilogram}. If „poor‟ braking action („aircraft braking coefficient‟) is chosen, the result shows that the available cornering force is rather small if skidding is to be avoided. The centripetal force must be even smaller if we allow for tangential acceleration (change of velocity in curvature) and / or crosswind. Indeed, skidding on compacted snow or ice in such rolling conditions is no rare event and is often evidenced by the wheel tracks. The above considerations are valid for every vector sum of longitudinal forces (friction force due to braking, F_x) and lateral forces (cornering force, F_y), see figure 3.

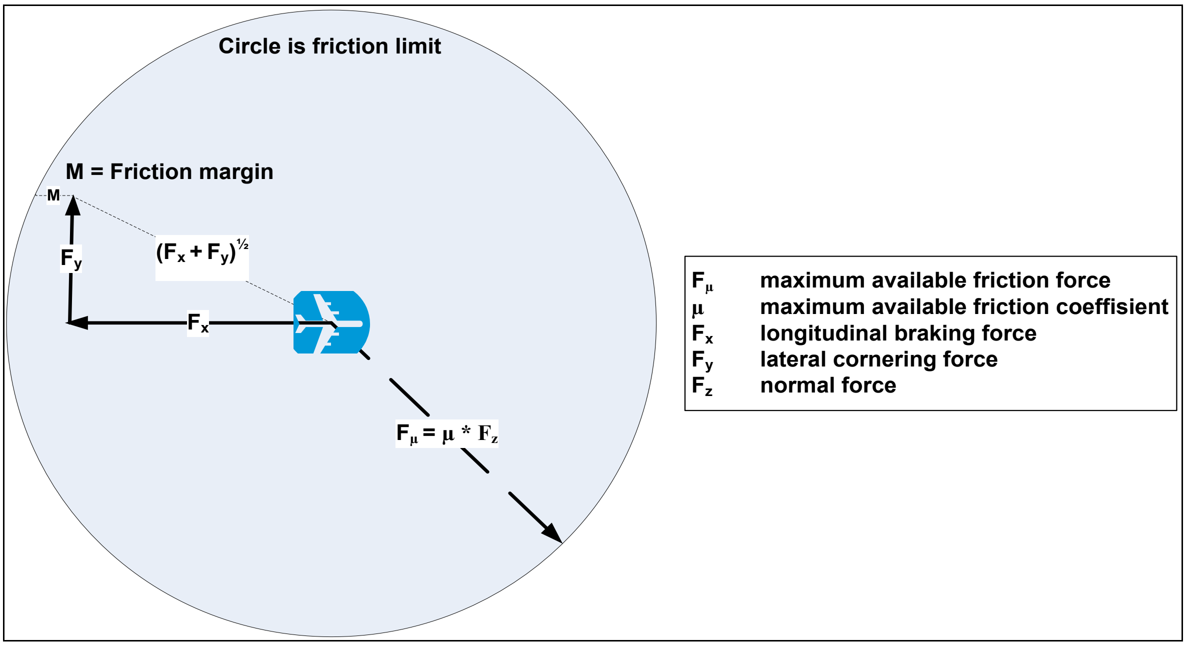

Figure 3. The active forces during skidding. In a circle with radius chosen geometrically equivalent to the maximum friction force available, F_μ, the equivalent length of the vector sum $F_x + F_y$ must not exceed that of the radius, hence not cross the circle line, in order to avoid skidding. F_x is representing the used longitudinal braking force, and F_y is representing the lateral cornering friction force. The cornering force F_y. can only be increased on the expense of the braking force F_x If the vector sum of the two forces exceeds the maximum available friction force F_μ, the aircraft start skidding.

For the sake of explanation, figure 3 shows graphically the balance between the force of the total available friction, F_μ, and the vector sum of the longitudinal braking force, F_x, and the lateral cornering force, F_y. No vertical acceleration except gravitation g is assumed, hence the normal force F_z is equivalent to the landing weight. The coefficient of friction, μ, is assumed associated with maximum exchange of shearing force between aircraft and runway possible. In case $F_\mu = \mu \cdot F_z$ is less than the vector sum of F_x and F_y , the friction force available is less than the required retarding forces. In that case the aircraft will not roll but skid. Actually, figure 3 is the graphical presentation of the equation $(F_x^2 + F_y^2)^{1/2} \leq \mu \cdot F_z$. From the equation (or figure 3) is seen that the margin for the lateral force F_y (in relation to F_μ) is reduced when the longitudinal force F_x is increased. If the vector sum of F_x and $F_y \geq \mu \cdot F_z$, skidding will occur.

Figure 3 assumes an aircraft landing from left (vest) to right and a cross wind component, eventually centripetal force or accelerations by tracks in ice, etc. directed from up (north) downwards. The crosswind force is opposed by a lateral cornering force directed upwards. The vectors are drawn with geometric length proportional to their force. The distance between the start of F_x (centre) and the tip of F_y is equivalent to the vector sum. Analytically, the sum corresponds to the length of the hypotenuse of a right angled triangle.

In order to compare the length of F_μ with the sum of F_x and F_y, dividers may be used. In stead, a circle with radius F_μ and centre at the start of F_x is constructed. As the arc of the circle is the geometric location of F_μ, the location of the tip of F_y shows whether F_μ is larger or smaller than the vector sum of braking and cornering forces. In the first case, skidding should not happen. In practical use, F_μ might be used as unit (value 1). Then any vector sum [F_x and F_y] < 1 would mean sufficient friction force available to avoid skidding.

The inclination of a runway and any elements of roughness, for example elevated patches of ice, applied vertical forces to a vehicle in motion, increased or decreased acceleration of gravity g, will affect changes to the friction coefficient μ (see the relationship above).

The overall outcome is that rolling wheels will partially slide as a result of the favourable properties of rubber. When braking, the distance covered by a sliding wheel (and the vehicle) is larger than indicated by the number of revolutions of the wheel. The coefficient of friction for maximum exchange of shear force, μ (referred to in Figure 3) is associated with a certain share of slip. For example, a slip of 0.15 at a speed of 50 kt would mean a sliding (slip) velocity of 0.15 x 50 = 7.5 kt.

In addition to the longitudinal slip, there is a lateral slip due to cornering (lateral) forces. See Figure 4. Some braking is achieved by drag. The antiskid logic tries to mark off the interval of optimum slip (or the peak μ). Antiskid systems work by measuring wheel speeds, determining slip and adjusting brake pressure to keep the tyre working at or near the max μ value. The difference between wheel velocity and slip velocity is the input signal. Comparing the speed of pairs of wheels, the logics may prevent the wheels from locking. On ice, wheel speed can be compared to inertial ground speed. In cases where these signals contradict the logics or are not released at all, heavy braking (exceeding the shear force that may be exchanged with the runway) will necessarily result in skidding and loss of directional control. The tyre is not then capable of producing the required friction force on the pavement.

From figures 3 and 4 it can be noted that any increase in the cornering friction is gained on the expense of the longitudinal braking friction. This is illustrated by an example of an aircraft which is landing on a slippery runway in crosswind. If the total available friction coefficient is of the order of poor, the pilot is using a certain amount of the available friction as cornering friction in order to keep the aircraft on the centreline. Thereby the remaining friction as available for longitudinal braking is reduced. If the pilot is increasing his braking any further, he will exceed the total available friction and the aircraft start skidding. The aircraft may then skid sideways and loose directional control.

The macroscopic law of friction is independent of the area of contact between frictional partners. However, decisive is the area of effective contact between asperities on the microscopic scale. Adhesion and hysteresis, the latter depending on micro texture roughness, show a maximum related to sliding (slip) speed, which depends on temperature. Load, and ultimately frictional work influences on the temperature, and may change frozen liquid into water. Flash melting may release heat that results in the transformation of ice to steam. Thus, there are complex feedback mechanisms related to sliding speed and sliding friction. A certain degree of slip is crucial for maximum braking by shear forces. The definite slip is an essential component in the process resulting in the aircraft braking coefficient. Further increase of the slip ratio would mean to apply a retarding force exceeding the shear force that can be transferred by the physical conditions given. The latter would result in locked wheels and skidding.

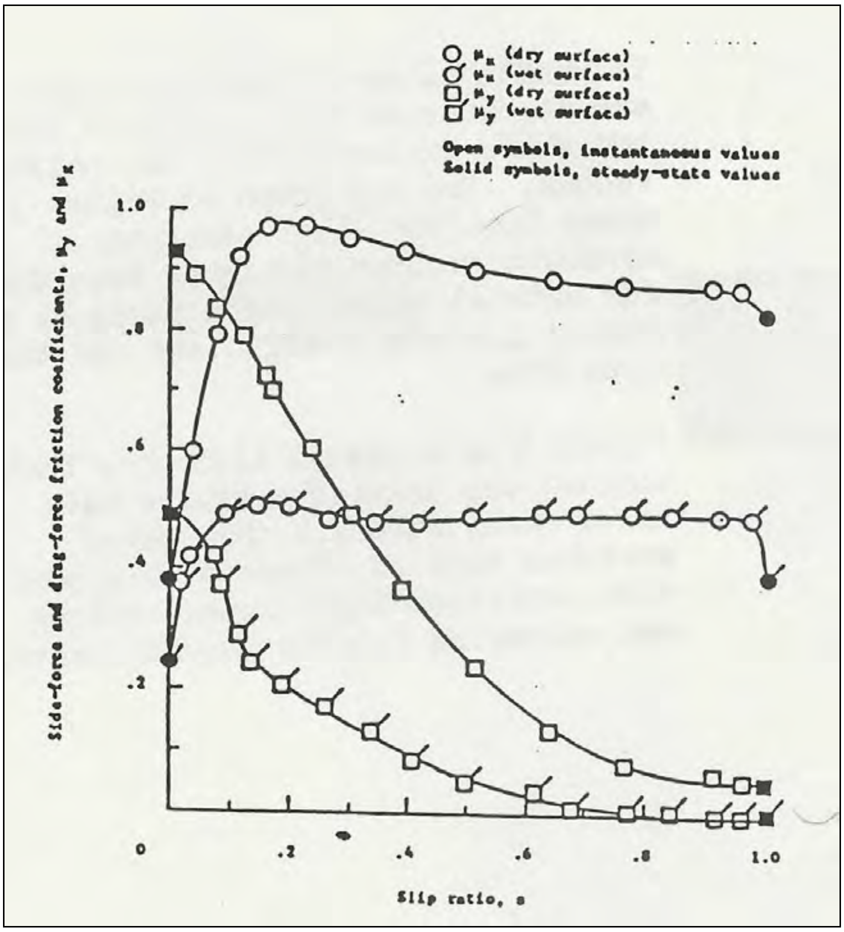

Figure 4. Longitudinal and lateral (cornering) braking coefficients (W. Horne, NASA 1990).

02 Measurement of friction

Main points: The effective coefficient of friction as objectively experienced by an aircraft (aircraft braking coefficient) must be distinguished from the subjective coefficient read by a specific measurement device. An aircraft braking coefficient cannot be inferred from a measured friction coefficient except with uncertainties that are imponderable in practice.

Every vehicle has its own specific dynamic properties of motion. An aircraft at an air speed of less than 60 kt (for example the Boeing 737 series) may be considered to be dependent on wheel braking, as the aerodynamic forces are negligible. As Kollerud demonstrated in the late 1940s and early 1950s at Oslo Airport Fornebu, the coefficient of friction derived from the inertia of a strongly braked lorry was about twice as high as the coefficient derived from aircraft braking (DC 4, DC-6 and DC-6B). This finding has been confirmed by various subsequent studies up to the present time.

All friction-coefficient measuring devices have their individual characteristics and thus may show correct results on their own terms. For example an SKH (BV-11) or a Griptester may return correct results in terms of what is registered by that device in specific conditions. (SKH is a skiddometer with a high pressure tyre). The results of a large number of such measurements may correlate more or less with the braking coefficients experienced by aircraft, depending to some degree on aircraft type and braking performance. However, there is considerable uncertainty attached to deriving the aircraft braking coefficient from individual measurement data. As all friction-coefficient measuring devices are relative, not absolute instruments, equivalents for conversion, including aircraft braking coefficients, cannot be deduced physically.

According to ICAO and other sources, the standard error of a measurement carried out by skiddometer is ±0.1 on compacted snow or dry ice, ±0.2 on frozen but wet contamination. According to the Gaussian distribution, the true coefficient of friction is estimated with probability 0.34 in the interval made up by the measured coefficient of friction FC minus 0.1 or minus 0.2 respectively. (The case of a larger true coefficient of friction than measured is not of concern). For example, if FC is measured 0.33, the likelihood is 34 per cent to find the true coefficient in the interval between the limits 0.33 and 0.33 – 0.10 = 0.24, or between 0.33 and 0.33 – 0.20 = 0.14 respectively. The true coefficient may be less than 0.24 (dry ice) or 0.14 (wet ice) with likelihood 16 per cent. These numbers indicate that an observed value characterized as MEDIUM with a rather large probability may represent a true but not exactly known value POOR not observed due to deficiencies in the measuring procedure.

In general, any digit to rely upon in reported figures, except for the zeros to put the point of decimals, is considered as significant. Hence, a reported FC =0.33 would be understood as two significant digits. However, a standard error ±0.1 shows that the first digit behind the decimal point only may be considered as significant at best. Therefore, no better detailed information than GOOD, MEDIUM, POOR is available from skiddometer measurements. In the case of standard error ±0.2, even the first digit may be considered as too uncertain to be interpreted as significant. Therefore, the friction coefficient on wet ice should never be put better than POOR, if not NIL, irrespective what measurements show (if the device is certified for wet conditions.)

As the information given by the friction coefficient is that of a ranking scale only, there are no defined distances between the qualitatively ranking marks. The lack of information cannot become cured by any links to a metric scale. Actually, a measured FC = 0.2 numerically is half a measured FC = 0.4. There is an absolute point zero as $\mu = -a / g$ approaches 0 when retardation –a achieved reduces to zero. Therefore, FC = 0.2 and FC = 0.4 express retardations in the proportion 2 to 4. However, the quality in the measured FC as expressed by the standard error does not allow to pretend a metric scale because the lack of sufficient information in the FC. To underline that item, an analogue example may be given: Age may be expressed precisely on a metric scale with an absolute point of zero. However, when exact age cannot be determined as in cases of archaeology or historical demography, then ranking in terms of “before” and “later” only makes empirical sense due to the lack of better information in the data.

An international friction coefficient (IRFI) has been derived, but not yet introduced. The reason for this is the individuality of each kind of friction measuring device. In addition, as far as frozen water is concerned, specific climatic conditions cause variations in the specific properties of the same kind of contamination in different locations.

Objective measurements have to be independent of the devices used and of subjective judgement relating to their use. So far, the friction measuring devices used in practical operations have satisfied neither the first nor the second condition concerning restriction of use (for example on wet surfaces).

It has been shown that the same individual friction measuring device can return different results when applied several times to an (apparently) identical runway texture. Therefore, reliability is not assured.

As friction coefficients obtained from friction measuring devices do not determine the aircraft braking coefficient ABC (also called ABM as an abbreviation for „airplane braking µ" or „effective µ"), there is only some degree of stochastic correlation and therefore reason to doubt the validity of measurements. Even if good reliability were to be proven, this would constitute a necessary, but not a sufficient condition, for regarding the validity as sound.

To sum up, friction measurements (by skiddometers) may at best justify some very rough ranking of expected aircraft braking coefficients, most likely on the level of a dichotomy (good / poor) only. The measured friction values lack the metric information that would be necessary to carry out valid numerical (arithmetic) calculations.

The shortcomings of skiddometers can partially be explained by their technical design. The driving and measuring wheels do not work independently of one another. If friction is to be measured, the most promising principle is, perhaps, that of inertia.

03 The frictional heat of tyres

Main point: Heat released from tyres may result in instantaneous melt water, which is decisive for the braking action achieved.

The surface of a rolling tyre is heated internally by kinetic energy and externally by sliding. At a more detailed level, it is not only deformations in the rubber, but also in the texture of the runway that generate heat. When the surface texture is made up of frozen water, it may change to liquid or vapour. In the case of asperities (elevations in the microtexture) caused by minerals and shown by substances changing colour with temperature, flash temperatures exceeding 150 ºC can be proven. In the case of ice, released heat will become latent in liquid water or vapour. Melting and mechanical pressure will deform the asperities and produce an increasingly large area of icy surface texture that comes into contact with the tyre.

Physically, work is defined as the product of force and distance covered. Work is done by braking a wheel. The rubber of the tyre is deformed in different ways. Kinetic energy is transformed into heat that then dissipates. The same applies to work done on tubes containing nitrogen. The nitrogen itself, which alternates between being compressed in the footprint of a rotating wheel and expanded elsewhere in the tube, undergoes alternate warming and cooling.

It seems to have been taken for granted that sliding and skidding on ice is caused by liquid water due to depression of the melting point by weight. However, when the normal forces (weight) needed to attain a reasonable depression is calculated, the outcome is beyond the range of realistic possibilities. Nonetheless, when the heat released by a sliding aircraft under the conditions likely to be encountered is calculated, a considerable yield of liquid water may be expected, in the order of some tenths of a millimetre water depth.

Melted water generated by sliding on ice is in brief discussed by a rough estimate: The depression of the melting point temperature by increasing pressure amounts to 0.0074 K / 100 kPa (100 kPa correspond to 1 bar). Obviously, the pressure necessary to achieve a significant amount of liquid water is neither realistic nor consistent with the existence of ice. However, sliding would do the physical work W (that means to transform energy) according to

$W = F \cdot d \cdot \mu$

Here, the force $F = m \cdot g$ (mass times acceleration by gravity), d means the distance of sliding, μ the coefficient of aircraft braking (ABC).

Approximating the value of $g = 10\ m / s^2$, the load on an aircraft wheel for example $15 \cdot 10^3$ kg, the force exerted would become $F = 150 \cdot 10^3$ N. In the case of ABC = 0.1, over a sliding distance d = 1 m the work W would amount to $15 \cdot 10^3$ Nm, or the equivalent unit J. As the specific heat to melt ice, $c_{melt\ ice}$, is $333 \cdot 10^3$ J / kg, the mass of ice at 0 °C melted would be $m_{melted} = W / c_{melt\ ice} = 15 / 333 = 0.048$ kg. The area of tread sliding over 1 m has to be reduced to the effective area of contact by asperities, perhaps by factor 0.01 or less. The above estimate, even if carried out for ice originally colder than 0 °C, shows that melting water from sliding must not be neglected. It may be augmented by water enclosed in and squeezed from recent snow. ABC is reduced significantly on a lamella of ice generated by re-freezing, especially when covered by hoar frost or snow.

At Svalbard Airport Longyear, an infrared sensor was used to take temperature readings in the tread of the inner main wheel just after parking aircraft in the Boeing 737-400 to 737-800 series over a period of several winter seasons. As a mean, the highest temperature, which exceeded the outside air temperature (OAT) by approximately 25 K, was found near the tyre‟s edges, while it was 15 K above OAT closer to the centre (of the tread). The amount by which the temperature exceeded the ambient temperature increased with the landing weight. If we look at the B 737-800 alone, the results were 35 K and 20 K above OAT, respectively. The temperature can increase during the first 10 minutes after parking. Cooling takes place very slowly. Though the progression is exponential, it can be approximated in linear terms. At an air temperature of minus 15 ºC, cooling in calm air may be 0.2 K/minute, or in the order of 0.1 K/minute at an air temperature 0 ºC.

Furthermore, the temperatures observed depend on the mode of braking, ventilation (wind) and exchange of heat by radiation. As a rule, Auto Brake setting 3 was chosen, with manual braking below 80 kt. (Deceleration settings for B737 Auto Brake are: 1) 3 ft/s^2, 2) 4 ft/s^2, 3) 7 ft/s^2, Max. 14 ft/s^2). SKH values reported on sanded ice were in the upper 0.30s or even exceeding 0.40, reported as „medium to good‟ or even „good‟. There was a tendency towards slightly higher tread temperatures when braking action was reported as „medium‟.

The lesson is that heat released from tyres in most cases will be sufficient to melt ice or compacted snow for the period of contact. A film of liquid water between tyre and frozen water exists, which reduces the shear force that can be transferred. An inspection of a tyre‟s path on compacted snow often confirms a lamella of refrozen water.

04 Frozen precipitation and condensation

Main point: Liquid water in frozen precipitation and its recent accumulation is significant to braking.

At air and runway surface temperatures close to or below freezing, precipitation is accumulated, most often as „snow‟. The shape of the crystals is related to air temperature in the vicinity of the clouds. The overhead temperature regime may be derived roughly from the crystal structures.

Snow always contains some liquid water, which generally increases with temperature, except for very low temperatures in the cloud region and below. As a rule, super-cooled droplets are the major constituent in clouds warmer than minus 12 ºC, and through to minus 20 ºC droplets and ice are equally common. Droplets formed in clouds do not freeze at temperatures warmer than minus 12 °C to minus 15 °C. Frozen precipitation falling from higher regions of a cloud will catch liquid water in the zone of droplets. Due to lower saturation vapour pressure above ice than above liquid water, air just saturated in respect to liquid water will be super-saturated in respect to frozen precipitation passing through a zone of droplets. Not necessarily frost but dew may be the result, thus contributing to the content of liquid water in snow.

At surface air temperatures colder than minus 10 ºC, newly fallen snow (at Svalbard Airport Longyear) contained liquid water with a mean value of less than 8 % of mass. In the temperature interval between minus 2 ºC and 0 ºC the mean proportion of liquid water was 17 %. Wet snow may be observed up to surface air temperatures of 3 ºC. The proportion of liquid water increased with temperature above 0 ºC, as a mean, from 22 to 28 %. In the latter case, the accumulated outcome must be characterised as „slush".

Surface air temperature is not a trustworthy indicator for deciding whether snow is „dry" or „wet", as there may be „warm" precipitating clouds aloft. The somewhat subjective and uncertain way of differentiating „dry" snow from „wet" (based on whether it is possible to form a ball or not) might be replaced by a scale 1) snow too dry to form a ball, 2) a ball can be formed, but no liquid water can be squeezed from it, 3) possible to squeeze liquid water from the ball, 4) too much water to form a ball.

The electromagnetic properties of snow, defined by the dielectric constants of ice and water, depend on the relative permittivity and absorption of electromagnetic microwaves. These depend on frequency, density and the volumetric amount of liquid water. The Denoth device allows the proportion of liquid water to be determined, when the density of the snow is known.

The point is that new fallen snow may contain an amount of liquid water sufficient to cause significant deterioration of braking conditions, and this may happen even at sub-zero surface temperatures. In addition to the case where there is warm air aloft, precipitating clouds that are forced to rise rapidly due to mountainous terrain may yield a rather large amount of liquid water locally (at certain airports). Proximity to a windblown (churned up) sea may contribute salt dissolved in water (brine) enclosed in snow aggregates and thus make for exceptionally slippery conditions.

Sweeping devices and other sharp-edged metal devices used on new fallen snow may squeeze out a film of liquid water that immediately freezes into a slippery covering of ice. This is the case with freezing to a lamella of ice referred in chapter 03.

Small hailstones, where the grains initially freeze onto the surface of the runway, may improve braking conditions temporarily. But melting grains behave like ball bearings in liquid water and act as a lubricant.

Rain reaching the ground at a temperature below freezing, or super-cooled rain (where the droplet‟s temperature is well below 0 °C) even if the ground temperature is above freezing, will form a coating and often transparent ice. Such ice may even result from freezing after rainfall, wetting fog, liquid water from melting or from dewfall. Due to the transparency of ice, devoid of small inclusions of air, it may be difficult to detect such ice visually (called „black ice‟, because the asphalt can be seen through the ice).

In rain upon a "black" area of traffic, following a period of temperatures below freezing, the area may be reported as presently "wet". However, surprisingly (and possibly not detected) ice happens to occur when the intensity of rain decreases, even though the reported air temperature does not fall. The ice may appear in patches as an emulsion of single needles in liquid water, or as an aggregate fastened to the pavement. - The apex for freezing or not freezing in the case considered depends on thermal conditions as follows: Freezing occurs when the heat transferred into the pavement as a sink for heat surpasses the input of heat carried by the droplets of rain, net radiation and sensible heat flowing from the atmosphere into the drained or standing water at the area of traffic. An additional and important input is the heat released by (starting) freezing. The input of freezing heat hampers and delays further freezing dependent on the rate of cooling by the pavement. The balance of heat may be very delicate. When the intensity of rain decreases and thus the volume of water involved, the loss of heat to the cold pavement at a temperature below freezing may just be sufficient to freeze the now reduced amount of water. The pattern of patches with or without ice mirrors the pattern of a pavement‟s different thermal properties.

When the temperature of a solid surface decreases below freezing and below the ambient air‟s dewpoint temperature (the temperature at which the actual water vapour would be saturated in relation to liquid water) water vapour pressure is directed from the air to the solid surface. Hoar frost develops. Due to a lower saturation vapour pressure above ice compared with liquid water, hoar frost may appear before the „spread‟ (the difference between air temperature and dewpoint temperature) reaches zero. As a rule of thumb, at an air temperature of minus 9 °C, hoar frost may form when the „spread‟ is still 1 K (the Kelvin scale is used when quoting the difference in temperature) as the „frost point temperature‟ is approx. 1 K above (warmer than) the dewpoint temperature. At an air temperature of minus 17 °C, hoar frost may appear, even though the „spread‟ is 2 K. As hoar frost is crushed and partially melted by aircraft wheels, which frequently results in slippery conditions, the difference between (reported) dew point and the actual effective frost point temperature (the temperature when the actual vapour would be saturated in relation to ice) might be significant.

The density of snow depends on the percentage of liquid water stored. In fairly dry snow, wind plays a major role in governing both the areal distribution of snow and the density of accumulation. Leeward of even small objects on the shoulder of a runway, snow carried by wind may be deposited downward and thus become the origin of subsequent patches of snow or ultimately ice. Such patches may even derive from the pattern of deposited and eroded snow caused by turbulence in the shallow boundary of air close to a runway surface. In calm, cold weather, densities as low than 65 kg/m^3 were observed (at Svalbard Airport Longyear), but densities as high as 330 kg/m^3 in heavily fragmentised and compacted ice particles after a gale have also been observed. Such differences in density may affect rolling resistance when snow is not removed (due to its shallow depth).

The variety of states of snow exposed to shear forces from braking wheels results in a large number of phenomena concerning the stability and structure of the frozen deposit. For example, “swimming in loose snow” occurs inter alia when the contaminating material is made up from 1) flower like dried fragments of ice particles grinded by numerous impacts with the ground along wind‟s trajectories, or 2) loose wet grains of ice due to disintegrated aggregates of ice in rain or due to treatment by a chemical depressing freezing temperature. Common in these examples is that the frozen particles do not tangle up to a consistent layer when exposed to an aircrafts normal force. Different from the case of recent (and therefore) to some proportion wet snow, when wheels make a track of compacted snow covered by a film of liquid water or (subsequent) a lamella of ice, the frozen material in case 1) or 2) remains loose. In such a contamination, wheels experience considerable slip or even locking. A similar outcome concerning slip is observed when 3) a layer of compacted snow due to shear forces is broken up into disarranged clods. This happens especially upon immobile ice.

Every single particle or aggregate of ice is exposed to forces acting in different directions. There is a) the weight due to density, directed from the point of gravity to the centre of mass of the earth, b) forces between solid particles due to their accumulation and to the load from traffic, in sum variable forces that compact the material, c) forces exchanged by liquid water and air between the frozen particles, d) inter-molecular forces as summarized by the concepts of “adhesion” and “cohesion”, depending on physical-chemical properties, inter alia the pH-figure and the strength of crystalline bonds or brigdes. As the sum of all the effective forces differs from zero, particles would move if there were not compensating reactive forces. They are essential for braking caused by the transfer of shear force. When elementary particles of ice {examples 1) or 2) above} hardly transfer shear force through their continuum (the internal friction is poor), cohesion made up by the sum of internal forces apparently is insufficient. When a layer of compacted snow by shear force due to braking is torn to clods sliding on ice {example 3) above}, those compensating forces causing the layer‟s cohesion and its adherence to the ice below are exceeded.

To sum up: The four groups of forces {a) through d) above} acting three dimensionally result in a normal component (right angle to horizontal runway) and a tangential one. If these two components are strong enough to compensate for the resultant of all activated forces, then the single ice grain or an aggregate of ice will not move. The structure of the contaminant is stable. Otherwise, grains or aggregates will be moved in relation to each other and to the environment, the structure is labile (not stable) and shear force from braking is transferred badly.

The tangential force in a contaminating layer, loose grains or coherent aggregates, depends on properties of surfaces in touch with each other, and on the normal force acting on the layer vertically. Because the latter builds up stress, or in case moves, vertical surfaces of contact in a horizontal layer, the normal force does have impact on the tangential force. The tangential force at a certain site therefore changes with a wheel passing it. Concerning the properties in touch, the geometry of grains of ice, toothed or rounded off, and especially the contents of liquid water (and its pH-figure) are important: The stability of a contaminating layer increases from a very liquid suspension of ice crystals over less watery slush, wet to rather dry snow or dry ice. Traces of salt (after application of chemicals) should reduce internal friction and tangential stability needed for effective braking. The last four paragraphs underline the need to remove loose contamination, and even a continuous layer of compacted snow when not sufficient fastened to a fix pavement (asphalt or ice).

05 Changes in accumulated frozen contamination

Main point: Thermodynamically induced changes in the composition of frozen contamination alter friction properties, even in „stable" weather.

The shape and mechanical properties of crystals of ice in natural snow cover, as well as in compacted snow (after preparation of a runway), and even in aggregates of ice, are in a constant state of change. This „metamorphosis" is due to internal differences in vapour pressure, partially caused by the geometric shape changing from convex, high pressure tapering edges towards low pressure concave surfaces, partially governed by gradients in temperature. These changes take place even in „stable" weather as reported by METAR and are often invisible unless specifically investigated. Because of internal thermodynamic processes, frozen contamination must not be assumed to be in a fixed frictional state on the basis that the weather is „unchanged". Actually, even the "unchanged" weather as indicated by the METAR is the result of continuously ongoing atmospheric processes.

At low air temperature, and thus low water vapour pressure, new fallen snow will evaporate liquid water in addition to undergoing internal changes in distribution and freezing. The snow „dries up". Density may decrease considerably, for example, from 300 to 100 kg/m^3 in a natural snow cover (at Svalbard Airport Longyear). Compacted snow on the runway may contain 500 to 700 kg/m^3, and when transformed into ice 800 to 900 kg/m^3; the latter figure applies to „black" ice. Repeated thawing and freezing together with pressure (for example on slush) may result in mechanically rather weak aggregates of sintered ice.

When exposed to the load of aircraft wheels, liquid water in the pores of compacted snow or between the aggregates of ice will be compressed and form an intermediate layer of liquid water. It will envelop asperities of ice and constitute a lubricant between tyre and solid frozen contamination. The water from rain falling on compacted snow or ice, in addition to causing dewfall yielding heat and liquid water, has both an enveloping and destructive effect (due to melting) on asperities. The melting and intrusion of water into the frozen contamination causes disintegration and weakening, especially at the upper surface. In any case, the mass of snow or ice, liquid water and vapour in the included pores, are subject to the forces of gravity, capillarity and surface tension, together with the driving gradients in vapour pressure.

When compacted, the particles of ice tend to form bridges of ice on the contact surfaces. The loose tangle of snow crystals becomes compressed into aggregates of grains. Zones of concave shapes in the particles are the favoured sites for ice deposits from internal water vapour. Thawing, refreezing, evaporation and sublimation into solid scales of ice may result in a surface made up by internal „hoar frost". In this way the contamination may include several layers of internal „hoar frost". Such a surface will be mechanically weak with respect to shear forces and thus present a potential sliding surface. An example is internally generated hoar frost between black ice or even the bare pavement beneath, and complex ice as formed from original slush above. Films of liquid water cause grains of ice to cohere by means of capillary forces. Some of the water may freeze and increase cohesion by creating bridges of ice. As the proportion of liquid water increases, the viscosity of snow decreases strongly.

The mechanics and thermodynamics of porous substances with unchanging microstructure are not yet fully understood. This applies all the more for snow, whose microstructure is in a constant state of change. Many of the relationships concerning the behaviour of snow have, up to now, been deduced empirically rather than from theory. As the properties of snow and ultimately ice depend on their three-dimensional structure, studies by computer tomography produce useful results, but it would be impractical to use this method to assess ABC on a daily basis.

Upon a layer of recent and still loose snow, the normal force of wheels compact the snow. The volume of pores then is reduced drastically, and mobile liquid water may be pressed up or aside, probably freezing to coats of ice covering aggregates of snow. Then following repeated stress by weight will concern a “new” material as compacting advances and ice may melt and refreeze. Besides probably different modes of braking, such differences in stressed contamination may contribute to explain when comparable aircraft landing at the same site shortly after each other experience different braking conditions.

06 Frozen water and heat exchange

Main points: Fluxes of heat into and out from frozen contamination. The transfer of heat is caused by changing aggregates of water. Air temperature and dewpoint temperature at 2 m above the surface compared to the conditions at the runway surface.

Principally, the exchange of heat takes place through different mechanisms. All the following transfer mechanisms of heat apply to runway contamination by water in its three phases and the changes between them.

These are:
1) Molecular flow of internal heat in direction of decreasing temperature. It takes place in solid bodies as well as in resting fluids. The thermal conductivity, unit W / (m K), is about 2.3 in ice, 0.5 to 2.0 in compacted snow. In liquid water, convection due to instable stratification, stirring by wind or mixing by transecting vehicles will rule out molecular flow of heat.

2) Convection due to water with larger density above water with less density, or forced mixing as indicated above.

3) Change of the aggregate of water in the surfaces of thermodynamic systems. It‟s the case when ice melts to liquid water, or liquid water as well as ice evaporate, or the other way condensation and freezing. The direct transition from ice to vapour, omitting the stage of liquid water, is known as sublimation. However, that term is used for the opposite process in chemistry. Therefore, to exclude confusion, the term evaporation may be preferred. In the presence of liquid water and ice, both may evaporate at the same time. The reverse process means that vapour is condensed to liquid water, or liquid water freezes to ice. The direct transformation of vapour to ice as in the case of hoarfrost may be termed de-sublimation. - These changes of aggregate are very significant in the present context because they involve both the exchange of considerable amounts of energy (heat) and, water as contaminant, involves essential changes in frictional properties. The heat “hidden” in liquid water from ice melting equals to 333 kJ / kg, the heat hidden in vapour by evaporation from liquid water is by far larger, about 2.400 kJ / kg near freezing temperature. In the reverse process, vapour is condensed to fluid, and further the liquid water freezes to ice, and the “hidden” heat is released.

4) Exchange of energy by electromagnetic radiation and absorption between „surfaces‟. In the case of solar radiation, direct or scattered, absorption upon, inside or at the bottom of ice or

liquid water is relevant. In the case of terrestrial (infrared) radiation, the net flow of heat is directed from the warmer towards the cooler source of radiation.

Whereas the first three mechanisms of transfer of energy depend on substances, the fourth one depends on transparency and thus is effective even in vacuum.

Heat conduction is forced by a gradient in temperatures and results in internal heating or cooling respectively. Convection entails the movement of a heated fluid. Change of aggregate „hides" or „releases" heat due to intensified or reduced molecular motion. When the density of heat flow at a surface is a given a value Q, and the difference in temperature between (thermodynamic) systems is ΔT, then the coefficient for the exchange of heat is

$$\alpha = Q/\Delta T$$

The coefficient α characterises the exchange of heat in a specific situation. An increasing value of α describes an increasing exchange of heat between systems concerned. Bordering surfaces of a pavement, water in different phases, layered snow or ice, and air define different systems.

To sum up, the solid surface of the ground (in the present context, the contaminated runway) transforms different vertical fluxes of energy: It absorbs solar radiation and infrared terrestrial radiation from the sky, and it reflects solar radiation and emits infrared terrestrial radiation depending on surface temperature. By means of exchanges with the air by the turbulent transfer of sensible heat (measured using a thermometer), as well as latent heat attributed to water vapour (heat is concealed in evaporated water), and by molecular conduction, heat is exchanged between the atmosphere and the body of the runway. The budget of heat is crucial for the state of a runway contaminated by water because the water may exist as ice, liquid or vapour. The fluxes of energy (heat) may be given in units of Watt/metre^2 (W/m^2).

Surface temperature of a „black" runway may vary by several degrees over a distance of less than one metre in the horizontal plane due to varying heat conduction properties of the body. Areas with the poorest conduction will show the most extreme temperatures, thus becoming the first to experience hoar frost or to conserve ice when they cool towards the atmosphere, and the first to experience thawing when heated by fluxes from the atmosphere. (Quoted example: A heat isolated section of Svalbard Airport Longyear).

Evaporating snow or ice on the point of thawing may not melt when the air temperature increases less than a certain amount above 0 ºC. This is due to heat „concealed" in the vapour. Provided all heat is covered by the sensible flux in the air only, melting does not occur at air temperatures of less than 1.2 ºC when the relative humidity is 80% or vapour pressure 6.33 hPa, at less than 2.5 ºC when 60% or 4.39 hPa, at less than 4.2 ºC when 40% or 3.30 hPa. Thus an air temperature warmer than freezing does not necessarily mean a wet surface of snow or ice.

When the water vapour pressure in the air is low and the runway is wet, films of ice may occur even at reported air temperatures greatly exceeding freezing (at 2 m above ground). This may be caused by cooling due to intensive evaporation, perhaps aided by the degree of outgoing radiation (W/m^2) exceeding the incoming radiation. Thus, typically in warm and dry wind conditions, slippery surfaces may be encountered when they are hardly expected.

The thawing of snow or ice increases rapidly due to dewfall when the water vapour pressure exceeds saturation pressure at 0 ºC. Neither the amount of dew or rain, but rather the heat released from condensation of vapour to dew determines the degree to which contamination is transformed into slush, standing water on ice or simply liquid water. The amount of heat released by 1 millimetre of dew may produce up to 7 millimetres of melting water.

The latter important phenomenon can be seen from an estimate as follows: The temperature of frozen contamination cannot exceed 0 °C. When the dew point temperature of the adjacent air exceeds the temperature of the ice or snow, vapour will condense to dew, or to hoar frost at lower than freezing point temperature. The heat released by condensation, $2490 \cdot 10^3$ J/kg water (dew), related to the specific heat to melt ice, $333 \cdot 10^3$ J/kg, show that 2490 / 333 = 7.5 times the mass of dew can be melted. Consequently, a layer of 1 mm of liquid water would contain 1/7.5 = 0.13 mm dew, the rest be made up by melting water.

Dewfall or hoar frost demand a dew point or frost point temperature warmer than the ice. The air temperature cannot be lower (colder) than the dew- or frost point. Thus, the gradient of temperature cannot be directed from ice to air, as heat cannot flow by itself from a cooler towards a warmer body. That means that most of the heat released by the formation of dew or hoar frost will go to melting or, if below melting point temperature, go to warming the ice.

Irrespective of evaporation and frequently when solar radiation is absent, heat output from the runway through radiation exceeds input and the runway will cool off. This typically happens on nights when the wind is calm and the sky is clear. The air above ground is cooled from beneath, but differences in temperature between the surface and the 2 m level for the measurement of air temperature as given in METAR, may exceed 10 K. Except when there is strong turbulent mixing of the air and radiative fluxes are small, the air temperature reading at 2 m above ground is hardly representative for the runway surface temperature. Similarly, this applies to water vapour pressure or dewpoint temperature measured at the 2 m level. Therefore, observation close to, and at, the solid surface is required. When the surface temperature of the frozen contamination (derived from the infrared radiation) is known, then the saturation vapour pressure prevailing at the surface at that temperature is determined.

Table 1. Svalbard Airport Longyear

Air temperature T_{air} at 2 m level (shelter) at time of lowest runway temperature in asphalt $T_{asphalt}$
Sun below horizon, wind speed at 10 m height was less than 10 kt.
Number of cases: Overcast N=59, Fair N=72

T_{air} minus $T_{asphalt}$ Kelvin (K)	<-2	-2	-1	0	1	2	3	4	5	6	7	8	9	10	>10	
Overcast %	2	3	5	9	24	23	16	11	4	1	1	1	0	0	0	Sum: 100
∑ %	2	5	10	19	43	66	82	93	97	98	99	100				
Fair %				2	5	8	20	18	13	9	8	5	4	3	5	Sum: 100
∑ %				2	7	15	35	53	66	75	83	88	92	95	100	

Table 1 shows the frequency distribution in per cent (N cases) of the difference between air temperature at the 2 m level (shelter) and corresponding minimum runway temperature of the asphalt. The class interval is 1 Kelvin. „Sun below the horizon‟ excludes heating by solar radiation. When the wind is less than 10 kt the largest differences in temperature develop.

Positive differences show that $T_{asphalt}$ is less (colder) than T_{air} as may be expected when long-wave radiation is dominant and advection limited (wind < 10 kt). The running sum designated by ∑ shows that the median (50% cases smaller than, 50% larger than median) temperature difference was 2 K in overcast conditions, and 4 K in fair weather conditions. The lesson is that the lowest $T_{asphalt}$ under the conditions in question may achieve significantly lower temperature than indicated by T_{air}. As a consequence, freezing in wet conditions or deposition of liquid or solid water from vapour may occur, even though a significant „spread" is reported (METAR as observed 2 m above ground). The AIBN „3-Kelvin-Spread Rule" (chapter 9) may in part be explained by the vertical gradient of temperature together with the distribution of water vapour close to the surface.

Table 2. Svalbard Airport Longyear

Runway temperature $T_{asphalt}$ minus Runway temperature $T_{surface}$.
Sun below horizon.
Number of cases: N= 89

$T_{asphalt}$ minus $T_{surface}$ Kelvin (K)	<-4	-4	-3	-2	-1	0	1	2	3	4	5	6	>6	
	2	1	2	3	6	16	25	23	9	5	5	2	1	Sum: 100
∑ %	2	3	5	8	14	30	55	78	87	92	97	99	100	

Table 2 shows the frequency distribution in per cent (N cases) of the difference between runway temperature $T_{asphalt}$ and contemporary readings of runway surface temperature $T_{surface}$ as read from an infrared sensing device. Most often, $T_{surface}$ applies to ice. All cases refer to sun below the horizon and wind speed <10 kt. As observations refer to early winter or midwinter, integrated through time there is a flux of heat from the body of the runway towards the atmosphere (contrary to spring time when the flux is in the opposite direction). Hence median of the differences between temperature of asphalt and (minus) the difference of the surface is not zero, but moved towards +1 Kelvin. That indicates for the sample as a whole the asphalt to be warmer than the surface. In any case, the maximum temperature amplitude is to be expected on the surface as it is in direct contact with the atmosphere. The principle point here is that the runway temperature as obtained from the asphalt may deviate by several Kelvin from the surface temperature. The latter determines the deposition of dew or hoar frost and in some cases melting and even evaporation.

Snow and ice are more or less transparent to solar radiation. Therefore, when this radiation is absorbed beneath or between layers of frozen contamination, thawing may occur. Melting water, when exposed to shear forces, may act as a lubricant in the foot zones of the layers.

The horizontal fluxes of sensible and latent heat, called „advection", are carried by wind. For example, in the case of open water near a runway, the warm water surface may act as a source of water vapour (extracting heat from the body of water), the cold runway may act as a sink for water vapour, creating hoar frost (and releasing heat). Similarly, sensible heat may be carried by advection into or away from the runway area and be exchanged vertically.

The freezing of liquid water on a runway or on a frozen layer may happen quickly (in the order of one minute), depending on the overall heat budget. The time scale cannot be covered by inspection. However, freezing may be „nowcast" by estimating the heat budget or monitoring surface temperature at a representative site.

The different terms in the heat balance of liquid water in compacted snow or ice determine whether liquid water in the path of the wheels freezes or remains liquid. Initially wet compacted snow or wet ice will obviously remain wetted by liquid water when a wheel has passed, until conditions eventually allow for general freezing. „Dry" compacted snow or „dry" ice at temperatures below freezing may melt at the boundary due to the temperature of the tyre and immediately re-freeze leaving a transparent lamella of „even" ice. Frequent landings may result in a carpet of icy paths.

In any case, an intermediate film of liquid water between snow or ice and rubber will deteriorate the transfer of shear forces. In other cases, liquid water beneath a cover of snow or aggregates of ice caused by heat from below may be forced up by the wheels, possibly along with liquid water squeezed out from new fallen snow. Under such conditions, water accumulated in a path, is not water melted by the heat of the tyres alone. Dependent on the conditions to release sufficient heat to the atmosphere, and on the amount of liquid water accumulated and exposed to the atmosphere, freezing may not occur immediately after a wheel has passed but delayed over some time.

Frozen slush-like ice or compacted shiny snow may be left in the path after re-freezing. That way, icy channels may result. A more or less coherent pattern of mobilised and then frozen water results in a surface of uneven ice in place of what was initially a uniform cover of snow. When the conditions for freezing are not present, typically at air temperatures above freezing or when heat is being gained through absorbed radiation, liquid water may remain in wheel paths cut in snow or ice. Liquid water beneath snow and the contents of movable water inside the snow will represent potentially poor braking conditions anyway.

Finally, rain on frozen contamination contributes to the amount of water available, either as a layer upon ice or compacted snow, or merged with loose frozen material. Rain contributes very little heat to melt ice at 0 °C. That can be seen from the following estimate: The specific heat capacity of water is $c_{\text{heat cap water}} = 4.2 \cdot 10^3$ J / kg · K, the specific heat to melt, $c_{\text{melt ice}} = 333 \cdot 10^3$ J/kg. Therefore, the heat in rain at temperature $\Delta T = 1$ K above freezing or +1 °C would melt $(c_{\text{heat cap water}} \cdot \Delta T) / c_{\text{melt ice}} = 4{,}2 \cdot 1 / 333 = 0.0126$ times the amount of rain. That means, less than 1.3 per cent of the amount of rain at +1 °C would be released as melting water. Rain at 5 °C would melt about 6 per cent of the amount of rain.

In order to forecast („nowcast") a chosen critical runway temperature, for example 0 ºC, the cooling rate of a specimen may be observed. As in the case of a katathermometer, the time to cool from a given higher to a lower temperature is determined. Thus the flux of energy {(Watt · second)/m^2 } as a property of the thermometer or specimen is relative to the time of exposure to reach the lower temperature threshold. The cooling rate {Watt/m^2 } correlates with the time required to cool down to a certain temperature (freezing point).

To sum up, the heat budget of a runway surface, whether „black" or contaminated by water, triggers thermodynamic processes that affect braking conditions on ice or snow in sometimes unusual ways.

07 Application of sand

Main point: Sand in „fluid" environment (water, slush, loose snow) is ineffective.

The application of sand on ice or compacted snow is intended to enhance the exchange of longitudinal and lateral shear forces between the tyre and contaminated pavement, primarily by applying the principle of a toothed wheel. However, there is also a component of adhesion. The first-mentioned principle requires sharp-edged, wedge-shaped grains that intrude into the rubber and the ice. The grains may be bonded by freezing into the ice in advance. As the edge angle of a grain acting as a wedge decreases, the force on the ice increases for a given force exerted by a wheel. When the temperature of ice approaches melting point, the homologous temperature (see Appendix) approaches value 1 (= 273 K/273 K), the plasticity (irreversible deformation approaching liquid state) increases exponentially and the forces keeping a grain clamped fast in the ice weaken correspondingly.

Grains melt into the ice when warmed above 0 °C due to net heat gain, often a result of absorbed solar radiation. Regelation (lowered freezing point of ice due to pressure) is not significant. The force that may be transferred by grains bonded in the ice depends on properties of the (natural) ice. They result from the history of the ice‟s formation and its subsequent transformations that influence the shape and stability of the ice crystals and their aggregates. Towards the tyre, the shape and dimensions of the grains protruding from the surface of the ice are key to the exchange of retarding force by „formschluss‟ („toothed-wheel principle‟ in contrast to „kraftschluss‟ due to adhesion).Thus, recent weather history and runway preparations have an influence on the effectiveness of the sand application.

The sand is intentionally „bonded‟ to the contaminant by using either hot sand alone (on ice), or by applying hot water together with hot sand (90 °C to 95 °C). Experience, rather than theoretical considerations, seems to be essential. Grains of sand melting all the way into the ice would be ineffective. Hot water thaws the surface of the original ice and creates a new cover that must not hide the upper part of the grains. The tops of wet grains dry quickly at high temperature. Ice covering every grain has not been observed and, most likely, is not a problem. Because the thermal properties of minerals and water are different, the process of cooling may differ and be dependent on the mass of both substances. There seems to be no significant effect on the outcome, most likely because cooling happens quickly as the temperature of air and runway will be well below freezing. Heat, including freezing heat, will dissipate easily. Of course, bonded sand will be of no use when covered by snow, regardless of how many millimetres are applied, or when the sand becomes coated by ice as in the case when freezing rain falls.

In order to achieve a long lasting effect – allowing sweeping of snow several times – hot sand has to be brought out at low temperatures. They have to be sufficiently below freezing to get the foot of a grain incorporated into the crystalline structure of ice. However, even at melting point temperature, hot sand may improve aircraft braking coefficient when loose sand (as in most conditions) would be redistributed by braking wheels and give little effect. Obviously hot grains of sand melt depressions into the ice. Provided the ice is not yet disintegrated by melting water and not has attained a soft consistency, the grains withstand at least partially to be redistributed by a wheel but remain in their depressions. This is the case though the grains are not frozen into a fastened position. The experience may be explained by ice surrounding the grains still strong enough to pick up shear force, but also by adhesion of grains dipping well into the wet ice environment. In general, when melting is going on, the grains will attain the state of loose sand in due time. But for a specific landing on (near) melting ice, hot sand may be helpful for the occasion. In the case of very rapid melting (rain upon ice), the time needed to prepare a runway may become outdated by the melting process. But in such cases, the ice may be picked up mechanically.

Loose sand may be carried away by fluids in motion. These are air, in the form of wind or created by an aircraft operating on the ground (propeller, turbine, drag by an aircraft‟s body including rotating wheels), or liquid water, slush and movable snow (the latter is considered as a „fluid‟ in the present context). The main effect is due to the sand‟s buoyancy or mechanical resistance in relation to the enveloping liquid water or movable ice, but there is also an effect whereby the sand moves by virtue of surface tension in the liquid water. The specific weight of sand is typically about 2.5 g/cm^3 compared with 1 g/cm^3 for water, thus the net effect of gravity is reduced to only 1.5 g/cm^3. (For comparison, the buoyancy in air is negligible due to its low specific weight of 0.001 g/cm^3). Hence, grains of sand are quite easily moved when water is pushed away by wheels. In slush and snow, the particles of ice prevent sedimentation of sand. The grains may follow the forced motion of slush or snow. Sand blown or pushed away is of no use, and the same applies for sand buried in ice, in compressed slush or snow-captured under wheels.

On hard ice, loose rounded grains may act as ball bearings. Grains bonded to a tyre by adhesion (when liquid water is present) and following the wheel‟s rotations possibly have a similar effect. Visual examination shows that trails partially cut, partially melted by grains of sand sliding along the ice are only cut by sharp-edged grains. These grains are moved by a wheel‟s longitudinal and lateral forces. Sliding grains are, after all, those that contribute most to improving the aircraft braking coefficient. Grains pressed into ice as wedges are an exception, and are likely to occur at weak locations on generally hard ice at low temperatures. In other conditions the mechanical strength of the frozen aggregates may be insufficient to counterbalance the tyre‟s pressure on grains. This is the case for ice exposed to melting and for compacted snow. Grains forced into and hidden inside a frozen contaminant will become ineffective for further braking.

For aircraft, the amount of grains pushed away from a wheel‟s path by forces transmitted by air, liquid water, slush or snow exceeds the amount of grains that are displaced by, and influence the outcome from, friction measurement devices. Therefore sanding may be reported to improve „braking action‟, whereas this is not true for an aircraft.

The horizontal and partially vertical displacement of sand and loose snow or aggregates of ice due to the slip of a wheel can be studied when the particles are dyed. At its front, some grains only seem moved forward and forced down into the contamination, thus potentially increasing friction. But most grains are pushed aside. When the main force has passed, grains are lifted and then settle on both sides of the wheel‟s path. The total outcome is therefore redistribution of the particles off the wheels track.

Grains intentionally bonded in ice may „melt out‟ and become loose due to different meteorological conditions including absorbed solar radiation or rain. Patches of accumulated dry sand on ice containing thermal isolating air may favour the conservation of ice by virtue of a small degree of thermal conductivity (0.1 to 0.3 W/ mK). Wet sand including water will facilitate melting by increased thermal conductivity (0.4 to 1.2 W/mK). A thin film of very fine sand (with little hollows), combined with a net gain of heat through radiation will also facilitate melting.

Grains of sand jutting out from the level of ice or compacted snow represent small obstacles to windblown snow. The fragments of ice crystals start to accumulate on the leeward side of the grains. The sensitivity of loose sand to being blown off by wind, or generally by air in motion, depends on the vertical gradient of velocity in the boundary layer, in the present context defined by the grains‟ geometry. The force from the airstream acting on the grains depends on the area of the grain exposed frontally to wind and the drag behind. The weight of the grains resting on the ice, or their adhesion to the ice, and the adhesive forces from a film of liquid water will be decisive whether an air stream may move the grains or not. The forces of air in motion acting on the grains depend on the relationship between the surface on which the forces act and the mass, and on the friction of rest between the grains and the ice or compacted snow or, for example, a film of bonding liquid water on top of ice.

The surface of a sphere increases with the square of its radius, whereas the volume increases with the cube. However, an exponential growth of the effective wind force with the height of a grain may cancel out the increase in mass or friction of rest by increasing the radius, and thus the height, to a certain magnitude. An applied force transferred by air in motion may sort grains according to size and weight. For various reasons, not least damage to an aircraft, large grains have to be excluded. As the mass (weight) of a grain increases by 3rd power while the wind surface increases by the 2nd power the weight of a sphere, density 2.5 g/cm^3, radius 0,01 cm would be 0.00001 g, where as radius 0.1 cm results in 0.01 g, and for a stone radius 1 cm in 10 g. The surface of corresponding spheres would be 0.0013, 0.13 and 13 cm^2 respectively. However, the vertical wind profile increases exponentially. The larger the grains, the stronger are the wind force exposed to in their top region. But that effect increases less than the force needed to move the grains. Deflation, saltation, and reptation (see Appendix) define a lower limit in the fraction of sand to be applied in strong wind. There is an upper limit in grain size limited by engine tolerances. Hence, there is an „optimal‟ range of grain sizes.

On the other hand, qualitative studies at Svalbard indicate that fine grained sand with a large surface relative to volume shows good adhesive properties vis-à-vis ice and rubber. Adhesion (especially when wetted), combined with the small dimensions of the grains may prevent the fine fraction of sand from being blown off. Salt water entered with strong wind from the sea improves the adhesive power on the grains. At Svalbard Airport Longyear good results were obtained with a fraction of sand measuring approximately 0.1 to 1.3 millimetres. The finest grains may bind a considerable amount of liquid water. An increasing proportion of water results in an emulsion that works as a lubricant on ice or even on the actual pavement of asphalt or concrete.

When ice has evaporated and dry sand still covers the runway, there may be distinguished between at least two fractions of residue put into motion by a rolling aircraft: 1. Grains of sand pushed along the ground or following through air the path of a projectile, 2. Dust suspended into the air, then sedimenting slowly along trajectories determined by the wind. The result is a very thin coat of dusty debris covering grains of sand as well as the pavement. That coat of mineral dust is hardly removed by washing in water. From that may be concluded that a layer of dust strongly attached to the surface of a runway by forces of adhesion may not result in a lubricating layer when damp only, not forming a mush in water.

Measuring the electric field at Svalbard Airport Longyear 38 m off the runway showed a cloud of dust charged negatively when passing the site of measurement, the ground charged positively. From this may be deduced that debris of fine dust may be attached electrostatically to the pavement. An analogous electrostatic effect may be expected when very small particles of ice (snow) get dragged into the air and settle upon compacted and polished snow. However, no ABC-improving impact could be shown.

Sliding grains of sand may clean off their coat of dust as well as dust at the surface of the pavement. That leveled dust may be accumulated in cavities between asperities. Removing sand from a runway may result in a pavement grinded off the dust and thus in effect reduce ABC. More, accumulations of loose dust may act lubricating when bloated in water.

Rounded grains of sand may, after skidding to begin with at a certain speed, act as ball bearing beneath the footprint of a tire. Therefore, natural sand formed by water or wind should be less suited to augment friction than sand produced by crushing rock. The normal force to press a grain as a wedge into the ice, increases with decreasing angle of the cutting edge. When the normal force is put unit 1 for an angle 180 º, the multiple for 120 º is 1.15, for 90 º 1.40, for 20 º 5.90. Grains of sand, pushed by tires and skidding on ice, get caught up by a tire‟s tangential speed and pressed into tire‟s rubber and the contamination.

A ball shaped grain put into skidding will change to pure rolling at a speed depending on the velocity when pushed ahead, independent of the coefficient of sliding friction. Calculating for a ball, when the starting speed of skidding is 17.5 m / s, pure rolling would onset at 12.5 m / s. The period of skidding before rolling would be 10 seconds and the distance 150 m. A surface covered by ball shaped grains would not start rolling at once, for example the at the point of setting. As follows from theory, the tangential force for a rolling ball to overcome an obstacle of given dimensions has to increase with decreasing radius of a ball. The chance for a rolling grain to become stopped by surface roughness and to transfer shear force from a braking wheel thus increases when the ”ball” is small.

08 Chemical treatments

Main points: Salts may be used to either prevent liquid water from freezing or from thawing frozen water. The dosage of chemicals is difficult to adjust to weather conditions; the outcome may be contrary to the intention. Salts may corrode aircraft and airfield infrastructure.

According to Raoult‟s Law, the freezing temperature of certain salt solutions is depressed proportional to the concentration of the salt dissolved. The coefficient of proportionality depends on the property of the solvent. The vapour pressure at the surface of the solution is lower than within the pure solvent because of forces of attraction on the dissolved molecules. Therefore, surfaces covered by a film of such chemicals may look „wet‟ as they attract atmospheric water. Relationships become complex when water is dominated by salt in high concentrations.

These properties can be applied either to prevent ice formation on a runway or to melt ice that has been formed earlier. In the first case, the chemical may be called „anti-icer‟ (preventing ice formation), in the second case, „de-icer‟ (removing ice). Consequently, there are two strategies: one is to prevent the accumulation of frozen water, and the other is to get rid of already accumulated ice or compacted snow. The optimum strategy is a question of climate and specifically, weather forecasts and real time changes in the weather hour by hour, together with financial considerations.

The first strategy is aimed at covering up, and, as time goes by, maintaining the cover on „black‟ runways by applying fluid anti-icing chemicals. The applied concentration, therefore, must be sufficient to melt several successive occurrences of solid precipitation, or the diluted chemical must be supplemented by new applications of a more concentrated solution in due course.

The second strategy is based on (wetted) granulates. Through a combination of melting and gravity, the particles penetrate an accumulated layer of ice or compacted snow. The solution then is intended to be applied at the level of the „black" runway, to melt and to release ice from the pavement and to allow removal of flakes of ice or slush mechanically.

When a salt is applied to ice, the ice will melt provided that the freezing temperature of the solution is lower than that of the ice, i.e. 0 ºC (normal conditions). As melting water dilutes the salt solution, the freezing temperature rises. In addition, the heat needed to melt the ice will reduce the temperature of the aqueous (watery) solution. Therefore, the eutectic temperature, the lowest freezing temperature of a (saturated) solution, cannot be exploited completely. For example, in the case of technical urea $\{(NH_2)_2CO\}$, the eutectic temperature is minus 11 ºC, but urea cannot be effectively used to melt ice below a temperature of about minus 6 ºC. Some heat is needed to dissolve solid salt.

The salts used commonly on runways are based on potassium formate $CHKO_2$, potassium acetate CH_3OOK, sodium formate HCOONa, or sodium acetate CH_3OONa, all of which have much lower eutectic temperatures (lowest freezing points) than technical urea: formate products minus 50 ºC to minus 60 ºC, sodium products minus 20 ºC to minus 25 ºC. Typically, the freezing point for products with a concentration of 20 weight % is about minus 12 ˚C, at 10% concentration it is about minus 5 ºC, and at 5% the freezing point is about minus 2 ºC. Potassium-based salts in concentrations of 30 weight % reach freezing points at around minus 20 ºC to 22 ºC, while concentrations of 40% freeze at minus 40 ºC. Effective melting is likely to be limited to minus 30 ºC, and, as a general rule, to a temperature of half the eutectic temperature.

The ADDCON product Aviform L50, for example, is a 50 weight % potassium formate solution with a freezing point „below" minus 50 ˚C, and a typical pH value of 10.9 to 11.4. At minus 2 ˚C, the amount of melting water in relation to the agent applied (in grams) is 3 after 5 minutes and as high as 7 after 30 minutes. At minus 10 ˚C, the proportion of water to agent would be 2.5 after 5 minutes and 3.5 after 30 minutes. Aviform S-solid contains more than 97 weight % sodium formate and 1 to 3% corrosion inhibitor. The freezing point of the 25% solution is minus 19 ˚C. Similarly, the KEMIRA product Clearway F1, made from potassium formate and corrosion inhibitors, has a freezing point of „less" than minus 50 ˚C, and a pH of 9.5 to 11.5. The same freezing points are indicated for potassium acetate based Clearway 1 and 3, whereas the freezing points of the solid Clearway SF3 based on sodium formate and Clearway 6s based on sodium acetate are approximately minus 18 ˚C at concentration 23 weight %. Another manufacturer, Clairant, makes the Safeway series. Competition apparently revolves more around the commercial conditions than the products" properties. At present (year 2010), every Norwegian AVINOR-owned (state-owned) airport uses Aviform products (fluid L50 and solid S-Solid), but sporadically other products may be applied.

All the commercial salts contain additives to reduce corrosion (due to *inter alia* electrical installations in the wheel wells are exposed). The typical pH value is in the order of 10. (The pH value is defined as the negative decade logarithm of an ionised hydrogen concentration. A pH of 7 indicates a neutral solution; lesser values are acid, larger values show a basic reaction when dissolved in water).

The effect of runway de-icers and anti-icers depends on a variety of environmental conditions such as „spread" (humidity), wind, radiation balance and precipitation, as well as the addition of melting water. The precise extent of these variables is rarely known. Hence the dosage of chemicals is often a question of best guess and experience. The preventive use (anti-ice) of chemicals to avoid ice generally requires lower concentrations than those required to melt ice (de-ice). Pre-wetting pellets or the combination of chemicals may intensify the effects.

From experience and theoretical considerations, when considering all the usual chemicals together, approximate dosages as given in Table 3 below in g/m^2 may be applied:

Table 3. Approximately dosage of chemicals.

	Dry conditions		Humid conditions	
	Propensity to soft ice <1 mm		Propensity to hard ice <1 mm	
	preventive	curative	preventive	curative
Temperature ˚C:				
0 to minus 5	20	25	20	30
minus 5 to min. 10	25	30	30	40
min. 10 to min. 15	30	40	40	50

	Humid conditions		Humid conditions	
	Loose or compacted snow		Freezing rain or ice 1-3 mm	
	preventive	curative	preventive	curative
Temperature ˚C:				
0 to minus 5	30	40	40	50
minus 5 to min. 10	40	50	50	60
min. 10 to min. 15	50	60	60	60

In the case of a wet runway, 10 to 15 g/m^2 may be sufficient for preventive purposes. The same concentration may be used for corrective purposes in the case of hoar frost. Some minor deviations of composition may apply.

To prevent fast run-off and to lengthen holdover time, viscosity and specific weight greater than that of water may be an advantage. Dynamic viscosity η (referred to in chapter 11) can be understood as follows: Shear tension $\eta = F/A$ when F is force (unit Newton) and A is area (unit m^2). Shear gradient $D = \Delta\ v/\Delta\ x$ when Δv signifies a difference in velocity (unit m/s) across a difference Δx (unit m) in distance, hence a unit of D is 1/s. As $\eta = \eta/D$, dynamic viscosity has unit (N/m^2) s equivalent to a Pascal second (Pa s). The dynamic viscosity of acetates at 0 ºC is in the range 10 to 50 mPa s (milli-Pascal second; 1 Pa s = 1 N/m^2); of formates at 0˚C: 3 to 4 mPa s; of water at 0 ºC: 1.8 mPa s. The specific weight of the liquid, for both acetates and formates, is in the range 1.25 to 1.35 g/cm^3. Thus both properties have values exceeding that for pure water.

Principally, anti-icing or de-icing chemicals contaminate the „black" runway and are likely to reduce the adhesive effect of asperities on tyres, except when cleaned mechanically by traffic. In any case, the use of chemicals acts to reduce the braking characteristics of a pavement, though to a much lesser extent than frozen water. Some solution may stick to tyres and thus create very slippery conditions if the tyres should come into contact with the frozen contaminants. A similar effect is known to occur when recently precipitated snow contains sea salt. Slippery episodes are suspected to have been caused by the increase in viscosity at low temperatures of chemicals that have not been removed.

It becomes a matter of urgency to remove a diluted solution when the freezing point of the solution increases (gets warmer). Diluted chemicals may freeze and become unusually hard („black") ice with strong bonds to the pavement. Such freezing is not a rare occurrence. To optimise the amount of chemical applied, it would be necessary to be able to forecast prevailing temperature and the quantity of melting water. For example, when 20 g/m^2 of liquid anti-ice chemical has been applied and falling snow of 1 millimetre water equivalent (corresponding to 1000 g / m^2) has been melted, the dilution reached will be 2 weight %. It may freeze in the temperature range of minus 0.5 ˚C to minus 1 ºC.

Dilution will happen sooner or later, even when more (expensive) chemical per area is used preventively. Apart from the freezing risk, non-removal of a diluted liquid contaminant increases the risk of aquaplaning on accumulated melt water that has not been drained off.

As saturation vapour pressure at the surface of the solution is reduced with respect to liquid water or ice, dew will form when the actual vapour pressure in the air exceeds the pressure on the solution. This may frequently be the case as a film of saturated vapour that adheres to precipitation or accumulated frozen (wet) water should be expected. Even though the contribution of dew diluting the salt solution may be negligible, the amount of heat released may contribute considerably to melting the ice.

Occasionally, some small rise in runway temperature can be observed when a liquid chemical has been applied. This may possibly be explained by meteorological conditions, such as an increase in absorbed radiation, or possibly by dew fall. Commonly, a decrease in temperature occurs. The extent will depend on the chemical and the intensity of ice melting. Initially, the potassium salts tend to melt quickly, but this rate of melting tapers off, whereas sodium melts less quickly but with even intensity.

Liquid chemicals must not be used on accumulated ice or compacted snow. The reason for this is that a film of any chemical, even when diluted, combined with melting water, would create an intermediate layer with little capacity to transfer shear forces. It would also melt away asperities in the frozen contaminant. However, granulated chemicals together with liquid chemicals may be applied to melt heavy ice (more than 3 millimetres thick) quickly. The runway is closed during this process.

In frequent traffic it might be observed that diluted chemicals that normally would be expected to freeze at the actual air temperature may remain liquid. It is assumed that heat from roll-over and exhaust from the engines may prevent freezing in such cases.

Much attention is given to the biological environmental effect of the chemicals, expressed in mass oxygen demanded per mass of de-icer as an indirect measure of organic compounds in water. The best relationship is that for potassium formate, 0.1, whereas potassium acetate has 0.3, compared to 2.2 for technical urea. This is the main reason for not using urea, despite it being less expensive than the other alternatives, even if temperatures would allow it. Its main use is as a nitrogen-releasing fertilizer.

Acetate, on the other hand, in contrast to urea, causes disintegration of pavement, bitumen and asphalt concrete, and even results in loose stones. Corrosion of exposed aircraft components has also been reported when acetate as opposed to urea is used. The Society of Automotive Engineers Aerospace, together with Star Alliance and Continental Airlines, in a recent update presented in Berlin by Ed. Duncan, identified the corrosive effects of potassium acetate, potassium formate and sodium acetate that cause damage to aircraft landing gear systems, switches, relays and the electronics of electrical systems. The scale of damage includes the shorting of electrical systems as well as corrosion of composite material and harm to the anti-slip properties of flight deck coatings. There may also be damage to airport infrastructure.

However, as demonstrated by the Runway Deicing Commitee by E. Duncan at the Montreal-meeting November 4th 2010, research is done to allow relative ranking of runway deicers with respect to expected corrosiveness as well as to develop runway deicers less destructive to pavement and aircraft. Fighting ice at runways may in future be left to other substances as organic salts due to their electrolytic character are prone to act corrosive.

In the case of carbon brake catalytic oxidation damage breakdown and failure are unpredictable. Whereas the rate of carbon oxidation is of little concern in the case of urea, a loss of strength is likely or even significant for generic potassium acetate, and very significant or even causing total carbon brake destruction for generic potassium formate. Work is done to standardize specific tests as for example the procedure for cadmium corrosion, emphasizing what actually happens to exposed materials during winter operations over time.
There is a need for agreement in testing the outcome of different melting procedures (ice melting -, ice penetration - , and ice undercutting method) applied in various conditions.

Another item is the aerodynamic effect of residue upon an aircraft exposed to spray or jet blast from slush or standing water containing de-icing or anti-ice chemicals. Both operators and manufacturers of aircraft cooperate. The strategy is to avoid banning of any existing runway chemical, rather to guide purchasers and to encourage the development and marketing of less damaging chemicals.

09 The AIBN '3-Kelvin-Spread Rule'

Main point: Poor braking is often associated with moist atmospheric low-level conditions and constitutes a small „spread‟ that can be used to notify of hazardous conditions.

The relevant rule states: When the „spread‟ (air temperature minus dewpoint temperature read at level 2 m) is less than 3 K, compacted snow or ice may constitute slippery conditions.

The rule intends to call attention to the possibility of poor braking action. It has been derived from findings by the Accident Investigation Board of Norway (AIBN), and is based on a majority of cases when frozen contamination was a cause factor of incidents or accidents.

The rule may be read as follows: When the dew point reported for 2 m above ground, as given in METAR, is approximately 3 K or less below air temperature at the same level, the likelihood that frozen contamination may represent slippery conditions increases. This applies especially at air temperatures lower than plus 3 °C. It covers cases of current or recent precipitation, snow containing liquid water, as well as cases when the surface of frozen contamination is considerable colder than the air 2 m above. Densification of water vapor to liquid or solid state at the surface may occur. The rule covers even other physical conditions that may cause small coefficients of friction. The rule is to be understood as an indication, but not as absolute. An example showing the importance to distinguish between dew point and frost point temperature at low air temperature is the case 1) presented in chapter 13.4 when reported (rounded) temperature was minus 14 °C and dew point was minus 16 °C. The dew point spread was 2 K while the frost point spread was approx 0.5 K.

It has to be borne in mind that the „spread" reported always refers to liquid water, even at temperatures below freezing. The „spread" related to ice as compared to liquid water shrinks as temperatures decrease. That means the ratio of the saturation vapor pressure over water to that over ice at the same temperature is at 0 °C 1.00, at minus 10 °C 1.10, at minus 20 °C 1.22, at minus 30 °C 1.34. As pointed out in chapter 04 and is seen from chapter 15.1 (appendix), head word „frost point temperature", as a rule of thumb water vapor will be saturated in respect to ice at roughly minus 9 °C when „spread" (in respect to liquid water) is reported as 1 K, at minus 17 °C when spread is reported as 2 K. At minus 30 °C vapor would be saturated in respect to ice when „spread" reported is as large as 3 K. These relations apply when the surface of a pavement is colder than air in the 2 m-level and is effective as a sink of water vapor by deposition of hoar frost (deteriorating braking action). The „rule of thumb" may also be expressed as „the frost point spread decreases by 1 K pr 10 °C below freezing". The mass of water involved can be read from chapter 15.1 (appendix), headword „mixing ratio".

The empirical setting.

"Spread" 3 K or less means large relative humidity

A "spread" of 3 K or less means air containing water vapor not very far from saturated. For example, at air temperature 0 °C the saturation vapor pressure over water is 6.108 hPa, the corresponding figure at -3 °C is 4.898 hPa. Hence a "spread" of 3 K or less would mean relative humidity (4.898 / 6.108) · 100 = 80 per cent or more. At - 27 °C and - 30 °C the corresponding figures are 0.673 and 0.509 hPa, thus a "spread" of 3 K at air temperature -27 °C would mean a relative humidity of 76 per cent or more.

"Spread" 3 K or less indicates likely precipitation

Often a "spread" less than 3 K occurs in precipitation, intermittent precipitation, precipitation in the vicinity or in conditions of possible fog. At least, an air mass relatively close to saturated vapor is indicated. How that atmospheric condition may affect braking conditions is not considered by the rule of experience. But actually, incidents due to insufficient friction were often linked to precipitation or deposition of water, liquid or frozen. The validity of the rule may depend on its correlation with precipitation. But it may also, at least in part, depend on the exchange of water at the air-ice interface.

The 3 K-spread-rule does not cover close to surface phenomena.

Besides the input of water by precipitation, the transport of water vapor to or from the surface of frozen contamination affects aircraft braking coefficient. Evaporation or deposition of dew or hoar frost is not explicitly considered by the rule. Its aim is an easily accessible over all indication. The rule does not imply any details as the vertical gradient of vapor pressure between saturated vapor in respect to liquid water or ice at the surface and observed air temperature and dew point at the 2 m level. Except for effective eddy mixing by wind, strong gradients in air temperature and vapor pressure will prevail close to a surface of contaminating frozen water. A frozen surface will represent saturation vapor pressure conditions over ice.

"Spread" related to frost point is less than related to dew point.

Readings of air temperature and humidity at 2 m above ground rarely represent surface conditions. Actually the 2 m level has been chosen to achieve data representative on a far larger scale than relevant in the present context. Due to lack of surface data, the 2 m level figures have to serve as indicators concerning the surface level.

As air temperature and dew point are reported in rounded figures only, the actual spread may be less than given. More, the dew point temperature (related to vapor saturated over liquid water) by international agreement is reported even at temperatures below freezing. Due to the lower saturation pressure over ice than over liquid water at a given temperature, the “spread” in respect to dew point exceeds “spread” in respect to frost point. That means the figure of “spread” reported is larger than the relevant one in respect to ice. “Spread” related to frost point may approach zero though “spread” related to dew point may indicate a figure of 1 or 2 K.

Three-Kelvin-Spread as a rule of thumb.
In spite of all these and other details not explicitly taken into account by the 3 K spread rule, it should be considered as a valuable tool, easy to adopt, but not absolutely valid. The rule turns out to be useful on the purely empirical level. However, the fact that 2 out of 3 incidents related to braking upon ice or snow correlate with “spread” 3 K or less, must not hide from consciousness all the cases of uneventful landings on ice or snow in conditions of a small “spread”. Therefore, a small “spread” must not mean definitely poor runway conditions, but be taken as a signal of alert.

The physical setting - interpretations of 3 K “spread”.
A “spread” of 3 K can be interpreted in different equivalent terms. By definition “spread” means that air temperature is 3 K above the dew point temperature. That is to say that actual vapor pressure is the saturation pressure in respect to water at 3 K lower than the air temperature observed. In terms of the mixing ratio (mass water vapor in respect to mass dry air) “spread” 3 K says that the mass of water vapor given would be saturated vapor at an air temperature of 3 K colder than the observed one.
As the rule says “3 K or less”, the whole interval from 3 K to 0 K is included. In terms of mixing ratio this would mean that saturation may have occurred at air temperature given, or utmost would occur when the air temperature had decreased by 3 K. In the first case, “spread” 0 K, cooling of the air by 3 K would mean to remove an amount of water vapor equal the difference between the saturation mixing ratios at the two temperatures of 3 K difference.

Saturation vapor pressure as a function of air temperature.
Though super cooled water (liquid water at temperatures below freezing) is quite common in clouds, the state of aggregate at the ground is often ruled by freezing below 0 °C. Therefore the frost point temperature may apply concerning to physical processes on a runway, though dew point temperature is reported. In table 1, as a basis for calculation, the saturation vapor pressure above ice and water is given in columns (II) and (III) dependent on air temperature in column (I). The difference in saturation vapor pressure between ice (II) and liquid water (III) is found in column (IV).
The largest absolute differences exceeding 0.260 hPa occur in the interval of temperature -10 °C to -14 °C. The smaller differences in pressure over water and ice at lower air temperatures than -15 °C result from decreasing absolute figures of saturation vapor pressures. However, the differences between saturation vapor pressure over water and ice expressed in per cent of one of the saturation vapor pressures, here chosen over liquid water, column (V), increase with decreasing air temperature. These figures (V) mirror the increasingly strong bonds of water molecules to the ice with falling temperature.

Saturation mixing ratio as a function of air temperature.
In order to quantify the amount of water that may be covered by the 3 K-spread rule, the saturation mixing ratio at 1 000 hPa over ice (VI) and over liquid water (VII) are given. The

difference of these figures for ice and liquid water are found in (VIII). Logically, as for the differences in saturation vapor pressure, the largest differences in gram water vapor (referring to 1 kg of dry air) over ice and water are found in the temperature interval between -10 °C and -14 °C. From (VI) and (VII) is seen that the mixing ratio at - 3 °C is about the factor 10 larger than at - 30°C. Already for that reason, one may not expect that the 3K-rule based on a certain fixed "spread" should be valid for any temperature.

The divergence between dew point and frost point temperature.
As saturation vapor pressure, logically also the saturation mixing ratio, over liquid water exceeds the corresponding figures over ice, the frost point temperature for a certain quantum of air is at a higher (warmer) temperature than the dew point. Reading the temperature in column (I) as dew point, the corresponding frost point temperature is found in (IX), the difference between dew- and frost point temperature in (X). As a rule of thumb, the difference is in the order of factor 0.1 K multiplied with the (negative) figure of dew point temperature on the Celsius scale. For example, when dew point -15 °C is reported, the frost point may be expected at about 1.5 K towards the warmer side, at about - 13.5 °C.
The 3 K-rule refers to dew point. Applied to frost point that may be the essential figure as to runway conditions, the actual spread in the example would be 1.5 K only. When the dew point decreases towards lower (colder) figures, the 3 K "spread" interval actually shrinks in respect to frost point. This may make the rule applicable even at temperatures as low as perhaps -15 °C when other effects (see 3.6) should be considered.

Corresponding changes in air temperature and saturation mixing ratio.
In table 2 the differences in saturation mixing ratio for steps of 3 K temperature (line I) are given in respect to ice (II) and to liquid water (III). The table may be interpreted as maximum amount of water removed from the air (gram water / kg dry air) when the reported "spread" is 3 K or less and air temperature decreases by 3 K. When "spread" is 3 K and temperature drops by 3 K, no water will be removed. However, when actual "spread" is 0 K, then the amount of water equal the difference of saturation mixing ratio in the 3 K temperature interval will be removed as the case of maximum. For example, at air temperature – 3 °C and "spread" 0 K, a drop in the temperature by 3 K, from – 3 °C to - 6 °C, would mean removed water vapor 0.676 g / kg over ice and 0.625 g / kg over liquid water. The actual amount will differ as to the interval of "spread" of 3 K or less.
As is seen from table 2, the saturation mixing ratio over ice decreases stronger (the changes for 3 K dropping temperature are larger) than over liquid water at temperatures warmer than - 13 °C. This is consistent with the saturation vapor pressure over ice less than over liquid water, table 1, (II), (III), (IV). Towards lower temperatures, the decrease of saturation mixing ratio over water is in excess of that over ice as the air in respect to liquid water is dried up less at higher (warmer) temperatures than in the case of ice. As shown for the saturation mixing ratio at a given temperature, the changes in the saturation mixing ratio due to changes (3 K steps) in the temperature decrease by a factor of roughly 0.1 when temperatures near freezing point are compared with about -30 °C. This again underlines that small amounts of water vapor are involved at low a temperature, though "spread" may be small.

Low temperature limit of the 3 K spread rule.
With decreasing temperature, the frictional properties of ice or compacted snow improve considerable. (At – 30 °C the aircraft braking coefficient on pure ice may be as good as in cases with icebound sand). Therefore at temperatures below perhaps -15 °C, the 3 K-spread-rule may lose its practical meaning in dry and near calm weather. However in the case of precipitation including debris from blowing snow, improving frictional properties cannot be

expected due to an intermediate layer of lose frozen material. Very slippery conditions may prevail on ice or snow exposed to the polishing effect of blown particles of ice, especially at low temperatures.

Table 4:

The dependence of water vapor from air temperature
Column (I) air temperature in °C, or dew point temperature related to (IX) and (X).
Column (II) saturation vapor pressure in hPa over ice.
Column (III) saturation vapor pressure in hPa over liquid water.
Column (IV) difference (III) – (II) in hPa.
Column (V) difference (III) – (II) in per cent of saturation vapor pressure over water.
Column (VI) saturation mixing ratio at air pressure 1000 hPa in g water / kg dry air over ice.
Column (VII) as (VI), but in respect to liquid water.
Column (VIII) difference (VII – VI) in g water / kg dry air.
Column (IX) corresponding frost point temperatures in °C when temperatures column (I) are read as dew point temperatures.
Column (X) absolute difference dew point (I) – frost point (IX).

(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)
-30	0.380	0.509	0.129	25.3	0.238	0.318	0.080	-27.2	2.8
-27	0.517	0.673	0.156	23.2	0.323	0.421	0.098	-24.4	2.6
-24	0.699	0.883	0.184	20.8	0.437	0.552	0.115	-21.6	2.4
-21	0.937	1.150	0.213	18.5	0.586	0.720	0.134	-18.8	2.2
-18	1.248	1.488	0.240	16.1	0.781	0.931	0.150	-16.2	1.8
-15	1.652	1.912	0.260	13.6	1.034	1.197	0.163	-13.4	1.6
-12	2.172	2.441	0.269	11.0	1.360	1.529	0.169	-10.7	1.3
-9	2.837	3.097	0.260	8.4	1.778	1.941	0.163	- 8.0	1.0
-6	3.685	3.906	0.221	5.7	2.310	2.450	0.140	- 5.3	0.7
-3	4.757	4.898	0.141	2.9	2.986	3.075	0.089	- 2.7	0.3
0	6.108	6.108	0	0	3.839	3.839	0	0	0
3	-	7.575	-	-	-	4.769	-	3	-

Table 5:

Changes in air temperature and corresponding changes in saturation mixing ratio at 1000 hPa.
Line (I) air temperature in °C.
Line (II) change in saturation mixing ratio in g water / kg dry air over ice for a 3 K-decrease in temperature.
Line (III) as (II) but in respect to liquid water.

(I)	3	0	-3	-6	-9	-12	-15	-18	-21	-24	-27	-30
(II)	0.930	0.853	0.676	0.532	0.418	0.326	0.253	0.149	0.195	0.114	0.085	
(III)	0.930	0.764	0.625	0.509	0.412	0.332	0.266	0.211	0.168	0.131	0.103	

10 The effect of wind

Main points: Windblown snow polishes ice or may constitute planing conditions. Gusty wind implies the risk of sudden cornering forces. Landing calculations should be based on 10-minutes-wind rather than on “wind now” alone.

There are at least four effects of wind on braking conditions when there is frozen water contamination.

Firstly, the pattern of accumulation of drifting or blowing snow („blowing" includes in this case precipitated snow) has already been dealt with in the last paragraph of chapter 4. Grains of sand as well as the surface texture of the pavement in combination with turbulent wind may result in shallow patterns of accumulated snow. They may not be removed by sweeping and ultimately they result in patches of heavily compacted snow transformed into ice.

Secondly, there is a polishing effect due to the movement of fragments of ice crystals on the surface of frozen water.

Thirdly, wind exerts a force on an aircraft and that has to be transferred to the ground.

Fourthly, at high wind speeds in excess of 25 to 30 kt, at low temperature and with a heavy load of ice particles, an aircraft may plane on the aerosol. The latter (fourth) phenomenon is not discussed here but in chapter 11, together with planing by other causes such as slush or hoar frost on ice.

In detail, the second phenomenon, polishing, depends on the fact that ice hardens with decreasing sub-zero temperatures, and the molecular film of liquid water likely to have formed on top of the ice disappearing at low temperatures. Therefore, friction related to the microtexture of frozen water usually improves with decreasing temperature (below minus 15 ºC to minus 20 ºC). This holds true in more or less calm weather where there is no drag on ice particles. However, snow moved by sliding and skipping over a period of hours polishes the microtexture.

Qualitative observations (by magnifying glass) indicate that a visible abrasive effect may be accomplished quickly, within half an hour. The time span clearly decreases with temperature and increasing wind speed. These findings are reasonable from the point of view of increasing the hardness and kinetic energy of the ice particles.

The polishing effect is confirmed by several cases of skidding on contaminated runways exposed to snow carried by wind (chapter 13), which were unexpected because of the low temperatures.

The third phenomenon, cornering, results from the force of wind acting on an aircraft. That force (dealt with in chapter 01) has to be transferred to the solid runway. Cornering is a rather complex process when the variability of the wind vector is taken into consideration. The turbulent flow of the air may be understood by drifting „bodies" of air at different speeds and densities (which entails different temperatures) relative to each other. The „bodies" of turbulence may be considered as vortices. In the atmosphere, these occupy a very wide spectrum of different geometric dimensions. The vortices are broken down by internal friction in the air and by shear force towards the earth"s surface; these processes dissipate heat. Changes in the wind vector relevant for aircraft landings take place at random. In frontal zones or topography prone to induce special vortices, wind speed may change by 30 kt/10 seconds and switch to the opposite direction under extreme circumstances.

Again, the fourth phenomenon, planing on an aerosol as a result of windblown snow being captured between pavement and tyre, is dealt with in chapter 11.

The wind vector, especially the cross wind component, may decide whether the expected aircraft braking coefficient is considered to be sufficient or not. Therefore, even in the present context, information is needed concerning likely adverse wind to be prepared for. At aerodromes, the vector of „surface wind‟ is monitored by a sensor 10 m above ground. Often, the sensor is of an optoelectronic or acoustic (supersonic) type. Internationally, the sensor in use is required to take readings every 0.25 seconds as a minimum. From these signals, the rolling average of wind speed during the previous 3 seconds is calculated. The most extreme reading (3-second average) during the most recent 10 minutes is described as a „gust‟.

The rolling average for 2 minutes is given to aircraft as the „actual wind speed‟, in common phraseology often reported as the wind „now‟.

The rolling average for 10 minutes‟ speed and direction is an obligatory part of METAR, together with „gusting‟ in cases where the 10-minute average is exceeded by 10 kt or more. When the direction changes by 60 degrees or more during the 10-minute period and speed is at least 2 kt, the variability in direction will be included in the notification.

Aircraft exposed to crosswind force (pressure) experience cornering including torque (weathervane effect). When the crosswind pressure working on the aircraft exceeds the total force (sum of vectors) that can be transferred by the wheels to the solid ground, skidding will result (force is described in chapter 1, examples in chapter 13). The crosswind component and thus the force exerted are variable, as indicated by the gust observed. The relative strength of the crosswind component in relation to the longitudinal (head wind) air speed of a rolling aircraft increases as the aircraft slows down relative to the runway.

Whereas an anemometer represents the wind at the instrument‟s position only, the aircraft follows a path along a considerable distance not covered by anemometry. The wind stated by METAR refers to one (main) anemometer that may be placed near the threshold used most frequently. When several indicators for wind are installed, the readings may be given as wind „now‟. The nature of terrain or an obstacle (for example a building) disturbs the downward pattern of the wind field in an upward direction. As a very rough rule of thumb, the disturbances cover a distance 20 times the elevation of the obstacles inducing vortices.

The variations in wind speed and direction may be represented by a stochastic distribution and even simulated by interfering waves, but cannot be forecast in sufficient detail for an aircraft to respond to. Extreme wind speeds occur in a gusty wind field far more frequently than would be expected from a Gaussian normal distribution.

The reported 2-minute wind does not allow extrapolation in time. In general, the wind „now‟ may deviate by 20 to 30% from the 10-minute mean wind; gusts may occasionally exceed the 10-minute speed by more than 100%. The general synoptic situation of the weather, as observed and shown by METAR and expected by TAF, has to be considered together with local topographic peculiarities. Gusts, when forecast and especially when observed recently, should be expected to happen again (and possibly more strongly) at any time. A low wind speed reported „now‟ on final approach does not exclude wind gusting at a time (seconds) and at a site (decametres) encountered by the aircraft further ahead.

In several cases, wind considerably stronger than reported as „wind now" and barely anticipated has been encountered and, combined with poor braking conditions, resulted in loss of directional control (chapter 13).

The difference between mean wind speed (analogue considerations are valid for the mean wind direction) over a period of 10 minutes in contrast to 2 minutes („wind now") can be understood from the distinctions as follow:

The actual wind speed u may be considered composed by the mean wind ū and momentary deviations u*, thus u = ū ± u*. Though this simple definition does not cover the phenomenon of turbulence completely, it is sufficient to explain the aeronautically essential consequences of means deduced from different time intervals Δt. A vehicle in motion continuously changes its position. However, as first approximation, a fixed position is assumed. There, the wind speed u(t) is observed at any time t, see Figure 7.

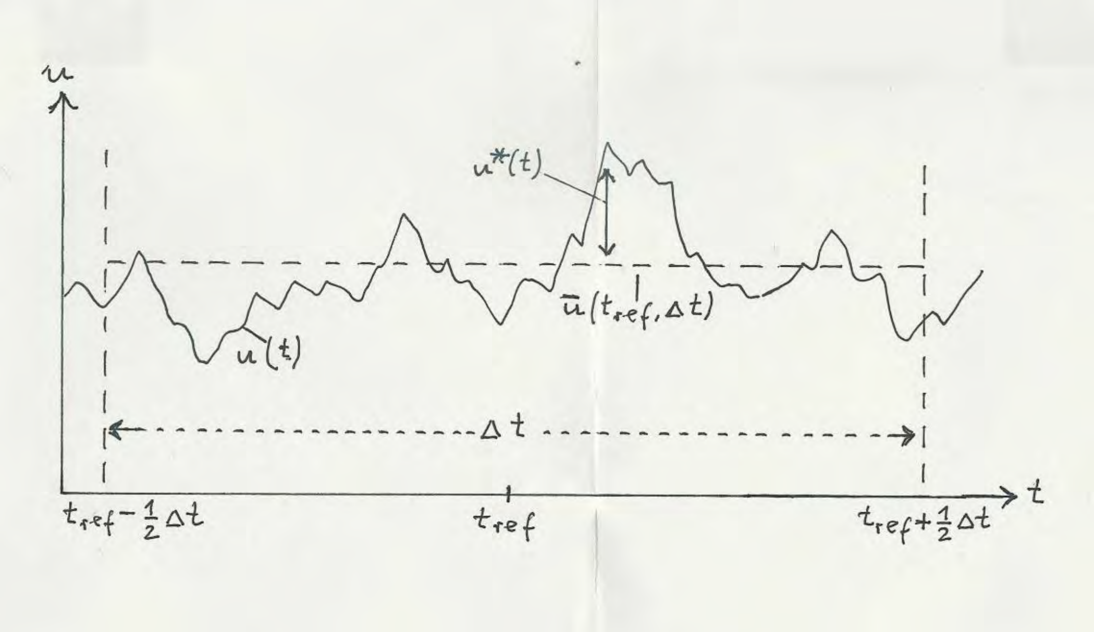

Figure 7. The mean wind speed ū is defined by the time of reference t_{ref} and the interval of time Δt. The actual wind speed at time t, u(t) = ū (t_{ref}; Δt) ± u*(t), when u* designates the deviation from ū at time t.

The mean wind speed ū observed in the time interval Δt refers to the moment of time of reference t_{ref} . Thus ū depends on (t_{ref},Δt). As a rule, the time t_{ref} means the half of Δt. In the case of 10-minute mean wind given in METAR valid for 50 minutes past the whole hour, that time would be t_{ref}. The period Δt would last from 45 to 55 minutes past the hour, as indicated by the figure. Hence, the momentary wind speed at any time throughout the interval chosen for observation, u(t) = ū(t_{ref}, Δt) ± u*(t). This means the METAR wind as a 10-minute mean is determined by t_{ref} and Δt. As u*(t) at any time t in the interval refers to the mean wind ū, the wind u(t) actually observed at a specific site at a time t in the period, the choice of Δt is crucial.

The reason not to rely only on the 2-minutes wind is the frictional drag by the ground that retards the horizontal mean wind speed when approaching the surface. Both its roughness and the thermal stability of the adjacent layer of air interfere with the wind. Wind decreasing with decreasing height means a net downward flux of momentum (chapter 01) contributed to the solid earth‟s momentum. The shear force exerted by the atmosphere on the surface is equally opposed by the shear force impacted by the ground on the atmosphere (Newton‟s Third axiom). Due to different wind velocities in different heights and hence different wind shear, momentum is carried vertically by turbulent eddies. Downdraft of a "parcel" of air with larger velocity (and hence momentum) than represented by the mean wind in a certain level, for example an anemometer at 10 m above ground, represents a gust, updraft of a „parcel‟ of little momentum is observed as a lull. A 2-minutes-time interval is too short to represent the "sample" of gusts and lulls.

11 Planing motion

Main points: Hydroplaning (dynamic planing) and viscous planing may change from one state to the other. Skidding may result in steam planing. Heavy loads of ice in a gale may lead to aerosol planing.

Apart from adhesion to the pavement, the rolling resistance of the wheels is determined by the wheel cutting into, displacing and rolling over fluids, including slush, snow and even loose sand. The depths of contamination allowed by the regulations are small and the rolling resistance is negligible. However the frozen contamination changes the transfer of shear stress for the worse. This is a complex process, especially when the contamination is built up of layers with different mechanical properties. These layers can then slide relative to each other. This may happen, for example, when ice is covered by loose snow or hoar frost.

A broad interpretation of „planing‟ would cover all cases of a medium between pavement and tyre. The viscosity of liquid water, slush and wet snow may prevent a tyre from penetrating to the pavement. The tyre may roll on top of a contaminating viscous film, but ice or a polished pavement below the film prevents the transmission of shear forces. Viscous planing may take place at low tangential speeds. (For dynamic viscosity, see chapter 8).

A common and narrower use of the term „planing‟ is found in the well-known definition for „aquaplaning‟ (=„hydroplaning‟): Water, a non-compressible fluid, is captured under a wheel with such high tangential speed that not all the water gets pushed away, but builds up a wedge instead. The wheel (and thus the vehicle) is lifted. As the layer of water does not transmit shear forces, control of the vehicle is lost. Hydroplaning is an example of „dynamic planing‟. This phenomenon is also experienced on slush and wet snow. Dynamic planing is a result of high speed and low tyre pressure, dependent on the degree of rolling relative to sliding.

In the case of skidding, the heat released may be sufficient to convert a thin film of liquid water, slush, wet snow, ice or loose crystals of blowing snow captured by a (locked) wheel into steam. The steam pressure may be sufficient to keep a tyre above the solid ground (pavement). Skidding at a ground speed as low as 30 kt may result in steam planing as experienced in a case where reverted rubber was identified in the tyre‟s skidding footprint. Except for certain indications such as reverted rubber, abundant slush as in the case of dynamic planing, or ice wetted by fog in the case of viscous planing, or other prerequisites, the „types‟ of planing are not readily distinguished from each other. Viscous planing may go over to dynamic planing or vice versa.

Conditions for viscous planing, a polished surface of compacted snow, can be established by blowing snow (chapter 10). The polishing effect increases with decreasing temperature due to increasing hardness of the moving particles of ice. As a consequence, low temperatures do not mean good aircraft braking on compacted snow or ice in polishing conditions. An aerosol made up by heavy loads of fragmented ice crystals in air some millimetres thick and close to the solid surface leads to aerosol planing. In wind of more than 25 kt, gusts of 30 kt to 45 kt (at 10 m above ground) it is likely that up to 60 or 80% of the transported air volume carries ice at less than1 to 2 cm above ground. The wheels lose contact with the solid (and polished) snow or ice surface. This type of planing may be assisted by lifting forces acting on the aircraft in strong headwinds.

12 Aircraft braking coefficient

Main points: Estimated low aircraft braking coefficients are reported. They differ considerably from skiddometer coefficients.

The term „aircraft braking coefficient" (ABC) comprises a coefficient summarising the retarding forces acting on a wheel under braking. {Boeing defines ABC = $F_{braking}$ / (M g – L) where F indicates force, M mass, L lift, g gravitational acceleration}. Strictly speaking, ABC will be specific for the type of aircraft concerned, and for other constant parameters (for example the inclination of a runway). The microtexture of a runway (asphalt) will change seasonally (freezing, thawing) and by chemical corrosion. In the case of frozen contamination, the original pavement is substituted by frozen water in a large variety of compositions. The plasticity of ice is one of the reasons why the classical laws of friction are not valid as a component of ABC, or if so, only to a limited extent. (The coefficient of friction is independent of normal force, speed and the area of contact between frictional partners.)

The need for economy in both observation and flow of information demands that data for a certain point and time on or near the runway (the meteorological readings) be extrapolated to an area and point in time that will be reached in the immediate future. Categorised and simplified descriptions (as in „Snowtam") are also required. The surface of compacted snow or ice is in reality confined to asperities in the frozen water in contact with the rubber of the tyre. Here, high pressure and heat result in the deformation and melting of asperities. Thus traffic, along with meteorological factors and runway preparation, changes the conditions under which shear forces are transferred.

When snow or ice acts as substitutes for pavement, they are never in a constant state. Physical processes significant for ABC take place continuously. Except when a runway is returned to „black" (and dry) conditions immediately following any contamination, a more or less complex layered structure of frozen water is built up. In reality, there are hardly any sharp boundaries between air and frozen water, and between different layers of contamination. Even compacted snow has pores. These are filled or may become filled with water. The details of water accumulated in, and drained from, frozen contamination (studied at Svalbard) cannot be dealt with here. An essential element for ABC is water pressed up to the surface towards a wheel or accumulated at the foot of frozen contamination acting as a lubricant against the pavement. Liquid water, irrespective of its source, will melt asperities effectively when it comes in contact with a surface of ice or compacted snow and thus reduce the ABC.

The surface temperature of frozen contamination is a key parameter concerning ABC. This is because the resultant ABC is determined in part by temperature-dependent thermodynamic processes that create contamination, for example the formation of hoar frost, and in part by temperature-dependent transformations of a given contamination. All the different categories of frozen contamination are related to the recent or previous history of temperature, proportion of liquid water, mechanical forces, and preparation of the runway and use of chemicals. As a general rule, ABC decreases when the temperature of contamination increases towards freezing point and the proportion of liquid increases.

Apart from heat from the meteorological environment, heat is also released by operating aircraft. The heat from gliding or even skidding tyres primarily affects the ABC experienced by the wheels of the aircraft concerned and secondarily the state of contamination for the aircraft that follow. The heat from engines, as a rule, may have consequences for following aircraft only. Heat and mechanical stress from heavy traffic density explains why ice may not form until decreasing temperature approaches a level significantly below „theoretical" freezing temperature.

Sliding, or „planing" (see chapter 11), depends more or less on the presence of liquid water. The „initial capital" of water is an immobile film on ice, increasing with temperature from 10^{-9} m to 10^{-6} m (nanometre to micrometre). The sources of mobile water are melting as a result of frictional heat (and traffic) and water from meteorological processes such as liquid water in new fallen snow or from rain. The content of liquid water in snow has proven to be especially significant for ABC. An indication of the volume of liquid water in snow and ice can be found by using True Domain Reflectometry. The time taken for a very high frequency electromagnetic impulse to travel to and fro through the medium depends on its dielectric properties (= permittivity). By definition, permittivity in a vacuum is 1. The relative value for air is 1.006, for ice (without liquid water) at minus 20 °C it is in the order of 3.2, depending on the frequency. The time of travel increases with the proportion of the liquid water volume.

GOOD („dry") friction may be expected when surface temperature is below approx. minus 15 °C. From minus 15 ºC to minus 2 ºC more water is formed and the ABC is likely to gradually decrease from GOOD to MEDIUM. In the interval minus 2 °C to 0 °C melting water from friction establishes a coherent film of some depth in the trace of the tyre"s footprint resulting in POOR ABC. In conclusion, the liquid water content in snow cannot be deduced from air temperature alone (see chapter 4).

The European Aviation Safety Agency (EASA) operates with a „Default Friction Coefficient". This coefficient for certification assumes the same coefficients for standing liquid water as for slush. However, all experience shows that ABC in standing pure water does not equate with slush, and slush does not equate with movable snow or snow containing different proportions of liquid water. This is due to the increasing „viscosity" of these media. In reality, pure water, slush and snow seldom occur alone, but result from what has previously been ice or compacted snow. Airbus" regulations also summarise the differentiated real compositions of frozen contamination to such an extent that differences significant for ABC are eliminated.

Liquid water, slush and movable snow may be interpreted as „fluids" having different dynamic viscosities. These media must not be considered as being „at rest", but may slide or otherwise move not only relative to a sliding wheel, but also relative to the stationary pavement when exposed to forces induced by a braking aircraft. For this reason and because of the difference between viscous planing on slush at low speed and dynamic hydroplaning (aquaplaning) on water at higher speeds, the EASA concept seems to conflict with AIBN observations when the „Default Friction Coefficient" (EASA) for both contaminants are taken as being equal. Wet and dry snow have different properties due to different water content, thus they cannot result in the same ABC due to the dominant lubricating role of liquid water distributed inside the texture of ice crystals (accumulated snow). Therefore, there seems to be some contradiction when the EASA assumes that a 5-millimetre layer of wet snow should be equal to 10 millimetres of dry snow with respect to the „default friction coefficient".

The estimated ABC at Svalbard Airport Longyear experienced by braking B737 series aircraft at speeds of 55 kt to 30 kt confirm very low values in the case of liquid water on ice, irrespective of sand. The ABC values increase on frozen water with decreasing (colder) temperature on bonded sand. However, in spite of low temperatures, small values occurred on compacted snow polished by windblown particles of ice. New fallen snow containing liquid water as well as ice-aerosol planing on compacted snow polished by windblown particles of ice at low temperature all showed low ABC values. Even if the estimated ABC were consistently too small compared with the unknown true ABC, measured FC derived from skiddometer measurements (SKH = BV 11) also seems to show figures that are overly optimistic.

As experienced ABC values are seldom referred to, the figures observed at Svalbard are presented in Table 6.

Table 6. Estimated Aircraft braking coefficients as compared with observed friction coefficients on different runway surface conditions at Svalbard Airport Longyear.

Contaminant	Number of cases	Air temp. °C	Surface temp. °C	Spread K	ABC	FC
Liquid water on sanded ice	4	2 to 3	0	2	0.04	0.32
Slush on sanded ice	11	2	0	1	0.05	0.38
Dry snow on sanded ice	13	M04	M07	3	0.11	0.47
Dry snow on sanded ice (cold)	9	M14	M17	5	0.14	0.45
Drifting snow on sanded compacted snow	5	M09	M12	4	0.07	0.36
Blowing snow on compacted Sanded snow	3	M15	M16	2	0.03	0.38
New fallen snow on sanded ice	4	M02	M04	1	0.06	0.32

Table 6 assumes that braking occurred at the point of maximum possible transferred shear force. In order to deduce the ABC without such an assumption, it would be necessary to analyze from aircraft"s data the retardation achieved at the point of actually maximum possible transferred shear force (the point of „kraftschluss"). On a black runway, the available ABC is not fully exploited as this would mean an uncomfortable retardation.

Due to the relation between the maximum coefficient µ and the maximum centripetal acceleration obtainable (chapter 1), an ABC for different conditions of contamination may be derived from the observed radius of turning, speed and occurred lateral skidding or not. Such studies are possible at low frequented airports (Svalbard Airport Longyear) when individual aircraft"s tracks can be identified and inspected. Speed has to be measured or recorded from a reliable source. So far, only sporadic estimates of ABC are done. On loose sanded ice at surface temperatures 0 °C and minus 4 °C, ABC of 0.04 and 0.07 respectively were estimated. On fastened (frozen) sand on ice at minus 11 °C an ABC of 0.11 was stipulated. On approximately 1 to 3 millimetre snow accumulated upon fastened sand on ice, at snow surface temperature of minus 5 °C, an ABC of 0.06 was found. All these estimates refer to turning at Apron or the intersection runway-taxiway.

13 Experiences from insufficient aircraft braking

Main point: Application of principles discussed in the previous chapters to empirical results and learning from phenomena.

Some cases of slippery runways or excursions reported to the AIBN are described with the emphasis on contamination. The cases discussed in the present chapter are organized due to kind, structure and generative history of the contamination encountered by landing aircraft. Different cases in the same category represent different additional conditions, meaning, any accident or incident is unique. Nevertheless, common patterns can be found. However, the variety of conditions, not nearly all identified or readily observed, prohibits deterministic prognostics of ABC, apart from the limited observational abilities of airport supervisory staff. The cases referred to represent neither a sample in the stochastic sense, nor do they cover all the conditions that may result in poor braking and loss of directional control.

Many, if not most, cases of skidding on frozen contamination are caused by planing of the viscous type. It takes place at much slower speeds than dynamic planing, on a layer of water of only some hundredths of millimetres thick, which is less than required for hydroplaning. Loose particles of ice, as in the case of hoar frost or a thin layer of movable fragments of snow crystals, may be considered as a „fluid" even without liquid water being involved. In practice, heat released from tyres and the frictional effect rendered at the top of asperities will result in some melting. Other factors to be borne in mind include rapid changes in the state of the aggregate such as freezing when the amount of water involved is small, and general changes from (mechanically) stable to unstable conditions, for example when the exchange of shear forces gives way to „sudden" loss of such exchange without any significant transition.

One condition of major importance is crosswind. Even an infinitely long runway could not prevent side excursions caused by the cornering effect. Another condition is when sand is applied. However, in most cases cited, sand played a marginal role in improving ABC, though the friction measurement coefficient, which is misleading with respect to ABC, may improve.

Other conditions may be interrelated. Planing on an aerosol of ice particles, for example, is always connected with heavy wind. Thus the windblown particles of ice polish the surface of ice or compacted snow. This means not only abrasion of asperities, but increased wind velocity and load of displaced particles closely adjacent to the fixing surface. Recent new fallen snow always contains liquid water, except at very low temperatures.

The „3-Kelvin-Spread Rule" (chapter 9) is to be understood as a danger signal, predicting meteorological conditions through moisture in the atmosphere often related to present, past or future precipitation. With one exception, none of the cases cover the application of chemicals.

Another component concerns the perception of information about meteorological phenomena, whether by own observations or reported, and their interpretation, or rather lack of interpretation of braking conditions. This aspect will be considered briefly.

All times are given in UTC.

13.1 Wet snow on runway warmer than freezing

Early snow in autumn may fall on a runway when the body of the pavement still stores a large amount of heat accumulated during the summer. In late winter, the fringe of a runway may have been heated by absorbed solar radiation, followed by frozen precipitation. The cases presented in this section all took place in late winter. In the first case there were spells of sunshine and in the second there was sunshine until past noon prior to the incident. One common feature was that either a dry or wet runway was reported. Intensified snowfall during approach of the aircraft concerned exceeded the rate of melting. Thus, more or less unexpected by the pilots, landing occurred on a white runway.

Heat in the runway melted the base of accumulated snow. Runoff from melting water and possibly intercepted water drained by gravity was retained by the snow above, likely creating a zone of slush on top of liquid water. Thus working from the top down, there was a fluid medium of wet snow, partially melted by the heat of the tyre, slush and a film of water on the pavement itself, resulting in optimum conditions for planing and skidding.

The first case occurred at Tromsø (ENTC) on 11 May 2000 at 19.24. The MD87 landed on RWY19. The decision to land was based on reported measured runway friction (FC) 53-56-64 measured by BV11 on 1 mm slush at 18.45, and a calculated and acceptable tail wind of 8 kt. When cleared for landing, the northern indicator for wind showed 330° 12 kt.

At 19.20, METAR informed about wind at 280° 09 kt, air temperature of minus 2 ˚C, and a dewpoint of minus 3 ˚C. Thus, the spread was 1 K. The TAF valid from 18.00 to 03.00 indicated 300° 15 kt gusting to 25 kt. The approach was performed through a cumulonimbus with a heavy snow shower at the airport. When the runway became visible through clouds at near to minimum height, the pilots were surprised to see the runway covered by snow.

The aircraft turned 40˚ into the wind, skidded near the centre line 70 m beyond the end of the runway and came to a stop on an upwardly inclined vaulting road bridge. After the accident, at 19.42, friction (FC) was measured at 23-26-26 on wet snow, depth unknown.

An aircraft had landed prior to the one in question and the pilots did not report POOR braking action. There may be a critical threshold as to the amount of mobilised liquid water. A small increment in snow depth may be crucial for sliding or planing, or sufficient transfer of shear force. In any case, a significant change in ABC had to be expected due to the change from 1 mm slush to accumulated snow. Furthermore, the good coefficient of friction measured on slush should have been considered doubtful.

The second case occurred at Sandefjord Airport Torp (ENTO) on 26 March 2006 at 17.58. An A321-211 landed on RWY18. At 17.20 the crew had learned from ATIS that braking action was good, the runway dry, in spite of light snow fall, spread only1 K, and visibility 2,500 m. In reality, the runway was wet from snow melting immediately on contact with the pavement.

At 17.20, METAR showed wind at 030° 06 kt, an air temperature of minus 2 ˚C, and a dewpoint of minus 3 ˚C. At 17.50 „light snow" had intensified to „snow". Though the last read TAF, valid form 12.00 to 21.00, indicated the change from fair weather to snow between 12.00 and 14.00, the pilots were not prepared for a cover of wet snow. Three minutes before touchdown, they learned about the measured friction (FC) 32-33-31 on what was actually 8 mm of wet snow.

The pilots experienced POOR braking action (ABC). The aircraft skidded on locked wheels straight ahead due to its momentum. With the parking brake engaged and the nose wheel steered away from uneven terrain beyond the end of the runway, an increasing angle between the wheels‟ orientation and the direction of the movement of the aircraft resulted. Displacement of snow caused by the wheels‟ lateral skidding caused retardation to take place, and the aircraft ultimately came to a stop when it collided with the base of an antenna.

As in the first case (ENTC), snowfall intensified and was accumulating just before landing on a runway with surface temperature above freezing. In both cases, the newly precipitated snow was wet, in spite of the air temperature being minus 2 ˚C (2 m above ground). Melting water, as described above, together with heat from the tyres and liquid water squeezed out of the snow by the pressure of the tyres, resulted in copious liquid water to cause planing as the snow was compressed by the wheels into slush. After the accident the watery path left by the aircraft froze.

The EASA as well as Airbus and other sources recommend estimated ABC depending on the type and depth of the contamination. Even if such a simplification is tempting because of its ease of use, it runs the risk of conflicting with the actual ABC that can be achieved. Both cases demonstrate this.

In both cases, when the pilots were confronted with unexpected runway conditions there was insufficient time to consider the impact on ABC or to question the validity of the measured friction coefficients used as input to calculate the length of runway needed. If they had „gone around‟, both pilots might have coped with the surprise and allowed the airport supervisor to prepare the runway (remove the snow).

Rule: Examine past weather data to establish whether a runway surface might maintain a temperature above freezing. In such case, accumulated snow will melt at the interface. Released melt water together with water in the snow and melting caused by the tyres‟ temperature will almost inevitably result in planing conditions.

13.2 Liquid water on ice

This section briefly presents different cases linked to liquid water on ice. Regardless of the source of the water, a film of liquid between the tyre and a very smooth fixed surface (ice, compacted snow) is to be expected. The yield of melting water from heated tyres may be negligible compared with drizzle or rain, for example. The history of moistening influences on friction due to surface disintegration of frozen material depends on the length of time of exposure to liquid water.

Wet ice alone can cause poor longitudinal braking conditions. But additional acceleration by lateral forces, especially due to crosswinds or a curving path, or both, reinforces the need to transfer shear force. A lack of retardation and loss of directional control is commonly caused by cornering (chapter 1).

The state of the runway, meteorological conditions and the speed and braking behaviour of an aircraft, vary in place and time along a wheel‟s path. The variation in these conditions constitutes the differences between individual cases. Each of the root conditions, either separately or combined, may contribute to an undesirable incident. To avoid this, learning from experience has to be linked to decisions put into practice.

1) Inconsistent estimated B/A and ABC

At Evenes (ENEV), on 27 April 2010 at 23.26 a CRJ-200 experienced poor braking and skidded close to the edge of the pavement of RWY17. Medium B/A had been expected. The runway was covered by wet ice. Wet snow had been removed at 23.15. B/A was estimated to be 4-4-3 (a Tapley meter was used as a reference).

METAR at 22.50 showed 24013KT 9999 –SHSN BKN045 M02/M03 Q1009 RMK WIND AT 1400FT 24011KT.

The spread was just 1 K, in accordance with precipitating conditions. Although the air temperature was below freezing, the ice on the runway was wet from new fallen snow. There is a possibility that (small spread) dewfall occurred. Sliding took place. The runway was not sanded.

The crosswind component at 70 degrees to the runway combined with wet ice and probably a thin layer of wet snow were sufficient to cause temporary loss of directional control. The case demonstrates the fact that B/A recorded „medium to good" is inconsistent with wet ice. „Medium to good" is not plausible on wet ice, and „poor" to NIL should be expected. Tapley meter readings on wet ice are not to be relied on.

2) Standard deviation of B/A ±0.20 on wet ice confirmed

At Svalbard Airport Longyear (ENSB), on 9 December 2005 at 12.54, a B737-400 landed on wet ice on RWY28. The aircraft began sliding to a stop when turning. When branching off to TWY A, the aircraft skidded at least 50 m along the runway at an angle of approx. 90 degrees to the centreline, triggered by weathervane momentum. At 12.50, the wind (eastern threshold) had been 190/19 kt. The B/A measured by BV11was reported as 40, and estimated by the pilot to be 20.

The runway was covered with ice. There had been warm spells with air temperatures above freezing three days prior to the incident. During the previous two days the dewpoint had exceeded (fallen below) the melting point of ice, thus indicating dewfall.

METAR 1250 showed 03/M04, light showers of rain. The B/A was measured (BV11) at 12.10 as 46-42-38.

At 13.00, just after the incident, the B/A was measured outside the aircraft"s track as being 49-41-39, and following in the track it was 39-36-38. Polishing of the wet ice by the tyres explains the difference. Runway temperature was reported as minus 1.2 ºC. Cold sand had been applied, but was pushed aside by the tyres.

The case confirms that standard deviation of ±20 for skiddometer measurements on wet ice (ICAO, referred to in chapter 2) has to be taken into account. This means that in individual cases „poor" B/A (and consequently low ABC) must be expected on wet ice even if the B/A measurement indicates „good" conditions.

3) Wet ice and large "spread" may give POOR Braking Action

At Svalbard Airport Longyear (ENSB), on 16 January 2006, at 04.34, a B737-400 intended to depart on RWY28. The decision was based on measured B/A of 04.30 32-33-39 (BV11). The pilot calculated take-off assuming a B/A of 27 with crosswind 10 kt. When taxiing, the aircraft experienced loss of control and moved as dictated by the wind. Sand was applied, but it failed to mitigate the condition. After arbitrary movements on the runway, the aircraft came to a stop at approx. 90 degrees to the runway and 15 to 20 m to one side of the centreline. Passengers and crew disembarked the aircraft on the runway.

The runway was covered with wet ice and there was intermittent light rain. At 02.50, METAR showed an air temperature of 7 ºC, dewpoint of 1 ºC, and at 03.50 it showed an air temperature of 6 ºC, and dewpoint of 0 ºC. The spread of 6 K was well above the „AIBN 3-Kelvin Rule", in spite of temporary precipitation. This exemplifies that the rule referred to must not be employed absolutely. On the other hand, the rule is intended to help identify moist conditions when these are less discernible. When ice is wetted by precipitation it should be obvious to the observer. Wind reported (eastern sensor) was 100 degrees 12 kt gusting to 21 kt.

Before scheduled departure, a sanding lorry and an inspection car had both experienced sliding. Airport supervisors and pilots trusted „objectively" measured friction coefficients in preference to „subjective" evidence. Again, one must take into account the standard deviation for friction measurement devices on wet ice.

4) Inefficient wet sand

At Svalbard Airport Longyear (ENSB), on 23 January 2010, at 13.41, on RWY28, a B737-400 based its landing on reported B/A „medium-poor", corresponding to a value of 25. At a speed of 15 kt the aircraft turned into the wind. At that site, the Tapley meter reading was 35, whereas to the east the readings were 40 to 45. The aircraft stopped at an angle of 100 degrees to the centreline. Braking was found to be effective at a speed of 7 kt, but at 10 kt sliding occurred. {Provided that the model $\mu = a/g$ applies (see chapter 1), with the same retardation at both speeds and acceleration due to gravity constant, then it could be concluded that coefficient μ depends on speed}.

The wind at the eastern threshold (main anemometer) was 207/12 kt, air temperature 0.6 ºC, dewpoint was minus 4.5 ºC, and runway temperature was minus 0.8 ºC. The spread of 5 K exceeded the limit of the AIBN 3-Kelvin Rule (based on measurements at 2 m).

The runway was covered with wet sand on ice, frozen to the ice. The latter was consistent with a runway temperature just below freezing, but the ice was apparently thawing at the surface towards the sand and atmosphere.

Thorough examination of the aircraft"s track revealed that melting water attached to grains of sand. The melting water had mobilised the sand, and was possibly caused by heat generated by friction and the dynamics of the tyres. It was picked up and pushed aside by the tyres" momentum. Sideward skidding of the tyres ploughed sand off, leaving a path of clean ice. At the time of inspection, the track was covered by a film of re-frozen water.

The case shows that wet sand, even when loosely frozen superficially to ice, does not greatly improve the ABC. This was consistent with all other similar cases. In addition to walking on the sanded wet ice, the B/A measured with the Tapley meter led to the estimate of ABC being too optimistic.

5) Wrong temperature and late urea

At Bardufoss Airport (ENDU), on 2 February 2007, at 13.08, a B737-700 scheduled for Tromsø (ENTC), but diverted because of sweeping, landed on RWY28, which was covered with sanded wet ice. Autobrake 3 was applied, followed by max. autobrake as retardation was less than expected. The aircraft started to turn into the wind. It stopped inside the clearway area.

METAR at 12.50 was 20008KT 130V250 7000 –SHRASN FEW015 BKN030 02/00 Q0981 TEMPO 3000 –SHSNRA VV014

With the runway sanded and a reported B/A of 37-38-41 (Griptester) at 11.41, reasonably good braking was expected. At 12.58, the B/A had deteriorated to 25-28-28, and after landing was 23-26-23. The sand had been pushed aside or catapulted off.

After the incident, urea was applied and the ice was removed mechanically.

Air temperature on the night before 2 February had been approx. minus 10 ºC. At 10.50 the runway temperature was still as low as minus 6.1 ºC. At that time, sleet turned into freezing rain, coating both the runway surface and the sand with ice. The aircraft landed on a film of water covering the fairly uniform membrane of ice precipitated as freezing rain.

The extra workload on board caused by the diversion may have contributed to the mistake regarding the temperature. The correct spread was 2 K, within the frame of the AIBN 3-Kelvin Rule. At Bardufoss, the increased workload due to diverted aircraft may have been the reason for the postponement of corrective treatment of the ice when the B/A starting falling.

6) Decreasing B/A with decreasing aircraft speed in gusty wind

At Svalbard Airport Longyear (ENSB), on 25 January 2010 at 11.31, a CRJ-200 landed on RWY28. When its speed fell below 60 kt the aircraft lost directional control, turned into the wind, touched the box of Precision Approach Path Indicator (PAPI) with its wing, and ultimately came to a halt at an angle of approx. 90 degrees to, and approx. 50 m before the end of the runway. Loose sand was pushed away.

The runway was covered with ice, wetted especially in the west. Warm sand had been laid out at 10.00. The B/A along RWY28 was estimated (using measurements from a Tapley meter) to be 2-3-4 (decreasing towards the west). At 11.04 the wind data reported to the aircraft for RWY28 was 190/09 kt, max. 17 kt, for RWY10 max. 25 kt.

METAR at 10.50 was 22006KT 170V260 9999 FEW015 BKN030 03/M01 Q1007 TEMPO 23020KT RMK WIND 1400FT 22029KT

METAR at 11.50 was 22020G33KT 9999 –RADZ FEW015 SCT025 BKN040 04/00 Q1006 TEMPO 21010KT RMK WIND 1400FT 24028G40KT RMK WIND RWY28 21005KT

There are three anemometers at ENSB, with the main indicator at RWY28. The 2-min. mean wind at 11.33 was RWY 28 210/08 kt, RWY MID 200/09 kt, RWY10 210/17G27 kt.

Air temperature was well above freezing, and the „spread" was 4 K. At the time of the incident drizzle reached the western part of the runway. In any case, fine sea spray is carried into RWY 28 by a strong south-westerly wind. Thus, wet (icy) conditions with reduced ABC in strong wind represent a regular pattern towards the end of RWY28. Liquid sea water on ice reinforces the lubricating effect of a liquid film. A lorry in the area concerned had lost control, but the Tapley meter had indicated a B/A of 3. The supervisor conservatively reported a B/A of 2.

The incident demonstrates a convergence of various simultaneously reducing safety margins. Wind shear on final approach, as expected from the interaction of wind field and topography, resulted in increased landing speed and late touchdown. Along RWY28, when aerodynamic braking had ceased and wheel braking increasingly had to be relied upon, the B/A deteriorated and thus the ABC became insufficient in gusty crosswinds. On their own initiative, the airport supervisory staff had declared an alert and arranged to inform the aircraft explicitly about the B/A decreasing to the west. The pilots had based the landing on „actual" information that was too optimistic (as compared to METAR). The wind was given as:

1129 RWY28 190/10 kt max. 18 kt, variable 150-260 degrees, combined with B/A 3.

7) „Two-minute wind" not to be trusted

At Evenes (ENEV), on 30 January 2005 at 13.59, a B737-500 landed on sanded wet ice on RWY17. When the aircraft was about to turn to TWY D, a gust of wind turned it into the wind. The aircraft lost control and had to be shut down on the runway.

Excerpts from METAR: At 11.50: 00/M01 SHRASN; at 12.50: 04/01 SHRA; at 13.50: 02/M01 VCSH.

The temperature had increased to above freezing, with a spread of 3 K. At 12.50 the dewpoint exceeded the ice temperature of 0 ºC, indicating dewfall. The runway had been cleared of wet snow, and, starting at 04.26, sand had been applied frequently. At 13.40 the B/A on RWY 17 showed 24-24-37 measured by BV11. The airport team stated that it would not be able to improve the B/A by applying more sand.

METAR wind readings at 13.50 was 210/16 kt, gusting to 42 kt. At 13.49 the „2-min. wind" given to the aircraft was 210/20 kt, gusting to 32 kt; at 13.53 it was 200/18 kt „now". Wind reported to another aircraft within the same minute (13.53): 210/22 kt, gusting to 34 kt. When cleared to land, the wind reported was 210/17 kt.

The pilots decided to land based on 18 kt. METAR and gusts (the latter is a 3-sec. mean wind) indicated rather large variations. At the entrance to TWY D the topography forms an outlet shaped as a wind channel open to the southwest. The aircraft encountered a gust just as it was turning off the runway. Wet ice, soft at its upper fringe and with sand merged into it, was incapable of transferring the shear force required.

The lesson to be learned is that „actual wind" in the form of „two-minute mean" must not be expected to prevail for the time needed to approach and land following „cleared to land/runway free‟. Although METAR wind is the mean value over a period of 10 minutes, and deviations from it increase as intervals of time decrease, the METAR wind indicates the wind most likely to be encountered during the final approach and rolling phases. Maximum deviations towards stronger wind are found from „gusts‟ reported when the gust exceeds the METAR wind by at least 10 kt.

To sum up, there is a high probability of poor ABC on wet ice. In such conditions the possibility of „medium to good‟ or „good‟ is practically zero, even on wet sanded ice. Though wet sand may appear to be frozen to ice, or fixed by adhesion only, it will be moved by the shear force exerted by an aircraft‟s wheels. Black ice or ice from freezing rain covered by water heightens the risk of sliding. Landing based on „wind now‟ being more favourable than METAR wind runs the unintentional risk of encountering more adverse wind during the time required to complete the landing.

13.3 Recent new fallen snow on top of ice

The term „snow‟ in the heading covers any kind of frozen contamination, including sleet, small hail or ice pellets. Except for rare polar conditions, frozen precipitation as a rule contains some supercooled liquid water (chapter 04). Partial melting occurs when frozen particles pass a layer of air warmer than freezing. Recently accumulated snow therefore has to be considered as more or less „wet‟. Operational runways „drying up‟ over time due to crystalline changes and evaporation to the atmosphere is a phenomenon that only affects compacted snow. Before strong freezing bonds between recent (wet) snow and fixed ice are established, loose snow may slide on the ice when exposed to shear force. At the interface between rubber and snow compacted by the rolling tyre, an intermediate film of liquid water will result from the snow being compressed, supplemented by melting due to the heat from the tyres. As a result, there are two possible layers prone to sliding, i.e. the layers between ice and snow, and between rubber and compacted snow, with water acting as the lubricating fluid in both. In „deep‟ snow (>5 cm) internal sliding inside the mass of snow may cancel out sliding at the fixed ice surface. The following cases focus on different aspects of recently accumulated frozen precipitation.

1) Unrecognised wet sand

At Kirkenes (ENKR), on 9 December 2006 at 09.53, a B737-700 landed on RWY24. Autobrake 3 was selected. Switching to manual braking did not improve retardation. The aircraft needed must of the runway to come to a stop.

METAR at 09.50 read: 15003KT 5000 SN VV011 M06/M08 Q997 – WIND AT 300FT 11011KT. Light snow had started at 09.30. Until 10.20 the air temperature had not increased, but the spread decreased from 2 K to 1 K, well inside the frame of the AIBN 3-Kelvin Rule. Since November ice had built up on the runway. Sand was frozen to the ice. The B/A measured by BV11 at 09.30 were 70-68-68. After the landing on 1 mm of new fallen snow on top of ice the B/A figures were only 21-24-28.

Airport staff driving by car from the town Kirkenes and passing higher terrain had experienced icing of their vehicles. The significance of this had not been understood and therefore was of no concern. In fact, both temperature and mixing ratio (mass water vapour/mass dry air, see 14.1) increased with height, indicating an intrusion of warm moist air above a shallow layer of cold air close to the ground. The relevant TAF had forecast snow with a probability of 30%. The staff did not consider that snow was expected and found no reason to consult weather maps or the regional meteorological office. Meteorological personnel no longer worked at Norwegian state-owned airports (Avinor). The airport supervisor relied on long-term experience which showed that snow precipitated in cold weather (at ground level) was usually „dry".

Due to the downward vertical gradient of water vapour, the runway may have been exposed to hoar frost, a phenomenon that might have gone unnoticed. When precipitation started, freezing rain may have been involved. A thin film of clear ice was soon covered by snow and thus hidden. The aircraft"s wheels met a thin layer of loose particles of ice embedded in some liquid water on top of fixed ice (old ice possibly topped by recent clear ice).

The failure to sweep the runway can be explained by the lack of meteorological knowledge. If the content of liquid water in frozen precipitation is to be estimated from temperature, upper air data (850, 700 and 500 hPa levels) should be considered together with surface temperature.

2) Extra slippery snow

At Evenes (ENEV), on 25 November 2004 at 21.36, an A320 was about to take off on RWY 35.
After approx. 50 m the aircraft deviated from the centreline and stopped in snow. The aircraft"s centre of gravity was 20 m off the edge of the pavement and the axis was positioned at 40 degrees to the runway.

In strong upper level wind from the northwest there had been heavy showers of snow all day, and frequent sweeping and sanding had therefore been carried out. METAR at 19.50, 20.50 and 22.50 (21.50 omitted) reported showers of snow at an air temperature of minus 4 ºC, and a dewpoint of minus 6 ºC. A spread of 2 K means „may be slippery" according to the AIBN 3-Kelvin Rule. At 19.50 the B/A on „dry" snow on top of sanded ice was measured at (BV11) 34-32-32, and at 21.06 the B/A was 24-26-35. The pilots required a minimum B/A of 29. Therefore, more sand was applied. At 21.20, the B/A showed 30-32-32. In the area where the subsequent excursion took place the figure read from the skiddogram was approx. 23. When turning the aircraft after backtracking in order to take off from the southern end of the runway (which is exposed to the open water of the Ofoten fjord and is thus sometimes more slippery than the remaining part of the runway in winter) the nose wheel skidded. More sand was applied. After the incident, at 22.11, the B/A was measured at 29-29-27.

At the time of takeoff the wind at the southern threshold was calm and at the northern end it was 330/10 kt. The excursion is explained by asymmetric thrust of the engines due to icing in the left engine. As the aircraft waited for the runway to be sanded, snow might have been built up in that engine. The momentum created by the different levels of thrust from the engines could not be transferred to the fixed runway due to insufficient cornering friction, which was reduced as a result of at least 3 mm of „dry" (but in reality, wet) snow on top of sanded ice. The sand, at places blown off by the engines during backtrack, was mixed into the snow. It is likely that the aircraft actually slid off on loose snow and on snow compacted by the aircraft"s wheels on the fixed ice.

The required minimum is a B/A of 29. It seems that takeoff had been calculated on premises that were not fulfilled. The B/A is neither measurable precisely to 1/100 on the (questionable) scale, nor does the B/A correlate reasonably with the ABC (see chapter 2). The complex stratification and consistency of the contamination encountered would not lead to any expectation of such a correlation.

It is a common experience among pilots that new fallen snow at certain places, including Evenes, results in unusually slippery conditions. There may be different causes for this, such as salt (brine) in strong wind borne in with spray from the sea, or because the mountains cause air to rise rapidly forming clouds with a large portion of liquid water in frozen precipitation.

3) Deep wet snow

At Oslo Airport Gardermoen (ENGM), on 28 February 1999, at 20.25, a DC-9-41 landed on RWY19R. The aircraft lost directional control soon after touchdown, turned into the wind and left the pavement at speed of approx. 60 kt, coming to a stop after approx. 130 m, 15 m off the pavement. Control surface (rudder) and nose wheel steering could not prevent the excursion.

At 19.20 METAR read: 13007KT 090V170 1700 SN FEW001 SCT 002 BKN003 00/M00 Q0991 TEMPO 1000. At 19.50 the pilots was informed by ATIS of 4 mm of wet snow, B/A (BV11) 23-25-20. These figures and other parameters indicated that landing could proceed. After the excursion, the depth of snow was found to be approx. 50 mm, but the B/A could not be measured. It is uncertain whether the snow had accumulated on the runway itself or on ice wetted by the snow. The aircraft operator (SAS) concluded, not surprisingly, that the aircraft had lost traction and cornering due to wind.

The spread had been 0 K at an air temperature of 0 ºC. In a period of one hour approx. 45 mm of wet snow had accumulated to total 50 mm. The content of liquid water would have been more than enough to trigger even dynamic planing (chapter 11) under the pressure of the wheels. That the aircraft had already experienced directional problems at higher speeds may indicate such planing. In the viscous material of deep wet snow, even internal gliding may have taken place. It would explain the loss of directional control, irrespective of whether there was a layer of fixed ice below or not.

Landing in wet snow, especially when it has accumulated to a depth of several centimetres, should be considered as potentially poor ABC due to planing or internal sliding, effects that significantly cancel out increased rolling resistance.

4) Hoar frost followed by slush

At Svalbard Airport Longyear (ENSB), on 21 November 2005 at 12.53, a B737-400 landed on RWY28. The B/A (BV11) had been measured as 39-40-39. Turning into the apron, the aircraft skidded sideways for some 2 metres. The pilot estimated the B/A as being just 30. Loose sand was laid out, and the B/A (BV11) at 13.43 measured 45-45-43. Due to liquid water on the runway, which had a temperature below freezing, the B/A was measured for control purposes using the Tapley meter, which showed still higher values than BV11. Taxiing for departure at 14.01 on RWY28, the aircraft skidded on locked wheels. The pilot estimated the B/A as being 25. A Dornier 228 was about to depart at 14.25. When requested, the pilot of the Dornier checked the B/A. He estimated it to be approx. 30.

Since 18 November, the air temperature had risen from minus 12 ºC to about freezing early on 20 November. The air temperature remained at approx. 1 ºC. On 21 November at 12.50

METAR reported light sleet at 3 ºC, and dewpoint of 0 ºC. Wind was 340 / 04 kt. At a time close to departure, 13.50, temperatures were 2 ºC / 0 ºC. Thus the spread was approx. 3 to 2 K, consistent with the reported sleet showers.

On the morning of 21 November, 25% of the runway was covered by ice and there was hoar frost over the whole surface. The internal runway temperature was minus 2.3 ºC, which was below the dewpoint temperature. Although the runway surface temperature was higher than the internal runway temperature, the hoar frost should have indicated what to expect. When sleet started at 10.30, freeze-bonded sand (heated sand) was applied. At 12.15, the grit melted into and had become fixed to the ice.

It is assumed that slush on the runway and intruding hoar frost froze into a thin lamella of ice on the surface of the asphalt itself, whereas the mass above remained as a loose mass („fluid"). These conditions were conducive to „planing" and sliding in the layer towards the ice underneath. The lowest figures of ABC might have occurred in slush on top of smooth patches of fixed massive ice. Both the warm sand and the subsequently applied loose cold sand were enveloped by the mixture of ice particles in water. The sand could hardly prevent sliding or „planing".

Once again, the case demonstrates large differences between the measured B/A (BV11 and Tapley meter) on the one hand, and estimated and experienced low ABC in slush on ice or equivalent conditions on the other.

5) Ice pellets as lubricant

At Molde Airport (ENML), on 14 March 2000, at 19.39 on RWY07, a F-27-50 turned into the wind, encountered the edge of the snow bank with its left main wheel, turned 90 degrees to the left and stopped with the nose wheel 10 m off the pavement.

METAR at 19.20 reported: 32016KT 9999 VCSH FEW010 SCT020 BKN035 01/M01 Q1002. The spread, therefore, was 2 K. The air temperature of 1 ºC indicated that frozen water would be in a wet state and low ABC values were to be expected. At 19.09 the runway was reported to be covered by 1 mm of compacted snow, sanded, and then topped by another 1 to 3 mm of loose wet snow. The B/A was measured (instrument not known) at 47-47-44. A Boeing 737 had landed at 19.23 without any remarks concerning friction when braking. Three minutes before the Fokker landed, a shower of „hail", most likely ice pellets, was reported. (According to ICAO Recommendations only ice particles with diameter of at least 5 mm qualify as „hail").

At 19.35 the wind reported to the Fokker was 330/15 kt varying between 300 degrees and 20 degrees. At 19.36 a light shower of „hail", at 19.37 a shower of „snow and hail" together with wind 320/20 kt and finally at 19.38 a wind of 340/20 kt was communicated to the aircraft. As it was about to land, the airport supervisor"s intention to remove loose contamination was postponed. The published B/A was still considered to be valid. Following the incident, the B/A at 20.01 was measured at 30-30-28 on 10 mm of wet snow.

The incident was obviously caused by weathervaning (cornering) due to wind on a runway unable to support the lateral shear force. Ice pellets at below-freezing temperatures tend to freeze-bond to the surface and improve the ABC. But when melting, loosening and becoming covered by liquid water, they act as lubricated ball bearings and the ABC deteriorates significantly. In the present case wet snow covered the ice pellets. Nevertheless these pellets may have acted as ABC-reducing ball bearings lying on previously compacted snow. Sliding on that plane must not be excluded.

This case also threw up some surprises (as in 13.1). The pilots did not encounter the shower; they approached in clear air. The airport supervisor did not expect any significant change in the B/A as a result of the shower. As is frequently the case, cleaning of the runway had been assigned lower priority than traffic.

To **sum up** these cases: The common pattern discussed is recently accumulated wet frozen contamination on top of ice or compacted snow. Surface and internal sliding as well as two types of planing are mechanisms that may apply. The presence of liquid water magnifies the effects or is even a prerequisite. The cases cited refer to near-freezing temperatures. The content of liquid water in frozen precipitation does not correlate with surface temperature alone, but is heavily dependent on upper air temperature. In the case of temperature inversions and precipitation (warmer air aloft), the surface temperature does not correlate with the temperature aloft. Certain localities are known to show extraordinary small ABC figures due to specific lubricating phenomena. In deep wet snow planing and sliding is very likely due to the abundance of liquid water. Slush or wetted hoar frost on a runway at freezing temperatures results in a lamella of ice in the proximity of the cold surface. In this way, „slush-on-ice" conditions are established. Among the wide range of possibilities, the ABC is influenced by the consistency of the loose contaminant. Thus loose and wet pellets of ice constitute friction-decreasing ball bearings.

13.4 Aerosol on ice

An aerosol refers strictly to a two-phased system (liquid and solid particles in gas). Small airborne droplets or crystals of ice do not necessarily constitute such a system. In the present context, air packed with fragments of ice acts like and is considered as a whole. One precondition is strong wind at below-freezing temperatures. A surface of fixed ice or compacted snow is then polished by windblown rolling, skipping or bouncing particles of ice. The density of the air and its particles may cause planing (chapter 11). This phenomenon and an ice-polished surface of fixed ice occurring at the same time as crosswind, is problematic in itself (chapter 10). On the other hand, increasing crosswind reinforces the need for large ABC figures in order to compensate for cornering (sliding).

1) Sliding on densely drifting needles of ice

At Vadsø (ENVD), on 6 January 2003 at 13.09 a DHC-8-103 landed on RWY 08. The initial retardation was normal, but decreased as speed decreased below 60 kt. At 35 kt the aircraft veered to the right into the wind and stopped in the bank of cleared snow, at an angle of 45 degrees. The left wheel left behind a black trace on the asphalt.

METAR 1250 17009KT 0700 BCFG IC VV004 M14/M16 Q1014 ARCTIC SEAFOG

METAR 1320 17010KT 140V210 0900 BVFG IC VV005 M15/M17 Q1013 ARCTIC SEAFOG

A spread of 2 K refers to the dew point. When frost point temperature (rounded to whole degrees) is considered, spread related to frost point temperature has to be taken as zero (vapour saturated with respect to ice).

At 12.44, AFIS notified the aircraft of wind at 170/11 kt, visibility „at the moment" 600 m, arctic sea fog and ice needles. The B/A had been measured at 11.50 by Griptester to be 48-52-40, ice and hoar frost on the runway, dry snow blown off. Sweeping at about 13.00 resulted in a B/A between 39 and 25 in the area where the aircraft subsequently lost directional control. After the excursion, the measured B/A was 80-75-58.

The excursion was partly caused by a failure in the braking circuits. The aircraft had been operating for several flights with the latent fault without the pilot's knowledge. This deficiency had not had any consequences on bare and dry runways until powerful retardation was required at Vadsø, due to the state of the runway. The open water of the Varanger fjord as a source of water vapour in low air temperature meant intensive evaporation and immediate condensation to arctic fog. Initially, supercooled droplets, and later needles of ice reached the airport. This may be deduced from white ice on the windward side of texture asperities in the order of one millimetre, and fine loose material deposited behind the asperities. At the time of the accident, there was a predominance of needles of ice. The formation of black ice and hoar frost, as observed in situ, was not unexpected. Black ice may have coated the texture and grains of sand, but could not be identified on a video (because it was transparent). Ice on top of fixed ice, in the form of crystals of hoar frost mechanically pulverised to flour-like particles, is known to be especially ill-suited to transferring shear forces, thus resulting in poor ABC. This should also be the case for accumulated needles of ice and fragments thereof.

The left wheel showed reverted rubber indicating steam hydroplaning due to locked-wheel skidding. There were indications of evaporated ice in the wheel track. Wind from the right-hand side contributed to the momentum turning the aircraft to the right (weathervaning into the wind). Though asymmetric braking was caused by a technical defect, the primary cause for the low friction was the meteorologically induced state of the runway.

„Good" B/A measured by Griptester were inconsistent with the actual condition. Griptester obviously does not cover the case (black ice, hoar frost, blowing needles of ice) described.

2) Planing on ice aerosol

At Kirkenes (ENKR), on 30 January 2005, between 13.48 and 14.04, two different aircraft experienced extremely low ABC on the in-use runway, RWY 06-24. A BEECH-2000 took off and a DHC-8-100 took off and landed in that interval of time. Earlier that day, between 11.00 and 13.16, a B737 and a DHC-8 series had both landed and taken off without any comments about the friction conditions. The essential difference between the two time intervals was an increase in the mean wind speed.

METAR at 13.20 showed wind 150/16 kt, at 1350 160/25 kt, at 14.20 160/25 kt gusting to 35 kt.
METAR at 13.50 showed air temperature to be minus 9 ºC, dewpoint at minus 12 ºC, blowing snow with light snowfall and visibility of less than 1 km.

The runway was covered by ice, with warm sand applied. At 13.40 the B/A was measured (BV11) at between 55 and 30, in sharp contrast to the pilots" experience. Later it emerged that the measurement wheel showed adhesive rubber. An estimated B/A of 30 was accepted by the supervisor, but the traffic control officer on duty communicated a „not-made-up‟ report on experienced ABC, which stated that it was „very slippery‟, „very bad‟. All the six scheduled flights for the remainder of the day were cancelled or diverted.

The spread was 1 K with reference to the dewpoint, but 0 K with reference to the frost point. The air was filled with blowing ice crystals. Polishing of the fixed ice on the runway had continued for approx. 20 hours. Particles of ice were deposited in the wake of grains of sand and in patches showing a pattern caused by a combination of the incident and turbulence. Shallow accumulations of loose particles had probably hidden the sand.

When wind speed increases to 25 kt or more, the load of blowing and rolling loose ice in the lowest millimetres above the surface becomes significant in planing terms. The load increases by the 3rd power of wind speed (doubling of the wind speed means an increase of the load by 2 times 2 times 2 = 8 times), and may become larger as the mass moves along the surface. Thus an intermediate layer of ice aerosol and rolling ice between the rubber and the fixed ice of the runway is likely to have occurred. The phenomenon explains the extraordinary experience, though it cannot be isolated from other effects, such as polished ice.

3) Polished ice

At Evenes (ENEV), on 16 January 2005, at 19.45, a B737-300 landed on RWY 17. Calculations for landing were based on a B/A of 32-34-35 measured by BV11. After landing, the pilots informed about the B/A, which they estimated at only 25 at a taxiing speed of 20 kt. Another aircraft (SAS) estimated „medium low‟ B/A. The runway was covered with sanded ice. Drifting snow had accumulated and had been removed several times. Cold sand, which had blown off, had been replaced.

During the morning the wind had increased.

METAR at 10.50 showed wind at 110/18 kt gusting to 28 kt, air temperature of minus 1 ºC, and a dewpoint of minus 5 ºC. These conditions persisted.

METAR at 18.50 showed wind at 090/13 kt, gusting to 23 kt, air temperature of minus 2 ºC, and dewpoint of minus 7 ºC.

The runway temperature throughout the day was approx. minus 4 ºC. The spread was 4 K to 5 K, even when related to frost point, making evaporation and thus dry ice likely.

Reduced ABC can be expected from flash melting at asperities due to tyre heat and frictional effect, as well as skidding on partially melted fragments of loose ice. Crosswinds increased the need for cornering friction. In addition to all these processes, polishing of the fixed ice by drifting snow over a period of at least 10 hours had eroded the ice, smoothed out asperities and thus contributed to low ABC.

To **sum up**: At air temperatures lower than approx. minus 5 ºC spread should be related to frost point. Arctic sea fog may cause black ice from supercooled droplets. In the case of ice needles, flour-like particles of ice may be deposited by the wind behind elements of a runway‟s texture asperities. Particles of ice on top of black ice results in poor B/A. When wind speeds reach 25 kt to 35 kt the load of moving loose particles of ice in immediate proximity to the surface creates the conditions for planing. At low temperatures, when ice may usually be expected to offer good ABC (as heat from tyres melts only limited amounts of water), such planing conditions may result in ABC NIL. Persistently drifting snow on top of fixed ice or compacted snow erodes asperities. This smoothing effect may contribute to an aircraft skidding. Sand hidden by particles deposited by wind becomes ineffective.

13.5 From deposited water to transparent ice

The topic of this section is the transition of gaseous or liquid water to ice under unusual and rather unexpected conditions.

1) Unnoticed moisture that froze to ice

At Stavanger Airport Sola (ENZV), on 21 January 2007, at 20.45 a B737 landed on RWY36. Retardation was less than expected. Full reverse power was applied, and the aircraft came to halt at the very end of the runway. The runway had been reported as „black‟, except for some patches of ice, in sharp contrast to the pilot‟s estimate of POOR. Approx. half an hour before landing, B/A had been measured (BV11) at 49-41-48. After the landing, B/A was calculated at between 20 and 30.

METAR at 20.20 showed: 08005KT 9999 FEW015 BKN030 M01/M03 Q1002
The weather that evening had been CAVOK. Together with GOOD figures for B/A, airport officers on duty were surprised by the poor ABC experienced. Their surprise can be explained by an examination of SYNOP (detailed weather observations).

On 21 January at 06.00, the sky had been overcast with intermittent rain. Between 06.00 and 18.00, total precipitation had been 2.3 mm. From morning to noon wind had been in the range of 5 to 10 kt from northwest to north, air temperature 3 ˚C, dewpoint 1 ˚C. From about 09.00 to past 15.00 there were scattered clouds and precipitation in the distance only. At 13.00 the wind turned towards the east at about 5 kt, and from 17.00 onwards northeast at approx. 10 kt. The speed increased temporarily to 15 kt at 18.00 when the sky became temporarily overcast, and slight intermittent snow was reported. Air temperature started dropping after 14.00 and fell below freezing between 17.00 and 18.00. At 18.00 the air temperature read minus 0.6 ˚C, with a dewpoint of minus 1.9 ˚C. The corresponding spread, 1.3 K, had reached that day‟s minimum. From 19.00 the sky started clearing up. The air temperature at 21.00 was minus 1.8 ˚C, the dewpoint was minus 4.7 ˚C, and the spread increased to 2.9 K, which is at the upper end of the AIBN 3-Kelvin Rule (criterion).

During the first part of the day, a spread of only 2 K and an absence of solar radiation cast doubt on whether the runway had completely dried up after the rainfall. Advection, not radiation, prevailed and dominated the heat conditions. Obviously, a change of air mass, cooler and dryer than before, had occurred at about 18.00, coinciding with light snow. Although the runway had not been characterised as „wet‟, some adhesive moisture might have been retained. The light snow at 18.00 most likely melted on the runway, the temperature of which remained above freezing. Otherwise a white contaminating cover would have been conspicuous. Air temperature remained below freezing; at 21.00 it was minus 1.8 ˚C, and the moisture froze to a thin film of clear ice. The transformation from liquid to solid could have taken place over a period of one minute due to the small amount of liquid and thus the small amount of freezing heat to be released.

After all, some moisture on the runway had not been reported internally in the airport system. When the air temperature fell and remained below freezing in CAVOK weather, the likely consequences for ABC due to the formation of „black ice“ were not considered.

2) Dew and icing after period of sub-zero temperatures (cold soaking below the top layer of snow)

At Evenes (ENEV), on 18 January 2005, at 14.35, an Airbus approached the international gate 27 via APRON A. During this time, the aircraft experienced uncontrolled sliding for at least 50 m, which altered its course by 20 degrees. It managed to stop by means of reverse thrust. The incident site had not been used for one week (since 11 January). The accumulated snow on the apron had not been removed until 1½ hours before arrival. The ice-covered surface was sanded, as is the normal practice for other aprons and runways covered with ice.

The air temperature and weather had been variable throughout the preceding week. Sleet at 0 ºC conditions on 11January was followed by approx. minus 5 ˚C on the 12th, minus 10 ˚C on the 13th, snow in temperatures ranging from minus 2 ˚C to minus 10 ˚C on the 14th, air temperature decreasing to minus 17 ˚C on the 15th, again snow at a temperature of about 0 ˚C on the 16th, up to 2 ˚C on the 17th, and a maximum of 6 ˚C on the 18th. At 14.50 on 18 January the air temperature was 3 ˚C, dewpoint was 0 ˚C, and there were light showers of rain. The ice on APRON A was described as „soft“, in accordance with metamorphic developments (chapter 5).

Based on temperature developments during the preceding week, it must be assumed that the ice surface uncovered from snow stayed at a temperature below freezing, i.e. below the actual dewpoint of 0 ˚C. Water vapour condensed to hoar frost upon the cold ice. Such loose crystals upon fixed ice are known to result in low ABC, especially in the presence of liquid water. Besides the recent light rain, liquid water was also a result of the heat of the tyres melting the ice. The grains of sand had been pushed aside when the aircraft started skidding, or pressed into the ice by the aircraft.

3) Persistent ice below de-icing liquid

At Oslo Airport Gardermoen (ENGM), on 6 December 1999, at 19.58 a DC-10 landed on RWY19L (eastern runway). Summer-like ABC was expected, but virtually no retardation was experienced on the last third of the runway. The aircraft passed the threshold at a speed of approx. 30 kt, rolled 150 m on the asphalt and another 120 m on the grass before coming to a stop. The ground was frozen.

RWY19L had been used for takeoff only on the day in question and RWY19R for landing. To save spacing time behind the „heavy“ aircraft (wake turbulence) and to shorten taxiing on a taxiway known to be icy, the aircraft was cleared for RWY19L. The last third of this runway had not been touched by any aircraft because it was not used for takeoffs.

At 19.20, the pilots learned from ATIS that 19R was in use, and that the air temperature was zero, and the dewpoint was minus zero. The weather was calm, with visibility of 800 m, vertically 100 ft in light drizzle from fog (wetting fog). When cleared for 19L, the measured B/A (BV11) at 13.33 (some 5½ hours before landing) was reported as 57-58-54, and the runway characterised as „wet“. After the accident, the B/A at 20.20 was measured at 59-58-43.

Controlling measurements at 20.33 and at 20.42 showed 61-60-42 and 63-62-42 respectively, locally 30 at the end of the runway. There a car experienced sliding on the „wet" runway.

Cold weather had persisted from 3 – 6 December. The lowest air temperature was minus 12 ˚C on 5 December. The cold spell broke on the morning of 6 December. That day the air temperature had risen from minus 6 ˚C to 2 ˚C. As confirmed by the runway temperature of minus 0.5 ˚C, read after the accident, a deficit of heat had accumulated in the body of the runway. As a consequence, zero ^{0}C conditions and wetting fog throughout the day caused ice formation on the runway surface. The ice was treated with Aviform (potassium formate; see chapter 8) and sand. The freezing point of this de-icing fluid is below minus 50 ˚C, with a specific weight of approx. 1.35 gram / cm^3, compared with 1.00 gram / cm^3 for water. The ice was bonded to the surface of the runway. Where as in the first two sections, traffic had mechanically broken up the ice and mixed the fragments with liquid Aviform, the chemical in the third section made up an undisturbed layer upon the ice. The runway was indeed „wet" as reported, but the transparent „black" ice at the very surface of the pavement had not been noticed. Grains of sand may have contributed to the B/A figures measured earlier that day, but they were probably pushed aside or buried in the ice, the upper surface of which can be assumed to have been in disintegration due to prolonged exposure to the chemical.

The various wheels of a DC-10 (or other large aircraft) encountered different conditions: the first set of wheels probably broke up the ice, the second set rolled on a mixture of liquid chemicals and fragmentary ice. Low ABC would be expected for both cases, and any subsequent sets of tyres.

To **sum up**: Small amounts of moisture on a runway can reduce ABC dramatically in a very short time („suddenly") when heat conditions allow for freezing, which, as a rule, is indicated by air temperature (a better indication would be surface temperature). The relevant history of weather up to the preceding day, for example precipitation and the development of air and dewpoint temperatures, should be kept in mind in order to analyse and interpret any present situation. The body of a runway or of accumulated frozen water has a greater capacity for retaining heat over lengthy periods than is the case for air. Cold preserved in ice and shielded from heat exchange with the atmosphere can, when exposed to the atmosphere, act like a sink for water vapour. In liquid or solid form on ice, the water vapour will reduce the ABC. When a liquid chemical is laid out curatively on a surface of ice, the effect depends on mechanical destruction of the ice and mixing of the fragments of ice with the chemical. Alternatively, the chemical and ice may coexist in undisturbed layers.

14 Conclusions

Main point: How to analyze determinants essential to ABC.

In principle, any physical process can be described by (mathematical) relationships that combine the relevant physical quantities. Not every formally possible combination will actually occur. In connection with braking on ice or compacted snow, only certain combinations of meteorological variables are relevant. Such variables may be identified as "risk factors". An example is the AIBN 3-Kelvin Rule or similar „indicators of danger" in order to enhance safety. Consecutive METARs that show air temperature approaching 0 ˚C together with a spread of 1 K and recently reported damp runway should be interpreted in terms of a runway that might already be coated with a film of black ice. Wind reported at 180 / 15 kt „now" should be understood as a „lull" when METAR reported 150 / 18 kt gusting 28 kt and, perhaps, TAF forecasts increasing wind speed. When the wind vector at the threshold is just below the limit, and wind conditions further down the runway deteriorate and the B/A on wet ice decreases as the wind becomes more problematic, then these relevant variables, when considered together, indicate that landing is not advisable. It would be beneficial to identify such “risk factors” as temperature near freezing point, dewpoint spread, showers of snow/sleet, sea spray, strong crosswind, etc.

The following review is organised into five categories of relevance: 1. Physical goal; 2. Geometric (topographic) determinants; 3. Determinants of the process of friction; 4. Properties of materials; and 5. Physical constants.

14.1 Physical goal

The physical variable desired is ABC (the coefficient of friction experienced by an aircraft when braking by the maximum shear force that can be transmitted in the case of specified frozen contamination). This goal could be achieved by using a braking aircraft as the measurement device. The use of ground-based measuring devices, such as BV11 (SKH), Griptester, Tapley meter etc., is based on the assumption that the measured FC (or observed braking action, B/A) would correlate sufficiently with ABC. One of the main causes for poor correlation is the different characteristics of the motion dynamics of aircraft and measurement device. Further, the most frequent types of frozen contamination in Norway are complex stratifications whose properties change with temperature, contents of water in all three phases, and mechanical stress due to preparation of and traffic on a runway. Hence, the fundamental premise for a strong correlation between measured FC and the required ABC cannot be expected to be fulfilled, irrespective of the different rolling dynamics of aircraft and measurement devices. When the need for measurement guidelines is greatest, measured FC (or observed B/A) is least reliable.

At an assumed linear scale of two digits, the standard deviation is ± 0.20 on wet ice, resulting in an ABC range of 0.40. At best, three qualitative categories may be identified as ranking indicators: GOOD, MEDIUM and POOR. All individual cases need to be critically examined to establish the true characteristics of the contamination. In terms of physical causes, wet ice cannot yield GOOD ABC; POOR ABC is much more likely. Loose snow of shallow depth or hoar frost upon fixed ice is incompatible with GOOD ABC.

At present, a five-category B/A scale is approved by the Norwegian CAA, though differentiation to increments of less than 0.10 is impracticable as evident from a large volume of empirical data. The five-category scale allows for the frequently used MEDIUM TO POOR category attributed to the figures 0.26 to 0.29. They are used to calculate expected braking distance. As only differences larger than 0.10 are of operational value at best, the five-category scale hardly agrees with common sense. It presupposes a precision that is not present. Uncertain ABC, probably outdated at the time of landing (due to sudden freezing for example), uncertain wind vectors (due to turbulent oscillations), uncertainty as to the temperature of compacted snow or ice along the runway because often only air temperature at 2 metres above ground at one end of the runway is known. These uncertainties may result in the need for a considerably longer runway than indicated by the calculations. The use of a scale not physically possible may result in undesirable occurrences. Implausible runway conditions should be critically examined (for example, alleged B/A MEDIUM TO GOOD for slush upon ice). Use of friction data believed to be based on scientific standards may explain why information concerning B/A is used uncritically instead of calling upon and trusting one‟s own experience.

Future investigation should derive ABC from braking and deceleration on different kinds, structures and properties of frozen contamination. There will most likely be different findings depending on climate and type of the aircraft. The goal would be the ability to make conclusions, based on the specified contamination, about the most likely ABC. EASA, Airbus and others attribute a specific value of ABC based on the type and depth of contamination (or equivalent water depth). Published coefficients relating to frozen contamination do not agree with findings in Norway. More specific work should be carried out.

14.2 Geometric (topographic) determinants

The regional climates of different airports result in differences in the properties of frozen contamination. This applies especially to the regimes of temperature and humidity. There is a link with the liquid water content in frozen precipitation due to forced lifting of cloud-bearing air induced by the topography, as well as brine (salt) carried from breaking waves in strong wind. Some places are known for unusually slippery conditions following a recent snowfall. Many of the runway thresholds in Norway are exposed to nearby open water as a source of sensible heat and vapour, and there are even cases of liquid sea water deposited on the runway and freezing. Opposite thresholds may experience significantly different wind vectors, including wind from opposite directions induced by the topography. Small elevated areas upwind of and close to a runway influence crosswinds by generating downwind vortices as well as increased downwind accumulation of snow. Cold air may flow through channels in the terrain from more elevated terrain towards lower and crossing a runway.

The different patterns of heat conduction and heat capacity in the body of a pavement is reflected by the distribution of hoar frost; the most extreme surface temperatures and places of earliest deposit of hoar frost appear at sections where thermal conductivity is poor. Another geometric determinant is the runway‟s texture in terms of adhesion, which may involve a number of layers and interfaces between these layers. An example would be the interfaces between asphalt and compacted snow, between compacted snow and loose snow, and finally between loose snow and the tyres. Conditions detrimental to the transfer of shear forces arise as a result of layered frozen contamination, especially when liquid water is present (for example melting water between ice and loose snow).

Local climates along a runway explain systematic patterns in ABC. These patterns should be examined and described (mapped) for different winter weather conditions at individual airports.

14.3 Determinants of the process of friction

Intensity and speed of thermodynamic processes are determined by differences in temperature (gradients of temperature) and water vapour pressure. These result in changes in the state of aggregates (vapour, liquid, ice); for example, the structure of ice crystals and their aggregates. Another example is the proportion of liquid water in snow. In the present context, emphasis is placed on the determinants of friction, not on the processes of friction themselves.

Any frozen contamination permanently changes crystalline configurations and bridges in aggregates. These changes, which have an effect on ABC, take place even in CAVOK conditions or in otherwise „stable" weather. A state of thermodynamic equilibrium may change suddenly into a different state, as in the case of freezing or thawing. It would be difficult for regulations, whether issued by the CAA or another authority, to take account of every significant change in the physical quantities contributing to the resultant ABC. There is, therefore, an urgent need for the regulations to be reviewed with critical awareness, based on current knowledge and experience. At the same time, current regulations need to be updated based on this knowledge.

Theory states that ABC generally improves with decreasing temperature below freezing, and this is confirmed empirically by different studies. The output of melting water from heated tyres and the amount of liquid water attached to the frozen component decrease with decreasing temperature. ABC correlates with „true" surface temperature (to be measured by infrared radiation) of ice or compacted snow. The surface temperature may differ considerably (especially in conditions governed by radiation) from air temperature measured at the standard level of 2 metres above ground. The positive effect of improving ABC with decreasing temperature can be negated by the effect of ice or compacted snow polished by drifting particles of ice, and certainly when planing on an aerosol heavily laden with ice particles.

Theory and experience also show that ABC deteriorates with increasing content of liquid water in recent snow or slush at constant depth. If the amount (or part volume) of liquid water is not measured, it should at least be estimated in accordance with the four-category ranking. As proposed in chapter 04, the contents of liquid water in snow might be qualitatively estimated by four ranking categories. That should be done if quantitative measurements cannot be carried out.
Generally, the amount of liquid water decreases with decreasing temperature. Surface air temperature gives some indication of the amount of liquid water, provided that temperature is correlated with the temperature aloft. In the case of an inversion of the temperature (increasing with height) due to warm air above colder air, ground temperature will be misleading, as the proportion of (supercooled) liquid water depends on the temperature of the air mass surrounding the clouds.

At macroscopic level (disregarding microscopy as barely applicable at an operative runway), ABC is related to the kind of contaminant, layered or not, its prehistory and transformation by heat and pressure by tyres. Longitudinally arranged wheels, as is the usual case on heavy aircraft, run in the same track and experience different ABC as contamination is transformed by the wheels that have already passed. Similarly, frequent landings in the tracks of preceding aircraft will change ABC. ABC will probably deteriorate when melting and freezing together with mechanical transformations taking place repeatedly. Systematic studies are needed.

The effect of sand on ABC seems to be uncertain, and in some cases non existent. The effect may be doubtful, especially when loose particles of ice cover fixed ice, in slush and in liquid water. Further studies should be conducted.

The majority of cases reported to the AIBN concerning loss of control involve cornering not compensated for by the available ABC. This indicates that ABC is systematically overestimated. As a rule of thumb, the 10-minute wind as given in METAR (or, as a cautionary measure, a less favourable wind) should be used for landing, rather than the more arbitrary 2-minute wind. Both METAR and TAF should be used to anticipate the state of contamination in respect to air temperature, spread and recent precipitation. The AIBN 3-

Kelvin Rule indicates that compacted snow or ice may be wet, as a result of either precipitation or saturated vapour pressure in the fringe of air adjacent to frozen contamination. Hence, a film of water stemming from dew or hoar frost may exist. At low temperatures, spread should be related to frost point temperature.

When a change from wet to freezing conditions is to be expected, measurement of the cooling power (heat loss from a representative body) may allow a „nowcast‟ of the likely moment of freezing.

14.4 Properties of materials

In the present context, relevant properties include the hardness of ice, heat capacity of a pavement, density of compacted snow, surface roughness and mechanical strength of frozen slush. An example of physical conditions is liquid water on ice, combined with air-borne ice particles polishing fixed ice. Such conditions can be created deliberately. Indications of whether to apply sand, cold or heated, dry or in hot water, the kind of mineral and in what fraction, have, so far, followed rules of thumb rather than been based on investigations. Similarly underdeveloped is the practice of using chemicals, whether preventive in use to avoid the formation of frozen contamination on a runway, or curative to clean a runway. Inappropriate dosages may ultimately result in unexpected hard ice from the frozen diluted chemical, or in a lubricating film on ice. Masses of slush or snow display properties similar to viscosity of fluids.

14.5 Physical constants

This category refers to the constants of physics, such as the earth‟s acceleration of gravity relevant to the coefficient of dynamic friction. Thermodynamic constants, such as specific heat, may be dependent on air pressure and thus on elevation.

14.6 Closing remarks

Pilots, as well as people estimating B/A, need to have at least a mental model of braking, and the transfer of shear forces including cornering, when considering the phenomena of frozen contamination. Those concerned should be able to decide which processes, in terms of variables and quantities, that might be relevant, and be able to consider interdependencies and thus estimate the likely minimum ABC.

15 Appendices

15.1 Recollection of thermodynamics

Chapters 03 to 13 assumed as known some facts from thermodynamics. The aim of the present section is to recall as background reading some concepts concerning heat in thematic order. Focus is put at air and water. Further details for selected head words are given in paragraph 15.2 „Some meteorological definitions‟.

15.1.1 Quantities

The zero Law of thermodynamics

The general concept „when two quantities equal a third quantity, they all equal each other" may be applied to three closed systems (see 15.1.4) in thermal equilibrium: When each of two closed systems are in thermal equilibrium with a third one, then they all are in thermal equilibrium with each other. Two closed systems are in thermal equilibrium when both have the same temperature.

Temperature is the quantity measured by a third system in order to show whether thermal equilibrium is given or not. The third system is a thermometer. A thermometer does never show the air temperature, but its own temperature. Only when the thermometer shows a constant temperature, then it may be concluded (!) that it even shows the temperature of the air on the condition of thermal equilibrium.

As the air temperature nearly always is changing, the thermal inertia of a thermometer should be designed to show the mean of thermal equilibrium for a reasonable interval of time. In the case of runway temperature, the system „mass of pavement (asphalt) and temperature sensor" has a thermal inertia larger than the system „fringe of the asphalt towards the atmosphere". Therefore, rapid changes of true surface temperature may be indicated smoothed and delayed by the thermometer system. Exact thermal equilibrium is not established between the system, hence freezing may occur at the pavement"s surface in advance of freezing temperature indicated by a thermometer reading.

Temperature

The measurement of temperature has been built on arbitrary agreements, for example the Celsius-scale. In advance of the kinetic theory (15.1.3) temperature had to be introduced as one of the basic quantities in physics. The present quantity is the difference in temperature $\Delta T = 1$ Kelvin (K). The temperature T of any body is given in Kelvin by the difference from the absolute point of temperature zero. It can be deduced from quantum mechanics.

Water is one of the few natural substances that under terrestrial conditions occur solid, liquid and gaseous. Therefore it is useful in meteorology and aviation to give the temperature as difference from the melting point of ice (=freezing point of liquid water), $T = 273.16$ K. For most practical purposes, the figure 273 K is sufficient. Thus, 273 K corresponds to 0 ˚C (Celsius). The difference of 1 K equals to the difference of 1 ˚C. (In Fahrenheit: Freezing point of water 32 ˚F, boiling point 212 ˚F, human body temperature 37.8 ˚C = 100 ˚F, minus 17.8 ˚C = 0 ˚F). It follows from the Zero Law (above) that systems at different temperatures are not in thermal equilibrium.

Heat

The transfer of energy from one body (or system) to another is called „work", defined by the figure of energy that is exchanged. The work may, for example, be mechanical, electrical, magnetic or electromagnetic radiation. In case energy is exchanged due to a difference in temperature only, the „work" is called „heat", no matter what kind of energy. A system has internal energy (due to motion of elementary particles) and therefore has the attribute of temperature, but a system does not "contain" heat or work except in the meaning of internal energy.

The exchange of energy due to different temperature continues until thermal equilibrium (the same temperature for all bodies involved) is achieved. Loss of energy from some bodies equals the gain by others in accordance with the principle of conservation of energy. For example, snow at temperature 0 ˚C may melt by heat transferred from a warmer runway until the pavement attains 0 ˚C; the energy is then "hidden" in the liquid state of former frozen water. Solar radiation passing a (hypothetically) perfect transparent layer of ice upon traffic area does not do any work at the ice, but work is done when the absorbing pavement is heated, and again work is done when the heated pavement by conduction of heat melts the cover of ice from below.

The unit of heat is the same as for any work, Joule (J). Power, work related to time or wattage is the figure of Joule pr. second equivalent to Watt (W). Therefore, W · s = J. In meteorology, power often refers to an area. For example, the density of solar radiation is expressed in W / m^2. - In elder literature or tables the former unit „calorie" (not conform to the Système International d"Unités) may be found: 1 cal = 4.19 J. (The figure 4.19 refers to the specific heat of water 4.19 J/g K).

Specific quantities

Thermodynamic properties often depend on mass (kg) or volume (m^3) of a body (or system) and therefore refer to these quantities. Then, the properties are called „specific". For example, the „specific volume" of snow or air, V_s, is the volume V related to the mass m, $V_s = V / m$. Hence, the density $\rho = m / V = 1 / V_s$.

15.1.2 Fundamental relations

Ideal gasses

An ideal gas has properties as follows: No forces act between atoms or molecules; collisions between them are elastic; the particles are small relative to the volume considered; the motion of the particles is arbitrary. Air or its constituents at atmospheric pressure may in several meteorological contexts be treated as „ideal". There are exceptions, for example concerning properties of water vapour. For an ideal gas the following relations are valid when p designates pressure, V volume, T temperature:
In the special case of constant T (the Law by Boyle-Mariotte)
$p \cdot V = \text{constant}$
The general relation (the Law by Gay-Lussac) is
$(p \cdot V) / T = \text{constant}$, as a rule designated as gas-constant R.
The constant R depends on specific heat, is therefore different for different gases (for example water vapour) or a gaseous mixture (air).

The above relation can be exemplified by the static stability of air: METAR-temperature at the 2 m level in calm weather may be considerable warmer than air adjacent to the surface of a pavement cooled by net outgoing radiation. As air pressure in the present context (small difference in altitude) can be considered as constant, volume V decreases as temperature T decreases. As V decreases, the density of the air cannot but increase (see 15.1.1 specific quantities). Thus the coldest air is stratified stable lowest above the ground.

Capacity of heat

Assume that the temperature of a body changes by $\pm \Delta T$ when the heat Q is added or withdrawn. The temperature is proportional to the heat exchanged,

$Q = c \cdot \Delta T$ or $c = Q / \Delta T$
The constant of proportionality, c, is the „capacity of heat" or „thermal capacity". It shows the amount of energy necessary to achieve a change in temperature by 1 K in the mass 1 kg (or the volume of 1 m^3) of a substance. Different from the (nearly) incompressible solid and liquid bodies, gasses are compressible. Therefore, the thermal capacity at constant pressure and at constant volume is different (see 15.1.3).

When no change in the temperature but in the state of aggregate is concerned,
$Q = \lambda$
Here λ means the specific heat of melting or of evaporation (or of sublimation in the case of direct transfer from ice to vapour only); negative figures apply for reverse change of the state of aggregate.

To calculate the heat (for example from net absorbed radiation) necessary to melt ice at minus 5 ˚C, the heat to warm to melting temperature and the heat to melt the ice have to be taken into account. The specific heat of ice is approximately 2.1 kJ/kg K, thus 10.5 kJ are needed to heat 1 kg ice from minus 5 ˚C to 0 ˚C. Melting involves 333.5 kJ/kg. This shows that the major part of heat is needed for melting. Ice or snow may warm up rather quickly, as compared to melting.

When net outgoing radiation is 0.2 kW/m^2 the mass of 1 kg water distributed over 1 m^2 (a layer of 1 millimetre water) looses the heat (work done) 4.18 kJ. The time t needed is found from work W and power $P = W/t$, therefore $t = W/P$, hence 4.18 kJ/0.2 kW = 21 seconds. However, freezing would take the time t = 333.5 kJ / 0.2 kW = 1667 seconds or 28 minutes. A layer of 0.1 millimetre water would freeze in less than 3 minutes. Actually turbulent transfer of heat from water to air in addition to cooling by radiation would accelerate the process.

Change of state of aggregate

Crystalline substances (as ice) melt or freeze always at the same temperature, provided constant pressure. (The 0 ˚C reading at a thermometer can be controlled in field work by a mixture of snow and water). The input of energy or output does not change the temperature until the substance is melted or frozen totally. Therefore, slush irrespective of the proportion of ice contained, holds the temperature 0 ˚C. The heat supplied or withdrawn changes the potential energy of the molecules (state of aggregate) only, not their kinetic energy (temperature). Constant temperature for the period of melting or evaporation at the boiling point indicates that energy (heat) does work against cohesive forces between the molecules, thus allowing the change from solid to liquid and further gaseous state.

The change from liquid to gas is called „evaporation". Evaporation from the surface (!) of a liquid is going on at any temperature when the pressure of vapour in the gaseous sphere is less than saturation in respect to the liquid sphere. Evaporation by boiling means that vapour occurs even inside (!) the whole mass of liquid. Boiling happens at a fixed temperature, provided constant air pressure (Water: 100 ˚C at sea level pressure 1013 hPa). Input of energy does not increase the boiling liquid"s temperature as long as liquid is left. Evaporation from solid bodies (ice or snow) without the intermediate stage of a liquid is called „sublimation" or understood from the context. (In chemistry, the term „sublimation" may mean the opposite process).

When vapour is saturated in respect to a surface, then condensation at the surface from gas to liquid (water: at dew point temperature) or from gas to solid (water: at frost point temperature) takes place, provided heat is withdrawn and temperature decreases below boiling or freezing temperature. At constant air pressure, the amount of heat "hidden" by evaporation is released to "sensible" heat by condensation or de-sublimation. Densification from vapour to the solid state reverses the sublimation, for example the formation of hoar frost at surfaces or the formation of diamond snow in the air. As a kind of contamination, both may cause „slippery frost" characterized by generally small friction coefficients.

At the three-phases-point for water, 273.16 K, ice, liquid and vapour are in equilibrium concerning their surface pressures. Different from most substances the melting point of water decreases with increasing pressure. However, the effect is negligible in the context of the present paper (see chapter 03).

As saturation vapour pressure over ice is less than over liquid water, the dew point temperature (in respect to liquid water) is lower (colder) than the frost point temperature of actual interest in temperatures below freezing (see chapter 04).

The critical temperature of water is 647 K. At that temperature, liquid and vapour have the same density and cannot be distinguished any more. Increasing density of vapour with temperatures approaching the critical is relevant in steam planing (chapter 11). In other words, vapour cannot be liquefied when the temperature exceeds the critical point.

15.1.3 The kinetic theory

Temperature

The atoms or molecules in solid bodies, liquids and gases are in motion, both mutually and internally. The kinetic energy corresponds with temperature. In an ideal gas, the temperature is directly proportional to the kinetic energy of the particles of gas. When kinetic energy and thus the temperature are constant, theory leads to the empirical relation $p \cdot V = \text{constant}$ (see 15.1.2). For temperature $T = 0$, the kinetic energy is zero; atoms or molecules are in absolute rest. As any cooling device holds a temperature warmer than $T = 0$ K, the point of absolute zero empirically cannot but be approximated only.

The concept of kinetic theory explains the relation (see 15.1.2) between pressure, temperature and volume of an ideal gas. The pressure of a gas (or a mixture as air) is proportional to the kinetic energy of the molecules, and the same is the case for the temperature. The changes of aggregate (solid, liquid, gaseous) can be understood as significant changes in the mobility of atoms or molecules in respect to mutual forces. By condensation and freezing kinetic energy is released as heat, where as by melting and evaporation heat is "hidden" in the increase of kinetic energy. The kinetic energy (mobility) of the particles as shown by the state of aggregate and indicated by the temperature is considered as internal energy (conventionally designed by U) of a system.

Specific thermal capacities of gasses

In contrast to solid bodies and liquids, gasses are compressible. A change in heat ΔQ means a change of internal energy (temperature) $\pm \Delta U$ and the external work $\pm p \cdot \Delta V$ (the product of

pressure and change of volume). When air (gasses) is heated at constant pressure, the volume increases, the work of expansion is done.
$\Delta Q = \Delta U + p \cdot \Delta V$
Contrary to incompressible bodies, in the case of gasses the specific heat at constant pressure, c_p , has to be distinguished from the specific heat at constant volume, c_v . In the case of constant pressure p, the figure of change in heat ΔQ is called enthalpy. It may be interpreted as heat capacity, a property of the substance concerned.

To underline the point, there are two different cases: 1) Temperature changes by input of heat without changing the volume (V = constant, $\Delta V = 0$). In that case, all the heat increases the kinetic energy of the atoms or molecules and thus results in increasing temperature as $\Delta Q = \Delta U$. 2) Temperature changes by input of heat without changing the pressure (p = constant). In that case, input of heat ΔQ not only rises the temperature by increasing ΔU, but in addition does the work $p \cdot \Delta V$ in order to augment the volume by ΔV and hold the pressure constant. Therefore, in case 2) the rise in temperature is less than in case 1).

As can be shown (not done here), the difference between the specific heat capacity at constant pressure, c_p, and the specific heat capacity at constant volume, c_v, equals to the specific constant of the gas concerned, R_s. The latter can be interpreted as „work of expansion" divided by „the product of mass m and change in temperature", $R_s = c_p - c_v = (p \cdot \Delta V) / (m \cdot \Delta T)$. From the kinetic theory, for two-atomic molecules (dry air) the figures $c_v = R_s \cdot (5/2)$ and $c_p = R_s \cdot (7/2)$ are derived. The proportion $\kappa = c_p / c_v = 1.40$

Specific enthalpy of liquid water

The specific enthalpy means the change in heat capacity when the temperature changes 1 K in 1 kg of water at constant pressure. For water $c_p = 4.2$ kJ / kg · K, for ice 2.1 kJ / kg · K (approximate figure, dependent on temperature). The figure for liquid water means that an input or output of 4,2 kJ in 1 liter (1 kg) of water, equivalent a layer of 1 millimeter water covering 1 square meter of a runway, would change the temperature of water by 1 Kelvin.

For the sake of comparison of work, but also as an example for the First Law of thermodynamics 15.1.4), the height z that the mass m = 1 kg water could be lifted by 4.2 kJ is calculated. It is found from the relation for potential energy, $m \cdot g \cdot z = 4.2$ kJ. For the gravitational acceleration $g = 10$ m / s^2 the height z = 420 m is found. Put the other way, 1 kg of water has to fall that height in order to warm by 1 K. From the relation for kinetic energy, $\frac{1}{2} (m \cdot v^2) = 4.2$ kJ is learned that the amount of energy (heat) in question would be released by 1 kg of water at a speed of 92 m/s when it impacts inelastic with the ground. – In the case of precipitation, due to friction with the air, speeds of 5 to 10 m/s may be found. Therefore, by 1 kg water 0.013 to 0.050 kJ only would be released at the ground, increasing water temperature by 0.003 to 0.01 K.

Adiabatic process

A process without any exchange of heat with the environment is „adiabatic", in the case of gasses $\Delta Q = \Delta U + p \cdot \Delta V = 0$.
Any work done on the volume ΔV increases or reduces the internal energy ΔU, and thus the temperature. A parcel of air descending in the atmosphere is exposed to increasing air pressure. Compression increases the air temperature. Expansion done by the gas means

decreasing temperature as the work has to be covered by the internal energy. In adiabatic processes, pressure, volume and temperature are changed at the same time.

From the relation between $p \cdot V = R \cdot T$ (see 15.1.2), applied to adiabatic processes, the Poisson-equation can be derived (not shown here):
$p \cdot V^{\kappa} = \text{constant}$,
when κ stands for the proportion of specific heat at constant pressure to the specific heat at constant volume, $c_p / c_v = \kappa = 1.40$ (for dry air).

Many natural processes in the atmosphere can be considered as adiabatic because conditions change faster than exchange of heat is possible. Adiabatic cooling due to expansion of air is a well known cause of engine icing.

When air is trapped under a rotating tire, the change in temperature between the earlier stage 1 „before" and a stage 2 „later" can be calculated from $T_2 = T_1 \cdot (V_1/V_2)^{\kappa-1}$ with the exponent $\kappa-1 = 0.40$. For example, when air at 270 K (minus 3 ˚C) and unit volume 1 is compressed to volume 0.7, the outcome in temperature is 311 K (38 ˚C). In case $V_2 = 0.5$, the temperature rises to 356 K (83 ˚C). A figure $V_2 = 0.4$ would result in 390 K (117 ˚C). For $V_2 = 0.25$, the temperature 470 K (197 ˚C) would occur. Far larger compression and higher temperature might occur in pockets between asperities. Though the thermal capacity of air is about the factor 1500 less than the thermal capacity of ice, and compressed air attached to a passing tire experiences rapid expansion and cooling after heating, the rise of temperature in adiabatically trapped air might contribute together with the heat in tires to melt an utmost superficial film of ice or compacted snow.

15.1.4 The First Law of thermodynamics

Closed or open system and process

In a closed system, the material conditions remain unchanged, but exchange of energy is possible with other systems, for example with the environment. A system is open, when mass can be exchanged. The following refers to a closed system.

Any thermal state of a closed system is achieved by a „process". In the case of gasses, changes in temperature, pressure and volume constitute processes. Changes of the state of aggregate as freezing or melting, changes of internal energy as cooling or warming of a pavement by thermal conductivity, absorption or emission of radiation are outcomes of processes. All thermodynamic processes are caused by the exchange of energy and generally result in a change of energy attributed to the systems concerned.

Internal energy, work and heat

Any system contains internal energy symbolized by U, the kinetic energy, except at T = 0 K. There is to distinguish a) the potential and kinetic energy of the molecules, the sum of both represent the internal energy U, but the kinetic energy only shows up as temperature observed (see 15.1.2), b) the macroscopic mechanical potential and kinetic energy, E_p and E_k a system. Work done by a dissipative force, for example the force of friction, always increases the internal energy U at the expense of macroscopic mechanical energy $E_p + E_k$. As the sum of energy E in a closed system is constant, the sum of any internal mutual exchanges ΔE of energy is zero,

$\Delta E = \Delta(E_p + E_k + U) = 0$
Braking of an aircraft at a horizontal runway means to reduce E_k and to increase U as brakes, tires and air are considered as closed system heated.

However, in the case work W is done at or by a system, input or output of energy takes place, $\Delta E \neq 0$. The work done equals to the change in the total energy of the closed system:
$W = \Delta E = \Delta(E_p + E_k + U) \neq 0$
For example, the work done by crosswind either contributes to the lateral kinetic energy E_k of a braking aircraft (blown off the runway) or, when compensated by friction, increases U.

When the entire work done on a rolling aircraft by wind, grooves of ice etc. is converted into heat by frictional forces, then $E_p + E_k = 0$. It means that the entire work W results in change of the internal energy ΔU represented by the motion of atoms or molecules.

The First Law or Principle of Energy

Not only work W, even the exchange of heat Q with the system‟s environment changes U. Concerned with work W and heat Q only, the sum of potential and kinetic energy taken zero, $W + Q = \Delta U$.

That relation expresses The First Law of thermodynamics. In words: The energy added to or taken from a closed system by work or by heat, thus their sum, equal the change of internal energy. This implies that work and heat are equivalent, in accordance with the definition of heat as work (see 15.1.1). The temperature of a system may change by many processes due to work or heat or both. The First Law is identical with „The principle of energy‟, is to say the conservation of energy. The equivalence of work and heat implies that the saying a body would “contain” heat is not correct.

The example given in 15.1.3 concerning specific enthalpy illustrates the conservation of energy. The same is true when the system of liquid water at a runway receives work done rolling aircraft and looses heat due to net outgoing radiation and turbulent cooling towards the atmosphere. If, for example, the input by work were W = 10 kJ and the loss of heat –Q = 6 kJ, then the internal energy would increase by ΔU = 4 kJ, and in case explain why liquid water on runways or roads with heavy traffic may not freeze though ambient temperatures should indicate freezing.

15.1.5 The Second Law of thermodynamics

Reversible or non-reversible process

The principle of energy allows warm brakes after parking to cool down by transfer of energy to the environment as part of a system, but does not exclude the opposite process. However, cooling of the environment by itself to warm up the brakes to their initial temperature is never observed. Such a reversible process that by its own returns exactly to the state of the starting point would not contradict the equation $W + Q = \Delta U$ and would not violate the First Law of thermodynamics. However, the flow of heat observed is always in the direction from higher towards lower temperature, from larger towards smaller internal energy U.

Processes in nature are non-reversible (irreversible), or at best reversible in part, for example bouncing of an aircraft after touch down due to the elasticity of tires. The First Law of thermodynamics does not exclude fully reversible processes because it does not contain any statement concerning the direction of processes. As bouncing shows, a reversible process is a theoretical borderline case of an irreversible process.

The Second Law of thermodynamics

In terms of Lord Kelvin the Second Law states that mechanical work can be converted into heat totally, but it is impossible to convert heat into mechanical work, except when changes in a system or its environment take place. This is the case when for example electric energy (power) is put into the system to "pump" heat from a colder reservoir into a warmer one (as done by the heat pump or cooling aggregates), or when solar energy conserved in fuel is burnt by a motor generating mechanic energy as in an aircraft engine. However, in all cases the total sum of entropy increases. Without taking energy from "outside" (left to its own), in terms of Clausius, the flow of heat from a cold towards a warm body is impossible without leaving changes in the environment.

Entropy

It is common for all the irreversible processes that the universe of all the systems and their environments change towards a state of reduced organization. When a pavement is cooled towards the atmosphere, the flux of heat triggered in the bed of the runway is directed up towards the sink of heat and dissipated into the atmosphere. The exhaust gasses from an engine are dispersed in the air, never concentrated again.

As can be derived from kinetic theory (15.1.3), processes run in the direction from a more towards a less organized state. In accordance with that principle, any exchange of heat driven by differences in temperature, left to it self ends up in an equally distributed temperature. Described by likelihood, well organized patterns are less likely than arbitrary distributions and states of disintegration. Irreversible processes run in the direction from a state of less to larger likelihood. That direction in natural processes is described by the function of entropy S, its figure only increases for all irreversible processes. Not the absolute figure of S, its change ΔS augmenting S is of interest as it shows the direction of processes.

The entropy of a system describes its state as does pressure, volume, internal energy or temperature. All these show the state of a system, no matter the “way” how the state has been attained. Considering incremental changes Δ, changes in work and changes in heat result in changes of internal energy, $\Delta W + \Delta Q = \Delta U$ (see 15.1.4). Referring this relation to (dividing by) temperature T, the function ΔS (change of entropy) is established showing the properties described above:
$\Delta S = \Delta Q / T = (\Delta U + \Delta W) / T$

In case the work W is done by changing the volume V of a gas at pressure p, ΔW can be replaced by $p \cdot \Delta V$. Then the entropy is written
$\Delta S = (\Delta U + p \cdot \Delta V) / T$

The change of entropy (the change of heat related to temperature) equals the sum of change in internal energy together with the work done (for example expansion of the volume), related to (or measured in units of) the temperature. When there is no input or output of heat to or from a system (a parcel of air), then the only changes of state possible are changes in temperature,

ΔT, and pressure, Δp. This is the case of adiabatic processes (see 15.1.3). As the exchange of heat $\Delta Q = 0$, even the change in entropy
$\Delta S = \Delta Q / T = 0$. Therefore, rapid changes in the atmosphere (air) that may be considered as adiabatic, do not change the entropy.

The Second Law and the entropy

The Second Law states that the entropy of a closed system of bodies in interaction with each other increases. The entropy by a process left to itself never decreases. This implies that the nature as a whole is changing one-sided directed. A state realized in the past does never come back again. Therefore it is impossible to construct any device that would take heat from the ground and totally convert it into electrical power (to supply a parking aircraft).

An example for the Second Law is the dissipative heat from friction. The motion of an aircraft implies that the frame‟s molecular motions are superposed by the well organized vector of velocity. By braking (friction), the established order of velocity is transformed into additional far less organized motion or internal energy by heat. Another example for the Second Law is when rain precipitates on ice, disintegrates its structural bonds and results in slush at freezing temperature. The concept of entropy is the only criterion given in nature to distinguish „before‟ and „after‟, the direction of time. Consider an irreversible process in a closed system, as for example the flux of heat or the metamorphism in undisturbed snow. That state is the later one that represents the larger entropy.

When heat Q flows from the warmer surface layer of a pavement at temperature T_w (for example asphalt heated by solar radiation) to the colder body of the construction at temperature T_c, the entropy of the surface layer changes by
ΔS_w,= - (Q/T_w), the entropy of the colder body by $\Delta S_c = +(Q/T_c)$. The total change of entropy in the universe (heat from warm to cold) is $\Delta S_{universe} = \Delta S_c + \Delta S_w = (Q/T_c) - (Q/T_w) > 0$
When the colder zone is at 268 K (minus 5 ˚C), the warmer surface at 288 K (15 ˚C), the flow of heat Q = 10 kJ, the entropy is 10 / 268 = 0.037 and 10 / 288 = 0.035 respectively, the increase $\Delta S_{universe} = 0.002$ kJ/K

The course of increasing entropy in a closed system, for example the terrestrial system, can be reversed by interference from other systems, for example the sun, incorporated into a widened original closed system. Then a partially decrease in entropy, for example the rise of a gradient in temperature due to absorbed solar radiation, does not contradict that the entropy increases in the system as a whole (earth and sun). Slush may end up as liquid water or ice depending on the input or output of heat. Freezing means to reduce the entropy in the water as molecules get organized into a lattice. Freezing heat is dissipated to the environment as a sink of heat, totally increasing the entropy.

The concept of entropy describing irreversible processes gives the energy no more usable for work. The figure is $Q = T \cdot \Delta S$, (the temperature T is the lowest one). In the example above,
$Q = 268 \cdot 0.002 = 0.536$ kJ are invalidated energy in respect to work.

The Third Law of thermodynamics

From quantum theory can be deduced that the entropy of all solids approaches zero when the temperature declines towards 0 K. The thermal capacity is zero at the temperature 0 K. A device that hypothetically attained 0 K exactly could not but receive heat from its environment with thermal capacity exceeding zero. Therefore the temperature exactly 0 K cannot be reached experimentally.

An analogy to the role of small differences in temperature is the fact that liquid water cannot freeze except when its temperature decreases below the theoretical point of freezing as freezing heat has to be dissipated. Both the depth (and thus amount) of liquid water represented by a film on a runway and the freezing heat released influence on the speed of the freezing process, a very thin film freezing fast than water of some depth.

A real substance changing the state of aggregate

The concept of entropy and the Laws of thermodynamics concern the contamination of traffic areas by water because they show and quantify the heat involved in changing the state of the contamination. Any management of contamination by water covering freezing/melting as well as evaporation involves estimates of energy, of heat exchanged in a time to come.

Summarizing, the change from ice at minus 30 ˚C (runway Svalbard airport) to water vapour at 150 ˚ (assumed between ice and rubber of a braking wheel) the internal energy of 1 kg water increases in stages as follow. The true figures of energy however will deviate from the figures given in the example as the capacities for heat at constant atmospheric pressure c_p (1013 hPa) are used, but higher pressures will occur. At higher pressure, the boiling temperature would be a figure warmer than 100 ˚C. Anyway, the relative magnitudes of the figures of c_p should be noticed. To heat ice to melting temperature needs far less heat than to melt ice, and again far less than evaporation as necessary to dry up a wet runway.

Increasing the temperature of ice from minus 30 ˚C to 0 ˚C, $c_p = 2.1$ kJ/kg K, needed $Q_1 = 2.1 \cdot 30 = 63$ kJ.
Melting at constant temperature 0 ˚C requiring the specific heat of melting $\lambda_m = 334$ kJ/kg, thus needed $Q_2 = 334$ kJ.
Increasing the temperature of liquid water from 0 ˚C to 100 ˚C, $c_p = 4.19$ kJ/kg K, needed $Q_3 = 100 \cdot 4.19 = 419$ kJ.
Formation of saturated vapour at 100 ˚C, requiring the specific heat of evaporation $\lambda_e = 2260$ kJ/kg, thus needed $Q_4 = 2260$ kJ.
Increasing the temperature of vapour from 100 ˚C to 150 ˚C, $c_p = 1.9$ kJ/kg K, needed $Q = 1.9 \cdot 50 = 95$ kJ.
The sum of all the four terms is $Q = 3171$ kJ. That figure of energy would be converted even in case the ice had been vaporized directly (sublimation). Evaporation at temperatures common in nature, for example to heat melting water to 5 ˚C, would need $5 \cdot 4.19 = 21$ kJ. In order to evaporate a layer of 1 millimetre of water covering 1 m^2 (1 kg liquid water) 2260 kJ are needed (see 15.1.2). In case the heat supply is 0.2 kW/m^2, the time to evaporate that layer would be $t = 2260$ kJ/0.2 kW = 11300 second or 3.14 hours. When energy supply is expected for that time and freezing not is likely, the runway may dry up and the use of ice preventive chemicals can be saved.

The input of heat Q has to be taken from a warmer reservoir. The entropy (see 15.1.6) describing the thermodynamic state of the whole system in the first example increases by $\Delta S_{universe} = 3171/243 - 3171/423 = 13.05 - 7.50 = 5.55$ kJ/K. The amount of heat due to the irreversible process got unable to do further work is $Q = 243 \cdot 5.55 = 1349$ kJ.

15.1.6 The transfer of energy by conduction of heat

The principle

Conduction of heat depends on atomic and molecular interaction (diffusion) directed from a warm to a cold reservoir according to the Second law of thermodynamics and augmenting entropy (see 15.1.5). The driving force is proportional to the gradient of temperature T along the distance x, $\Delta T/\Delta x$.

When in the interval of time Δt the amount of heat Q is conducted, then the flow of heat Φ has the speed $\Delta Q/\Delta t$. The flow (current) is proportional to the gradient of temperature, the area A of the conducting cross-section, and the thermal conductivity k. Therefore, by definition,
$\Phi = - k \cdot A \cdot \Delta T/\Delta x$
The negative sign indicates the direction of heat from warm to cold. The thermal conductivity for recent snow is about 0.1 W / (m · K), ice or standing water 0.6, concrete 1 W /(m · K).

The definition above can be written
$\Delta T = \Phi \cdot \{\Delta x/(k\cdot A)\} = \Phi \cdot R$
By definition, R describes the resistance met by the flow of heat, given in K/W.

The coefficient of resistance to heat conduction is $r = \Delta x/k = R \cdot A$. It is defined as resistance in 1 m^2 area when the layer is Δx m strong. Common units for r are (m^2 K)/W.

When two reservoirs maintain the constant temperatures T_1 and T_2, (stationary conditions), then
$\Phi = - \alpha \cdot A \cdot \Delta T$
The coefficient α describes the exchange of heat {W (effect) / m^2 (area) K (temperature)}. The figures for standing water upon a traffic area may be in the order of $3 \cdot 10^2$ to $6 \cdot 10^2$ W / m^2 K, for standing (calm) air 5 W/m^2K, increasing with air speed (see 15.1.7).

The coefficient of heat transfer α can be interpreted as follows: In order to exchange energy, a driving difference in temperature ΔT is needed in respect to the limiting surface of a system. The density of the flow of heat is described by the transferred energy per time $Q / t = \Phi$ (unit J/s) and related to an area (unit W/m^2). The reference to an area shows that the total transferred energy changes with the area for a given ΔT. Therefore energy related to an area only expresses the "quality" of the energy (!) transferred. But because even a change in the figure of ΔT changes the total amount of energy flowing, the density of the flow alone is not sufficient to characterize the "quality" of the transfer (!) of heat. However when the density of the flow of heat is related to (or given in units of) the driving difference in temperature, then the coefficient for heat transfer $\alpha = \Phi / A \cdot \Delta T$ is an analytic expression showing the "quality" of the flow of heat in a specified concrete condition. Example: At Svalbard Airport in calm air above asphalt at a certain site $\alpha = 5$ W/m^2 K, in wind 8 kt (4 m/s) close to the surface as determined from the movement of snow, $\alpha = 22$ W/m^2 K. The relation to the thermal resistance R follows from $R = \Delta T / \Phi$ and $\Phi = \alpha \cdot A \cdot \Delta T$, therefore $R = 1/\alpha \cdot A$. The smaller the thermal resistance, the larger is the transfer of heat.

As Φ gives Q/t (W/s), the time left can be calculated before Q may result in a significant change of the state of traffic area contaminating water.

The Newtonian law of cooling

The speed of cooling is approximately proportional to the difference in temperature between two attaching bodies or a body and its environment.

The temperature of a warmer body in a colder environment, the latter at constant temperature, approaches to the environment"s temperature as a logarithmic (exponential) function. This applies to a thermometer (test-body) for measurement in air or cover of a runway, but also to the surface layer of a runway adapting to an equilibrium in the flow of heat (input =output). The corresponding is true for warming a colder body in a warmer environment at constant temperature.

The Newtonian law is valid for all kinds of transfer of heat, by conduction as well as by convection and radiation.

Vertical flow of heat through layers, stationary conditions

The following applies to heat flowing through one or more consecutive layers as is the case in contaminated runways, or different layers of a runway construction.

Assumed are stationary conditions: Temperatures are constant and thus the flow Φ (generally in Watt) is constant as input to the system equals output. This is a simplification of real conditions when the temperature and its gradient changes through time. The stationary condition may never the less result in realistic estimates.

The system, for example, is a layer of thawing ice at temperature T_0, upon asphalt heated by solar radiation at the warmer temperature T_1, and the lower temperature T_3 of adjacent air upside the ice. The differences in temperature result in flow of heat as follows:
$T_1 - T_0 = \Phi \cdot R_1$
$T_0 - T_3 = \Phi \cdot R_0$
The difference of temperature between asphalt and air is
$\Delta T = T_1 - T_3 = \Phi \cdot (R_1 + R_0) = \Phi \cdot R$
R is the resistance through the whole system. The term ΔT is the difference in temperature between the two spheres (asphalt and air) on either side of the layer.
From the last relation follows $\Phi = \Delta T/R$
As Φ is proportional to ΔT, the Newtonean law of cooling is fulfilled.

In the case of number n several layers upon each other, for example n = 3, snow upon ice upon liquid water, the total thermal resistance is the additive sum of the individual layers,
$R = R_1 + R_2 + \ldots + R_n$
The same applies to electrical resistances in row.
Analogue the total coefficient of resistance equals the sum of the coefficients for the individual n layers,
$r = r_1 + r_2 + \ldots + r_n$

Assume the question for the temperature in the interface between a layer of 1 millimetre concrete, and 1 millimetre of ice, when a gradient $\Delta T = 1$ K throughout the two each 2 millimetre strong layers (concrete below 1 millimetre, air above the ice) is observed, for example 270 K below the layer of concrete, 271 K above the ice. Solar radiation transmitted through the ice is excluded (night) and likewise changes in the state of aggregate of water

(temperatures well below freezing). From these data referring to an area 1 m^2, and the coefficients for heat conduction in ice and concrete, the heat resistance is $R = \Delta x / k \cdot A$, in figures:
$R_{concrete} = 0.001/ 1 \cdot 1 = 0.0010$ K/W, $R_{ice} = 0.001/ 0.6 \cdot 1 = 0.0017$ K/W
The sum of the total heat resistance is $R_{total} = 0.0027$ K/W
The flow of heat is $\Phi = \Delta T/R$, in figures results
$\Phi = 1/0.0027 = 370$ W
The difference of temperature in each of the two layers is
$\Delta T_{concrete} = 370/0.0010 = 0.4$ K, $\Delta Tice = 370/0.0017 = 0.6$ K
The temperature in the interface between concrete and ice is $T_{interface} = 270.4$ K, in reference to the point of freezing 273.15, K minus 2.8 ˚C.

Parallel flow of heat through different resistances, stationary conditions

This case applies for example to a runway covered with patches of snow, or constructed with different thermal properties side by side. (At Svalbard Airport a section of the runway is intentionally built with large thermal resistance as to conserve permafrost).

With the symbols used in the previous section, the difference ΔT means the temperature between two columns of a substance, for example bare asphalt aside asphalt covered by snow. In the case of number n different parallel vertical flows of heat, the sum of Φ is requested:
$\Phi = \Phi_1 + \Phi_2 + \ldots + \Phi_n = \Delta T/R_1 + \Delta T/R_2 + \ldots. + \Delta T/R_n = \Delta T\ (1/R_1 + 1/R_2 + \ldots + 1/R_n)$
Obviously for parallel organized thermal resistances (as for electrical resistances) the sum
$1/R = 1/R_1 + 1/R_2 + \ldots + 1/R_n$
From that relation is seen that the total resistance always is less than the individual resistances.

As with layered heat resistance is the parallel resistance proportional to ΔT. Thus the Newtonian law of cooling applies.

Non-stationary conditions

For detailed studies, the stationary condition assumed above simplifies the real process too much. The thermal conductivity of a solid layer is governed by the thermal conductivity (coefficient k, see above). The temperature attained by a substance depends not only on the amount of heat transferred, but also on the property to absorb that energy as described by the thermal capacity c (see 15.1.2).

Changes in the flow of energy (heat) Φ along the depth x of a layer result in changes of temperature T with time t. Written as small increments Δ, this can be expressed as
$\Delta\Phi/\Delta x = c \cdot (\Delta T/\Delta t)$

From this relation (in differential form) a relation can be derived that describes variations of temperature T with depth x in a layer and time t. The variations of temperature inside a layer depend on a coefficient specific for any substance, the thermal diffusivity δ. It equals the thermal conductivity k (see above) expressed in units of the thermal capacity c, thus
$\delta = k/c$

The thermal diffusivity describes the propagation of temperature in a medium and indicates therefore how fast differences in temperature can be eliminated. Calm air shows both low thermal conductivity and relatively much lower thermal capacity, therefore a rather large thermal diffusivity transmitting temperature well. The thermal diffusivity for ice is about $1.2 \cdot 10^6 = 0.0000012\ m^2/s$, compacted snow and concrete both $0.8 \cdot 10^6$, but calm air about $20 \cdot 10^6\ m^2/s$.

The variation of temperature through time in different depths of a layer with different thermal diffusivity is described by differential equations not presented here.

15.1.7 The transfer of heat by convection

In the present context, the term "convection" is used for any turbulent exchange of air due to static instability, internal friction in the air and friction related to the ground.

As to the static stability, the change of air pressure Δp with a step Δz in height is described by the fundamental equation of hydrostatics:
$-\Delta p/\Delta z = g \cdot \rho$
Here g means the acceleration of gravity $9.81\ m/s^2$, ρ is the density of the air. The weight of a parcel of air equals $g \cdot \rho \cdot \Delta z$, a parcel that would "fall" to the ground if it were not borne by the force of the vertical gradient of pressure $-\Delta p/\Delta z$. The minus sign indicates that pressure decreases with increasing height. The parcel of air is exposed to tension by environmental air.

Vertical motions in the atmosphere can be considered to occur adiabatically. The exchange of heat with surrounding air is negligible. Therefore, the enthalpy (see 15.1.3) is zero. In symbols (meaning as in 15.1.3) the equation $\Delta Q = \Delta U + p \cdot \Delta V = 0$ applies and is in accordance with the First law of thermodynamics. The term $\Delta U = c_p \cdot \Delta T$, and $p \cdot \Delta V = 1/\rho \cdot \Delta p$. The equation for adiabatic conditions, written
$c_p \cdot \Delta T + 1/\rho \cdot \Delta p = 0$ means that changes in pressure and temperature only correspond to each other. The specific heat at constant pressure $c_p = 1.005$ kJ /kg K, note that $1\ J = 1\ (kg \cdot m^2)\ /s^2$. From this one derives $-\Delta T/\Delta z = g / c_p = 0.976$ K/100 m as the vertical gradient of temperature.

That gradient assumes no additional heat from condensation or evaporation of water vapour. The figure 1 K/100 m (1 K/ 1000 ft) therefore is called "dry adiabatic" lapse rate. In the case of condensation or evaporation, the actual lapse rate deviates from the dry adiabatic, dependent on the intensity of the changes of the aggregate of water, the amount of water involved per time. The "moist adiabatic" lapse rate may be in the order of 0.4 K/100 m to 0.8 K/100m. The moist adiabatic lapse rate depends on ambient temperature and air pressure. As a climatic value in Norway, 0.65 to 0.70 K/100 m is reasonable, thus 2 K/1000 ft in the atmosphere is a rule of thumb. However, the thermodynamic laws and relations apply also in small scale as related to the boundary layer of a runway.

Hence the parcel of air will ascent by its buoyancy. This is often the case when absorbed solar radiation at a pavement results in large over-adiabatic lapse rates (several 100 K/100 m in the lowest meter). The convection is indicated visually by flickering when the rays of light pass vertically exchanged parcels of air at different temperature and thus different refraction. When the vertical gradient of temperature is less than the adiabatic, or temperature even increases with height, then the air is stable. This is the situation of „inversions", a regular phenomenon when the heat budget of the surface is negative (mainly due to negative net radiation) and thus a runway acts as a sink for heat.

In the case of wind, due to internal friction in the air and in contact with the ground shear forces result in turbulent mixing of air by eddies. The properties of air, temperature (sensible heat) and water vapour (latent heat) are carried vertically and horizontally (the latter termed „advection"). These complex processes cannot here be dealt with in detail. Of interest is finally the heat exchanged between a surface (or a body) and the atmosphere. The vertical transport of sensible heat (temperature) and of latent heat (water vapour) are, as an approximate description, assumed proportional to the vertical gradients of temperature and mass of water vapour in the air. In addition, the flow of water vapour is dependent on the gradients of vapour pressure.

An effect of turbulence is the ability to carry properties of the air far more effectively (by a power of 10^5) than by molecular conduction or diffusion. When any property, for example the sensible or latent heat (water vapour) of air is called s, then its eddy flow $S = E \cdot \Delta s/\Delta z$ when E is a coefficient of exchange (international "Austausch") proportional to the vertical gradient of property s. The flow of sensible heat H, for example, can be written $H = E \cdot c_p \cdot \Delta T/\Delta z$, usual unit J /$m^2$ s. For E, even the quantity E/ρ is used when ρ stands for the density of air. The quantity E/ρ is called "eddy diffusivity". It represents the volume transferred through an area per time.

From empirical studies and theoretically derived models it often is possible to estimate the flow of heat. The specific capacity of heat for dry air at constant pressure is $c_p = 1005$ J/kg, at constant volume $c_v = 718$ J/kg (see 15.1.3). Concerning sensible heat, a body at temperature T_b (runway) adjacent to the environment (air) at temperature T_e looses or gains energy by the flow of sensible heat S proportional according to the Newtonian law of cooling, $S = - \alpha \cdot (T_b - T_e)$. The coefficient of proportionality α describes the transfer of heat {W (effect) / m^2 (area) K (temperature)}, depending on geometrical conditions. For example, when the wind speed 1 m above a runway is 1 m/s, α may attain 20 W/m^2 K, at 5 m/s about 100 W/m^2 K, at 10 m/s attains α figure 150 W/m^2 K.

When the surface of a runway is wet or covered with ice and evaporation is going on, or in the case of dew fall or the formation of hoar frost, the heat involved due to water has to be considered together with the exchange of sensible heat. The heat needed to melt 1 kg of ice is 335 kJ, to evaporate it (without changing the temperature) 2300 kJ (see 15.1.2). The process to melt ice at 0 ˚C and to evaporate 1 millimetre of water covering 1 m^2 would need 2635 kJ (equivalent to 0.73 kW/hour) that may be covered by radiation, sensible heat (turbulent air) and conduction in the pavement. For different expressions describing moisture in the atmosphere see 15.2 (Some meteorological definitions).

15.1.8 The transfer of heat by radiation

Flow through the terrestrial system

The flow of energy by electromagnetic radiation is the only one independent from any transmitting medium. Decisive for the thermal equilibrium of the terrestrial system is the balance of input of energy by solar radiation and the output of terrestrial radiation. The thermal state of a traffic area including contamination depends on the net radiation absorbed by or emitted from the surface, besides the turbulent (convective) flow of sensible and latent heat as well as conduction of heat in the ground. All the thermal processes described, the transformations of energy involved in the heat budget of a runway including contamination, are links in the conversion of solar energy to heat unable to do work as entropy has increased (see 15.1.5).

The Law of Planck describes the radiation from a „black body" (an ideal emitting body) by the spectrum of wavelengths of the radiation and the black body temperature. The solar radiation spectrum indicates an emitting black body temperature (solar) of 5750 K. The terrestrial radiation (outside the atmosphere) corresponds to a temperature 255 K (the equilibrium between input and output of energy). The global surface temperature however holds about 288 K, the "green-house-effect" (due to the partial absorption of outgoing terrestrial radiation in the atmosphere). As the terrestrial temperatures are far cooler than the effective solar radiation temperature, the wavelengths of the terrestrial radiation cover the infrared part of the electromagnetic spectrum. Hence the distinction between „shortwave" radiation (solar) with maximum energy in the 492 to 542 nm (nanometer: 10^{-9} m) region visible as marine green, and „long wave" radiation of magnitude 10 000 nm.

The solar radiation

The density of solar radiation received vertically at an imagined surface (or a space vehicle) outside the atmosphere is called „solar constant", though actually variable. Its figure is generally accepted as 1370 W/m^2. Referring that figure to a globe (ball), 342 W/m^2 are taken as a scale for the flow of energy in meteorological settings.

The term „global radiation" means the sum of direct and spread solar radiation on a horizontal surface. Compared to the density $I_{h=90}$ of solar radiation directed vertically (from the zenith) upon a horizontal surface, the density is attenuated when the rays upon the surface arrive at an angle less than 90 ° to the horizontal. Therefore, when the sun is h degrees above the horizon, or z degrees from zenith, the density of energy I received is
$I = I_{h=90} \cdot \text{sinus } h$, or $I = I_{z=0} \cdot \cos z$
The radiation energy received at the ground is reduced by backscatter from clouds, the atmospheric gasses (molecules) together with absorption, all dependent on the height of the sun and thus the length of the ray"s way through the atmosphere. In June, the mean global radiation is in the magnitude of 200 W/m^2 both in Southern Norway and in the Arctic, dependent on the duration of sunshine (midnight sun) and cloudiness, whereas the mean for December is about 15 W/m^2 in the southernmost part of Norway. At Svalbard Airport, in June short time densities of 700 W/m^2 may occur, enhanced by multiple reflections from snow. A black runway there attains surface temperatures reaching 30 ˚C, dependent on conduction into the pavement and loss of heat to the atmosphere.

Only the proportion of radiation absorbed at the surface or in its pores contributes to the heat budget. The term „albedo" means the per cent proportion of energy spread at the surface and thus "lost" as a source of heat (at the runway). Asphalt has an albedo about 0.10 (10 per cent), concrete about 0.20 per cent, recent snow even 0.90, wet melting snow 0.50, liquid water 0.05. A wet surface of asphalt transforms most of the incoming solar radiation into heat, except for low solar angle when the water (or ice) reflects a considerable part of the energy.

The actual figures for albedo at a pavement may deviate considerable from the figures published. This is partly caused by dark contaminants (rubber, exhaust), but for a large part by the transparency of snow or ice covering the pavement by a thin layer only. The albedo of 0.40 m undisturbed snow measured to 0.85 may show, after sweeping and compression to few millimetres upon asphalt in sun an albedo 0.35 only.

The incoming solar radiation can be calculated from astronomical data (height above the horizon) and meteorological data (clouds and aerosol). For the management of traffic areas, the measurement of the global radiation is the method to chose.

Terrestrial radiation

The density of this radiation I_{black} emitted from a "black body" equals $I_{black} = \zeta \cdot T^4$, with ζ for the Stefan-Boltzmann-constant $5.6696 \cdot 10^{-8}$ W/m^2K^4. The essential issue is the increase of the density of radiation with the 4th power of the absolute temperature (Kelvin). The emission of a black body at minus 20 ˚C is 233 W/m^2, at minus 10 ˚C 272, at 0 ˚C 316 W/m^2. Most of the substances in nature and outdoors may, more or less, be considered as „black body". The emission from asphalt and concrete are about 96 per cent of an ideal black body"s, the factor for snow is 0.98, liquid water 0.95. The figures are small for polished metals. The deviation from a black body (the actual body is grey) can be considered by the factor of emission $\varepsilon < 1$. As in the case of solar radiation, incoming atmospheric long wave radiation is absorbed in the pores of the surface layer, and emitted radiation has its origin in the pores. The „surface temperature" deduced from infrared radiation actually is the temperature of a level below the asperities. This applies especially to a very porous medium as snow.

The exchange of energy by terrestrial radiation, directed to the ground from the atmosphere, directed from the ground to the atmosphere, is in the case of two „black" surfaces (cover of cloud) given by $\Delta I = \zeta \cdot (T^4_{ground} - T^4_{cloud})$. In principle this equation applies too for grey substances, or for the atmospheric longwave radiation emitted from aerosol and especially water vapour. A runway may cool down due to negative net radiation, but emission decreases as temperature is reduced. Ultimately equilibrium with net radiation zero will be attained. Increasing atmospheric radiation due to warm air, increasing amount of water vapour and clouds aloft will result in net gain of energy on the side of the runway. Its temperature will increase.

The equation for net radiative exchange of energy ΔI is valid in general for the temperature difference between a body and its environment. When the difference in temperature can be considered as small (usually in natural conditions), then ΔI is proportional to the difference in temperature ΔT as can be seen from the following:
$\Delta I = \zeta \cdot (T^4_{body} - T^4_{environment}) = \zeta \cdot (T^2_b + T^2_e) \cdot (T^2_b - T^2_e) = \zeta \cdot (T^2_b + T^2_e) \cdot (T_b + T_e) \cdot (T_b - T_e)$
where the last term corresponds to a difference ΔT. For an emitting body (runway) the Newtonian law of cooling applies. As for small difference in $T_b - T_e$, the above relation for ΔI can be written as a row, ΔI can be approximated by $\Delta I = 4\zeta\, T_e^3\, (T_b - T_e)$. When T_e is unknown, but T_b is known, T_b^3 may be used.

The flow of terrestrial radiation may be measured, estimated from meteorological data as temperature, the atmospheric content of water vapour and cloud cover, or calculated by various models developed for different purposes.

15.1.9 The energy budget

Summing up, the budget of energy governed by heat can be calculated or estimated for a body, especially a traffic area contaminated by water, by the terms as follow.
I: The net sum of solar and terrestrial radiation,
S: The sensible heat (temperature) carried by the air,
E: The latent ("hidden") heat (evaporation or condensation) carried by the air,

F: Change of aggregate (freezing or melting),
G: Heat flowing into or from the ground (contaminating layers and pavement).
Other terms may consider special phenomena as heat carried by precipitation, energetic effects due to the use of chemicals etc.
By convention, the terms are positive when the flow of energy is directed towards the surface (of traffic area) considered. As a surface cannot accumulate energy, the sum of the terms has to be zero.
I + S + E + F + G +… = 0
This fundamental relation for the energy budget is crucial for any management of traffic areas. If, for example, in winter at Svalbard (Spitsbergen) the runway absorbs of solar radiation 25 W/m^2 (all figures in that unit), net longwave radiation is -100, then the total loss of energy by radiation passing the runway surface is I = -75. Into cold air the pavement may release S = - 25, and G flowing from the interior to the surface of the pavement may likewise amount to G = 25. Finally, the surface considered will gain E + F = 75 by condensation and freezing due to the formation of hoar frost from vapour. Thus the equation -75 (I) -25 (S) + 75 (E+F) + 25 (G) = 0 is fulfilled.

15.2 Some meteorological definitions

Adhesion: Attracting molecular forces.
Adsorption: Adhesion between a solid body and gas.
Advection: Lateral (horizontal) transport of air.
Aerology, indirect: Conditions aloft assessed on the basis of observations on the ground. For example: interpretation of precipitation based on cloud conditions (liquid water in frozen precipitation).

Aerosol: Mixture (emulsion) of air with solid or liquid particles.
Aircraft Braking Coefficient: Coefficient of friction actually experienced by an aircraft.
Albedo: Fraction (per cent) of solar or terrestrial radiation not absorbed but scattered towards the atmospheric sphere). For solar radiation: New fallen snow 95 to 80, old and wet snow 70 to 40, concrete 20 to 15, asphalt 10 to 5, liquid water when sun is 15º above horizon 10 to 3, when 5º above horizon 80%. For terrestrial radiation: Snow, ice, liquid water 4 to 2, concrete and asphalt 9 to 6%.
Asperities: Tops of microtexture.
Atmospheric longwave radiation: Emission towards the ground from clouds, gasses, aerosols. Gasses (most significantly water vapour) absorb and emit in distinct spectral lines. Clouds may be considered as „black bodies". As most of the atmospheric radiation is emitted from water vapour close to the ground, it may be estimated from vapour pressure and air temperature at standard level 2 m.

Braking action; Coefficient of friction as observed by measurement devices or estimated. Present qualitative scale employed: Good, medium-good, medium, medium-poor, poor, nil.
Black body: See „Infrared radiation".
Black ice: Transparent ice showing the (black) asphalt surface beneath.
Blowing snow: Snow lifted by wind more than 2 m above ground.

Coefficient of friction: Proportion of acceleration (deceleration) with respect to acceleration by gravity, or acceleration (deceleration) in units of gravitational acceleration.
Counter radiation: See „Atmospheric longwave radiation".

Default friction coefficient: Effective coefficient of friction experienced by an anti-skid steered tyre.
Deflation: Blowing off of particles (snow, sand) due to shear force in wind and small scale differences in air pressure caused by surface roughness as well as differences in the wind velocity around single particles.
Dewpoint temperature: Temperature at which a given content of water vapour at an actual temperature, air pressure and mixing ratio in the air, would condense into liquid water (would be saturated with respect to water at the actual air pressure and mixing ratio). See also „Frost point temperature".
Dielectric constant: See „permittivity".
Drifting snow: Snow moved by wind below 2 m above ground.

Energy: Capacity to exert work. Unit: Joule.
Flow of energy unit: Joule/second = Watt.
Density of flow of energy: Joule / second m^2 = Watt / m^2
Eutectic temperature: Freezing temperature of a saturated aqueous solution of salt.

Formschluss: Term for transfer of force due to the principle of a toothed wheel.
Freezing point temperature: Temperature (of water) changing from liquid (or gas) to solid state. In the reverse direction: Melting point temperature. Pure water: 0 ºC
Frost point temperature: Temperature at which a given content of water vapour in the air would form solid ice (hoar frost). Corresponding values for dew and frost point temperatures:

Dewpoint ºC:	M25.0	M20.0	M15.0	M10.0	M05.0
Frost point ºC:	M22.6	M17.9	M13.4	M08.9	M04.4
Difference K:	2.4	2.1	1.6	1.1	0.6

Global radiation: Sum of direct and spread solar radiation from sky (hemisphere) on horizontal area. Unit: W/m^2

Heat: Energy represented by the kinetic energy of molecules. Internal energy.
Heat (capacity): See „Thermal capacity"
Heat (conductivity; thermal conductivity): The molecular transfer of heat. Heat that passes through 1 m of a (solid) substance in 1 second when the difference in temperature is 1 K. Unit: W/m K. Asphalt: 2.7, concrete: 4.6, runway body: 1.5, ice: 2.3, compacted snow: 0.5 to 2.0, recent dry snow: 0.1 W/m K.
Heat (exchange): Density of heat flowing through an area per difference in temperature due to (turbulent) exchange of air (wind), depending on geometrical shape. Unit: W/m^2 K. The coefficient of heat transfer by exchange of air (usual symbol α). For a leaf: 10 to 200 W/m^2 K in calm air and a breeze respectively, increasing roughly by the square root of wind speed.

Heat (evaporation): „Hidden" as „latent heat" in the vapour by evaporation, released as „sensible" heat by condensation. For water 2,400 kJ/kg
Heat (melting): „Hidden" when melting, released when freezing. For water 333 kJ/kg
Heat (specific): Amount of energy changing temperature by 1 K in a mass 1 kg. Unit J/kg K. Concrete: 0.7 to 0.9, air: 1.0, ice 1.9 to 2.1, liquid water: 4.2 J/g K
Homologeous temperature: Temperature (in Kelvin) given in units of freezing (or melting) temperature of the substance. Water at M10 ºC = 263 K has homologeous temperature 263/273 = 0.96
Humidity (absolute): Mass of water vapour in relation to mass of dry air, or expressed as concentration of mass vapour per volume.

Humidity (relative): Proportion of actual vapour pressure to saturation water vapour pressure. Or the proportion of actual mixing ratio to saturation mixing ratio (expressed in per cent).
Example: At M10 ºC observed vapour pressure 2.60 hPa (hectoPascal). Saturation vapour pressure with respect to (supercooled) liquid water is 2.86 hPa. Hence, relative humidity is 2.60/2.86 = 0.92 (92%). Note: In relation to ice, saturation vapour 2.60 hPa, relative humidity would be 100%. However, relative humidity (at dewpoint) is defined with respect to liquid water even at temperatures below freezing.

Humidity (specific): Mass water vapour with respect to mass moist air. (Compare „Mixing ratio")
Hygroscopic substance: Attracts water though relative humidity less than 100% due to lower saturation vapour pressure in a solution of, for example, salt.

Infrared (longwave) radiation: Terrestrial radiation, of wavelength in the order of $10\ \mu = 10^{-5}$ m.
Natural solid substances and water (including clouds) absorb and emit in approximately the same way as „black body" radiation (continuum of wavelengths). The density of the emission increases by the fourth power of the absolute temperature according to the Stefan-Boltzmann law. The density of the radiation can be used to determine the emitting surface temperature. The density of „black" radiation is:

Surface temperature ºC:	M30	M25	M20	M15	M10	M05	00	05	10
Density of radiation W/m^2:	196	217	233	259	276	293	321	339	370

Longwave radiation from atmospheric gasses is „grey", as absorption and emission is limited to certain wavelengths (spectral lines).

Joule: Unit of energy. Energy is force multiplied by distance; hence one Joule is equivalent to one unit Newton metre when force kg m/s^2 is equivalent to one Newton.

Kelvin: Thermodynamic scale for temperature. 0 ºC equals 273 K. A change in temperature by 1 ºC equals 1 K, however all differences in temperature are to be given in K.
Kraftschluss: Term that covers maximum shear force transferred by sliding (maximum coefficient of friction to be achieved due to adhesion).

Latent heat: See „heat (evaporation; melting)".

Metamorphosis: Changes in type of (ice) crystals and their aggregates due to internal differences in vapour pressure, and impact by external heat and mechanical force.

Mixing ratio: Mass water vapour in relation to mass dry air. Saturation mixing ratio at pressure 1000 hPa:

Temperature ºC:	M25	M20	M15	M10	M05	00	05	10
Saturated vapour over liquid water, g/kg:	0.48	0.75	1.14	1.71	2.64	3.84	5.50	7.76
Saturated vapour over ice, g/kg:	0.40	0.65	1.03	1.63	2.52	3.84	-	-

The mixing ratio is numerically almost equivalent to specific humidity and one may substitute the other.

Saturation mixing ratio at a given temperature and atmospheric pressure means that water vapour coexists in equilibrium with liquid water or ice at the same temperature and pressure.

Nowcast: Forecast of very near future (less than 1 hour) conditions.

Permittivity (dielectric constant): Specific property of a substance to influence on the travelling time of very high frequency electromagnetic pulses. The travelling time depends on the volumetric content of liquid water in frozen water (snow).

Potential temperature: The temperature a „parcel" of air would attain if adiabatically (dry or moist adiabatic) moved to pressure level 1,000 hPa. As potential temperature is a conservative property, it may be used to identify and to compare different air masses.

Psychrometer: Psychrometric difference is given by wet bulb and dry thermometer, a measure of humidity (see „Wet bulb"). Combined with evaporation, a wet or ice-covered surface (runway) behaves as a psychrometer, provided that radiation and heat flow in the ground is negligible compared with the flow of sensible and latent heat, on which ice or snow at 0 ºC (ready to melt) will not melt until the air temperature exceeds the melting point temperature as follows:

Saturated vapour pressure, hPa:	6.11	5.33	4.39	3.30
Relative humidity in per cent:	100	0	60	40
Dewpoint temperature, ºC:	0	M1.9	M4.5	M8.2
No melting below air temperature ºC:	0	1.2	2.5	4.2

Reptation: Loose particles of ice or grains of sand moved by the impact of landing particles due to saltation.

Saltation: Grains of ice or sand lifted near vertically by upward suction in turbulent wind follow a parabolic path.

Saturated mixing ratio: Mixing ratio for water vapour saturated with respect to water or ice. Depends on air pressure. See „mixing ratio".

Saturated water vapour pressure: Maximum vapour pressure at a certain air temperature.

Temperature ºC:	M30	M25	M20	M15	M10	M05	00	05	10
Sat. vap. press. (liquid water), hPa:	0.51	1.20	1.25	1.83	2.86	4.06	6.11	9.03	12.27
Sat. vap. press. (ice), hPa:	0.38	0.98	1.03	1.58	2.60	3.85	6.11	-	-

Shear force: Frictional force related to area.
Shear force velocity: Tangential velocity. It depends on the roughness length, approximately the height of the level defined by wind velocity zero. The shear force velocity takes into account different vertical gradients of wind velocity due to different aerodynamic surface roughness.
Slush: Fragments of (melting) ice particles suspended in more than 25 to 30 weight % liquid water (otherwise wet snow).
Solar constant: Mean density of solar radiation perpendicular to an area outside the atmosphere: 1,370 W/m^2. Used as „unit‟ to compare densities of meteorological flows of energy.

Spread: The difference between air temperature and dew point temperature.
Supercooled water: Liquid water at temperature below ordinary freezing temperature. In the atmosphere M50 ºC is possible.
Surface shear stress: See „shear force‟. Between atmosphere and earth‟s surface: Force equally opposed by that exerted by the surface on the atmosphere.
Surface tension: Molecular force tending to minimise the surface of a liquid. Saturation vapour pressure increases with surface tension. On a spherical surface (droplets, tops of wet asperities) surface tension and thus saturation vapour pressure exceed that of a plane surface. Therefore, saturation in relation to a plane surface does not mean saturation in relation to a sphere.

Terrestrial radiation: At terrestrial temperatures, emitted and absorbed radiation is in the infrared spectrum. According to Kirchhoff‟s law, absorptivity equals emissivity for a given wavelength of radiation and temperature. Most solid natural substances, including liquid water, may be treated in approximately the same way as black bodies (see above).
Thermal capacity: Energy that changes the temperature of a volume of 1 m^3 of a medium by a temperature of 1 K. Unit: J/m^3 K. Liquid water: $4.18 \cdot 10^6$, concrete: $1.8 \cdot 10^6$, new fallen snow: $0.2 \cdot 10^6$ to $1.5 \cdot 10^6$, ice: $2.1 \cdot 10^6$ J/m^3 K. Thermal capacity is defined in relation to volume, whereas specific heat is defined in relation to mass (see „heat (specific)‟)
Thermal conductivity: See „Heat (conductivity)‟.
Thermal diffusivity: Conduction of a given temperature in a medium, depends on heat capacity and thermal conduction. Unit: m^2/s. Liquid water: $0.14 \cdot 10^{-6}$, ice at 0 ºC: $1.16 \cdot 10^{-6}$, compacted snow: 0.4 to $0.8 \cdot 10^{-6}$, concrete: $2.2 \cdot 10^{-6}$ m^2/s

Vapour pressure (water): The vapour contributes to the atmospheric pressure p with its partial pressure e. With r for mixing ratio (= mass vapour / mass dry air) the vapour pressure is $e = p \cdot r / (0.62197 + r)$, the numerical figure showing the proportion of the molecular weight of vapour / dry air.
Viscosity (dynamic): Resistance of a fluid due to molecular attaching forces, described by a coefficient of proportionality. Unit: Pascal second (see chapter 8). Typically, the coefficient decreases as the temperature increases. Water at 0 °C 1.8 mPa·s, at 20 °C 1.0 mPa·s

Watt: Flow of energy / time. Unit: J/s = W. In meteorological contexts, often related to an area, which means the density of flow of energy, unit: W/m^2.

Wet bulb thermometer: Thermometer bulb covered by water (wick). Evaporation results in a temperature lower than shown by dry thermometer (air temperature), except in saturated water vapour. The difference is a measure of humidity in the air (to be expressed as „spread‟ or relative humidity). At an air temperature of 0 ºC a wet bulb temperature of M 4 ºC corresponds to relative humidity of 30%, M 1.5 °C to 70%, M 0.5 °C to 90%.

Wien‟s (displacement) law: The maximum intensity of radiation is constant for a given temperature. For solar radiation, the maximum at wavelength 0.50 µ (1 µ = 10^{-6} m) points to temperature of 5,780 K, whereas a terrestrial surface temperature of 287 K means a maximum radiation of 10 µ.

Wind (transition layer): Deep when free or forced convection (vertical exchange of air) is strong, shallow in stable air. Sharp wind gradient near top of temperature inversion.

Wind (vertical gradient): Depends on stability of the air (dependent on vertical gradient of temperature), often an exponential (logarithmic) function. Velocity above aerodromes at 10 m about 40% of free wind, at 100 m, 90%. Above sea (often adjacent to runways in Norway) at 10 m, 50%, at 50 m, 90%.

15.3 Table of estimated monthly mean number of days with sleet, snow or rain (1994-2009)

Contamination of runways by water is partially dependent on precipitation. Often slippery conditions occur in connection with precipitated slush or wet snow. To indicate their frequency at some Norwegian airports, the monthly mean number of days (1994 to 2009) was roughly counted from daily observations (Norwegian Meteorological Office) when the water equivalent exceeded 0.1mm. Days with sleet were counted as days with both snow and rain. The variations throughout the year are smoothed, and the numbers rounded to whole days.

Besides the actual number of days, the proportion of days with snow N_{snow} to days with rain $N_{rain,}$ (N_{snow}/N_{rain}) is given. Proportions larger than 1 reflect the predominance of days with snow in relation to rain, whereas proportions smaller than 1 indicate the predominance of days with rain. Similarly, the proportion of the number of days with sleet, N_{sleet}, relative to the number of days with snow is given as N_{sleet}/N_{snow} . A decreasing proportion shows that the number of days with sleet declines compared to days with snow for the period in question.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean number of days												
Kirkenes sleet	1	0	0	3	3	2	0	0	1	1	4	1
snow	16	14	16	11	7	1	0	0	2	9	14	15
rain	2	1	1	6	11	14	13	18	18	14	4	2
N_{snow}/N_{rain}	8	14	16	1.8	0.6	0.1	-	-	0.1	0.6	3.5	7.5
N_{sleet}/N_{snow}	0.1	0	0	0.3	0.4	2	-	-	0.5	0.1	0.3	0.1

Month		J	F	M	A	M	J	J	A	S	O	N	D
Alta	sleet	1	0	0	1	3	0	0	0	0	2	1	0
	snow	13	13	14	11	9	0	0	1	2	10	11	14
	rain	1	0	2	4	9	14	13	16	15	11	4	3
	N_{snow}/N_{rain}	13	13	7	2.8	1	-	-	-	0.1	1	2.8	4.7
	N_{sleet} /N_{snow}	0.1	0	0	1.0	0.3	-	-	-	0	0.2	0.1	0
Tromsø	sleet	2	2	2	3	4	1	0	0	1	4	3	2
	snow	16	16	17	15	9	2	0	0	2	8	12	15
	rain	4	4	6	8	14	17	15	20	20	18	9	8
	N_{snow}/N_{rain}	4	4	2.8	1.9	0.6	0.1	-	-	0.1	0.4	0.3	1.9
	N_{sleet}/N_{snow}	0.1	0.1	0.1	0.2	0.4	0.5	-	-	0.5	0.5	0.3	0.1
Bardufoss	sleet	3	3	2	2	3	1	0	0	1	3	2	2
	snow	15	13	14	12	8	2	0	0	2	10	10	14
	rain	5	4	5	6	12	16	15	19	19	15	7	6
	N_{snow}/N_{rain}	3	3.3	2.8	2	0.7	0.1	-	-	0.1	0.7	1.4	2.3
	N_{sleet}/N_{snow}	0.2	0.2	0.1	0.2	0.4	0.5	-	-	0.5	0.3	0.2	0.1
Evenes	sleet	2	3	3	4	4	1	0	0	0	3	4	2
	snow	16	15	16	14	6	1	0	0	0	6	9	12
	rain	7	6	9	10	16	19	17	20	20	18	12	9
	$N_{snow}//N_{rain}$	2.3	2.5	1.8	1.4	0.4	0.1	-	-	-	0.3	0.8	1.3
	N_{sleet}/N_{snow}	0.1	0.2	0.2	0.3	0.7	1	-	-	-	0.5	0.4	0.2
Bodø	sleet	6	7	7	6	3	1	0	0	0	4	5	7
	snow	16	17	15	12	5	1	0	0	0	5	9	11
	rain	9	9	11	13	14	18	15	17	20	21	14	13
	N_{snow}/N_{rain}	1.8	1.9	1.4	0.9	0.4	0.1	-	-	-	0.2	0.6	0.8
	N_{sleet}/N_{snow}	0.4	0.4	0.5	0.5	0.6	1	-	-	-	0.8	0.6	0.6
Værnes	sleet	5	5	4	4	2	0	0	0	0	2	4	4
	snow	11	10	11	8	3	0	0	0	0	3	8	9
	rain	9	8	8	7	13	17	14	14	18	17	11	10
	N_{snow}/N_{rain}	1.2	1.3	1.4	1.1	0.2	-	-	-	-	0.2	0.7	0.9
	N_{sleet}/N_{snow}	0.5	0.5	0.4	0.5	0.7	-	-	-	-	0.7	0.5	0.4

Month	J	F	M	A	M	J	J	A	S	O	N	D
Flesland sleet	6	5	6	3	1	0	0	0	0	1	3	4
snow	12	10	10	6	1	0	0	0	0	1	4	7
rain	14	13	14	20	15	18	18	19	20	22	21	20
N_{snow}/N_{rain}	0.9	0.8	0.7	0.3	0.1	-	-	-	-	0	0.2	0.4
N_{sleet}/N_{snow}	0.5	0.5	0.6	0.5	1	-	-	-	-	1	0.8	0.6
Sola sleet	5	4	2	1	0	0	0	0	0	0	2	6
snow	10	9	5	3	0	0	0	0	0	0	3	8
rain	14	12	12	16	14	15	15	18	21	20	20	18
N_{snow}/N_{rain}	0.7	0.7	0.4	0.2	-	-	-	-	-	-	0.2	0.4
N_{sleet}/N_{snow}	0.5	0.4	0.4	0.3	-	-	-	-	-	-	0.7	0.8
Gardermoen sleet	3	2	2	3	1	0	0	0	0	1	3	3
snow	14	12	8	6	1	0	0	0	0	3	9	12
rain	4	3	3	7	9	14	14	16	14	12	13	8
N_{snow}/N_{rain}	3.5	4	2.7	0.9	0.1	-	-	-	-	0.2	0.8	1.5
N_{sleet}/N_{snow}	0.2	0.1	0.3	0.5	1	-	-	-	-	0.3	0.3	0.3

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APPENDIX K-1

From: DD

THE NORWEGIAN CIVIL
AVIATION ADMINISTRATION

THE CENTRAL
ADMINISTRATION

To: DL

INTERNAL CORRESPONDENCE

Case officer	Our date	Our reference (please state in your reply)
Armann Norheim	8 Oct. 1996	9505745
	Your date	Your ref.

WIDERØE – WINTER OPERATIONS DHC 8 – REQUIREMENTS FOR WINTER MAINTENANCE OF RUNWAY SYSTEM

Pursuant to CAR Norway E, winter maintenance should be carried out in such a manner and scope that air traffic can be maintained without any risk to aviation safety, and that regularity is maintained as far as possible. Recently, focus has been placed on the requirements of the DHC 8 for winter maintenance, and phrases such as ‘the DHC 8 requires a black runway during winter operations on the short runway network’ have been used. HLH have used the phrase ‘no worse than wet condition’ about the same standard for runways.

Taking into consideration the dimensions of the rolling stock used for winter maintenance, DD would like DL to specify the requirements of the DHC 8 relating to the runway standard in order to maintain aviation safety and with the aim of maintaining an acceptable regularity for winter operations on our short runway network.

Yours faithfully

Lasse Bardal (sign.)
Lasse Bardal
Deputy Director General of Aviation

APPENDIX K-2

From: DD

THE NORWEGIAN CIVIL
AVIATION ADMINISTRATION

THE CENTRAL
ADMINISTRATION

To: DL

INTERNAL CORRESPONDENCE

Case officer	Our date	Our reference (please state in your reply)
Head of Department Gerhard D. Pettersen	31 Oct. 1996	9505745
Flight inspector Birger A. Bull	Your date	Your ref.
	8 Oct. 1996	9505745

WIDERØE – WINTER OPERATIONS DHC-8-10
REQUIREMENTS FOR WINTER MAINTENANCE OF RUNWAY SYSTEM

Reference is made to the internal letter from DD to DL, dated 8 October 1996.
DL is requested to specify the requirements of the DHC-8-103 relating to runway standard so that aviation safety can be maintained, and with the objective of maintaining an acceptable regularity for winter operations on our short runway network.

The operation of the DHC-8-103 on the short runway network is based on performance data described in the aircraft's flight manual (AFM), including supplement 37 NCAA (issue #2 dated 14 September 1995).

Use of the AFM supplement is conditional on the fulfilment of certain runway maintenance requirements.

AFM supplement 37 NCAA prescribes what to do when operating on 'contaminated runways'. Great emphasis is placed on pointing out that the level of safety is reduced compared with that on black runways.
AFM DHC-8-103 supp. 37 NCAA 6.37.1 d):
'The level of safety is decreased when operating on contaminated runways and therefore every effort should be made to ensure that the runway surface is cleared of any significant contaminate.'

This is also stated in JAR 25 AMJ 25X1591 section 5.1.

An aerodrome must be adequately equipped so that the level of safety can be maintained, including during winter operations. This means that the aerodrome must be equipped so that the standard that forms the basis for the 'black runway' safety assessment can be maintained.

Operating at a reduced level of safety as a result of ’contaminated runways’ must only take place as an exception.

It should be noted that an acceptable total probability for incidents of the type ’low speed overrun, failure to achieve net takeoff flight path etc.’ the consequence of which is ‘minor damage or possible passenger injuries’ lies in the region of 10^{-5} – 10^{-7}. If we then accept a probability of ’low speed overruns’ alone of 10^{-6}, such an incident, in the case of Widerøe, should only occur on average once every seven years given the current scope of operations (approx.140,000 takeoffs + landings per year). (Ref. The Aircraft Performance Requirements Manual by R.V. Davies.)

In light of the above, it would seem reasonable to have a target whereby 95% of the operations on an annual basis and no less than 80 % of the operations in any one month should take place on black runways.

The issue of regularity should be considered in light of the above.

Yours faithfully

Viggo Løfsgaard (sign.)
Viggo Løfsgaard
Director
Aeronautical Inspection Department

Internal copies to: LO, LOF

APPENDIX K-3

From: DD

THE NORWEGIAN CIVIL AVIATION
ADMINISTRATION

To: The Regional Directors concerned

1947 50 1997

CENTRAL
ADMINISTRATION

INTERNAL CORRESPONDENCE

Case officer	Our date	Our reference (please state in your reply)
Armann Norheim	17 Jan. 1997	9505745
	Your date	Your ref.

OPERATIONS WITH THE DHC-8 103 – REQUIREMENTS FOR WINTER MAINTENANCE OF THE RUNWAY SYSTEM

Reference is made to the enclosed letter from the Civil Aviation Administration, dated 31 October 1996, in which the operational requirements of the DHC-8 103 relating to winter maintenance of the runway system are specified.

1. The aerodromes must be adequately equipped so that the standard that forms the basis for the ’black runway’ safety assessment is maintained.Operating at the reduced level of safety that is associated with ’contaminated runways’ must only take place in exceptional cases.

3. On an annual basis, at least 95 % of operations should take place on black runways.

4. In no one month should less than 80 % of operations take place on black runways.

5. The issue of regularity should be considered in light of the afore-mentioned.

After the above-mentioned letter was written, DD has received further clarification of the interpretation of the ‘black runway’ safety assessment in relation to DHC-8 operations on the short runway network. It is stated that:

1. A runway is considered contaminated when 25% or more is covered in a contaminate. Snow, ice and slush and the pertaining accumulation of water is deemed to be contamination.
2. If, on a contaminated runway, it is possible to achieve a friction coefficient greater than 0.4, the runway is deemed to be a black runway.

For the sake of clarity, a brief account of friction measurements follows:

1. Friction measurements are included in the runway report when the runway system conditions fall within the validity range of the friction-measuring instrument.

2. A runway report shall be issued when the runway friction coefficient is lower than 0.40.

3. When the conditions on the runway system fall outside the validity range of the friction-measuring instrument, and other conditions of the runway system are such that a runway report must be issued, the braking action shall be stated as non-measurable. Depth measurements of contaminants on the runway system shall then be included in the runway report.

For the rest of this winter, the appended form shall be filled in and used as documentation that the requirements that apply to DHC-8 10 operations on black runways are met. The form is enclosed on a diskette (DDRSORT.XLS). The completed forms/diskette(s) should be sent to the Norwegian Civil Aviation Administration attn. RL by 1 May for compilation. DD proposes that the completion of the forms be left to the Air Traffic Services/AFIS.

Yours faithfully

Ole M. Rambech (sign.)
Ole M. Rambech
Deputy Director General of Aviation

APPENDIX L

THE HISTORY OF THE ICAO SNOWTAM TABLE, 1956-1983

GOOD – MEDIUM – POOR

HISTORY OF THE TABLE

Mid 1950's

Tests at Bromma airport in Sweden using a "Skiddometer BV 2" measuring device. The BV 2 was used in regular service on the Bromma airport since the winter of 1956/57.

LATE 1950's (Sweden)

Based upon a questionnaire sent out by SAS to pilots, with 3000 answers, following was developed.

Good	0.40 and above
Medium to Good	0.36 to 0.39
Medium	0.30 to 0.35
Medium to Poor	0.26 to 0.29
Poor	0.25 and below

The answers shoved that when a friction coefficient of 0.40 or above had been reported there were no pronounced problems on braking or controllability in crosswind. When 0.25 or lower had been reported the problems became severe.

History of friction measurements at airports by Gunnar Antvik

(Late 1950's. Piston driven aircraft used. Measuring device used, BV 2, total weight 3000 kg, load measuring tyre 1000 kg.

From the minutes of the Internordic Meeting in 1959, the origin of the table was a proposal by Engineer T. Göransson , Bromma airport, Sweden, based upon own research and exchange of information with the other Nordic Countries at the internordic meeting)

March 12 - April 15, 1957 (ICAO)

At the Sixth Session of Aerodromes, Air Routes and Ground Aids Division, Montreal, the Meeting considered that there was an operational need for reliable and uniform information on braking action on icy or snow-covered runways.

The best manner of presenting the information to the pilot was to express it in one of the following three categories:

Runway icy (or snow-covered);

braking action	Good
braking action	Medium
braking action	Poor

It was suggested that the following friction coefficient μ values might be associated with these categories:

Good	0.35 and above
Medium	below 0.35 and above 0.25
Poor	0.25 and below

The Division was of the opinion that the μ values related to the three categories above are not exact and require further study because of the lack of knowledge regarding the correlation between friction coefficient applicable to a large heavily loaded aircraft wheel at high speed, and a relatively lightly loaded test vehicle wheel at a lower speed. Furthermore the many variables attached to aircraft operations must be taken into consideration for each individual operation. The values as measured and their interpretation are merely guidance as a measure of braking action on the surface of the runway during icy or snow conditions. However, the figures were considered to give the best possible guidance, on the basis of present experience.

ICAO Doc 7791-AGA/592-1

April 28 - May 25, 1959 (ICAO)

At the Aeronautical Information Services and Aeronautical Charts Division, Meeting in Montreal, the NOTAM Code was discussed and relative to braking action the following was recommended under:Hazard or status of operation or condition of facilities:

AX Braking action is:

A = Good
B = Medium
C = Poor

<u>Comment</u> The demand for detailed and last-minute information regarding aerodrome conditions during the winter season has increased considerably during recent years. Approval of these recommended assignments will permit their NOTAM Code use thereby reducing the amount of plain language information now being employed in such NOTAM messages. As it concerns the signification assigned to AX, the ICAO guidance material of Annex 14, Attachment B, para. 8 relative to the expression of braking action on icy or snow-covered runways is of relevance - it is hoped, however, that the further experience accruing from measurement

techniques being evaluated in some Contracting States may soon result in the development of some reliable and uniform classification system for promulgating internationally the measure of braking action.

ICAO Doc 7993, AIS/MAP

October 13 – 14, 1959 Inter-nordic meeting (Stockholm)

The meeting came together based upon a OPS committee meeting 22 september 1959 where a uniform reporting of braking action at runways during winter was wanterd. At the meeting the States Finland, Denmark, Norway and Sweden met in addition to SAS.

Finland	2 representants	Background from aviation and road
Denmark	1 representant	Background from aviation
Norway	2 representants	Background from aviation
Sweden	6 representants	Background from aviation and road
SAS	4 representants	Background from aviation

The different countries had following experience:

Finland

(Calàs) Using the Tapleymeter method at all Finnish airports. Measurements for every 200 300 meter along the centre line and 15 on either side of the centreline. Tapleymeter installed in a 6.5 ton lorry. Speed 40 km/h. With temperatures close to 0^{O}C the measurements are unreliable and pilots have often had an other experience of the real braking action. The average for the total runway is reported. Following scale is used:

Good	0.45 and above
Medium	0.30 – 0.44
Poor	0.29 and below

Denmark

(Axelsen) At Kastrup airport, used a lorry where the braking was transformed to braking coefficient by use of tables. The method to complex and the last two winters used the Tapleymeter in test mode installed in a Volkswagen. Measurements for every 400 meter along the centre line and 15 on either side of the centreline. Speed 40 km/h. The average for the total runway is reported. Following scale is used:

Good	0.35 and above
Medium	0.26 – 0.34
Poor	0.25 and below

Norway (Kollerud)

At Fornebu airport Fornebu, the Full-Stop-Method developed by Kollerud had been used since 1950. Vehicle used was a GMC lorry and the average retardation is recorded. Speed 40 km/h and the time to full stop was measured by a stopwatch. Measurements along the centreline and distance between measurements was more frequent on poor conditions. In 1952 the Tapleymeter method was tested. The finding was that the method was good in very cold conditions and completely snow covered runway. The method showed such shortcomings at temperatures close to 0^{O}C that the method was abondoned. The average for the total runway was reported. Following scale was used: (Retardation m/s^2)

Good	2.7 and above
Medium	2.2 – 2.6
Poor	2.1 and below

Sweden (Göransson)

At Bromma four methods had been tested.

1. Full-Stop-Method with 21 measurements
2. Tapleymeter in mode “free” – (test method abondoned)
3. Tapleymeter in mode “test” – 30 measurements along the centrline and 15 meter on either side of the centreline.
4. Kullbergmethod – Skiddometer BV 2.

SAS (Antvik)

Wanted the Good, Medium and Poor to be reported similarly by the States. SAS wanted the limit for Good to be raised to 0.40 and that Medium covered 0.25 to 0.40. Discussions from the AGA VI meeting were referred to.

Sweden

Based on discussions a proposal from engineer T Göranson (Bromma) was put forward and agreed upon.

Good	≥ 0.40
Medium to Good	> 0.35 - < 0.40
Medium	0.30 - 0.35
Medium to Poor	> 0.25 - < 0.30
Poor	≤ 0.25

The meeting had seven (7) numbered recommended conditions associated with the table.

PROTOCOL FROM THE MEETING

October 28, 1959 (Sweden) NOTAM-SWEDEN

The data on braking action given to aircraft correspond to the following figures:

Friction coefficient	Condition
0.40 or higher	Good
Higher than 0.35 - lower than 0.40	Medium to Good
0.30 - 0.35	Medium
Higher than 0.25 - lower than 0.30	Medium to poor
0.25 or lower	Poor

In strong crosswinds (over 10-12 knots), efforts made to improve braking action are intensified, if necessary and possible.

In landing instructions, braking action will be given as GOOD, MEDIUM or POOR etc. for each section of the runway.

On request, the friction coefficient will also be given.

NOTAM-SWEDEN, 1146/59

November 30, 1959 (Denmark) NOTAM-DENMARK

The data on braking action given in NOTAMs or to aircraft correspond to the following figures:

Friction coefficient:	Information:
0.40 or higher	Good
Higher than 0.35 - lower than 0.40	Medium to Good
0.30 - 0.35	Medium
Higher than 0.25 - lower than 0.30	Medium to poor
0.25 or lower	Poor

On request the friction coefficient will also be given. When deemed necessary, details regarding snow conditions and braking action will be included in routine messages passed to aircraft by RTF before landing.

NOTAM-DENMARK, 200/1959

January 1, 1960 (Suomi - Finland) NOTAM Suomi - Finland

The data on braking action given to aircraft correspond to the following figures:

Friction coefficient	Condition
0.40 or higher	Good
lower than 0.40 but higher than 0.25	Medium
0.25 or lower	Poor

Intermediate values which are given on request of the pilot are as follows:

Friction coefficient	Condition
Higher than 0.35 but lower than 0.40	Medium to Good
Higher than 0.25 but lower than 0.30	Medium to Poor

On request, the friction coefficient is also given.

In strong crosswinds (over 10-12 knots), efforts made to improve braking action are intensified, if necessary and possible.

After landing the braking action on taxiways and apron is given.

NOTAM Suomi - Finland, 1/60

February, 1961 (Norway) NORWAY, Runway Condition Report

Friction coefficient	Information	In RSR
0.40 or higher	Good	A
0.35 – 0.40	Medium to Good	B/A
0.30 – 0.35	Medium	B
0.25 – 0.30	Medium to Poor	B/C
0.25 and lower	Poor	C

From Runway condition Report

Nov. 13 - Dec. 14, 1962 (ICAO) Aerodromes, Air Routes and Ground Aids Division, Report of the Seventh Session, Montreal.

Measuring, Reporting and Improving Braking Action

There is an operational need for reliable and uniform information on braking action on icy and snow-covered runways. Though further operational experience is required in this field to correlate the many variables between aircraft speed, braking mechanism, tire and undercarriage characteristics and load with the results obtained from test equipment, good indications of braking action can be obtained.

The measurement of the friction coefficient μ appears to provide the best basis for determining braking action. This value of μ should be maximum value which occurs when a wheel is braked but still rolling with some 10 to 20 per cent slip.

Various ways may be used to measure the friction coefficient. In the AGA Manual, measuring techniques which have been used in some Contracting States are described. Operational considerations will generally determine the most suitable method to be used at a particular airport.

The braking conditions of a runway may, for the present, best be reported to the pilot in descriptive term as follows:

> Braking action
>
> Good
> Medium
> Poor
>
> When braking is expressed “Medium” it may in cases be practical to indicate if it is medium towards the “Good” or “Poor” side by using the expressions “Medium to Good” or “Medium to Poor” respectively. The µ values could also be given, if especially requested by the pilot.

ICAO Doc 298-AGA/593

April, 1963 (IATA) IATA 15th Technical Conference, Lucerne

May 21, 1963 (ICAO) ICAO, WORKING PAPER AN-WP/2689

> This paper follows from the Air Navigation Commission’s consideration of IATA’s proposals for a system of dissemination of information on aerodrome pavement conditions It contains a survey of pertinent aspects developed in the light of informal discussions during the IATA 15th Technical Conference in Lucerne in April 1963, at the ICAO Paris Office and after a study of the relevant ICAO and State provisions on the subject.

ICAO, AN-WP/2689

August 7, 1963 (IATA)

The table appears in the SNOWTAM pro-forma. At the meeting the revision 4 of the SNOWTAM pro-forma was discussed:

> This sceme was put to an IATA preporatory meeting on August 7, 1963, and with a few slight amendments was adopted as apractical idea. It was sent to the ICAO Paris office and tabled at the ICAO informal meeting which took place from September 16 to 21.

Flight International 10 December, 1964

September 16 – 21, 1963 (ICAO)

The First Informal Meeting on Snow/Slush problems in Europe, Paris.

Agreed on certain measures to be proposed to States for adopting during the 1963-64 winter in respect of clearance, measurement and reporting of snow, slush, ice or water on aerodrome pavements. Snow NOTAMs (SNOWTAMs) format recommended. Definitions for precipitants (snow dry and wet, slush) was developed) The SNOWTAM pro-forma was a UK recommendation and following was commented in an internal UK document dated 6. March 1992 –

> “*The Snow, Ice and Slush you quote as being on BAA Form F/2992 was proposed by Sweden about 30 years ago when we in this country knew little about friction in snow. And because of this I advised it be accepted.*

Later, I understand tests at Arlanda in Sweden showed that the Table gave a lower verbal reading than pilots opinion. This was never published. It did however only cover compacted snow and ice, not slush. …. So the Table (if it is to remain) should have a qualifying note".

IATA had not been alone in their anxiety about snow-reporting methods. As a focal point for the reception, in this country, of such messages abroad, the United Kingdom Aeronautical Information service had been equally worried. On many occasions they had known that their foreign snowstates were out of date and had endeavoured to do something about it. They had learned, the hard way, that the average airline captain was not satisfied with a snowstate that was three or four days old, even when it was from somewhere in Scandinavia, where conditions are frequently stable for days on end. He was, quite understandably, not prepeared to accept the explanation that because there had been no amendment conditions must still be the same. He wanted confirmation and, what is more, wanted it then and there. AIS also knew from experience that the Notam Code, although still a good tool for routine work, was outmoded and cumbersome when it came to snow and slush reporting. With this in mind AIS suggested scrapping the code and instituting a pro-forma system, not unlike a flight plan. This it was felt, would have several advantages. It would act as an automatic check-list in that whoever was compiling it would see immediately all the items which needed to be reported; it would consist of letters and figures which could be transcribed at the other end on to asimilar pro-forma printed in the local language; it would standardize reporting and – most important of all – cut message length to about one-third or less.

(SNOWTAM pro-forma)

This was not without incident or heat, but in the end the plans – the transmission of abbreviated runway reports every half-hour on MOTNE and the UK Snowtam, as the pro-forma was styled, were both accepted for use in Europe on a trial basis during the coming winter. Nearly all States co-operated in the MOTNE trials – the exceptioum being Belgium and France – and the regular flow of reports which resulted served to give pilots confirmation of up-to-date conditions; while the new Snowtams, which were used by most of the major States, represented a breakthrough in standards of reporting.
The results of these trials were analysed at a further ICAO meeting in Paris in April of this year and it was unanimously decided to continue the use of MOTNE again this year. The Snowtam was revised to make for easier working and it, too, was re-adopted for a further year.

Flight International 10 December, 1964

October 22 – 25, 1963 (ICAO)

ICAO, informal Ad Hoc Meeting on Snow/Slush Problems in Europe, Berne.

Additional suggestions in respect of the dissemination of snow NOTAMs (SNOWTAMs).

April 27 – May 2, 1964 (ICAO)

ICAO, the Second Informal Meeting on Snow/Slush Problems in Europe, Paris.

From the discussion on the SNOWTAM format:

Item H

The titles of the two columns indicating measured and estimated Coefficient were amended to read “ MEASURED OR CALCULATED COEFFICIENT” and “ ESTIMATED BRAKING ACTION”

From the discussions on measurement of pavement conditions:

The need for compatibility in the measurements of the friction coefficient by different methods was agreed. In the Region, two methods of measurements are in common use:

a) the Tapley meter, and
b) the Skiddometer.

The conditions of utilisation of the Tapley meter affect the results obtained and it was found necessary:

1) to adopt common conditions of utilisation for all users of the Tapley meter;
On the other hand, it was also necessary;

2) to ensure that measurements made with the Tapley meter are compatible with those made with the Skiddometer.

From the discussions of desirable arrangements for the 1964/65 winter:

Measurement of pavement conditions

The Meeting agreed on the need of obtaining compatibility in the measurement of friction coefficient and invited States to circulate information on their practices and, for those States so equipped, to conduct comparison tests with the Skiddometer and Tapley meter.

Sweden, Denmark and the Netherlands indicated their readiness to facilitate visits of personnel from other States to view snow clearance facilities and acquire experience in related techniques.

Final Approved Revision of SNOWTAM Proforma, Item H

BRAKING ACTION ON EACH THIRD OF RUNWAY

MEASURED OR CALCULATED COEFFICIENT or ESTIMATED BRAKING ACTION

0.40 and above	GOOD	- 5
0.39 to 0.36	MEDIUM/GOOD	- 4
0.35 to 0.30	MEDIUM	- 3

0.29 to 0.26	MEDIUM/POOR	- 2
0.25 and below	POOR	- 1

(When quoting a measured coefficient use the observed two figures, when quoting an estimate use single digits.)

From the MOTNE six digit group – Braking Action (B_R)

The factor B_R should be denoted by single digits from 1 to 5 having the following meaning:

5	Good
4	Medium/Good
3	Medium
2	Medium/poor
1	Poor

NOTE:

Where braking action is assessed at a number of points along a runway, the mean value should be reported or, if operationally significant, the lowest value.

April 13 – May 7, 1966 (ICAO) At the Aeronautical Information Services and Aeronautical Charts

Divisional Meeting, Montreal, the Meeting considered subjects related to Snow Plans and SNOWTAM and recommended that, on basis of the experience gained in the EUM Region in the trial application of the collective address system for SNOWTAM and NOTAM, ICAO study the possible application of that system on a worldwide basis.

The delegation of the United States of America made following statement:

> *The Delegation of the United states of America wishes to record a reservation to Recommendation 2/1 – Amendment to Annex 15, (Snow Plans), Recommendation 2/2 – SNOWTAM reports, and Recommendation 2/3 – Amendments to Annex 15 (Snowtam proforma). This reservation is based on the fact that without having looked at the substance of EUM V Recommendations 4/9, 4/10 and 4/11, the Air Navigation Commission referred these recommendations to the AIS/MAP Meeting only insofar as the reporting and dissemination procedures are concerned. This was done less than 14 days before this Meeting convened. Consequently, the Delegation of the United States and perhaps many other delegations were not prepared to consider all of the various aspects of the problems raised by these recommendations from the Fifth EUM Meeting.*

In formulating its recommendations, this Meeting clearly exceeded the terms of reference given it by the Air Navigation Commission. Nevertheless, it is hoped that action by this Meeting will not be considered to have prejudged the importance and continuing work of the iCAO Study Group on Snow, Slush, Ice and Water on Aerodromes, which may in due course produce more mature and considered recommendations for world-wide standards, practices and procedures.

The Delegation of the United States of America wishes to record a reservation to "Recommendation 2/9 – Amendment to Annex 15 (Regulated System – AIRAC)" and give notice of intention to file a difference if this recommendation is accepted and approved by the Council.

Although a regulated system of notifications and changes is favoured and an effort will be made by the United States to implement one, it is submitted that the detailed specifications for the operation of the system developed at this Meeting lack sufficient simplicity and maturity to warrant status as International Standards.

ICAO Doc 8598, AIS/MAP

February 8, 1968 (ICAO) Amendment 10 to Annex 15 including SNOWTAM adopted June 13, 1967, Effective October 8, 1967 and Applicable February 8, 1968.

ICAO, Annex 15

April 1-24, 1970 (ICAO)

At the Fifth North Atlantic Regional Air Navigation Meeting, Montreal, it was considered that States should conduct surveys to identify runways which were slippery when wet and to take corrective measures to improve the braking action.

Recommendation 8/1

That States:

a) survey runways to identify those which are slippery when wet.

b) for those runways so indicated, take action to improve braking through some form of corrective surface treatment.

Recommendation 8/2

That States:

a) when using measuring devices for the assessment of runway braking action resulting from conditions of snow, slush or ice on runways, report the measurements in accordance with the following table and interpret the descriptive terms in this table to have the indicated meanings:

Code	Measure or calculated coefficient of friction	Descriptive Terms	Operational Meaning
5	0.40 and above	Good	Aircraft can expect to land comfortably within the scheduled distance, where this is "wet" distance, without undue directional control problems.
4	0.39 to 0.36	Medium to good	
3	0.35 to 0.30	Medium	Aircraft are likely to use all the "wet" scheduled distance including the safety factor part of the distance, and may run even further. Directional control might be impaired.
2	0.29 to 0.26	Medium to poor	
1	0.25 and below	Poor	Aircraft can expect to run for up to the full "very wet" or aquaplaning distance where this too is scheduled. Directional control will also be poor.

b) should ensure that the measuring devices used in slush be capable of indicating aquaplaning conditions.

Snow removal was a common problem at most aerodromes but, in general, authorities were able to cope with most situations. It was noted that with the introduction of the B747 aircraft into operation, greater attention would need to be paid to keeping snow banks farther from taxiway edges. One State reported that it would clear down to ground level a 47 m (155 ft) width along all taxiways.

ICAO Doc 8879. NAT/V

November 2-27, 1971 (ICAO) At the Sixth European-Mediterranean Regional Air Navigation

Meeting, Geneva, the recommendations from EUM/V concerning the presence of snow, slush, ice or water on aerodromes was considered. Since the EUM/V meeting world-wide action had been taken which made most of these recommendations unnecessary. However the Meeting still found it necessary to reaffirm or develop new recommendations in a number of areas:

Permissible snow bank height

Use of chemicals for ice removal

Measurement of runway braking action

Correlation of braking action measuring equipment.

Reporting of runway braking action

That when measuring devices are used for the assessment of runway braking action, the results be reported in accordance with the following table:

CODE	WATER AND SLUSH		ICE AND SNOW		OPERATIONAL MEANING
	Coefficient of friction	Description	Coefficient of friction	Description	
5	0.40 & above	Good	0.40 & above	Good	Aircraft can expect to land comfortably within the scheduled distance, where this is "wet" distance, without undue directional control problems.
4			0.39-0.36	Medium to Good	
3	0.30.039	Medium	0.35-0.30	Medium	Aircraft are likely to use all the "wet" scheduled distance including the safety factor part of the distance, and may run even further. Directional control might be impaired.
2			0.29-0.26	Medium to Poor	
1	0.29 & below	Poor	0.25 & below	Poor	Aircraft can expect to run for up to the full "very wet" or aquaplaning distance where this too is scheduled. Directional control will also be poor.

The reporting of the coefficient of friction along with the descriptive term was discussed. Though the present guidance material in Annex 14 advises that the coefficient of friction be provided if requested by the pilot, the Meeting did not consider this useful and did not include it in its recommendation. This was because the measured coefficient of friction would vary depending upon the measuring equipment used and would in any case be different from that experienced by the aircraft. Further, most pilots would not be able to use a more exact measure of the braking condition.

The Skiddometer, which was discussed at the EUM/V Meeting, had been modified and a new lighter model was now available. Braking action values obtained with this new model correlated well with those of the older model. Another piece of measuring equipment, the Mu-meter, was also being used extensively.

ICAO Doc 8994, EUM/VI

July 20, 1978 (ICAO) ICAO State Letter

Subject: Amendment of Annex 14 concerning runway braking action.

ICAO, AN 4.1.1.13 – 78/68

September 11, 1978 (SAS) Amendment of Annex 14 concerning Braking Action.

Letter contains SAS comments on State Letter AN 4.1.1.13 – 78/68. Comments sent to IATA, Canada with copy to CAA in Sweden, Norway and Denmark.

Even if the state of art at present is not considered to permit a reliable measuring and reporting of wet runway friction coefficient we feel that *such measuring and reporting should be the ultimate goal and that adequate equipment should be developed.*

In fact, recent research in Sweden with test vehicles equipped with test wheels of special design, made of natural rubber and using higher pressure has shown promising improvement in the correlation of braking action between test equipment and aircraft on runways with contamination. Further tests, made with the Skiddometer and the SAAB Friction Tester, are in progress.

We also realize that the braking action of wet surface can vary rapidly at the beginning of, during and after a rainfall. Consequently the reporting of braking action of wet runways can be misleading and a requirement as now recommended in para 2.8.4. is in our opinion unrealistic at this stage.

STOOI/LE/ip

October 26, 1978 (IFALPA) IFALPA – Comments State Letter

Notwithstanding the lack of success to date in the development of methods to measure braking action which correlates satisfactory with aircraft performance, we consider that the removal of this requirement would be premature and its effect would be to terminate work on what are promising developments. In this context, information has recently become available to IFALPA which indicates that in one State a measuring vehicle has reached an advanced state of development and shows considerable potential for overcoming the lack of correlation with aircraft performance.

AIR/10/5 LT/BAC

October 26, 1978 (IFALPA) IFALPA – Internal letter

Herewith your copy of our belated response to State Letter 78/68. As you can see, we have a number of objections to the ICAO proposals and I should like to add a note of explanation to you in a way which we cannot include in the official response because of violation of our "product endorsement" rule.

The main reason why the AIR and AGA Study Groups feel that ICAO's proposals are premature is that the Scandinavians have developed a friction measuring system which is believed to show great promise in regard to the reliable prediction of aircraft braking action on contaminated runways.

Unfortunately, I do not have any descriptive literature so I will try to provide a summary of the characteristics of the vehicle (as presented to the recent AGA and AIR Study Group meetings by Captain Knut Anfindsen of Norwegian ALPA). I offer this somewhat cautiously as it is admitted by Knut that there is yet no data available to conclusively prove that this system does correlate adequately with the real aircraft *but nevertheless it is regarded with some enthusiasm by the people involved to be "nearly there".*

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This, then, is the basis of our response. We cannot claim to be entirely sure that the continuing Scandinavian research will produce eventually a µ-measuring vehicle which will meet all the requirements satisfactorily, but the Study Group Members were adamant in their opposition to the removal of the basic requirement because they felt that this would seriously inhibit ongoing research such as that in Scandinavia.

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1.1.1 **AIR/10/5 GPN/BAC**

April 22, 1983 (NTSB)

NTSB Special Investigation Report. Large Airplane Operations on

Contaminated Runways.

Abtract:

The National Transportation Safety Board's investigation of the fatal airplane accidents involving an Air Florida B-737 at Washington, D.C., on January 23, 1982, and a World Airways McDonnell-Douglas DC-10 at Boston, Massachusetts, on January 23, 1982, focused on the performance capabilities of airplanes while taking off and landing on contaminated runways. The accidents and the accident investigation experience of the Safety Board demonstrated that dealing with the issue of airplane performance in the face of adverse airport conditions is influenced by many elements in the airport-airline-air traffic control relationship. The Safety Board's special investigation examined the issue of maintenance of runway surfaces, the measurement and reporting of runway friction values, the exchange of runway information among ATC, airport personnel and pilots, the airplane certification criteria for operation on contaminated runways, the capability of existing technology to measure runway friction accurately, and the technology available to monitor airplane acceleration.

The investigation buttressed the need for: (1) reliable, objective means to measure runway friction during all weather conditions; (2) reliable methods of transmitting that information to pilots; and (3) methods of correlating measured runway friction to airplane performance. As a result of the special investigation, the Safety Board made a number of safety recommendations to the Federal Aviation Administration to resolve the problems associated with airplane performance and contaminated runways.

From the report:

Although pilot associations and the ATA support the use of friction measuring devices, their positions differ with respect to the mandatory use of such devices. Pilot associations recommend regulatory action to require airport management to measure friction and report the information to flight crews. In their view, pilots thereby would be able to use the runway friction information in conjunction with expected performance values in the airplane flight manuals. Additionally, they observe that regular and repeated use of runway friction values would expand the operational significance of the values to each pilot.

The ATA has a program to encourage the operational use of friction measuring devices, and it believes that the current equipment is adequate to measure friction on runways to provide advisory information to pilots. The ATA stresses that, while the friction readings cannot be correlated directly to airplane stopping performance, the runway friction advisory information will assist the pilot through repetitious use in relating the information to his airplane’s stopping capability on that runway.

Representatives of several foreign governments and one U.S. air carrier indicated at the hearing that they use systems for measuring coefficients of friction on runways contaminated with snow, ice, slush and water, and for relating the measured values to airplane performance in both general and quantitative terms. However, they admit that the correlations are not precise and they are rarely, if ever, used to impose landing or takeoff weight penalties on airplanes. Further, extensive pilot experience with the system is required before reliable operational judgments can be made. In other words, the systems used are runway condition advisory systems that have evolved over many years of use and experience. Although the systems are recognized as far from perfect, the users are confident that they are providing useful advisory information to experienced pilots.

The Safety Board recognizes that research is needed to establish the value of the use of runway friction measuring devices for operational purposes when the runway is covered with contaminants, such as snow, slush, or ice, and to establish a correlation between measured values and airplane stopping performance. However, the Safety Board believes that the development of reliable equipment to determine runway condition in quantitative terms for advisory purposes is a realistic objective.

The major problems is that all of the airplane performance data used to establish operational limitations are obtained under ideally controlled conditions and are not representative of the performance actually attained during normal line operations. The test airplane used during certification is new, its brake and antiskid systems produce peak design performance, the tires are in good condition and at optimum operating pressures, and the test pilot’s reaction times to activate deceleration devices, such as ground spoilers and wheel brakes, during a rejected takeoff or after landing may not accurately reflect line pilot performance. Most significant, however, is that all of the airplane acceleration and stopping performance data are for dry, smooth, hard runway surfaces; yet takeoff and landing operations are frequently conducted on runways covered with water, ice, slush or snow, or contaminated by rubber deposits.

Conclusions:

1. Airlines, ATC, airport management, and pilots each play a crucial role in the development and transmission of information relating to runway conditions during periods of inclement weather.
2. Because of the small number of FAA airport inspectors compared to the total number of certificated airports, the FAA must rely on airport management to conduct snow removal operations without continuing FAA surveillance.
3. The lack of specific requirements in 14 CFR Part 139 for airport removal programs can result in ineffective local snow removal programs.
4. The requirements of 14 CFR Part 139 should be amended to require that airport snow plans include both standards and procedural guidelines for airport operators, specifically criteria for closing, inspecting, and clearing contaminated runways, procedures to be followed upon receipt of “poor” or “nil” pilot braking action reports, and more specific requirements for runway inspections by airport operations personnel.
5. When pilots report braking action as “nil” or “poor to nil”, airport management should be required to determine and correct the reason for the reduced runway friction before further airplane operations are permitted on the runway.
6. While braking action reports are subjective, they remain the most timely and most available source of runway condition information.
7. The timing, form, and content of braking action reports must be standardized in order to minimize subjectivity.
8. The role of ATC is central to the transmission and dissemination of runway surface information to both pilots and airport management.
9. The ATIS should not be the sole means for transmitting runway condition reports during periods of rapidly changing runway conditions.
10. Air traffic controllers should anticipate the need and request braking action reports from pilots well before they land so that the pilot can make an evaluation of the entire landing roll.
11. Controllers should understand the operational significance of braking action reports, and their training should include information regarding the effects of contaminated runways on the performance of landing and departing airplanes.
12. Industry groups do not agree on the reliability and adequacy of existing runway friction devices.
13. The use of mechanical friction measuring devices to measure runway coefficients of friction is an attainable, reasonable objective; friction data should be developed and used to establish a basis for objective evaluations of the braking quality of a runway surface.

14. Few friction measuring devices are currently used at U.S. airports; some airport managers who use friction measuring devices reportedly have used them successfully.
15. All parties agree that friction measuring devices could be used for assuring that the concrete or asphalt surface friction is not degraded, although airport management believes runway maintenance tests can be conducted equally well without the expensive and complicated equipment.
16. Airport management does not believe that adequate technology exists to measure runway friction with sufficient accuracy and reliability for such measurements to be used for operational purposes.
17. Pilot groups and the ATA support the use of friction measuring devices to provide, at a minimum, advisory information to pilots for assessment of takeoff and landing performance.
18. The FAA should measure runway friction during inspections of all full certificate airports and require that a Notice to Airman (NOTAM) be issued when the coefficient of friction falls below the minimum value reflected in Advisory Circular 150/5320, Chapter 2.
19. The problem of measuring the coefficients of friction of contaminated runways and correlating measurements to airplane stopping performance is a complex one because of the large number of variables that must be accurately accounted for.
20. Several FAA and NASA projects for the measurement of runway coefficients of friction and correlation of the measurements to airplane stopping performance indicate that such correlation is an achievable goal.
21. Sufficient research has been completed to warrant further testing to establish correlation between runway friction measurements and airplane performance.
22. During airplane certification, the FAA should require manufacturers to show through analytically derived data the airplane's stopping performance on surfaces with coefficients of friction representative of typical wet and icy runways.
23. Measurement of runway coefficients of friction and their correlation to airplane performance will have to be both accurate and consistent before their use will be accepted voluntarily by the aviation industry.
24. The FAA should adopt rules which provide adequate runway length safety margins in relation to existing runway conditions.
25. Techniques of time-distance and time-to-V_1 are not accurate methods of measuring airplane acceleration on the takeoff roll and have not found general acceptance.
26. The development of an accurate and reliable takeoff performance monitoring system would permit pilots to assess subnormal takeoff acceleration in time to effect a safe rejection of the takeoff.

APPENDIX M

Minutes of Inter Nordic meeting 13-14 October 1959 relating to measuring and braking action on runways.

Present:

A Blomgren, chief engineer, Royal Aviation Board, Sweden; O. Kollerud, chair, airport manager, Norwegian Directorate of Aviation; E H Axelson, aviation inspector, Danish Directorate of Aviation; G.K. Kristiansen, traffic inspector, Norwegian Directorate of Aviation; C-E Calås, aviation inspector, Finnish Aviation Agency;
O. Tuliainen, director general of the Finish Board of Road and Water Construction; G. Kullberg, head of department, National Road Research Institute, Sweden;
G. Artvik, master of engineering ('civilingenjör'), SAS;
S. Orbert, engineer, SAS;
Captain K-G Knutsson, SAS (13/10);
Captain K.A. Oldne, SAS (14/10);
T Anderson, chief traffic controller, Swedish Aviation Administration;
T Göransson, engineer, Swedish Aviation Administration;
E Nyren, chief engineer, Royal Aviation Board; and
S-E Ofverström, assistant, Swedish Aviation Administration, keeper of the minutes.

The chair welcomed everybody and informed about the purpose of the meeting. He mentioned that, at the OPS committee meeting on 22 September 1959, a wish for uniformity had been expressed concerning measuring and reporting of braking action on runways during winter. So that those present could learn how such tests are carried out in the various countries, he asked those present to describe this.

Axelsen: At Kastrup we used to use a truck. The results of the braking tests were converted to braking coefficients using tables. However, we found the method so laborious that, for the past two years, we have switched to using a Tapley-meter 'test' mounted on a Volkswagen, and the results have been good. Measuring is carried out at a speed of 40 km/hour every 400 meters along the runway's centreline and 15 meters to the right and left of this line when the braking values are believed to deviate from those along the centreline. We then calculate the mean for the runway as a whole. Other Danish airports use Tapley meters mounted on various types of vehicle, for example a Willy's jeep or Land Rover. The limits for Good, Medium and Poor are as follows:

0.35 and higher	Good
0.34 - 0.26	Medium
0.25 and lower	Poor

The braking tests are published in NOTAMs and conveyed to the pilot via TWR. The pilot is informed about the coefficients on request.

Kollerud: At Fornebu, we have used the full stop method since 1950, obtaining mean retardation values with the aid of a GMC lorry. We use a speed of 40 km/hour and the time is measured using a stop watch. Braking tests are carried out along the centreline and, the poorer the braking action, the shorter the distance between the tests. We tried using the Tapley-meter method in 1952. We found that it worked well with temperatures well below freezing and a completely snow-covered runway, but was so unreliable at temperatures around zero degrees, that we gave up using the method. We calculate the mean for the runway as a whole. Systematic braking tests are not carried out at other Norwegian airports, but the braking action is assessed subjectively.

The limits

2.1 and lower	Poor
2.2 – 2.6	Medium
2.7 and higher	Good

Kollerud also stressed the importance of ensuring that correct landing speeds were used. An excessive speed of 10 knots increases the required landing distance by approximately 300 metres.

Calås: Starting this year, the Tapley-meter method is used at all Finish airports. Measurements are carried out every 200-300 metres along the centreline and 15 metres to the right and left of the centreline. We use a two-axled 6.5-tonne Sisu truck and a speed of 40 km/h. We calculate the mean for the runway as a whole. At temperatures around zero degrees, the braking test is uncertain and the pilots have often had deviating opinions about effective braking values compared with the measured ones. The limits for good, medium and poor have been prepared in consultation with the pilots and defined as:

0.45 and higher	Good
0.30 - 0.44	Medium
0.29 and lower	Poor

Göransson: At Bromma we have tried out four different methods: The full stop method with measurements in 21 places, the Tapley method with the hands in the ’free’ position (this method has now been completely abandoned), the S.K. Kullberg method or skiddometer method BV 2 and the Tapley-meter method with the hand in the test position and measurements in 30 places. Measurements are taken along the centreline and 15 metres to the right and left of this line.

Other Swedish airports use the method described in TF Ma 16/1958 of 1 October 1958 (Annex 1.)

Öfverström informed about the method of conveying information about braking action to pilots and other relevant parties. The results of the braking tests are available in TWR and, on request, the pilots are also informed about the friction coefficient. NOTAMs are issued to airports at home and abroad. Departing crews get a more detailed description of variations in braking action by means of a runway map that we have prepared, on which particularly poor braking values are noted.

Kullberg reported that the braking tests carried out by the National Road Research Institute were mainly carried out on roads, and that there was limited experience of braking tests on runways. Some of the important problems that must be addressed when conducting braking tests are the speed, the load on the measuring vehicle, whether the wheels lock or roll during the test, and the condition of the tyres. On a snow-covered runway, the results of the braking tests are affected by both the covering layer and the underlying surface. The amount of traffic to which the runway has been exposed will affect the results of the braking tests. A snow-covered runway with little or no traffic has a higher coefficient than a runway with a greater traffic load.

Antvik: SAS is indifferent to the method used to measure braking values. What is desirable is for the values good, medium and poor to have the same meaning and for our pilots to receive uniform information with the same meaning in all the Scandinavian countries. We would also like to raise the limit for good to 0.40, which would also imply a wider medium of 0.25 to 0.40. It would also be an advantage if braking values were stated uniformly as braking coefficients. Antvik also presented the views that came to light at the AGA VI meetings in Montreal in 1957.

This gave rise to a discussion among the participants, which led to a proposal from Göransson to define the limits for good, medium and poor as follows:

Good	≥ 0.40
Medium to Good	> 0.35 - < 0.40
Medium	0.30 - 0.35
Medium to Poor	> 0.25 - < 0.30
Poor	≤ 0.25

Axelsen raised the question of how the pilot interprets the reported braking action values good, medium and poor, and what measures he takes. To this, Knutsson replied that more stringent requirements would always have to be observed with braking values of from medium to poor. Particular attention must also be paid to the prevailing crosswind conditions. The friction coefficient, which can be obtained from the tower, is a good aid in this context.

An attempt at differentiation of braking value information by dividing runways into sections was also discussed.

Öfverström: During the past winter, a number of meetings were held to discuss the problems relating to maintenance of winter airfields. It lead to a proposal in two parts: braking tests should be conducted every 200 metres (instead of every 300 metres) along the runway centreline and 15 metres to the right and left of the centreline, and the runways should be divided into three sections called A, B and C, with A always representing the part of the runway with the lowest runway number. These sectional designations should only be used in NOTAMs about snow and braking conditions. For the transmission of information from the tower to the pilot the designations ’the first', 'the second' and 'the third' part in relation to the aircraft’s landing direction were to be used. The friction coefficient was to be calculated as a mean for each section. A NOTAM should be issued if the friction coefficient varied by 0.05 units or more.

The proposal that was presented would lead to some differentiation in that it would be possible to calculate mean values across three sections of the runway instead of just one mean value for the whole runway as before. This system was also tried out, but since the winter was drawing to an end, it was not possible to gather enough experience.

The proposal was discussed by those who were present, who found that its nature was such that trials should be conducted during the coming winter season.

Kullberg pointed out that there are certain risks involved in stating coefficients as mean values. As an example, he mentioned that the mean value of 0.20 and 0.40 is 0.30. If the pilot is informed that the braking value is 0.30, he is misled in that he is not told that the braking value is in fact 0.20 in some places.
Antvik replied that a low braking value of, for example, 0.20 is an indication that measures must be taken in order to improve the braking value in that particular location, something that is in fact done through sanding.

The chair asked whether the submitted proposals were now ready for recommendation.

It was decided, that the meeting should submit a threefold recommendation to the respective aviation authorities: that the coefficient (µ-max) for braking value good be changed to 0.40 and that the table should otherwise be presented as proposed by Göransson, that runways be divided into sections (called A, B and C in NOTAMs and "the first", "the second " and "the third" in landing instructions) in accordance with Öfverström's proposal, and that braking values be stated as friction coefficients.

Calås supported the proposal in principle. It was with some reservations, however, that he consented to the proposal to lower the friction values in Finland's case.

As far as Norway was concerned, the switch to stating braking values as friction coefficients would mean that, where the Tapley meter is not used, the retardation values obtained today must be converted to friction coefficient values.

Where the full stop method is used, a diagram will be used for the conversion. (Annex 2.)

Axelsen asked what role the various vehicles played in deciding braking values.

Antvik replied that there was insufficient experience on which to base an answer to that question at present. However, it should be studied during the coming winter and experience should be subsequently exchanged.

Antvik reported that they had prepared a diagram in SAS (Annex 3), which showed how far the runway must be extended for various types of aircraft types to take account of changes in braking action. He stressed that this diagram did not constitute a recommendation, but only a compilation of available information on the subject.

Kollerud asked the direct question of whether SAS was interested in having braking tests conducted at all Norwegian airports. If so, it would be carried out in accordance with the Tapley method and the full stop method using available vehicles.

Antvik replied that SAS was interested in having braking tests carried out at all Norwegian airports used by SAS.

A detailed discussion ensued, about when, where and how braking tests should be carried out. Axelsen claimed that having too closely spaced measuring points on long runways is much too time-consuming, and Calås proposed that measurements should be taken at shorter intervals on short runways. Kallberg pointed out that it was absolutely necessary to carry out an equal number of measurements in each section. If this was not the case, the section with the fewest measurements would play a misleading and disproportionately dominant role when the mean was calculated for the runway as a whole.

The participants finally agreed on the following recommendation: The scope of braking tests should be such as to ensure that a representative picture of the runway friction conditions is obtained.

Note. Experience has shown that when there is a need for a more complete evaluation of the friction conditions, the distance between the measuring points should be 8-10% of the runway length. Measurements are taken along the centreline and 15 metres to the right and left of this line.

Concerning the speed of the measuring vehicle in connection with braking tests, it was decided to submit the following recommendation: When a Tapley meter is used, the speed of the vehicle should be approximately 35 km/h. A higher speed is an advantage under certain runway conditions. However, the speed on starting to brake must always be constant. The same speed shall always be used along the runway’s three measuring lines.

When the full stop method is used, it is important to that the speed is as intended. This requires calibration of the vehicle’s speedometer.

Concerning the times at which measurements should be carried out, the following recommendation was proposed: Braking tests shall be carried out on a daily basis when the runway is partially or completely covered in snow or ice and at fixed times (hours of the clock) to be decided in consultation with the air traffic management at the respective airports. In principle, the chosen time should be one that enables the braking tests to be completed one hour before the first known departure of the day destined for the airport in question. However, after consultation with the air traffic management, braking tests must be discontinued if the runway conditions are considered to be unchanged since the previous braking test.

Additional braking tests (over and above the daily test routine) shall be carried out as soon as changes in the braking action are suspected or if so requested by the air traffic management.

The effect of sanding and sand grain sizes on the braking results was also discussed in some detail.

Kullberg: Some studies of the subject have been carried out by the National Road Research Institute in Stockholm. The results have been published in the National Road Research Institute’s Report No 28: *Studier og forsøk med sandning og saltning på vinterväglag* (’Studies and trials with sanding and salting of top layer on winter roads’ – in Swedish only). (Annex 4.)

Both natural gravel and crushed gravel have been used in the trials. The trials showed that fine-grained material resulted in a higher starting coefficient than coarse-grained material; but that coarse-grained material resulted in a greater braking action on an icy surface. The effect of sand that is spread out without bonding to the frozen surface has proved doubtful in terms of braking action.

Studies have also been carried out concerning the amount of sand that is required. The studies showed that with a grain size of 0-8 mm, 5 m^3/10.000 m^2 of sand was required to get a friction coefficient of 0.7, using a method whereby the sand bonded to the frozen surface on contact. If the friction coefficient was lowered to 0.5, the requirement was 1.6 m^3/10.000 m^2 based on use of the same method.

Antvik: The engines of the Caravelle are sensitive to gravel particles, particularly with grain sizes exceeding 2 mm, which will reduce the economic life of the engines. The gravel is pulled up with the nose wheel and thrown up over the wings so that it is sucked into the engines. Correspondence between SAS and the Rolls Royse factory concerning this problem has resulted in acceptance of a grain size of 4 mm.

However, the consequences of using coarser grains can be catastrophic. What we wish for is that the runways be kept completely free of snow and ice, so that the need for sanding is kept to a minimum.

Calås asked whether any of the participants had experience of the use of wood shavings as braking agent.

There was not much experience relating to this. However the sensitivity of the jet engines might be one reason why wood shavings should be tried out in the future. The respective countries should conduct some trials.

Concerning future jet traffic and the special demands that jet aircraft place on safety, the available options were discussed, as were necessary improvements relating to equipment that would have to be procured in order to keep the runways free of ice and snow.

Calås reported on various types of trials conducted abroad, such as melting of snow and ice with immediate suction into tanks, blowing of runways and electrical heating of runways. However, these methods are tremendously expensive. He also pointed out that it may become necessary to install protective nets at the end of the runways to catch the aircraft.

Blomgren informed about this years' studies in the USA and Canada. There, they had demonstrated 4.5-metre wide sweeping machines, whose brush rollers had a diameter of 1 metre and a speed of rotation of 600 rpm. The snow was quickly swept away and flung outside the runways by means of a fan. In Sweden, three such machines are currently being made, for delivery in December this year. The price is SEK 80,000 per machine.

Göransson proposed that statistics be kept of braking test measurements during the upcoming winter. He also presented a proposal for the presentation of such statistics. (Annex 5.) The statistics would then be used as the basis for future discussions.
It was decided to recommend keeping statistics as proposed.

It was proposed that a summary of the results of this Nordic meeting should be sent to ICAO's AGA division. To simplify matters, it was decided that each country should send those instructions and regulations that were drawn up on the basis of the recommendations and proposals of this meeting.

It was proposed that a new meeting should be held in February 1960 to discuss experience of snow removal gained during the winter. Particular emphasis should be given to studies of any difficulties encountered by jet aircraft during the winter.

Kollerud said how much he and the other participants appreciated the initiative that had been taken to enable this discussion between delegates from countries that shared the same problems. He claimed that the good results that had been gained from this conference were an incentive to redouble our efforts to solve any difficulties encountered during the coming winter.

The chair thanked the participants for the willingness to cooperate that they had displayed during these two days. Since there was no further business, he declared that the meeting was adjourned.

Compilation of recommendations and proposals

Recommendations

1. The limits for Good, Medium and Poor shall be:

Good	≥ 0.40
Medium to Good	> 0.35 - < 0.40
Medium	0.30 - 0.35
Medium to Poor	> 0.25 - < 0.30
Poor	≤ 0.25

2. Runways shall be divided into three equally long sections called A, B and C, where A shall always be the part of the runway with the lowest runway number. These sectional designations shall only be used in NOTAMs relating to snow and braking conditions. In information from the tower to the pilot, the designations "the first", "the second" and "the third " part shall be used, where 'the first' shall be the nearest part of the runway viewed from the landing direction.

3. Recorded braking values shall be stated as friction coefficients.

4. The scope of braking tests should be such as to ensure that a representative picture of the runway friction conditions is obtained.

   Note. Experience has shown that when there is a need for a more complete evaluation of the friction conditions, the distance between the measuring points should be 8-10% of the runway length. Measurements are taken along the centreline and 15 metres to the right and left of this line.

5. When a Tapley meter is used, the speed of the vehicle should be approximately 35 km/h. A higher speed is an advantage under certain runway conditions. However, the speed on starting to brake must always be constant. The same speed shall always be used along the full length of the runway's three measuring lines.
   When the full stop method is used, it is important to that the speed is as intended. This requires calibration of the vehicle's speedometer.

6. Braking tests shall be carried out on a daily basis when the runway is partially or completely covered in snow or ice and at fixed times (hours of the clock) to be decided in consultation with the air traffic management at the respective airports. In principle, the chosen time should be one that enables the braking tests to be completed one hour before the first known departure of the day destined for the airport in question. However, after consultation with the air traffic management, braking tests must be discontinued if the runway conditions are considered to be unchanged since the previous braking test.

   Additional braking tests (over and above the daily test routine) shall be carried out as soon as changes in the braking action are suspected or if so requested by the air traffic management.

7. Statistics shall be kept of braking test measurements during the coming winter.

Proposals

1. Studies shall be carried out to determine what effect the use of different vehicles has on the determination of braking values.

2. Trials with wood shavings as braking medium should be carried out in the respective countries.

3. Attention should be paid to any improvement of snow removal equipment that may be affordable in the future. The use of protective nets should also be studied.

4. ICAO’s AGA division should be informed by the respective countries of any instructions and regulations that are drawn up on the basis of the recommendations and proposals of this meeting.

5. A new meeting is proposed for February 1960 to discuss the experience of snow removal gained during the winter. Specific studies of difficulties encountered by jet aircraft should be carried out.

S-EO/SN

ROYAL SWEDISH AVIATION
BOARD
GROUND SERVICES BUREAU

RULES FOR THE SWEDISH AVIATION
ADMINISTRATION'S PERSONNEL

SERVICE REGULATIONS

Ma 16/1958 1
Oct

MEASUREMENT OF BRAKING ACTION ON RUNWAYS (BRAKING TESTS)

The 'Log for runway braking test' has been prepared for Tapley-meter tests, (Ma 168), and it includes instructions for how to conduct the test.

Braking tests shall be carried out:

once a day when the runway is partially or completely covered in snow or ice; however , after consultation with the air traffic management, the test shall be suspended if the runway conditions are deemed to be unchanged since the previous braking test and at any specific time (hour of the clock), as decided in consultation with the air traffic management at the respective airports. In principle, the chosen time should be one that enables the braking tests to be completed one hour before the first known departure of the day destined for the airport in question.

Additional braking tests (over and above the daily test routine) shall be carried out as soon as changes in the braking action are suspected or if so requested by the air traffic management.

The following shall apply to making entries in, calculations and checks etc. of the 'Log for runway braking tests'.

1. A log shall be kept by the person who conducts the braking test.
2. The log shall be calculated, signed and checked in accordance with instructions drawn up by the respective airport managers.
3. If the friction coefficient is below the following values, attempts at improvement shall be appropriate to achieving these values.

Weight of aircraft	Crosswind (maximum)	Coefficient
Less than 25,000 kg	10 knots	0.27
25 000 kg or more	12.6 knots	0.30

If the crosswind component exceeds the above values, the coefficient must be increased by 0.012 for each knot above 10 or 12.5 knot, whichever is applicable.

4. The log shall be stored for one year. After each winter season, statistics shall be submitted to the Ground Services Bureau on a special form for the purpose.

Information about braking action that is transferred to aircraft shall correspond to the following friction coefficients:

Friction coefficient	Information
0.35 and higher	Good
lower than 0.35 but higher than 0.25	Moderate

0.25 and lower	Poor

’Moderate’ shall be further broken down into’ Moderate to good’ or ’Moderate to poor’, depending on whether the values are closer to 0.35 or closer to 0.25.

At the aircraft’s request, the friction coefficient shall be stated.

The requisite instructions relating to the above shall be drawn up for the respective airports by the respective airport managers.

Repeals TF-Ma 1/1957.

LOG
for runway braking test with
TAPLEY BRAKING TEST METER

Braking test on runway (of more than 1,400 metres) starting at end of runway				
Braking point	15 m to the right	Centreline	15 m to the left	Comments
100 m				
400 m				
700 m				
1,000 m				
1,300 m				
1,600				
1,900				
Total				
Mean				

Mean for the runway as a whole =

Test performed by

Date Time Temp ^{0}C

Braking test on runway (not exceeding 1,400 metres) starting at end of runway				
Braking point	15 m to the right	Centreline	15 m to the left	Comments
100 m				
300 m				
500 m				
700 m				
900 m				
1,100 m				
1,300				
Total				
Mean				

Mean for the runway as a whole =

Test performed by

Date Time Temp ^{0}C

Log checked by
Log handed over to by

INSTRUCTIONS FOR BRAKING TESTS

The test shall be carried out with the instrument mounted on a truck or heavy vehicle, in which the speedometer shows the correct values and the brakes are in good working order. The tyres shall have normal pressure and the vehicle should be loaded to at least 50%.

The instrument shall be steadily mounted so that the instrument display is horizontal and so that the digital range (the digits) can move accurately in the vehicle’s direction when braking,
NOTE: The installation instructions must be followed carefully so that the pendulum inside the instrument can move accurately in the same direction as the vehicle is moving, or the measured values will be incorrect.

The braking segments along the runway shall be measured up using the distances specified in the respective tables and the end of the braking segments shall be marked using, for example, flags.

HOW TO CONDUCT THE TEST

1. Immediately before each individual test, the instrument shall be set to the zero level. The locking arm is then set to ’test’.

2. The test is carried out along three parallel lines, namely, along the centreline and along lines 15 m to the left and right of the centreline.

3. Each individual braking test is carried out along the respective lines at the pre-marked braking point, braking hard (locked wheels) from a speed of 30 km/h.
4. The value on the right-hand instrument scale is read after each individual braking test. The value obtained is recorded in parts per hundred in the table (in the column for the braking point in question).
   For example: the value ’37’ is written as ’0.37’.
   If a braking test is doubtful (if the car skids etc.), it shall be repeated immediately.

When all the tests have been completed along the three lines and at the pre-marked braking points on the runway in question, the runway’s friction coefficient is calculated as follows:

a). sum up the values for each line;
b). divide the sum total by the number of braking points to obtain the mean value for each line;
c). state the respective mean figures in the bottom row of the table;
d). calculate the mean (friction coefficient) for the runway as a whole.

RULES FOR THE SWEDISH AVIATION
ADMINISTRATION'S PERSONNEL

SERVICE REGULATIONS

STATISTICS - FRICTION COEFFICIENTS ETC. FOR RUNWAYS

With effect from February 1957, in connection with measuring of braking action on runways, statistics shall be kept of friction coefficients and prevailing runway conditions, crosswind components (exceeding 10 knots) and temperature conditions at the time of the tests.

The information shall be submitted to the Ground Services Bureau after each winter season.

INSTRUCTIONS

The above parameters shall be recorded in the appropriate columns in form Ma 169 in accordance with the following instructions:

Runway conditions

In connection with braking tests, an 'x' shall be entered in the applicable columns to make use of the possible combinations.

Example 1 A clean runway free of ice but with patches of snow is indicated by checking the columns for: 'Clean runway', "Ice-free runway' and 'Snow patches'.

Example 2 An even layer of snow on a ploughed, ice-free and sanded runway is indicated by checking the columns for: "Even snow layer', 'Ice-free runway', 'Completely sanded runway' and 'Ploughed runway'.

Friction coefficient, Crosswind component and Air temperature in °C .

The respective values are entered for each braking test and marked by a line corresponding in length to the graded values in the column.

The respective values are entered along the line.

Example

Friction coefficient 0.1 0.2 0.3 0.4 0.5 0.6	Crosswind component. 10 15 20	Air temperature in °C -20 -10 +0 +10
0.40	15	-5

Measures

If sanding, ploughing or flame throwing is carried out in an attempt to improve the braking action following a braking test, the measure(s) used shall be marked in the relevant column(s) immediately opposite the result of the previous braking test.

Example: Braking test carried out on completely sanded runway with even snow layer (coefficient 0.28) showing particularly low values at some braking points. Sanding is carried out at the points in question and the measure is marked with an ’x’ in the column for ’Partial sanding’ immediately opposite the result of the previous braking test. A new braking test is then carried out, resulting in a coefficient of 0.35.

Comments

This is where you enter explanatory text (as required) to the information entered in the columns and other information that may be required in order to determine the reason for <u>variations in the friction coefficient</u>.

INSTRUCTIONS FOR BRAKING TESTS

1. The tests shall be conducted using an empty GMC 10-wheeler truck. Normal pressure in the tyres.
2. The tests are conducted after having achieved a speed of 25 miles/hour with maximum brake application (skidding).
3. Tests are taken along three runway lines, namely approximately 10 m east of the centreline (IL), at the centreline and approximately 10 m west of the centreline.
4. The tests are taken at the following points of the runway along the three lines, reckoned from the beginning of the runway in the landing direction: 250 m, 500 m, 700 m, 800 m, 900 m and 1,100 m.
5. During the tests, braking distances and braking times are measured as accurately as possible (using a stop watch) and the data is recorded on a printed form. On the form, braking times are entered under T and braking distances under L.
6. When all the tests have been conducted, columns R 1, R 2 and R 3 for retardation shall be filled in. The table of retardation versus measured distance and time is used as an aid in this connection. If the runway conditions make it is difficult to measure braking distances, measured times shall be used as the basis for calculations.

7. Example:
   The time recorded (T) for 250 m and 10 m east on the brake test form is looked up in the table to find the corresponding R. In the same way, the braking distance (L) recorded on the braking test form is looked up in the table to find the corresponding R. The mean of these two R values is then entered in the form under '250-R'. When all the values for R 1, R 2 and R 3 have been found for each braking point, the values in each column are added up. The totals are then divided by six to find the average R for each column. The mean of the three average R values is then determined, together with the average R value for the runway as a whole (Total average).
8. If the total average is less than 2.7, or if one of the three values R 1, R 2 and R 3 is less than 2.4, sanding must be carried out to bring the values above the figures mentioned before a DC-4 is permitted to land.
9. When the form has been completed, it shall be sent to the tower with a copy to the airport manager. The completed form must be received by the tower at least one hour before a DC-4 landing.
10. All tests and filling in of forms must be carried out thoroughly, and the tests must be repeated in cases of doubt.
    The person who conducts the tests and fills in the form shall sign the form, and the calculations shall be checked by another person who shall endorse the form by his/her signature before it is sent to the tower.
11. The tests shall normally be conducted at least once every day. Before a DC-4 landing, the tests shall be carried out approximately three hours before the notified landing time.
12. If the runway conditions change within three hours before the DC-4 lands, it must be checked that the runway satisfies the requirements for braking power as close up to the DC-4's landing time as possible.

Oslo Airport, Fornebu, 20 January 1950.
The Airport Manager

(Enclosure with letter of 21 January 1950 (cf. 54/50/OK/I) from the airport manager to the Directorate of Aviation)

APPENDIX N

Report on the procedure for correction of Minimum Runway Length under winter conditions at Oslo Airport Fornebu

By O. Kollerud
Airport Manager

Oslo, March 1954

Because of the varying braking possibilities which occur on runways covered by snow and ice, it is desirable to find a procedure by which to prepare runways under different conditions and a safe method for measuring the braking action.
The estimated braking possibilities at most of the airports are given as good, medium and poor. This is perhaps satisfactory on airfields having runway lengths far above those stipulated for the types of aircraft using the airport, but for airfields which have not this excessive runway length, the condition should be such that the braking action would be sufficient for the required retardation (60 % of R) and that braking possibilities may be safely determined.
Friction coefficient on clear runways is so large that it cannot be utilised by aircraft. Measured by means of a lorry having a speed of 25 mph the coefficient was between 0.7–0.9. On snow and ice covered runways the coefficient was measured in the same way – friction coefficient from about 0.13–0.33.
Analyzing the factors affecting the braking of an aircraft (not using the engines for reversing) either on landing or take-off, these will be found to vary with speed. Friction coefficient will be reduced at greater speeds, vertical load will increase with decreasing speeds inasmuch as the lift on the wings will be reduced with the square of the speed and the drag is reduced with the square of the speed. Braking is thus a result of several varying factors. It is therefore considered that the simplest way of finding a method for establishing the requirements for braking possibilities is by means of experiment and measurement. For the time being the use of reversing of the propellers for braking will not be taken into account. This, however, will be referred to later.

Measuring methods and units

Before one could start experimenting and measuring one had to have a method of measuring which safely gave the necessary figures for judging the braking possibilities. After different experiments one found that the use of an accelerometer for measuring the retardation gave the best results.
The advantage of this method is that the retardation is measured as a result of various factors previously mentioned which affects the braking. The accelerometer also draws up retardations graphically and one obtains a basis by which the measurements can be fitted into theory.
As the purpose of these tests is to take measurements in practice which would give the braking possibilities on the runway, one chose to use the retardation of a lorry being braked at a speed of 25 mph (40 km/h) as a measure for braking action. It is difficult to use an aircraft for such tests. As the unit for retardation is m/sec^2 it would be natural to use this as a unit for measuring.

Measurements

The problem now arose as to what braking possibilities an aircraft has on landing or at discontinued take-off at varying speeds with a certain measured retardation in relation to a lorry which is braked at a speed of 25 mph (40 km/h).

This was on the assumption that the braking of the aircraft should take place without the wheels skidding and one then assumed that the braking of the lorry should take place in the same way. It was, however, impossible to get any uniformity in braking the lorry in such a way that the wheels were not skidding, inasmuch as it was also dependent upon how the brakes were used and not friction only. One therefore started to measure the retardation when the braking of the car was made with locked wheels.

The measurement should therefore decide the retardation possibilities of the aircraft without skidding in relation to a lorry with a measured retardation with locked wheels from a speed of 25 mph (40km/h).

For these tests a DC-4, a Chevrolet station wagon and a GMC lorry with 10 wheels were used. By placing the accelerometer alternatively in the aircraft and in the lorry one obtained a graphic picture of the retardation.

Three landings were carried out. Conditions were 2–3 cm hardened snow on top (no sand) temperature minus 1.8°C (very good braking conditions). The following retardations were obtained with a touch-down speed of 75 kt: 1.23 – 1.32 – 1.41 m/sec.^{2}. The difference between these figures is a result of using the brakes differently, inasmuch as there was no skidding during braking. By means of a lorry with locked wheels from a speed of 25 mph the retardation was measured at 3.26 m/sec.^{2} (average 8 tests).

This measurement only showed us that the braking effect (retardation) at 3.26 measured with the lorry was satisfactory, but the possibilities of more pronounced braking of the aircraft without skidding in these conditions were present.

New tests were therefore carried out under very poor runway conditions. Ice with wet snow on top, temperature plus 3.0°C (not sanded). An experiment with the wheels of the aircraft locked during a landing was considered. However, as the runway was extremely slippery and there were piles of snow along the sides, one did not dare to risk such a test. Four taxi tests were therefore made with locked wheels at speeds from 45–65kt. The retardation measured varied from 0.65 to 0.78 m/sec^2. There was a varying wind during the test and one assumes that this was the reason for such great variations. The retardation of the lorry measured 1.54 m/sec.^{2} (average 7 tests).

These tests showed that by comparing the braking of the lorry and aircraft with the wheels skidding, the retardation of the aircraft was below half of the lorry. One knows that when the wheels are skidding during braking, the braking effect is below that which you might get under the same conditions when the wheels are rolling. Tests are therefore continued on the assumption that the retardation of the aircraft is half that of the lorry.

The measurement of the braking of the aircraft showed that the retardation was so to say constant for the whole braking distance. This gives a theoretical possibility to calculate approximately the stopping distance for aircraft at varying speeds and retardation possibilities. As previously pointed out the friction coefficient decreases with higher speeds. Its effect on the retardation is small during the first seconds after braking has started. Furthermore, the speeds which are of interest are within a limited area. This variation of the friction coefficient has such a small influence on the retardation that it has no practical importance for the theoretical calculations. According to the above-mentioned adjustments, figure 1 shows the calculated retardations and stopping distances.

Necessary braking possibilities for different types of aircraft

A minimum runway length for take-off and landing for the different aircraft is found in the Flight Manual and from this one can calculate an average retardation for take-off and landing. For the DC-6 and DC-6B the retardations will be about 1.7 and 1.45 respectively. This equals a retardation measured by means of a lorry in accordance with previous-mentioned procedure of: 3.4 and 2.0 to be able to stop within the required minimum runway length given in the Flight Manual.

These retardations should therefore be the maximum for normal landings and the above-mentioned retardation possibilities must be present when the runway length equals the minimum runway length with regard to aircraft type and weight.

To reach a braking effect on snow and ice covered runways at 3.4 is very difficult. Under such runway conditions one must calculate with a lower retardation and one must therefore add such a distance to the runway lengths given in the Flight Manual that the aircraft gets a retardation which equals the braking effect. With regard to landing the new stopping distance should be calculated at 60% of the runway length to satisfy the requirements.

It has been found possible, under all runway conditions, to prepare the runway in such a manner that one can count on a braking effect of 2.7. Theoretically, on this basis one can approximately determine the aircraft types and weights with which to operate the airport without hindrance from weather conditions.

In figure 2, 3 and 4, based on the Flight Manual and the theoretical adjustments shown on the diagram in figure 1[1], diagrams have been drawn which show the DC-6 and DC-6B with discontinued take-off and landing lengths with different braking effects. As shown in these diagrams extensive runway lengths are required, especially for landing. They can perhaps appear a little exaggerated, but one is of the opinion that it is best to be on the safe side. Especially for short runways one must be aware of the fact that on final approach and touch-down the aircraft uses a speed which lies above the educated minimum speed in the diagrams in the Flight Manual. An excessive speed of 10 kt on the touch-down speed shown in the Flight Manual calls for an additional landing runway length of about 300 m at these low braking effects. Taking this into consideration the results arrived at, may not be so unreasonable. The fact that larger aircraft use full reversing as a principal means for braking, is the reason why one generally does not see the necessity for this requirement. But according to valid regulations regarding the calculation of necessary runway lengths, full reversing must not be reckoned with. If the regulations are to be based on snow and ice covered runways, one must either be permitted to calculate with more reversing or the braking effect must be increased so that the retardation possibilities equal the runway length (shown in figure 2, 3 and 4)[2] or a combination of both.

It is considered that under no circumstances must the braking effect be much lower than 2.0. A braking effect of 1.5 is so poor that an aircraft cannot be controlled by the nose-wheel or brakes during take-off or landing even at low speeds. Even a braking effect of 2.5 is insufficient for the warming up of an aircraft at high RPMs. Below this value the aircraft will immediately start skidding.

The valid calculating method has also been chosen for retardation which is below that upon which the minimum runway length in the Flight Manual is based. The runway is therefore prepared so that the braking effect on a 1.800 m runway satisfies these requirements. For a DC-6 and DC-6B a braking effect of 2.7 for landing and 2.4 for braking has been anticipated. Take-off and landing for a DC-4 is now put at 2.2. For a runway of 1.250 m it was previously 2.17 with a reduced weight.

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[1] Figures 1, 2, 3, 4 and 5 are not included in this Appendix.

[2] Not included.

Experience regarding measurements

Since January 1950 one has worked along these lines and in close contact with the pilots. During the first months most of the landings were controlled and they showed that they were consistent with the assumptions which had been made. The pilots who continually use the airport have become familiar with this procedure and have confidence in it.
As previously mentioned, an accelerometer was used for the actual measuring of retardations. However, this appeared to be difficult in practice as the instrument is very delicate and intricate and only special people could operate it. A GMC 10-wheeled lorry was therefore also used during the tests. By measuring the braking distance a value for the retardation was also obtained and these values coincided with the accelerometer. The time used for braking was taken by a stopwatch and in these instances when it was difficult to measure the braking distance accurately, the calculations were based on the time.
An empty GMC 10-wheeled lorry (good tyres) is therefore used for measuring the braking effect and there are always people on the airfield who are able to do these tests. By measuring both breaking distance as well as taking the time a double check is obtained, thus obviating the possibility of inaccuracy. During the last five winters the braking effect has been measured in this way and the result has been quite satisfactory.
One has come to the conclusion that the tests should be made at the following points on the runway: 300 – 600 – 800 – 1000 – 1200 – 400 – 1600 – 1700 m in the direction of take-off and landing and at each of the above distance along the centreline and at 15 metres on either side. It takes about 1 hour to carry out such a test, and it is often difficult to use the runway for such a long period in view of incoming and outgoing aircraft, but it is not often that the entire test must be carried out. One finds it unnecessary to carry out the whole braking test if by making check at a few places along the runway, the braking effect is found to be above the value which is laid down for the actual condition. If there is any doubt the entire test would be carried out.

Experience with regard to runway conditions and braking effect

On snow and ice covered runways the braking effect varies from about 1.5 – 3.5. It is very difficult to state exactly how and why the runway conditions vary. If, however, the braking effect is good, it will not be worse if the temperature decreases, but if the temperature rises to zero degrees C or more, the braking effect will decrease rapidly. The braking effect is very much dependent upon the temperature and especially when it is around zero degrees C. Some of the various conditions influencing the braking effect are given below:

Braking effect 1.5 – 2.0

a) Slush or rain on snow or ice covered runways.
b) Change from frost to temperatures above zero.
c) Change from mild to frost (not always).
d) The type of ice which is formed after long periods of cold.
e) A thin layer of ice which is formed by frozen ground having been exposed to humidity or rain at zero degrees C or above.

Braking effect 2.0 – 2.5

f) Snow conditions at temperatures just under zero.
g) Snow covered runways at temperatures under zero, exposed to sun.

Braking effect 2.5 – 3.5

h) Snow covered runways which have not been exposed to higher temperatures than about minus 2 - 4 °C.

This classification is only meant as a guide based on our own experience and it must not be used for establishing the requirements for the braking effect. There are so many variations in runway conditions that each condition must be measured to be able to judge the braking possibilities. This classification has been included to give those who work with the problem an impression of what the figures which we give as braking effect represent with regard to the runway conditions.

Preparation of the runway in order to obtain the necessary braking effect

In this report the question of how runways are cleared of snow has not been included as this is no longer a technical problem but rather as economical one. One has come to the conclusion, however, that the runway should not be cleared right down to the permanent surface for the following reasons: in the first case the runway will be much more slippery because the humidity forms ice on the cooled down surface at temperatures above zero (see braking effect 1.5 – 2.0) and secondly, the runway surface may be damaged by snow clearing machines.
The runway is covered by 2” – 3” layer of ice and snow throughout the winter. This does not create any difficulty when it begins to melt in the spring.
As previously mentioned, the braking effect should be at least 2.2 for the DC-4 and 2.7 for the DC-6 and DC-6B. Extensive work is often involved in preparing the runway so that a braking effect of 2.7 is obtained. In the past years a great deal of experience has been gained at this airport which has shown how this work should be done under different runway conditions.
Sand is used for the preparation of the runway. Damp sand with such a temperature that freezing is prevented during the sanding process is preferred, because it adheres well to the ice. Dry, warm sand did not show very good results.
The same classification is used with regard to the preparation of the runway as was used for the braking effect.

a) Slush or rain on snow and ice covered runways

This condition is the most difficult. The runway is scraped with a motor grader until the firm surface is reached. This motor grader makes stripes in the snow and ice. Then the surface is sanded until the desired braking effect is reached. It sometimes happens that a braking effect of not more than 2.5 is reached under such conditions. Sanding must be carried out every day as long as the temperature is above zero. A 6 – 9 mm layer of gravel was also previously used, but some aircraft were damaged by the larger stones being thrown up by the propellers slipstream. By using sufficient gravel a braking effect of up to 2.7 could always be reached.

b) Change from frost to temperatures above zero

Normally sanding alone is sufficient, but if the upper layer of the snow and ice becomes slushy, both scraping and sanding is necessary.

c) Change from mild to frost

Damp sand which is so warm that it does not freeze during the sanding is used. As long as the frost continues and the sand adheres to the ice, a runway prepared in such a way will last several days without further sanding.

d) Ice which is formed after long period of cold

In the beginning this condition created great difficulties because it was not possible to get the sand to adhere to the ice. For the last three winters a flamethrower has been used which rapidly gave a good braking effect. The runway is first sanded and then the flamethrower is drawn over the surface at a speed of 15 km/h. The flamethrower will then warm up the ice to such extent that the surface throws off moisture.
When the moisture freezes, the sand will adhere to the ice. As long as frost continues, sanding is unnecessary, except when the cold period has lasted so long that too much sand has been loosened by the aircraft.

e) A thin layer of ice formed by frozen ground having been exposed to humidity or rain

Normal sanding is often sufficient, but occasionally it is necessary to use large quantities.

f) Snow conditions at temperatures under zero

The runway is scraped and sanded.

g) Snow covered runways at temperatures under zero, exposed to sun

The runway is sanded. If the surface is too soft it must be scraped, this condition occurs mainly in the spring. In the scraping process the sand used on previous occasions will be reached and this will give a good braking effect.

h) Snow covered runways which have not been exposed to temperatures above minus 3 – 4 ºC

If the braking effect is not quite up to the requirements, a little sanding is sufficient. It can be mentioned that a quantity of about 300 m^3 of sand is used each winter for the preparation of the runways. As previously mentioned, conditions are varied, especially when the temperature swings around freezing point. The method for the preparation of the runway will therefore also vary dependant upon the climatic conditions of the airport. Thus every airport will have its own special method for some of the conditions mentioned.

Propeller reversing on snow and ice covered runways and runway lengths

As previously mentioned, we have looked away from that part of propeller reversing which for certain aircraft types is included in the calculation of the minimum runway length. In the Aeroplane Flight Manual for those aircraft types we know, only a small part of the propeller reversing effect is included when calculating accelerate-stop distance. For the braking effects (retardations) which has been established, reversing makes such little difference that it can be disregarded in the theoretical adjustment made. For a braking effect below 2,0, however, it will be more important because the time used for braking is longer and reversing will thus be a greater percent of the total work necessary to stop the aircraft.
The opinion is, that at these low braking effects, one should not calculate with such a great reversing effect as that used for the calculation of the required runway length. The reason for this is that by reversing on three engines the aircraft will have a tendency to yaw as the runway is so slippery that one cannot use the brakes or the nose wheel for steering. At the same time, the rudder effect decreases rapidly. To avoid this, reversing on two engines only should be reckoned with, one engine on each side.
Taking into consideration one cannot fully use that amount of the reversing which has been included in the calculations and also that the accelerate stop distance has no safety margin, one

has come to the conclusion that the runway lengths shown in figures 2 & 3[3] are not excessive, in spite of the fact that the risk is minimal because discontinued take-off seldom occurs.
When landing, however, a certain reduction of the runway lengths shown in figure 4[4] may be justified. As the landing distance from 50 ft to full stop gives a safety margin of 40%, the reversing effect will, if not taken into account, be regarded as additional safety margin. A certain percentage of the reversing effect from two engines may, however, be considered justified.
As for the landing distance, various gross weights and runway lengths regarding braking effect as shown in figure 5[5] has been considered. In this diagram the landing distance according to the braking effect is not 60% of the minimum landing runway length, but to the minimum runway length given in the Aeroplane Flight Manual is added the increase in landing distance obtained by the aircraft having a lower retardation than that specified in the requirements. Further reduction of the runway lengths is not justified, because the snow banks on each side of the runway often cause the braking to be performed moderately to prevent the aircraft from turning off the runway.

Views on jet aircraft under winter conditions

The above report has only dealt with piston engine aircraft, as the knowledge of the requirements of a jet aircraft with regard to the braking possibilities is very small. As figure 1[6] shows, the speed of the aircraft at the commencement of braking is very important. The landing speed of a jet aircraft is larger than that of a piston engine aircraft. These jet aircraft which today are in scheduled service have only drag and friction as means of braking, and the safety margin which the reversing effect gives is not present. These aircraft therefore require more attention with regard to runway lengths and the preparation of the runway surface.
As to sand on the runway, this may also cause difficulties as a jet engine is very sensitive to sand particles which may be sucked into the engine. A further point is that a jet aircraft may reduce the braking effect because of heat radiation and the blowing off of the sand.

Necessity of further tests

This report has been based on the weather conditions of this airport and on the aircraft types which use the airport. The results reached are satisfactory and the problem has therefore not been ventured deeper into.
It would have been of great interest, however, to have performed further measurements of the retardation of the aircraft under different conditions, especially at poor braking effects. At Fornebu airport the latter is disregarded, as the runway surface under such conditions must be specially prepared because of the short runways. At airports having excessive runway lengths, however, it would perhaps be necessary to perform such tests at conditions with poor braking effect. To satisfy the requirements, these braking tests should be performed without reversing during the landing run. It should again be pointed out that the runway length is not the only factor to be considered when establishing the minimum braking effect, but also the steering possibility of the aircraft. The latter is especially important when snow is piled up along the sides of the runway. The simplest method of analysing the braking effect is possibly by means of an accelerometer which shows the retardation graphically.

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[3] Not included.
[4] Not included.
[5] Not included.
[6] Not included.

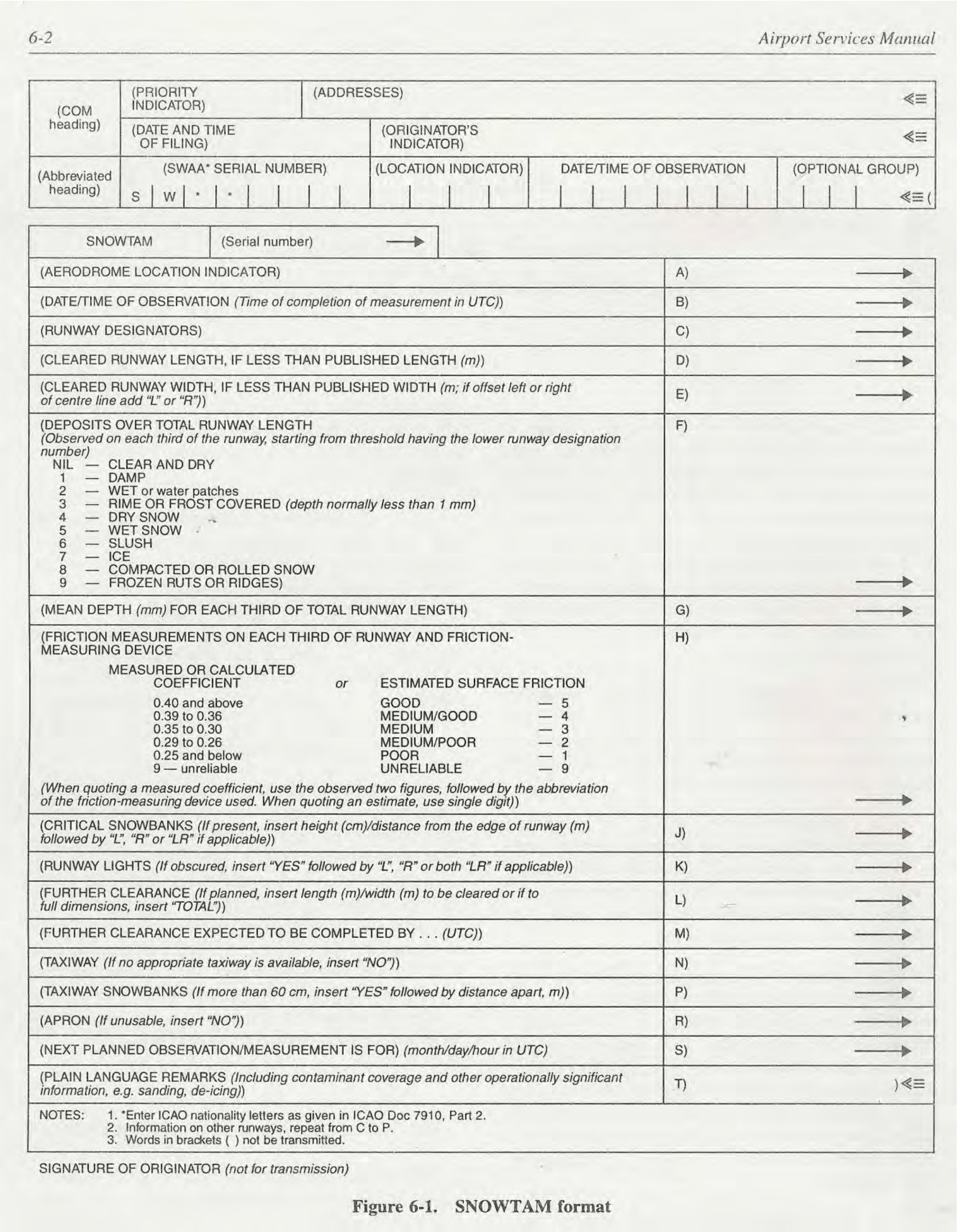
The instrument used at Fornebu also marked off the time, thereby making it possible to analyze the whole program of braking.

As previously mentioned, this accelerometer was very sensitive and intricate. If any one should proceed with such tests an instrument which is more suitable for this special task is to be recommended.

Oslo Airport, Fornebu
O. Kollerud

APPENDIX O

ICAO SNOWTAM FORMAT



6-2 *Airport Services Manual*

(COM heading)	(PRIORITY INDICATOR)	(ADDRESSES)			≪≡
	(DATE AND TIME OF FILING)	(ORIGINATOR'S INDICATOR)			≪≡
(Abbreviated heading)	(SWAA* SERIAL NUMBER) S W * *	(LOCATION INDICATOR)	DATE/TIME OF OBSERVATION	(OPTIONAL GROUP)	≪≡ (

SNOWTAM	(Serial number) →

(AERODROME LOCATION INDICATOR)	A)	→
(DATE/TIME OF OBSERVATION *(Time of completion of measurement in UTC)*)	B)	→
(RUNWAY DESIGNATORS)	C)	→
(CLEARED RUNWAY LENGTH, IF LESS THAN PUBLISHED LENGTH *(m)*)	D)	→
(CLEARED RUNWAY WIDTH, IF LESS THAN PUBLISHED WIDTH *(m; if offset left or right of centre line add "L" or "R")*)	E)	→
(DEPOSITS OVER TOTAL RUNWAY LENGTH *(Observed on each third of the runway, starting from threshold having the lower runway designation number)* NIL — CLEAR AND DRY 1 — DAMP 2 — WET or water patches 3 — RIME OR FROST COVERED *(depth normally less than 1 mm)* 4 — DRY SNOW 5 — WET SNOW 6 — SLUSH 7 — ICE 8 — COMPACTED OR ROLLED SNOW 9 — FROZEN RUTS OR RIDGES)	F)	→
(MEAN DEPTH *(mm)* FOR EACH THIRD OF TOTAL RUNWAY LENGTH)	G)	→
(FRICTION MEASUREMENTS ON EACH THIRD OF RUNWAY AND FRICTION-MEASURING DEVICE MEASURED OR CALCULATED COEFFICIENT *or* ESTIMATED SURFACE FRICTION 0.40 and above — GOOD — 5 0.39 to 0.36 — MEDIUM/GOOD — 4 0.35 to 0.30 — MEDIUM — 3 0.29 to 0.26 — MEDIUM/POOR — 2 0.25 and below — POOR — 1 9 — unreliable — UNRELIABLE — 9 *(When quoting a measured coefficient, use the observed two figures, followed by the abbreviation of the friction-measuring device used. When quoting an estimate, use single digit)*)	H)	→
(CRITICAL SNOWBANKS *(If present, insert height (cm)/distance from the edge of runway (m) followed by "L", "R" or "LR" if applicable)*)	J)	→
(RUNWAY LIGHTS *(If obscured, insert "YES" followed by "L", "R" or both "LR" if applicable)*)	K)	→
(FURTHER CLEARANCE *(If planned, insert length (m)/width (m) to be cleared or if to full dimensions, insert "TOTAL")*)	L)	→
(FURTHER CLEARANCE EXPECTED TO BE COMPLETED BY . . . *(UTC)*)	M)	→
(TAXIWAY *(If no appropriate taxiway is available, insert "NO")*)	N)	→
(TAXIWAY SNOWBANKS *(If more than 60 cm, insert "YES" followed by distance apart, m)*)	P)	→
(APRON *(If unusable, insert "NO")*)	R)	→
(NEXT PLANNED OBSERVATION/MEASUREMENT IS FOR) *(month/day/hour in UTC)*	S)	→
(PLAIN LANGUAGE REMARKS *(Including contaminant coverage and other operationally significant information, e.g. sanding, de-icing)*)	T)	)≪≡

NOTES:
1. *Enter ICAO nationality letters as given in ICAO Doc 7910, Part 2.
2. Information on other runways, repeat from C to P.
3. Words in brackets ( ) not be transmitted.

SIGNATURE OF ORIGINATOR *(not for transmission)*

Figure 6-1. SNOWTAM format

APPENDIX P

EXAMPLES OF AIRBUS FRICTION CURVES

6. A321-100 AIRCRAFT TYPE

6.1. JAA certification

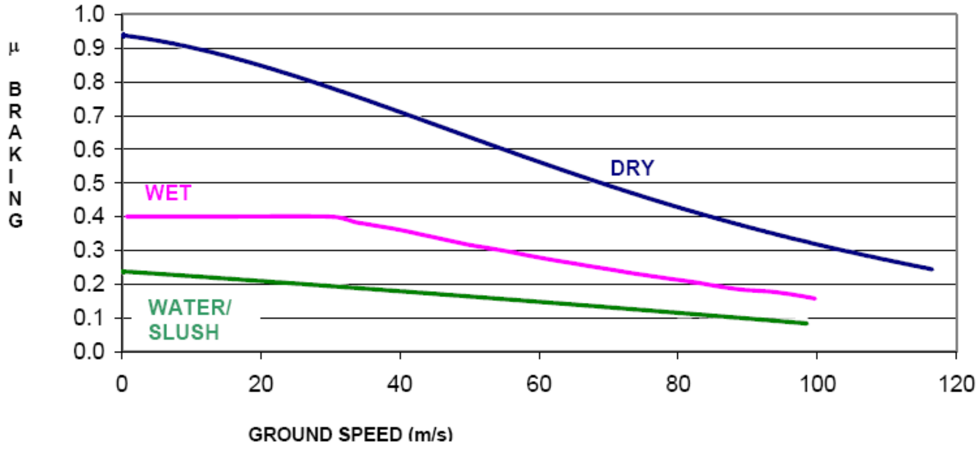
- ❑ Wet runways

The WET braking coefficient is defined in compliance with CRI F4012 as :

$\mu_{WET} = 0.5 * \mu_{DRY}$ is limited to 0.4.

- ❑ Contaminated runways

The braking coefficient on standing water or slush covered runways is defined as $0.25*\mu_{DRY}$.
The SNOW braking coefficient is $\mu = 0.2$
The ICY braking coefficient is $\mu = 0.05$.



6.2. FAA certification

- ❑ Wet runways

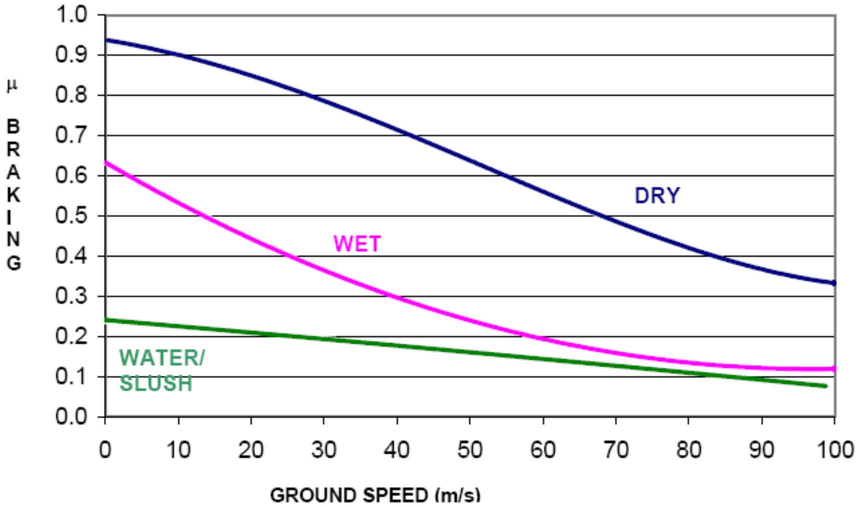
The WET braking coefficient is defined in compliance with CRI F4012. The WET braking friction coefficient is based on ESDU data. It is determined with 200 PSI tyre inflate pressure, UK wear limit, runway surface effect intermediate between B-type and C-type runways and 92% antiskid efficiency (demonstrated through flight tests).

$\mu_{WET} = \mu_{WET(ESDU)}$

$\mu_{WET(ESDU)} = 0.92*(0.692-0.00658*V + 2.52*10^{-5}*V^2 - 3.31*10^{-8}*V^3)$

- ❑ Contaminated runways

The braking coefficient on standing water or slush covered runways is defined as $0.25*\mu_{DRY}$.
The SNOW braking coefficient is $\mu = 0.2$
The ICY braking coefficient is $\mu = 0.05$.



7. A321-200 AIRCRAFT TYPE

- Wet runways

The WET braking coefficient is defined in compliance with CRI F4012. The WET braking friction coefficient is based on ESDU data. It is determined with 200 PSI tyre inflate pressure, UK wear limit, runway surface effect intermediate between B-type and C-type runways and 92% antiskid efficiency (demonstrated through flight tests).

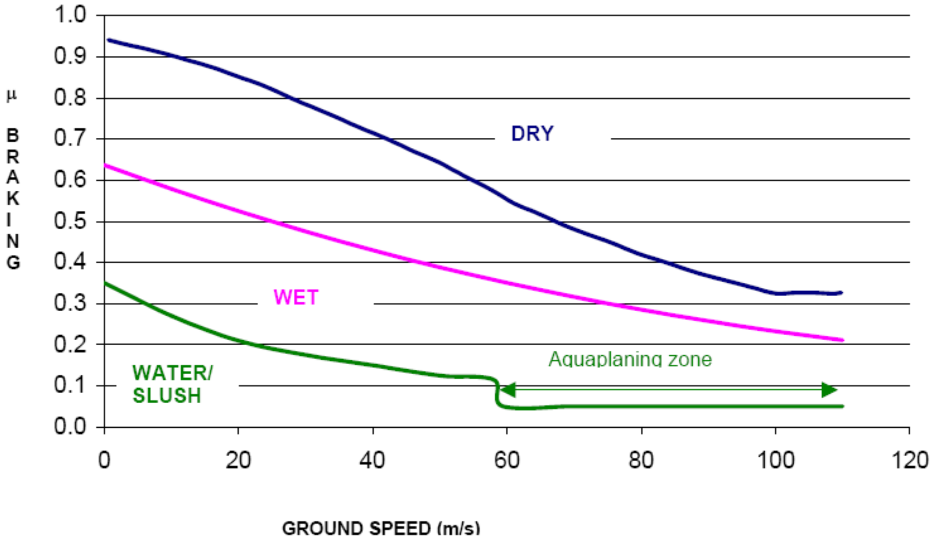
$\mu_{WET} = \mu_{WET(ESDU)}$

$\mu_{WET(ESDU)} = 0.92*(0.692-0.00658*V + 2.52*10^{-5}*V^2 - 3.31*10^{-8}*V^3)$

- Contaminated runways

On standing water and slush, the braking friction coefficient results from an amendment based on flight test campaign defined in CRI F4012.
The SNOW braking coefficient is $\mu = 0.2$
The ICY braking coefficient is $\mu = 0.05$.

The aquaplaning phenomenon is taken into account.



APPENDIX Q

The History of Friction Measurements at Airports

By Gunnar Antvik, 1997

Historical review – Early it was realised that flight safety required some control of the slipperiness on the take-off or landing surface. Many of the surfaces were in the old days grass surfaces. Only a few airports had hard surface runways.

The airport manager in many cases checked the friction conditions by making a skid test. If he was skidding too long he issued a ban on use of the airport. Due to accidents and incidents it was gradually found that better methods had to be developed for measuring friction of runway surfaces.

Why measure friction?

Flight Safety is the main reason for measuring friction. As the transport aeroplanes became larger it became also more important to check friction in a better way than making skid tests as mentioned above. *Scandinavia*, particularly Sweden, has taken a considerable part in the development of friction measuring technique.
Among reasons for friction measurements are:

- Determine friction characteristics of runways under winter conditions
- Verify friction characteristics of new or resurfaced runways
- Assess periodically the slipperiness of paved runways when wet
- Assess the effect on friction when drainage characteristics are poor
- Assess friction of runways becoming slippery under unusual conditions

Development of the "Kollerud method" for friction measurements

Scandinavian Airlines System, *SAS*, started 1946 to operate **Douglas DC-4** aeroplanes on the then opened route from *Scandinavia* to *New York*. When in traffic the aeroplanes landed at the large military airport *Gardermoen*.
For maintenance reasons *SAS* had occasionally to operate the large **DC-4** aeroplanes also at the Oslo *Fornebu* airport. The main runway at this airport was then only 1200 m long with steep lopes at both ends. In order to avoid accidents at his airport the Airport Manager, Ottar Kollerud, started measurements of friction on the runway surface under winter conditions before **DC-4** operation should take place.
Mr. Kollerud developed a method for friction measurements. According to this method a *big truck* was loaded with sand, accelerated to 30 km/h and then full brakes were applied resulting in *locked wheels*. Time and/or distance to a full stop were recorded.
From the recorded time, **T**, and distance, **S**, retardation, **r**, can be calculated:
$r = V/Tr = V2/2S$(r: m/s^2, V: m/s at brake application, T: s, S: m)
Kollerud reported the retardation in **m/s^2**. By test flights made by *SAS* it was found that the reported *retardation* determined according to the formulas above corresponded to approximately half the value for the retardation of the aeroplane. The test flights were made with aeroplanes of the type DC-4. Later tests and calculations have shown that this is valid also for a lot of other aeroplane types.
The Kollerud method for retardation measurements is included in the ICAO Airport Services Manual, ICAO, Doc 9137-AN/898, Appendix 5. The method is somewhat modified. In the

ICAO document one instead of retardation calculates the friction coefficient, μ (mu). This is made by dividing retardation with g = 9.81 m/s^2. Simplified corrections are given to convert the measured friction values from μ (mu) skid toμ (mu) max.
Naturally, units can be in the **ft** system. Retardation will have a different value and **g** has to be in **ft/s^2**. US Air Force has used for friction measurements the *James Brake Decelerometer*, **JBD**, and that uses the ft-system. The JBD is corresponding to the Tapley-meter mentioned in Section 3.1.3 below.
It should be noted that according to the Kollerud method **skidding friction** is recorded. When *ICAO* discussed friction coefficient measurements it was concluded that the **maximum friction** should be reported. The friction is recorded at a **certain slip**. Comments on this will be given later.

Need for friction measurements at other airports

The airport manager, Bertil Florman, at *Bromma* airport soon realised that he had need for friction measurements also at his airport under Winter conditions. At *Bromma* there are roads with intense traffic at both ends of the main runway. *SAS* and other Swedish operators found a need for friction measurements also at additional Swedish airports. *SAS* wanted friction measurements also at Danish and Norwegian airports used by *SAS*. At this early time, late forties and the very early fifties, friction measurements had not been recognised as a problem internationally.

Early development of friction measurement technique

Mr. Florman started at *Bromma* airport operational friction measurements using the Kollerud-method. Soon it was found that this method could be used because of the low frequency of **DC-4** operation at *Fornebu*, but that frequent use of the Kollerud-method was too time consuming and was ruining the brakes and the tires of the trucks.
Therefore, Mr. Florman introduced the Tapley-meter for operational friction measurements. The Tapley-meter is a **decelerometer** that easily can be installed in a car. The car is accelerated and at a selected speed the brakes are applied. When the wheels had become locked and skidding the recording of the Tapley-meter was read.
The Tapley-meter method was also far less time consuming and its introduction was a great step forward in friction measuring technique. Friction characteristics were normally recorded at nine points along three lines, namely along the centreline and five meters on each side of this line.
Although the introduction of the Tapley-meter method was a great step forward in friction measuring technique Mr. Florman asked his friend the Chief Engineer, Mr. Kullberg, at the *Swedish Road Research Institute*, if he could develop a unit that would provide a continuous record of the friction along the runway.
Mr. Kullberg proposed to Mr. Florman to introduce his **Skiddometer** method to record runway friction at *Bromma* airport. The skiddometer method would mean that the maximum-friction was being recorded instead of the skidding friction, as up to that time had been the case with the Kollerud and Tapley-meter methods.
With a research Skiddometer, **BV-1**, Mr. Kullberg had shown as early as 1939 that on good summer roads the maximum friction for automobile tires is recorded at about 17 % slip, i.e. the peripheral speed of the braked wheel is 17 % lower than the peripheral speed of the free rolling wheels.
An advantage of the Skiddometer method is that 80 to 85 % of the braked energy can be fed back to other wheels as a propelling force. During normal braking heat generation is a problem,

especially when using the Kollerud method for friction measuring but also when using the Tapley-meter method.

Mr. Florman decided in the early fifties to introduce the Skiddometer for operational friction measurements at Bromma airport. A special Skiddometer, **BV-2**, was built. It was a trailer. *SAS* expressed the view that the Skiddometer had to be a heavy vehicle in order to reasonably represent normal transport aeroplanes of that time. As a reasonable compromise was decided to load the measuring wheel with *1000 kg* and the total weight of the Skiddometer **BV-2** was *3000 kg*.

The **BV-2** had three wheels on the same axle. All three wheels had their own bearings and the shaft was equipped with two universal joints allowing the middle wheel, the measuring wheel, to have a smaller diameter than the two outer wheels. The diameters of the tires were chosen to result in a 17 % slip.

As the braking force under good friction conditions can be *500 to 600 kg* or even more, if the load on the measuring wheel is *1000 kg*, it was very important that 80 to 85 % of this force was fed back to the outer wheels and used to assist in towing the trailer.

The **BV-2** was used at Bromma for many years for operational friction measurements.

Through the introduction of the Skiddometer method Swedish procedures were changed to measuring the **maximum friction** instead of the skidding friction that had been used up to the introduction of the Skiddometer method. Measuring and reporting the maximum friction is in line with ICAO procedures.

As the administrations of busy airports found that trailers had certain disadvantages SAAB started in the late sixties to develop a friction-measuring unit, the **SAAB Friction Tester, SFT**. A fifth wheel, the friction measuring wheel, was installed in the rear of a SAAB car model 99. The measuring wheel was connected to the rear wheels of the car via chains and sprocket wheels. This means that the Skiddometer principle is used and some 80 to 85 per cent of the braking force is used as propelling force. By selecting the teeth on the sprocket wheels and the diameter of the measuring wheel suitably the desired slip could be obtained. The slip of the **SFT** is *12 %*. This slip is selected for operational measurements in order to reduce tire wear.

The wheel load on the **SFT** is *140 kg*. As in the case of the Skiddometer trailer further development of the **SFT** has taken place. The **SFT** is since long introduced in the *ICAO*, and *FAA* documents and *ICAO* changed the name **SAAB Friction Tester** to **Surface Friction Tester**, which also can be abbreviated **SFT**.

Calibration measuring

It was shown by tests made by the *Aeronautical Research Institute*, Stockholm, Sweden, that reliable calibration friction measurements results also were obtained, when the runway surface was contaminated by some loose snow or slush. Provided the friction measurements are made with a **SFT** with *a grooved tire*, *with tire pressure 700 kPa* and a test speed of 95 km/h is used. Now in Sweden, we have more than 25 years of experience, using this method. This technique is still the foundation for all **ASFT CFME**.

Early reporting technique

The early reporting technique was developed in co-operation between the *Airport Authority at Bromma Airport* and *SAS*. This took place in the early fifties. During a landing the friction characteristics of the middle portion and the far end of the runway are of primary importance. This led to reporting friction characteristics for three parts of the runway seen in the direction of landing. Soon the thirds were called A, B and C. A is always called the low number runway end.

An aeroplane landing from the high number direction got the report on friction in the order C, B and A.
SAS and domestic Swedish operators understood what the friction numbers meant to them. However, operators coming in to e.g. *Bromma* airport did not understand what the reported numbers meant. Therefore, the expressions **Good**, **Medium** and **Poor** were introduced.
SAS sent out a questionnaire asking for information from pilots on how they experienced information on braking action, i.e. friction, and also on controllability in crosswind.
About 3000 answers on these questionnaires were received. The answers showed that when a friction coefficient of 0.40 or above had been reported there were no pronounced problems on braking or controllability in crosswind. When 0.25 or lower had been reported the problems became severe. As a result of this study in Sweden was introduced the terminology:
Good 0.40 and above
Medium to Good 0.36 to 0.39
Medium 0.30 to 0.35
Medium to Poor 0.26 to 0.29
Poor 0.25 and below
As can be seen from the table we consider that no more than two significant figures should be reported. More than two figures would give a false impression of accuracy of the friction measuring equipment.

International recognition of Scandinavian procedures

An international recognition of the *Scandinavian* procedures of measuring of friction characteristics at airports was when the *Flight Safety Foundation* awarded the *Admiral Louis de Florez Flight Safety Award* to the spokesman of *SAS* and the *Swedish Civil Aviation Administration* at numerous *IATA* and *ICAO* meetings since the early fifties. Saab friction testers have ever since helped make flying safer all over the world. Today all ASFT's friction testers are using these principals and techniques.

FEDERAL AVIATION AGENCY

FLIGHT STANDARDS SERVICE

[14 CFR Special Civil Air Regulations Nos. SR–422, SR–422A, SR–422B]
[Notice 63–28; Docket No. 1866]

NOTICE OF PROPOSED RULE MAKING

SPECIAL OPERATING LIMITATIONS FOR TURBOJET TRANSPORT CATEGORY AIRPLANES

Notice is hereby given that there is under consideration a proposal to amend certain operating rules of Special Civil Air Regulations Nos. SR–422, SR–422A, and SR–422B, which are used in determining the minimum runway lengths for takeoff and landing. The proposal would affect only operators of turbojet airplanes under Parts 40, 41, and 42. For the purpose of determining the minimum runway length for takeoff, the proposed amendment would require the addition of a constant distance margin of 800 feet to the accelerate-stop distance. For landing, the proposal would require increased lengths of the runway at alternate airports at all times and increased lengths of runway at the airport of destination when weather reports and forecasts indicate that the runways will be wet or icy at the estimated time of arrival.

Interested persons are invited to participate in the making of the proposed rule by submitting such written data, views or arguments as they may desire. Communications should identify the notice or docket number and be submitted in duplicate to the Federal Aviation Agency, Office of the General Counsel: Attention Rules Docket, Room A–103, 1711 New York Avenue, N.W., Washington 25, D.C. All communications received on or before September 23, 1963, will be considered by the Administrator before taking action upon the proposed rule. The proposals contained in this notice may be changed in the light of comments received. All comments submitted will be available, both before and after the closing date for comments, in the Rules Docket for examination by interested persons.

Sections 4T.115 and 4T.122 of the SR–422 series regulations set forth requirements for establishing accelerate-stop and landing distances respectively. Sections 40T.81 and 40T.84 of the SR–422 series regulations set forth operational runway lengths for takeoff and the operating limitations for landings at the destination and alternate airports respectively. The FAA and industry have recognized that some takeoff and landing runway lengths, especially when operating under adverse runway conditions (wet, snow, slush, icy, etc.), are inadequate. Some airlines are applying special factors to takeoff distance and landing runway lengths to account for operations under these adverse runway conditions.

An attempt was made to account for operations under adverse runway conditions by proposing rationalized requirements for accelerate-stop and landing distances in a proposed Special Civil Air Regulation No. SR–422C, issued as a Notice of Conference dated May 4, 1962. The proposed SR–422C basically was intended to reflect a rationalization of the type certification requirements to the extent that the required demonstrations would utilize operational practices and procedures, would require runway surface and crosswind accountability, and would grant performance credit for the use of deceleration devices including arresting gear. It was contemplated that certain provisions of SR–422C would be made retroactive to presently operated turbine-powered airplanes. Two months after proposed SR–422C was issued, a Notice of Withdrawl was sent out cancelling the Notice of Conference and stating that the FAA would conduct a flight test program to determine the effect of the proposed SR–422C. Subsequently, it was concluded that the contemplated flight test evaluation was not economically feasible and an alternate approach was explored of those provisions in SR–422C which were intended to be made applicable to presently operated airplanes. There is included in this notice a proposed alternate approach which treats the most important safety problems and which is simple in concept and application and does not require an additional testing.

Accelerate-stop distance. The accelerate-stop distance determined in accordance with § 4T.115 is a requirement which is considered to result in the absolute minimum level of safety. There are no built-in safety margins to account for normal operational variations other than 50 percent headwind and 150 percent tailwind accountability. As a result thereof, airline pilots have stated that they cannot reproduce the certificated accelerate-stop distances for turbojet airplanes during air carrier operations. There is a need, therefore, to increase the accelerate-stop runway lengths to account for some of the expected operational variations.

The accelerate-stop distance determined in accordance with § 4T.115 is based on an all-engines-operating acceleration to the critical engine failure speed V_1, and a subsequent stop from this point on a dry runway. The accelerate-stop tests are normally conducted with new tires and brakes and with full knowledge of the test pilot. The type certification procedure used in the past has permitted immediate brake application upon recognition of the engine failure at V_1 speed followed by subsequent actions on the part of the pilot, after appropriate time delays, to bring the airplane to a stop. There are no arbitrary factors applied to the accelerate-stop distance to account for operational variations; i.e., pilot technique, runway surface conditions, etc.

The takeoff distance requirements of § 4T.117, in contrast to the accelerate-stop requirements, contain built-in safety margins. The 35-foot height at the end of the takeoff distance specified in all SR–422 series regulations and the application of the 115 percent factor to the all-engine-takeoff distance specified in SR–422A and SR–422B are margins which allow for reasonably expected operational variations. The takeoff distances, however, also include wind accountability as in accelerate-stop distances.

In airline operations, airplanes are operated at times with tires and brakes that do not provide maximum braking action. If an engine failure occurs at V_1 speed during airline operations, there is a time period during which the pilot decides whether to abort or continue the takeoff and also a reaction time to initiate braking. These operational variations (presently unaccounted for during type certification tests) tend to lower the level of safety because operational accelerate-stop distances would be longer than those obtained during type certification. The airlines have stated that the takeoff distances to the 35-foot height have more safety margins included therein than the accelerate-stop distance, even at speeds lower than V_1. Since the introduction of turbojet equipment, airline pilots have been indoctrinated with the idea that they cannot stop these airplanes within the specified accelerate-stop distances if an engine failure occurs at V_1 speed. This becomes of utmost concern when operating from runway length limited airports. The airlines, therefore, have trained their pilots to be "go-minded" if an engine fails near V_1.

The effective runway length required for accelerate-stop distance can be exactly equal to the runway length. No allowance need be made for the runway consumed in positioning the airplane. The distance from the end of the runway to where the airplane is positioned on the runway varies with pilot technique and taxiway arrangements. It is conceivable that some pilots position the airplane with the tail over the end of the runway. The location of the taxiway and runup pad with respect to the end of the runway and even the position of the airplane on the runup pad may result in the positioning of the airplane an appreciable distance from the starting end of the runway.

In consideration of these facts, it is proposed to require 800 feet to be added to the accelerate-stop distances determined in accordance with § 4T.115 to arrive at the minimum runway length required for takeoff of turbojet airplanes. Six hundred feet of the 800 feet are considered the minimum distance traveled during a time period of 3 seconds following recognition of engine failure. The 3 seconds are considered to be a minimum time period for a decision and reaction time on the part of airline pilots before initiating the stopping action. Four seconds are considered to be an average time period for an average pilot to recognize the precise difficulty, to decide on the appropriate corrective action, and to initiate this action. Two hundred feet of the 800 feet are considered to be the average amount of runway consumed in positioning the airplane at the starting end of the runway. The addition of the 800 feet to the accelerate-stop distance does not preclude the operator from lowering the currently established V_1 speeds and adjusting the required takeoff runway lengths accordingly.

Air carriers are currently operating in accordance with an FAA policy, which provides for increased takeoff runway lengths, and thus indirectly for increased runway lengths for an aborted takeoff, when runways are covered with standing water, wet snow, or slush. These increases are based on the deteriorating effect that these mediums have on an airplane's acceleration capability. No consideration, therefore, is being given in this notice to account for increased accelerate-stop distances due to operations under adverse runway conditions (wet snow, slush, etc.).

Landing distances. The currently required landing runway lengths for turbojet airplanes are considered adequate for dry runway operations but not for wet or slippery runway conditions. A recent regional survey indicated that most of the major airlines operating turbojet equipment apply some correction factor for landing on slippery or wet runways. By this action, the airlines indicate that the presently required landing runway lengths for turbojet operations on adverse runways are inadequate and as such tend to bring about a lowered level of safety. An FAA policy sets forth conditions for approval of turbojet operations with 200–½ landing minimums. It requires that the landing runway lengths be increased 1,000 feet or 15 percent, whichever is greater, when these low minimums are utilized. There is a need, therefore, to increase the required minimum runway lengths for turbojet airplanes for landings to account for operations on adverse runways.

The landing distance determined in accordance with § 4T.122 is based on a steady gliding approach which allows the airplane to cross the threshold at a height of 50 feet and a speed of 1.3 V_s. The landing distance is the horizontal distance from the 40-foot height to the point where the airplane comes to rest on a dry runway utilizing maximum operational braking. This landing distance, as determined during type certification tests, is then increased by dividing it by a factor of 0.6 to obtain the required minimum runway length for landing at the airport of destination. The 0.6 factor accounts for operational variations; i.e., excess threshold height and touchdown speed, variations in piloting technique, adverse runway conditions, etc.

In the realization that the performance regulations for turbine-powered transport airplanes were subject to reevaluation on the basis of experience, the Agency has been collecting operational data on landings of large turbojet airplanes, mostly in actual air carrier service. Some of these data stem from phototheodolitic measurements performed by the Agency and evaluated in Flight Standards Service Release No. 470. Additional data were derived from measurements taken in the United Kingdom and elsewhere. Further data were gained from more limited tests, including some conducted by the Agency to establish braking and friction characteristics on wet or slippery runways. On the basis of an analysis of all presently available data, it is concluded that in actual operations large turbojet airplanes require 1,300 more feet under wet runway conditions.

Since the presently required 0.6 factor is considered a necessary margin for landing operations under adverse runway conditions when operating the airplane in accordance with type certification procedures, we believe that the 1,300-foot additional distance actually being achieved in turbojet operational landings is consuming most of this margin. To restore this margin for turbojet airplanes, an equivalent of 1,200 feet should be added to the required landing runway lengths. Since for the airplanes involved in the analysis, the required runway length at higher weights was in the neighborhood of 6,500 feet, the addition of 1,200 feet is equivalent to changing the factor from 0.6 to 0.5.

In consideration of these facts, it is proposed to require that landing distances for turbojets be scheduled with a factor of 0.5 when the runways at the airport of destination are apt to be wet (visible moisture) or icy. Compliance would be determined on the basis of weather reports and forecasts at the time of dispatch. The landing runway lengths for dry runways would continue to be based on the 0.6 factor.

The increase in runway lengths found necessary on the basis of the conducted analysis of operational practices applies equally to alternate airports. In this case, however, it would not be practical, nor sufficient, to allow scheduling for either dry or wet runways. It is being proposed, therefore, to increase the required runway lengths at alternate airports by establishing a factor of 0.6 in lieu of the present 0.7. In this manner, operational safety would be increased including those instances when an airplane is dispatched on the basis of a dry runway, but the actual runway conditions at the time of landing at the airport of destination are so unfavorable that a landing at an alternate would be preferble.

To permit orderly application of the proposed rules in actual operations, it is proposed to make them effective six months after adoption of the resulting amendments.

This proposal is subject to the FAA Recodification Program announced in Draft Release 61-25 (26 F.R. 10698). The final rule, if adopted, may be in the recodified form; however, the recodification itself will not alter the substantive contents proposed herein.

These regulatory changes are proposed under the authority of sections 313(a), 601, 603, and 604 of the Federal Aviation Act of 1958 (49 U.S.C. 1354, 1421, 1423, 1424).

In consideration of the foregoing, it is proposed to amend Special Civil Air Regulations Nos. SR–422, SR–422A, and SR–422B as hereinafter set forth and to require compliance with the resulting amendments by not later than six months after adoption.

1. By amending § 40T.81(c) of Special Civil Air Regulation No. SR–422 to read as follows:

40T.81 *Airplane's certificate limitations.*

* * * * *

(c) No airplane shall be taken off at a weight which exceeds the weight at which, in accordance with the minimum distances for takeoff scheduled in the Airplane Flight Manual, compliance with subparagraphs (1) and (2) of this paragraph is shown. These distances shall correspond with the elevation of the airport, the runway to be used, the effective runway gradient, and the ambient temperature and wind component existing at the time of takeoff. (See §§ 4T.123(a)(3) and 4T.743(a).)

(1) For turbopropeller transport airplanes, the accelerate-stop distance shall not be greater than the length of the runway. For turbojet airplanes, the accelerate-stop distance plus 800 feet shall not be greater than the length of the runway.

(2) The takeoff distance shall not be greater than the length of the runway.

2. By amending § 40T.81(c) of Special Civil Air Regulation No. SR–422A to read as follows:

40T.81 *Airplane's certificate limitations.*

* * * * *

(c) No airplane shall be taken off at a weight which exceeds the weight at which, in accordance with the minimum distances for takeoff scheduled in the Airplane Flight Manual, compliance with subparagraphs (1) through (3) of this paragraph is shown. These distances shall correspond with the elevation of the airport, the runway to be used, the effective runway gradient, and the ambient temperature and wind component existing at the time of takeoff. (See §§ 4T.123(a)(3) and 4T.743(a).)

(1) For turbopropeller transport airplanes, the accelerate-stop distance shall not be greater than the length of the runway. For turbojet airplanes, the accelerate-stop distance plus 800 feet shall not be greater than the length of the runway.

(2) The takeoff distance shall not be greater than the length of the runway plus the length of the clearway if present, except that the length of the clearway shall not be greater than one-half of the length of the runway.

(3) The takeoff run shall not be greater than the length of the runway.

3. By amending § 40T.81(c)(1) of Special Civil Air Regulation No. SR–422B to read as follows:

40T.81 *Airplane's certificate limitations.*

* * * * *

(c) * * *

(1) For turbopropeller transport airplanes, the accelerate-stop distance shall not be greater than the length of the runway plus the length of the stopway if present. For turbojet airplanes, the accelerate-stop distance plus 800 feet shall not be greater than the length of the runway plus the length of the stopway if present.

4. By amending § 40T.84 of Special Civil Air Regulations Nos. SR–422, SR–422A, and SR–422B by adding a clause at the end of paragraph (b) and by adding a new paragraph (c) to read as follows:

40T.84 *Landing limitations.*

* * * * *

(b) *Alternate airport.* * * * for turbopropeller airplanes and 60 percent of the effective length of the runway for turbojet airplanes.

(c) *Wet or slippery runways.* When the appropriate weather reports and forecasts, or a combination thereof, indicate that the runways at the airport of destination may be wet (visible moisture) or icy at the estimated time of arrival, the provisions of paragraph (a) of this section shall apply to all turbojet airplanes, except that 50 percent in lieu of the 60 percent of the effective length of the runway shall be applicable.

G S Moore
Director,
Flight Standards Service.

Issued in Washington, D.C., on July 15, 1963.

FS-X3 [illegible]

Advance copy pending issuance of
change to FAR Part 121

Title 14—AERONAUTICS AND SPACE

Chapter I—Federal Aviation Agency

[Reg. Docket No. 1866; Amdt. 121-9]

PART 121—CERTIFICATION AND OPERATIONS: AIR CARRIERS AND COMMERCIAL OPERATORS OF LARGE AIRCRAFT

Landing Performance Operating Limitations for Turbojet Powered Transport Category Airplanes

The purpose of this amendment to Part 121 of the Federal Aviation Regulations is to increase for turbojet powered airplanes the required runway length for landing, at alternate airports at all times, and at destination airports whenever weather reports and forecasts indicate that the runways will be wet or slippery at the estimated time of arrival.

This amendment is based on a notice of proposed rule making (Notice 63-28) issued on July 15, 1963, and published in the FEDERAL REGISTER on July 25, 1963 (28 F.R. 7565). Notice 63-28 also proposed to increase the accelerate-stop distance for turbojet powered airplanes. This proposal is being withdrawn for the reasons set forth below.

The Agency received numerous comments, both favorable and unfavorable, addressed to both of the major proposals contained in Notice 63-28. In view of the wide divergency of the comments received, the Agency held a public hearing on June 23, 1964. As stated in the notice of public hearing (29 F.R. 5640), the hearing was held to give interested persons further opportunity to express their views, and in addition, the Agency solicited specific recommendations as to the criteria or procedures that could be used in establishing adequate accelerate-stop and landing distances for each type and model turbojet powered airplane.

The basis for the Agency's original proposal and the significant comments, both favorable and unfavorable, received by the Agency, before, at, and after, the public hearing are hereafter summarized and discussed.

Accelerate-stop distance. The Agency's proposal to add an additional margin of 800 feet to the accelerate-stop distance was based on the following:

(1) The existing accelerate-stop distance is considered to result in the absolute minimum level of safety.

(2) There are no built-in safety margins to account for normal operational variations other than 50 percent headwind and 150 percent tailwind accountability.

(3) Airline pilots cannot reproduce during normal operations the accelerate-stop distance determined during type certification.

(4) There are no arbitrary factors applied to the accelerate-stop distance to account for operational variations; i.e., pilot technique, runway surface conditions, etc.

(5) In airline operations, airplanes are operated at times with tires and brakes that do not provide maximum braking action.

(6) If an engine failure occurs at V_1 speed during airline operations, there is a time period during which the pilot decides whether to abort or continue the takeoff and also a reaction time to initiate braking.

(7) The effective runway length required for accelerate-stop distance can be exactly equal to the runway length. No allowance need be made for the runway consumed in positioning the airplane.

Based on the preceding, the Agency proposed to add 800 feet to the normal accelerate-stop distance for turbojet airplanes, 600 feet to provide a 3-second decision time to the pilot and 200 feet to account for runway used in positioning the airplane.

Synopsis of comments opposed to proposed increase in accelerate-stop distance. (1) Airport taxi aprons are normally located so as to allow airplane positioning on the runway edge. However, where airport layout precludes such positioning "effective runway length" should be redefined rather than to arbitrarily add a 200-foot increase that would penalize airports at which there is no problem.

(2) There are safety margins not recognized in the notice such as reverse thrust, low probability of engine failure at V_1 speed, and time delays imposed during type certification.

(3) There is no basis for increasing accelerate-stop distances for turbojet airplanes only, when the reciprocating engine powered airplane is statistically more likely to experience an engine failure and aborted takeoff.

(4) Type certification performance in an aborted takeoff is repeatable if the specified procedures are followed. Furthermore, a decision time is inappropriate since the pilot's decision is already made depending upon whether the airplane's actual speed is below or above V_1. Once V_1 is reached, the pilot no longer will consider aborting, and until it is reached, he will automatically abort if an engine fails.

(5) The type certification accelerate-stop distance is based on: (a) acceleration to V_1; (b) complete power loss on one engine at this exact point; (c) pilot reaction time; and (d) full braking on a dry runway. The very basis for determining accelerate-stop distance has a built-in conservatism that provides an adequate safety margin for normal operations. This is true for several reasons: In practice, if an engine fails before V_1 is reached, more distance is available for stopping; if after, the pilot's decision to takeoff has already been made.

(6) Several comments from foreign manufacturers and operators stated that even if an increase was justified for some turbojet airplanes type certificated in the United States, such an increase should not apply to those airplanes type certificated in a foreign country whose type certification process contained additional safety factors (such as additional decision time) not considered in U.S. type certification process.

Synopsis of comments in favor of proposed increase in accelerate-stop distance. Several comments that favored the proposed 800-foot increase in accelerate-stop distance agreed with the Agency based on the justification contained in the notice. Several qualified favorable comments were received that agreed that for some airplanes at some airports there could be a safety problem. These commentators favored an approach directed at the specific problem situations rather than an arbitrary 800-foot increase that would affect all turbojet operations.

Conclusion. After reviewing all of the comments received relating to the proposed increase in accelerate-stop distance, the Agency believes that it does not at this time have sufficient facts to justify the proposed increase.

The Agency agrees that the proposed 200-foot increase to account for positioning the airplane on the runway is not justified in all cases and would therefore penalize operations in which there is no problem. The Agency believes that a better approach to solve this problem where it does exist would be to redefine effective runway length so as to account for any runway lost due to positioning. However, this approach would affect the takeoff distance and takeoff run as well as the accelerate-stop distance and would therefore be outside the scope of Notice 63-28. The Agency also agrees that there are additional safety margins built into the accelerate-stop distance determined during type certification not considered in Notice 63-28. Since these additional built-in factors were listed above, they need not be repeated. Furthermore, the Agency finds that there have been no overrun aborted takeoffs experienced in air carrier operations with a turbojet powered airplane on a dry runway. Thus, if the present accelerate-stop distance is inadequate in some cases, it would appear that any in-

(As published in the Federal Register /30 F.R. 8568/ on July 7, 1965) crease should be based on runway conditions and not applied arbitrarily to all operations.

In view of the above, the Agency has decided to withdraw the proposed increase in accelerate-stop distance contained in Notice 63–28. The Agency will continue to study the adequacy of the present accelerate-stop distance requirements with particular attention to the effect of adverse runway conditions. If it finds that the present accelerate-stop distance is inadequate under certain conditions, the Agency will consider more particular regulatory action that would not arbitrarily penalize operations in which there is now no safety problem.

Landing distance limitations. The Agency's proposal to increase the required landing runway lengths for turbojet airplanes as stated in Notice 63–28 was based primarily on the following:

(1) A survey completed by the Agency indicated that some of the major airlines operating turbojet equipment already apply some correction factor for landing on slippery or wet runways.

(2) FAA policy for approval of turbojet operations with 200–½ landing minimums requires that runway lengths be increased by 1,000 feet or 15 percent, whichever is greater.

(3) In actual operations, the landing technique differs from that on which the type certification landing distance is based, i.e., in operations the airplane usually touches down at a greater distance from the runway threshold and at a higher touchdown speed.

(4) The effectiveness of the braking systems is substantially reduced on wet or icy runways.

(5) That, as a result of the factors discussed in Item 3 a substantial portion of the 40 percent runway margin that is presumably available for adverse conditions is used up in normal operations on dry runways leaving an inadequate margin for operations in adverse conditions, such as wet or slippery runways.

Based on the preceding, the Agency proposed to increase the required runway length at the destination airport by 20 percent whenever the weather reports or forecasts indicated that at the estimated time of arrival wet or slippery runways could be expected.

Synopsis of comments opposed to proposed increase in landing distance. (1) The use of actual landing data obtained on runways where there is a substantial excess runway length over that required by the regulations is not a proper basis for concluding that the type certification landing conditions cannot be met. Pilots in normal operations will frequently use as much runway as they have available, and, therefore, the fact that the actual landing involves a longer touchdown distance at a higher speed than that used during type certification is not relevant unless the landing is made on a runway where the length is critical.

(2) Additional factors that are not considered in the type certification process, such as reverse thrust, together with the presently required margin, compensate for the fact that operational landings differ from type certification determinations.

(3) The accident/incident record does not justify an increase in landing distance runway lengths since that record would not have been changed had the proposed landing requirements been effective before the accidents.

(4) The proposed increase in landing distance would cause an economic burden that would far outweigh any increase in safety that might be achieved. The burden from reducing landing weights to meet the proposed 20 percent increase in required runway length was estimated to be in excess of 18 million dollars per year for the affected airlines, on an actual load factor basis.

(5) Only a few of the airlines apply additional margins similar to those proposed in Notice 63–28 and these usually apply to specific airports and are used at the discretion of the pilot in command.

Synopsis of comments in favor of proposed increase in landing distance. Basically, the favorable comments agreed in substance with the Agency's reasons for proposing an increase in the required landing distance for wet or slippery runways. Particular attention was given to the fact that pilots did not feel that they could duplicate the type certification landing distances in normal operations. The history of overrun, underrun, missed approach, cross wind, and wind shear, and other terminal area accidents indicates that longer runways are necessary. The Air Line Pilots Association stated that while it supported the proposed increase as an interim measure it felt that an increase of 40 percent over existing runway requirements is actually needed to cover slippery runway conditions encountered in actual operations.

Discussion. The Agency has thoroughly examined all of the comments and detailed data submitted in connection with the proposed increase in landing distances for wet or slippery runways. On the basis of this review, the Agency believes that many of the persons who commented on the notice misunderstood much of the basis for the Agency's determination that additional runway length was necessary for landings on wet or slippery runways. This belief is based on the numerous comments critical of the use to which the Agency was putting the operational data evaluated in Flight Standards Service Release No. 470 and also critical of the basis set forth in the notice upon which the Agency concluded that an equivalent of 1,300 feet should be added to the required landing runway lengths. In view of this possible misunderstanding, the Agency believes that further discussion of the basis for its original proposal is warranted.

The phototheodolite data accumulated on 183 daylight turbojet landing operations of scheduled air carriers reported in Flight Standards Service Release No. 470 were used by the Agency basically to determine information concerning the airborne portion of the average operational landing. This data revealed that the mean threshold speed was $1.39V_s$ (round to $1.4V_s$ for the purpose of this preamble) (type certification $1.3V_s$), mean touchdown distance 1,514 feet (type certification 1,000 feet), and mean touchdown speed $1.3V_s$ (Type certification $1.2V_s$). The Agency realizes that, as pointed out in many of the comments, a large portion of the 183 landings studied in obtaining this data were made at airports at which there was substantial additional runway to that required to meet the present landing distance requirements. The Agency also recognizes that, to some extent, pilots will use as much runway as they have available. However, the Agency found that there was little difference in the mean values of threshold speed, touchdown distance, and touchdown speed between runways with excess length as compared with those that might be termed critical. Furthermore, the relevance of the mean values stated above is supported by the data obtained by the United Kingdom in similar studies.[1]

Touchdown distance and touchdown speed are controlling factors affecting the total landing distance whether the runway is wet or dry. However, landing on wet or slippery runways is more critical because braking effectiveness is reduced. For example, for a typical turbojet powered airplane landing at a weight of 155,000 pounds using the type certification techique (threshold speed $1.3V_s$ at 50 feet above threshold, touchdown speed $1.2V_s$ and touchdown distance 1,000 feet), the type certification distance from threshold to stop is about 3,300 feet and the present operationally required runway length is 5,500 feet. Thus a margin of about 2,200 feet is presumably available to cover variations in landing techniques and runway conditions. However, when the mean touchdown speeds ($1.3V_s$ instead of $1.2V_s$ and mean touchdown distances (1,500 feet instead of 1,000 feet) found to occur in actual operations on dry runways are considered, this margin drops to about 1,300 feet. When the effect of wet or slippery runways on braking effectiveness is considered, the Agency finds that this remaining margin completely disappears for some airplane types. Thus, the Agency concludes that the present landing distance requirements provide barely enough margin over the average type certification technique landing to account for the mean airline technique and wet or slippery runway landing conditions. When probable deviations from the mean operational landing are considered, the Agency finds that no margin remains when the runway is wet or slippery and that in fact if the runway length available was equal to the present requirements an overrun would likely occur. The Aerospace Industries Association submitted data based on type certification landing techniques on wet runways to which the effect of 50 and 100 percent reverse thrust was applied that would appear to

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[1] "Analysis of Operational Landing Statistics of Turbine-Engine Airplanes"; ICAO Paper AIR C–WP/195, May 21, 1962.

"Photographic Measurements of Landings at London Airport," ICAO Paper AIR C–WP/163, Feb. 21, 1962.

"Photographic Measurements of Landings at Prestwick Airport," ICAO Paper AIR C–WP/187, Apr. 16 and July 10, 1962.

refute the above stated conclusions. However, when the AIA data are corrected to account for average operational landing techniques, the above stated conclusions are confirmed.

It is for the above stated reasons that the Agency feels that operations with turbojet powered airplanes into airports with wet or slippery runways, that do not have any excess length over that required under the present rules, are of sufficient potential danger to warrant a requirement for additional runway under adverse conditions (or compensating reduction in weight).

While the Agency did not in Notice 63–28 base its original proposal on the accident/incident record of turbojet airplanes, many of the comments received were addressed to this record. The Agency recognizes that in each of the 10 incidents (1960–64) that involved overruns with turbojet airplanes there were so many contributing factors that no firm conclusions can be drawn therefrom. However, the Agency believes it is relevant that nine of the ten overruns occurred on wet or slippery runways. These incidents also indicate that where operational conditions into wet or slippery runways vary to any substantial degree from the average conditions, there is a strong likelihood that an overrun will occur unless the runway length is substantially in excess of that required by the present regulations. The Agency believes that the fact that there have been so few such overruns as compared to the total number of airline landings is attributable to a large degree to the fact that most of the airports into which the large turbine engine powered airplanes have been operating have runways that are substantially longer (partially due to takeoff distance requirements for long range operations) than the minimums required by the regulations for landing. For example, a typical runway length required under the present regulations for landing a fully loaded turbojet airplane is about 6,800 feet. Of the top 80 airports, based on the frequency of air carrier operations, approximately 50 have at least one runway available in excess of 7,800 feet.[2] Thus, even if the average operation into these airports was with a fully loaded airplane, there would be substantial excess runway over that required by the regulations. Most of the overruns have occurred on runways that were substantially (7 to 30 percent longer than required. This enabled the airplane to go off the end or the sides of the runway at a lower speed, thereby minimizing the potential damage. There have been no fatalities in turbojet overruns on wet runways, but one case resulted in serious injuries.

However, in the future, the number of turbojet airline operations into smaller cities with smaller (i.e., short range) airports is expected to increase, and unless the Agency takes regulatory action, it believes that the margins of safety which presently exist outside the requirements of the regulations will frequently disappear.

Conclusion. Based on the above, the Agency concludes that an increase in the runway length required for landing on a wet or slippery runway is justified. From its study of the accident/incident record and the operational data, the Agency believes that an increase of 15 percent over the runway length required by the present regulations is adequate to cover those runway conditions that may frequently be expected and also reasonable variations in landing techniques. The Agency recognizes that to require runway length increases of the magnitude that would be necessary to prevent overruns when all the possible adverse conditions and extreme operating techniques are accumulated would be to impose economic burdens that have no relationship to the increased safety obtained. The Agency believes that compliance with the normal operating rules, such as sections 91.9, 121.551, and 121.553, is the proper means of preventing such incidents. The Agency believes that the economic burdens imposed by the increase adopted by this amendment are commensurate with the additional safety achieved thereby. These economic aspects will be discussed more fully hereafter.

Alternative operational method. Many of the comments received indicated that, in view of the advanced braking systems installed on many of the newer airplanes together with reverse thrust (not considered during type certification), any arbitrary increase would impose unjustified burdens on operations with some airplanes that are fully capable of landing even on wet or slippery runways within less than a 15-percent increase in the present required runway lengths. The Agency recognizes the validity of this comment and this amendment therefore provides an alternative whereby a particular type and model airplane may be approved for operations involving wet or slippery runways into airports with less than 115 percent of the normal required runway length upon obtaining approval from the Administrator. An advisory circular is being issued with this amendment that sets forth an acceptable means of compliance whereby this approval can be obtained. Basically, this advisory circular sets out criteria that require demonstration landings on wet or slippery runways at what the Agency considers normal operating conditions and giving credit for partial reverse thrust when available. To the average landing distance indicated by such demonstrations, an additional 15 percent margin is added to cover conditions that vary somewhat from the average. If the resulting figure is less than that which otherwise would be required by this amendment, it will be approved providing that in no event will the margin imposed by the present rule be decreased.

At the public hearing, the Air Transport Association of America proposed that a 10-percent increase in required landing runway length be made applicable to only the 707–120 type airplanes. The Agency considered this proposal, but it is not being adopted because the Agency believes that a 10-percent increase is not adequate for this type (with the original brake and thrust reversing systems) and that an increase for other types is also justified. Since many airplanes have been or may be altered with respect to brake and reversing systems, this rule permits all of these factors to be taken into account under the alternate operational method.

Economic aspects. The Agency recognizes that, notwithstanding the duty resting upon air carriers to perform their services with the highest possible degree of safety, the economic burden added by any new safety requirement is relevant to the justification for that requirement.

Many of the comments received contained economic data indicating the burden that the proposed rule would place on individual operations and on overall air carrier operations. The Agency found that much of the economic data submitted was difficult to evaluate, and even more difficult to cumulate if a total operational cost was to be determined. This resulted from the fact that some calculations were based on actual loads while others were based on assumed 100 percent loads. The Agency now believes that the economic burden imposed by this rule, when effective, is commensurate with the additional safety that will be provided. The Agency further believes that there are four possible ways in which the objectives sought by this regulation may be achieved. These are—

(1) Comply with the 115-percent requirement for wet or slippery runways making any necessary payload reductions.

(2) Utilize the alternate operational method to obtain approval for operations into airports with less margin than required by (1) above.

(3) Increase the length of runways at those airports into which operations would otherwise be substantially affected by this amendment.

(4) Install improved antiskid systems and/or automatic spoilers that would make it easier to make the necessary showing under (1) or (2) above.

The Agency believes that none of the above alternatives will place an undue economic burden on those affected by this regulation for operations with the present turbine engine powered fleet. A study of landing weight penalties at a number of critical airports indicated that a 15-percent increase in required runway length would result in about one-half the total penalty associated with the 20-percent increase proposed in Notice 63–28. Furthermore, the most likely solution is a combination of the above alternatives depending upon the economic and operational feasibility of each. Thus, as airports, brake systems, and thrust reversing systems are improved, any weight penalties imposed by this rule will decrease further. Furthermore, while it is impossible to estimate accurately an annual dollar savings from prevented overshoots, the Agency believes that such savings will be an offsetting factor to any economic burden resulting from this amendment.

For future operations for such airplanes as the B–727, DC–9, and BAC 1–11, the Agency realizes that it is more difficult to estimate the effect of this regulation since these airplanes are specifically designed for operation into airports with shorter runways than those

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[2] FAA Air Traffic Activity, fiscal year 1964; Table 7, pp. 51–53.

being used by the present fleet. The Agency does have some data for the B–727 that would indicate that a showing can be made under the proposed operational method such that that airplane would not require any significant increase in runway length for wet or slippery conditions over that required by the present regulations. If a similar showing can be made with the DC–9 and BAC 1–11, this regulation would not impose any burden on operation of these aircraft. If such a showing cannot be made under the operational method for these aircraft for operations into wet or slippery runways, the 115-percent requirement must be met.

Critical airports. Much of the estimated economic burden of the proposed landing distance increase was indicated to be due to operations into six airports with critical length runways. These are Kansas City (Municipal), Newark, Dallas, Cleveland (Hopkins), Detroit (Willow Run), and Atlanta. Since the issue of the notice, several of these most critical situations have been alleviated. The ILS runway at Atlanta has now been extended to 8,800 feet. The ILS at Cleveland (Hopkins) has now been moved to the 9,000-foot runway. At Detroit (Willow Run) the longest runway is still the 7,521-foot runway, but Detroit is also served by Wayne Airport whose longest runway is 10,500 feet. At Kansas City Municipal Airport the longest runway is still the 7,000-foot runway, but the new Mid-continent Airport has a 9,000-foot runway that could presumably be used once the terminal building is constructed. At Newark the longest runway is still the 7,000-foot runway which would be adequate for all but the largest airplanes when heavily loaded which presumably could use John F. Kennedy International Airport. Accordingly, the Agency does not believe that this rule will cause a substantial economic burden even at those airports which can be termed the most critical for operation with large, heavily loaded turbojet airplanes.

Alternate airport requirements. Notice 63–28 proposed to increase the alternate airport landing distance requirements to provide a 40-percent runway margin beyond the type certification landing distance for all turbojet powered airplanes rather than the present 30-percent margin. The Agency's basis for this proposal was substantially the same as that for increasing the destination airport landing distance requirements. However, since operations into alternate airports are fairly infrequent, the Agency did not believe that it was worthwhile to propose this increase on the basis of the condition of the runway. While few comments were directly addressed to the proposed alternate airport landing distance increase, the Agency has assumed that most of the comments received were applicable alike to the alternate airport proposal. The Agency believes that, for the reasons stated above relating to destination airports and those stated in the notice, the proposed increase in the alternate airport landing distance requirement should be adopted and should apply to all turbojet landings thereat. Section 121.197 is being amended accordingly, and a paragraph (e) is being added to § 121.195 consistent with the change to § 121.197.

Low weather minimum criteria. Notice 63–28 mentioned the relevance of the FAA policy (reflected in Advisory Circular 120–4) for approval of turbojet operations with 200–½ minimums. This advisory circular permits operations with landing minimums of 200–½ at certain approved airports provided additional operational requirements are met. One of these additional requirements is that there be 15 percent or 1,000 feet (whichever is greater) additional runway over that required by the present regulation. These operations are not affected since the 15-percent increase (for turbojet powered airplanes) in runway lengths for wet or slippery runways required by this amendment is not in addition to the 15-percent required for operations into approved airports with low minimums. However, the Agency is studying the effect of the combination of wet or slippery runway conditions and low weather minimums to determine whether the required 15 percent increase is adequate for such operations.

To allow time for affected persons to prepare and issue revised runway landing weight limitations and if possible to take steps toward alleviating possible payload penalties, this amendment is to become effective six months after the date of adoption.

In consideration of the foregoing, Part 121 of the Federal Aviation Regulations is amended, effective January 15, 1966, as follows:

a. Paragraph (b) of § 121.195 is amended by striking the words "paragraph (c)" and inserting the words "paragraphs (c), (d), or (e)" in place thereof.

b. Paragraph (c) of § 121.195 is amended by striking out the first word "An" and inserting the words "A turbopropeller powered" in place thereof.

c. Section 121.195 is amended by adding the following new paragraphs (d) and (e) at the end thereof:

§ 121.195 Transport category airplanes: turbine engine powered: landing limitations: destination airports.

* * * * *

(d) Unless, based on a showing of actual operating landing techniques on wet runways, a shorter landing distance (but never less than that required by paragraph (b) of this section) has been approved for a specific type and model airplane and included in the airplane flight manual, no person may takeoff a turbojet powered airplane when the appropriate weather reports and forecasts, or a combination thereof, indicate that the runways at the destination airport may be wet or slippery at the estimated time of arrival unless the effective runway length at the destination airport is at least 115 percent of the runway length required under paragraph (b) of this section.

(e) A turbojet powered airplane that would be prohibited from being taken off because it could not meet the requirements of paragraph (b)(2) of this section may be taken off if an alternate airport is specified that meets all the requirements of paragraph (b) of this section.

§ 121.197 [Amended]

d. Section 121.197 is amended by inserting the words "for turbopropeller powered airplanes and 60 percent of the effective length of the runway for turbojet powered airplanes," immediately after the words "length of the runway".

(Secs. 313(a), 601, 603, and 604, Federal Aviation Act of 1958 (49 U.S.C. 1354, 1421, 1423, and 1424))

Issued in Washington, D.C., on June 29, 1965.

N. E. HALABY,
Administrator.

38392 3000

Federal Aviation Agency

ADVISORY CIRCULAR

AC NO: AC 91-6

GENERAL OPERATING AND FLIGHT RULES

EFFECTIVE: 1/21/65

SUBJECT: WATER, SLUSH, AND SNOW ON THE RUNWAY

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1. PURPOSE. This Circular provides background and guidelines concerning the operation of turbojet aircraft with water, slush, and/or snow on the runway.

2. BACKGROUND.

   a. Early in the operation of turbojet aircraft, it was determined that correction factors should be applied to the takeoff data in order to maintain the aircraft performance requirements as specified in the SR-422 series of the Civil Air Regulations and the Federal Aviation Regulations when water, slush, and/or snow are on the runway. The first test, using a Boeing 707 airplane, with slush depth of 6/10 inch on the runway, showed that retardation of acceleration on takeoff was of such consequence that an off-load from the maximum gross weight should be made for a critical field length.

   b. In August 1961, further slush tests were conducted at the National Aviation Facilities Experimental Center (NAFEC) by the Federal Aviation Agency/National Aeronautics and Space Administration, using the Agency's Convair 880/22M type transport. The test program was designed to obtain data regarding the retardation effects of slush and the effects of aquaplaning on the aircraft's takeoff performance, as well as aircraft control problems and damage encountered when operating in a runway slush environment.

   c. The tests at NAFEC were conducted on a slush covered section of a 10,000-foot runway at depths of 0 to 2.0 inches and at velocities of 80 to 160 knots. The retardation forces measured from the deceleration data were considerably greater than those predicted from earlier wheel and tire drag tests and theoretical studies which neglected the factors of slush spray impingement and aquaplaning. Impingement of slush against the aircraft and landing wheels contributed significantly to slush drag forces. At velocities above 120 knots, aquaplaning occurred and as a result, drag forces were reduced.

3. FAA GUIDELINES. Based on the available information, the following guidelines are basically sound:

a. Takeoffs should not be attempted when standing water, slush or wet snow greater than 1/2 inch in depth covers an appreciable part of the runway.

b. Since SR-422 series regulations are predicated on clean, dry runways, certain correction factors should be applied to the takeoff data when operating in wet snow, slush, or standing water in depths up to 1/2 inch.

c. At the present time there are no validated engineering data available on which to establish accurate correction factors; however, a considerable amount of information and experience has been accumulated and is available to operators. The following tables show examples of corrections currently being used by operators which are consistent with tests conducted by the Agency. These tables are based on approximately 1/2 inch of wet slush on the runway. The first table shows how a compensating correction is applied by increasing the required runway. For example, the required runway for a DC-8 weighing 251,000 pounds is 6,500 feet under certain takeoff conditions (wind, runway temperature, pressure altitude, etc.). The correction factor in the table for that weight is 10 percent which equals 650 feet to be added to 6500 feet. The total required runway with 1/2 inch of wet slush is now increased to 7,150 feet.

Type Aircraft	Takeoff Weight	Required Runway Increase (Approximate)
Douglas DC-8	251,000	10%
Boeing 707/100 Series	247,000	15%
Douglas DC-8	296,000	14%
Boeing 707/300 Series	296,000	15%
Convair 880/22M	150,000	15%

The following table shows how another operator applies a different correction factor by reducing the aircraft's takeoff weight. For example, the maximum allowable takeoff weight for a given (dry) runway under certain takeoff conditions (wind, runway temperature, pressure altitude, etc.) is 140,000 pounds. With

1/2 inch of wet slush on the runway, the aircraft's allowable takeoff weight must be reduced by 17,500 pounds. The new maximum allowable takeoff weight for that particular runway is now 122,500 pounds.

Type Aircraft	Takeoff Weight	Weight Reduction
Boeing 727	140,000	- 17,500
Boeing 727	152,000	- 19,800
Boeing 720	180,000	- 10,000
Boeing 720	190,000	- 11,000
Caravelle	110,000	- 11,000

Note: These are only samples and should not be used in computing takeoff data.

d. The operations manual of the air carrier and commercial operator or other appropriate documents for general aviation aircraft should include specific instructions for each type of turbojet aircraft showing the gross weight reduction and/or additional runway length required for the conditions described. These instructions should clearly outline details of the methods to be used in determining runway conditions as closely as possible to the planned departure time and this information should include the method by which the condition of the runway is determined.

for E W Walker
George S. Moore
Director
Flight Standards Service

Federal Aviation Agency

ADVISORY CIRCULAR

AC NO: AC 121-12

AIR CARRIER AND
COMMERCIAL OPERATIONS

EFFECTIVE:
8/17/67

SUBJECT: WET OR SLIPPERY RUNWAYS

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1. PURPOSE. The intent of this circular is to provide uniform guidelines in the application of the "wet runway" rule by certificate holders operating under FAR 121.

2. BACKGROUND. FAR 121.195(d), which became effective on January 15, 1966, is applicable in planning the allowable landing weight of a turbojet airplane for the destination airport when the runways are expected to be wet or slippery at the estimated time of arrival. In order to ensure uniform application of the "wet runway" rule, the following guidelines are considered necessary and appropriate.

3. FAA GUIDELINES. The following criteria are acceptable in complying with FAR 121.195(d).

   a. A flight may be dispatched on the basis of a dry runway when the following conditions are forecast for the destination airport and no other factors or conditions (including those listed in subparagraphs b., c., and d.) indicate that the landing runway may be wet or slippery at the estimated time of arrival:

      (1) Scattered showers in the area.

      (2) Intermittent drizzle of no greater than moderate intensity.

      (3) Intermittent light rain (with surface temperatures above freezing).

      (4) Light snow with surface temperatures below 28° F.

   b. Judgment must be exercised prior to dispatching or releasing a flight on the basis of a dry runway in order to ensure compliance with the spirit and intent of FAR 121.195(d). This judgment should be based on operating experience into the particular airport, considering such factors as geographic location, the period during which precipitation conditions have existed, prevailing temperature, wind, known condition of surface with respect to contamination such as soot, dust, oil, an estimate of pavement temperature based on recent temperature conditions, (etc).

c. When precipitation conditions are reported or forecast other than those cited in subparagraph a. above, and are not forecast to end in sufficient time to allow the runway to dry, the runway should be considered as being wet or slippery for purposes of complying with FAR 121.195(d). Such conditions include showers or occasional showers, heavy drizzle, continuous light rain, moderate or heavy rain, freezing rain of any intensity, and any snow intensity other than light with surface temperatures below 28°.

d. Frequently, runways remain covered with ice, snow, or slush for some period of time after the weather which caused this condition has passed. Even though this information may not appear in a weather report, it is the operator's responsibility in complying with FAR 121.551 or 121.553 to consider the probability of such runway conditions in determining whether the runway may be wet or slippery upon arrival.

4. NOTES ON APPLICABILITY OF FAR 121.195(d).

a. Section 121.195(d) does not apply to a pilot who was dispatched or released, based on a dry destination airport but who finds wet or slippery runways on arrival. However, the changed conditions should be considered in his decision to land on a particular runway.

b. In lieu of adding 15 percent to the required runway length for landing when it is anticipated the landing runway will be wet or slippery on arrival, FAR 121.195(d) permits use of a lesser additional distance based on a showing using actual operating landing techniques on wet runways.

James F. Rudolph
Director
Flight Standards Service

R 672

Technical Report

TIRE–PAVEMENT FRICTION COEFFICIENTS

April 1970

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NAVAL FACILITIES ENGINEERING COMMAND

NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

TIRE—PAVEMENT FRICTION COEFFICIENTS

Technical Report R-672

Y-F015-20-01-012

by

Hisao Tomita

ABSTRACT

An investigation consisting mainly of a literature review and a review of current research done outside NCEL was conducted to determine the methods needed to provide safe, skid-resistant surfaces on Navy and Marine Corps airfield pavements. Much of the information reported herein serves to update the information contained in NCEL Technical Report R-303. For example, new information is included on friction-measuring methods, correlation of the measuring methods, factors affecting friction coefficients, minimum requirements for skid resistance, and methods of improving the skid resistance of slippery pavements. However, some new topics which are of recent interest are also discussed in detail. These topics include hydroplaning, the mechanism of rubber friction, the friction associated with various operating modes of aircraft tires, the relationship of friction coefficients to pavement surface texture and to surface drainage of water, and the effects of pavement grooving on hydroplaning and on friction coefficients.

All the information from the investigation is summarized, and recommendations are given for research and development efforts needed to provide safe, skid-resistant surfaces for airfield pavements.

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INTRODUCTION

Background

The Navy has experienced a number of aircraft skidding incidents on airfield runways. Some of these incidents have been the direct result of low friction coefficients between aircraft tires and water- or slush-covered runways. As a result the Naval Civil Engineering Laboratory (NCEL) was requested to study the problem in fiscal years 1963 and 1964. The objective of the investigation was to develop a set of criteria from which a reliable and accurate field device could be designed and constructed to measure tire-pavement friction coefficients. A review of the aircraft skidding problem was made, and a thorough literature search was conducted on the subject of tire-pavement friction coefficients. Summarized landing-incident reports for a 2-year period were reviewed to determine if the magnitude of the friction coefficients was an important factor. The literature review resulted in a state-of-the-art study and covered the skid prevention research of companies and agencies involved in the design and construction of highway and airfield pavements and in the design of aircraft, vehicles, brakes, and tires. All results and findings from the investigation were reported by Tomita (1964). The report recommended against developing a field measuring device for the Navy then since the Federal Aviation Agency was involved in developing a similar device under contract.

More recent reports of skidding incidents on Navy and Marine Corps airfield runways have shown the need for better methods of providing skid-resistant surfaces to new as well as to old pavements.* For example, a newly constructed runway in Vietnam is closed to aircraft traffic during the monsoon season; lack of braking action was reported by pilots landing on fog-sealed, wet runways at two Navy airfields; and a tanker skidded over a rubber-deposited area and overran a runway at a Navy airfield. In FY-68 NCEL was assigned the task of investigating and developing methods of making new and existing airfield pavement surfaces resistant to the skidding of aircraft, whether the surfaces are wet or dry. This report is the preliminary step of that assignment.

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* The examples given were related to the author during his investigations.

The end results and findings from future research and development efforts are to be incorporated into appropriate Naval Facilities Engineering Command manuals and specifications for distribution to design and field personnel.

Scope

This report covers many of the important factors involved in friction coefficients as related to pavement surfaces and aircraft tires and brakes. Most of the information was derived from a comprehensive literature review. Emphasis in this report will be placed on updating the information found in Technical Report R-303 (Tomita, 1964) by presenting new information found in recent publications. Some new topics include the phenomenon of hydroplaning, which has been receiving much consideration in recent years; the mechanism of rubber friction; the relationship of pavement surface texture and surface drainage of water to friction coefficients; and the grooving of pavements to combat hydroplaning and to increase the friction coefficient. The report also includes recommendations for research and development efforts needed by the Navy to meet the objective of providing skid-resistant runway surfaces for aircraft operations.

Since the information has been gathered from various sources, different terms relating to the friction coefficient between tires and pavements have been encountered. An effort has been made in this report to reduce the number of terms as much as possible. However, it is not possible to use a single term since the phenomenon is considered under various conditions and modes of wheel rotation. In addition, measurements are taken with various devices. The basic terms used in this report are coefficient and number (100 x coefficient). Where appropriate, various adjectives are used with the basic terms to describe the phenomenon as accurately as possible.

TIRE HYDROPLANING PHENOMENON

A considerable amount of interest has been generated in recent years on the phenomenon of tire hydroplaning on wet pavement surfaces. The phenomenon is serious because the braking coefficient during hydroplaning equals that on an icy surface, or, according to some investigators, approximately 0.05. Knowledge of hydroplaning is accumulating at a rapid rate. Three types of hydroplaning are now identified:

1. *Dynamic.* The tire is lifted off the pavement surface and is completely supported by a layer of water.

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1. *Dynamic.* The tire is lifted off the pavement surface and is completely supported by a layer of water.

2. *Viscous.* This phenomenon occurs generally on a smooth, damp pavement surface which provides a very thin film of fluid not penetrated by the tire. It can occur at much lower velocities than those required for dynamic hydroplaning.

3. *Reverted rubber.* In this phenomenon the heat from the friction at the tireprint boils the water and softens the rubber. This forms a seal, which delays water expulsion, and the steam then prevents contact of the tire with the pavement surface.

All three types of hydroplaning can occur during one landing. However, only the dynamic hydroplaning, because it appears to be the most usual phenomenon observed, will be discussed in detail in the subsequent paragraphs.

Physical Description of Dynamic Hydroplaning

When enough water is present on a pavement surface to cover the protruding aggregates, the tire at some critical ground velocity can encounter the phenomenon of dynamic hydroplaning. This phenomenon can be explained by the fact that the water film must be ejected by the pressure of the rolling tire before contact can be made with the pavement surface. This process is time-dependent because of the effects of inertia and viscous forces of the water. With an increase in velocity, the time available for ejecting the water film decreases, and vertical hydrodynamic lift of the tire is initiated. This initiation is the beginning of hydroplaning. With continued increases in velocity, the area occupied by the water film increases with respect to the total contact area of the tire, and partial hydroplaning occurs. At some critical velocity the entire contact area is occupied by the water film. When this condition exists the entire load is supported by the hydrodynamic lift, and complete hydroplaning is attained. Under this condition the tire may stop rotating and plane along the wet surface. Thus the phenomenon is termed "hydroplaning" or "aquaplaning." The braking effectiveness and lateral stability of a vehicle or an aircraft are almost entirely lost when the tires are at the complete hydroplaning condition.

Horne and Dreher (1963) reported that the hydroplaning phenomenon was first noticed and experimentally demonstrated by the National Aeronautics and Space Administration (NASA) during a tire treadmill study by Harrin (1958). The treadmill study was prompted by an indication of the hydroplaning phenomenon during the landings of aircraft ranging from modern jet fighters with high tire pressures and high landing velocities to small executive planes with low tire pressures and low landing velocities. From experimental investigations involving an extensive analysis of still photographs and motion picture film and from other research efforts, Horne and Leland (1963) found the following factors present during hydroplaning:

1. *Detachment of tireprint.* Photographs taken through glass plate showed that at complete hydroplaning the tire is completely detached from the glass plate and totally supported by water.

2. *Suppression of bow wave.* Photographs revealed that the spray angle of the tire bow wave from the horizontal progressively decreases with an increase in forward velocity. The bow wave completely disappears at the higher velocities.

3. *Maximum fluid drag.* Experimental results indicated that the fluid drag reaches a maximum value at a ground velocity near the complete hydroplaning velocity. A large reduction results with further increases in ground velocity.

4. *Spin-down of tire.* Photographs and motion pictures showed that freely rolling wheels in the hydroplaning condition slow their spin or completely stop spinning on water-covered runways. There are two causes of this spin-down: First, the fluid drag can approach near zero, and of course there is no other drag because the direct tire—pavement contact is eliminated by the detachment of the tire. Second, the center of pressure of the lift force moves forward of the axle and creates a spin-down moment. This moment is apparently great enough to cause the spin-down.

5. *Loss of directional stability.* Results from tests with a jet transport on a slush-covered runway in the presence of a 9-knot direct crosswind indicated that the aircraft in the hydroplaning condition drifts in the lateral direction and yaws. These results suggest that hydroplaning can cause serious problems during takeoffs and landings in the presence of crosswinds.

6. *Loss of traction.* Test results indicated that the loss of braking traction is associated with hydroplaning. Since the tire is detached from the pavement and since water cannot develop significant shear force, it is futile to apply the brakes.

Apparently these six factors apply to both aircraft and automobile tires on wet pavement surfaces.

Hydroplaning Velocity

The velocity at which a tire experiences complete dynamic hydroplaning is of great importance. For example, knowledge of the critical velocity will permit a decision by a pilot to land on a wet runway or divert to another

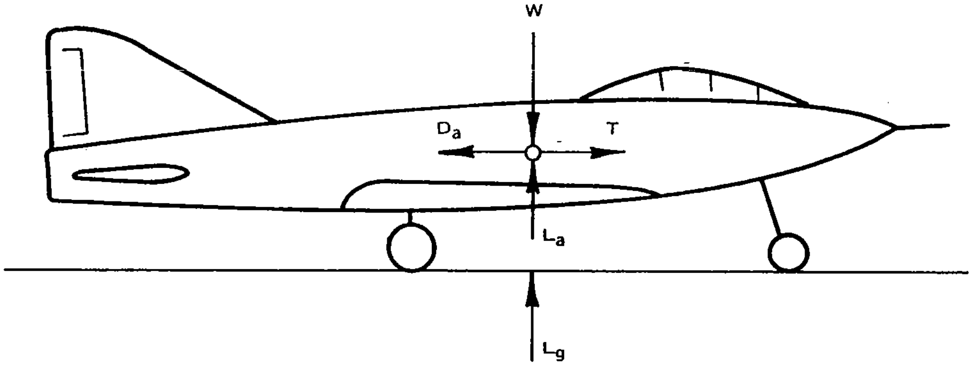

Figure 1. Forces on a landing jet aircraft under hydroplaning condition.

airfield. The dynamic hydroplaning velocity can be determined by considering the forces on an aircraft during unbraked landing rollout (Figure 1). It is assumed that the horizontal forces—residual thrust, T, and aerodynamic drag, D_a—are approximately equal and create no net moment about the nose or main wheels. In addition, no drag force is assumed to be present at the wheels. Summing the vertical forces will give

$$L_g + L_a = W^* \tag{1}$$

where L_g = sum of the vertical ground forces through all gears

L_a = aerodynamic lift

W = static weight of the aircraft

At complete hydroplaning, L_g can be considered to be the vertical component of the hydrodynamic pressure on the tires. Thus

$$L_g = \frac{1}{2} C_t \rho V^2 A_t \tag{2}$$

where C_t = lift coefficient of the tire

ρ = mass density of water

V = forward velocity

A_t = tire contact area

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* The reader is referred to the nomenclature on the foldout page at the end of the report.

From aerodynamic theory, L_a can be expressed as

$$L_a = \frac{1}{2} C_a \rho_a V^2 A_a \tag{3}$$

where C_a = lift coefficient of the aircraft

ρ_a = mass density of air

A_a = uplift area of the aircraft

Substituting Equations 2 and 3 into Equation 1 yields

$$V = V_h = \left(\frac{2W}{C_t \rho A_t + C_a \rho_a A_a} \right)^{1/2} \tag{4}$$

where V_h is the hydroplaning velocity, or the minimum velocity at which complete hydroplaning occurs. The complete hydroplaning condition remains at velocities higher than V_h. At some velocity below V_h hydroplaning begins, and in between these velocities the tires are in a state of partial hydroplaning. The velocity at which hydroplaning begins has not been clearly defined.

It is desirable that the hydroplaning velocity, V_h, in Equation 4 be as high as possible, and if it is higher than the aircraft touchdown velocity, the problem of complete hydroplaning will not be encountered during the landing rollout. However, for a given landing, most of the terms in Equation 4 remain constant and cannot effect a change in V_h. As stated by Hurt (1960), the aircraft lift coefficient, C_a, is a function of the shape of the wing and the angle of attack and its magnitude can be varied by changing the position of the flaps and other aerodynamic control surfaces. But a change in C_a will bring about an opposite change in A_t. For example, a retraction of the flaps will decrease C_a but will increase the net vertical wheel load. This in turn increases A_t, as reported by Kummer and Meyer (1962). Thus, there is no significant net change of the denominator of Equation 4.

Moore (1966) reported that hydroplaning may occur when the tire is initially rolling or locked as in braking. The hydroplaning velocity for the rolling and locked wheel is called the hydroplaning-limit-in-rolling and hydroplaning-limit-in-sliding, respectively. The hydroplaning velocity of Equation 4 corresponds to the rolling limit, which is higher than the sliding limit by as much as 100% under certain conditions. Thus, the dangerous condition of hydroplaning can be experienced continually from velocities above the rolling limit to that of the sliding limit if the wheels are locked. For example, assume that an aircraft lands at a velocity above the rolling limit and the brakes are applied shortly after touchdown. The wheels lock and control of the aircraft cannot be regained until a velocity below the sliding limit is reached. During the deceleration caused only by air drag, the aircraft might drift out of control and off the edge of the runway. It may be argued that wheel rotation at velocities below the rolling limit will be regained upon release of brakes. This argument is logical. However, Moore (1966) reported that once a tire stops rotating under hydroplaning at velocities above the sliding limit, rotation is not usually regained.

Horne and Dreher (1963) presented an equation similar to Equation 4, obtained by equating the vertical wheel load, F_v, to Equation 2, resulting in

$$V = V_h = \left(\frac{2F_v}{C_t \rho A_t}\right)^{1/2} \tag{5}$$

Based on experimental studies at NASA Langley Research Center, Horne and Dreher (1963) were able to simplify Equation 5 to

$$V_h = 9\sqrt{P_t} \tag{6}$$

in which V_h is expressed in knots and the tire inflation pressure, P_t, in psi. This simplification is based on three assumptions: First, that the average tire contact pressure, F_v/A_t, in Equation 5 is approximately the same as P_t; second, that the fluid density is approximately that of water; and third that C_t is approximately 0.7. All assumptions seem logical, but Yoder (1959) indicated that the contact pressure depends on the magnitude of P_t. For high-pressure tires, the contact pressure is actually less than P_t, since the walls are in tension. For low-pressure tires, the converse is true. No quantitative values were provided by Yoder to support these statements, but it can be seen that the V_h determined on the basis of Equation 6 can be on the unsafe side if P_t is high and the contact pressure low. However, Horne and Leland (1963) reported good correlation of V_h as determined by Equation 6 and experimental results. As shown in Figure 2, there appears to be reasonable agreement between the experimental and calculated velocities for F_v ranging from 925 pounds to 22,000 pounds and for P_t ranging from 24 psi to 150 psi.

Horne and Leland (1963) investigated the susceptibility of aircraft to hydroplaning by comparing the maximum velocities at takeoff and at landing with the V_h of many aircraft. The results, as shown in Figure 3, indicate that practically all aircraft considered are susceptible to hydroplaning during ground operations.

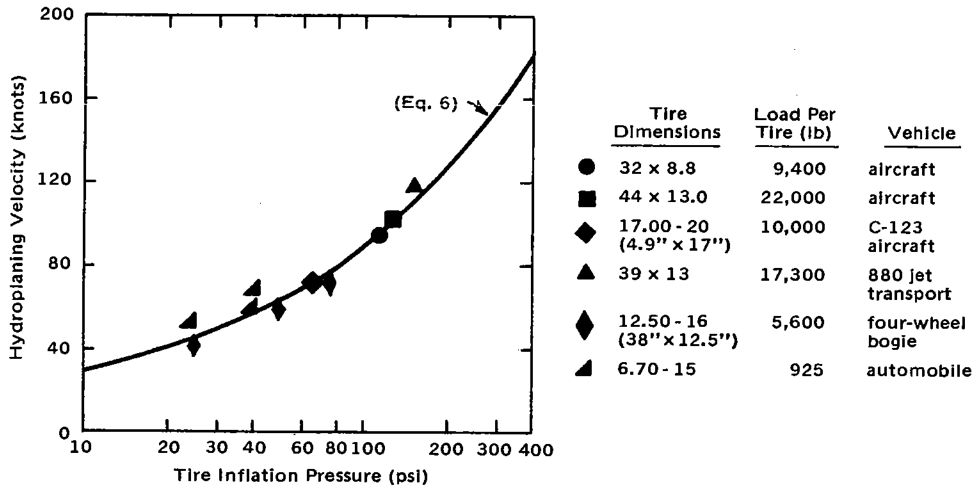

Figure 2. Experimental and calculated tire hydroplaning. (© Horne and Leland, 1963. Used by permission.)

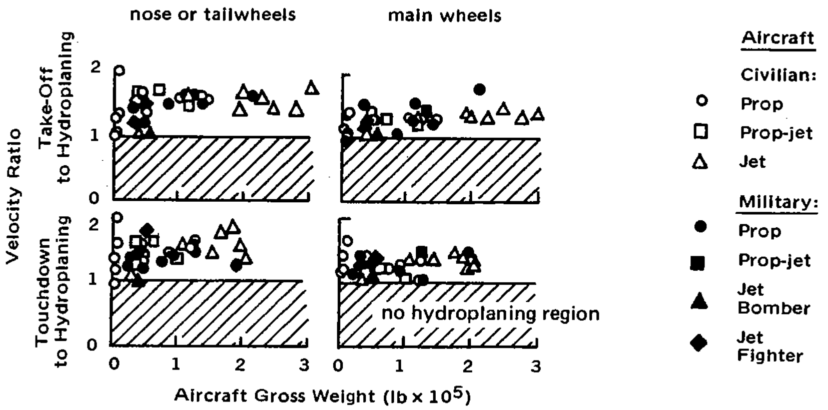

Figure 3. Susceptibility of current aircraft to hydroplaning. (© Horne and Leland, 1963. Used by permission.)

Factors Affecting Hydroplaning

The fluid depth on the pavement is assumed to be greater than the depth of the tire tread groove in Equation 4. However, the effects of some important factors contributing to the depth of water and to hydrodynamic pressure are not considered. Some of these factors affecting hydroplaning, especially those related to the pavement surface, will be discussed in this section.

Depth of Water. As previously mentioned, water on the runway surface is responsible for tire hydroplaning. The depth of water on the runway surface is dependent on many factors. These include the intensity of precipitation, the presence of transverse and longitudinal slopes, the flow coefficient, the unevenness of the pavement, resulting in puddles of water in the depressed areas, and the velocity of wind directly above the pavement surface.

The depth of water generally increases with increasing intensity of precipitation, but decreases with increasing slope of runway surface. The sloping of runway surfaces is limited because of aircraft operational requirements. A high transverse slope will cause lateral instability of aircraft during crosswind conditions, especially on wet runways with low friction coefficients. Horne and Dreher (1963) reported that a 9-knot crosswind yawed and displaced a full-scale jet transport on a slush-covered runway. The slope of the runway was not given. The Department of the Navy (1959) requires a transverse slope of 1% to 1-1/2% for Navy runways with no longitudinal slope. A minimum of 1% longitudinal slope is required if there is no transverse slope. The origin and basis of these specifications for Navy runways are not known. However, a recent series of landing incidents on a newly constructed runway in Vietnam has indicated a need for a critical review of these specifications.*

The flow coefficient (such as Manning's) for pavement surfaces can range between 0.010 and 0.020. In the theory of open channel flow this range can vary the flow by 100%. However, the actual effect of the flow coefficient on the depth of water on pavement surfaces is not simple to determine because of the difficulty in measuring the flow coefficient.

A uniform depth of surface water on a runway is not easily maintained because of pavement unevenness that results in the formation of random water puddles of various sizes. The unevenness is partly caused by lack of construction control and by differential pavement settlement under load. Resurfacing is necessary when a large number of puddles are created during normal precipitation. In recent years, however, refined electronic control systems on the newer types of paving machines have minimized the unevenness during construction to a great extent.

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* Personal communication to NCEL representative.

Proper water drainage can be offset by the effects of a forceful surface wind blowing up the pavement slope. Such a wind can hold back the draining water, resulting in depths greater than normal under the same intensity of precipitation.

The interaction of the previously discussed factors makes it difficult to predict precisely the depth of water on a runway surface during precipitation. Variation in depth can be expected from one precipitation period to the next; the changes in intensity during a given precipitation period as well as the location of the runway are factors that contribute to this variation. The variation in turn has made it difficult to define accurately, from field experiments, the depth or range of depth at which hydroplaning is induced. Horne and Dreher (1963) reported that for smooth tread tires on comparatively smooth simulated pavement surfaces, hydroplaning can occur at depths as low as 0.02 to 0.09 inch. For full-scale aircraft tires, also with smooth tread and operating on a smooth concrete surface, hydroplaning can occur at depths ranging from 0.1 to 0.4 inch. Trant (1959) indicated that water depths of 0.2 to 0.3 inch are required on a concrete runway to hydroplane a rib-tread automobile tire. Horne and Dreher (1963) reported that hydroplaning can also occur at depths slightly greater than 2 inches.

Lift Pressure. The foregoing discussion indicates that a normal precipitation or a slushy condition on a runway can create a water depth great enough to result in a vertical component of hydrodynamic pressure sufficiently large to lead to hydroplaning. At the Langley landing-loads track Horne and Dreher (1963) successfully measured the hydrodynamic pressure acting on the wet surface under a tire. Their measurements were accomplished with flush diaphragm-type pressure gages, which were placed just below the surface of the runway at the centerline of the tire path. Figure 4 shows the pressure distributions at ground velocities of 30 knots and 85 knots. At V = 30 knots the tire is in the partial hydroplaning region, and at V = 85 knots in the complete hydroplaning condition. Horne and Dreher (1963) noted three points of interest suggested by the distribution in Figure 4: (1) the hydrodynamic pressure develops ahead of the initial tire contact point; (2) negligible hydrodynamic pressure is developed at the rear of the tire print; and (3) the peak hydrodynamic pressure for the 85-knot pressure distribution is much greater than the tire inflation pressure. The first two points combine to shift the center of pressure forward with increase in velocity. This shift together with the increase in pressure causes the spin-down moment of an unbraked wheel in the complete hydroplaning condition.

Basically, two factors are involved in changing the lift pressure: tire-tread design and pavement surface textures. Tires with an adequate tread design, such as circumferential grooves, provide vents or voids for water drainage and

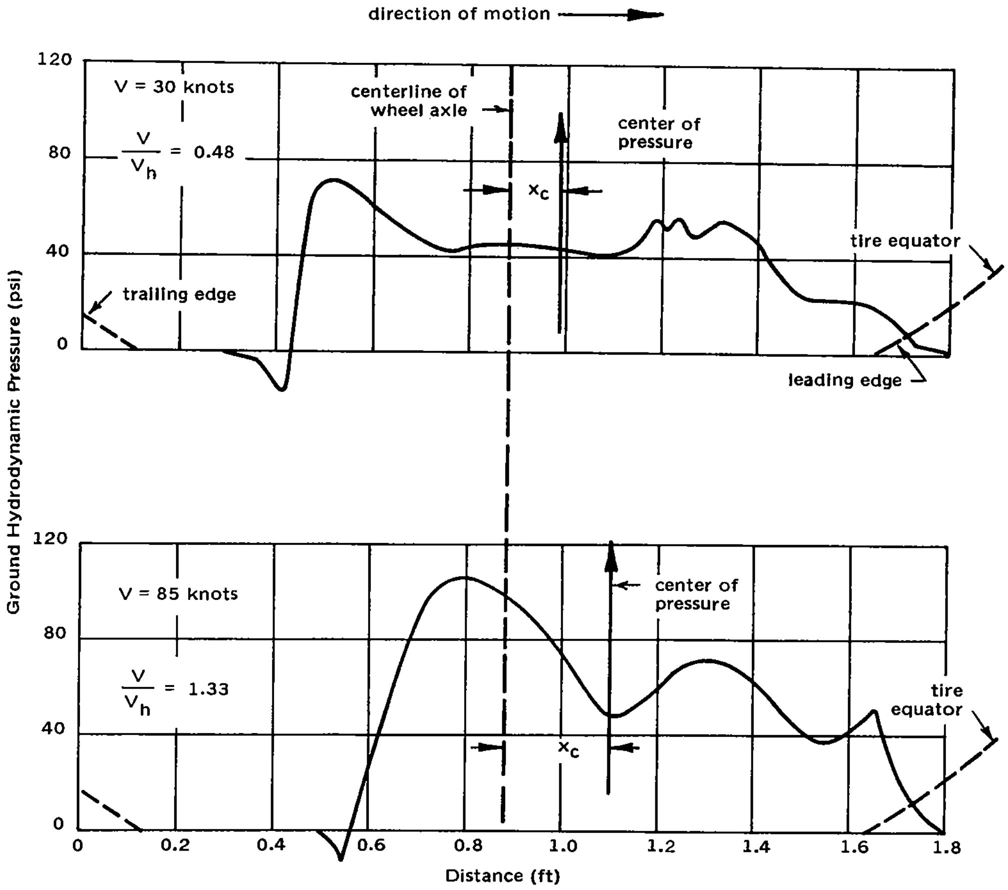


Figure 4. Tire ground pressure signatures on water-covered runway. Vertical load per tire, approximately 5,600 pounds; tire pressure, 50 psi; water depth, 0.5 inch. (© Horne and Dreher, 1963. Used by permission.)

pressure relief. Lateral edges made with molded slots and cut slits provide a wiping action over wet pavement surfaces. These tire tread features result in a higher hydroplaning velocity than do smooth tires. In addition, the grooves increase the minimum depth at which hydroplaning occurs. Horne and Dreher (1963) reported that the partial hydroplaning region is considerably less for rib-tread tires than for smooth-tread tires, even when the water depth is greater than the tire groove depth. Mainly because of shear strength requirements, the extent of treading is generally limited to circumferential grooves in high tire pressure—high speed aircraft tires used on modern jet aircraft.

By similar reasoning, a coarse or open-textured pavement surface will permit hydrodynamic pressure to be relieved more readily than a smooth or dense-graded surface. Thus, a coarse surface results in a higher hydroplaning velocity and requires a deeper minimum water depth than does a smooth surface. Moore (1966) developed a method of measuring the water drainage capabilities of various surface textures under static conditions. However, a method of measuring the water drainage or the pressure-relieving capabilities of various surface textures under hydrodynamic conditions is needed, since the water under the rolling tires of high-speed aircraft must be rapidly expelled to prevent hydroplaning. No quantitative values relating the hydrodynamic pressure and the variation in coarseness of surface textures have been uncovered during this investigation. A method of establishing such a relationship will contribute greatly to the determination of the texture required to effectively combat hydroplaning.

Transverse and longitudinal grooves have been cut in pavement surfaces on an experimental basis to reduce the possibility of hydroplaning on airfields as well as on highways. The Ministry of Aviation (1961) used transverse grooves 1/4 inch wide and 1/8 inch deep, with 1-inch pitch, on a portland cement concrete (PCC) runway. Apparently, experience has shown this groove size and pitch to be the most desirable for relieving hydrodynamic pressure.

Grooving is more recent in the United States than in Great Britain. However, Horne (1967) reported that grooving is being intensively studied in the United States by NASA, the Air Force, and the Federal Aviation Agency (FAA). The objectives of grooving are to provide a pressure-relieving mechanism, thereby reducing the opportunity for hydroplaning, and to increase the friction coefficient. Horne (1967) reported that 22 freeze—thaw cycles had no apparent effect on grooved PCC slabs. No decrease is detected in the friction coefficient with an increase in the number of freeze—thaw cycles. Horne (1967) also conducted an extensive investigation to determine the optimum groove arrangement for tire traction at the Langley landing-loads track. Preliminary results indicated that the 1/4-inch-wide, 1/4-inch-deep, 1-inch-pitch groove pattern provides the greatest increase in traction over the ungrooved PCC surface.

However, all groove arrangements improve traction. In addition, the results indicated no increase in rolling resistance nor any tire damage under yawed rolling conditions or during braking well beyond the incipient skid point.

In April 1967 the FAA grooved the instrumented runway at Washington National Airport in its entirety to improve aircraft-stopping performance when the runway is wet. A 1/8-inch-wide, 1/8-inch-deep, 1-inch-pitch transverse groove pattern was used on the 150-foot by 6,800-foot asphaltic concrete (AC) runway. The cost of the grooving operation was $0.09 per square foot. Results of pilot reports obtained by Horne (1967) indicated an improvement in stopping performance as a result of the grooving. However, the grooves have been fouled by soft rubbery material which appears to be reverted rubber from tires.

The FAA also grooved PCC and AC taxiways at Cleveland, Salt Lake City, Las Vegas, Miami, and New York City airports to determine the effects of water, snow, ice, varying ambient temperatures, and aircraft traffic loads on pavement grooves. The groove patterns varied: 1/8-inch, 1/4-inch, or 3/8-inch widths, with 1/8-inch or 1/4-inch depths, with 1-inch, 1-1/2-inch, or 2-inch pitches were used. Horne (1967) reported that the grooves in the AC taxiway at the Las Vegas Airport have started to fail through plastic flow of the asphalt. A similar trend has been observed at Miami and Salt Lake City. There are some indications that the wider grooves (1/4 inch to 3/8 inch wide and 1/4 inch deep) trap stones on runways, causing a potential housekeeping problem.

In August 1966 the Air Force grooved two PCC runways in an effort to improve landing performance during wet operations. A 1/4-inch-wide, 1/4-inch-deep, 2-inch-pitch transverse groove pattern was selected. However, only the center 37-foot width of the runway was grooved in a discontinuous pattern consisting of a series of 26-inch grooved and 26-inch ungrooved sections. Improved drainage during precipitation has been observed, and aircraft skidding incidents have been significantly reduced. Horne (1967) reported that one accident occurred on one of the grooved runways, but the aircraft was off the side of the grooved section. The Air Force plans grooving more runways.

The Air Transport Association (ATA), in the interest of aircraft safety, sponsored the grooving of selected runways at two commercial airports, Kansas City Municipal Airport and Kennedy International Airport. At Kansas City the 1/8-inch-wide, 1/4-inch-deep, 1-inch-pitch transverse grooves were sawed in May 1967. Both AC and PCC sections of a runway were grooved at a cost of approximately $0.14 per square foot. Horne (1967) reported no deterioration of the pavement sections which can be attributed to grooving after 5 months of service. Increased water drainage has been observed during precipitation. Practically no water spray from aircraft wheels has been observed during operations on the grooved runway; in contrast a considerable amount is generally observed on ungrooved runways. In addition, since grooving, fewer aircraft are now diverted to another airfield during precipitation. This factor indicates improved landing performance as well as the pilots' confidence in landing on the grooved runway.

A PCC runway at Kennedy International Airport was grooved in its entirety in August 1967 at a cost of $0.13 per square foot. The transverse grooves were 1/8 inch deep, with a 1-3/8-inch pitch, and with the width varying from 3/8 inch at the pavement surface to 5/32 inch at the bottom of the grooves. In addition to the beneficial effects of grooving found at Kansas City, Horne (1967) reported that during precipitation most aircraft use the high-speed turnoff rather than the end taxiway turnoff.

It has recently been reported in the popular press that at least six states have grooved sections of highway pavements to combat hydroplaning: California, Texas, Washington, Oregon, Minnesota, and Georgia. New York and New Jersey are considering grooving. The grooves are generally in the longitudinal direction, 1/8 inch deep and 3/4 inch apart, with the width equal to the thickness of diamond-cutting blades. Such grooving patterns have been used in California on several freeway sections that had high accident rates during wet weather prior to the grooving. On one 900-foot section of a freeway, there were 48 wet-weather accidents per year prior to grooving. In the year following the grooving only one accident occurred. In another section of a freeway 26 accidents were experienced within a year before grooving and none after. The popular press, reporting periodically on grooving, indicates that the grooves serve to offset the tendency of hydroplaning without sacrificing the riding qualities of the pavement or the handling characteristics of automobiles.

MECHANISM OF RUBBER FRICTION

Some aspects of the basic laws of friction and the theory of skidding were reviewed during the previous investigation reported by Tomita (1964). H. W. Kummer and W. E. Meyer of Pennsylvania State University have conducted a thorough investigation on the mechanism of rubber friction (1962, 1967). The following discussions on the subject are based mainly on their work.

When a rubber tire is in contact with a pavement surface, almost all the deformation is taken up by the rubber, since the modulus of deformation of the pavement, especially that of PCC, is much greater than the modulus of deformation of the rubber. Thus the behavior of rubber is important in the frictional process even though the surface characteristics of the pavement

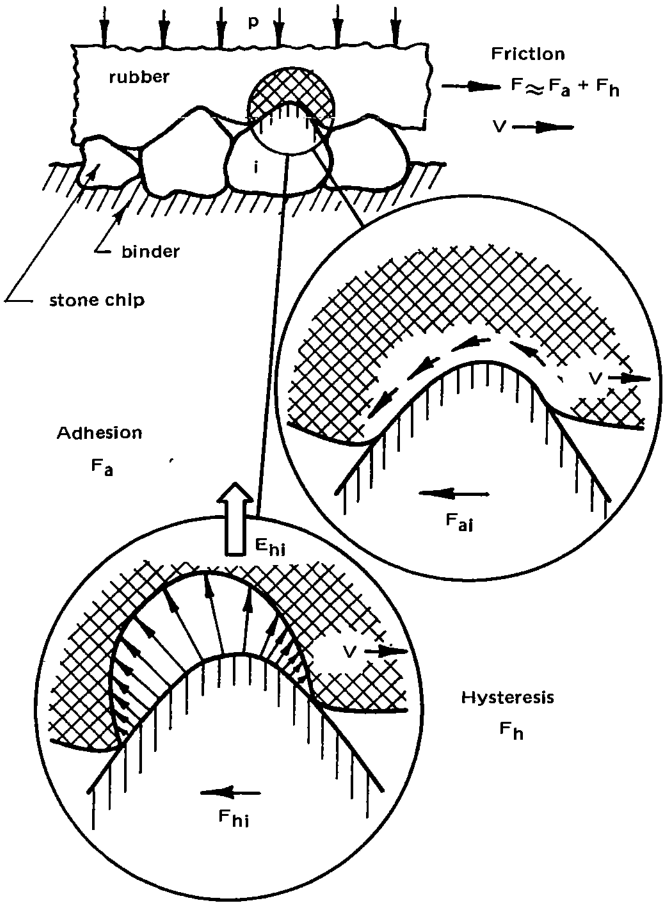


Figure 5. The two principal components of rubber friction: adhesion and hysteresis. (© Kummer and Meyer, 1967. Used by permission.)

govern to a large extent the magnitude of the available friction. The frictional process takes place on a molecular scale, with its magnitude affected by a large number of factors and combination of factors. For this reason, it is difficult to isolate and determine the controlling factors from a purely empirical or theoretical approach. Kummer and Meyer (1967) have taken a simplified theoretical approach combined with laboratory and field experiments to better understand the tire–pavement frictional process.

In the simplified theoretical approach Kummer and Meyer (1967) consider a uniformly loaded rubber block sliding over a rough-textured dry or wet pavement surface, as illustrated in Figure 5. The total friction force, F, is the sum of two major components: the adhesion force, F_a, and the hysteresis force, F_h. Thus

$$F = F_a + F_h \qquad (7)$$

The F_a for the rubber contacting a simple particle is the product of the interface shear strength, B, and actual contact area, A_i. The summation of all the individual products yields the available adhesion force:

$$F_a = B \sum_{1}^{N} A_i = BA \qquad (8)$$

where A is the total area of contact for N number of aggregate particles.

The hysteresis force, F_h, is the effect of damping or reacting elastic pressure of the rubber during the deformation around the aggregate particle. The unsymmetrical deformation of the rubber is opposed by its damping, producing the pressure distribution shown in the lower enlargement of Figure 5. Integrating the pressure over the area will provide the resulting force, the horizontal component of which is F_h. The hysteresis force can also be expressed as the summation of the unit energy, E_i, dissipated for each aggregate particle during a unit sliding length, b. That is

$$F_h = \frac{1}{b} \sum_{1}^{N} E_i = \left(\frac{1}{b}\right) E \qquad (9)$$

where E is the total energy dissipated within the rubber for N number of aggregate particles.

Substituting Equations 8 and 9 into Equation 7 yields

$$F = BA + \left(\frac{1}{b}\right) E \qquad (10)$$

The total vertical load of the rubber block is the contact pressure, p, times the gross geometric area, A_n, of the block. Dividing Equation 10 by the load yields

$$FC = FC_a + FC_h \qquad (11)$$

where $FC = F/pA_n$ = the measured friction coefficient

$FC_a = BA/pA_n$ = the adhesion coefficient

$FC_h = E/bpA_n$ = the hysteresis coefficient

or $FC_h = QD/bpA_n$ because $E = QD$ where Q is the volume of rubber involved in the deformation and D is the energy dissipated per unit volume of rubber caused by damping.

The equation for the measured friction coefficient is expressed as

$$FC = \left(\frac{A}{A_n}\right)\left(\frac{B}{p}\right) + \left(\frac{QD}{A_n}\right)\left(\frac{1}{bp}\right) \tag{12}$$

A number of implications can be drawn from Equation 12. Under the dry condition a high adhesion coefficient, **FC_a**, can be obtained by making the ratio of the actual particle—rubber contact area to the gross geometric area of the rubber block, **A/A_n**, as high as physically possible. This can be accomplished by providing a very smooth surface together with a soft rubber which will readily adapt to any remaining microscopic surface roughness. Then the ratio **A/A_n** will for all practical purposes be equal to unity. A high ratio of shear strength to vertical pressure, **B/p**, will also provide a high **FC_a**. Removing contaminants from both surfaces for a clean contact area and reducing the pressure will provide a high **B/p** ratio. Contaminants consist of any dirt, debris, or lubricant which will decrease **B** at the contact interface. Water also acts as a lubricant, and a smooth surface traps the water film, greatly weakening the **B** of the bond. Improvement in **B** is made by increasing the surface roughness to facilitate water drainage. The increase in the **FC_a** provided by the water drainage more than compensates for the decrease caused by lowering the A/A_n ratio.

Equation 12 indicates that the hysteresis coefficient, **FC_h**, can be increased by increasing the volume of the rubber involved in the deformation, **Q**, and by increasing the energy dissipated by damping, **D**. Sharp-tipped particles with a high height-to-width ratio combined with soft rubber will provide a high **Q**.

Equation 12 also indicates that both **FC_a** and **FC_h** are decreased by increasing the pressure, **p**. However, Kummer and Meyer (1967) reported that a detailed investigation has shown the **FC_h** to be practically independent of pressure applied to a rubber block. If this is true, **p** effects only the **FC_a** and in turn the **FC**. It can then be concluded from experimental results that the decreasing effect of p on the **FC** is greater than the increasing effect of the **A**.

From Equations 11 and 12 and the previous discussions, it can be seen that for a knobby, well-polished, and lubricated surface **FC** will primarily represent the **FC_h** (**$B \sim 0$** and hence **$FC_a \sim 0$**). The **FC_a** is predominant on a clean, dry, and macroscopically smooth surface (**A** is large, but **$Q \sim 0$** and **$FC_h \sim 0$**). These statements can be confirmed by results of skid tests on smooth, dense-graded and coarse, open-graded asphaltic concrete surfaces under both dry and wet conditions. Some of these results have been previously summarized by Tomita (1964).

Snowdon (1963) reported that the dynamic modulus and damping properties of rubber are functions of temperature as well as frequency. The mechanical properties of high-damping rubber are more temperature-sensitive than those of low-damping rubber, such as natural rubber. Since the friction coefficient is dependent on material properties, it will obviously be sensitive to temperature and velocity. Results of laboratory and field measurements by practically all researchers in this field have shown that on wet surfaces the friction coefficient decreases as the velocity increases. The effects of temperature on the friction coefficient have been given less attention than those of velocity.

Figure 6 illustrates the relationship between the sliding velocity, pressure, and adhesion coefficient of rubber sliding on a glasslike or a macroscopically smooth surface. The following features, noted by Kummer and Meyer (1967), help to explain the relationship between these factors:

1. On a dry, macroscopically smooth (glasslike) surface the $\mathbf{FC_a}$ increases very rapidly and peaks at the critical sliding velocity of approximately 0.1 mph.

2. The $\mathbf{FC_a}$ decreases with an increase in pressure, **p**.

3. There is a drastic reduction in the $\mathbf{FC_a}$ when the surface is wet, and there is no prominent peak in the curve. This reflects the reduction in shear strength, B, at the contact interface. The remaining $\mathbf{FC_a}$ reflects in part the hysteresis coefficient, caused by the microscopic roughness.

4. Though not illustrated in Figure 6, the shape of the curves, especially the peaks at the critical sliding velocity, is dependent on the rubber properties previously described. There is also a corresponding shift of the curves towards higher critical velocities with an increase in the temperature of the contact interface and towards lower velocities with a decrease in temperature.

Figure 7 shows the hysteresis coefficient, FC_h, for three types of tire-tread rubber sliding on an open-textured, well-lubricated surface. The natural rubber is considered a low-damping rubber, the styrene butadiene rubber a medium-damping rubber, and the butyl rubber a high-damping rubber. The following features noted by Kummer and Meyer (1967) help to explain the characteristics of the hysteresis coefficient:

1. The $\mathbf{FC_h}$ is not sensitive to a change in velocity in the range where the FC_a experiences the greatest change. A significant increase in FC_h occurs at high velocities.

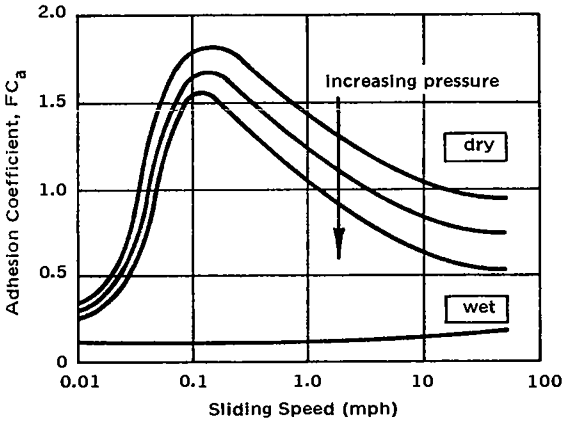


Figure 6. Typical adhesion coefficients of tire tread rubber sliding on macroscopically smooth surfaces. (© Kummer and Meyer, 1967. Used by permission.)

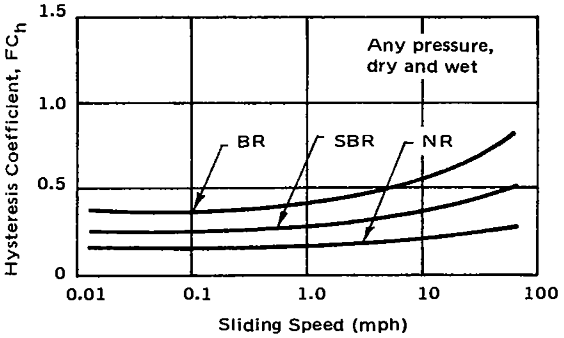


Figure 7. Typical hysteresis coefficients of tire tread rubber sliding on a pebblelike, well-lubricated surface (NR = natural rubber; SBR = styrene butadiene rubber; BR = butyl rubber). (© Kummer and Meyer, 1967. Used by permission.)

2. Though not illustrated in Figure 7, FC_h increases with an increase in the damping properties, D, of the rubber block, provided the volume of rubber deformed, Q, is not affected. The FC_h is for all practical purposes independent of pressure, p. It is not significantly affected by contamination and lubrication at the contact interface. The FC_h, like the FC_a, changes with variations in temperature. However, at any given vehicle velocity the FC_h always decreases with an increase in the temperature of the contact interface.

The preceding discussions on the effects of various factors on the FC_a and FC_h have been summarized in Table 1. Although the discussion has been for idealized conditions, namely a rubber block sliding on a smooth or rough, wet or dry surface, it should be helpful in understanding the friction characteristics between tires and pavements. The relationship can be seen if the rubber block connected to a common base or tire carcass is regarded as tread elements in contact with the pavement.

Table 1. Change of Adhesion and Hysteresis Coefficients Due to the Increase of an Individual Variable (All Other Variables Held Constant) (© Kummer and Meyer, 1967. Used by permission.)

Variable	Adhesion Coefficient	Hysteresis Coefficient
Surface characteristics:		
Roughness (micro, macro)	decreasing	increasing
Contamination	decreasing	not affected
Lubrication	decreasing or zero	slightly decreasing
Rubber characteristics:		
Elasticity	decreasing	decreasing
Damping	increasing	increasing
Operational parameters:		
Slider load	decreasing	not affected
Sliding speed:		
Range 0-10 mph	increasing or decreasing*	not affected
10-50 mph	decreasing	slightly decreasing
50-100 mph	decreasing	increasing
Temperature	increasing or decreasing**	decreasing

* At contact area temperatures above 200°F the adhesion peak may shift to a critical sliding speed of as much as 10 mph.

** Depending on sliding speed.

OPERATING MODES OF AIRCRAFT TIRES AND ASSOCIATED FRICTION

The airfield pavement surface must provide sufficient friction forces during all operating modes of aircraft tires. Various types of aircraft are operated by the Navy and Marine Corps. However, the fighter-attack aircraft with single-wheel tricycle landing gear are in the majority and appear from experience to be critical with respect to meeting skid-resistance requirements. Transport and patrol aircraft generally have lower landing velocities and reverse thrust for deceleration. Fighter-attack aircraft can be considered to have nose wheel steering for maneuvering on the ground and brakes on the main wheels only. One or two of the newest attack aircraft are equipped with an antiskid braking device, but many of the naval aircraft now in service are not. Antiskid brakes are being developed for automobiles and are expected to be introduced on a limited basis in the near future. The function and resulting effect of antiskid brakes on stopping capability have been previously discussed by Tomita (1964). Rudder and other aerodynamic surfaces also provide control for aircraft, but these are generally effective only at high velocities. Aircraft tires can roll and slip under normal operating conditions and skid under emergency conditions.

Free-Rolling Mode

The free-rolling mode of the aircraft occurs when no brakes are being applied to the rotating wheels. This occurs during taxiing, takeoff, and landing. Most of the friction forces caused by the differential movement of the tread elements at the contact interface are canceled under this mode. Therefore, the net free-rolling force transmitted by the tire is small on dry pavements and is of little interest in general. However, any significant amount of resistance to the free-rolling tires during takeoff can result in a longer takeoff distance, requiring a correspondingly longer runway length or a higher engine thrust than normal. Tabor (1959) concluded that this resistance can be kept low by modifying the geometry of the tire to give a long, narrow configuration of contact and by using a fine-textured pavement surface. This decrease must necessarily be limited since rolling resistance is directly related to hysteretic loss of the rubber, which in turn is directly related to frictional resistance. In addition, any amount of frictional resistance will add to the total resistance and aid in the deceleration when landing.

When a pavement is covered with a film of water or with slush there is a fluid-displacement drag of the free-rolling tire at velocities below hydroplaning. This fluid drag can be represented by a hydrodynamic equation similar to that for lift (Equation 3). In addition, the aircraft will be retarded by spray drag, which results from water spray impinging on the landing gears and the underside of the aircraft. Horne and Leland (1963) reported on the various aspects of the retarding force caused by water or slush on the pavement. Figure 8 shows the variation of slush drag with velocity for a single wheel. Note that the calculated results from the fluid drag equation are close to the average experimental results. Thus the retardation can be represented by the hydrodynamic drag equation. Figure 9 shows the variation of slush drag with velocity for a jet transport, for four slush depths. The results show that the drag increases and peaks at approximately 120 knots and decreases with a

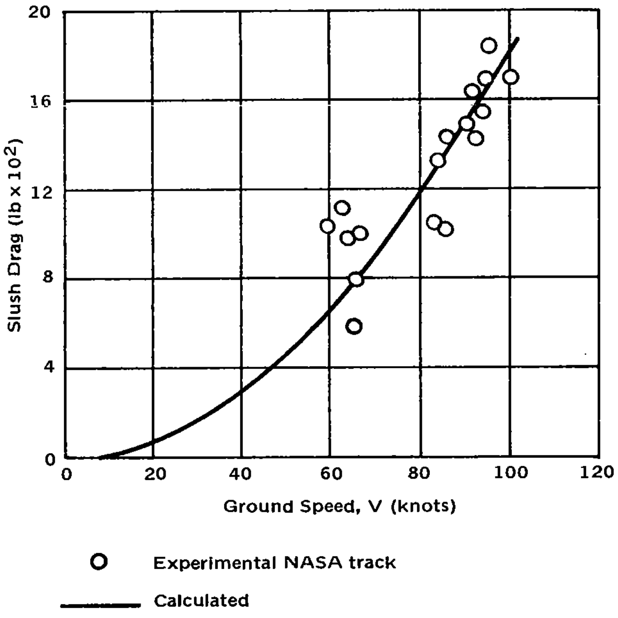


Figure 8. Slush drag on single wheel. (© Horne and Leland, 1963. Used by permission.)

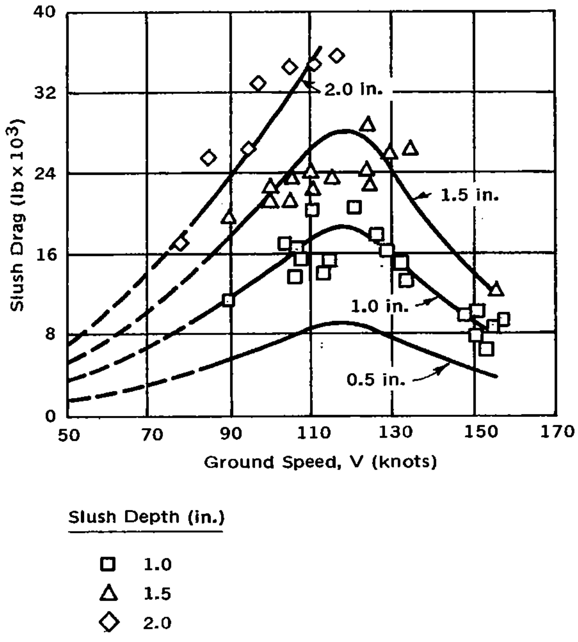


Figure 9. Slush drag on jet transport. (© Horne and Leland, 1963. Used by permission.)

further increase in velocity for three of the four slush depths. The slush drag is greater for the deeper slush at all velocities. The effect of tire pressure, P_t, on slush drag, as determined from tests at the NASA landing-loads track, is shown in Figure 10. The results show that the peak slush drag is higher for the higher P_t and that the peak for the higher P_t occurs at a higher velocity than does the peak for the lower P_t. The effect of slush depth on the takeoff performance for a jet transport is shown in Figure 11. The curves in Figure 11 correlate well with those of Figure 9. That is, the deeper slush depths cause higher drag and consequently more decrease in takeoff performance than the shallower depths.

The preceding discussion indicates that friction force is small and of little consequence for a free-rolling aircraft wheel on dry pavement. However, the presence of water film or slush on the runway can cause drag forces which can seriously tax the takeoff performance of aircraft. During a landing, however, these drag forces can be of benefit in decelerating the aircraft if the velocity is below that at which hydroplaning occurs.

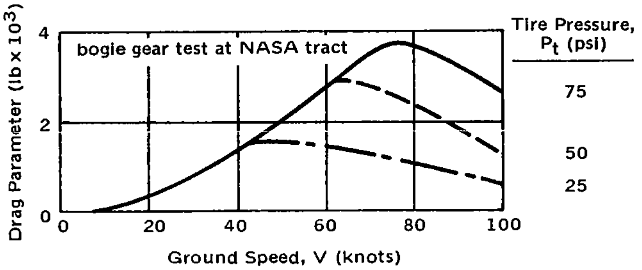


Figure 10. Effect of tire pressure on fluid drag. (© Horne and Leland, 1963. Used by permission.)

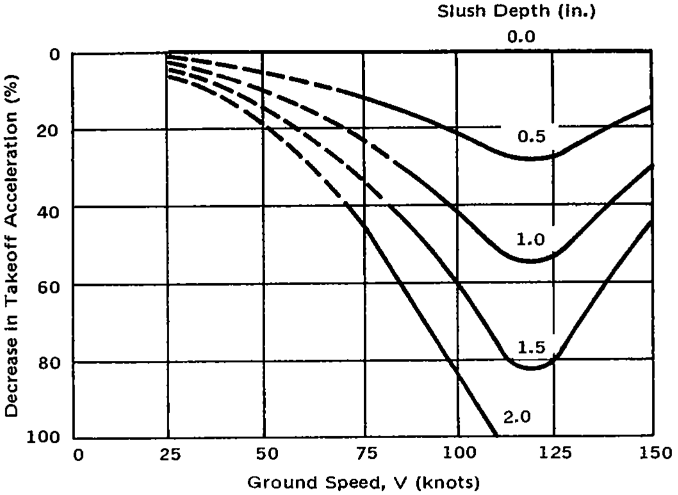


Figure 11. Loss of takeoff performance in slush. (© Horne and Leland, 1963. Used by permission.)

Slipping Mode

Tires are subject to three slipping modes: the drive slip, the brake slip, and the cornering slip. Drive slip is defined as

$$S_d = 100\left(\frac{\omega_t - \omega}{\omega}\right) \qquad (13)$$

where S_d = drive slip in percent

ω_t = angular velocity of the slipping tire or torqued wheel

ω = angular velocity of the freely rolling tire corresponding to the velocity of the vehicle

In drive slip the ω_t is greater than ω, and the drive slip becomes 100% when the wheel spins twice as fast as the rolling wheel. The drive slip mode is important for ground vehicles that apply torque to the wheels for mobility. Such is not the case for aircraft operating on an airfield. Only a very small amount of S_d might be generated during takeoff because of the angular momentum of the wheels. There is also some S_d during wheel-spinup at touchdown, but only for a short period of time. Since the S_d is of lesser importance than brake or cornering slip, it will not be considered further in this investigation.

The brake slip, S_b, may be defined as

$$S_b = 100 \left(\frac{\omega - \omega_t}{\omega} \right) \tag{14}$$

For a free-rolling wheel the S_b is zero ($\omega_t = \omega$), but for a locked wheel the brake slip is 100% ($\omega_t = 0$). At this maximum brake slip the tire is in the skidding mode. The importance of the S_b has been emphasized by many researchers in skid resistance. However, it will be discussed further here because tires of aircraft as well as ground vehicles are primarily in the brake slip mode during deceleration. For the purpose of distinguishing the results obtained under the brake slip mode from others, the term brake slip coefficient (BSC) will be used. The term is defined as

$$\text{BSC} = \frac{F_b}{F_v} \tag{15}$$

where F_b = friction force under the brake slip mode

F_v = wheel load

Figure 12 shows the changes in brake slip number (BSN) with respect to slip for a tire on dry and wet surfaces (BSN is 100x BSC). Kummer and Meyer (1967) reported that initially the BSN increases approximately in proportion to the brake slip. This occurs because the tire tread elements must slide at a velocity in proportion to the increasing S_b. As shown in Figure 6, the adhesion coefficient initially increases with sliding velocities. The critical sliding velocity of most tread elements is reached at the critical brake slip point. This peak point is sometimes referred to as the incipient skid point and the coefficient as the peak coefficient. Any further increase in braking torque cannot be balanced by the resistance at the tire—pavement interface, and the wheel locks and skids. In general, there is a rapid transition from the

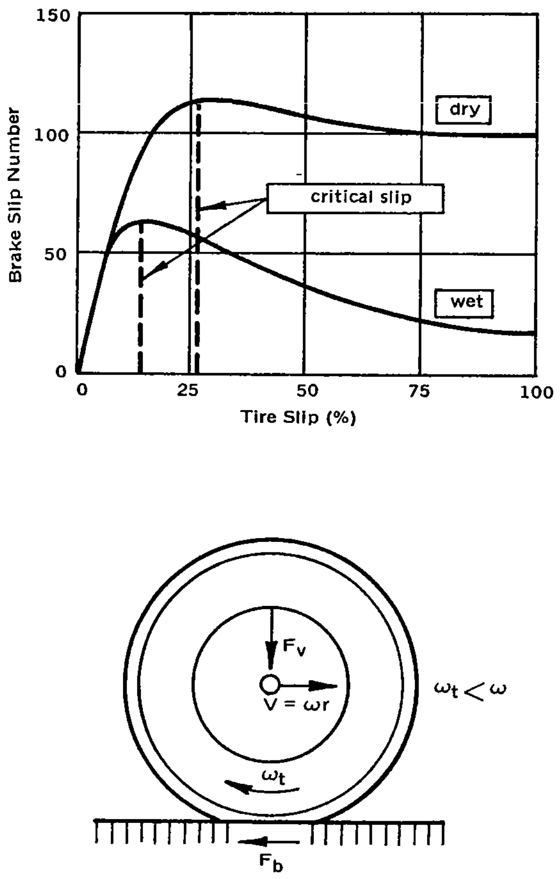


Figure 12. Frictional characteristics of tires operating in the brake slip mode. (© Kummer and Meyer, 1967. Used by permission.)

critical slip point to the full skid point or locked-wheel condition. On a dry surface a slight reduction in BSN is observed between these two points. This light decrease is caused by the increase in temperature and velocity above the critical sliding velocity. A higher rate of reduction is observed on a wet surface because of the buildup of hydrodynamic pressure as well as some of the temperature and velocity effects.

The hysteresis coefficient peaks at high velocities and contributes to the BSN. Tomita (1964) reported that some increase in friction coefficient between aircraft tires and runways is found above a certain high velocity and that this increase is attributed to the decrease in vertical load caused by aerodynamic lift. However, the hysteresis component may be the major contributor to the increase at such a high velocity.

Another important slipping mode of a tire is the cornering slip mode. The cornering slip in percent may be defined as

$$S_c = 100 \sin \alpha \qquad (16)$$

where α is the slip angle or the angle between the direction of motion and the tire plane. An aircraft turning off a runway to a taxiway especially through a high-speed turnoff requires a high cornering force to successfully accomplish the maneuver. The cornering slip coefficient (CSC) is defined as

$$\mathrm{CSC} = \frac{F_c}{F_v} \qquad (17)$$

where F_c is the cornering slip resistance or force. Figure 13 shows the characteristics of a tire in the cornering slip mode and the relationship of cornering slip number (CSN) with α (CSN is 100xCSC). Figure 13 shows that the CSN increases with slip angle up to the point of critical slip angle and then begins to decrease. As expected the peak CSN and critical slip angle are higher for a dry surface than for a wet surface. The explanation for this behavior is the same as that for the brake slip mode except that the tread elements have a sidewise component.

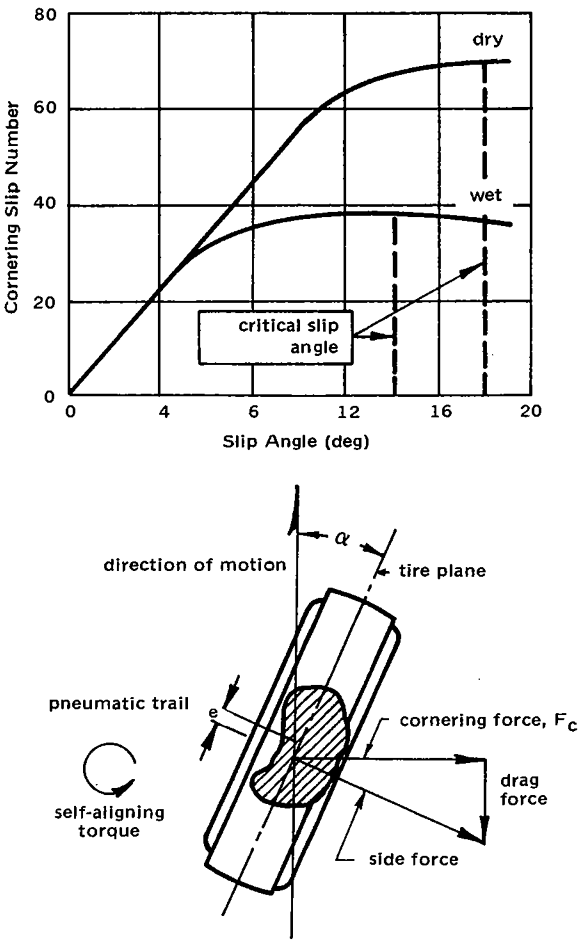


Figure 13. Frictional characteristics of tires operating in the cornering slip mode. (© Kummer and Meyer, 1967. Used by permission.)

Skidding Mode

As previously mentioned, the skidding mode of a tire occurs at the maximum slip of 100%. This mode is generally not a normal operating mode but can be considered to occur during an emergency. A driver of a vehicle sensing an oncoming accident will generally "stand" on the brakes, which causes the wheels to lock and skid on the pavement surface. This results in a stopping distance longer than that under the critical brake slip condition for the vehicle. As pointed out by Tomita (1964), the skidding of aircraft tires even for 1 second can result in excessive tire wear and sometimes in tire blowout. The skidding mode of the tire for aircraft, therefore, should be avoided as much as possible. However, the skidding mode has been used to measure and appraise the frictional characteristics of many pavements and will be considered in this investigation.

The friction coefficient under the skidding mode is designated the skid coefficient (SC) and is defined as

$$SC = \frac{F_{sk}}{F_v} \tag{18}$$

where F_{sk} is the friction force under the skidding mode, or skid resistance. Under this mode it appears that all the tread elements slide at the same velocity and in the same direction. However, the elements are subjected to different pressures. Those near the center of the contact area are subjected to higher pressures than those near the entrance or exit of the contact area. The thicker fluid film at the entrance lowers the shear strength in that area and the volume of rubber deformed at high velocities. Thus the contributions of the various tread elements to the total skid resistance differ.

Figure 14 shows the relationship of skid number (SN) with velocity for two types of rubber tires on a dry, smooth PCC surface (SN is 100xSC). As shown in Figure 14 the SN increases to a critical sliding velocity and decreases thereafter like the BSN versus slip ratio curves of Figure 12. Kummer and Meyer (1967) reported that the decrease in SN is sometimes accompanied by an audible chatter of the rubber. Under wet conditions the SN can be low at high velocities. The reasons for the low SN are the effects of high velocity, low shear resistance, low volume of deformed rubber, and high temperature.

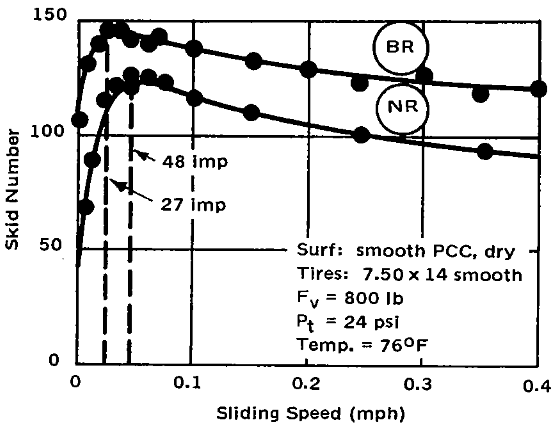


Figure 14. Frictional characteristics of natural rubber (NR) and butyl rubber (BR) tires operating in the skidding mode. (© Kummer and Meyer, 1967. Used by permission.)

FRICTION-MEASURING METHODS

Various types of equipment and methods for measuring tire-pavement friction coefficients have been discussed in the previous report by Tomita (1964). The types include the stopping-distance method, the deceleration method, the skid trailer method, the bicycle wheel apparatus of the National Crushed Stone Association, and the British pendulum tester. Brief descriptions of the devices and methods were provided; results from correlation tests were compared; and the advantages and disadvantages of the devices or methods were given. The following paragraphs describe some of the improvements made to the various methods, variations in test procedures, newly developed devices, and results of correlation tests conducted since those reported by Tomita (1964).

Stopping-Distance Method

The stopping-distance method duplicates the conditions of an automobile in a panic stop better than any other method. This method is generally considered to measure the friction coefficient under the non-steady-state sliding mode. An average **SC** is measured between two points of a skidding vehicle. However, some **BSC** is included if the distance measurement is made from the point of brake application and not from the onset of the skid. Thus a higher value than the actual **SC** can be obtained with this method.

In the stopping-distance method an automobile is properly instrumented for the continuous monitoring of velocity, distance, and time. As reported by Rizenbergs and Ward (1967) combinations of these parameters can be used in appropriate work-energy equations to obtain friction coefficients. The work-energy principle applied to a stopping automobile states that

$$F(X) = \frac{1}{2}\left(\frac{W}{g}\right)\left(V_1^2 - V_2^2\right) \qquad (19)$$

where X = skidding distance

W = static weight of the vehicle

g = gravitational acceleration

V_1 = initial velocity

V_2 = final velocity

From Coulomb's law of friction

$$F = (FC)W \qquad (20)$$

Combining Equations 19 and 20 and substituting the proper factors for velocity in mph yields the stopping-distance coefficient (SDC)

$$SDC \sim FC \sim \frac{V_1^2 - V_2^2}{30X} \qquad (21)$$

The skidding distance can be expressed in terms of average velocity and time by

$$X = \frac{1}{2}(V_1 + V_2)(t_2 - t_1) \qquad (22)$$

where t_1 = time at the start of measurement

t_2 = time at the end of measurement

Combining Equation 22 with Equations 19 and 20 and substituting the proper factors for V in mph and 32.2 ft/sec for **g** yields

$$SDC = FC = \frac{0.0456(V_1 - V_2)}{t_2 - t_1} \qquad (23)$$

After conducting an extensive investigation, Rizenbergs and Ward (1967) reported that the use of an automobile is extremely unsatisfactory for regular skid testing. Interference with traffic flow, time required for the test, hazards to testing personnel, number of technicians required (4) and high average cost ($25.00 per site per lane) are some of the reasons. Kummer and Meyer (1967) reported that the use of stopping-distance automobiles for routine skid tests appears to be on the decline. Csathy, Burnett, and Armstrong (1968) also reported on the declining use of the stopping-distance method.

All of the previously cited difficulties with the stopping-distance method are not applicable to testing airfield runway pavements. Tests will generally be conducted on runways when no aircraft traffic exists, so there will be no interference and fewer hazards to testing personnel. A runway also has a wider paved area on which the vehicle can veer during the skid, permitting possibly higher test velocities than can be used on highways. In addition the brakes of the test vehicle can be modified to provide diagonal braking, which ensures lateral stability. The modification consists of installing solenoid valves between the brake master cylinder and wheel cylinders so that brake pressure can be applied only to the left-front and right-rear wheels or to the right-front and left-rear wheels. A hard application of brakes will result in locking only one set of the diagonally opposite wheels. The other set of wheels receiving no brake torque rotates at a velocity corresponding to the velocity of the decelerating vehicle. These rotating wheels, as reported by Tomita (1964), are capable of generating side force and provide lateral stability to the vehicle.

Deceleration Method

The deceleration method is generally used in conjunction with the stopping-distance method. A decelerometer is usually mounted on the floor of the automobile, and the deceleration is measured during the skid. The friction force caused by the deceleration is given by

$$F = md = \frac{Wd}{g} \qquad (24)$$

where m = mass

d = deceleration

By use of Coulomb's law of friction, Equation 24 can be reduced to a simple function for the deceleration coefficient (DC):

$$DC = FC = \frac{d}{g} \qquad (25)$$

During braking, the front end of the automobile tilts down, and a correction factor for this tilt is generally used. The use of an improper correction factor has been cited as the major error in this method. This error associated with the "dive" has long been recognized. It has been thoroughly discussed by Tomita (1964).

Some of the disadvantages previously cited for the stopping-distance method also apply to the deceleration method. In spite of its shortcomings, the deceleration method appears to be capable of showing the variation in friction coefficient with changes in the pavement surface conditions. Table 2 shows average decelerometer readings on asphaltic concrete surfaces before and after application of a fog seal coat. The seal coat was applied at the rate of 0.1 gal/yd^2. As expected, the readings in Table 2 are lower for the wet surface than for the dry surface. They are also lower after the seal coat has been applied.

The Air Force has developed a method of determining the ground roll distances of aircraft on runways with various surface conditions (Figure 15). The method is based on decelerometer readings, called the runway condition readings (RCR), taken with the James brake decelerometer. Aircraft ground rollout distance measurements are taken on a dry PCC runway having an RCR of 23 or above. Ground roll distances corresponding to lower values of RCR are obtained by analysis. A chart such as shown in Figure 15 is developed for each type of aircraft and is included in the corresponding Air Force flight manual.

Table 2. Mean Decelerometer Readings (ft/sec^2) on Asphaltic Concrete Runways Before and After Seal Coat

Pavement Area	Before Seal Coat		After Seal Coat		Remarks
	Dry	Wet	Dry	Wet	
El Paso Airport					
Runway 8-26	25.9	23.2	22.3	19.6	initial speed, 20 mph
Taxiway J	–	–	25.9	22.7	initial speed, 20 mph
Taxiway L	–	–	24.2	–	initial speed, 20 mph
Taxiway D	26.2	–	–	–	initial speed, 20 mph
Taxiway C	–	–	24.5	23.5	initial speed, 20 mph
NAS, Point Mugu					
Runway 9-27	–	–	17.5	9.0	initial speed, 30 mph
Parallel taxiway	20.3	19.8	–	–	initial speed, 30 mph
Runway 3-21	–	–	17.5	11.5	initial speed, 30 mph

In the Air Force method, RCR are periodically taken on runways when the surfaces are dry, wet, slushy, snow covered, or icy. A manual is available on the installation, adjustments, and test procedures for the James brake decelerometer. The current readings are given to air traffic control personnel, who relay the applicable reading to the pilots. The pilots determine the required ground roll distances and decide to land or divert to other airfields for safe landings.

The Air Force method assumes that a safe landing can be made on a runway if the runway length is greater than the required ground roll distance. It does not relate the RCR to aircraft braking coefficients in usable form mainly because of the low test velocity (20 mph) of the vehicle used to obtain the RCR. Consequently, the Air Force method provides little information on a runway whose condition is slippery and on which an aircraft may exhibit lateral instability during ground operations. Test data for the Air Force method evaluated on various types of pavement surfaces are being analyzed and results are expected in the near future.

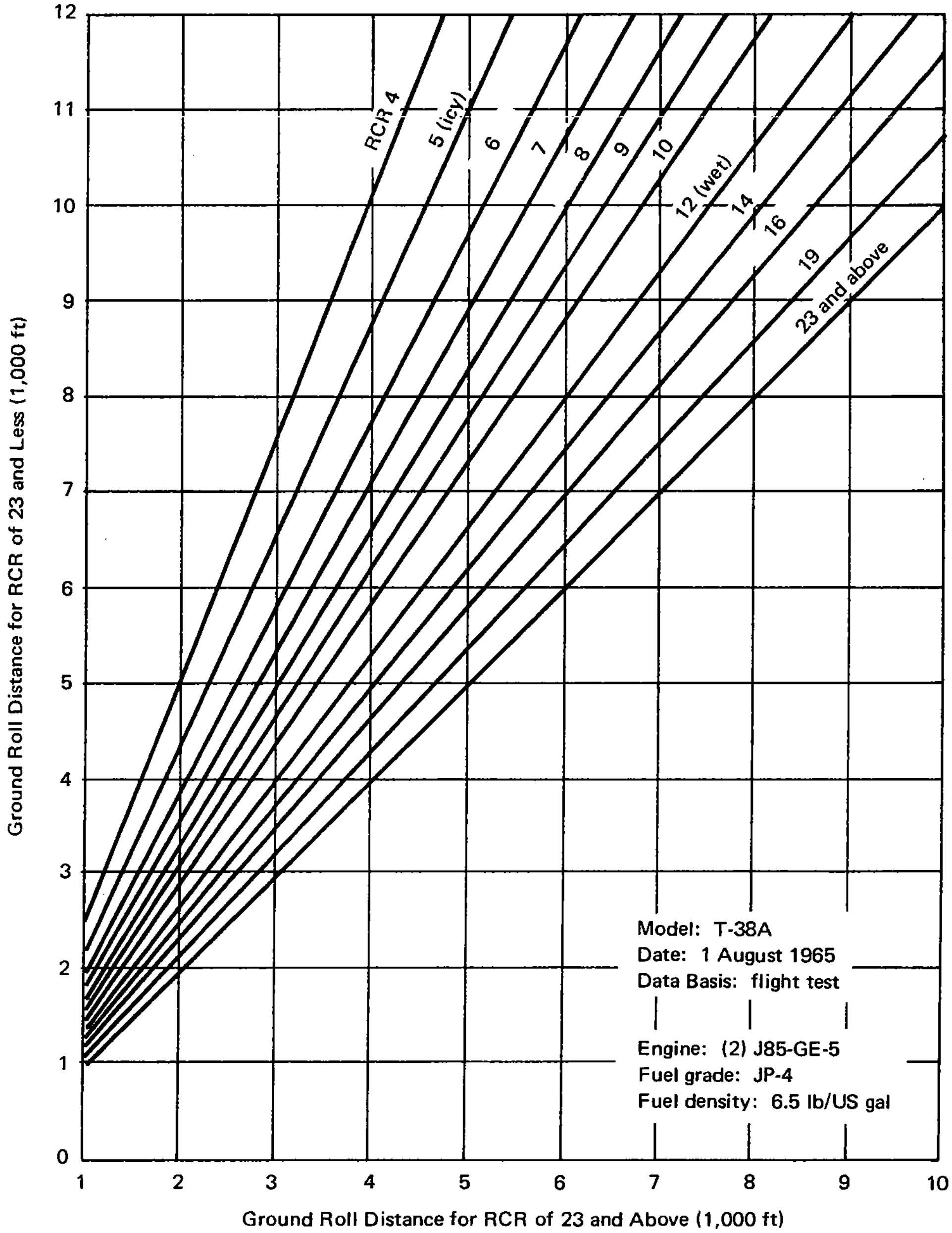


Figure 15. Effect of runway condition readings (RCR) on ground roll distance of T-38A aircraft. (From Department of the Air Force, 1967.)

Skid Trailer Method

Considerable effort has been made in recent years to improve the skid trailer method. Its quick testing capability and the fact that it does not significantly interfere with traffic may have stimulated developers to make the improvements. ASTM Committee E-17 on Skid Resistance has approved a tentative method of testing the skid resistance of pavements by using a skid trailer (ASTM E274-65T). For this trailer, the skid-resistant force at the tire-pavement contact is obtained from the measurement of wheel torque. Kummer and Meyer (1967) reported that trailers which measure the hitch forces have proven to be unsatisfactory and are no longer in use.

With the exception of the trailers used by NASA, FAA, and some European countries, all trailers measure the friction coefficient under the skidding mode. Thus, the results are presented as skid coefficients or skid numbers. Figure 16 shows the three basic variations of the trailer method currently in use. The bending moment, M, is measured with the trailer in the skidding mode shown in Figure 16a. As shown in Figure 16a

$$SC = FC = \frac{F_{sk}}{F_v} = \frac{\frac{M}{F_v} - k - \left[(h-r)\left(\frac{d}{g}\right) - (k-f)\right]\left(\frac{a}{a-f}\right)}{r + \left[(h-r)\left(\frac{d}{g}\right) - (k-f)\right]\left(\frac{a}{a-f}\right)\left(\frac{j}{a}\right)} \qquad (26)$$

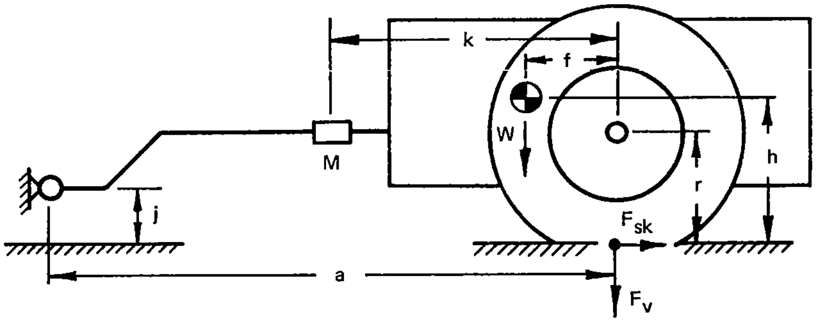
Equation 26 shows that the **SC** is not directly related to **M** and is affected by many other factors. These factors include the location of the center of gravity, deceleration or acceleration effects, and the geometric ratio j/a. In general, fluctuations in velocity are unavoidable during testing and the ratio $d/g \neq 0$. The only simplification of Equation 26 which can be made is to let **h** approach r for the trailer.

The force F_1 is measured for the type of trailer shown in Figure 16b. The **SC** for this type is given by

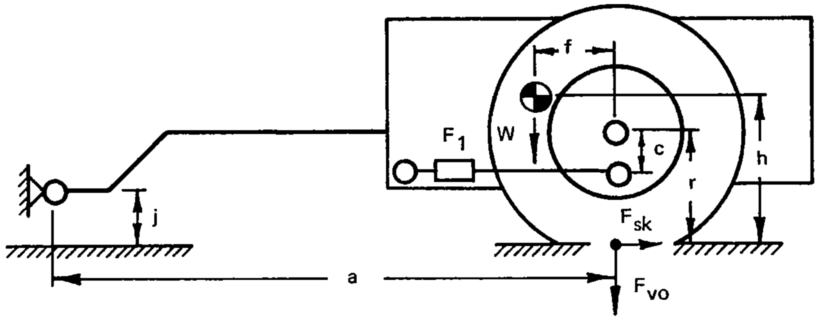
$$SC = FC = \frac{\left(\frac{c}{r}\right)\left(\frac{F_1}{F_{vo}}\right)}{1 - \left(\frac{h-j}{a-f}\right)\left(\frac{d}{g}\right) - \left(\frac{j}{a}\right)f_o} \qquad (27)$$

where $f_o = F_{sk}/F_{vo}$

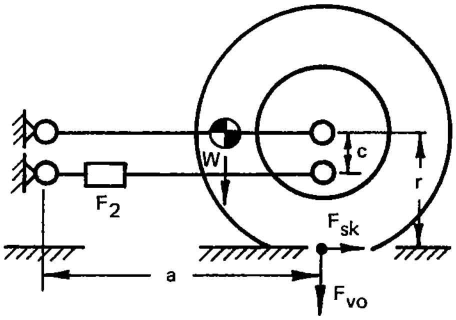
F_{vo} = static wheel load



(a) General Motors original design.



(b) Cornell Aeronautical Laboratory design.



(c) Pennsylvania State parallelogram design.

Figure 16. Skid trailer types used in the United States. (© Kummer and Meyer, 1967. Used by permission.)

As was found for the preceding type of trailer, the **SC** is not directly proportional to the measured parameter F_1 and is affected by operational and geometric factors. Since $d/g \neq 0$ for this type of trailer either, Equation 27 can be simplified when **h** approaches **j**. In addition, if the ratio $j/a = 0$, a linear relationship is obtained between F_1 and **SC**. However, this ratio cannot be achieved but only approached by making **j** small and **a** large. Thus, this type of trailer is generally constructed with a low **j** and a long **a**. The **h** should also be low and ideally the same as **j**. Again, this ideal condition can only be approached but not attained in practice.

The type of trailer shown in Figure 16c represents the most simple and compact design. The **SC**, which is proportional to F_2, can be represented by

$$SC = FC = \left(\frac{c}{r}\right)\left(\frac{F_2}{F_{vo}}\right) \tag{28}$$

Equation 28 shows that the **SC** is directly proportional to the measured force F_2, and no effects of velocity fluctuations or of geometric factors are present.

Equations 26, 27, and 28 relate the three measured parameters, the bending moment **M** and the forces F_1 and F_2, to the **SC** for the three types of trailer. In the locked-wheel mode the friction force shifts the center of the tire contact area rearward with respect to the wheel axis. The effects of this tireprint relocation is neglected in the equations.

The original trailer developed by General Motors Proving Ground (GMPG) in 1957 was of the type shown in Figure 16a, but it was later converted to the type shown in Figure 16b. Goodenow, Kolhoff, and Smithson (1968) reported on the recent improvements made on the GMPG model II trailer. The improvements include the addition of the slipping mode and the elimination of the effects of inertial torque at points between free-rolling and locked wheel modes. Also considered was correcting the effects of tireprint relocation caused by the application of the brakes.

The slipping mode of the GMPG model II trailer is monitored during the regulated lockup of one of the trailer wheels. Zero to 100% slip constitutes one cycle. The time rate of this cycle can be varied up to a maximum of 10 seconds. However, no provisions are made to hold the percent slip at a fixed value or to recycle within the range of zero to 100%. In obtaining the percent slip the direct current voltages representing the unbraked wheel velocity and the braked wheel velocity are summed in a difference amplifier. Then this quantity is divided by the direct current voltage of the unbraked wheel and is presented as output on an oscillograph.

The corrected wheel torque of a braked wheel is the total wheel torque less the inertial torque, which is the product of the polar moment of inertia and angular deceleration of the braked wheel. This correction is achieved in the following manner:

1. The total wheel torque is converted to the volts per inch-pound scale.

2. The analog voltage representing the braked wheel velocity is differentiated to obtain voltage representing the angular deceleration. A potential which represents the inverse of the polar moment of inertia is divided into the deceleration voltage, and the result is scaled to the same volts per inch-pound scale as the total wheel torque.

3. A difference amplifier is used to sum the voltages representing total wheel torque and the quantity obtained in step 2, resulting in an analog voltage for the corrected wheel torque. This analog voltage is recorded on a direct-writing oscillograph.

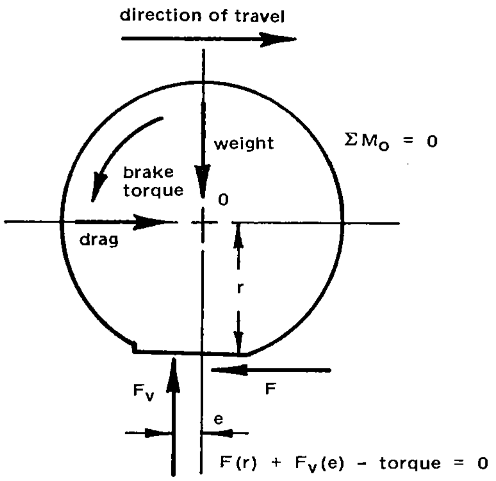


Figure 17. Free-body diagram of braked tire. (© Goodenow, Kolhoff, and Smithson, 1968. Used by permission.)

Figure 17 illustrates the relocation of the tireprint of the braked wheel. The moment created by the relocation adds to that caused by the friction force. To define the magnitude of the effects of this phenomenon, Goodenow, Kolhoff, and Smithson (1968) made static and dynamic measurements of all the components of the free-body diagram in Figure 17. Tests were performed on various types and brands of tires at room temperature and immediately after warm-up on a vehicle. A range of tire inflation pressures was also used. The test results for all tires and conditions showed a linear relationship between tireprint displacement and friction force up to an equivalent friction coefficient above 1. Thus, for any given vertical load, the effects of tireprint displacement can be expressed as a percent error, defined as

$$H = \left(\frac{T_m - F_t r}{F_t r} \right) 100 \qquad (29)$$

where H = percent error

T_m = measured torque

F_t = true friction force

r = tire radius

The test results showed that the variation in inflation pressure and temperature has considerable effect on the **H**. Pressure variation in some tires can change the percent error by a factor of 3, with the error decreasing with increasing pressure. Percent error ranged from 2% to 10% for the static tests at room temperature and from 3% to 9% for the warm tires. A similar range of percent error was obtained under dynamic tests. However, differences exist between corresponding static test results and between corresponding dynamic test results.

The skid trailer developed by the Cornell Aeronautical Laboratories is of the type shown in Figure 16b. Similar trailers are currently used by the Bureau of Public Roads, the New York State Department of Public Works, and the Portland Cement Association.

The type of trailer shown in Figure 16c, developed by Pennsylvania State University, is a single-wheel trailer that is currently being used by the Pennsylvania Department of Highways as well as by the University. The British Road Research Laboratory has developed a smaller trailer of similar design.

Domandl and Meyer (1968) reported on the addition of the brake slip mode to the Pennsylvania trailer. To control the locking of the wheel, the signal from the impulse generator is used to deenergize the brake system solenoid. Wheel lock can be prevented altogether or for a predetermined period of time. The following modes of operation are achieved:

1. A cycle timer actuates the brake at constant time intervals and releases it automatically.

2. The release signal can be used as an override. For this mode, the brake is actuated each time the wheel velocity increases above a certain point set on the release control. If the setting on the release control is varied, the wheel can be made to run-up to the free-rolling velocity or to some velocity below free-rolling velocity.

3. Manual braking and release are possible at any time. So that the testing capability in the skidding mode is retained, provisions are made to bypass the brake release. This permits locked-wheel tests in accordance with ASTM E274-65T.

Figure 18 shows two reproduced oscillograms illustrating the brake slip and skidding modes of the Pennsylvania trailer. The behavior of the angular wheel velocity, ω, velocity of the vehicle, V, and friction force, F, during the braking procedure is indicated by numbers 1 through 5 in the lower oscillogram and 1, 2, 4, and 5 in the upper oscillogram. At point 1 the brakes are applied and ω begins to decrease and F to increase. The critical slip point is reached at point 2, where F is maximum. At point 3 on the lower oscillogram the skidding mode begins with $\omega = 0$ and continues until point 4. Under the locked-wheel condition, F is lower than the F at critical slip. Brake release begins at point 4, and spin-up to free rolling occurs at point 5. Between these points, F again passes through the critical slip point before decreasing to zero. The lack of point 3 in the upper oscillogram indicates that the skidding mode was not reached by the wheel.

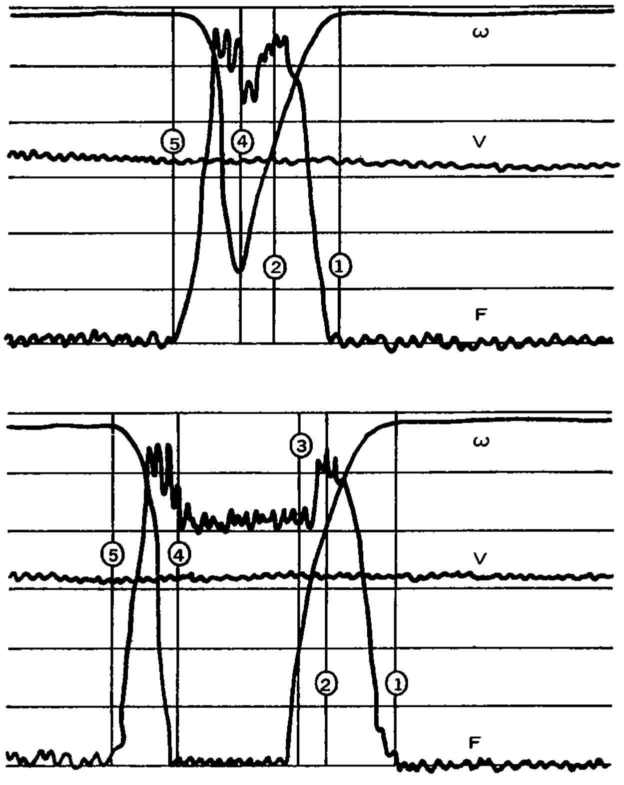


Figure 18. Replicas of typical oscillograms of brake slip and skidding modes of the Pennsylvania trailer. Numbers are explained in text. (© Domandl and Meyer, 1968. Used by permission.)

Portable Testers

Two small portable skid testers were previously described by Tomita (1964): the bicycle-wheel apparatus of the National Crushed Stone Association and the British pendulum tester. No basic changes have been made on these testers since then. The British tester has gained some popularity recently in the United States, mainly because it is comparatively small, inexpensive, and accurate. The tester basically works on the principle that the energy lost by the pendulum during the swing is equal to the work done in overcoming the friction between the slider and the surface. A tentative method for testing and calibrating the tester is found in ASTM E303-66T. The tester may be used for field as well as for laboratory testing. It is especially suitable for laboratory testing because it requires only a small test area (3 by 5 inches).

Pennsylvania State University developed the Pennsylvania State drag tester as a supplement to the Pennsylvania State trailer. It consists of a small two-wheel cart which drags the edge of a small rubber specimen over the pavement. As the tester is "walked" along the pavement, the drag force in the skidding mode is measured by a hydraulic load cell and is displayed on a dial gage as a multiple of the friction coefficient. The operator has little difficulty in reading the dial because of the careful damping of the system. The tester is small and is simply constructed. It requires no set-up time and is suitable for spot-checking the skid resistance of pavement surfaces. The commercial version of the tester is called the Keystone Mark IV Resistance Tester. Kummer and Meyer (1967) reported that it is presently undergoing field trials by seven state highway departments.

Walsh (1966) reported on the development of the New York Thruway skid test cart. It works on the principle of twin parallelograms suspended on friction-free bearings and mounted on a wheeled chassis. A skid fitted with a section of the tire tread and attached to a pick-up device slides on the pavement surface. For testing on wet pavement, a watering system wets the pavement surface ahead of the tread. Two jets are provided for laying lines of red dye on the pavement. One jet is fixed on the cart, the other on a movable arm. As the friction coefficient increases, the arm moves away from the stationary jet, increasing the distance between the dye lines. The reverse is true with a decrease in the friction coefficient. A calibrated scale is provided to convert the distance between the dye lines to friction coefficients.

Table 3 lists the principal specifications of the three portable testers. All three are commercially available from the distributors shown. Since instrument constants, variations in sliding length, and adjustments by operators are involved in skid measurements, the resulting data are not the same. Thus, as indicated in Table 3, the number from the scale of the pendulum tester is referred to as the British pendulum number (BPN) and from the scale of the New York drag tester as the drag test number (DTN). The skid test cart results are in friction coefficients.

Table 3. Specifications of Commercially Available Portable Pavement Friction Testers (© Kummer and Meyer, 1967. Used by permission.)

Specification	Pendulum Tester	Drag Tester	Skid Test Cart
Principle	energy balance	force measured	force measured
Mechanism	mechanical	hydraulic	mechanical
Slider form	inclined shoe	inclined shoe	curved segment
Rubber*	natural†	natural or ASTM E-249	ASTM E-249
Contact width (in.)	3	3	1-1/2
Length‡ (in.)	1/8	1/8	3/4
Area‡ (sq in.)	0.37	0.37	1
Slider load (lb)	5.9	6.0	20-25
Contact pressure‡ (psi)	16	16.2	22.5
Test weight (lb)	27	20	110
Transport weight (lb)	27	20	40
Sliding speed (mph)	6-7	3-4	3-4
Data reported as	BPN	DTN	FC
Dimensions (in.)	26 x 18 x 26	30 x 10 x 22	36 x 14 x 14
Distributor	Soiltest§	Die-A-Matic¶	Test Lab§
List price ($)	795.00	550.00	1,200.00

*Furnished by distributor.

†ASTM Method of Test E303 for use of the pendulum tester prescribes for the slider rubber the compound specified in ASTM Standard E-249 for the standard pavement test tire.

‡Typical conditions; actual values depend on state of slider wear.

§Chicago, Ill.

¶York, Pa.

CORRELATION STUDIES

Efforts made by various organizations to correlate the results of skid measurements obtained with various devices were reported by Tomita (1964). One of these earlier correlation studies was associated with the First International Skid Prevention Conference, held in August 1958. Recently, similar studies have been given increased emphasis, resulting in extensive programs at Tappahannock, Virginia, during the summer of 1962; at Dunnellon Airport, Florida, in October-November 1967; and at NASA's Wallops Station, Virginia, in the spring of 1968.

Correlation Between Friction-Measuring Devices

Dillard and Mahone (1963) reported on the correlation study at Tappahannock, Virginia. The objectives of the primary experiment were as follows:

1. To determine the relationship between devices within the three groups tested (trailers, stopping-distance cars, and portable testers).

2. To determine the relationship between the three groups of devices.

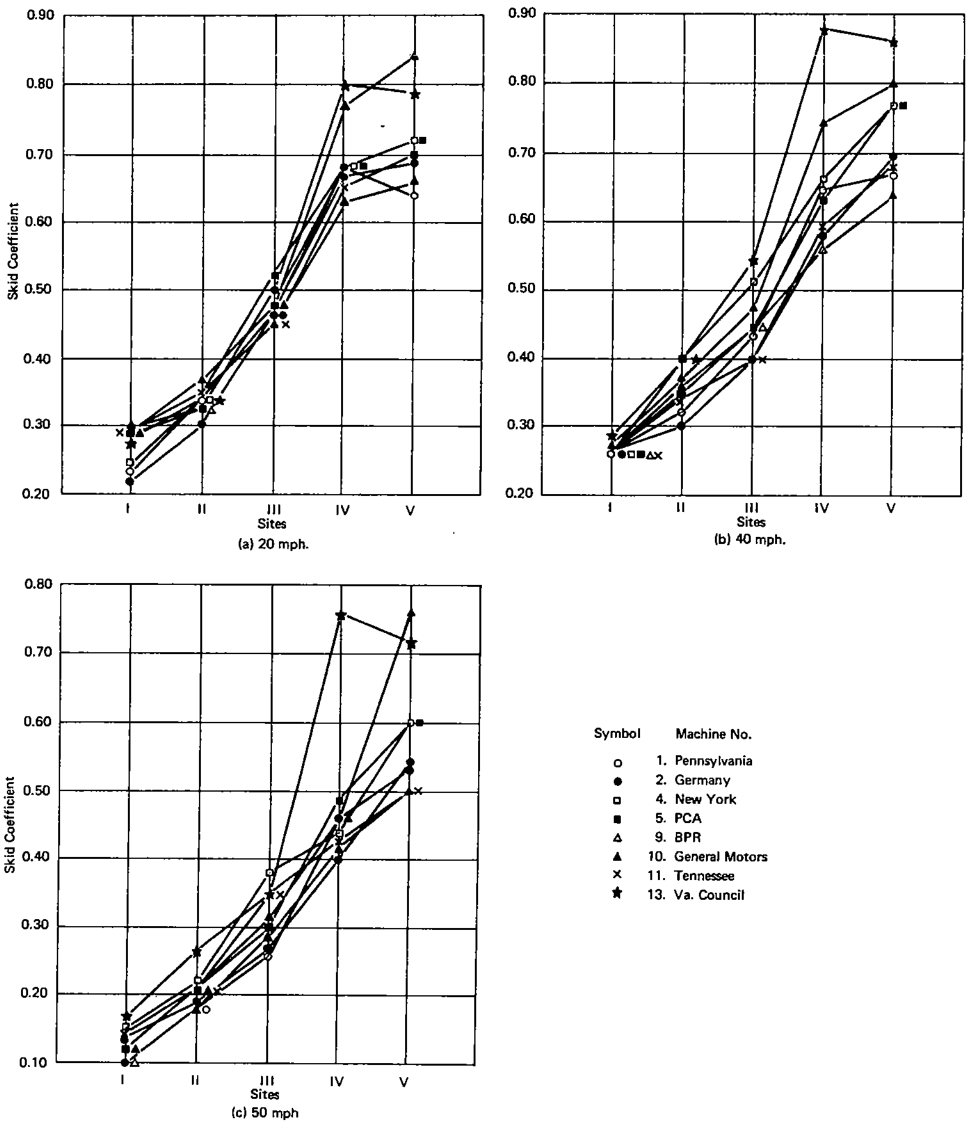
3. To determine the factors causing any discrepancies in measurements taken with devices of similar design.

4. To provide an opportunity for discussion between developers of friction-measuring devices.

In addition to the primary experiments, secondary experiments were conducted at Tappahannock. These experiments were devoted to studying the effect of water film thickness, comparing the self-watering systems of various trailers, investigating the effect of vertical load on friction coefficients, and studying the variations associated with the British pendulum tester. The primary experiments are discussed in detail, and findings from the secondary experiments are recorded, in the following paragraphs.

A total of eight skid trailers, four stopping-distance automobiles, and three types of portable testers were included in the program. The portable testers included the Pennsylvania State drag tester, the bicycle wheel appartus of the National Crushed Stone Association, and ten British pendulum testers.

The standard ASTM E-17 tire for pavement tests (ASTM E240-66) was used wherever possible. Since standard tires of the proper size were not available for some of the trailers and cars, tires were purchased with the same


(a) 20 mph.

(b) 40 mph.

(c) 50 mph

Figure 19. Summaries of trailer data. (© Dillard and Mahone, 1963. Used by permission.)

rubber compound used in the ASTM E-17 tires. The same compound was used in the sliders of five of the ten British pendulum testers, British natural rubber sliders being used in the other five testers.

Five test sites were selected on a flight strip at Tappahannock. Site I was sprayed with yellow traffic paint and polished with a steel bristle power broom. Site II was a relatively rough textured asphaltic surface sprayed with an asphalt emulsion. Site III had a fine slurry seal made with the same emulsion as Site II mixed with 6 to 8 lb/gal of fine sand. Site IV was a fine-textured sand mix similar to the one used by the Virginia Department of Highways. Site V was a section of the existing strip which had a siliceous sand-gravel surface in good condition.

The skid coefficients for the trailers on all five sites at 20 mph, 40 mph, and 50 mph are shown in Figure 19. Each data point represents an average of four measurements. All trailers show the same general trend of skid coefficient with respect to the test sites. However, there is some spread at each test site for every test velocity. The spread is greatest in Sites IV and V, with trailer numbers 10 and 13 providing appreciably higher skid coefficients than others.

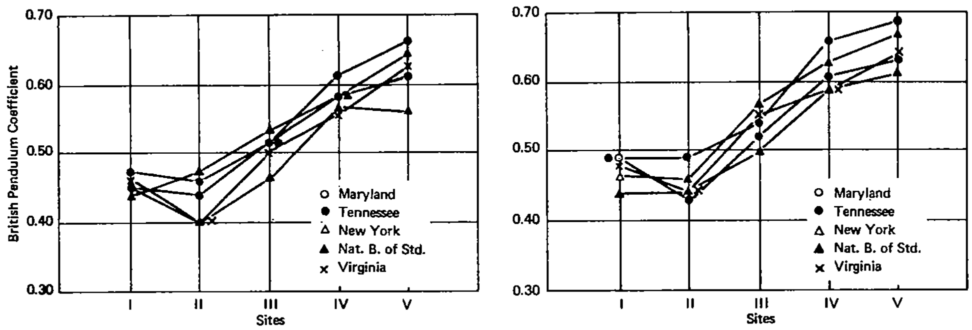
Three types of stopping-distance measurements were made: (1) the "chalk-to-gun" method, (2) the stopmeter connected to a fifth wheel (both previously described by Tomita, 1964), and (3) the observed stopping distance, which is the distance from the beginning of the skid mark to the back wheels of the stopped vehicle. An observer is necessary to note the beginning of the skid for the last measurement.

Table 4 shows the stopping-distance coefficients obtained from the three types of measurements for 20 mph, 30 mph, and 40 mph. The stopping-distance coefficients obtained with the stopmeter are lower than those for the other two methods. However, the results from the chalk-to-gun and observed stopping distance measurements agree closely. Both the differences and agreements in the results can be easily explained. A fast-responding micro-switch activated the stopmeter shortly after braking but before the wheels locked. Thus the stopmeter included the locked-wheel distance plus some distance traveled during wheel retardation. In effect, the stopmeter measured the total distance covered from the time of brake application to the point where the vehicle came to rest. On the other hand, the observed stopping distance was measured between the wheel-lock point and the vehicle resting point. Apparently the delay in the chalk gun upon braking marked the pavement near the point of wheel lock. Therefore, close agreement between the results obtained from these last two methods is to be expected.

Since the test velocity is constant for the British pendulum testers, the slide lengths were varied in the investigation. These were 4.6 inches, 4.8 inches, and 5.0 inches. Prior to any testing, the instrument constants of the British pendulum testers were determined. This involved measuring the pendulum weights, the moment of the bearing housing, the center of gravity,

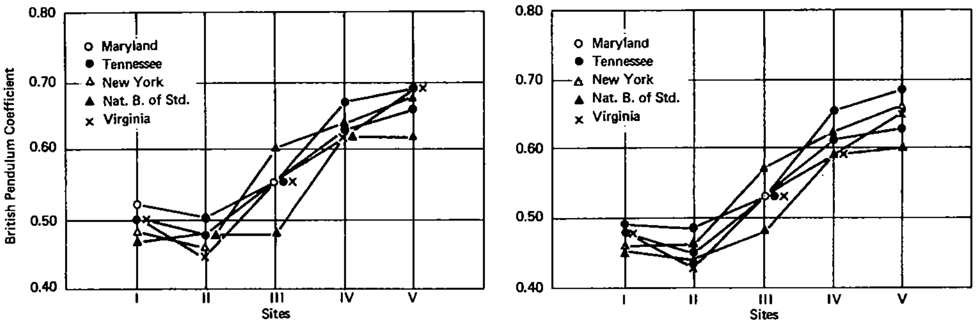
Table 4. Comparison of Stopping-Distance Data Obtained by Three Methods, Indiana Skid Test Car (© Dillard and Mahone, 1963. Used by permission.)

Type of Speed Measurement	Stopping Distance Coefficient														
	Site I			Site II			Site III			Site IV			Site V		
	20	30	40	20	30	40	20	30	40	20	30	40	20	30	40
Chalk-to-gun	0.32	0.28	0.22	0.44	0.36	0.30	0.54	0.48	0.39	0.78	0.68	0.61	0.87	0.80	0.71
Observed	0.31	0.29	0.21	0.44	0.38	0.32	0.54	0.46	0.38	0.75	0.68	0.63	0.75	0.92	0.75
Stopmeter	0.28	0.26	0.20	0.35	0.31	0.28	0.44	0.42	0.36	0.58	0.57	0.54	0.62	0.65	0.60



(a) 4.6-in. slide length.

(b) 4.8-in. slide length.



(c) 5.0-in. slide length.

(d) Average of 4.6-, 4.8-, and 5.0-in. slide lengths for each machine across all sites.

Figure 20. Mean BPC of testers using British rubber. (© Dillard and Mahone, 1963. Used by permission.)

the distance between the center of oscillation and center of gravity, and the slider load. The deviation of each instrument constant from the average instrument constant was used as a correction factor for the British pendulum coefficient (BPC).

Figure 20 shows the BPC for the five testers using the British rubber. Figure 20d is the average of the three slide lengths across all sites. The five testers do not maintain an identical relationship across all sites and slide lengths. A statistical analysis was conducted based on the least significant difference of the average for each tester on all sites. The purpose was to determine if the differences between the testers were great enough to be of consequence. There are 10 possible comparisons of the results between the five testers. The results showed that there is no significant difference in 3 of the 10 comparisons of the measured BPC, and this improved to 7 out of the 10 comparisons of the corrected BPC. The differences for the remaining comparisons are considered statistically significant. However, this does not indicate that the differences are significant from the practical standpoint. Results from similar tests and analyses for American rubber sliders showed that, based on both the average and corrected BPC, there is no significant difference in 5 out of the 10 comparisons. The lack of improvement in correlation by application of the correction factor can be explained by the low maximum difference in the average BPC. In addition, the measured averages and the corrected averages are not too different because of the degree of agreement in the correction factors.

Table 5 shows the mean values of all the British pendulum testers using British and American rubber for all three slide lengths, together with the mean values for the National Crushed Stone Association bicycle wheel apparatus and those for the Pennsylvania State drag tester. A comparison of the results of the portable testers leads to the following conclusions:

1. Good agreement exists between the results of the bicycle wheel apparatus and the drag tester on all surfaces except that of Site III.

2. The British pendulum testers using the American rubber sliders have better agreement with the other two types of portable testers than those using the British rubber sliders.

3. More realistic values are given by the bicycle apparatus and the drag tester than either group of the British testers.

4. The five testers using British rubber sliders give lower readings than the five using American rubber sliders. However, the difference is not entirely caused by the rubber, since the correction factor did not consider the relationship between the two types of rubber.

Table 5. Mean Friction Values Measured by Portable Testers
(© Dillard and Mahone, 1963. Used by permission.)

Site	British Rubber	American Rubber	Drag Tester	Bicycle Wheel*
4.6-In. Slide Length				
I	0.45	0.46	–	–
II	0.43	0.49	–	–
III	0.50	0.59	–	–
IV	0.58	0.64	–	–
V	0.62	0.71	–	–
4.8-In. Slide Length				
I	0.48	0.47	–	–
II	0.45	0.50	–	–
III	0.54	0.62	–	–
IV	0.62	0.65	–	–
V	0.65	0.74	–	–
5.0-In. Slide Length				
I	0.49	0.50	0.38	33 deg = 0.40
II	0.47	0.53	0.50	29 deg = 0.52
III	0.55	0.65	0.61	20 deg = 0.79
IV	0.64	0.67	0.73	22 deg = 0.73
V	0.67	0.78	0.75	21 deg = 0.76

* The National Crushed Stone Association bicycle wheel gives readings in degrees. For the purpose of comparing values in this study an arbitrary relationship of 1 deg = 0.03 from 20 to 33 deg has been employed.

Figure 21 shows the averages of all the various types of devices used in the investigation. The values for the trailers and stopping-distance cars are for 40 mph. There is a similarity in the shape of the curves for the trailer and cars. The difference is quite uniform on all five sites, the trailer values are slightly lower than those for the cars. However, there is a different relationship between the portable testers and the trailers or stopping-distance cars. The portable testers provide higher values, especially at Sites I, II, and III, but show a lower rate of rise with respect to the increase in test site numbers than the other devices. This lower rate of rise permits the results to be closer at Sites IV and V.

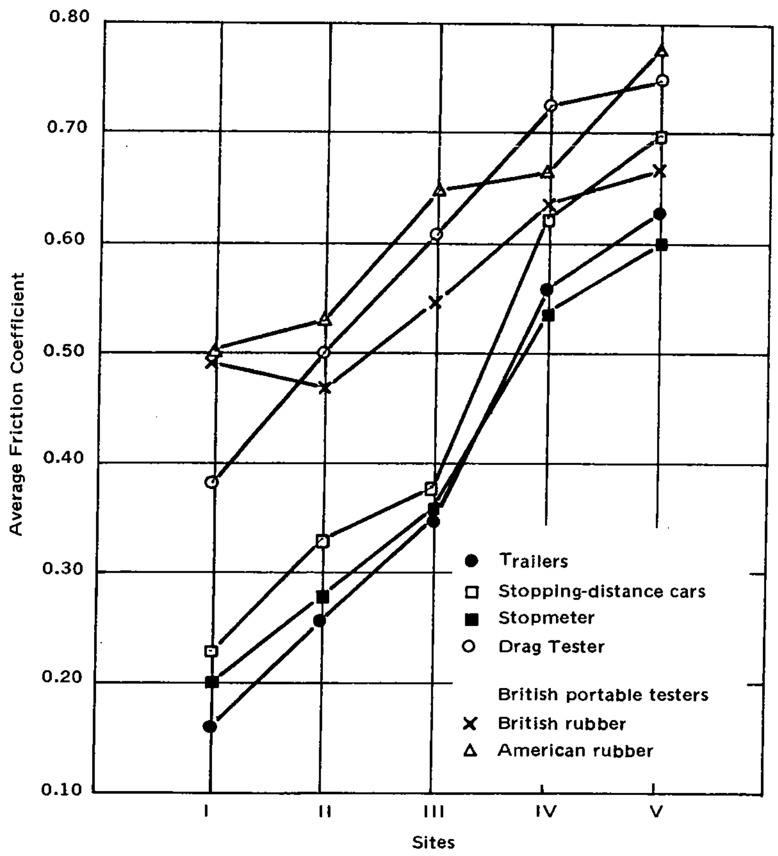


Figure 21. Comparison of average of trailers, stopping-distance vehicles (40-mph test speed), British testers (British and American rubber) and Pennsylvania State University drag tester. (© Dillard and Mahone, 1963. Used by permission.)

The secondary experiments had varied objectives. In general, the main objective was to provide an insight into some aspects of the correlation study. The following findings were obtained from the experiments:

1. Variation in water film thickness does not appreciably influence the test results of the trailers and stopping-distance cars. It should be noted that there were differences in the amount of water accumulated on the five sites used in the investigation.

2. Many of the British pendulum testers give lower values with an increase in water film thickness, while the reverse is true for a few of the other devices. The mean values of all testers, however, show a decrease as the film thickness is increased.

3. On the basis of the results from one trailer test, lowering the center of gravity has little effect on the SC.

4. Watering the pavement surface with the self-watering system of the trailers generally provides a higher **SC** than watering with the regular sprinkling system.

5. The addition of weights up to 410 pounds on a trailer and 900 pounds on a stopping-distance car has very little effect on the results.

6. Changing the tread design of tires (ASTM E-17 standard test tire to General Jet Air) with the same rubber composition does not appreciably vary the results of a stopping-distance car.

7. The statistical analyses made on the device-operator-site variables for the portable testers indicate that a well-designed experiment was used in the study. The analyses show that the devices and operators taking part in the experiment were alike for all practical purposes and that the sites were significantly different from each other.

8. In the experiments with experienced and inexperienced operators of the British pendulum testers, an inexperienced operator is able to provide valid results after receiving 15 minutes of instruction plus 15 minutes of practice.

Rizenbergs and Ward (1967) conducted an extensive investigation on six selected pavements using the stopping-distance method. The purpose of the investigation was fourfold: (1) to compare theoretically similar coefficients obtained from measurements of different parameters, (2) to determine the repeatability of tests, (3) to correlate dissimilar coefficients, and (4) to select a standard test. The test vehicle was a 1962 Ford sedan instrumented to record time, distance, velocity, and deceleration. Brake application, brake light energization, and wheel rotation were also recorded. All skid measurements were made using ASTM E-17 standard tires (ASTM E249-66) with an inflation pressure of 24 psi. The various measurements taken are shown in Figure 22; the **SDCs** derived by using the various measurements in Equations 21 and 23 and the **DCs** derived by using the various measurements in Equation 25 are given in Table 6. The magnitudes of the **SDCs** and **DCs** are listed in Table 7.

Table 7 reveals that the theoretically similar **SDCs** are generally different. For the same interval of skid, the **SDCs** determined from velocity and time measurements are higher than those determined from velocity and distance measurements. However, there are almost no differences in **SDCs** over small increments of velocity above 10 mph if the velocity, distance, and time measurements are used. These characteristics of the SDCs indicate that the equations used do not properly relate the nonlinearity of the parameters over large increments. Thus, it appears best to determine the **SDC** based on velocity and time, or velocity and distance, from 30-20 mph or 20-10 mph rather than from 30-0 mph.

Table 6. Coefficients Obtained From Various Measurements in the Stopping-Distance Method and Deceleration Method

(After Rizenbergs and Ward, 1967)

SDC_{O_o} = Coefficient, computed from Equation 21, obtained from measurement of observed stopping distance and meter-indicated velocity at the instant of brake application.

SDC_{O_w} = Coefficient (Equation 21) obtained from the measurement of observed stopping distance and the actual (Sanborn chart) velocity at wheel lock.

SDC_{M_o} = Coefficient (Equation 21) obtained from measurement of magnetic counter-indicated stopping distance and meter-indicated velocity at the instant of brake application.

SDC_{M_1} = Coefficient (Equation 21) obtained from measurement of magnetic counter-indicated stopping distance and actual velocity at the instant brake light was energized.

SDC_{M_w} = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter on the C. E. chart, in the velocity increment between wheel lock and 0 mph.

$SDC_{M(30\text{-}0)}$ = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter in the velocity increment between 30 mph and 0 mph.

$SDC_{M(20\text{-}0)}$ = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter in the velocity increment between 20 mph and 0 mph.

$SDC_{M(10\text{-}0)}$ = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter in the velocity increment between 10 mph and 0 mph.

$SDC_{M(V_w\text{-}30)}$ = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter in the velocity increment between wheel lock and 30 mph.

$SDC_{M(30\text{-}20)}$ = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter in the velocity increment between 30 mph and 20 mph.

$SDC_{M(20\text{-}10)}$ = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter in the velocity increment between 20 mph and 10 mph.

$SDC_{M(V_w\text{-}10)}$ = Coefficient (Equation 21) obtained from measurement of skid distance by counting impulses of the input to magnetic counter in the velocity increment between wheel lock and 10 mph.

SDC_{V_1} = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between brake light energization and 0 mph.

SDC_{V_w} = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between wheel lock and 0 mph.

$SDC_{V(30\text{-}0)}$ = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between 30 mph and 0 mph.

Continued

Table 6. Continued

$SDC_{V(20-0)}$ = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between 20 mph and 0 mph.

$SDC_{V(10-0)}$ = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between 10 mph and 0 mph.

$SDC_{V(V_w-30)}$ = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between wheel lock and 30 mph.

$SDC_{V(30-20)}$ = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between 30 mph and 20 mph.

$SDC_{V(20-10)}$ = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between 20 mph and 10 mph.

$SDC_{V(V_w-10)}$ = Coefficient (Equation 23) obtained from measurement of elapsed time in the velocity increment between wheel lock and 10 mph.

DC_{D_w} = Average coefficient obtained from measurement of area under the deceleration curve on the Sanborn recording between wheel lock and 0 mph divided by the corresponding chart length (Equation 25).

$DC_{D(15)}$ = Coefficient obtained from measurement of deceleration at 15 mph by interpolating the deceleration trace between 12 and 18 mph (Equation 25).

$DC_{D(25)}$ = Coefficient obtained from measurement of deceleration at 25 mph by Interpolating the deceleration trace between 22 and 28 mph (Equation 25).

$DC_{D(35)}$ = Coefficient obtained from measurement of deceleration at 35 mph by interpolating the deceleration trace between 32 and 38 mph (Equation 25).

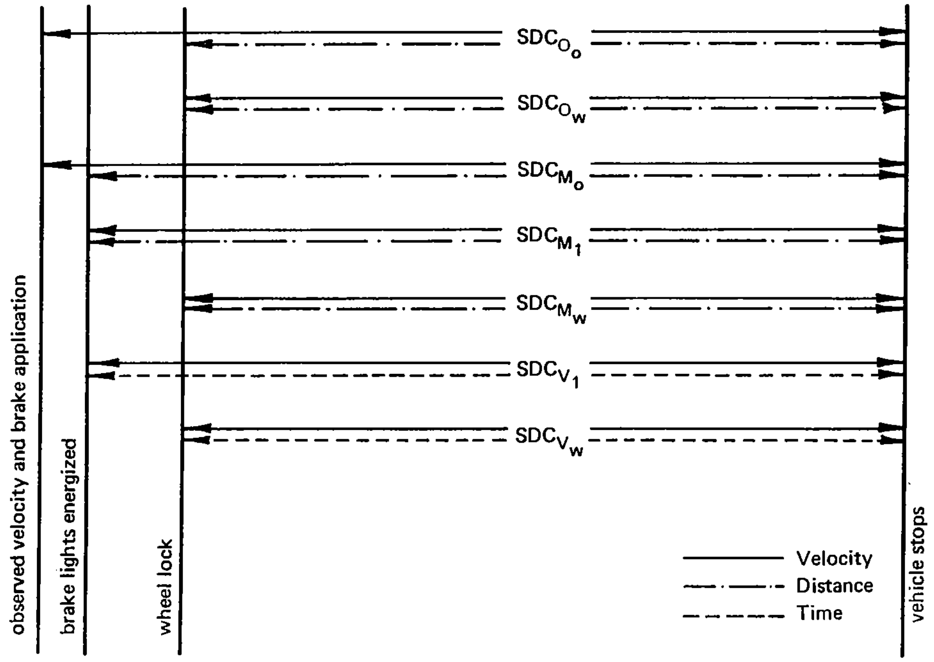


Figure 22. Measurements made for determination of several skid numbers.
(© Rizenbergs and Ward, 1967. Used by permission.)

Table 7. Correlation Study Test Data (After Rizenbergs and Ward, 1967)

Velocity (mph)	Site Ia	Site Ib	Site II	Site III	Site IV	Site V
V_o	34.9		40.0	40.1	40.0	40.1
V_b	35.4		40.4	40.5	40.1	40.4
V_1	35.3		40.3	40.5	39.9	40.1
V_w	34.3		39.4	39.6	38.5	38.9
Coefficients	Velocity and Distance					
SDC_{O_o}	0.38	0.49	0.43	0.60	0.65	0.79
SDC_{O_w}	0.37	0.46	0.41	0.58	0.61	0.74
SDC_{M_o}	0.34	0.43	0.39	0.52	0.56	0.68
SDC_{M_1}	0.35	0.43	0.40	0.52	0.55	0.68
SDC_{M_w}	0.36	0.46	0.41	0.55	0.58	0.72
$SDC_{M(30\text{-}0)}$	0.37	0.52	0.44	0.60	0.61	0.74
$SDC_{M(20\text{-}0)}$	0.45	0.60	0.50	0.66	0.68	0.79
$SDC_{M(10\text{-}0)}$	0.59	0.69	0.61	0.76	0.77	0.83
$SDC_{M(V_w\text{-}30)}$	0.35	0.39	0.37	0.50	0.54	0.71
$SDC_{M(30\text{-}20)}$	0.33	0.46	0.40	0.53	0.57	0.69
$SDC_{M(20\text{-}10)}$	0.41	0.58	0.47	0.62	0.66	0.79
$SDC_{M(V_w\text{-}10)}$	0.35	0.45	0.41	0.54	0.57	0.72
	Velocity and Time					
SDC_{V_1}	0.40	0.49	0.44	0.48	0.62	0.73
SDC_{V_w}	0.41	0.52	0.44	0.60	0.64	0.76
$SDC_{V(30\text{-}0)}$	0.42	0.57	0.47	0.64	0.67	0.78
$SDC_{V(20\text{-}0)}$	0.50	0.66	0.54	0.72	0.73	0.83
$SDC_{V(10\text{-}0)}$	0.63	0.75	0.62	0.81	0.81	0.87
$SDC_{V(V_w\text{-}30)}$	0.34	0.41	0.36	0.50	0.55	0.71
$SDC_{V(30\text{-}20)}$	0.33	0.47	0.40	0.54	0.57	0.70
$SDC_{V(20\text{-}10)}$	0.41	0.59	0.48	0.64	0.67	0.80
$SDC_{V(V_w\text{-}10)}$	0.36	0.47	0.41	0.55	0.59	0.73
	Deceleration					
DC_{D_w}	0.36	0.41	0.38	0.56	0.60	0.66
$DC_{D(15)}$	0.38	0.46	0.41	0.60	0.61	0.68
$DC_{D(25)}$	0.28	0.36	0.34	0.45	0.51	0.61
$DC_{D(35)}$		0.30	0.31	0.42	0.49	0.54

As shown in Table 7, differences are also found between SDC determined from measurements of observed stopping distance or observed velocity at brake application and those from measurements of velocity and distance from actual wheel lock. Errors in measuring observed stopping distances from wheel lock to the stopping point cause differences in SDCs when compared to those measurements determined from a magnetic counter. Differences are small between SDCs determined from observed velocity and those determined from recorded velocity at the moment of brake light energization. These differences indicate the importance of using distances and velocities recorded by instruments rather than those based on observations.

The repeatability of a particular test in the investigation was based mainly on the standard deviation of the test results obtained during one series of tests. Careful examination is required since the standard deviation is influenced by the pavement, the magnitude of the SDC, and instrumentation errors. The standard deviations indicated that the most repeatable test results are obtained by selecting the largest velocity increment for the computation of the SDC. Three reasons for this finding were given by Rizenbergs and Ward (1967):

1. The accuracy of velocity, distance, and time measurements increases with an increase in velocity increments.

2. The variability in skid resistance below 10 mph is minimized.

3. The errors are reduced in establishing the instant of rear-wheel lock and premature or delayed front-wheel lock.

In the 10-0 mph velocity increment, the cause of poor repeatability is the inability to steer the skidding vehicle in the wheel tracks. Variation in skid resistance is encountered with skids outside the wheel tracks.

The SDCs determined from measurements of velocity—time and velocity—distance for the 30-20 mph increment reveal smaller standard deviations than the deviations for the 20-10 mph increment. The reasons previously given for the most repeatable test results also apply here.

A regression analysis was made to correlate the various SDCs and DCs. The degree of correlation was based on the standard estimate of error, H_s, and the correlation coefficient, C_c. As shown in Table 8 the linear regression equations permit conversion from an SDC to another SDC or to a DC. Good and fair correlations can be obtained between many results.

Table 8. Correlation Equations (After Rizenbergs and Ward, 1967)

U	R	Equation	H_s	E_s
Good Correlation				
SDC_{O_o}	SDC_{O_w}	$R = 0.024 + 0.909U$	1.000	0.004
SDC_{O_o}	SDC_{M_o}	$R = 0.036 + 0.811U$	0.999	0.004
$SDC_{V(30\text{-}20)}$	$SDC_{V(20\text{-}10)}$	$R = 0.058 + 1.067U$	1.000	0.006
$SDC_{V(30\text{-}20)}$	$SDC_{M(30\text{-}20)}$	$R = 0.009 + 0.974U$	1.000	0.006
$SDC_{V(30\text{-}20)}$	$SDC_{V(V_w\text{-}10)}$	$R = -0.031 + 1.084U$	0.998	0.006
SDC_{V_w}	SDC_{V_1}	$R = 0.020 + 0.932U$	0.997	0.006
$SDC_{V(30\text{-}20)}$	SDC_{M_w}	$R = -0.023 + 1.058U$	0.998	0.007
$SDC_{V(30\text{-}20)}$	SDC_{V_1}	$R = 0.036 + 1.000U$	1.000	0.008
SDC_{O_o}	SDC_{M_w}	$R = 0.036 + 0.857U$	0.999	0.008
SDC_{V_w}	SDC_{M_w}	$R = -0.036 + 0.981U$	1.000	0.009
$SDC_{V(30\text{-}20)}$	SDC_{V_w}	$R = 0.917 + 1.073U$	0.997	0.009
SDC_{V_w}	$SDC_{V(30\text{-}0)}$	$R = 0.065 + 0.948U$	0.996	0.009
Fair Correlation				
$SDC_{V(30\text{-}20)}$	SDC_{M_o}	$R = -0.024 + 1.006U$	0.994	0.011
SDC_{V_w}	$SDC_{V(20\text{-}10)}$	$R = 0.071 + 0.955U$	0.993	0.012
$SDC_{V(30\text{-}20)}$	$SDC_{V(30\text{-}0)}$	$R = 0.082 + 1.012U$	0.992	0.012
SDC_{V_w}	$SDC_{V(V_w\text{-}10)}$	$R = -0.045 + 1.005U$	0.996	0.013
$SDC_{V(30\text{-}20)}$	SDC_{O_o}	$R = -0.074 + 1.242U$	0.995	0.014
$SDC_{V(30\text{-}20)}$	$SDC_{V(V_w\text{-}30)}$	$R = -0.094 + 1.120U$	0.995	0.015
SDC_{V_w}	$SDC_{V(V_w\text{-}30)}$	$R = -0.151 + 1.111U$	0.990	0.017
$SDC_{V(30\text{-}20)}$	$SDC_{V(20\text{-}0)}$	$R = 0.184 + 0.944U$	0.988	0.017
SDC_{V_w}	$DC_{D(25)}$	$R = -0.070 + 0.889U$	0.971	0.017
$SDC_{V(30\text{-}20)}$	$DC_{D(25)}$	$R = -0.062 + 0.967U$	0.982	0.018
Poor Correlation				
SDC_{V_w}	$SDC_{V(20\text{-}0)}$	$R = 0.187 + 0.860U$	0.981	0.027
SDC_{V_w}	DC_{D_w}	$R = -0.054 + 0.973U$	0.981	0.029
SDC_{V_w}	$SDC_{V(10\text{-}0)}$	$R = 0.336 + 0.735U$	0.938	0.029
$SDC_{V(30\text{-}20)}$	DC_{D_w}	$R = -0.027 + 1.024U$	0.964	0.032
$SDC_{V(30\text{-}20)}$	$SDC_{V(10\text{-}0)}$	$R = 0.364 + 0.754U$	0.939	0.032

In selecting an interim standard test, Rizenbergs and Ward (1967) considered several criteria. These included accuracy, repeatability, rapid availability of test results, simplicity of measurement, and a minimum of instrumentation. Several ways of measuring velocity, distance, and time fulfilled most of the requirements. However, the SDC determined from Equation 23 by using the measurement of time during the 30-20 mph velocity increment was selected for the following reasons:

1. Time can be measured within an accuracy of 1%.
2. The SDC is nearly linear in the 30-20 mph velocity increment.
3. Repeatability is good, requiring five tests for an error of 5% or less.
4. Only a one-channel recorder is required.
5. The chart from the recorder can be interpreted relatively easily.

Rizenbergs and Ward (1967) included in the investigation the effects of some factors related to the stopping-distance method. These factors are velocity, air resistance, vehicle dynamics, and tire inflation pressure. Safety considerations limited the maximum test velocity to approximately 35 mph in the investigation. The test results showed that an increase in the velocity of the test vehicle decreases the SDC. This SDC—velocity relationship has been found by practically everyone engaged in skid measurements and is generally accepted.

The air resistance of an automobile can be represented by an aerodynamic equation similar to Equation 3, with the drag coefficient and frontal area of the automobile substituted for the lift coefficient and uplift area, respectively. By dividing the air resistance by the weight of the automobile and by using the proper conversion factors, constants, and other information from the automobile manufacturer, Rizenbergs and Ward (1967) provided the following equivalent friction coefficient (FC) equation for air drag:

$$FC = 7.18 \times 10^{-6} V^2 \qquad (30)$$

The velocity in terms of mph is the velocity of the automobile with respect to that of the wind velocity, which may or may not have a headwind or tailwind component. Equation 30 shows that the air resistance has little effect on FC because of the low constant, 7.18×10^{-6}, unless V is high. At the velocities used in the investigation, Rizenbergs and Ward (1967) concluded that air resistance has little effect on the measured SDC.

For the effect of vehicle dynamics, tests were conducted with the front suspension blocked, both front and rear suspensions blocked, or both unblocked. The test results were not significantly altered. Therefore, Rizenbergs and Ward (1967) concluded that vehicle dynamics has little influence on SDC.

The effect of tire inflation pressure was observed at five test sites. Inflation pressure was increased from 20 to 32 psi in 4-psi increments. The test results showed a general decrease in SDC with an increase in inflation pressure: approximately 5% (for 30-20 mph) between 20 and 32 psi. From this change, Rizenbergs and Ward (1967) concluded that the variation associated with a change in inflation pressure is significant.

Tables 7 and 8 show the various DCs determined from different incremental measurements of deceleration and the correlations associated with the SDCs. These test results indicate that, in general, the DCs are much lower than the SDCs for similar velocities. As previously mentioned, improper correction for the tilt of the automobile is cited as the error in the deceleration measurement. In addition to the DCs being low, poor repeatability and poor correlation are generally associated with DCs. Rizenbergs and Ward (1967) suggest that the method used in the investigation for holding the plate-mounted accelerometer may have been unsatisfactory and the cause of poor repeatability.

Walsh (1966) reported on a brief correlation study conducted by the New York Thruway Authority. The purpose of the study was to obtain some insight into the significance of the previously described simple Thruway skid cart. This cart, together with the British pendulum tester and the New York State Department of Public Works trailer, was tested on a broom-finished PCC surface that had not been subjected to polishing wear by traffic. On the basis of a few tests on the PCC surface the following average skid resistance values were obtained for each device:

Thruway cart at approximately 3 mph = 0.825

New York State trailer at 40 mph = 0.706

British pendulum tester at approximately 6 mph = 0.810

A ratio was obtained for each device by dividing its average value into the value obtained from any other surface and multiplying by 100. This ratio was called the Thruway skid ratio.

The results of the Thruway skid ratio method applied on four test sites are shown in Table 9. Direct readings for the skid cart and the British tester are close, but those for the British tester and the trailer show some variations. However, the Thruway skid ratios show a close relationship between all three devices. Thus, this method simplified the determination of the existence of a close correlation between the devices which otherwise might have been difficult to show.

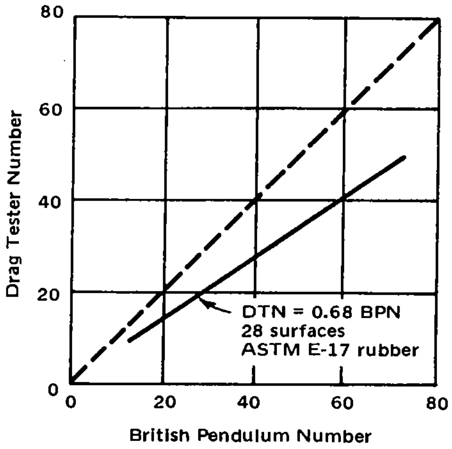


Figure 23. Correlation of British pendulum tester and drag tester. (© Kummer and Meyer, 1967. Used by permission.)

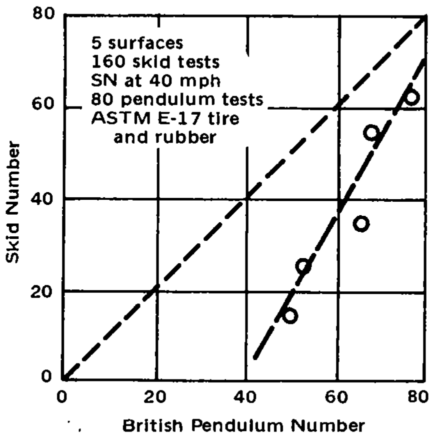


Figure 24. Correlation of British pendulum number and steady-state skid number. (© Kummer and Meyer, 1967. Used by permission.)

The correlation curve would be steeper if the trailer tests had been conducted at 50 or 60 mph. This effect of velocity change from 10 mph to 35 mph, together with the effect of tire tread design, is illustrated in Figure 25.

Some correlation curves between the Swedish "Skiddometer," a brake slip tester, and a German skid trailer are shown in Figure 26. As expected, the BSNs measured at or near the critical slip are higher than the corresponding SNs, all other factors being equal. The difference increases slightly with increasing velocity. Similar numbers are expected for both modes at velocities below 10 mph, because the relative sliding velocity of the tread elements is not very different at the lower velocities. In addition, an increase in velocity results in a decrease in SN because of additional frictional heating and hydrodynamic lift. This latter effect is more pronounced on slippery pavements, where the hydrodynamic lift is more easily developed. Thus, the SNs and BSNs are closer together on high skid resistant surfaces than on slippery pavements.

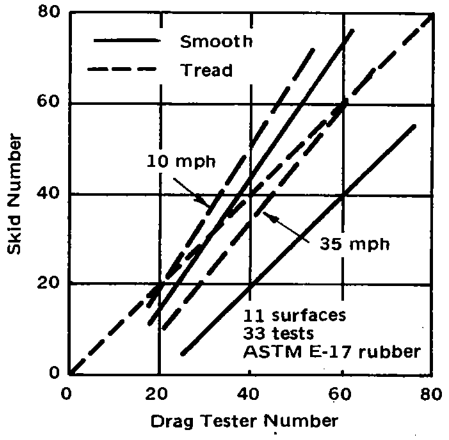


Figure 25. Effect of tire tread design and speed on correlation of drag tester and skid trailer. (© Kummer and Meyer, 1967. Used by permission.)

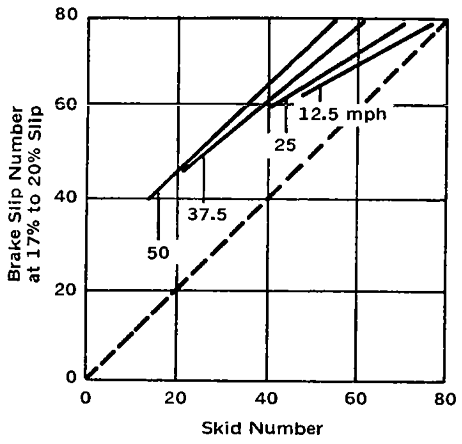


Figure 26. Correlation of stead-state skid and brake slip tests. (© Kummer and Meyer, 1967. Used by permission.)

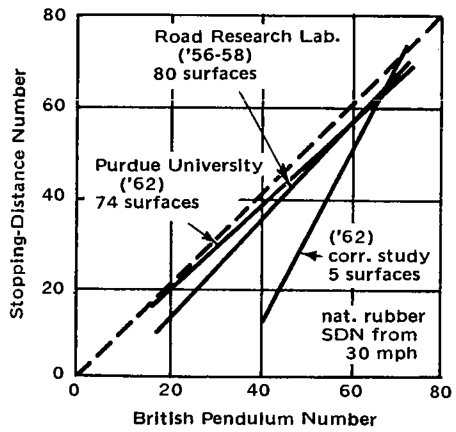


Figure 27. Correlation of British pendulum tester and stopping-distance car. (© Kummer and Meyer, 1967. Used by permission.)

The regression lines established for the SDN (100 x SDC) and the BPN by three agencies at different times and locations are shown in Figure 27. The regression lines are from the following equations, established by the different agencies:

$$\text{SDN} = -8.8 + 1.09\,\text{BPN (British Road Research Laboratory)}$$

$$\text{SDN} = 0.96\,\text{BPN (Purdue University)}$$

$$\text{SDN} = -66 + 1.82\,\text{BPN (Tappahannock)}$$

Figure 27 shows that the regression line established by the Road Research Laboratory is in good agreement with that of Purdue University at the higher friction numbers. However, the 1962 Tappahannock regression line shows poor correlation with the lines of the other two agencies. Kummer and Meyer (1967) reported that the major factor involved in the poor correlation is the limited number of surfaces used in the Tappahannock study.

Figure 28 shows the regression line for SDN and SN. As previously reported, the stopping-distance car yields higher readings than the skid trailers because of the increase in sliding friction at low velocities and the possible effect of the critical slip condition.

Mahone (1962) compared the results obtained by the British pendulum tester and by the stopping-distance car on 14 test sites with various surface textures and with friction levels ranging from dangerously low to high.

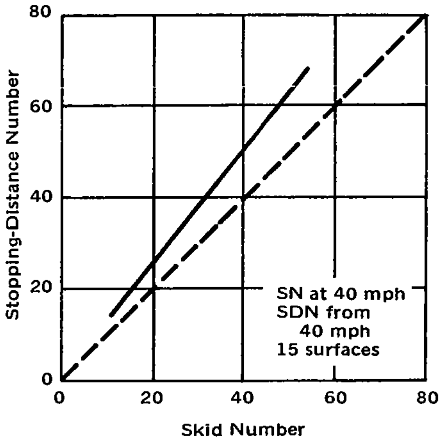


Figure 28. **Correlation of steady-state skid number and stopping-distance car.** (© Kummer and Meyer, 1967. Used by permission.)

Figure 29 shows the test results with the 95% confidence limits. The results show that certain combinations of slide length of the British tester and initial velocity of the stopping-distance car provide close agreement of results on some but not on all of the surfaces.

A statistical analysis was made by Mahone (1962) on the test results to determine a combination of slide length and initial velocity which will produce mean coefficients of close agreement. As shown in Table 10 there are significant differences in the mean coefficients for every slide length and test velocity combination on at least 50% of the surfaces. Thus, the two test devices do not give results which are interchangeable for all types of surfaces.

An analytical method was developed by Mahone (1962) for predicting the **SDC** when the **BPC** is known. This was done for four combinations of initial vehicle velocity and slide length. Estimating equations of the lowest order were derived which enabled the prediction of the **SDC** with 95% confidence limits. As shown in Figures 30 and 31, the derived curves with the 95% confidence limits envelop all the measured values. Thus, the **SDC** can be predicted from the measured **BPC** through the use of the estimating equations.

Table 10. Number of Sites on Which Mean Friction Coefficients From the Car and From the Pendulum Tester Were Demonstrated to be Significantly Different at the 95% Confidence Level (© Mahone, 1962. Used by permission.)

Slide Length (in.)	Test Speed (mph)			
	20	30	40	50
4.6	7/10*	7/12	7/12	1/2
4.8	5/10	10/14	6/12	2/3
5.0	6/10	11/14	9/12	3/3
5.2	—	2/2	—	1/1

* First number shows number of mean values that were significantly different; second number shows number of sites tested.

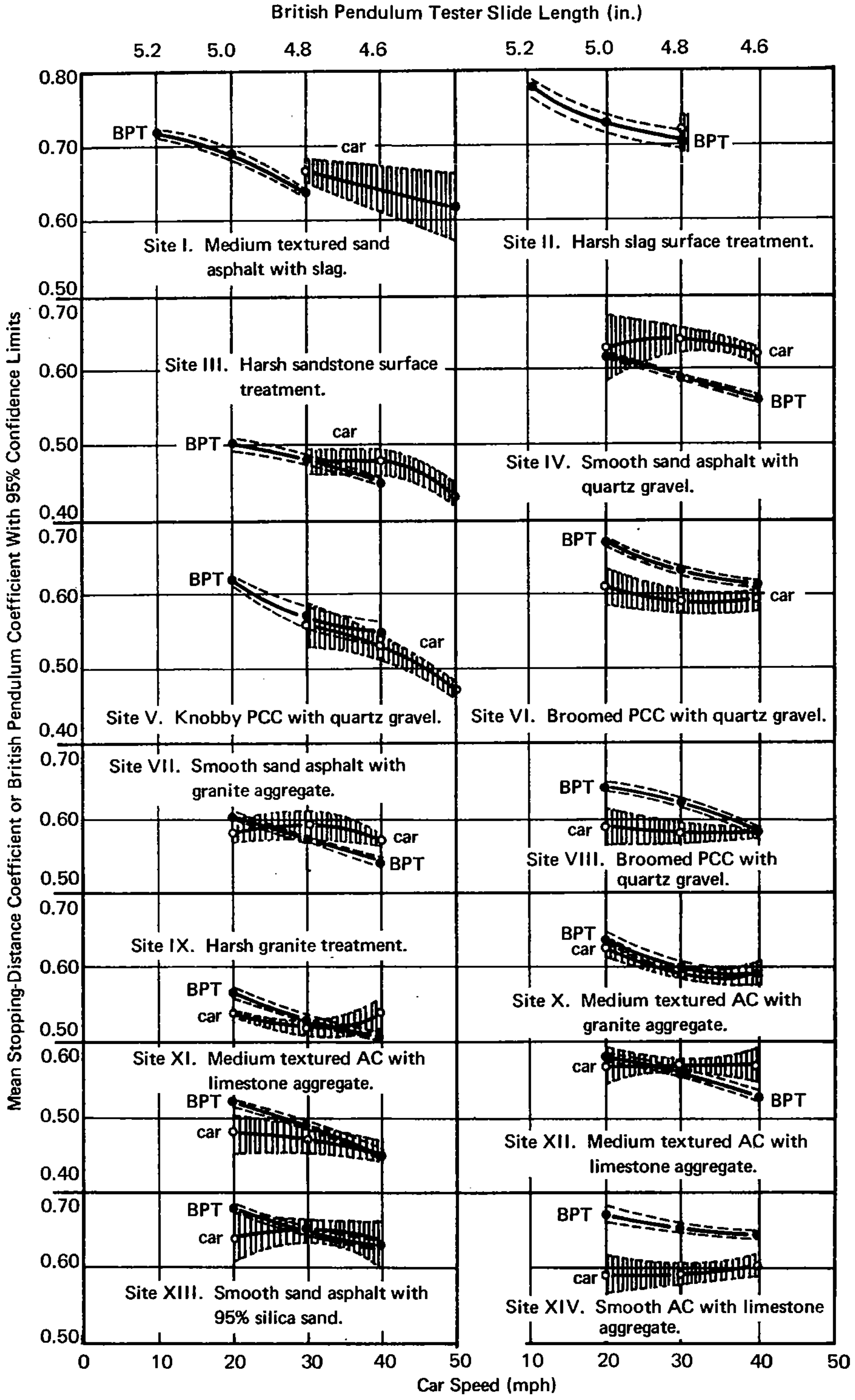


Figure 29. Relationship between the stopping-distance coefficient and test speed, and between the British pendulum coefficient and slide length.

(© Mahone, 1962. Used by permission.)

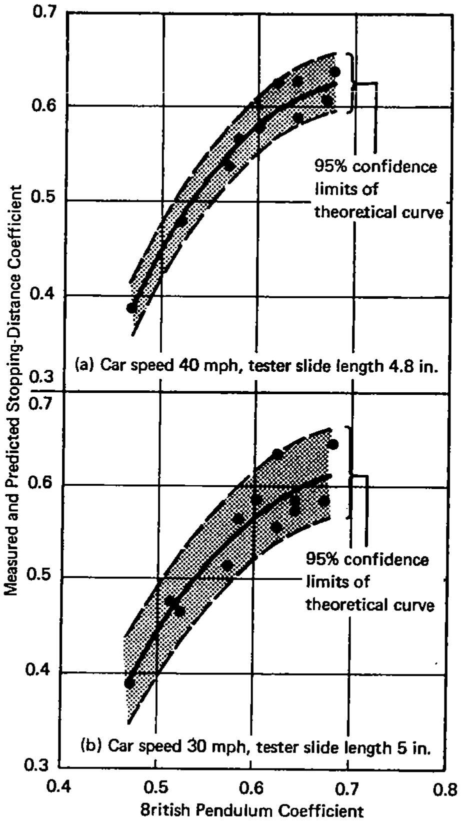


Figure 30. Prediction of mean SDC from BPC. (© Mahone, 1962. Used by permission.)

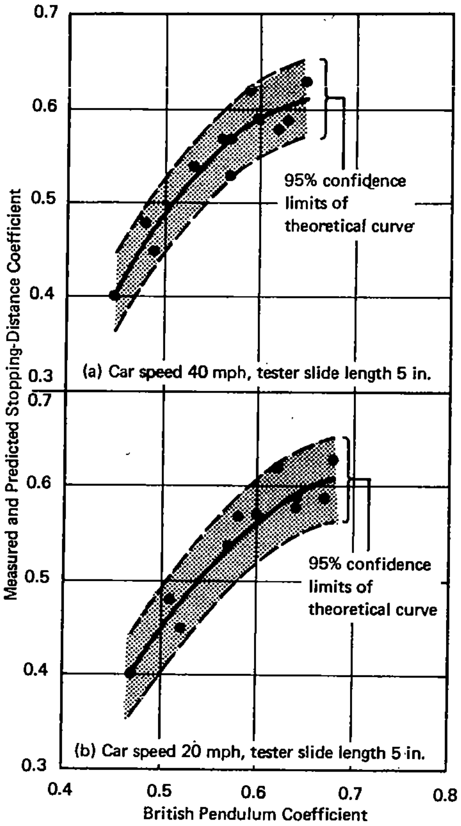


Figure 31. Prediction of mean SDC from BPC, for car speeds and test lengths different from those in Figure 30. (© Mahone, 1962. Used by permission.)

The foregoing discussions on the correlation of various friction-measuring devices indicate that generally one cannot readily convert the results obtained with one device to those obtained with another. The conversion factors can be predicted, but analysis is required which may not be simple, especially when many types of devices are involved. Thus, to avoid unnecessary difficulties, and for economic reasons, it appears best to establish a valid correlation between two or three selected devices rather than between many devices. The results from future correlation studies are expected to provide additional insight into the degree of correlation possible between various devices. An alternate solution is to correlate the skid resistance test result of a device with skidding accident frequency or risk of skidding on all types of pavement surfaces and to use the device for routine measurements. For airfield pavements, the device can be correlated with aircraft during braking. Such an effort by the FAA is discussed in the following section.

Correlation Between Devices and Aircraft

The literature search revealed that there is very little information on correlation between the friction values obtained by skid devices and by aircraft during braking. The report by Shrager (1962) is the only one uncovered during the search. Such information is vitally needed in order to appraise the various devices and to select one to measure the **FC** of Navy airfield pavements.

Shrager (1962) reported on the effort by the FAA to correlate the results of three friction-measuring devices with those of an aircraft during braking. The measuring devices were the Swedish Skiddometer, the British high-speed braking trailer, and a 1961 Plymouth station wagon equipped with a James braking decelerometer and a Tapley accelerometer. The test aircraft was a Convair 880 equipped with a modulating, automatic skid correction, antiskid braking system.

A **PCC** runway, free of visible evidence of contaminants, was used as a test site. Tests were conducted with the following five different runway surface conditions:

1. *Dry.*
2. *Damp.* This condition was obtained by spraying the runway surface with water from a fire truck and mechanically brooming the surface to remove all standing water.
3. *Wet.* This condition was characterized by standing water on the surface.
4. *Slush covered.* The concrete surface was covered with 1/2 inch to 3/4 inch of slush.
5. *Foam covered.* The concrete surface was coated with approximately 1 inch of organic foam.

In order to maintain similar conditions for purposes of comparison, the test surface was reconditioned prior to each test run.

For the initial aircraft test, the test section was entered with a velocity of approximately 140 knots and an idle power setting on the engines. Maximum braking was applied on the main landing gears throughout the test section. A similar technique was used on subsequent runs, with the entrance velocity 5 knots higher than the exit velocity of the previous run. This procedure was repeated until the aircraft stopped within the test section.

The initial run of the friction-measuring devices was made at an indicated speed of approximately 10 mph. Successive runs were made at speeds incremented by approximately 10 mph up to the maximum speed attainable by the device.

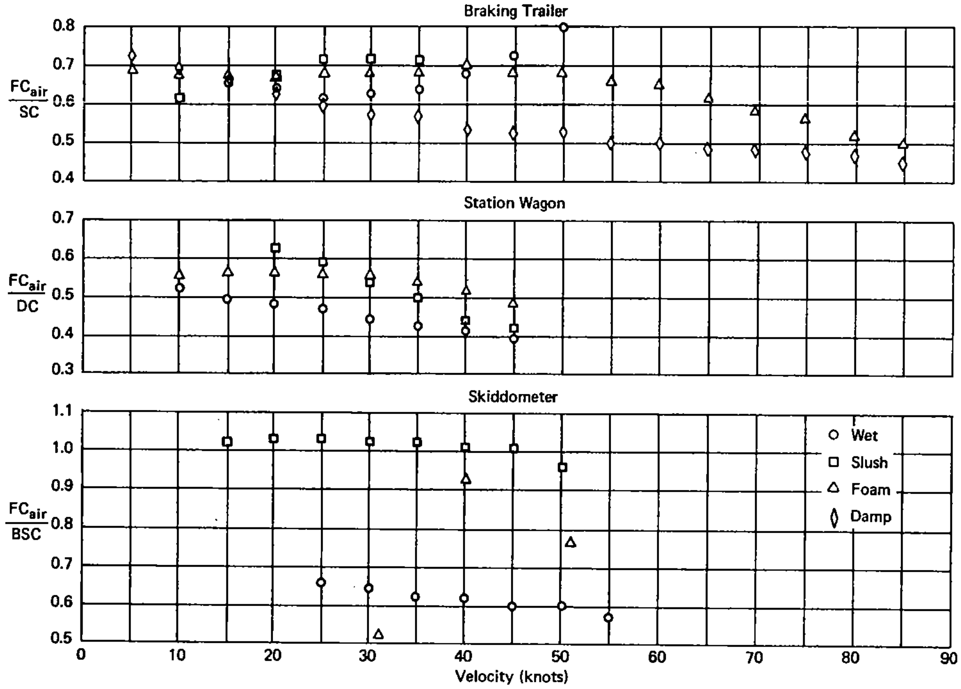


Figure 32. Ratio of aircraft to automotive vehicle friction coefficient for all test conditions. (© Shrager, 1962. Used by permission.)

Figure 32 shows the ratio of results from the aircraft braking tests to those from the measuring devices for all surface conditions. The ratio for each device does not vary significantly with velocity. A slight downward trend is noted with an increase in velocity. Low variations are indicated with respect to the various surface conditions for the braking trailer and station wagon. A higher variation is noted for the Skiddometer. Shrager (1962) indicated that the variations may have been caused by uncontrollable variations in the surface conditions.

The information from the FAA correlation study provided useful relationships between friction devices and aircraft. The results, however, are for one type of pavement and one type of aircraft and may not apply to other types of pavement surfaces and aircraft. Information received from NASA indicated that future correlation studies will provide a substantial amount of additional information on the correlation between military and civilian aircraft and skid-measuring devices.

FACTORS AFFECTING FRICTION COEFFICIENT

The factors affecting the magnitude of the friction coefficient were discussed in the previous report by Tomita (1964). All the factors were placed under three general categories: vehicle and aircraft operation factors, tire factors, and pavement factors. Speed and braking techniques were considered under the first category; tread design, tread composition, inflation, vertical load, and tire temperature under the second category; types of pavement, types of aggregates, surface textures, traffic, pavement surface contamination by foreign material, ambient temperature, weather, and climate under the third category. No new factors have been uncovered during the literature search of this investigation. However, more information has been found on the effects of the various factors and on the effects of various combinations of these factors. The additional information is presented in the subsequent paragraphs.

Velocity and Pavement Surface Wetness

The friction coefficient, though generally different for dry, damp, and wet conditions of pavement surfaces, is accepted as being independent of velocity on a dry pavement surface. However, a decreased friction level is expected at very high velocities comparable to those attained during brake application on high-speed jet fighters or attack aircraft. Horne and Leland (1962) attribute this decreased friction level to tire heating effects, which can partially be observed. At low velocities the rubber deposits on PCC pavements are observed to be in the form of small solid particles abraded during the skidding mode. Immediately after the operation the skidded area is warm to the touch. In contrast, similar skid marks resulting from locked wheels at very high velocities appear to have been deposited in a liquid state, as though they were painted on. This apparent smeared region is hot and sticky to the touch. Areas traversed after brake release show evidence of black tire imprint with each succeeding revolution of the tire. In addition, Horne and Leland (1962) reported that puffs of smoke can be seen from the tire contact region during braking at high velocities, with slip ratios ranging from 15% to 100%. Evidently the molten rubber acts as a lubricant to decrease the friction level. While this decrease is expected for landing aircraft, the real danger of braking at or near the 100% slip on a dry pavement lies in the rapid erosion of tire tread and carcass, resulting in a blowout. Horne and Leland (1962) reported that a full skid of 60 feet on a dry PCC runway can fail a high-pressure aircraft tire.

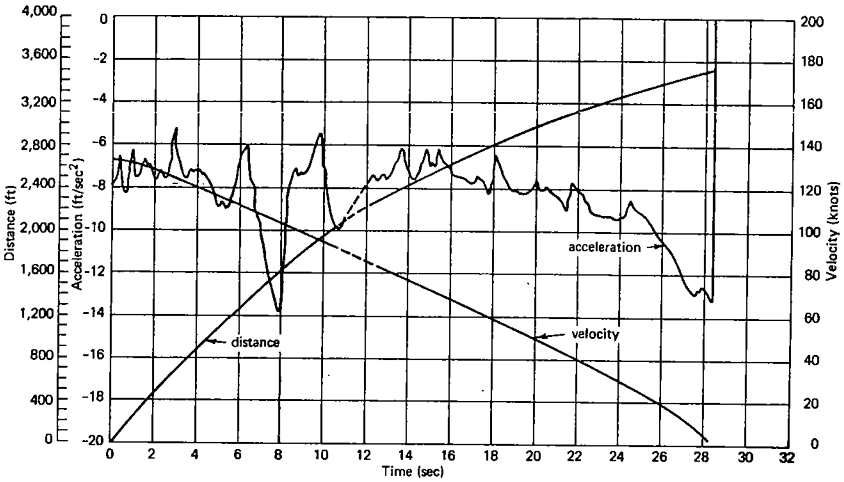


Figure 33. Test data for aircraft on a runway in a damp condition. (©Shrager, 1962. Used by permission.)

A damp condition may reduce the friction level even more than it is reduced by a dry condition, but the friction level is still not very sensitive to a variation in velocity. This is shown by the acceleration trace in Figure 33, recorded during a jet transport braking test by the FAA. An increasing trend in deceleration is indicated by the acceleration trace at low velocities. However, this may have been caused by more water on the pavement surface than the actual damp condition. On a truly damp surface there should be no film of water to be displaced or no bulk water to be removed by the tire. This condition is somewhat difficult to achieve in practice because of the formation of puddles of water in the depressed areas of the pavement.

A wet pavement is generally considered to be covered with a visible film of water. The friction level on such a pavement is dependent on velocity, because with an increase in velocity the water film makes it progressively difficult for the tread to make contact with the pavement surface. Kummer and Meyer (1967) identified three velocity ranges in which the friction-velocity gradient differs.

Range 1: $V \leqslant V_w$

where $V_w = 6.4\sqrt{P_t}$ = the velocity at which a wedge of fluid begins to penetrate the tireprint area. In this velocity range the time available for displacement of bulk water is adequate, and the friction-velocity gradient is influenced only by the effective reduction of the thin, viscous film of water.

Range 2: $V_w \leqslant V \leqslant V_h$

where $V_h = 13.2\sqrt{P_t}$ = the hydroplaning velocity or the velocity at which the wedge of fluid completely penetrates the tireprint area. The friction level in this velocity range is affected by the bulk water depth as well as the thin-film effects. Thus, the friction-velocity gradient is greater in this range than in Range 1.

Range 3: $V > V_h$

The tire is not capable of removing the bulk water completely and hydroplanes in this velocity range. Tire–pavement friction is no longer significant, and the prominent factor is the hydrodynamic drag force.

Kummer and Meyer (1967) reported that the transition from Range 1 to Range 2 occurs at approximately 30 mph and that the hydroplaning velocity, V_h, occurs at 65 mph for a passenger-car tire with an inflation pressure of 24 psi. Note that a lower value of V_h results from Equation 6. This change in friction-velocity gradient at 30 mph is shown in Figure 34 for a water depth of 3/8 inch. Note that there is no such change with water depths of 3/16 and 1/16 inch. In the experiment the depth of water in a trough was carefully controlled by depth gages.

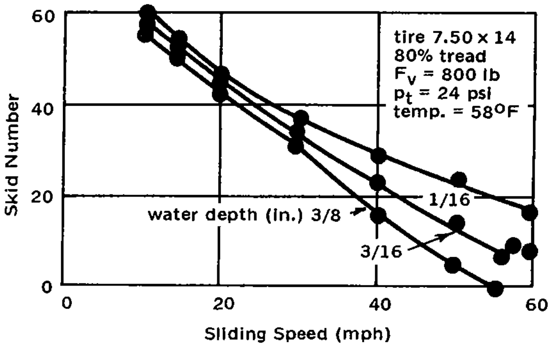


Figure 34. Demonstration of gradient increase due to penetration of fluid wedge into tire contact area. (© Kummer and Meyer, 1967. Used by permission.)

Figure 35 shows the effect of fluid depth on the effective friction coefficient, or retardation, of a jet transport braking on a concrete runway. Horne and Leland (1963) defined the shallow fluid as a wet runway surface without large puddles and the deep-fluid condition as a runway surface covered with 1/2 inch of artificially applied slush. As shown in Figure 35, there is a considerable loss in friction coefficient with an increase in water depth and velocity.

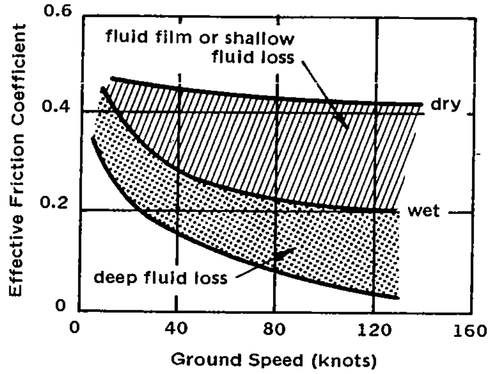


Figure 35. Jet transport braking traction on a concrete runway. New rib-tread tires and full antiskid used. (© Horne and Leland, 1963. Used by permission.)

Figure 36 shows the relationship between SDC and thickness of water film for two types of pavement surface textures. At 30 mph the SDC decreases with an increase in film thickness up to approximately 0.1 mm. Then it shows no significant change with a further increase in thickness.

Kummer and Meyer (1967) reported that large fluctuations up to 10 SN on homogeneous, smooth and fine-textured pavements indicate an insufficient amount of water used in the tests. With more water the fluctuations reduce to 2 SN. Thus, the results of some preliminary tests can be used to check the adequacy of the amount of water used in the tests.

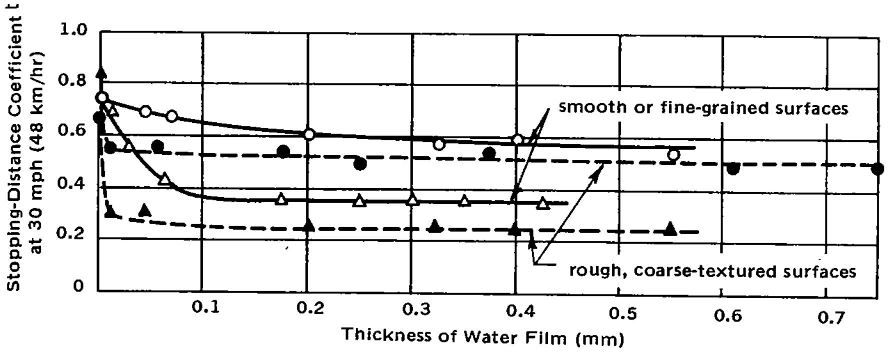


Figure 36. Water-film thickness and SDC on fine- and coarse-textured surfaces. (© Giles, 1959. Used by permission.)

Critical Slip and Skidding Modes

As previously discussed, the peak coefficient (PC) at critical slip for braking, driving, or cornering tires is higher than the corresponding skid coefficient. The exception to this condition is a smooth tire on a smooth surface such as ice. Kummer and Meyer (1967) gave the following three reasons for this condition:

1. At the critical slip point the majority of the tread elements are near the adhesion peak.

2. Tire tread temperature is lower at the critical slip point than at full skid.

3. The hydrodynamic lift is lower at the critical slip point since the relative velocity between tread elements and pavement surface is lower than at full skid.

Maycock (1965-1966) made two important statements on the ratio of **PC** to **SC**:

1. The ratios of **PC** to **SC** for most tire tread patterns and pavement surface textures are similar at a particular velocity. This statement is based on test results at 30 mph and 60 mph with ribbed or siped tires on seven different pavement surfaces. High ratios of **PC** to **SC** are obtained when the tire and pavement surface conditions provide extreme hydrodynamic lift conditions. These extreme lift conditions include smooth tires, smooth pavement surfaces, and high velocities.

2. The ratio of **PC** to **SC** increases with an increase in velocity.

Horne and Leland (1962) tested, on dry concrete, various sizes of Type VII aircraft tires (extra high pressure) with inflation pressures ranging from approximately 100 psi to 260 psi. The relationship between the ratio of **SC** to **PC** and velocity is shown in Figure 37. It should be noted that the ratio in Figure 37 is **SC** to **PC** rather than **PC** to **SC**. Thus, the **SC** to **PC** ratio, decreasing with increasing velocity, corresponds to Maycock's second statement.

Tire and Pavement Surface Effects

The principal factors involved in tires are the rubber properties and the tread design. Resilience or its complement damping, hardness of the rubber, tire inflation pressure, and contact pressure are of interest, together with various available treads ranging from smooth to grooved and slotted designs. The variations of these properties, coupled with those of pavement surface textures or the macroscopic and microscopic roughness of pavement surfaces, yield friction coefficients which are difficult to predict. However, some progress has been made through research towards understanding the effects of these factors, taken either singly or in combination.

Maycock (1965-1966) conducted a number of skid tests using the deceleration method. In these tests tires with three tread patterns and three tread compounds were used on seven pavement surfaces with varying textures.

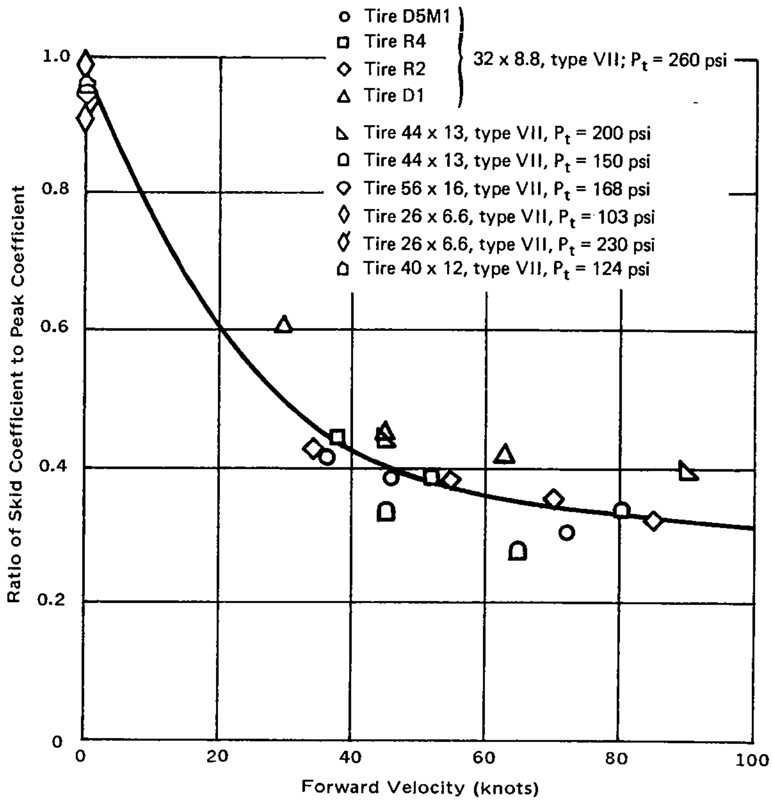


Figure 37. Effect of forward velocity on the ratio of skid coefficient to peak coefficient. Data obtained on dry concrete runways. (© Horne and Leland, 1962. Used by permission.)

The tires had (1) completely smooth tread, (2) ribbed tread with six plain circumferential grooves, and (3) fully developed modern tread patterns with multiple sipes. The specifications of the three tread compounds used are as follows:

1. *Natural rubber*: 48 parts per hundred of high abrasion furnace black.
2. *Synthetic rubber*: oil-extended styrene butadiene rubber with 55 parts per hundred of superior abrasion furnace black.
3. *High-styrene synthetic rubber*: oil-extended high-styrene butadiene rubber with 60 parts per hundred of superior abrasion furnace black.

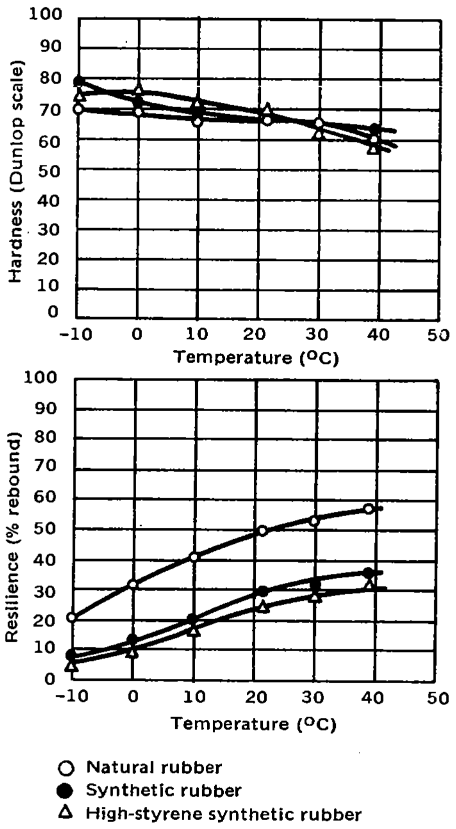


Figure 38. Hardness and resilience of tread materials as a function of temperature. (© Maycock, 1965-66. Used by permission.)

The hardness and resilience of these compounds were measured at various temperatures on sample blocks of these rubbers. As shown in Figure 38, there is only a small variation in hardness between the three compounds throughout the temperature range of $-10^{\circ}C$ to $40^{\circ}C$. In addition, there is only a slight decrease in hardness with an increase in temperature. This indicates the insensitivity of the rubber compounds to temperature variations within the temperature range. However, there is an increase in the resilience of all three compounds with an increase in temperature. The difference in resilience between synthetic rubber and high-styrene synthetic rubber is small and is approximately the same throughout the temperature range, the synthetic rubber being more resilient. The natural rubber exhibits almost twice as much resilience as the synthetic rubber throughout the temperature range.

The seven pavement surfaces listed below were special sections laid on the Road Research Laboratory's test track:

1. Mastic asphalt
2. Polished concrete
3. Fine cold asphalt
4. Asphalt with chippings
5. Rounded gravel carpet
6. Mixed aggregate
7. Quartzite

Surface textures of the above sections increase in coarseness as they increase numerically. Thus, the two smoothest and polished surfaces are 1 and 2, while the most harsh, coarse-textured surface is 7.

The test surfaces were sprayed with water from spray-bar facilities. As in many field experiments, a uniform water film was not obtained. It varied from 0.005 inch to 0.080 inch above the top of the aggregates and from 0.040 inch to 0.080 inch for the fine-textured surfaces.

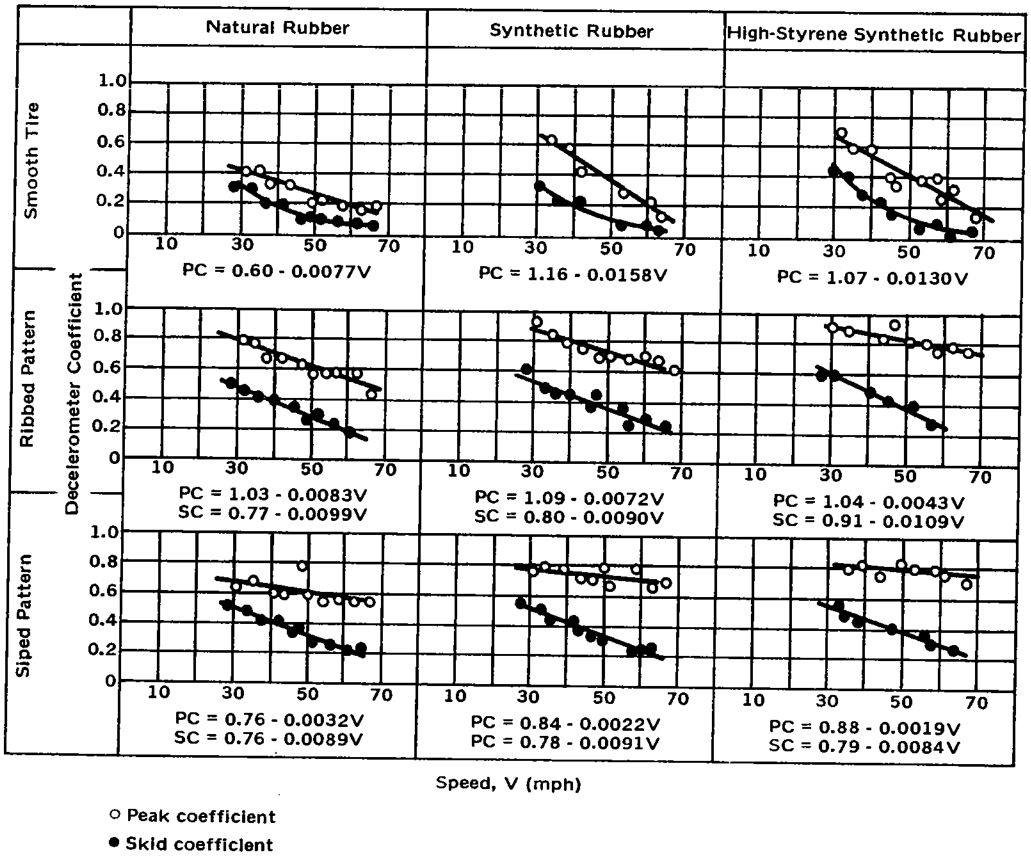


Figure 39. Test results on surface 4—asphalt with chippings. (© Maycock, 1965-66. Used by permission.)

Tire pressure for the tests was adjusted periodically to 24 psi. The measured air and water temperatures varied from 17°C to 24°C for all surfaces except surface 1, which had temperature ranges of 4°C to 7°C. The test velocity ranged from 30 mph to 65 mph.

The test results for surface 4 are shown in Figure 39, together with the equations from regression analyses. Maycock (1965-1966) presented similar results for the remaining surfaces. These are not repeated herein. Figure 39 shows the trend of the results to be typical. That is, the DC increases with an increase in velocity, and the PCs are higher than the SCs.

Table 11 shows the mean ratios of PC and the ratios of SC for the different tread designs. Table 12 shows similar ratios for the different rubber compositions. From the results given in Table 11 the following statements can be made concerning the effectiveness of tread design:

Table 11. Mean Ratios of Peak and Skid Coefficients Obtained With Different Tread Patterns on the Test Surfaces Numbered 1-7 (After Maycock, 1965-1966)

Ratio	Peak Coefficient							Skid Coefficient						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
	30 mph							30 mph						
Ribbed / Smooth	3.7	4.0	1.40	1.49	1.10	1.17	0.95*	**	**	1.43	1.44	1.04*	0.98*	0.96
Siped / Smooth	4.2	3.3	1.12	1.31	1.22	1.17	0.96*	**	**	1.31	1.40	1.26	1.10	1.01*
Siped / Ribbed	1.12	0.83	0.81	0.88	1.10	1.0*	1.0*	1.63	1.25	0.92	0.97*	1.21	1.12	1.06
	60 mph							60 mph						
Ribbed / Smooth	**	**	7	2.9	1.44	1.21	1.07	–	**	**	3.5	1.7	1.6	1.0*
Siped / Smooth	**	**	7	3.0	1.70	1.43	1.02*	–	**	**	3.6	2.0	2.0	1.13
Siped / Ribbed	1.63	1.40	1.04	1.04*	1.19	1.19	0.95	–	2.1	0.97*	1.09*	1.22	1.28	1.12

* Denotes that the ratio is not significantly different from unity at the 5% level.

** The denominator involved was very small.

Table 12. Mean Ratios of Peak and Skid Coefficients Obtained With Different Tread Compositions on the Test Surfaces Numbered 1-7 (After Maycock, 1965-1966)

(Results for smooth tires omitted.)

Ratio	Peak Coefficient							Skid Coefficient						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
	30 mph							30 mph						
S.R. / N.R.	1.27	1.32	1.21	1.14	1.16	1.32	1.33	0.81	1.03*	1.12	1.07	1.02*	1.23	1.14
H.S.S. / N.R.	1.45	1.32	1.24	1.20	1.30	1.47	1.34	1.08*	1.10*	1.19	1.16	1.10	1.27	1.30
H.S.S. / S.R.	1.13	1.02*	1.04*	1.06*	1.11	1.12	1.02*	1.35	1.10	1.07	1.08	1.07*	1.03*	1.15
	60 mph							60 mph						
S.R. / N.R.	1.48	1.37	1.20	1.24	1.25	1.32	1.23	–	–	1.02*	1.25	1.10*	1.0*	1.09
H.S.S. / N.R.	1.92	1.44	1.34	1.42	1.45	1.41	1.41	–	–	1.02*	1.36	1.29	1.15	1.19
H.S.S. / S.R.	1.27	1.06*	1.13	1.14	1.15	1.07	1.29	–	–	1.0*	1.11*	1.20	1.16	1.09

* Denotes that the ratio is not significantly different from unity at the 5% level.

Note: S.R. = synthetic rubber; N.R. = natural rubber; H.S.S. = high-styrene synthetic rubber.

1. Tread patterns provide vast improvements over smooth tires in both **PC** and **SC** on smooth surfaces. The effect is more pronounced at the higher velocities than at the lower velocities.

2. The siped tire or the tire with fully developed modern tread pattern having multiple sipes offers significant advantages over the ribbed pattern on smooth surfaces, especially at the higher velocities. This advantage diminishes on coarse open-textured surfaces.

3. The effectiveness of tread pattern decreases with an increase in the coarseness of the surface. This can be seen from both **PC** and **SC** ratios for surface 7.

The effectiveness of tread patterns on various pavement surface textures can be explained mainly on the basis of water drainage from the tire contact area. As previously discussed, the presence of water causes hydrodynamic lift and decreases the adhesion component of friction. On a smooth surface the drainage is facilitated by the grooves and sipes of the tire tread. On a coarse surface the channels combined with the grooves and sipes facilitate drainage. The channels in surface 7 appear to be sufficient to remove most of the water at 30 mph and 60 mph. Thus it appears that tire tread patterns are not very important on coarse-textured surfaces. However, their importance at velocities above 60 mph is not known.

From the ratios given in Table 12 the following statements can be made concerning the effectiveness of tread composition:

1. An increase in **PC** of 20 to 50% is obtained by using synthetic rubber rather than natural rubber. Approximately equal proportionate increases are found on all surface textures.

2. The corresponding improvements in **SC** are generally lower than those in **PC**. The increase rarely exceeds 30%. For 30 mph lower ratios are given for surfaces 1, 2, and 5 than for the others. This indicates that a large number of small, sharp asperities, such as those in surfaces 3 and 4, have better interaction with the tread materials than the larger rounded stones of surface 5.

3. The ratios reflect little difference between the two synthetic rubbers. The difference that does exist corresponds to the small difference in the resilient properties of the two rubbers shown in Figure 38. This fact indicates that there is a definite association between friction coefficient and resilience of tread rubber.

4. Both skid and peak ratios at 30 mph are, in general, similar to those at 60 mph, the latter being slightly higher.

Regarding the interaction between tread design and rubber composition, the ratios from Tables 11 and 12 indicate that the smooth tire—natural rubber combination should yield abnormally low PCs and SCs. The reason for this may be due to the peculiarity of the combination or strictly to the tread resilience. Another reason may be the cooling action of water in the grooves, providing higher values of decelerometer coefficient than expected.

Since the test results showed the importance of tire tread design, Maycock (1965-1966) conducted a second series of tests using eight different tread designs on surfaces 2, 3, and 4, with a water film thickness of approximately 0.04 inch. The tests were conducted in a manner similar to the first series. Table 13 summarizes the features of the tires and their effect on **PC** and **SC**. The following findings from this experiment can be made:

1. As found from the results of the first series, changes in tread design have greater effect on smooth and fine-textured surfaces than on coarse-textured surfaces. The effectiveness is greater at the higher velocities than at the lower velocities, where even some reduction in **SC** can be expected. In addition, tread design modifications affect **PC** to a greater extent than they do **SC**.

2. An increase in the number of ribs results in a considerable increase in the **PC** at high velocities, but only in a slight increase in **SC**.

3. An increase in the size of circumferential grooves improves both the **PC** and the **SC** at high velocities, especially the **SC**. An increase is also obtained with the introduction of diagonal drainage channels, particularly on the fine-textured surfaces. Of the two modifications, the wider circumferential grooves in general give a slightly higher **PC** and **SC** at the higher velocities. However, diagonal drainage channels provide a higher **PC** on the smoothest surface.

4. The radial-ply tire gives a higher **PC** but a lower **SC** at the higher velocities than the conventional tire with identical tread design. Since the results are for two test surfaces only and with test tires, this finding does not necessarily apply to other surfaces and production tires.

Horne and Leland (1963) reported on the effect of tread design on friction coefficient measured during full-scale aircraft braking tests. As shown in Figure 40 there is an increase in the average friction coefficient when circumferential grooves are cut in the aircraft tire. The process of tread wear may be considered as the reverse of cutting grooves, and the smooth tread can be assumed to represent a completely worn ribbed tread. The question as to what stage of wear the rib tread tire becomes ineffective is difficult to answer. Horne and Leland (1963) indicated that this may occur when 80 to 90% of the tread is worn.

Table 13. Summary of Results—Second Series (After Maycock, 1965-1966)

(Bold numbers indicate tread design; (2) = polished concrete; (3) = asphalt with sandpaper texture; (4) = asphalt with 3/4 in. chippings rolled into the surface.)

Tire Features		Effect of Changing From Tire *a* to Tire *b* on:			
Tire *a*	Tire *b*	Surface	Peak Coefficients	Surface	Skid Coefficients
1 5 ribs (straight circumferential grooves)	**2** 6 ribs (straight circumferential grooves)	(2)	Considerably reduced speed effect*	(2)	Slightly reduced speed effect*
		(3)	Considerably reduced speed effect	(3)	No effect
		(4)	Insufficient data	(4)	Insufficient data
3 Standard pattern (6 ribs)	**2** 6 ribs (as above)	(2)	Slightly increased speed effect	(2)	Increase in coefficient (0.05)
		(3)	No effect	(3)	No effect
		(4)	Insufficient data	(4)	Insufficient data
3 Standard pattern (radial ply)	**4** Standard pattern (biased ply)	(2)	Decrease in coefficient (0.08)	(2)	Slightly reduced speed effect
		(3)	No effect	(3)	Slightly reduced speed effect
		(4)	Decrease in coefficient (0.08)	(4)	Slightly reduced speed effect
3 Standard pattern	**5** Grooves straightened and widened	(2)	No effect	(2)	Reduced speed effect
		(3)	Reduced speed effect	(3)	Reduced speed effect
		(4)	No effect	(4)	Reduced speed effect
3 Standard pattern (6 ribs)	**8** 7 rib version	(2)	Increase in coefficient (0.04 and 0.12 resp.)	(2)	Slightly reduced speed effect
		(3)	Increase in coefficient (0.04 and 0.12 resp.)	(3)	No effect
3 Standard pattern	**7** Additional diagonal grooves creating blocks (experimental block)	(2)	Considerably reduced speed effect	(2)	Reduced speed effect
		(3)	Considerably reduced speed effect	(3)	No effect
		(4)	Slightly reduced speed effect	(4)	Reduced speed effect
7 Experimental block pattern	**6** Production block pattern	(2)	No effect	(2)	Slightly increased speed effect
		(3)	Increase in coefficient (0.05)	(3)	No effect
		(4)	No effect	(4)	No effect
5 Both tires standard pattern with additional drainage channels	**7**	(2)	Reduced speed effect	(2)	No appreciable effect
		(3)	Increase in coefficient (0.05)	(3)	Slightly increased speed effect
		(4)	No effect	(4)	Slightly increased speed effect

* Speed effect is the fall of coefficient as the speed increases. Every case above, in which the speed effect is recorded as having been reduced, has resulted in increased coefficients at the higher speeds.

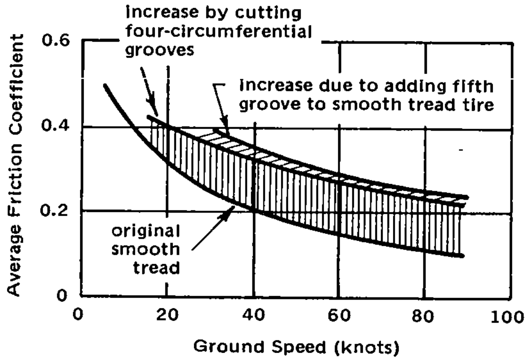


Figure 40. **Effect of tire tread on friction coefficient PCC surface; water depth = 0 to 0.3 inch.** (© Horne and Leland, 1963. Used by permission.)

Horne and Leland (1962) measured the variations in friction coefficient of various aircraft tires in the Langley landing-loads track. The vertical load was 10,000 pounds, with a tire inflation pressure of 260 psi. The track surface was PCC with a water film thickness of approximately 0.3 inch. Figure 41 shows the average friction coefficient for the tires with the various tread designs. It should be noted that very little difference in friction coefficient was measured between the smooth and dimple treads throughout the velocity range. Thus, a single curve is shown in Figure 41 for the two tread designs which provide the least average friction coefficient. The tire with nine circumferential grooves gives the highest values, followed by the tire with five grooves. Thus, an increase in the number of grooves generally corresponds to an increase in the friction coefficient. However, the design of tires involves a compromise between many requirements and factors, such as tread wear and the shear strength of rubber, which limit the number of grooves. For this reason, the tire in Figure 41 with nine grooves is not permitted for use on high-speed aircraft.

The curves for the two diamond tread tires in Figure 41 indicate that the small-diamond tread (more grooves) develops a higher friction coefficient than the large-diamond tread. This corresponds to the previous findings regarding the number of circumferential grooves. In addition, lateral grooves and diamond tread are shown in Figure 41 to be less effective than circumferential grooves.

Giles, Sabey, and Cardew (1962) used the British pendulum tester to find the relationship between the BPN and the resilience of rubber sliders for four different surfaces. As shown in Figure 42, the relationship depends on the type of surface. No change in BPN is seen for a glass surface. However, there is a definite decrease in BPN for the other surfaces. The rate of decrease is higher for coarse-textured surfaces than for smooth surfaces. The reasons for these characteristics appear to be that (1) resilience increases with a rise in temperature, which tends to decrease the friction coefficient and (2) with an increase in resilience more rubber is deformed, and there is a greater change in friction coefficient per unit change in resilience.

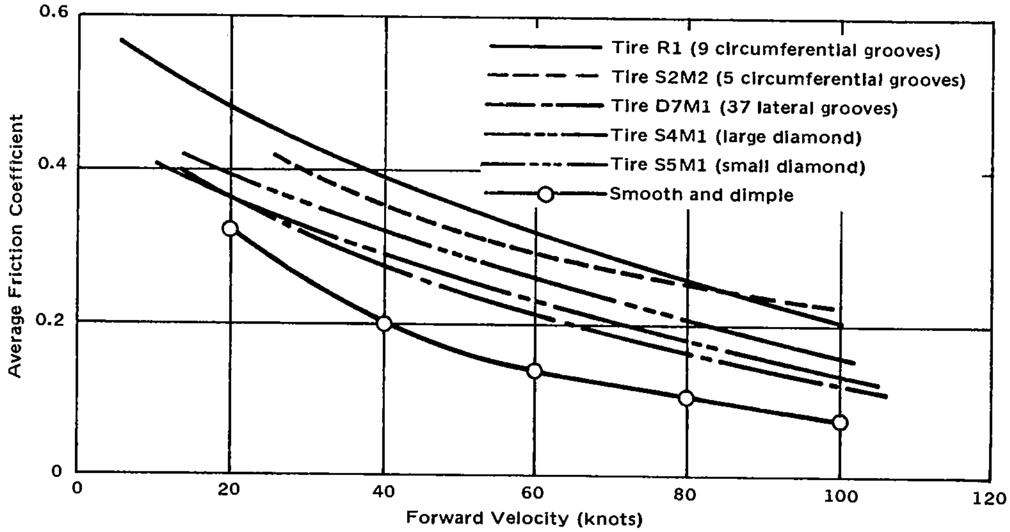


Figure 41. Wet-runway braking effectiveness of tire treads on a wet concrete runway. $F_v \approx 10{,}000$ pounds; $P_t = 260$ psi; water depth = 0 to 0.3 inch. (© Horne and Leland, 1962. Used by permission.)

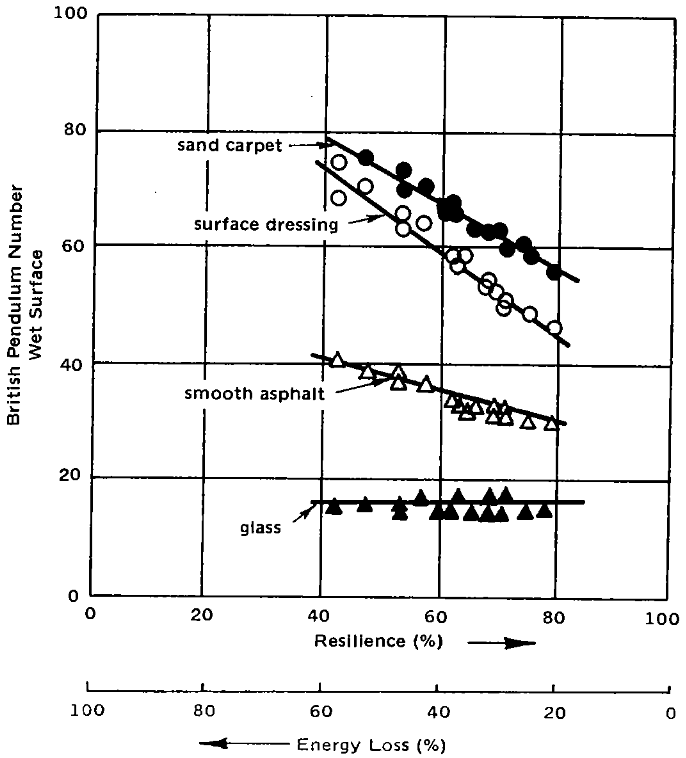


Figure 42. Dependence of BPN on rubber resilience (energy loss). (© Giles, Sabey, and Cardew, 1962. Used by permission.)

Table 14. Details of Rubber Compounds Used in the Resilience and Hardness Tests (© Sabey and Lupton, 1964. Used by permission.)

(All compounds are vulcanizates of a tire tread type, although not all are known to have been used in tires. The compounds are grouped according to the source of manufacture.)

Code No.	Basis of Compound	Remarks
1* 2* 3	Natural rubber	Specially compounded to give a range of hardness
4 5 6* 7	Natural rubber	Two compounds with different amounts and types of carbon black; no. 4, 5, and 6 are three batches of one compound made to nominally the same specification.
8 9 10 11*	Natural rubber	Specially compounded to give a range of resilience
12	Natural rubber	
13* 14	Natural rubber SBR**	Specially compounded to give low resilience
15 16* 17	Natural rubber SBR SBR (oil extended)	Normal tread compounds in use in Great Britain; no. 16 a normal synthetic compound in use immediately prior to 1961; no. 17 a new compound introduced in 1961.
18	SBR	Normal tread compound in use in Europe
19 20 21	SBR (oil extended) SBR (oil extended) SBR (extended)	Compounds extended to give decreasing resilience
22*	Polybutadiene	
23*	Ethylene/propylene	
24	Butyl	
25*	Butyl	

* Compounds selected for the friction tests.

** Styrene butadiene rubber.

Sabey and Lupton (1964) investigated the variations in hardness and resilience with temperature of a wide variety of rubber compounds and determined the effect of these characteristics on BPN under wet conditions. Twenty-five rubber compounds (listed in Table 14) were used in the hardness-

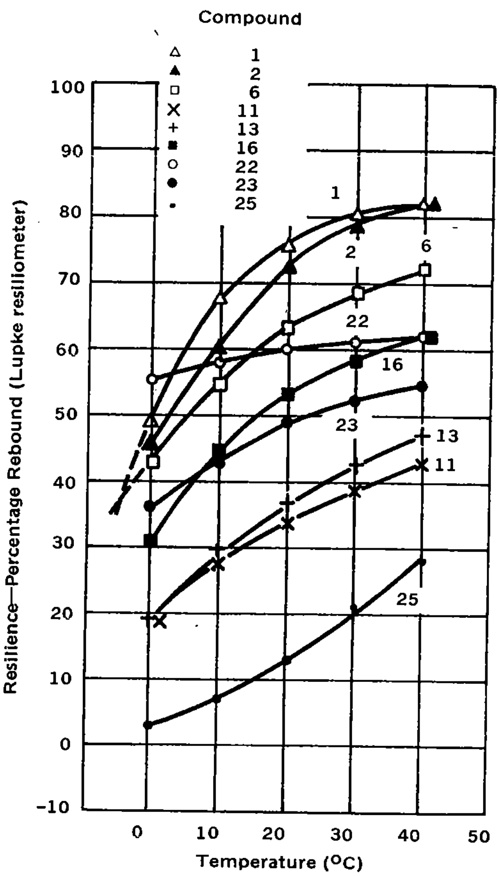


Figure 43. Variation in resilience with temperature for nine selected rubber compounds. (© Sabey and Lupton, 1964. Used by permission.)

resilience-temperature relationship study. The temperature for the hardness and resilience tests ranged from 0 to 80°C. Nine of these compounds were selected for the friction tests with the British pendulum tester on seven different surfaces (shown in Table 15), with temperature ranging from 1 to 40°C.

Figures 43, 44, and 45 show the relationship of temperature to resilience, hardness and BPN. In general, Figure 43 shows that all rubber compounds increase in resilience with an increase in temperature. However, the rate of increase varies from compound to compound. A batch-to-batch variation of up to 8% can also be expected. Natural rubber compounds have, in general, higher resilience than synthetic rubber compounds, although there is overlap in the results. The butyl compound, 25, is the least resilient over the 0 to 40°C temperature range.

Table 15. Test Surfaces Used in the Friction Tests With Nine Selected Rubber Compounds (© Sabey and Lupton, 1964. Used by permission.)

(Surfaces listed in increasing order of roughness.)

Code No.	Description	Texture Depth* (in.)
I	Very smooth, very highly polished	<0.001
II	Smooth, polished	0.002
III	Smooth looking, sandpaper texture	0.006
IV	Very harsh, projections of the order of 0.1 in. in size	0.026
V	Rough coarse, textured, mixture of harsh and polished stones	0.028
VI	Rough coarse textured, harsh stones	0.039
VII	Rough coarse textured, polished stones	0.040

* Measured by the sand-patch method.

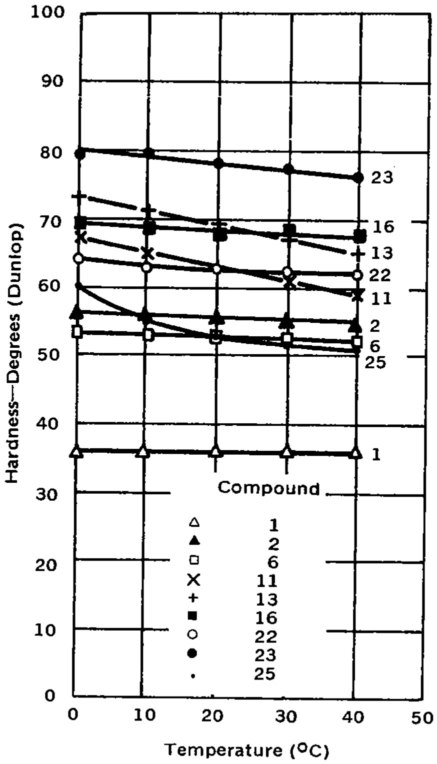


Figure 44. Variation in hardness with temperature for nine selected rubber compounds. (© Sabey and Lupton, 1964. Used by permission.)

Figure 44 shows that changes in hardness with temperature are much lower than changes in resilience. In general, there is a slight decrease in hardness with an increase in temperature. With the exception of one compound (no. 1), the hardness values range from 53 to 79 degrees on the Dunlop hardness gage at 0°C and 52 to 76 degrees at 40°C.

A comparison of Figures 44 and 45 indicates that some compounds (1, 2, 6, and 16) showing little hardness change with temperature exhibit significant changes in BPN with temperature. For other compounds with higher hardness changes the reverse is true. Thus, the results suggest that the effect of hardness is small, and that another factor has a greater influence on friction.

A comparison of Figures 43 and 45 indicates that changes in BPN with temperature are related more closely to resilience changes than to hardness changes. With the exception of compound 25, an increase in resilience with temperature is associated with a decrease in BPN. While this pattern is obvious, the order of BPN and resilience is not the same at the same temperature, as shown by the following example at 20°C, where compounds 22 and 23 particularly are out of order:

Increasing BPN (in Figure 45): 22, 23 (1 and 2), 6, 16, 13, 11, and 25.

Decreasing resilience (in Figure 43): 1, 2, 6, 22, 16, 23, 13, 11, and 25.

A direct comparison of the BPN and resilience values is complicated for two reasons: (1) the rubber is being deformed in different ways under the resilience test and the test with the British pendulum tester or other skid tests, and (2) the wide variety of surface textures influences the effective resilience.

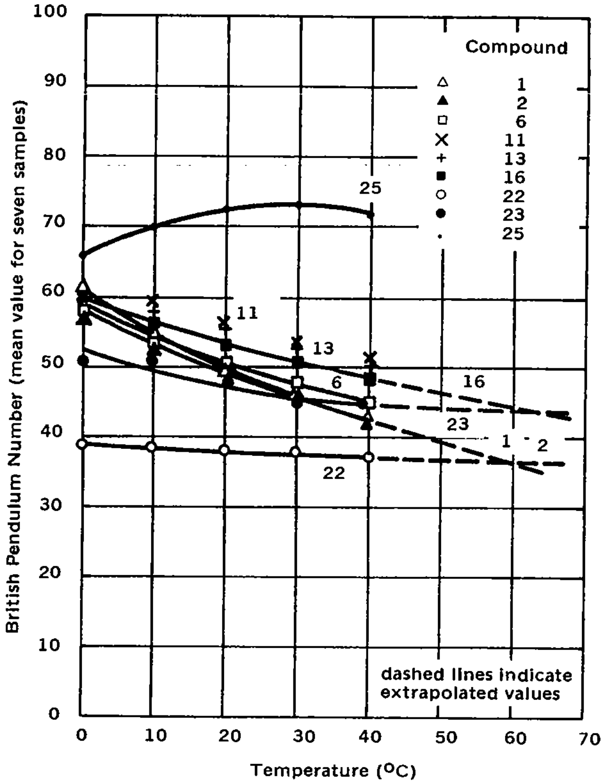


Figure 45. Variation in BPN with temperature for nine selected rubber compounds (mean value measured on seven surfaces).
(© Sabey and Lupton, 1964. Used by permission.)

Changes in tire-pavement contact pressure are brought about by variations in wheel load and tire inflation pressure, P_t. As previously discussed, the adhesion coefficient decreases with an increase in the contact pressure, but the hysteresis coefficient is not affected. Hofelt (1959) reported that the influence of tire inflation pressure is greater than that of wheel load on contact pressure. It should follow then that changes in the tire inflation pressure should have a more pronounced effect on the friction coefficient than changes in the wheel load.

Kummer and Meyer (1967) investigated the effects on SN of varying the wheel load at a constant tire inflation pressure and of varying the tire inflation pressure at a constant wheel load. As shown in Figure 46, there is a small reduction in SN associated with an increase in F_v at a P_t of 24 psi. The reduction is slightly more with the treaded tire than with the smooth tire at 10 mph. However, the curves for the treaded tire appear to converge faster with an increase in velocity.

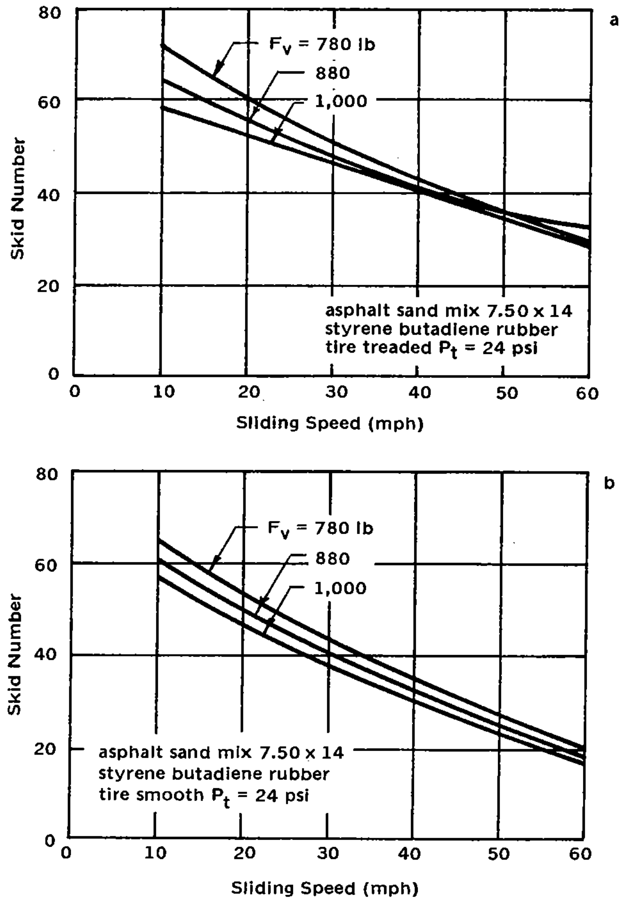


Figure 46. Influence of wheel load on skid resistance for (a) treaded and (b) smooth tires on fine-textured, rounded aggregate surface. (© Kummer and Meyer, 1967. Used by permission.)

As shown in Figure 47, increasing the tire inflation pressure, P_t, with an F_v of 800 pounds generally results in a decreasing SN. The reduction is again small. Surface 4 appears to show the highest difference in SN with changes in the tire inflation pressure.

Horne and Leland (1963) investigated the effects on the average friction coefficient of changing the tire inflation pressure. As shown in Figure 48, the test results obtained with three different tires on PCC indicate practically no effect. Some effect is shown for one tire on an AC runway. The water depth of 0 to 0.5 inch indicates shallow fluid on the runway, with puddles, but with the higher portions of the surface projecting through the fluid surface.

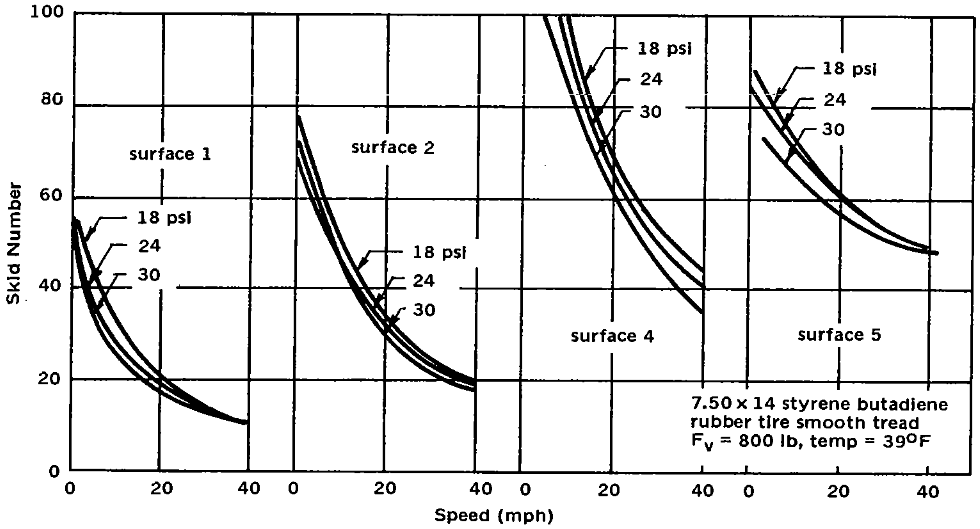


Figure 47. Effect of inflation pressure on the skid resistance of four different surface types. (© Kummer and Meyer, 1967. Used by permission.)

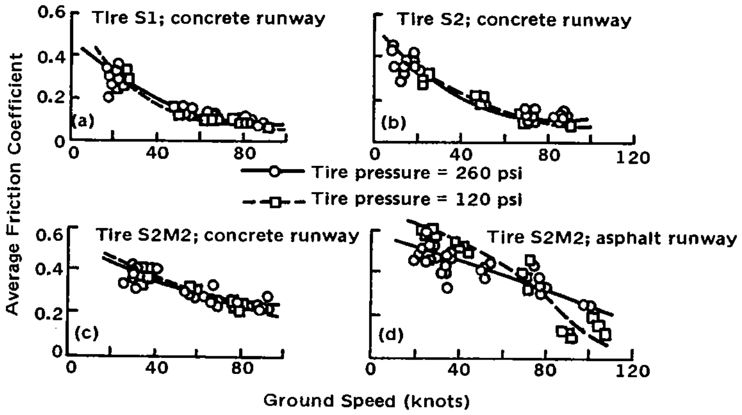


Figure 48. Effect of tire pressure and type of runway surface on friction coefficient; water depth = 0 to 0.5 inch. (© Horne and Leland, 1963. Used by permission.)

Horne and Leland (1962) investigated the effects on the friction coefficient of changing the wheel load while keeping the tire inflation pressure constant. As shown in Figure 49, an increase in wheel load of 12,000 pounds decreases the average friction coefficient by approximately 0.05 throughout the velocity range of 20 to 100 knots.

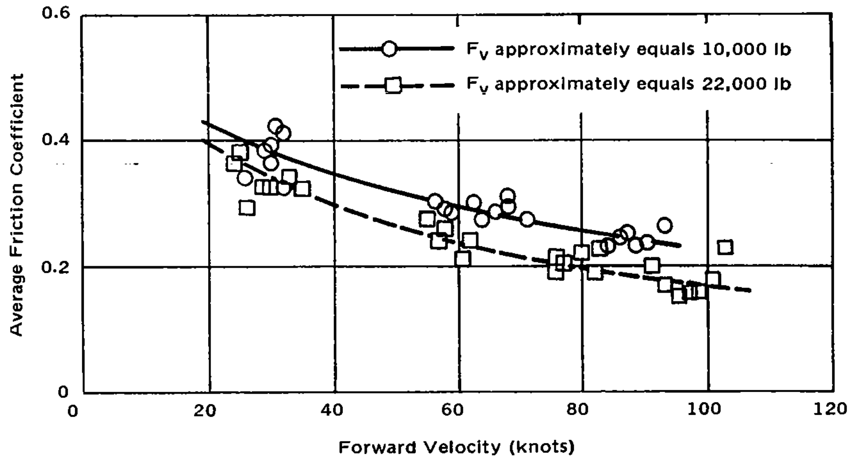


Figure 49. Average friction coefficients obtained during single-wheel braking runs with tire S2M2 at ground vertical loads of approximately 10,000 and 22,000 pounds. Wet concrete runway; water depth = 0 to 0.3 inch; P_t = 260 psi. (© Horne and Leland, 1962. Used by permission.)

As previously mentioned, the macroscopic roughness of the pavement surface and the microscopic roughness of the aggregate particles have the most effect on the friction coefficient. On any relatively clean, dry surface high skid resistance can be obtained regardless of velocity. Apparently the coupling of the adhesion and hysteresis coefficients in a complementary manner yields this characteristic. On wet pavement, however, the brake slip coefficient and, more so, the skid coefficient decrease with an increase in velocity. The rate of decrease is closely related to the macroscopic roughness of the surface and the velocity. The macroscopic roughness can be characterized by the mean width of the voids between the protruding aggregate particles or by the mean height of the aggregate particles.

Shulze and Beckmann (1962) investigated the effect of macroscopic roughness on the SC—velocity relationship; they based their conclusions on measurements made with a skid trailer on 48 wet pavement surfaces. Stereophotographs were taken to determine the macroscopic features of the surfaces, which were classified from close-textured (fine) to open-textured (coarse). These classifications were based on the mean width of the voids between the protruding aggregate particles. The difference in SC at 20 and 60 km/hr was used to characterize the steepness of the SC—velocity curves.

As shown in Figure 50, there is a significant correlation between the mean widths of surface voids and the gradient of the SC—velocity curve. The higher SC—velocity gradient is associated with the closer void width, and the lower SC—velocity gradient with the wider width. Better drainage capability

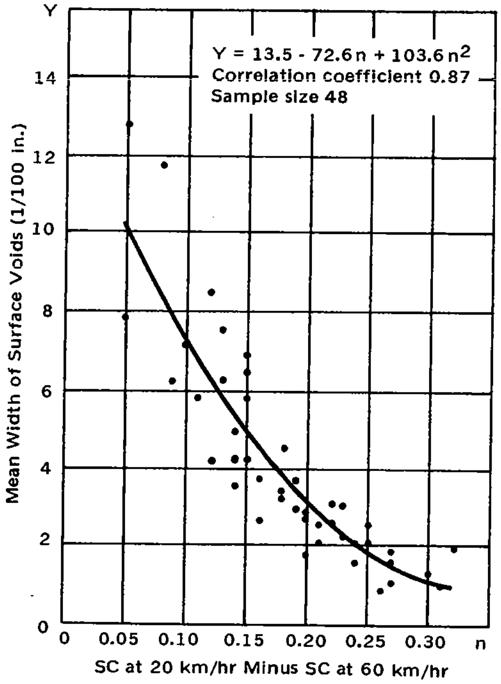


Figure 50. Correlation between surface texture and steepness of the curve relating skid coefficients to speed. (© Shulze and Beckmann, 1962. Used by permission.)

with an increase in void width is one explanation of the behavior. Thus, the advantage of the wider width occurs at higher velocities. At the lower velocities, however, the lower contact area of the open-textured surfaces may result in a lower **SC** than would be found on fine-textured surfaces.

Shulze and Beckmann (1962) indicated that the gradient of the **SC**—velocity curve is independent of the magnitude of the **SC**. For example, if two surfaces with the same mean void width but with different small-scale macroscopic roughness are tested at various velocities, the resulting **SC**—velocity curves will be similar, with a constant difference throughout the velocity range. The small-scale macroscopic roughness, or "grittiness," of the surface appears to determine the magnitude of the **SC**.

Sabey (1965) investigated the effect of texture depth on the percent decrease in **SC** from 30 to 80 mph as determined from measurements with a skid trailer. The texture depth was determined by the "sand-patch" method. In this method a known volume of fine, uniform-particle sand is poured on the pavement surface. The sand is spread to form a uniform circular patch so that the surface depressions are filled to the level of the peaks. The diameter of this patch is measured. The texture depth is the ratio of the volume of sand to the area of the patch. In general, surfaces with texture depth less than 0.010 inch are considered smooth, those with more than 0.020 inch coarse. Although the scatter is large in the results shown in Figure 51, the percentage decrease in **SC** decreases with an increase in texture depth, from approximately 40% at 0.010-inch texture depth to approximately 10% at 0.040 inch.

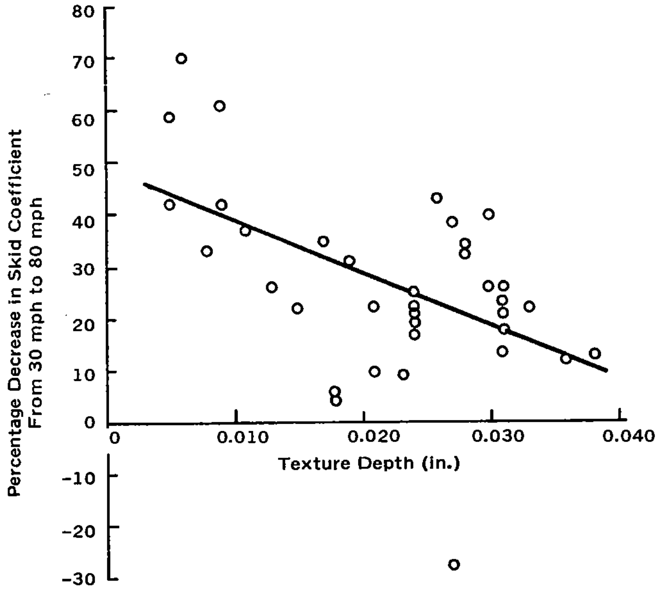


Figure 51. Relation between percentage decrease in skid coefficient resistance between 30 and 80 mph and texture depth. (© Sabey, 1965. Used by permission.)

In addition to the mean void measurement and the sand-patch method, the grease-smear method and the drainage meter have been used to determine the drainage capability of a pavement surface. The grease-smear method used by NASA yields a ratio of volume to area similar to that of the sand-patch method by relating a known volume of grease to the smeared area. The drainage meter, developed at Pennsylvania State University, is a transparent cylinder, approximately 5 inches in diameter and 12 inches high, with a rubber ring glued to one face. This cylinder is placed with the rubber ring in contact with the pavement surface. Various loads can be applied to the cylinder to obtain different contact pressures between the rubber ring and the pavement surface. The time it takes a known volume of water to escape from between the rubber ring and the pavement surface, together with the density of the aggregate particle peaks, determines the drainage potential of the surface.

As previously mentioned, the small-scale macroscopic roughness determines the magnitude of the friction coefficient. This roughness can be attributed to (1) the characteristics of the coarse aggregate particles exposed to the surface, (2) the mortar of sand and cement, or (3) a combination of the two. If a surface has a high percentage of exposed coarse aggregate, its polishing resistance mainly determines the relationship between friction coefficient and the number of vehicles. When the mortar forms a significant part of the surface, it governs the friction coefficient—traffic number relationship. This latter surface may contain coarse aggregates with small-scale macroscopic roughness and yet yield a low friction coefficient because of the predominant influence of the mortar. Bituminous surfaces can have a low percentage of coarse aggregates at the surface as a result of excessive rolling during construction or compaction under traffic. For **PCC** the coarse aggregate generally is less important in determining the small-scale texture, because it is less exposed than it is on some bituminous surfaces. Thus, the magnitude of friction coefficient for these surfaces depends on the type and grading of the fine aggregate and on the proportions of the mix.

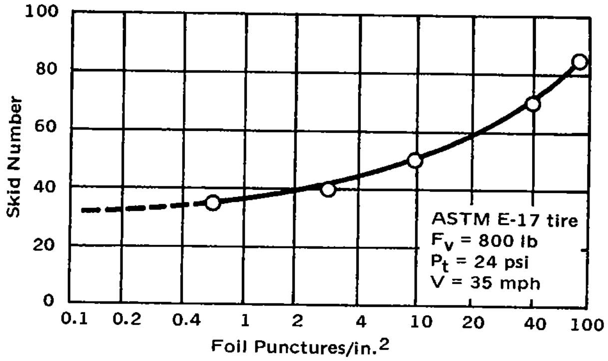


Figure 52. Characterization of friction properties of pavement surfaces by foil-piercing techniques. (© Kummer and Meyer, 1967. Used by permission.)

Kummer and Meyer (1967) reported on the relationship between the density of sand-size particles and the friction properties of pavement surfaces. The density was obtained by using a foil-piercing technique. In this technique a piece of aluminum foil placed on the pavement surface is impacted by a rubber-tipped plunger released from a predetermined height. The impact forces the foil to conform to the pavement texture, with the sharper particles piercing the foil. The number of piercings, or punctures, is counted in the foil or on a photographic negative of the foil. As shown in Figure 52, a minimum of 10 punctures/in.^{2} is needed to obtain an **SN** of 50.

Kummer and Meyer (1967) reported that, in addition to the large-scale and the small-scale macroscopic roughnesses of the pavement surface, the microscopic roughness of the aggregate particles must have a measurable influence on the friction coefficient. This statement is based on the variation in skid resistance before, during, and after rainy periods. Rain appears to attract the larger sizes of polishing agents on aggregate particles and also on tires. This increases the microscopic roughness rather readily on soft aggregates such as limestone, resulting in a temporary increased skid resistance. However, the polishing action is less effective on other aggregates, especially those with a high reading on Mohs' scale of hardness and a high resistance to polishing.

From the foregoing discussions it appears that the friction coefficient is dependent mainly on the large-scale and small-scale macroscopic roughnesses of pavement surfaces. Thus, the description or classification of pavement surfaces based on a single adjective appears to be insufficient. Kummer and Meyer (1967) proposed the following classification, which includes the two different roughness scales:

1. Smooth surfaces (bleeding surface; highly polished stone, asphalt, or PCC surfaces).

2. Fine-textured, rounded surfaces (worn stone or silica sand surfaces of fine gradation).

3. Fine-textured, gritty surfaces (new silica sand or metal carbide-epoxy surfaces).

4. Coarse-textured, rounded surfaces (polished slag or limestone surfaces of large gradation, or uncrushed gravel surfaces).

5. Coarse-textured, gritty surfaces (new slag pavements consisting of large particles resulting in a surface with large-scale and small-scale macroscopic roughness, or limestone surfaces which contain more than 10% sand-sized siliceous material).

The cross-sectional views and the SN—velocity relationships of the five surfaces are shown in Figure 53. Note that surfaces 2 and 3, which are fine-textured, have higher SN—velocity gradients than the coarse-textured surfaces 4 and 5. As discussed previously, the gradient is determined by the initial texture scale or the drainage ability of the surfaces. Also note that the second adjective, rounded or gritty, determines the magnitude of the SN within the texture type.

Sabey (1965) also described the types of pavement surfaces on the basis of two roughness scales. The surfaces shown in Figure 54 have the following descriptions:

A. Macadam: coarse-textured, harsh stones
B. Macadam: coarse-textured, some polished stones
C. Macadam: coarse-textured, all highly polished stones
D. Fine cold asphalt: fine-textured, sandpaper
E. Concrete: fine-textured, slightly polished
F. Mastic asphalt: fine-textured, highly polished

In these descriptions the harsh stones and sandpaper correspond to the word "gritty" used by Kummer and Meyer (1967) and the polished stones to the word "rounded." In Figure 54 the texture corresponds to the gradient, and the grittiness corresponds to the magnitude of the friction coefficient within the same texture type.

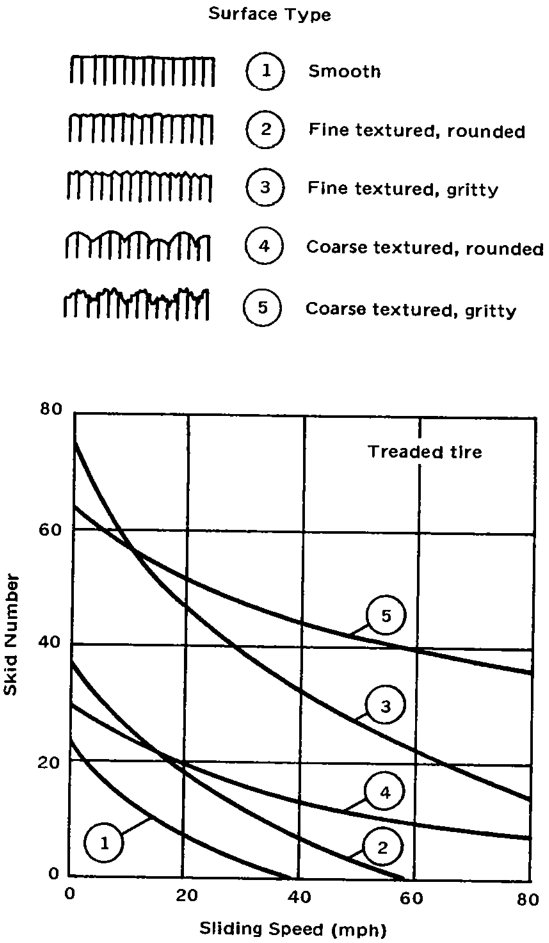


Figure 53. Classification of pavement surfaces according to their friction and drainage properties. © Kummer and Meyer, 1967. Used by permission.)

Some of the tire and pavement surface factors discussed in this section have a marked influence on slip and skid resistances. Tables 16, 17, and 18 summarize the influence of the factors in qualitative terms.

Traffic and Seasonal Changes

Some effects of traffic and seasonal changes on the friction coefficient were discussed previously by Tomita (1964). These changes included polishing wear and surface contamination caused by traffic, foreign material, and climate. The following paragraphs provide some additional results found in the literature.

Horne and Leland (1962) investigated the effects of JP-4 jet fuel spillage on AC surfaces and rubber deposits on PCC surfaces in the Langley landing-loads track. Fuel spillage on runways, though not a usual occurrence, may present a serious problem with asphaltic concrete. Evidence is numerous of rubber deposits on many of the Navy airfield runways, mostly confined to the runway ends. The test results, as shown in Figure 55, indicate that a damp asphaltic concrete surface with spilled JP-4 provides approximately 60% of the average friction number for a similar damp or wet surface without the spilled fuel. Figure 56 shows that rubber contamination of a dry PCC surface definitely lowers the friction values at slip ratios ranging from 0.1 to 1.0. These findings indicate that fuel spillage and rubber deposits can present a potential skid problem for aircraft operations.

Table 16. Influence of Pavement Surface Geometry on Skid Resistance (Treaded Tire, All Other Factors Constant) (© Kummer and Meyer, 1967. Used by permission.)

Surface Type	Surface Roughness		Surface Properties		Wet Skid Resistance	
	Scale of 1/32-1/8 in.	Scale of 1/8-1/2 in.	Friction	Drainage	at 0-35 mph	at 35-70 mph
1. Smooth	none	none	poor	none	poor	none*
2. Fine textured, rounded	yes	none	marginal	poor	marginal	poor
3. Fine textured, gritty	yes	none	excellent	poor	excellent	marginal
4. Coarse textured, rounded	none	yes	marginal	good	marginal	marginal
5. Coarse textured, gritty	yes	yes	excellent	good	very good	good

* Slipping tires with well-designed tread patterns will transmit small forces in this case.

Table 17. Change of Slip and Skid Resistance Due to Increase in Rubber Hardness and Damping and the Addition of Tread Grooves and Slots on Different Surface Types (Other Factors Constant) (© Kummer and Meyer, 1967. Used by permission.)

Surface Type	Change of Slip and Skid Resistance Due to Increase or Addition of			
	Rubber Hardness	Rubber Damping	Grooves*	Slots and Slits**
1. Smooth	increasing	not affected	increasing	increasing
2. Fine textured, rounded	increasing	not affected	increasing	increasing
3. Fine textured, gritty	not affected	increasing	increasing	not affected
4. Coarse textured, rounded	decreasing	increasing	decreasing	increasing
5. Coarse textured, gritty	decreasing	increasing	decreasing	not affected

* Grooves placed circumferentially.
** Placed transversely or obliquely to grooves (slots are molded, slits are cut after molding).

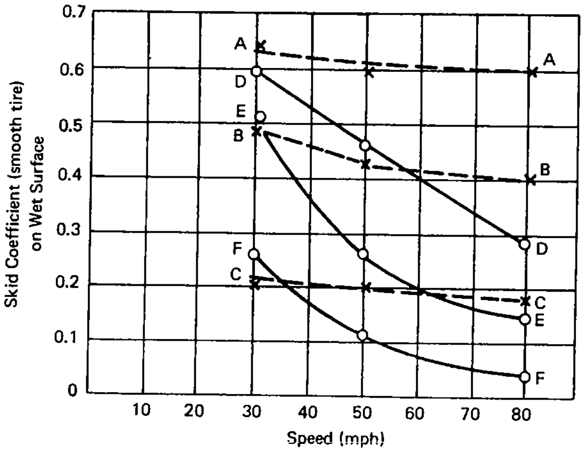


Figure 54. Change in skid coefficient with speed on six surfaces on the Road Research Laboratory test track. (© Sabey, 1965. Used by permission.)

Table 18. Influence of Surface Type and Tread Pattern Combinations on Slip and Skid Resistance (All Other Factors Constant) (© Kummer and Meyer, 1967. Used by permission.

Surface Type	Tread Pattern	Slip Resistance		Skid Resistance	
		at 0-35 mph	at 35-70 mph	at 0-35 mph	at 35-70 mph
1. Smooth	smooth grooves only slots and slits only grooves, slots, and slits	poor poor marginal marginal	none very poor very poor poor	very poor very poor poor poor	none none none very poor
2. Fine textured, rounded	smooth grooves only slots and slits only grooves, slots, and slits	marginal marginal marginal good	very poor poor poor marginal	very poor poor poor marginal	none very poor very poor poor
3. Fine textured, gritty	smooth grooves only slots and slits only grooves, slots, and slits	excellent very good excellent very good	good good good good	very good good very good good	marginal marginal marginal marginal
4. Coarse textured, rounded	smooth grooves only slots and slits only grooves, slots, and slits	good good very good very good	marginal marginal good good	marginal marginal good good	poor poor marginal marginal
5. Coarse textured, gritty	smooth grooves only slots and slits only grooves, slots, and slits	excellent excellent excellent excellent	very good very good very good very good	excellent very good excellent very good	good good good good

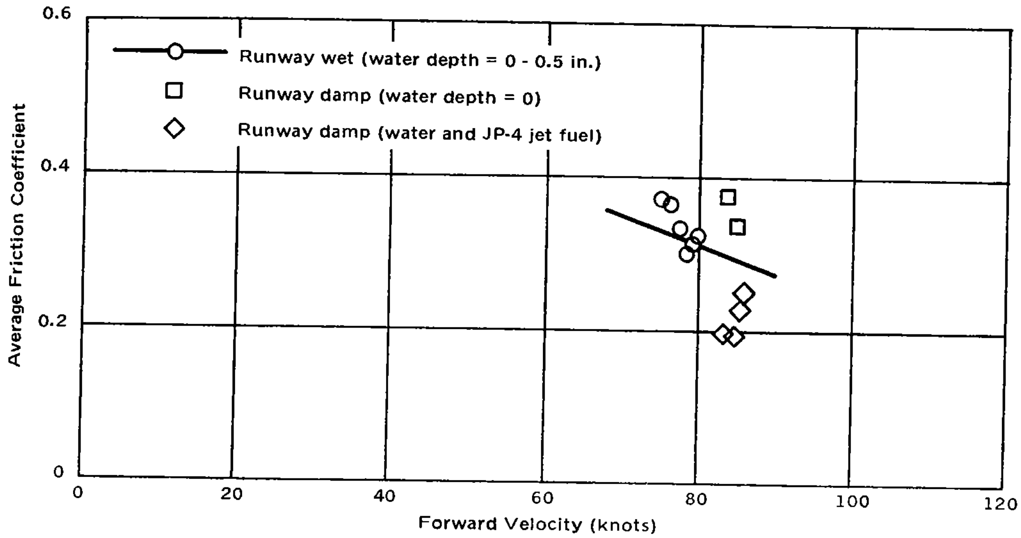


Figure 55. Comparison of average friction coefficients obtained on water-covered and damp asphaltic concrete runways. Data obtained during single-wheel braking tests. $F_v \approx 10{,}000$ pounds; $P_t = 260$ psi. (© Horne and Leland, 1962. Used by permission.)

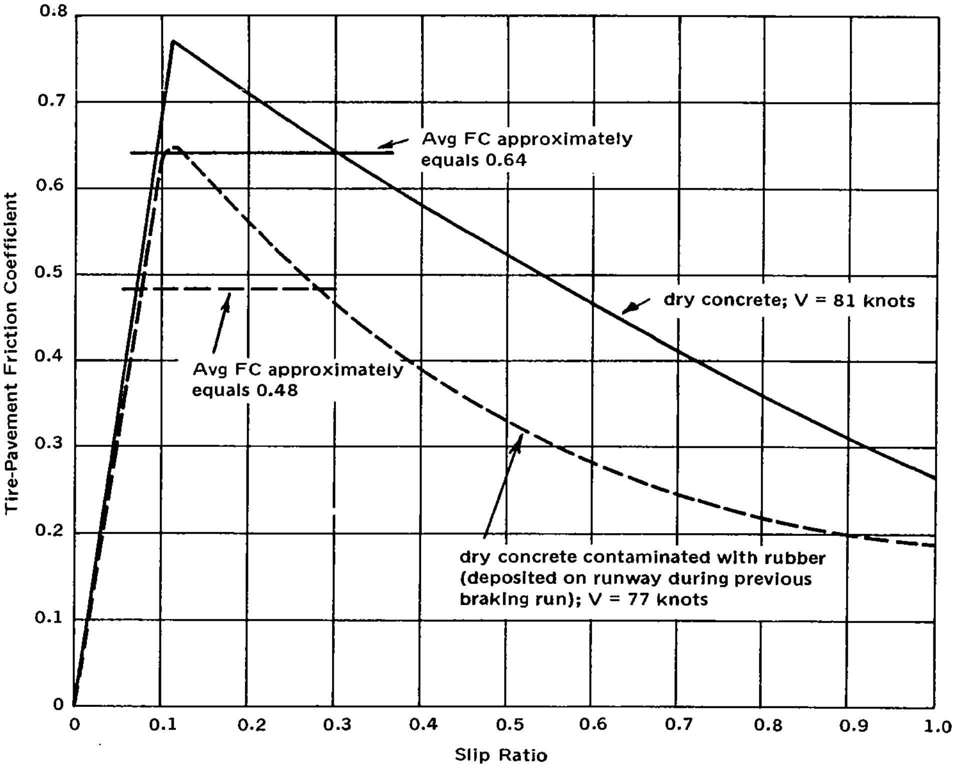


Figure 56. Effect of rubber contamination of a concrete runway surface on the braking friction developed by a 44 x 13, type VII, 26-ply-rated aircraft tire. $F_v \approx 20{,}400$ pounds; $P_t = 150$ psi. (© Horne and Leland, 1962. Used by permission.)

Giles, Sabey, and Cardew (1962) used the British pendulum tester to evaluate the suggested temperature correction on eight pavement surfaces with various surface textures. The results, shown in Figure 57, indicate that the temperature correction becomes really important for tests below 10°C, where the corrections are large. The corrections will permit a more accurate assessment of skid resistance experienced by tires, because tires in motion are generally hotter than the rubber slider of the pendulum tester. The following list, which relates the average temperatures of a rubber slider to those of tires on moving vehicles, is based on 500 comparative measurements:

Slider	Tire
5°C	15°C
20°C	25°C
30°C-40°C	30°C-40°C

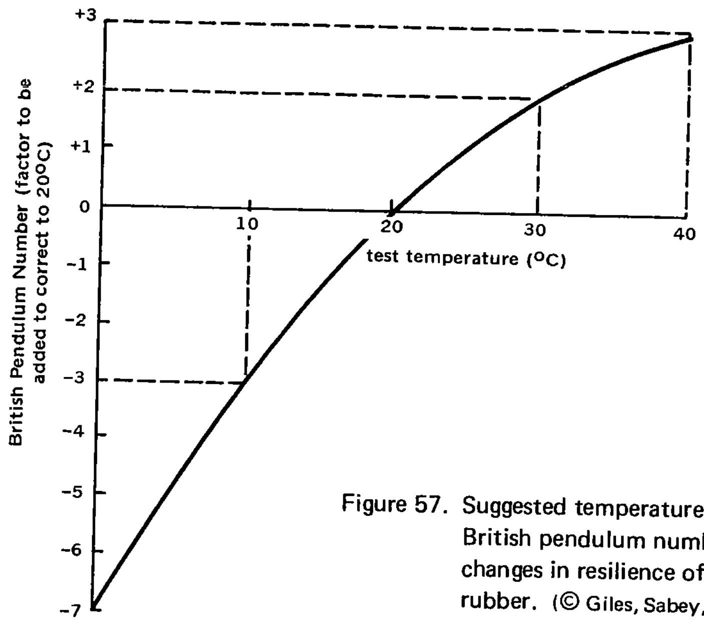


Figure 57. Suggested temperature corrections for British pendulum number to allow for changes in resilience of the slider rubber. (© Giles, Sabey, and Cardew, 1962. Used by permission.)

Since very high velocities are generally involved during the landing of aircraft, the temperature of the tires shortly after touchdown is expected to be much higher than those of highway vehicles. As previously reported by Tomita (1964), the tire surface temperature can be as high as 1,000°F under the locked-wheel condition. Under this high velocity and skid condition, the friction coefficient can be considered to be very low, because the rubber is in a molten state. Fortunately, the locked-wheel condition is not a usual operating mode of aircraft tires.

Sabey (1965) indicated that the time of year or season in Great Britain has a definite effect on the skid resistance of pavement surfaces. The seasonal variation is shown in Table 19 by the monthly index for seven years. In general, the results indicate that the minimum and maximum values of BPN are obtained during the summer and winter months, respectively. The minimum value obtained during the summer varies from year to year but generally occurs in June or July. Low values, however, can occur any time between May and September.

Sabey (1965) also reported that seasonal changes in BPN are related to the frequency of skidding accidents. As shown in Figure 58, the summer months, which are related to low BPN, show a higher percentage of wet skidding accidents than the winter months. Extrapolation of the straight

Table 19. Monthly Index of Seasonal Changes in British Pendulum Number (© Sabey, 1965. Used by permission.)

Month	1958	1959	1960	1961	1962	1963	1964
Jan.	114	117	112	105	119	130	114
Feb.	112	112	114	103	112	121	114
Mar.	114	107	107	93	110	115	107
Apr.	102	95	95	97	99	109	104
May	90	83	91	90	99	105	96
June	98	83	86	86	89	97	93
July	91	79	97	89	92	99	83
Aug.	97	81	98	88	90	97	92
Sept.	97	83	103	87	94	102	96
Oct.	100	95	103	103	97	103	102
Nov.	103	103	109	109	110	110	105
Dec.	114	112	117	112	114	113	112
Avg.	103	95	102	98	101	109	102

Note: An index of 100 is equivalent to the mean British pendulum number recorded over the years 1958-1960.

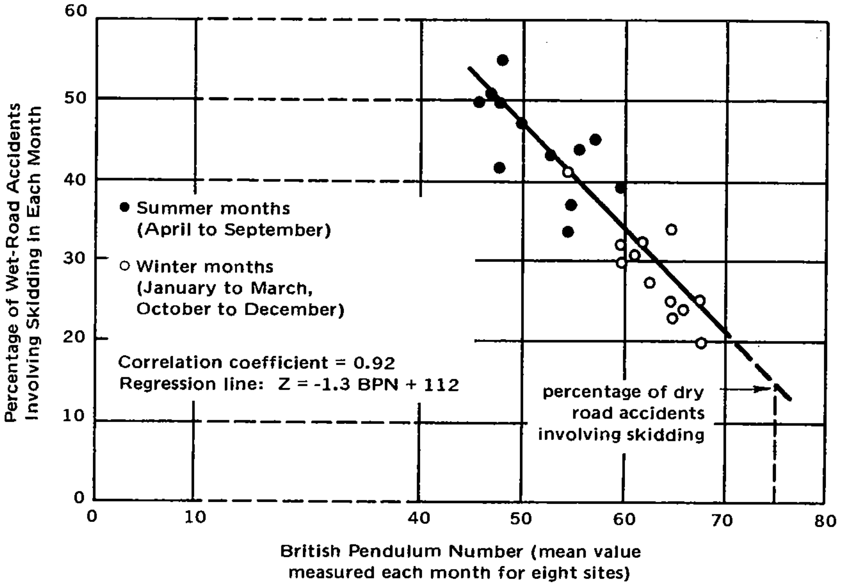


Figure 58. Monthly variations in the frequency of skidding in accidents on wet roads, and the measured skid resistance. (© Sabey, 1965. Used by permission.)

line to the percentage of skidding accidents on dry pavement corresponds to a BPN of 75. This correlation of seasonal change with accident data indicates that the British pendulum tester is able to measure effectively some of the frictional properties sensed by vehicles on wet pavement surfaces.

Kummer and Meyer (1967) found a correlation between the percentage of skidding accidents in five states and three of the four seasons. As shown in Table 20, the average percentage of skidding accidents for five years is highest during the summer and lowest during the winter, with the average for fall in between. The reduced accident rate during winter is caused by low wet-pavement temperatures (high damping of rubber) and high microscopic roughness of the surfaces. High temperatures and low microscopic roughnesses cause the high accident rates during the summer. Fall temperatures are lower, but the surface of the pavement usually has a higher polish during fall than it has during summer.

Table 20. Seasonal Distribution of Skidding Accidents in Five States, Expressed as Percentage of All Wet Pavement Accidents (© Kummer and Meyer, 1967. Used by permission.)

Year	Skidding Accidents (%)		
	Spring	Summer	Fall
1960	NA	54.7	41.3
1961	20.0	45.6	20.0
1962	14.5	8.6	33.2
1963	19.2	36.2	28.9
1964	15.8	22.3	19.0
Avg.	17.4	33.4	28.4

MINIMUM SKID-RESISTANCE REQUIREMENTS

It was reported by Tomita (1964) that very little information was available on skid-resistance standards or on acceptable minimum friction coefficients for highway pavements and that no such information was found for airfield pavements. The present literature search indicates that more effort is being made in determining the much-needed minimum requirements for highway pavements. However, again the literature reveals no such information for airfield pavements.

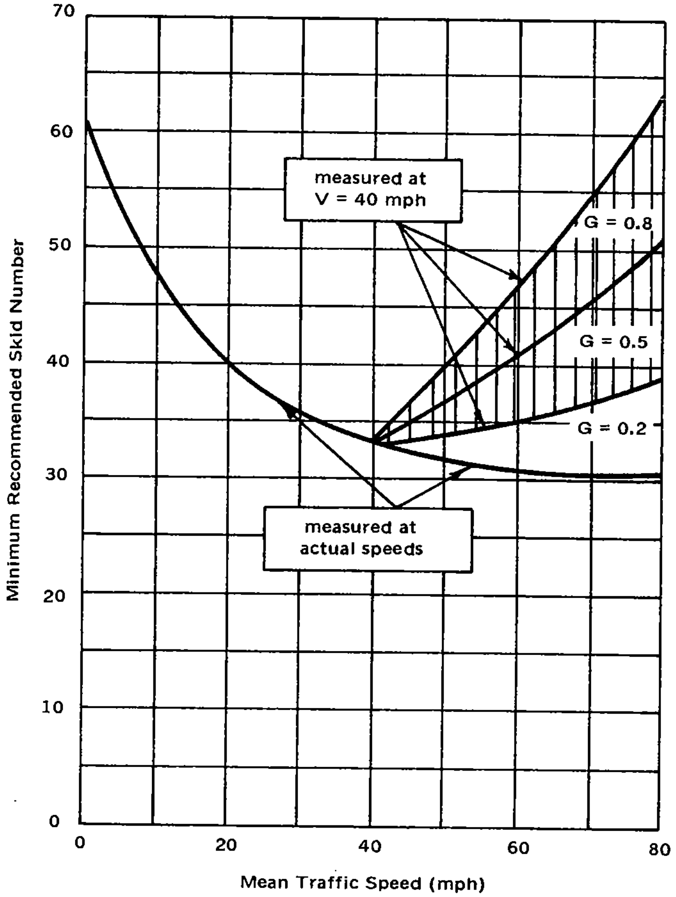


Figure 59. Minimum recommended skid numbers which satisfy normal frictional needs of traffic. (© Kummer and Meyer, 1967. Used by permission.)

Kummer and Meyer (1967) conducted a thorough investigation to provide minimum skid-resistance requirements for rural highway pavements. Many important factors were considered in this investigation which led to the selection of criteria for deriving the minimum requirements. These factors are listed below without the detailed information that can be obtained from the reference:

1. Technical and economic considerations.
2. Pavement friction and skidding accidents.
3. Frictional needs of traffic related to driver behavior.
4. Frictional needs of traffic related to vehicle and highway design factors.
5. Variable need of skid resistance by traffic.

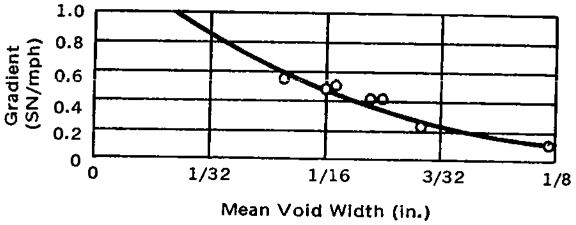


Figure 60. Characterization of drainage properties of pavement surfaces by aggregate spacing. (© Kummer and Meyer, 1967. Used by permission.)

The recommended tentative skid-resistance requirements for rural highways based on a study of driver behavior are shown in Figure 59. The gradient, G, in Figure 59 is $-\Delta(SN)/\Delta V$, which can be obtained from Figure 60. The skid numbers are minimum values measured with skid trailers in late summer or during fall, in accordance with ASTM E274-65T. The corresponding numbers measured with three other devices are given in Table 21. These values will reasonably ensure that rural highway surfaces meeting these requirements will satisfy the frictional needs of normal vehicle maneuvers. It is assumed that the vehicle is in good mechanical condition and equipped with recently designed treaded tires having a tread depth of 1/10 inch or more.

It should be noted that the recommended skid numbers in Figure 59 are minimum values and are tentative. These conditions indicate that the skid numbers for pavements should be higher if possible and that further research is needed to confirm or modify the recommended numbers. It should also be noted that the recommended values do not guarantee that the pavement surface will provide these levels under every possible surface and environmental condition or combination of these factors.

Table 21. Recommended Minimum Interim Skid-Resistance Requirements for Stopping-Distance Cars and Portable Testers* (© Kummer and Meyer, 1967. Used by permission.)

Mean Traffic Speed, (mph)	Skid Number† SN_{40}	Stopping-Distance Number,‡ SDN_{40}	British Pendulum Number §	Drag Tester Number¶
30	31	39	50	35
40	33	41	55	40
50	37	46	60	45
60	41	51	65	50
70	46	57	–	–
80	51	64	–	–

* All values based on use of ASTM E-249 rubber.

† Measured at 40 mph in accordance with ASTM E-274.

‡ Measured in accordance with current practice (ASTM method of test in preparation).

§ Measured in accordance with ASTM E-303.

¶ Measured in accordance with manufacturer's recommended test procedure.

When any highway pavement section is appraised, the skid tests should be carried out in the center of the most polished area in the direction of traffic and at the mean traffic velocity. When the maximum test velocity is lower than the mean traffic velocity, a minimum test velocity of 40 mph is recommended by Kummer and Meyer (1967). The required skid numbers at 40 mph to ensure minimum skid numbers at higher velocities can be determined from Figure 59 as a function of G. Kummer and Meyer (1967) propose use of G = 0.5 for calculating skid numbers at 50 mph from measurements at 40 mph. But for projection from 40 mph to 60 mph or higher velocities a representative gradient can be obtained from Figure 60 after estimating the mean void width of the pavement surface.

METHODS TO IMPROVE SKID RESISTANCE

Some methods employed to improve skid resistance were reported by Tomita (1964). All these methods involved the treatment of pavement surfaces. The following paragraphs present additional information found during the present investigation.

As previously mentioned, pavement grooving is a relatively recent technique used to improve skid resistance. Horne and Brooks (1967) investigated the effect of transverse grooving on braking performance. Their study was conducted with a smooth tread jet transport tire on the Langley landing-loads track. As shown in Figure 61, the skid coefficient is considerably higher for all three grooved concrete surfaces than for the conventional longitudinal burlap-dragged, ungrooved surface under damp or flooded conditions. Other test results from NASA's forthcoming experiments are expected to provide additional information on grooving.

At a Navy air station a newly fog-sealed AC runway was wire-brushed in an effort to improve its skid resistance.* Stiff wire brushes were mounted on a framework; the framework was weighted with sandbags and dragged in a circular pattern with a vehicle. It was determined, by weighing the sweeping from a given area, that this method is able to remove only a small amount of material from the pavement surface. A few before-and-after wire-brushing decelerometer readings indicated an average increase to 16 ft/sec^2 from 9 ft/sec^2. Though pilot complaints of slick pavement decreased after the wire-brushing operation, the effectiveness of this technique is questionable because the number of wet-runway landing operations before and after wire-brushing have not been compared.

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* Information derived from author's experience as a consultant for the air station.

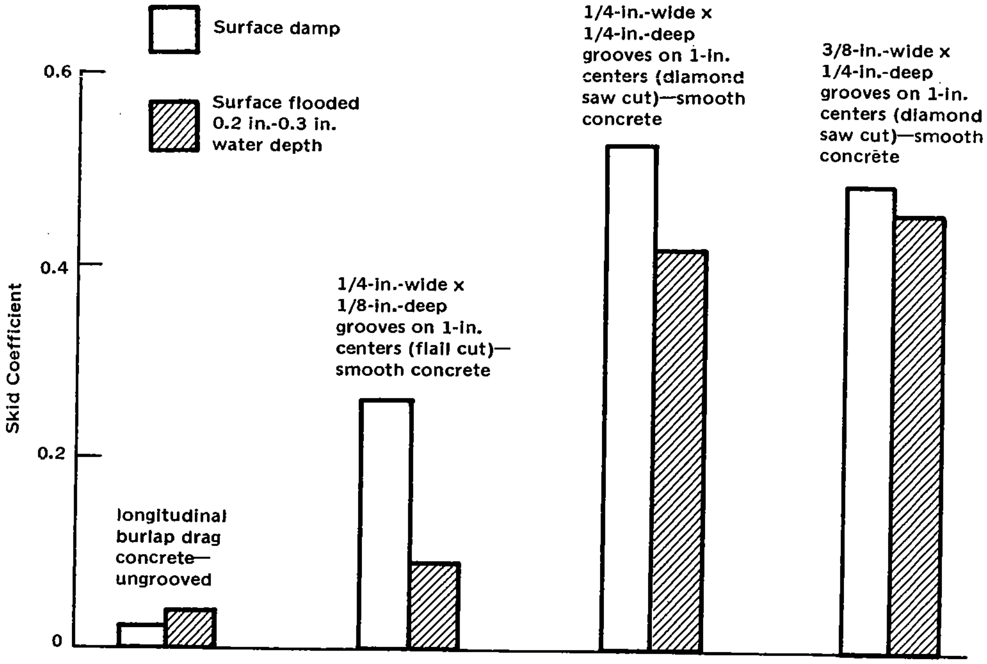

Figure 61. Effect of pavement grooving on skid coefficient of smooth-tread jet transport aircraft tire. (P_t = 170 psi; F_v = 30,000 pounds; V = 100 knots). (© Horne and Brooks, 1967. Used by permission.)

A section of a new AC runway in South Vietnam was chipped on an experimental basis to improve skid resistance.* The AC runway had a relatively smooth, tight surface. A rotating drum with many small, sharp projections was used in the operation. Average decelerometer readings increased to 19 ft/sec^2 from 16 ft/sec^2 under a wet condition. The initial test vehicle velocity was 40 mph. A coarse-grain slurry seal incorporating a maximum size aggregate of 1/4 inch was also tried on a section of the same runway in Vietnam. This type of slurry seal was used to provide a large-scale macroscopic roughness surface for better water drainage from the tireprint area, thereby increasing the friction value at the higher velocities of landing aircraft. The average decelerometer readings improved to 22 ft/sec^2 from 16 ft/sec^2 under a wet condition and in initial test velocity of 40 mph. Based on the results of these experiments, the slurry seal method was recommended for the entire runway. No report has been received on when the skid resistance work will be done.

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* Personal communication to NCEL representative.

For several years, the Navy has been using skid-resistant epoxy compounds on aircraft carrier decks and more recently on landing mats. These compounds, conforming to the requirements of Military Specifications MIL-D-23003 (SHIPS) and MIL-C-81346 (WP), apparently are very successful and satisfactory for the intended purpose. The manufacturers of these compounds have recently introduced a modified epoxy compound for PCC surfaces. Information from the manufacturers indicate that trial sections of such nonskid compounds have been placed on a runway surface at John F. Kennedy Airport and at NASA's Wallops Station to determine their long-term performance. No results have been received to date.

SUMMARY

An investigation was conducted to determine the research and development efforts needed to provide safe, skid-resistant surfaces on Navy and Marine Corps airfield pavements. The investigation consisted mainly of a review of the literature published since the previous study conducted in 1963 and 1964 and a review of work being conducted outside NCEL. Much of the information reported supplements that found in the previous report by Tomita (1964) and serves to provide the reader with the latest available results and findings. Hydroplaning, a subject only briefly discussed in the previous report by Tomita (1964), is dealt with in detail, as is the subject of friction coefficient.

The investigation revealed that aircraft tires do hydroplane on runway surfaces. The velocity at which a tire reaches complete hydroplaning can be determined with a satisfactory degree of accuracy by an equation. Various factors contributing to hydroplaning have been identified, and ways to combat the phenomenon are being investigated. Thus far, the grooving of pavements has received the most attention and appears to be the best remedial measure. However, it has disadvantages, especially with asphaltic concrete pavements in hot climates, where aircraft tire loadings can close the grooves. Additional work is needed to determine the degree of pavement surface roughness or texture necessary to successfully eliminate hydroplaning on airfield runways. A review of the current requirements for transverse and longitudinal slopes of runways is also needed to provide the best aircraft-runway surface system for ground operation.

The vast number of recently published references indicates a continuing interest in the skid resistance of pavements. Most of the work has been done in the interests of highway safety. However, some work has been oriented toward improving the skid resistance of aircraft on airfields.

Work on the mechanism of rubber friction helps to explain to a great extent the friction coefficient between tires and pavements. In general, the factors influencing the adhesion and hysteresis components in rubber friction are applicable to the tire–pavement frictional phenomena. These factors are the contact area, the shear strength between the tire and the pavement, the energy dissipated by the damping of the rubber, the volume of the rubber, and to a lesser extent, the contact pressure. The effects of these factors have been verified by experimental results.

The operating modes of aircraft tires consist of the free-rolling, slipping (drive, brake, and cornering), and skidding modes. Since the free-rolling mode is of little concern and the skidding mode is not usually permitted during aircraft deceleration, the friction coefficients associated with the cornering slip and brake slip modes are most important. Thus, the friction requirements of airfield pavements should logically be based mainly on the brake slip coefficient as well as on the cornering slip coefficient and, to a lesser extent, on the skid coefficient.

The investigation revealed that the skid trailer method is being used more and more and is becoming the standard field measuring device for highway pavements. The recent additional capability of this method for testing the slip mode gives this method versatility. Three basic designs of the skid trailer are available. Of the three, the parallelogram design appears to be the simplest. The stopping-distance and deceleration methods are also in use, but to a lesser extent. There appears to be a continued use of portable testers, generally in the laboratory and as supplement devices for the trailer, to check quickly the skid resistance of pavement surfaces.

Results of correlation studies indicate that good correlation can be obtained between some friction-measuring devices, but that poor correlation exists between others. Variations in test conditions, the design of the devices, the lack of a sufficient number of tests, and other factors can influence the degree of correlation. Forthcoming results from future correlation studies are expected to provide additional information on this subject. While much work has been done to correlate various friction-measuring devices, only a token effort has been made to find a correlation between devices and aircraft during braking. Such correlation information is needed, especially if realistic skid-resistance standards based on measurements with the devices are desired for airfield pavements. Additional aircraft-device correlation information is expected from NASA.

The investigation indicated continuing research to determine the effects on the friction coefficient of the numerous factors involved in the tire–pavement interaction. There is an increase in the friction–velocity gradient with an increase in the thickness of water film. The ratio of peak coefficient to skid coefficient increases with an increase in velocity. These factors point to the danger of the locked-wheel condition at high velocities on flooded pavement surfaces. The resilience of rubber appears to have a more significant influence on the friction coefficient than does the hardness of rubber. High resilience corresponds to a low friction coefficient. Appropriate tread patterns significantly improve skid resistance on smooth wet surfaces, especially at the higher velocities. This improvement decreases on coarse open-textured pavement surfaces. An increase in the wheel load and the inflation pressure decreases the friction coefficient, but the effect is not as significant as those of some other factors. The large-scale and small-scale macroscopic roughnesses of pavement surfaces are important factors. The microscopic roughness varies with the seasons and is less important. The large-scale macroscopic roughness related to the rate of water drainage from the tire contact area governs the friction-velocity gradient; the small-scale macroscopic roughness determines the magnitude of the friction coefficient. Other factors, such as fuel spillage, rubber deposits, and temperature and seasonal changes, can change the friction coefficient.

Some effort has been made toward establishing minimum skid-resistance requirements for rural highway pavements but not for airfield pavements. It is emphasized that the highway requirements are tentative and are based on minimum values. Further detailed research is needed to firmly establish skid-resistance requirements for highway and airfield pavements. Whenever possible, pavements should be built with skid-resistant qualities greater than established minimum requirements.

Various methods to improve the skid resistance of slick surfaces have been tried. These methods, which include grooving, wire brushing, chipping, and using carrier-deck-type nonskid coatings, supplement those discussed in the previous report by Tomita (1964). Only preliminary results on some methods are available from limited trials or investigations. Thus, no definite conclusions can be made at present on the performance of these skid-improvement methods.

RECOMMENDATIONS

1. Laboratory and field studies should be conducted to establish skid-resistance requirements for Navy and Marine Corps airfield pavements. The laboratory study should determine: (1) the required surface texture or roughness of both PCC and AC runways which will be effective against hydroplaning and (2) the friction coefficient and abrasion resistance of the required surface texture. Various surfaces found promising under the laboratory study should be duplicated in the field with conventional or specially developed construction methods. The friction coefficient—velocity

relationship of the surfaces should be established with a field-measuring device. The results should be used to determine the stopping distances and lateral stability of aircraft on these surfaces.

2. A skid trailer utilizing the simple parallelogram design and incorporating the slip mode should be developed and used as the field-measuring device. If possible, the device should be capable of measuring the cornering slip coefficient and have instrumentation sensitive enough to measure and record slush drag or hydrodynamic drag forces as well as the friction coefficient. This skid trailer should be used in the recommended field study; in any future evaluation of a promising skid-resistant surfacing material; and in combination with other subsequently developed, economical field test methods for periodically making skid measurements on Navy and Marine Corps air station pavements.

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NOMENCLATURE

Symbols

A	Total area of contact for N number of aggregate particles (in.^{2})
A_a	Uplift area of the aircraft (ft^2)
A_i	Particle-rubber contact area (in.^{2})
A_n	Gross geometric area of the block (in.^{2})
A_t	Tire contact area (ft^2 or in.^{2})
a	Distance from hitch to axle of skid trailer (in. or ft)
B	Interface shear strength (psi)
b	Unit sliding length (in.)
C_a	Lift coefficient of the aircraft (nondimensional)
C_c	Correlation coefficient
C_t	Lift coefficient of the tire (nondimensional)
c	Vertical distance from axle to point of force measurement (in. or ft)
D	Energy dissipated by damping (in.-lb/in.^{3})
D_a	Aerodynamic drag (lb)
d	Deceleration (ft/sec^2)
E	Total energy dissipated within the rubber for N number of aggregate particles (in.-lb)
E_{hi}	Energy for each mineral particle dissipated per unit sliding length (in.-lb)
E_i	Unit energy (in.-lb)
e	Pneumatic trail (in.)
F	Friction force (lb)
F_a	Adhesion force (lb)
F_{ai}	Adhesion force for a protruding mineral particle (lb)
F_b	Friction force under the brake slip mode (lb)
F_c	Cornering force (lb)
F_h	Hysteresis force (lb)
F_{hi}	Hysteresis force for a protruding mineral particle (lb)
F_{sk}	Friction force under the skidding mode (lb)
F_t	True friction force (lb)
F_v	Vertical wheel load (lb)
F_{vo}	Static vertical wheel load (lb)
F_1	Force measured on Cornell Aeronautical Laboratory skid trailer (lb)
F_2	Force measured on Pennsylvania State University skid trailer (lb)
f	Horizontal distance from wheel axle to center of gravity of skid trailer (in. or ft)
G	Gradient of friction coefficient—velocity curve (SN per mph)
g	Gravitational acceleration (ft/sec^2)
H	Percent error
H_s	Standard estimate of error
h	Vertical distance from pavement surface to center of gravity of skid trailer (in. or ft)
i	Any protruding mineral particle
j	Hitch height for skid trailer (in. or ft)
k	Horizontal distance from wheel axle to point of measuring bending moment M on skid trailer (in. or ft)
L_a	Aerodynamic lift (lb)
L_g	Sum of the vertical ground forces through all gears (lb)
M	Bending moment (in.-lb)
M_o	Moment at wheel axle (in.-lb)
m	Mass (slugs)
n	Difference between skid coefficient measured at 20 km/hr and at 60 km/hr
P_t	Tire inflation pressure (psi)
p	Contact pressure (psi)
Q	Volume of rubber involved in deformation (in.^{3})
r	Tire radius (in. or ft)
S_b	Brake slip (nondimensional)
S_c	Cornering slip (nondimensional)
S_d	Drive slip (nondimensional)
T	Residual thrust (lb)
T_m	Measured torque (in.-lb)
t	Time (sec)
t_1	Time at the start of the measurement (sec)
t_2	Time at the end of the measurement (sec)

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13. ABSTRACT

An investigation consisting mainly of a literature review and a review of current research done outside NCEL was conducted to determine the methods needed to provide safe, skid-resistant surfaces on Navy and Marine Corps airfield pavements. Much of the information reported herein serves to update the information contained in NCEL Technical Report R-303. For example, new information is included on friction-measuring methods, correlation of the measuring methods, factors affecting friction coefficients, minimum requirements for skid resistance, and methods of improving the skid resistance of slippery pavements. However, some new topics which are of recent interest are also discussed in detail. These topics include hydroplaning, the mechanism of rubber friction, the friction associated with various operating modes of aircraft tires, the relationship of friction coefficients to pavement surface texture and to surface drainage of water, and the effects of pavement grooving on hydroplaning and on friction coefficients.

All the information from the investigation is summarized, and recommendations are given for research and development efforts needed to provide safe, skid-resistant surfaces for airfield pavements.

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16. Abstract

The need for improved capacity at airports to accommodate the rapid growth of domestic air traffic in the United States has led to the investigation of Land and Hold Short Operations (LAHSO) as a safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity does not lead to a safety decline. A key task was to investigate the aircraft landing performance pertaining to operational safety guidelines for reducing the risks of incidents and accidents associated with LAHSO. For this, a clear knowledge of the day-to-day landing operations is required.

Data from quick-access recorders can be used to analyze aircraft performance. Aircraft landing field performance is influenced by many variables. Some variables were found to have a more dominating influence than others. Variables found to have a strong influence are height above the threshold, speed loss from flare initiation to touchdown, and the available runway length for landing. However, there is not one single factor that dominates the landing field performance.

This study used in-flight recorded data collected from day-to-day landing operations obtained from the quick-access recorders from two types of narrow-body jet aircraft.

17. Key Words
Operations safety, Threshold, Flare, Landing performance, Landing distance, Ground roll

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LIST OF ACRONYMS

A/THR	Autothrust
CAS	Calibrated airspeed
GMT	Greenwich Mean Time
GPS	Global positioning system
GS	Glide slope
ILS	Instrument landing system
kt	Knot
LAHSO	Land and Hold Short Operations
METAR	Aviation routine weather report
NLR	National Aerospace Laboratory
RA	Radio altitude (at main gear height)
rad/s	Radians per second
RDH	Reference datum height
TAS	True airspeed
THR	Thrust
Vref	Reference landing approach speed

EXECUTIVE SUMMARY

The need for improved capacity at airports to accommodate the rapid growth of domestic air traffic in the United States has led to the investigation of Land and Hold Short Operations (LAHSO) as a safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity does not lead to a safety decline. The introduction of new technology and procedures for improving the airport capacity must be integrated into the existing infrastructure so that maximum benefits for safety and efficiency are realized. The key task was to investigate the aircraft landing performance pertaining to operational safety guidelines for reducing the risks of incidents and accidents associated with LAHSO. For this, a clear knowledge of the day-to-day landing operations in required. At the request of the Federal Aviation Administration, the National Aerospace Laboratory was commissioned by the Dutch Civil Aviation Authority to conduct an analysis of day-to-day landing operations using in-flight recorded data.

This present study is focused on analyzing the operational landing field performance of two different narrow-body, turbofan-engined aircraft under various weather conditions. Two aircraft types were selected for a statistical study of a number of performance and flight control parameters with respect to the landing phase of flight: the Boeing 737-400 and the Airbus A319, A320, and A321. The present study is conducted using in-flight recorded data collected from day-to-day landing operations. These data were obtained from the quick-access recorder, which stores a limited number of the important flight data parameters. The objective was not intended to be a complete and conclusive study regarding landing field performance in relation to LAHSO issues. However, the results and knowledge obtained from this study can be useful for further analysis of LAHSO flight performance-related issues.

The following objectives were made:

- Data from quick-access recorders can be used to analyze aircraft performance. During this study, valuable insight and knowledge were gained on using quick access recorded data for aircraft landing field performance analysis.

- Aircraft landing field performance is influenced by many variables. Some variables were found to have a more dominating influence than others. Variables found to have a strong influence are height above the threshold, speed loss from flare initiation to touchdown, and the available runway length for landing. However, there is not one single factor that dominates the landing field performance.

- Not all results presented in this study can be used for the analysis of LAHSO. The results show that the ground roll performance is strongly influenced by the available runway length for landing. Therefore, for this study, only landings on shorter runways should be considered.

1. INTRODUCTION.

1.1 BACKGROUND.

The need for improved capacity at airports to accommodate the rapid growth of domestic air traffic in the United States has led to the investigation of Land and Hold Short Operations (LAHSO) as a safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity does not lead to a safety decline. The introduction of new technology and procedures for improving the airport capacity must be integrated into the existing infrastructure so that maximum benefits for safety and efficiency are realized.

A key task was to investigate the aircraft landing performance pertaining to operational safety guidelines for reducing the risks of incidents and accidents associated with LAHSO. For this, a clear knowledge of the day-to-day landing operations is required. At the request of the Federal Aviation Administration, the National Aerospace Laboratory (NLR) was commissioned by the Dutch Civil Aviation Authority to conduct an analysis of day-to-day landing operations using in-flight recorded data.

1.2 SCOPE AND OBJECTIVE OF THE STUDY.

This present study was focused on analyzing the operational landing field performance of two different narrow-body, turbofan-engined aircraft under various weather conditions. Two aircraft types were selected for a statistical study of a number of performance and flight control parameters with respect to the landing phase of flight: the Boeing 737-400 and the Airbus A319, A320, and A321.

The objective was to identify empirical distributions of the landing distance parameters such as the approach speed at threshold, the touchdown point, rollout distance, and total landing distance. Furthermore, the objective was to gain insight in those factors that affect the landing field performance. This study was explorative since it was the first attempt to analyze large quantities of flight data during landing.

The objective was not intended to be a complete and conclusive study regarding landing field performance in relation to LAHSO issues. However, the results and knowledge obtained from this study can be useful for further analysis of LAHSO flight performance-related issues.

1.3 STUDY APPROACH.

The present study was conducted using in-flight recorded data collected from day-to-day landing operations. These data were obtained from the quick-access recorder, which stores a limited number of the important flight data parameters.

1.4 ORGANIZATION OF THE REPORT.

This report is organized as follows: section 2 describes the data collection effort, section 3 describes the data processing applied to the collected data, and section 4 presents the results. In section 5, a brief discussion of the results is given, in section 6, the conclusions are summarized, and in section 7, recommendations are given.

2. DATA COLLECTION.

2.1 AIRCRAFT TYPES.

Two narrow-body jet aircraft were considered in this study: the Boeing 737-400 and the Airbus A319, A320, and A321 (see figure 1). Both aircraft are comparable in size and general performance (e.g., range and payload) and are used by many operators worldwide. One major distinctive feature of the two aircraft is the control system. One uses a conventional control system, and the other has a fly-by-wire control system. Although it was not the aim of this study to look at the advantages and disadvantages of these different control systems, it is likely that some differences in landing performance is attributable to the control system. This applies only to the airborne part of the landing and not to the ground roll part of the landing.

Figure 1. Aircraft Types Considered in the Study

2.2 DATA SOURCES.

All flight data analyzed in this study were obtained from a European airline. The flight data were obtained from the airline’s flight data monitoring program. The recording effort lasted for more than 7 months and covered winter, spring, and summertime operations. In addition to flight data, aviation routine weather reports (METAR) were collected. METAR reports contain hourly observations of the weather conditions at an airport. For each landing, the METAR that was the closest to the landing time was linked with the recorded flight data of this landing.

2.3 FLIGHT PARAMETERS COLLECTED.

The list of collected comparable flight parameters for the A320 series and the B-737-400 is provided in table 1. It should be noted that some units and sample frequencies may differ between these aircraft types.

Table 1. List of Recorded Parameters

Parameter List A320 Series		Unit	Sample Rate (Hz)	Parameter list B-737-400		Unit	Sample Rate (Hz)
1	Frame Counter	--	8	1	Frame Counter	--	8
2	RWY Heading	deg	8	2	Time	sec	8
3	GMT Hours	hr	1	3	Day of Month	--	1
4	GMT Minutes	min	1	4	Month	--	1
5	GMT Seconds	sec	1	5	Pressure Altitude	ft	1
6	Day of Month	--	1	6	Radio Altitude	ft	4
7	Month	--	1	7	Calibrated Airspeed	kt	1
8	Pressure Altitude	ft	1	8	True Airspeed	kt	1
9	True Airspeed	kt	1	9	Groundspeed	kt	1
10	Calibrated Airspeed	kt	1	10	N1 Engine 1	%	1
11	Groundspeed	kt	1	11	N1 Engine 2	%	1
12	N1 Engine 1	%	1	12	N2 Engine 1	%	1
13	N1 Engine 2	%	1	13	N2 Engine 2	%	1
14	N2 Engine 1	%	1	14	Normal Acceleration	g	8
15	N2 Engine 2	%	1	15	Longitudinal Acceleration	g	4
16	Normal Acceleration	g	8	16	Lateral Acceleration	g	4
17	Longitudinal Acceleration	g	4	17	Flap Position	deg	1
18	Lateral Acceleration	g	4	18	Training Edge Flap Position	deg	1
19	Flap	deg	1	19	Spoiler 2 Position	deg	1
20	Ground Spoiler Out	0/1	1	20	Spoiler 7 Position	deg	1
21	Thrust Reverser 1 Deployed	0/1	1	21	Thrust Reverser Deployed Left	0/1	1
22	Thrust Reverser 2 Deployed	0/1	1	22	Thrust Reverser Deployed Right	0/1	1
23	Air Ground	0/1	2	23	Air Ground	0/1	2
24	Glide slope Deviation	dot	1	24	Glide slope Deviation (Dots)	dot	1
25	Localiser Deviation	dot	1	25	Localiser Deviation (Dots)	dot	1
26	Autobrake High	0/1	1	26	Autobrake Level 1	--	1
27	Autobrake Medium	0/1	1	27	Autobrake Level 2	--	1
28	Autobrake Low	0/1	1	28	Autobrake Level 3	--	1
29	Gross Weight	kg	1	29	Auto Break Max	--	1
30	Magnetic Heading	deg	1	30	Gross Weight (lb)	lb	1
31	Pitch	deg	4	31	Gross Weight (kg)	kg	1
32	Angle of Attack	deg	1	32	Magnetic Heading	deg	1
33	Static Air Temperature	degC	1	33	Roll	deg	4
34	Radio altitude	ft	4	34	Pitch	deg	4
35	Roll	deg	4	35	Angle of attack	deg	2
36	Autopilot 1 cmd	0/1	1	36	Static air temperature	degC	1
37	Autopilot 1 cmd	0/1	1	37	Autopilot cmd A left	0/1	1

Table 1. List of Recorded Parameters (Continued)

Parameter List A320 Series		Unit	Sample Rate (Hz)	Parameter List B-737-400		Unit	Sample Rate (Hz)
38	Autopilot engaged	0/1	1	38	Autopilot cmd A right	0/1	1
39	Brake 1 pressure	bar	1	39	Autopilot cmd B left	0/1	1
40	Brake 2 pressure	bar	1	40	Autopilot cmd B right	0/1	1
41	Brake 3 pressure	bar	1	41	Brake pressure alternate left	psi	1
42	Brake 4 pressure	bar	1	42	Brake pressure alternate right	psi	1
43	Brake 5 pressure	bar	1	43	Brake pressure main left	psi	1
44	Brake 6 pressure	bar	1	44	Brake pressure main right	psi	1
45	Brake 7 pressure	bar	1	45	Brake pedal left	deg	8
46	Brake 8 pressure	bar	1	46	Brake pedal right	deg	8
47	Target approach speed	kt	1	47	Target airspeed	kt	1
48	GPS longitude	deg	1	48	FMC longitude	deg	1
49	GPS latitude	deg	1	49	FMC latitude	deg	1
50	Drift angle	deg	1	50	Track angle magnetic	deg	1
51	Brake pedal left position	deg	1	51	Track angle true	deg	1
52	Brake pedal right position	deg	1	52	Inertial vertical speed	fpm	1
53	Inertial vertical speed	fpm	8	53	Elevator left	deg	1
54	Elevator left position	deg	4	54	Elevator right	deg	1
55	Elevator right position	deg	4				

Cmd = Command
FMC = Flight management computer
Fpm = Feet per minute
G = Gram
GMT = Greenwich Mean Time
psi = pounds per square inch
GPS = Global positioning system
kg = Kilogram
kt = Knot
RWY = Runway
ft = feet
min = minute
sec = second
hr = Hour
deg = Degree
lb = Pound

2.4 DATA SAMPLE.

The data collection effort was set to obtain landing data for 50,000 landings (all aircraft types combined). These data were checked for errors and inconsistencies. Landings were removed from the sample if significant errors and inconsistencies were identified. The landing data that was collected concerned both instrument and visual approaches. To calculate the airborne distance (i.e., distance covered when crossing the runway threshold to touchdown of the main landing gear), the position relative to the runway should be known. Although global positioning system (GPS) coordinates were recorded, these data were not accurate enough to determine the position of the aircraft relative to the runway threshold[1].

Therefore, a different approach was adopted to determine the position of the aircraft relative to the runway threshold. This approach is discussed in section 3 and is based on the use of glide slope deviation data. Such data is only available for those approaches flown using the instrument landing system (ILS) as guidance. Not every landing is conducted using the ILS as an approach aid. Therefore, a number of landings from the initial sample were not considered for further

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[1] Although a GPS can accurately record the position of an aircraft, the flight data obtained from the quick-access recorder of an aircraft contains GPS coordinates that are stored with insufficient number of digits. Also, the sampling method of the GPS coordinates on the quick-access recorders influences the use in a negative matter.

analysis. In the end, data errors, inconsistencies, and the absence of ILS glide slope deviation data reduced the initial data sample of 50,000 landings to 40,764. The number of landings in the final data sample is listed in table 2.

Table 2. Landings in Data Sample

Aircraft Type	Number of Landings
A319	7,474
A320	13,245
A321	5,952
B-737-400	14,093

2.5 DATA EXAMPLES.

Example time histories for the four aircraft models in the data sample are provided in appendix A. Figures A-1 to A-8 show recorded data for the B-737-400, A320, A319, and A321, respectively. These data have not been processed in any way and are depicted as recorded by the aircrafts' onboard quick-access recorders.

The time histories are given in two series of 12 graphs each. The first series relates mainly to flight technical parameters, such as velocity, pitch, altitude, heading, and accelerations. The second series shows mainly aircraft controls, such as engine parameters, flaps, spoiler, thrust reversers, and brake pedal.

It should be noted that the data sets for the Boeing and Airbus types are not exactly identical, as addressed in section 2.3. Also, the units in which data are recorded differ between these aircraft types. For instance, the B-737 data set contains spoiler deflection in degrees, whereas in the Airbus types, spoiler deflection is recorded as a discrete (in/out).

In general, it was concluded—as also illustrated by these example time histories—that the data quality is fairly good, and there is good consistency among the data. However, a few remarks have to be made in this respect.

First, the recording of the GPS position (latitude and longitude) as recorded by the Airbus types appears to be anomalous. These anomalies were observed in the large majority of cases, but not in all cases. The reason for this behavior was not clear. The data processing, discussed in section 5.1, was not relevant because the actual position coordinates were not used to determine the landing performance indicators.

Another observation that was made from the example time histories concerned the characteristics of the various recorded velocities. The calibrated airspeed (CAS) was limited to a lower value of 45 kt for the B-737 and to 30 kt for the Airbus models. Similarly, the true airspeed (TAS) was limited to minimum values of 100 kt for the B-737 and 60 kt for the Airbus models.

3. DATA PROCESSING.

3.1 GENERAL.

This section treats the processing of the recorded data before they can be used for further statistical analysis. This processing consists of two steps:

- Data error check and removal
- Determination of derived parameters

The first step is performed to check whether the recorded data are consistent and do not contain obvious errors. If errors are found it is determined whether the data can be repaired or if the recording has to be rejected as a valid recording.

The second step concerns the processing of the data to establish a number of parameters that are not part of the original data set, such as instantaneous pitch rate and pitch acceleration. Subsequently, the data is further processed to determine a number of event parameters, such as threshold crossing height and the touchdown point.

This second step data processing is explained further in sections 3.2 through 3.7. Here, only the first step processing will be described.

This processing contains a number of subsequent elements:

- Altitude check—It is checked whether the initial altitude is sufficiently high. It appeared that a substantial number of recordings started at rather low altitude (<60 ft). Since this altitude is within the range of the expected threshold crossing height, all recordings with an initial altitude of less than 60 ft are rejected. If these recordings would be included, this could lead to a statistical bias in the threshold crossing height.

- Spikes—A number of relevant time histories (i.e., velocities, radio altitude (RA), vertical speed, and glide slope deviations) are checked for the presence of spikes. Spikes are effectively detected by a spike detection algorithm. This algorithm triggers on steep flanks in the data and can detect whether the spike occurs over single or multiple subsequent data samples. If the algorithm detects a single point spike, it will repair the data by replacing the spike by interpolation between the data samples before and after the anomaly. If the spike comprises multiple samples, the data from this landing will be rejected.

- Frozen data—A number of parameters appear to sometimes exhibit a frozen behavior. That means that a constant value is recorded. The glide slope deviation and vertical speed are parameters that appear to be especially susceptible to this phenomenon. For the glide slope deviation, this can occur when a nonprecision approach is carried out, and no ILS is used as a landing aid. For the vertical speed, it is not clear what the background of this behavior is. A special algorithm was developed to detect when data was frozen. If frozen data is detected, the data from that landing is rejected.

- Reasonableness—Parameters are checked to determine whether the recorded data are within reasonable limits. It appears that, in particular, recordings of vertical speed and ground speed are susceptible to being outside reasonable limits (e.g., ground speed < -50 kt). If data is found outside reasonable limits, the data from that landing is rejected.

Due to the initial data processing described above, approximately 10% of the available recordings were rejected for further processing.

3.2 DERIVATION AND SMOOTHING.

A number of the selected landing performance indicators, such as the flare initiation and the main gear and nose wheel touchdown points, require the determination of certain parameters that are not part of the recorded data list as presented in section 2.3. These parameters pertain mainly to derived signals, such as pitch rate, pitch acceleration, and change of normal acceleration. Determination of these parameters requires the calculation of the time derivatives of the recorded pitch attitude and normal acceleration.

It is well known that exact differentiation of continuous, real-time signals is theoretically impossible. For this reason, it is necessary to devise processing algorithms to estimate the actual time derivative signals as accurately as possible. For real-time data processing, various methods have been developed that can estimate time derivative signals, such as simple rate taking filters, complementary filters, and Kalman filters. It is beyond the scope of the present report to discuss these methods in more detail. However, the general drawback of these real-time processing methods is that they inherently introduce some time delay in the resulting time derivative signals, and, in addition, they may amplify the noise level of the original signal.

Consequently, in-flight data analysis, it is common practice to use postprocessing methods. The advantage of such methods is that they can use, in the point estimate process, the information of both past and future neighboring samples. By doing so, it is possible to minimize the effects of time delay and effectively reduce the noise level of the resulting signal.

A simple and effective method to estimate the time derivative of a signal in postprocessing is to determine the slope of the signal during the time interval before and after the actual data point and to average them, thus minimizing time delay. More advanced methods may make use of more data samples before and after the actual data point using, for instance, spline methods or moving averaging. However, it should be noted that the noise level can be reduced by using more data samples in the estimating process, but in general, at the expense of the frequency content (bandwidth) of the resulting signal. Therefore, the best method to use depends on the application at hand, which is based on required bandwidth, the basic sampling frequency, and the data quality.

In this respect, it should be noted that the sampling rate of the recorded parameters in the present study is relatively low, especially in comparison with dedicated flight test programs. For instance, in flight test programs, it is general practice to record the pitch angle at 16 or 32 Hz and accelerations at 64 or 128 Hz. In the present data set, the pitch angle is recorded at 4 Hz and accelerations at 8 Hz. Clearly, this presents some conflict between retaining sufficient bandwidth and required noise reduction.

As a rule of thumb, the bandwidth of pitch dynamics of a commercial transport aircraft (size of a B-737 or A320) is typically on the order 1.5 to 2.5 radians per second (rad/s), in the approach and landing phase. To record the aircraft motion of such frequency content with sufficient accuracy, it is necessary to sample the pitch angle with a sampling frequency that is at least 10 times the bandwidth. In this particular case, that is 10 x 2.5= 25 rad/s ~ 4 Hz.

From this simple analysis, it is clear that the sampling rate of the pitch angle in the present data set is the bare minimum to describe the pitch dynamics. For this reason, one should be careful in the determination of the pitch rate (the time derivative of the pitch angle) not to introduce noise-reducing filtering that would decrease the bandwidth of the resulting signal.

However, smoothing algorithms do exist, which can effectively reduce noise while minimizing the effects on bandwidth. Forward/backward moving averaging is such a method that can be applied in postprocessing to provide this smoothing. Forward/backward moving averaging is a method that takes the average value of a number of samples before and after the data point and averages over these samples to provide noise reduction without introducing time delay. Noise reduction is obtained because random noise, when averaged over a number of samples, will largely cancel out the noise. At the same time, however, the actual frequency content of the signal is averaged over a number samples and, therefore, somewhat reduced.

This particular problem arose about 20 years ago, during the flight test program of the Fokker 100, when it was required to accurately determine the vertical speed of the aircraft during the landing and touchdown as part of the autoland performance analysis. Vertical speed is a signal that cannot be measured directly, but has to be derived from either differentiating the RA or integrating the vertical acceleration. Both methods had their drawbacks, the first leads to amplifying noise, and the second may lead to large bias errors. Various filtering schemes were devised to solve those problems without affecting the dynamics of the vertical speed and without introducing time delays. It was shown that most real-time processing methods were not able to meet the requirements, but that postprocessing methods were most effective. Finally, it appeared that Gaussian forward/backward moving averaging of the RA provided the best results. This method is a variant of uniform forward/backward moving averaging by weighing the involved data samples according to a Gaussian function. The exact mathematical details of this method are still considered proprietary and, therefore, are not presented here.

An illustrative example is presented here to demonstrate how the procedure works on a data set, with similar properties as the recorded data used in this study. First, true data are generated by using a nonlinear, 6 degrees-of-freedom, aircraft simulation program of the Fokker 100 that is available at the NLR. In this particular example, the true data consist of the time histories of the pitch angle and pitch rate of a Fokker 100 during approach, in response to an elevator step-type of input. These time histories are calculated at small time intervals (1/64 sec). Subsequently, the pitch angle is sampled at 4 Hz, corresponding to the sample rate in the present recorded data set. Next, the pitch rate is determined by numerical forward/backward differentiation of the (4 Hz) sampled pitch angle. The result is the estimated pitch rate, which is also provided at 4 Hz. The results are depicted in figure 2.

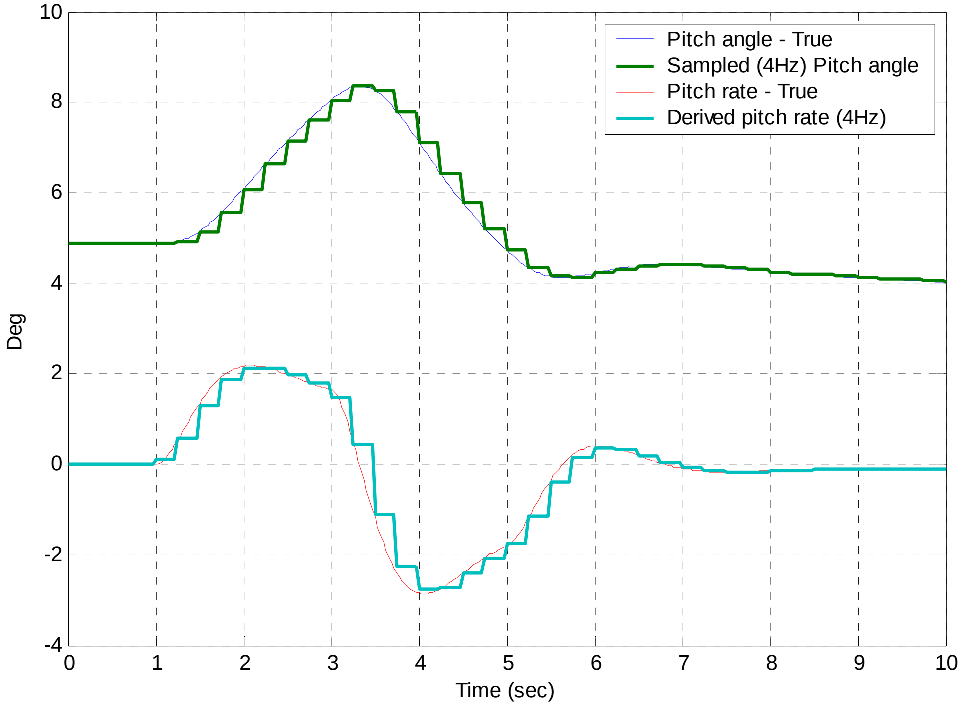

Figure 2. Sampling Process and Derivation of Pitch Rate From Sampled Pitch Angle

It is clearly shown that the forward/backward differentiation process provides an accurate estimate of the true pitch rate, and no time delay is introduced. Evidently, this performance can only be achieved when the original signal is fully noise free, as is the case here. In a second example, the effects of noise and the effectiveness of the Gaussian moving average method is demonstrated. In this example shown in figure 3, the true pitch angle signal is corrupted with random noise of a magnitude corresponding to a (low performance) Attitude and Heading Reference System. Now, the 4-Hz sampled pitch angle signal also includes the random noise values, as shown in figure 3. The noise-corrupted sampled pitch angle is now again numerically differentiated to obtain the estimate of the pitch rate signal.

As shown in figure 3, this leads to strong amplification of the noise in the derived rate signal and results in significant distortion. To reduce the effect of noise, the Gaussian moving average method is now applied to the derived pitch rate signal. Figure 3 clearly illustrates the effectiveness of this method. The resulting estimate of the pitch rate signal closely resembles the true pitch rate signal. Noise is significantly reduced, and no time delay is introduced. Figure 3 also shows that the derived rate signal is distorted at the start and end of the time series. This is a consequence of the forward/backward averaging process. At the start of the recording, data was missing from samples before the recording was started. Likewise, data was missing at the end of the recording, after the recording was ended.

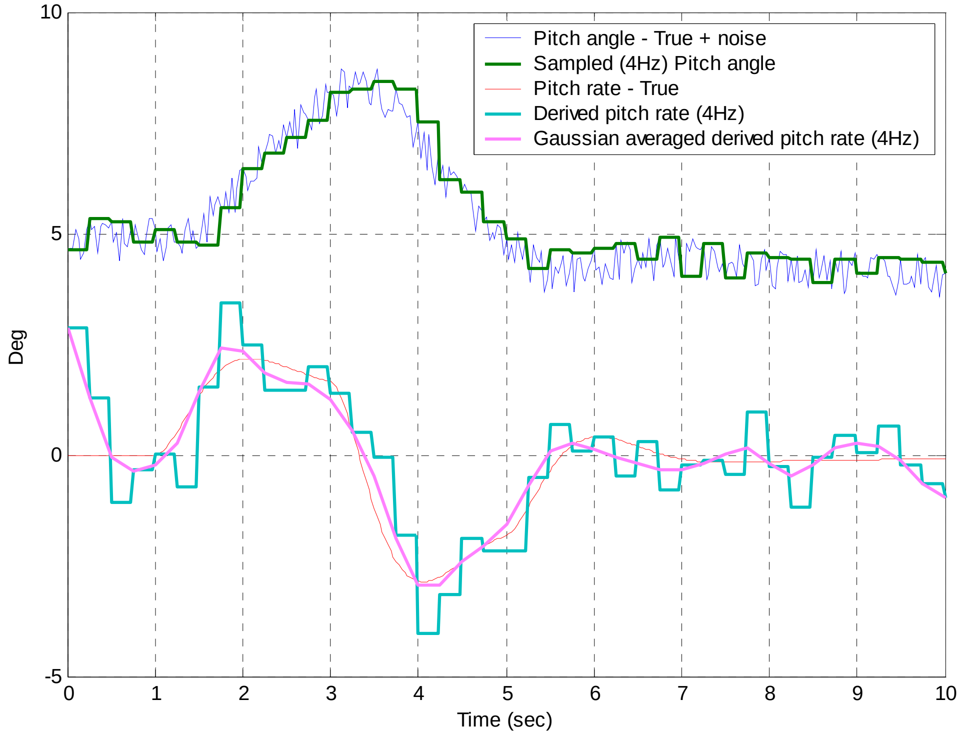

Figure 3. Gaussian Smoothing and Derivation of Pitch Rate From Sampled Pitch Angle Including Noise

To summarize, a short empirical analysis was performed to illustrate the problems that can arise from deriving rate signals from low rate sampled data. Moreover, the effectiveness of a smoothing algorithm that is used to remove noise from the resulting signals without significantly affecting the bandwidth of the signal or introducing time delay was demonstrated. The following sections show how these algorithms are applied to determine a number of landing performance related parameters.

3.3 THE AIRBORNE DISTANCE.

According to Title 14 Code of Federal Regulations Part 25.125 [1], the landing distance of an aircraft is defined as the horizontal distance from the point at which the main gear of the airplane is 50 ft above the landing surface to the point at which the aircraft is brought to a stop. To determine the landing distance, two parts are to be considered: the airborne distance (from 50 ft to touchdown) and the ground distance from touchdown to stop.

In this study, the focus is on the determination of the airborne distance from the recorded operational data. For this, it is essential to determine the point where the targeted 50-ft height above the runway is crossed and the actual point of touchdown. The determination of both parameters from operational data is discussed in section 3.3.1.

3.3.1 Threshold Crossing Height.

As indicated in Advisory Circular 25-7A, "Flight Test Guide for Certification of Transport Category Airplanes" [2], the airborne distance should be measured from a targeted -3 degrees glide slope that should be maintained prior to reaching a height of 50 ft above the landing surface. The reason for this requirement is that the usual glide slope of the ILS is -3 degrees, and 50 ft coincides with the usual ILS Reference Datum Height (RDH) that marks the height of the intersection of the glide slope beam with the runway threshold. The airborne distance, calculated in this way, will, therefore, be representative of common operational practice. However, in particular cases, the ILS glide slope or the ILS RDH may deviate from the standard -3 degrees and 50 ft, respectively. This might influence the actual airborne distance in practice.

For the present investigation, the interest is not in the airborne distance that is applicable to a particular airport, but in the actual air distance in operational practice when the -3 degrees glide slope and 50-ft height above landing surface would be targeted. For this reason, it is assumed that, for all airports in the data sample, a -3 degrees glide slope and 50-ft RDH is applicable[2].

Based on this assumption, the geometric point where the 50-ft RDH is passed is located 50/tan(3°) = 954 ft (~290 meters) in front of the ILS glide slope transmitter. For the determination of the airborne distance, it is, therefore, essential to determine when the airplane passes this geometric location.

Of course, in practice, the aircraft will not follow the glide slope exactly and, therefore, will not pass precisely at 50 ft over the threshold. These deviations are, however, measured as glide slope deviations by the ILS receiver onboard the aircraft. The glide slope deviation is an angular signal that provides the angular deviation from the reference glide slope. The actual deviation is measured according to the following relationship:

$$i_{gs} = \frac{625}{\left|\gamma_{gs}\right|} \cdot \varepsilon_{gs} \tag{1}$$

where:

i_{gs} is the current in µA, measured by the ILS glide slope receiver
γ_{gs} is the reference glide slope angle in degrees
ε_{gs} is the angular deviation in degrees

So, for a reference glide slope of 3 degrees, the angular glide slope deviation would be 0.0048° per µA of deviation measured by the ILS glide slope receiver. Since the full-scale deflection of the glide slope deviation pointer in the cockpit (i.e., two dots) is equivalent to 150 µA, the angular glide slope deviation would be equal to 0.36° per dot of deviation shown on the glide slope deviation pointer.

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[2] The published glide slope threshold crossing height does not represent the height of the actual glide path on-course indication above the runway threshold. It is used as a reference for planning purposes and represents the height above the runway threshold that an aircraft's glide slope antenna should be, if that aircraft remains on a trajectory formed by the 4-mile-to-middle marker glide path segment.

By measuring the glide slope deviation, the absolute line of sight angle to the glide slope transmitter is also established, i.e.,: $\gamma_{total} = \gamma_{gs} + \varepsilon_{gs}$.

Because the actual height (H) relative to the runway surface is known from the radio altimeter, the distance (R) to the glide slope transmitter can be computed, according to the following equation, see figure 4:

$$R = \frac{H}{\tan(\gamma_{gs} + \varepsilon_{gs})} \tag{2}$$

The actual threshold crossing point is found when R equals 50/tan(3°)≈954 ft.

When the threshold crossing point is established, the corresponding threshold crossing time (t_{TH}) and the actual threshold height (H_{TH}) also are determined.

$$\tan\,(GS + GSDev) = \frac{H}{R}$$

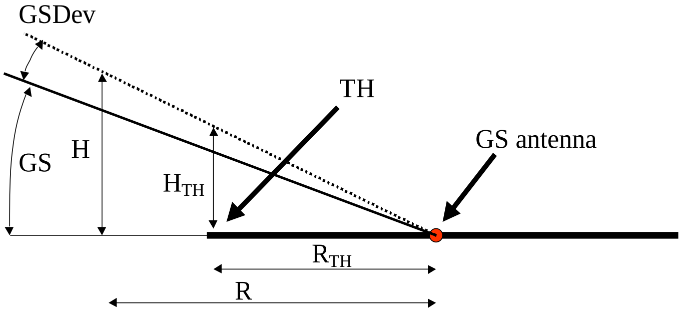

Figure 4. Calculation of Height Above Threshold (H_{th}) From Glide Slope Deviation (GS_{dev})

Clearly, the above described procedure is only accurate if the reference glide slope angle is 3 degrees. To get an indication of how the actual glide slope angle affects the calculated threshold height, the following analysis is presented.

Based on equations 1 and 2, the threshold crossing height is given by:

$$H_{TH} = \frac{50 \cdot \tan(\gamma_{gs} + \varepsilon_{gs})}{\tan(\gamma_{gs})} = \frac{50 \cdot \tan(\gamma_{gs}(1 + \frac{i_{gs}}{625}))}{\tan(\gamma_{gs})} \tag{3}$$

For small angles, it is known that, by good approximation, tan(γ) ≈ γ. Herewith, equation 3 can be written as:

$$H_{TH} \approx 50 \cdot (1 + \frac{i_{gs}}{625}) \tag{4}$$

Since the sensitivity of the glide slope receiver depends on the actual glide slope angle, the determination of the threshold crossing height is, by good approximation, independent of the glide slope angle.

Another aspect that has to be addressed is the fact that the actual glide slope deviation in the aircraft is measured at the location of the glide slope antenna in the nose of the airplane. The radio altimeter provides the height of the main gear above the earth's surface. The height of the ILS antenna above the surface needs to be compensated for this difference in location and the pitch attitude of the aircraft, as illustrated in figure 5. The height of the ILS antenna can be calculated as follows:

$$H_{ILS} = H_{RA} + x_{ILS} \cdot \sin\theta + y_{ILS} \cdot \cos\theta \qquad (5)$$

where:

H_{RA} = Height to main gear as given by radio altimeter
x_{ILS} = Longitudinal distance from ILS antenna to main gear (+ fwd)
y_{ILS} = Vertical distance from ILS antenna to main gear (+ up)
θ = Pitch attitude

So, the threshold crossing height is computed based on the crossing height of the ILS antenna and then, subsequently, the corresponding height of the main gear at that point in time is determined.

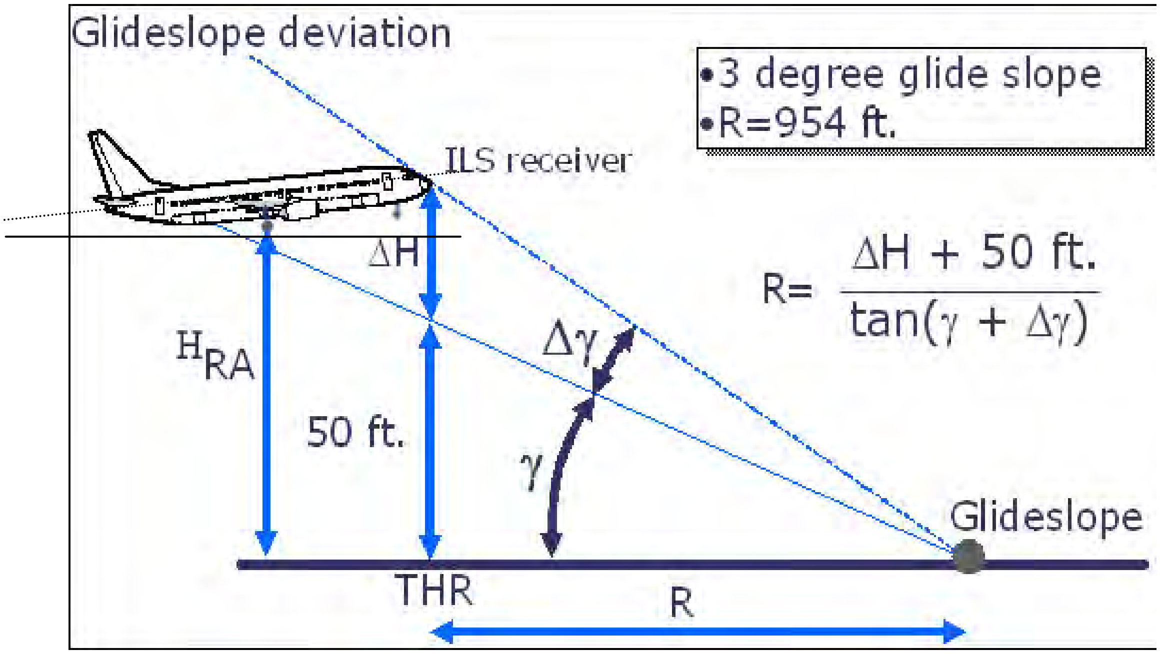

Figure 5. Difference Between RA and ILS Receiver Altitude

3.3.2 Main Gear Touchdown.

The second parameter that has to be determined to establish the airborne distance is the main gear touchdown point. In particular, it is important to determine the point in time of touchdown as accurately as possible. It should be noted that the airspeed of the aircraft types at hand during the landing phase is approximately 140 kt. This means that each second, a distance of approximately 200 ft is covered, which is about 15% of the average airborne distance. For this reason, it is necessary to determine the actual touchdown time with an accuracy of 0.1 to 0.2 second. Since the smallest sampling time interval in the data sample (pertaining to normal acceleration) is 0.125 second, it is important that the correct touchdown sample is found, and that the processing method should not introduce any additional time delay. The objective of this section is to briefly describe the method used to determine the touchdown point during the aircraft landing maneuver.

The available flight data comprises a number of indicators that could be used for the estimation of first ground contact. These are:

- Air-ground switch
- Ground spoiler deployment
- Normal acceleration

At first sight, the most logical choice is to use the air-ground switch. In practice, this switch is triggered by wheel spin-up and/or main gear strut deflection. However, for the aircraft types under consideration (B-737 and A320), this parameter appeared to be less suited for the intended purpose for several reasons. Inspection of the available test data showed that there were substantial differences in the method with which the air-ground switch was sampled for both aircraft types. (For the B-737, it was an alpha-numerical value, and for the A320, it was a digital value). This hampers the automatic processing of these data. Moreover, the sample rate of the air-ground switch is relatively low (2 Hz), which would preclude achieving the required timing accuracy. Finally, some inconsistencies were noted in the available data, showing that the air-ground switch was sometimes triggered after the ground spoiler deflection due to sampling delay.

For this reason, it has been decided to discard the use of the air-ground switch as an indicator and to use instead the point of first ground spoiler deflection. This parameter shows consistent behavior. Obviously, the ground spoiler deflection does not represent the actual point of first ground contact, because there will be some delay between first ground contact and ground spoiler deflection. For this purpose, the normal acceleration signal is used in combination with the ground spoiler deflection signal.

Figure 6 shows an example of the normal acceleration and the ground spoiler deflection for one case out of the test data set. Again, it may seem logical to use the first peak of the normal acceleration signal just before the ground spoiler activation as the trigger for the first ground contact. However, in practice, this procedure cannot be used for two reasons. First, in many cases, there can be a relatively soft touchdown such that a real peak can not be discriminated. Figure 6 presents a relatively firm touchdown. Second, the peak in the normal acceleration represents the point of maximum ground reaction forces, and that point will be somewhat later than the point of first ground contact. As shown in figure 6, the anticipated point of first ground contact is approximately 0.2 to 0.3 second before the point of maximum normal acceleration.

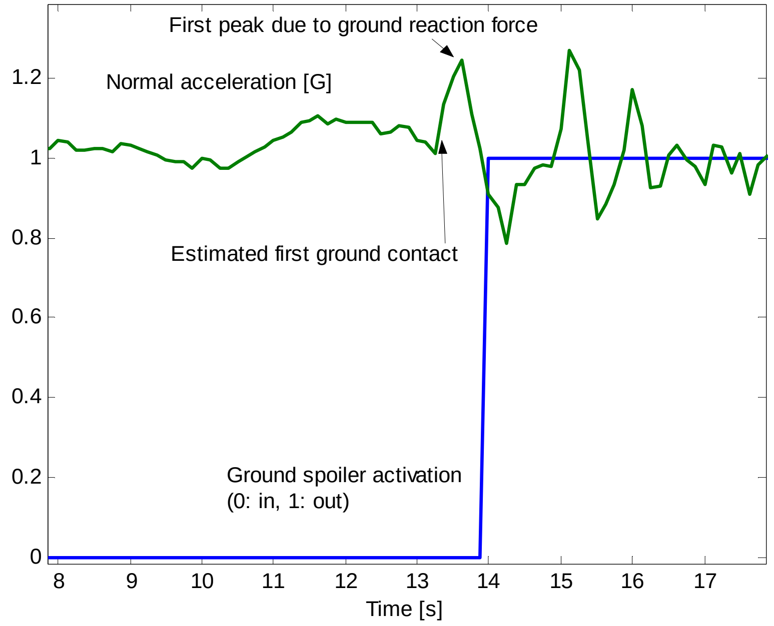

Figure 6. Time Histories of Normal Acceleration and Ground Spoiler Deflection During Landing (B-737)

Based on these observations, it was concluded that it is necessary to take into account the change of the normal acceleration to more accurately estimate the actual point of first ground contact. The procedure followed is to differentiate the normal acceleration signal (by means of forward/backward numerical differentiation, discussed in section 3.2). This derived signal is called the jerk.

It appears that the characteristics of the jerk are clearly correlated with the airborne and ground phase of the landing. Consequently, this signal is well suited to identify the transition from airborne to ground. Figure 7 provides an illustration how the jerk can be used to accurately identify the point of first ground contact. This method is also suited to be used, in an automated way, to process large quantities of flight data. A problem with this method is that after main gear touchdown, the jerk signal becomes rather noisy due to the ground surface reaction forces, leading to peaks that can be higher than the original first touchdown peak. To avoid false identification of the touchdown point, a procedure is used to first identify the time of ground spoiler activation and then search for the peak in the jerk signal in the time period of 2.5 seconds before this point. For the available test data, this appeared to provide consistent results, yielding an accuracy of one sample period (0.125 sec).

It is concluded here that the described methodology provides sufficiently accurate results and is usable in an automated data processing scheme.

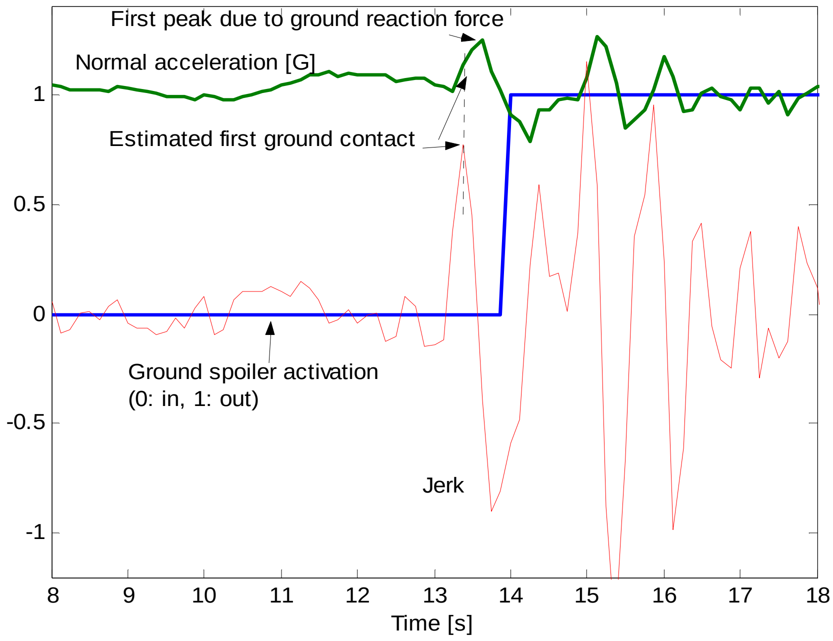

Figure 7. Method of Estimating First Point of Main Gear Touchdown

Examples of the performance of the described algorithm are presented in section 3.7.

3.3.3 Airborne Distance Calculation.

Once the point in time of crossing the threshold and the first main gear ground contact is established, the air distance can be computed by integrating the recorded ground speed of the aircraft over this time period, according to the next equation:

$$D_{airborne} = \int_{T_{THR}}^{T_{TD}} V_{ground} \cdot dt \tag{6}$$

For this integrating process, the ground speed has been used directly as recorded, i.e., it has not been smoothed or filtered. It is assumed that random noise on the ground speed will not affect the calculated airborne distance because the integration process will cancel out random noise. Bias errors on the ground speed could affect the calculated airborne distance. However, bias errors on the ground speed are usually small due to the way the ground speed has been calculated by the airborne Inertial Reference Systems/GPS systems. For this reason, it is expected that direct integration of the measured ground speed over the given time interval from threshold crossing to main gear touchdown provides a good approximation of the airborne distance.

3.4 NOSEWHEEL TOUCHDOWN.

An important parameter in the assessment of the aircraft touchdown dynamics is the time required to lower the nosewheel to the runway surface after main gear touchdown. To identify the instantaneous moment where the nosewheel hits the ground, it may appear that normal acceleration (or its time derivative) are suited signals. However, in general, the normal acceleration signal is, after main gear touchdown, significantly corrupted by high-frequency noise due to the main gear reaction forces on the runway. Moreover, the reaction force resulting from nosewheel touchdown will be, in general, much lower than that of the main gear. For that reason, it is difficult to identify nosewheel touchdown accurately based on the normal acceleration signal.

An alternative method is to use pitch rate or pitch acceleration. In general, the aircraft's nose will be lowered slowly until the nosewheel hits the pavement. At that point in time, the aircraft's pitch rate will reduce quickly to zero, which is associated with a short positive peak in the pitch acceleration. This peak can easily be identified by an automated process that detects the maximum positive (nose up) pitch acceleration after main gear touchdown. Obviously, this process requires the derivation of pitch rate and pitch acceleration from the available pitch attitude signal. This process was described in section 3.2. In section 3.5, the application of pitch rate and pitch acceleration is further elaborated to demonstrate its application for the identification of the flare initiation point. This is a more challenging application than the identification of the nosewheel touchdown point. Therefore, it suffices here to conclude that nosewheel touchdown can be accurately determined by this method. Examples demonstrating the performance of the identification process will be provided in section 3.7.

3.5 FLARE INITIATION.

To assess the aircraft dynamics during the airborne part of the landing maneuver, it is necessary to identify the point in time when the pilot is initiating the flare maneuver. In general, the flare maneuver is initiated by a discrete elevator pilot command input to raise the nose of the aircraft such that the vertical speed is reduced to an acceptable level at touchdown. In practice, however, the discrete command input is, in many cases, masked by the control activities of the pilot to correct flight path deviations and stabilize the aircraft in response to external disturbances. For this reason, the actual initiation of the flare maneuver is not clearly defined and cannot be directly derived from the pilot's control inputs.

An important characteristic of the flare maneuver is the noticeable increase in pitch attitude and the subsequent reduction of the vertical speed. Based on this characteristic, it is possible to make an estimate of the flare initiation point by identifying the initiation of the pitch increase close the ground and before the actual reduction in vertical speed takes place. The initiation of the pitch increase can be identified by finding the maximum pitch rate within a specific search window. However, the maximum pitch rate will be reached after the flare is initiated, and therefore inherently, this method would lead to some time delay in the identified flare initiation point. A better solution is to use the maximum pitch acceleration. From a flight physics point of view, the pitch acceleration is directly related to the pitch control input and, therefore, appears to be a logical choice for identifying the flare initiation point. The problem is whether the pitch acceleration can be derived with sufficient accuracy from the recorded pitch attitude signal to serve as a proper indicator for the flare initiation. It requires double differentiation of the pitch attitude signal, and therefore, it can be expected that the resulting signal will be severely corrupted by noise. To demonstrate that the derivation and smoothing process, as described in section 3.2, can be successfully tuned and applied to estimate the double derivative of the pitch angle, the following test case is presented here.

With the nonlinear Fokker 100 simulation program, available at NLR, a schematized flare maneuver has been simulated. In this particular simulation, the aircraft was subject to moderate to severe turbulence, such that the aircraft was continuously disturbed. Furthermore, the simulated pitch attitude signal (the truth signal) was contaminated with measurement noise and subsequently sampled at 4 Hz. This sampled signal is processed by the derivation and smoothing algorithms to estimate the pitch rate and pitch acceleration signals. These signals are subsequently compared with the true pitch rate and pitch acceleration computed by the simulation program. Results are presented in figure 8.

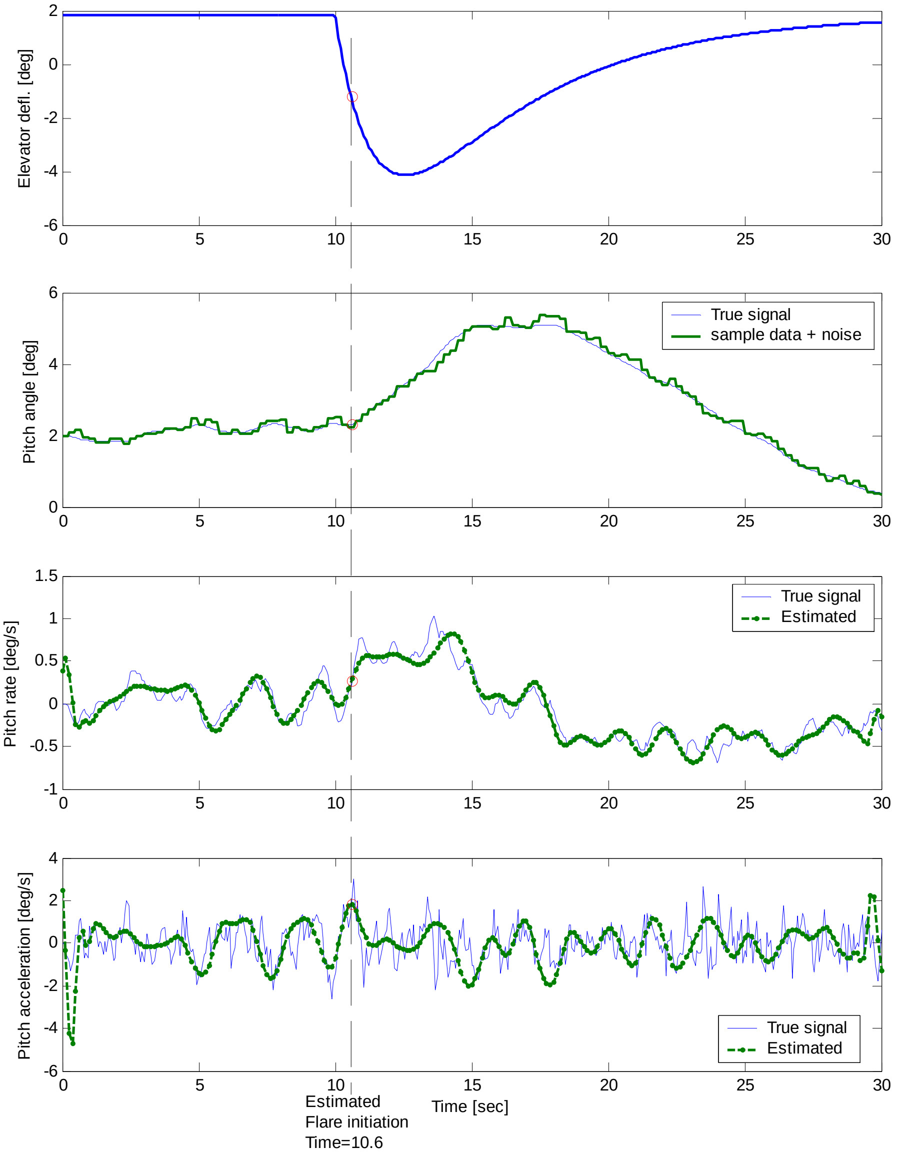

Figure 8. Determination of Flare Initiation Point Based on Estimated Pitch Acceleration

Figure 8 shows that the derived pitch rate signal compares well with the true pitch rate signal. The general dynamics of the aircraft are well matched, despite the fact that some high-frequency disturbances, resulting from the encountered turbulence, are somewhat filtered out. It is also clear that pitch rate could not be used as an indicator to identify the flare initiation point because the maximum pitch rate occurs approximately 5 seconds after the flare initiation.

In the lower graph of figure 8, the derived pitch acceleration is compared with the true pitch acceleration signal. It is clear that the true pitch acceleration is significantly affected by the turbulence. Due to the applied smoothing in the calculation of the derived pitch acceleration signal, much of these disturbances are filtered out. Nevertheless, the basic dynamics of the pitch acceleration is well matched by the derived signal. Apparently, the peak pitch acceleration, associated with the flare initiation, is correctly identified. Based on finding the maximum pitch acceleration in the full-time history, the flare initiation point is found at 0.6 second after the actual flare maneuver was first initiated. Given the fact that the aircraft requires some time to respond to pilot input, this is considered an excellent result. Based on visual inspection of the results, the identified flare initiation point exactly corresponds to the initiation of the pitch increase. Therefore, it is concluded that the method to identify the flare initiation point, as presented here, is in principle feasible for application to the available data set.

To minimize potential false identifications in the actual processing, a search window has been applied. This search window covers the time period from descending through 60-ft radio altitude to the moment that the vertical speed has reduced to 350 ft/min. This has been based on the concept that, in general, the flare will not be initiated above 60-ft altitude (which is above screen height). Also, once the vertical speed was reduced to 350 ft/min, this must have been caused by a deliberate action of the pilot to initiate the flare.

In appendix B, some results are presented to demonstrate the accuracy of the flare initiation determination process in practice. These will be further discussed in section 3.7.

3.6 OTHER PARAMETERS.

The complete list of parameters that are established for each of the recorded flights is presented in section 4. The determination of most of these parameters is straight forward and needs no further explanation. Nevertheless, a few important remarks have to be made here.

A number of the parameters are composed of combined signals. For instance, N1 at flare initiation provides an indication of the engine thrust at that particular point. However, the aircraft types in the data sample all have two engines, and therefore, the N1 is recorded for both the right and left engine. The actual presented parameter is the mean of the left and right engine N1 at that particular point. The same is true for thrust reverser deflection.

One of the established parameters concerns the maximum negative elevator deflection during the flare. This parameter provides an indication of the amount of elevator command that is used during the flare. It should be noted, however, that the sign conventions of the elevator deflection differs between the Boeing and Airbus types. For Boeing, elevator trailing edge up is considered a positive deflection, whereas for Airbus the reverse definition is used (trailing edge down is positive). The latter is the standard European convention. For this reason, in the determination of this parameter, the sign of the elevator deflection has been reversed as if it were for a Boeing aircraft. In this way, the maximum negative elevator deflection always corresponds to the maximum pitch up command during the flare.

A number of parameters require the determination of when full reverse thrust is applied. In practice, various levels of reverse thrust can occur and it is not clearly defined when full reverse thrust is actually selected. In the present analysis, it has been assumed, based on operational practice, that full reverse thrust has been applied if N1 exceeds 55%.

Furthermore, it should be noted that a number of parameters are related to either CAS or TAS at specific points. As mentioned already in section 2.5, those recorded speeds can have relatively high lower limits (e.g., for the B-737 the lower limit of TAS is 100 kt). For this reason, some of the mentioned parameters have lost their significance, such as the TAS at runway exit.

Finally, it is important to note that the glide slope deviation signal can also be subject to limiting values. For the B-737, the glide slope deviation signal has been limited to ±2.7 dots as long as the aircraft is airborne. In some cases, this affects the determination of the threshold crossing height. Based on a standard sensitivity of 0.36°/dot, the highest threshold crossing height to be calculated is limited at 66.2 ft. For the Airbus-type aircraft such a limitation does not exist.

3.7 EXAMPLES OF DATA PROCESSING PERFORMANCE.

In the previous sections, the processing algorithms that determine the key aircraft landing performance indicators were described. In this section, the effectiveness and validity of these algorithms are demonstrated using a number of illustrative example recordings. These examples concern cases with

- small and large glide slope tracking errors,
- calm wind, high wind, and severe turbulence,
- short and long air distances,
- hard and soft landings,
- high and low descent rates, and
- gradual and aggressive flaring.

Time histories of these 30 examples are presented in appendix B (figures B-1 to B-30). The results of these cases are addressed shortly hereafter.

However, before examining the examples mentioned above, figures 9 and 10 show a random sample of approximately 150 recordings from the entire data set that concerns the landing flare and touchdown of the A320 and B-737, respectively.

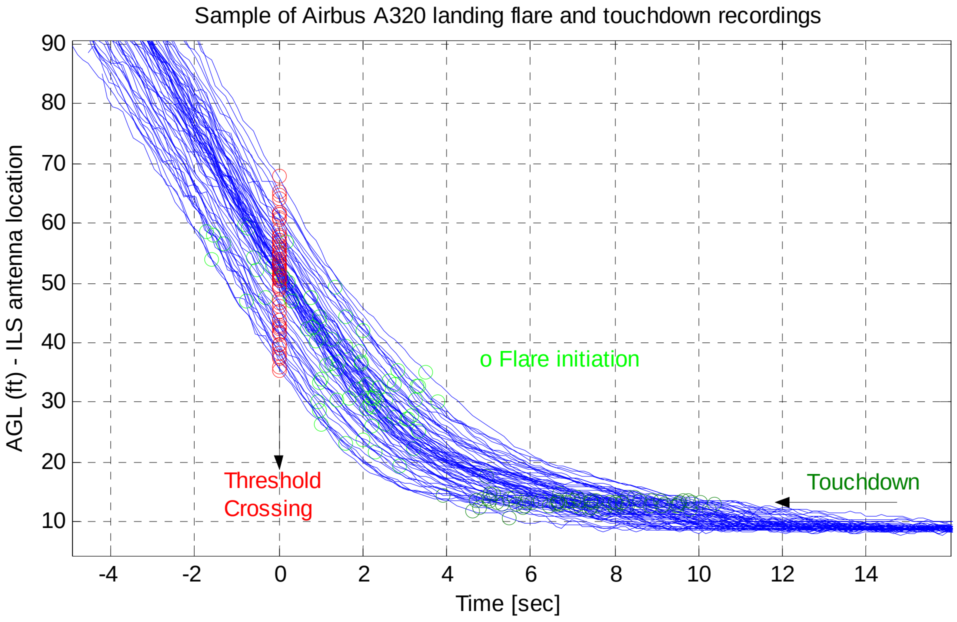

Figure 9. A320 Landing Flare and Touchdown Recordings

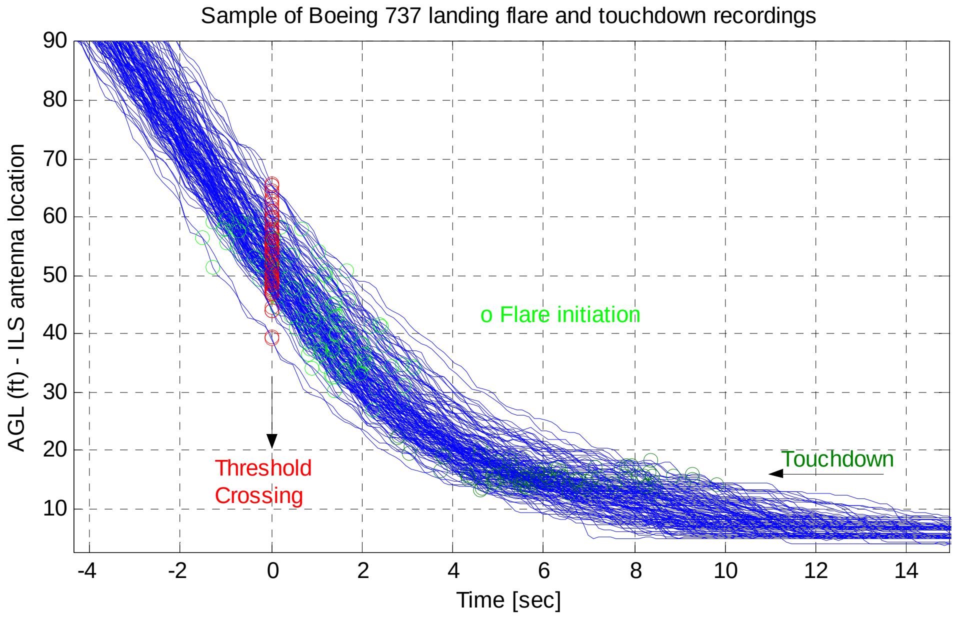

Figure 10. B-737 Landing Flare and Touchdown Recordings

For both aircraft types, these recordings cover approximately 1% of the available data set for each type. The graphs also show the estimated threshold crossing height, flare initiation, and the touchdown point for each of the time histories. The recordings have been synchronized in time such that crossing of the threshold coincides with T = 0 sec.

Figures 9 and 10 show that both aircraft types exhibit similar flare and touchdown behavior. However, some slight differences can be noted. It appears that flare initiation with the A320 occurs, on average, at approximately 30 ft, whereas the B-737 is slightly higher at approximately 40 ft. It is also noticeable that the recorded altitude signal for the B-737 appears to be slightly more affected by noise than that of the A320.

In the following paragraphs, the example cases presented in appendix B will be further discussed. For each example case, a series of selected parameters are presented. Because the examples are intended to demonstrate the validity of the determination of the threshold crossing height, flare initiation and touchdown relevant parameters are selected to be displayed. These are the radio altitude, pitch attitude, CAS, glide slope deviation and normal acceleration, and its time derivative (jerk) and spoiler deflection. Particular cases that were aimed to further demonstrate the identification of the flare initiation point (appendix B), the elevator deflections, derived pitch rate, and pitch acceleration are presented instead of glide slope deviation, normal acceleration, and jerk.

Example cases with small and large glide slope tracking errors are presented in figures B-1 through B-8. Figures B-1 and B-2 show landings of an A320 and B-737, respectively, while they were precisely positioned at the glide slope, and thus passed the threshold at 50 ft. In the case of the A320, a very soft touchdown was made that was, nevertheless, accurately identified. Also, the flare initiation point appears to be correctly identified. In both cases, the time from threshold to touchdown was approximately 6 seconds, resulting in an airborne distance of between 1200 and 1300 ft.

Figures B-6 through B-8 are cases where the aircraft passed high over the threshold (>2 dots deviation high). Figure B-3 shows a particular case with a clear floating tendency during the flare. In this case, the time from threshold to touchdown took approximately 12 seconds, which lead to an airborne distance of slightly over 3000 ft. Figures B-4 and B-5 show rather regular, but quite gradual, flare behavior despite the high threshold crossing.

Figures B-6 through B-8 show cases where the aircraft passed low over the threshold (>2 dots deviation low). In two cases, this leads to flare initiation before the threshold is crossed. The figures also show that the low threshold crossing leads to fairly aggressive and discrete flare maneuvers and that the time from threshold to touchdown is reduced. In the case shown in figure B-8, the time between crossing the threshold and touchdown was 2.5 seconds, resulting in a very short airborne distance and a very firm touchdown (>1.4 g).

Example cases with calm wind, high wind, and severe turbulence are presented in figures B-9 through B-12. The first two cases were selected based on wind reports indicating calm wind (<3 kt) and no turbulence. These two cases represent nominal landing cases undisturbed by external turbulence or wind. Both cases show (A320 and B-737, respectively) a smooth flare maneuver resulting in and a fairly normal touchdown (~1.15 g).

The two subsequent cases were selected based on weather reports indicating high wind (30 kt or more) and severe turbulence (gust values of 45 kt or more). Both cases show that the wind and turbulence significantly affect the aircraft response. During the airborne part, pitch excursions of

±1 degree are shown and normal acceleration varies between 0.8 and 1.2 g. Nevertheless, in both cases, a fairly normal touchdown is being made. In figure B-11, even a very smooth touchdown is realized, such that the acceleration due to the ground reaction can not be discriminated from the normal acceleration variations. Clearly, this is a challenging case for the touchdown determination algorithm. Nevertheless, the algorithm provides a reasonable estimate of the touchdown point, although one could argue that, in this particular case, it is perhaps slightly early.

Example cases with short and long air distances are presented in figures B-13 through B-16. The first two cases were selected based on an extremely short air distance (≈500 ft). Both cases are characterized by a low threshold crossing height, flare initiation before the threshold was crossed, and a hard landing (>1.4 g). These cases are fairly easy cases for the processing algorithms. The subsequent cases have been selected based on an extremely long air distance (>2600 ft).

In both cases, a fairly gradual flare maneuver is shown with a noticeable change in pitch, and a floating tendency can be observed. Nevertheless, a fairly normal touchdown was made (~1.12 g). It is clear that, due to the gradual flare maneuver, no distinct flare initiation point can be distinguished. However, the flare initiation point found by the algorithm appears to be reasonable.

Example cases with hard and soft landings are presented in figures B-17 through B-20. The first two cases have been selected based on high touchdown acceleration (>1.5 g). These cases are characterized by a relatively aggressive flare initiation at rather low altitude. The second case, figure B-18, is particularly interesting. It appears that the aircraft bounces back after a very hard touchdown to become almost airborne again. Apparently, the air-ground switch is deactivated after first touchdown, such that the spoilers are retracted again. Spoilers are deployed again approximately 8 seconds after initial touchdown. In this time frame, the aircraft is clearly unable to decelerate. As shown, the algorithm is able to identify the first touchdown point, despite the bouncing effect, and the subsequent activation and deactivation of the spoilers.

The next two cases have been selected on the basis of very low touchdown acceleration (~1.02 g). These can be expected to be challenging cases for the touchdown determination algorithm. As shown in figures B-19 and B-20, the variation in the acceleration level in the airborne phase is on the same order as the touchdown acceleration itself. Nevertheless, a credible estimate of the touchdown point is made. A particularly interesting case is shown in figure B-20 where a noticeable peak in normal acceleration can be seen after touchdown. This is caused by lowering the nosewheel aggressively towards the ground after very smooth main gear touchdown, which leads to a normal acceleration of approximately 1.15 g due to the nosewheel response. It is considered a favorable feature of the touchdown determination algorithm that the soft main gear touchdown was correctly identified and not confused with the marked peak due to the nosewheel touchdown.

Example cases with high and low descent rates are presented in figures B-21 through B-24.

The first two cases have been selected based on high descent rate at the threshold (>850 ft/min). It is shown that, in both cases, a rather aggressive flare maneuver is initiated (approximately 1.2 g during the flare). This maneuver is apparently sufficient to arrest the sink rate. In both cases, a relatively soft touchdown was made and was correctly identified.

The next two cases were selected based on low descent rate at the threshold (< 350 ft/min). In both cases, a very gradual flare was executed, which led to a very soft touchdown. Despite the gradual flare maneuver and soft touchdown, the flare initiation points and the touchdown points were estimated credibly.

Example cases with gradual and aggressive flaring are presented in figures B-25 through B-30. The first two cases have been selected based on being representative for a normal, average flare. From analyzing the complete data set, it appears that the maximum normal acceleration during the flare is, on average, 1.12 g. Evidently, many cases in the data set are present that satisfy this criterion. Two cases have been selected to represent normal flare behavior. These cases are given in figures B-25 and B-26. In both cases, a marked pitch increase of approximately 3 degrees was observed during the flare, and the flare initiation points were identified correctly.

The next two examples concern cases with aggressive flare behavior. From analysis of the data set, it was found that the highest values of normal acceleration during the flare amount to approximately 1.4 g. Two cases with such high acceleration levels during the flare are presented in figures B-27 and B-28. In both cases, a low threshold crossing occurred and required a fast pitch up, and the flare initiation point was identified accurately.

The final two examples concern cases with very gradual flare behavior. From analysis of the data set, it was found that a gradual flare is characterized by a normal acceleration level of approximately 1.05 g. Two of such cases are presented in figures B-29 and B-30. Evidently, these are challenging cases for the determination of the flare initiation point. Both cases show an almost continuous and gradual increase of pitch attitude during the landing flare maneuver. The derived pitch acceleration signal shows oscillatory behavior, from which it is difficult to identify which peak would coincide with flare initiation. However, due to the fact that a specific search window is being used, several peaks were discarded. The actual peaks identified by the algorithm to coincide with flare initiation can easily be disputed because, in these particular examples, the flare initiation is not sharply defined. However, if the elevator commands given by the pilot are taken into account, it appears that the identified flare initiation points correspond well with the initial flare command of the pilot. Therefore, it is concluded that, even in the case of a smooth and gradual flare, the algorithm was able to provide a credible estimate of the flare initiation point.

To conclude, based on the above examples, the processing algorithms (as discussed in sections 3.2 through 3.5) provide a valid method to determine threshold crossing height, touchdown point, and flare initiation with sufficient accuracy. It can also be concluded that these algorithms are suited for automatic data processing. Results obtained with these methods are further analyzed in the section 4.

4. RESULTS.

4.1 INTRODUCTION.

In this section, the results from the data analysis are presented and discussed. The airborne and ground roll parts of the landing are presented separately. Also, the results for the different aircraft types are discussed individually in most cases. The parameters derived from the data are listed in table 3. The metrological data were either obtained from, or were calculated from, METAR reports. The available runway landing distances were obtained from an airport database, which was matched with each individual landing. The sunset and sunrise times[3] were calculated using the date of the landing and the location of the airport.

Table 3. Parameter in the Landing Database

Airborne Part		Ground Roll Part	
Parameter	Unit	Parameter	Unit
Distance from THR to touchdown	m	Time from touchdown to thrust reverser engagement	s
Height of ILS receiver over THR	m	Distance from touchdown to thrust reverser engagement	m
Height of wheels over THR	m	TAS at T/R deselection	m/s
Height of wheels at touchdown	m	Ground speed at T/R deselection	m/s
Height of flare initiation	m	Time from touchdown to T/R deselection	s
Time from touchdown to nose wheel touchdown	s	Distance from touchdown to T/R deselection	m/s
Bug speed	m/s	Time period of full reverse	s
Autopilot setting	----	TAS at full reverse selection	m/s
Flight path angle over the THR	deg	TAS at idle reverse selection, after full reverse	m/s
CAS over the THR	m/s	Time from touchdown to nose wheel touchdown	m/s
TAS over the THR	m/s	Distance from touchdown to nose wheel touchdown	m
Ground speed over the THR	m/s	TAS at initial manual braking	m/s
Vertical speed over the THR	m/s	Groundspeed at initial manual braking	m/s
Pitch angle over the THR	deg	Distance from touchdown to manual braking	m
N1 over the THR	%	Time from touchdown to spoiler deflection	s
CAS at flare initiation	m/s	Distance from touchdown to spoiler deflection	m
TAS at flare initiation	m/s	TAS at runway exit	m/s
Ground speed at flare initiation	m/s	Groundspeed at runway exit	m/s
Pitch angle at flare initiation	deg	Localizer deviation at THR	m
N1 at flare initiation	%	Autobrake setting	----
Max Nz during flare	g	Distance from touchdown to runway exit	m
Max negative elevator deflection during flare	deg	Miscellaneous Parameters	

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[3] Sunrise and sunset refer to the times when the upper edge of the disk of the sun is on the horizon. The times of sunrise and sunset cannot be precisely calculated, because the actual times depend on unpredictable atmospheric conditions that affect the amount of refraction at the horizon. Thus, even under ideal conditions, the times computed for rise or set may be in error by a minute or more. However, for the present project, such small errors are not of great concern.

Table 3. Parameter in the Landing Database (Continued)

Airborne Part		Ground Roll Part	
Parameter	Unit	Parameter	Unit
CAS at touchdown	m/s	Airport code	----
TAS at touchdown	m/s	Date/time	----
Ground Speed at touchdown	m/s	Temperature	C
Pitch angle at touchdown	deg	Mean wind	m/s
N1 at touchdown	%	Gusts	m/s
Nz at touchdown	g	Wind direction	deg
Vertical speed at touchdown	m/s	Visibility	m
Heading at touchdown	deg	Ceiling	m
Bank angle at touchdown	deg	Runway condition	----
Time from flare to touchdown	s	General weather	----
Distance from flare to touchdown	m	Sunrise time	----
Speed loss from flare initiation to touchdown	m/s	Sunset time	----
		Landing distance available	m
		Runway heading	deg
		Flaps	deg
		Weight	kg

THR = Thrust
T/R = Thrust reverser

4.2 CHARACTERISTICS OF MISCELLANEOUS PARAMETERS.

The frequency distribution of the runway conditions prevailing at the time of each landing by the different aircraft types are shown in figure 11. These frequencies are estimations based on the precipitation conditions approximately the time the aircraft landed and are not based on the actual assessment of the runway. The results should, therefore, be treated with some caution. Figures 12 and 13 present the crosswind and head- and tailwind conditions that prevailed at the time of each landing for each aircraft type. The crosswind distributions were more or less symmetrical approximately the zero crosswind condition, suggesting that there was an equal probability of having wind coming from the left- or right-hand side of the aircraft. The distributions of the crosswind conditions are comparable for each aircraft type. However, the A319 data showed a slightly higher probability of wind coming from the right. When the direction of the crosswind was disregarded, the distribution became more similar. The head- and tailwind conditions were practically the same for the aircraft types considered. Figures 12 and 13 clearly show the preference for making headwind landings.

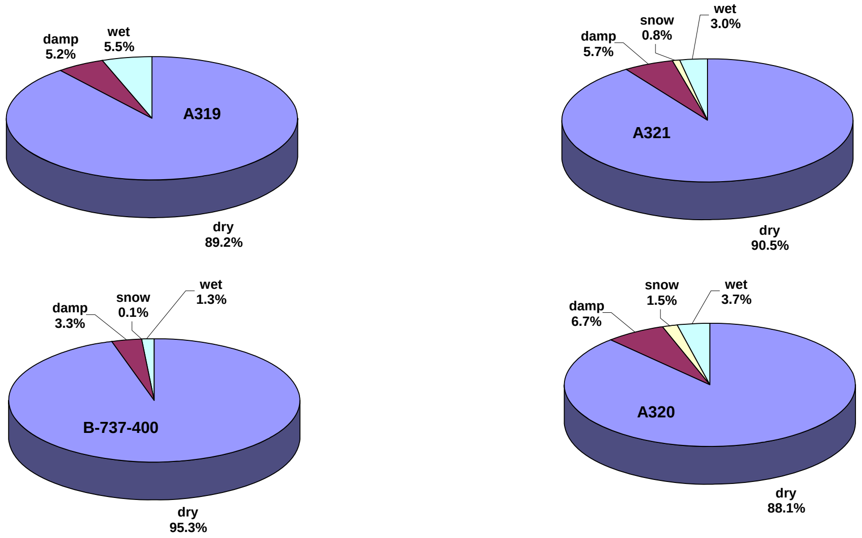

Figure 11. Runway Conditions Encountered

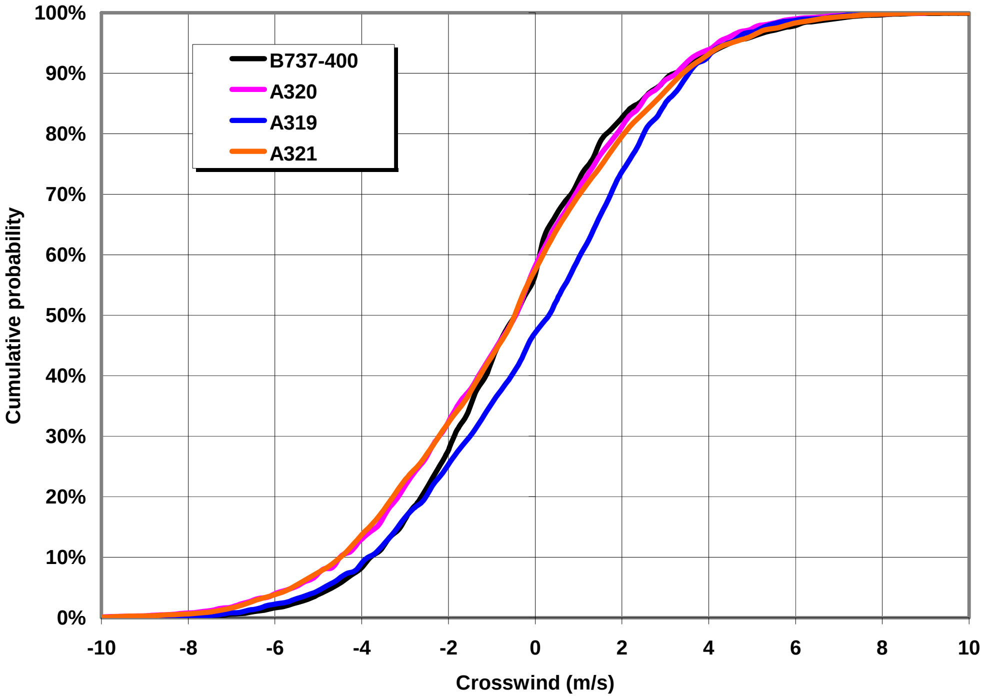

Figure 12. Prevailing Crosswind Conditions

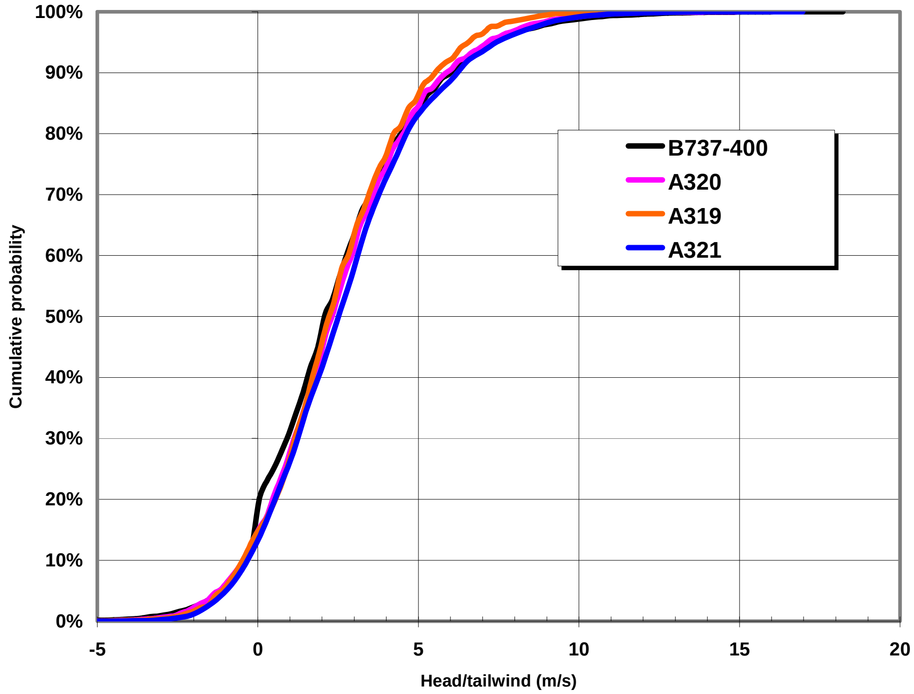

Figure 13. Prevailing Head- and Tailwind Conditions

The ceiling was only recorded for cases where the sky condition was broken or overcast (14% of all landings in the database). The ceiling conditions prevailing at the time of each landing for each aircraft type are shown in figure 14.

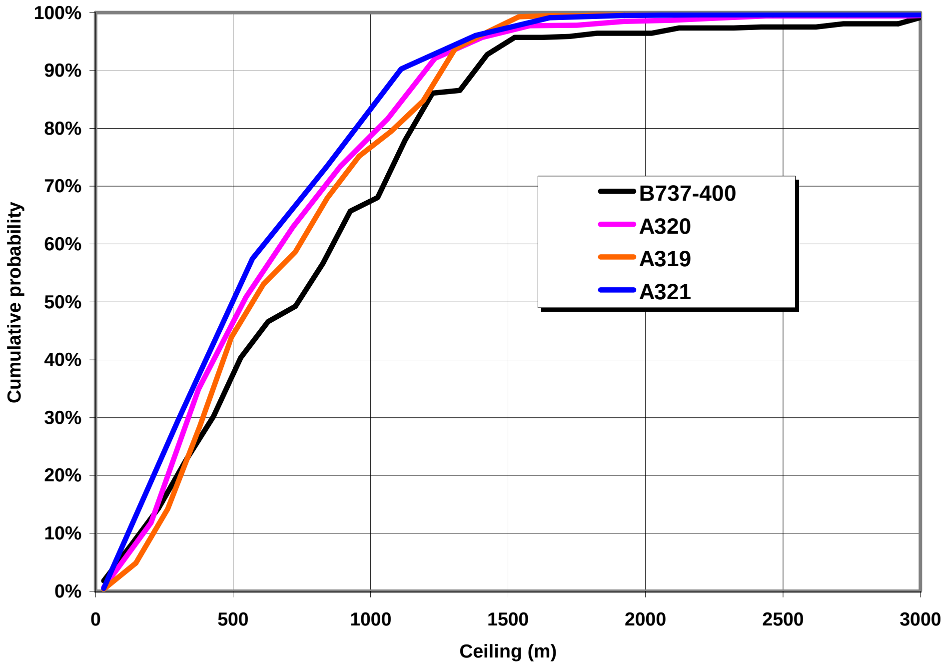

Figure 14. Prevailing Ceiling Conditions

A large number of landings in the database were in visibility conditions of 10 km or more. The visibility values were recorded as >10000 m whenever the visibility exceeded 10 km. In the database, these were changed into a visibility of 10 km. Table 4 shows the percentage of landings in which such visibilities existed. Figure 15 shows the visibility distribution for conditions below 10 km.

Table 4. Visibility Conditions of 10 km or Better

Aircraft Model	Landings with visibility condition 10 km or more
A319	92%
A320	81%
A321	80%
B-737-400	74%

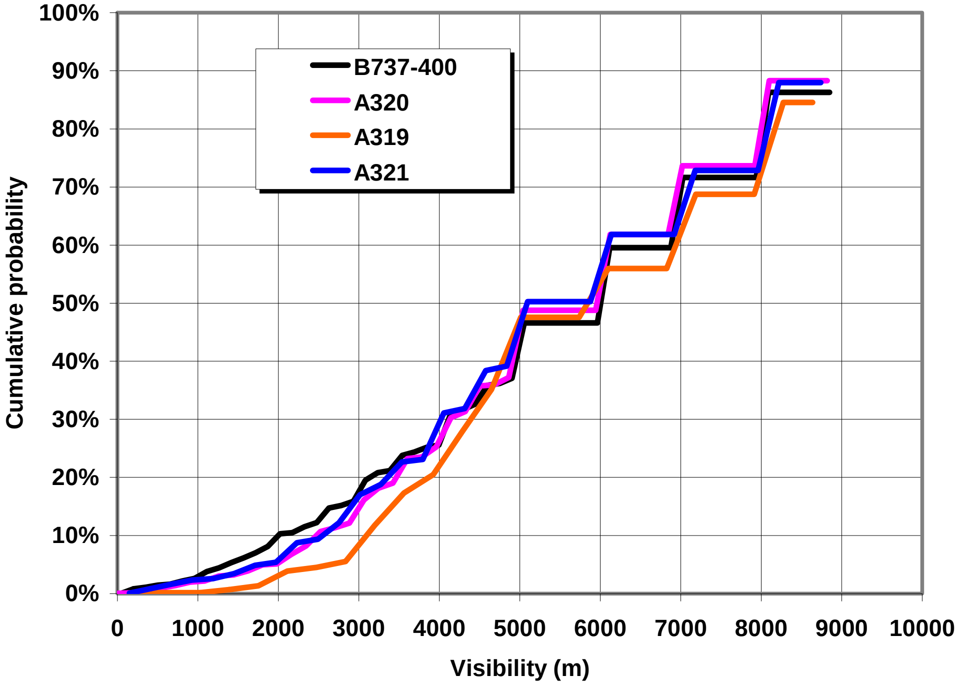

Figure 15. Prevailing Visibility Conditions Below 10 km

4.3 AIRBORNE PART OF THE LANDING.

Table 3 lists the parameters that were recorded in the database, which relate to the airborne part of the landing. Many of these parameters are related to the airborne distance (i.e., the ground distance covered from threshold to touchdown). The distribution of the airborne distance for the different aircraft types is shown in figure 16.

There are a number of parameters recorded in the database that can influence the airborne distance. To find the subsets of independent parameters that best contribute to the airborne distance, a linear best subsets regression analysis is conducted. Best subsets regression is a technique for selecting variables in a multiple linear regression by systematically searching through the different combinations of the independent variables and then selecting the subsets of variables that best contribute to predicting the dependent variable. The regression technique also looks at redundant information in the other independent parameters. This analysis was applied to the data and resulted in a list of parameters that influenced the airborne distance the most (table 5).

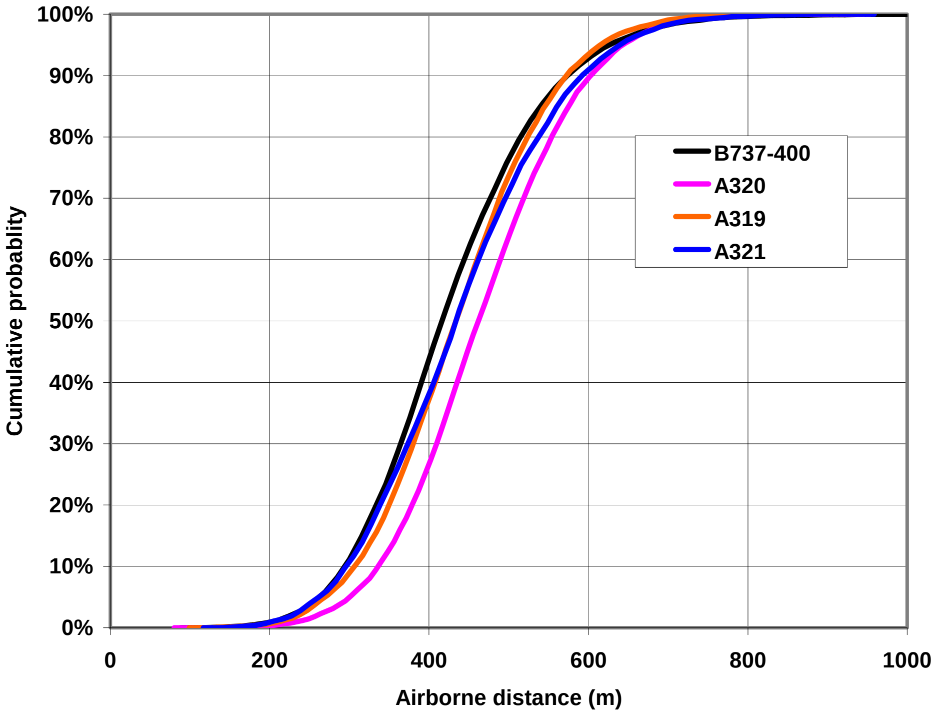

Figure 16. Airborne Distance

Table 5. Parameters That Influence the Airborne Distance

Parameter	Influence*	Correlation**
Height of ILS receiver over threshold	+++	+
Height of flare initiation	+	+
Flight path angle over the threshold	++	+
Ground speed over the threshold	++	+
Max Nz during flare	-	
Max negative elevator deflection during flare	++	-
N1 over the threshold	-	
Ground speed at flare initiation	-	

Table 5. Parameters That Influence the Airborne Distance (Continued)

Parameter	Influence*	Correlation**
CAS at flare initiation	+	+
N1 at flare initiation	-	
Head- and tailwind mean (m/s)	±	-
Difference between actual and reference speed over threshold	++	+
Speed loss from flare initiation to touchdown	+++	+
Difference in rate of descent at threshold and touchdown	+	-

* +++: very strong influence, ++: strong influence, +: minor influence, -: no influence.
** +: positive correlation, -: negative correlation.

The influence of the threshold crossing height appears to have the strongest influence on the airborne distance. The higher the aircraft crosses the threshold, the longer the airborne distance gets. Figure 17 clearly illustrates this relation for each of the four aircraft types. The glide slope deviations for the B-737-400 are limited to 2.7 dots, which explains the cutoff in data shown in the top left chart of figure 17.

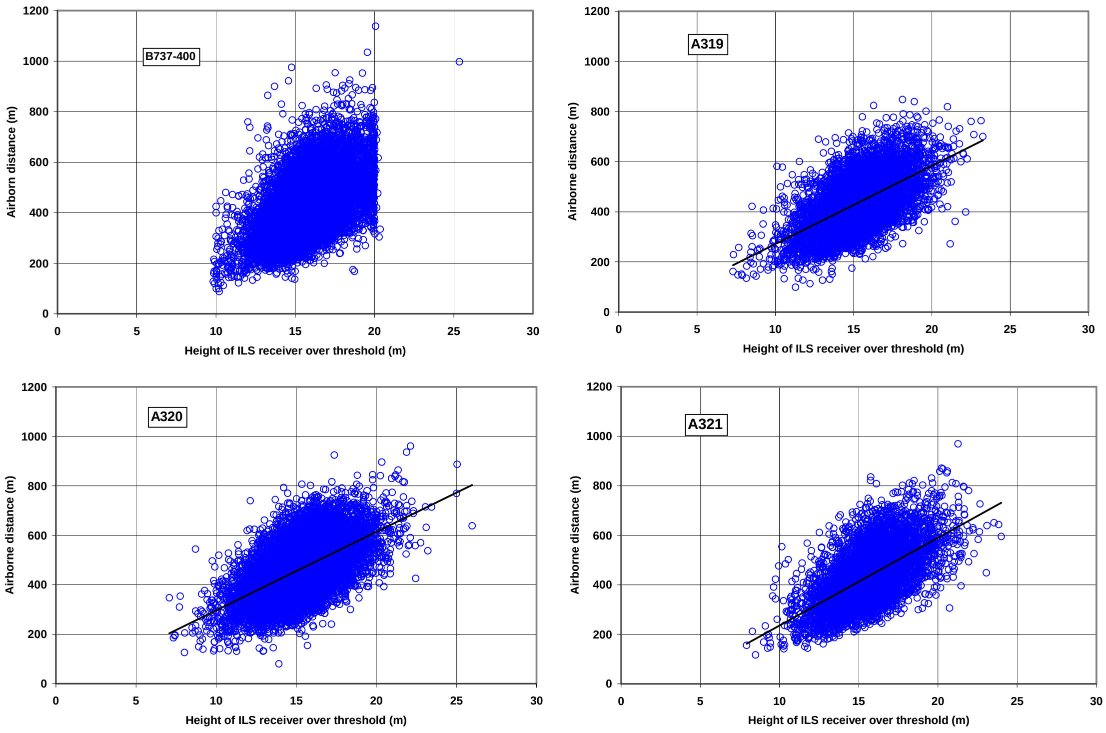

Figure 17. Influence of Threshold Crossing Height on Airborne Distance for the B-737-400

The speed loss from flare initiation to touchdown has a very significant influence on the airborne distance, as illustrated in figure 18. In this figure, the loss in speed is positive, and the airborne distance increases with a higher speed loss. As shown in figure 19, the time from flare initiation and touchdown increases with a higher speed loss. It takes time, and therefore ground distance, to reduce the speed. Note that it is normal to reduce some speed during the flare. Boeing, for instance, recommends touching down with a speed that is equal to the reference landing approach speed (Vref) plus the gust correction.[4]

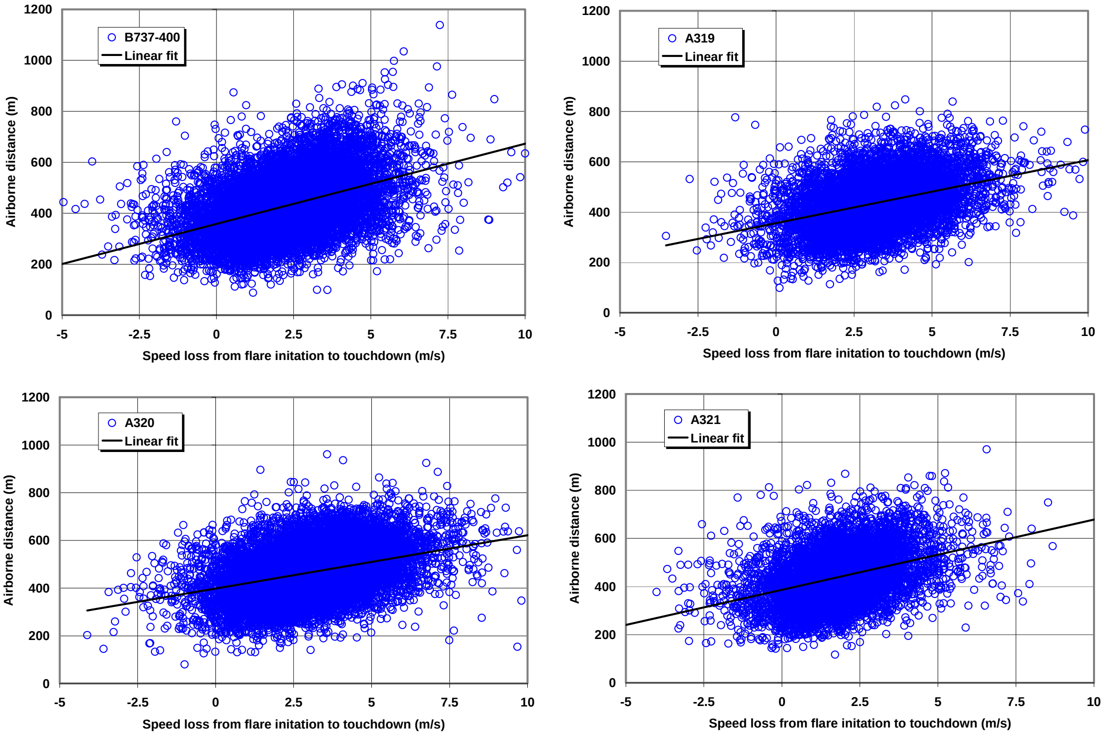

Figure 18. Influence of Speed Loss on Airborne Distance

The difference in the actual speed and the reference speed over the threshold has a strong influence on the airborne distance. This speed difference for the different aircraft types is shown in figure 20. The B-737-400 data shows a higher tendency to be faster than the reference speed at the threshold compared to the Airbus models. The reason for this is unknown. It may be because the standard practice for fly-by-wire aircraft is to fly with the autothrust (A/THR) engaged during a landing, whereas standard practice for a conventionally controlled aircraft with wing-mounted engines is to disengage the A/THR as soon as the autopilot is disengaged. With A/THR engaged, the speed control is more accurate, possibly explaining the results shown in figure 20. In figure 21, the influence of the speed difference at the threshold on the airborne distance is shown for the B-737-400. The linear fit is only shown to illustrate the general correlation between airborne distance and the speed difference at the threshold.

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[4] The wind corrections made on Vref are not the same for the Boeing and the Airbus aircraft. Boeing recommends to use an approach speed wind correction of half the steady headwind component plus all the gust increment above the steady wind, whereas Airbus recommends to use one third the total headwind component.

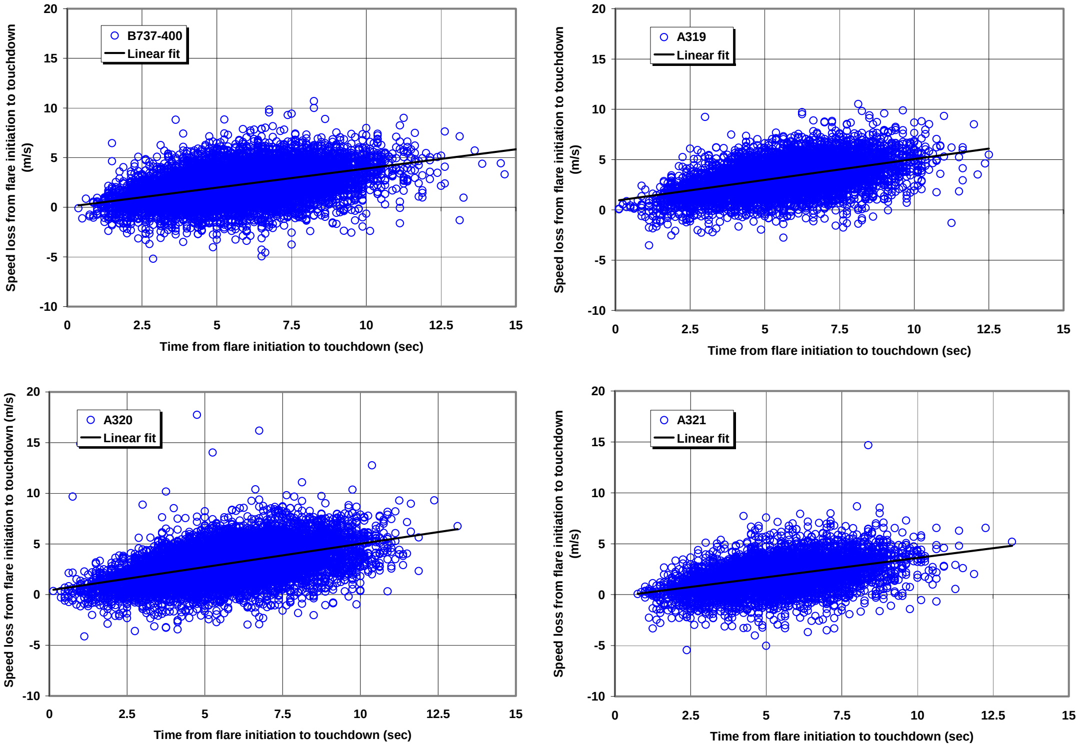

Figure 19. Time From Flare Initiation to Touchdown Versus Speed Loss

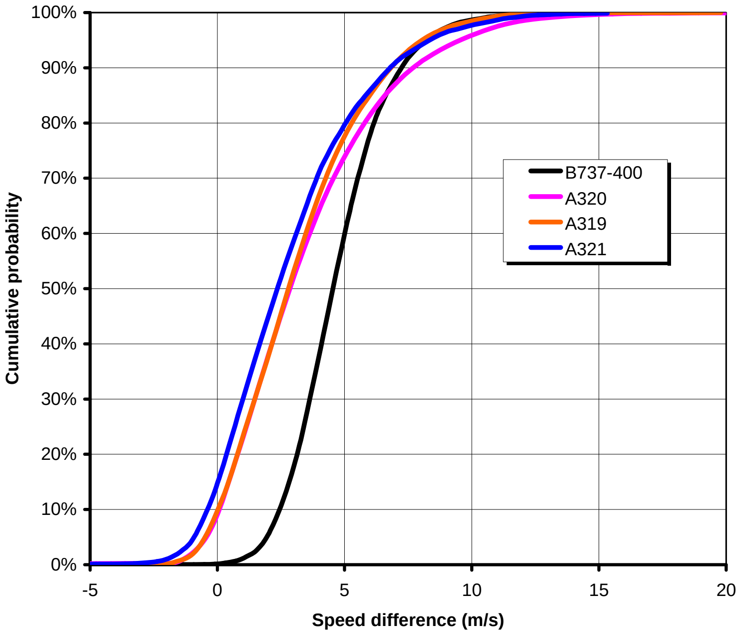

Figure 20. Difference in Actual Speed and Reference Speed at the Threshold

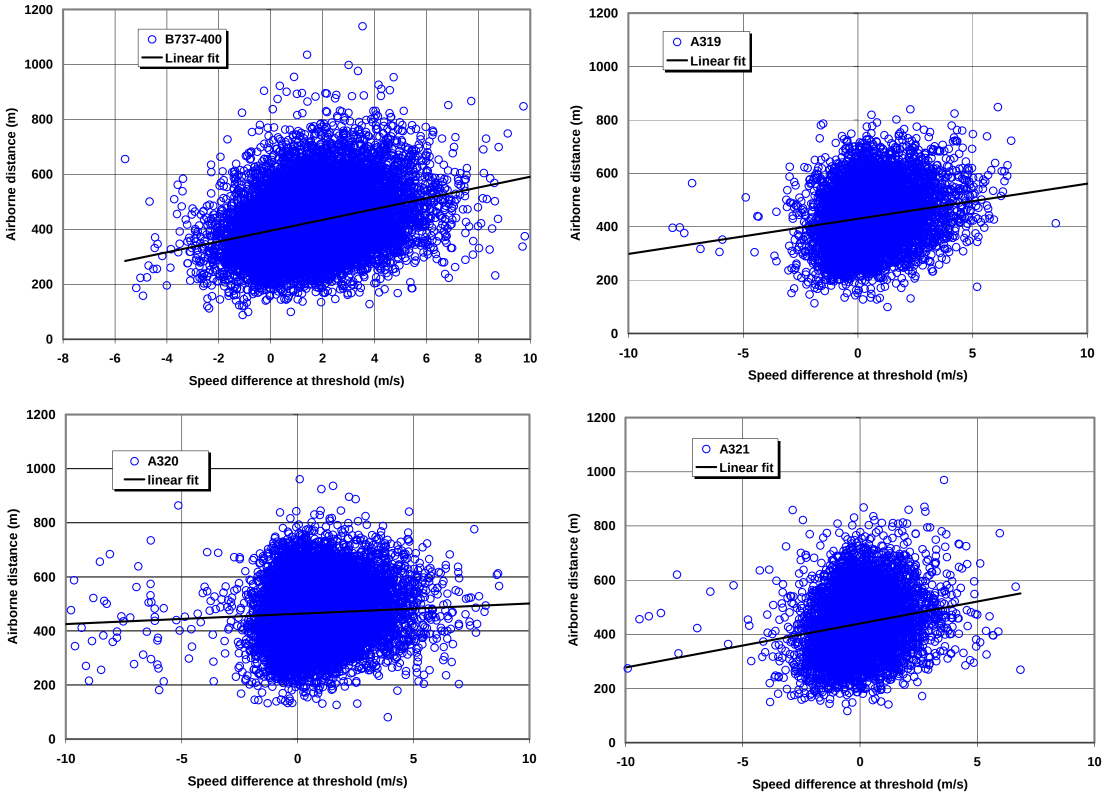

Figure 21. Influence of Speed Difference at Threshold on Airborne Distance for the B-737-400

The best subsets regression analysis showed that head- or tailwind does not have a large influence on the airborne distance. The final approach speeds of the aircraft considered in this study are corrected for wind conditions as part of the standard operating procedures of those aircraft. In case of headwind conditions, the final approach speed is increased and for tailwind conditions no corrections are made. However, when reaching the threshold, these wind corrections may be bled off according to recommended practices given by Boeing and Airbus. The results from figure 20 suggest that most landings are conducted with some additional speed above the reference speed. It seems that not all the speed additives are bled off. The data showed that this is particularly true during headwind landings. This could mean that the reduction in ground speed due to headwind is counteracted by the tendency to overspeed. As a result, there is not a large effect on airborne distance. Tailwind could increase the airborne distance; however, tailwind conditions only existed in 15% of all landings (see figure 13). The runways used for landing are normally selected with a preference for headwind conditions (see figure 13). Furthermore, for these cases, the tailwind itself was small in magnitude and, as a result, its effect on the airborne distance was also small. This explains the fact that head- or tailwind conditions have a small influence on the airborne distance. Figure 22 gives an example of the influence of head- and tailwind on the airborne distance of an A320.

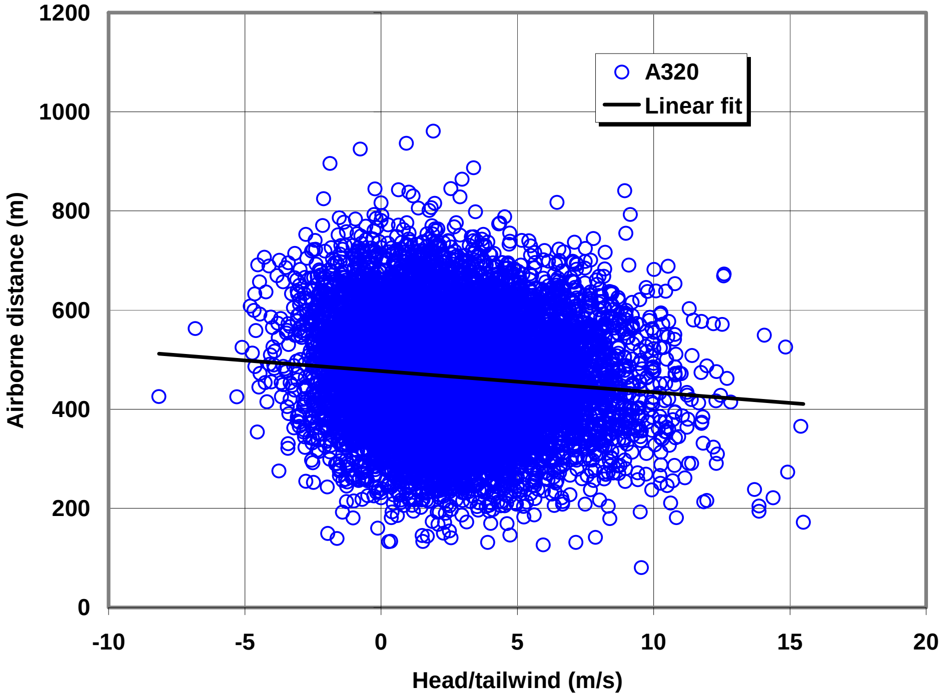

Figure 22. Influence of Head- and Tailwind on Airborne Distance

A limited number of landings were conducted with the autopilot and A/THR engaged until touchdown (511 in total). This number of autolands conducted by each of the four aircraft types is too small for meaningful statistical analysis. Therefore, only the results of all aircraft types together are considered. Figure 23 shows the comparison of airborne distance of autolands and manual landings for all aircraft types. As can be expected, the autolands have a lower average airborne distance than manual landings and also show less deviation from the average airborne performance. These findings are logical because autolands are not influenced by any human performance during the airborne maneuver. As a result, a more consistent and shorter airborne distance is realized during an autoland.

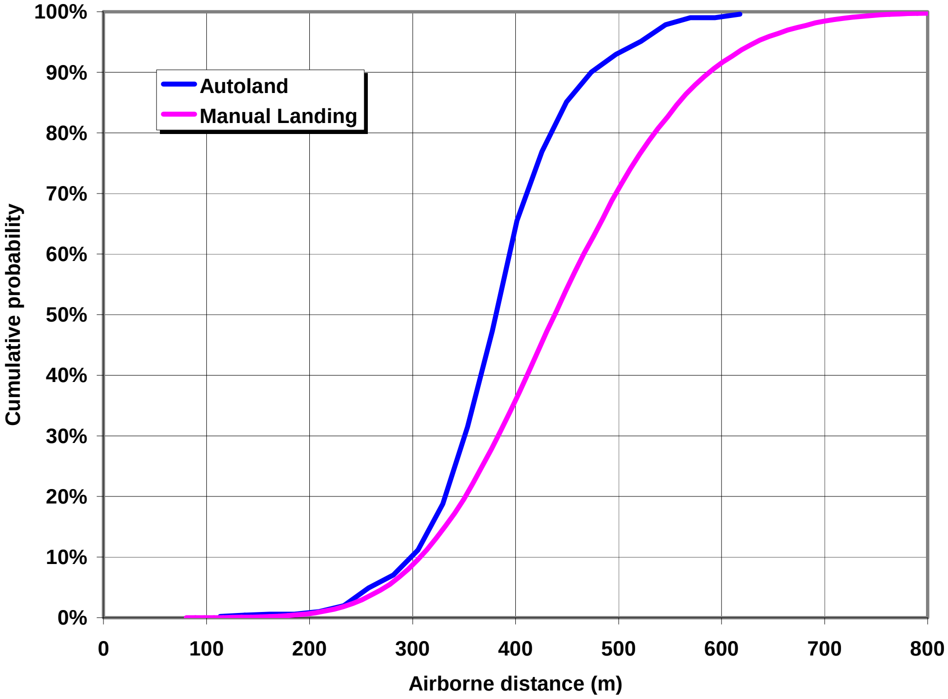

Figure 23. Comparison of the Airborne Distance Autolands and Manual Landings (All Aircraft Types)

The fly-by-wire aircraft in this study use a special flare law. When reaching 50-ft RA, the autotrim ceases and the pitch law is modified to a flare law. Through 30-ft RA, the system begins to reduce the pitch attitude at a predetermined rate. Consequently, as the speed reduces, the pilot will have to move the stick rearwards to maintain a constant path. The flare technique is, thus, very conventional to the pilot flying. The aircraft with the conventional flight control system in this present study does not have a flare law like the fly-by-wire aircraft. The flight crew training guide for the B-737-400 advises pilots to initiate the flare when the main gear is approximately 15 feet above the runway by increasing pitch attitude approximately 2° to 3°. Figure 24 shows the flare initiation heights as derived from the flight data for the four different aircraft models. These heights are relative to the ILS receiver position. Since the pitch angle is small at flare initiation, the height relative from the main gear wheels (RA) is approximately 2.5 and 3 meters lower than these heights for the B-737 and the A319, A320, and A321 aircraft. The data show that the A319, A320, and A321 aircraft have a lower flare initiation height than the B-737-400. Some care must be taken when analyzing the results shown in figure 24 because it is not always easy to derive the flare initiation height from the data. Sometimes there is no clear flare initiation due to the way the pilot handles the aircraft.

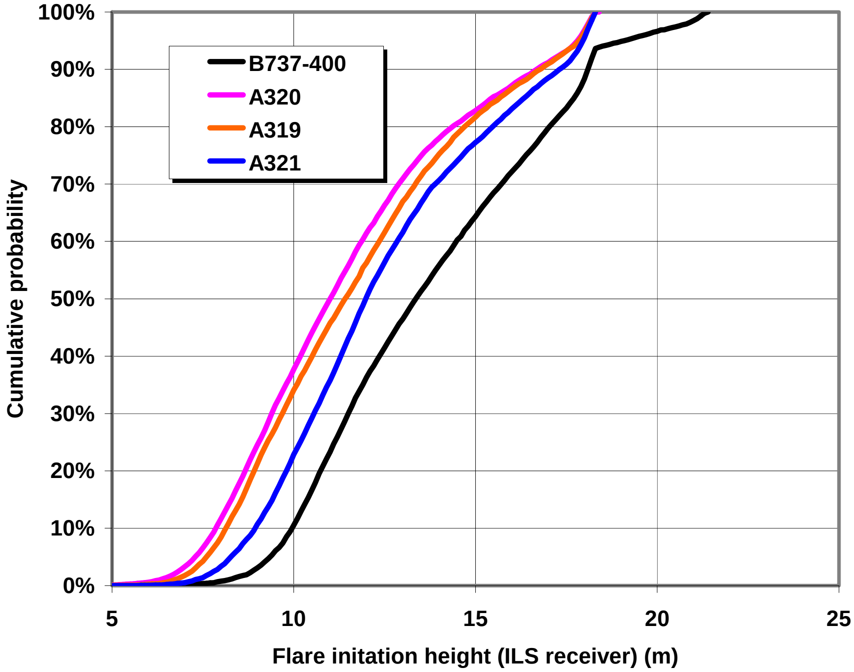

Figure 24. Flare Initiation Height

Approximately 25% of all landings in the data sample were conducted between sunset and sunrise (nighttime conditions). The influence of such conditions could not be addressed by the linear best subsets regression analysis. The airborne distance data for landings conducted between sunrise and sunset (daytime conditions) were compared to landings conducted between sunset and sunrise (nighttime conditions). The results are shown in figure 25 for all aircraft models considered in this study. From this figure, it appears that lighting conditions do not have an affect on airborne distance.

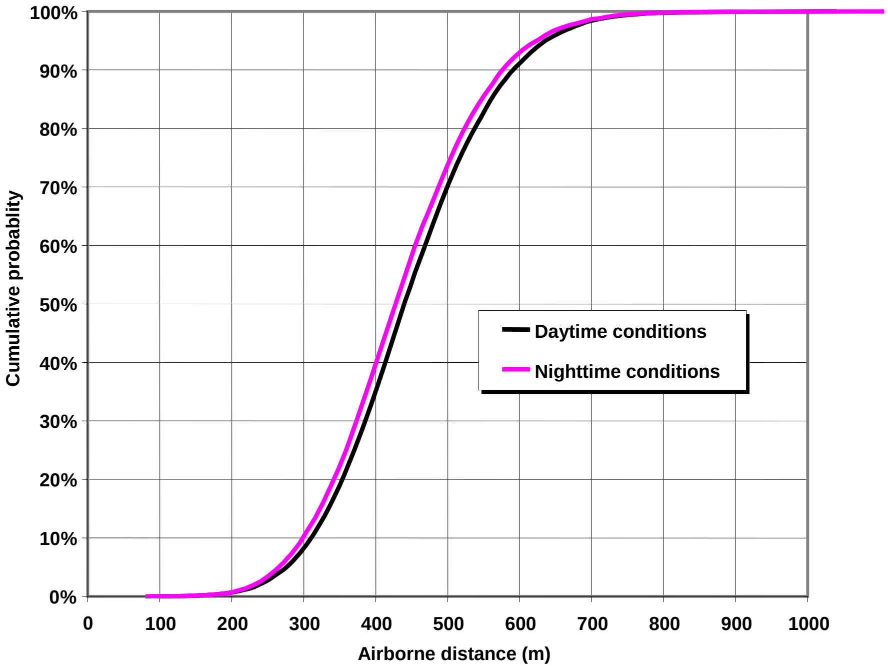

Figure 25. Influence Light Conditions on Airborne Distance

4.4 GROUND ROLL PART OF THE LANDING.

There are a number of parameters recorded in the database that can influence the ground roll distance. Unlike for the airborne distance, it was not possible to conduct a linear best subsets regression analysis to find the subsets of independent parameters that best contribute to the ground roll distance[5]. However, based on the theoretical background on aircraft landing performance and expert judgment, it was possible to identify those parameters that influence the ground roll distance. The following factors are important: thrust reverser use, runway conditions, autobrake use, time to lower the nose after touchdown, available runway length, speed at touchdown, and use of high-speed exits. Some factors are related to each other. For instance, the autobrake setting can be influenced by runway condition, available runway length, and the exit the pilot wants to take. If the runway is long and the pilots want to take the last available exit, the autobrake setting is normally set to a low value. Further, in this same example, the pilot might elect to overrule the autobrake system and continue using manual braking. If the runway is short or the pilot wants to take a high-speed exit, the autobrake setting is most likely high regardless of the runway condition. There are many more combinations of these and other factors possible. This makes the analysis of the ground roll somewhat difficult. Nevertheless, a number of results are discussed next.

The frequency distributions of the overall ground roll distance from touchdown to leaving the runway at the exit for the four aircraft are shown in figure 26. The ground roll distance for Airbus aircraft change, as can be expected, according to their increasing average landing mass

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[5] The autobrake setting has a significant impact on the ground roll distance. However, this parameter cannot be taken into the linear best subset regression analysis.

(54, 58, and 66 metric tons for the A319, A320, and A321 respectively). The B-737-400 shows a higher ground roll distance than the Airbus aircraft, which cannot be explained from the average landing mass (48 metric tons). The difference is most likely because the B-737-400 in the data sample frequently operated at an airport that had a high-speed exit at approximately 1350 m from the threshold. Analysis of the landing data for the B-737-400 at this airport showed that it often used this high-speed exit.

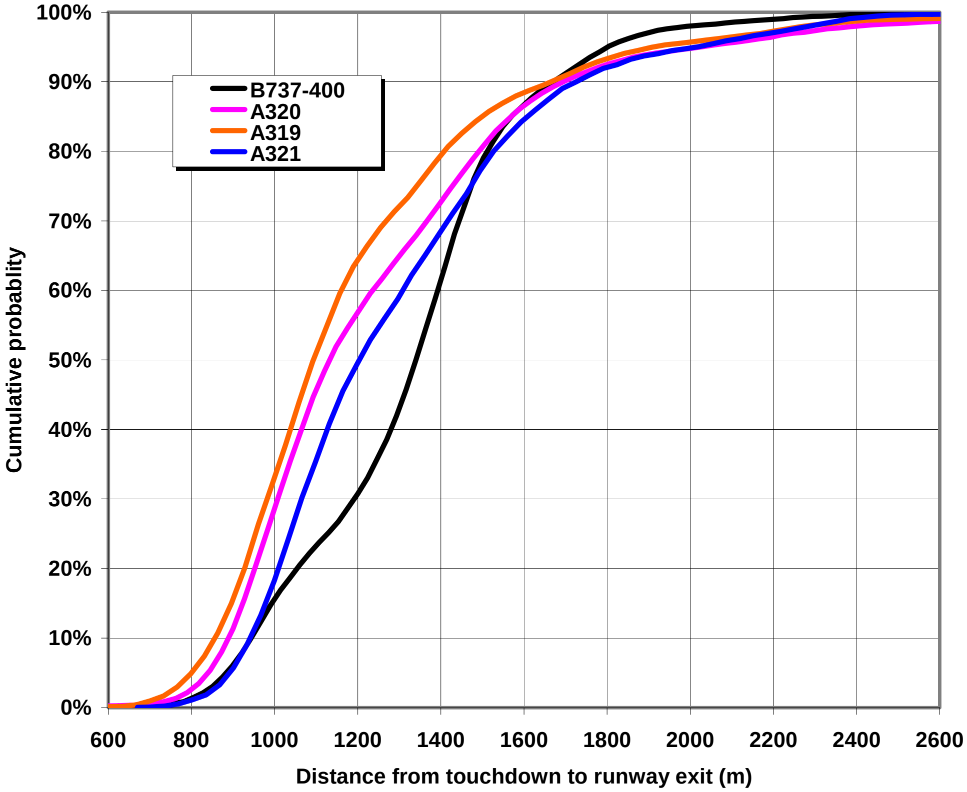

Figure 26. Frequency Distribution of Ground Roll Distance

The available landing distance of the runway that the aircraft lands on can also influence the ground roll distance. In figure 27, the available landing distance is shown as a function of the actual ground roll distance. This figure clearly shows that as the available distance to land, the aircraft increases the scatter in actual ground roll distance increases too. Long runways often have more (high speed) exits available than short runways. The aircraft considered in the present study can use most of these exists. Typically, depending on air traffic control instructions or the location of the gate, the pilots decide to take a particular exit. This is one reason why the scatter in ground roll distance increases as the available landing distance increases.

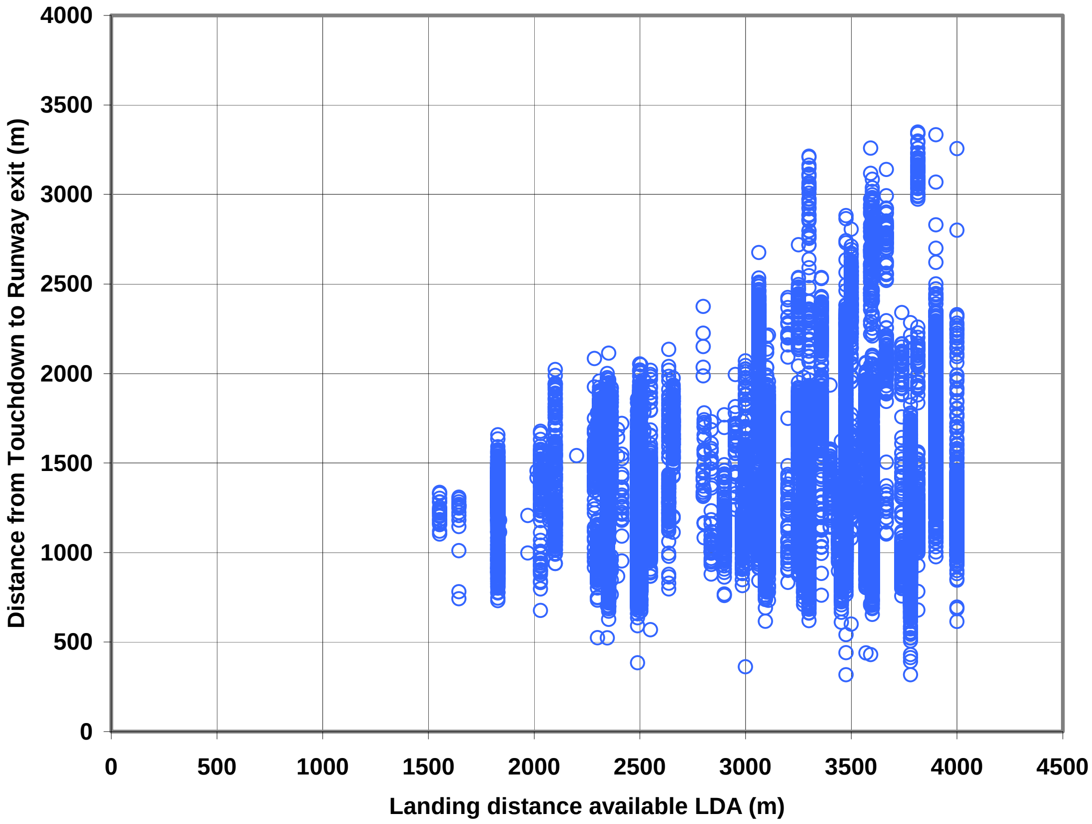

Figure 27. Available Landing Distance Versus Ground Roll Distance

After touchdown of the main wheels, the nose should be lowered without delay to maximize the load on the tires. Some fighter jet pilots tend to keep the nose up as long as possible to increase aerodynamic drag and shorten the required runway length. This technique is called aerodynamic braking and is an acceptable technique on some fighter jets. However, it is not a recommended technique for commercial transport aircraft. The stopping forces associated with this technique are only a fraction of those forces achieved when the aircraft is braked with the nose down. The time from touchdown to nose down for the four aircraft is shown in figure 28. The data show a strong variation in rotation duration. The ground distance covered in the time from touchdown to nose down increases proportionally to the rotation time, as illustrated in figure 29.

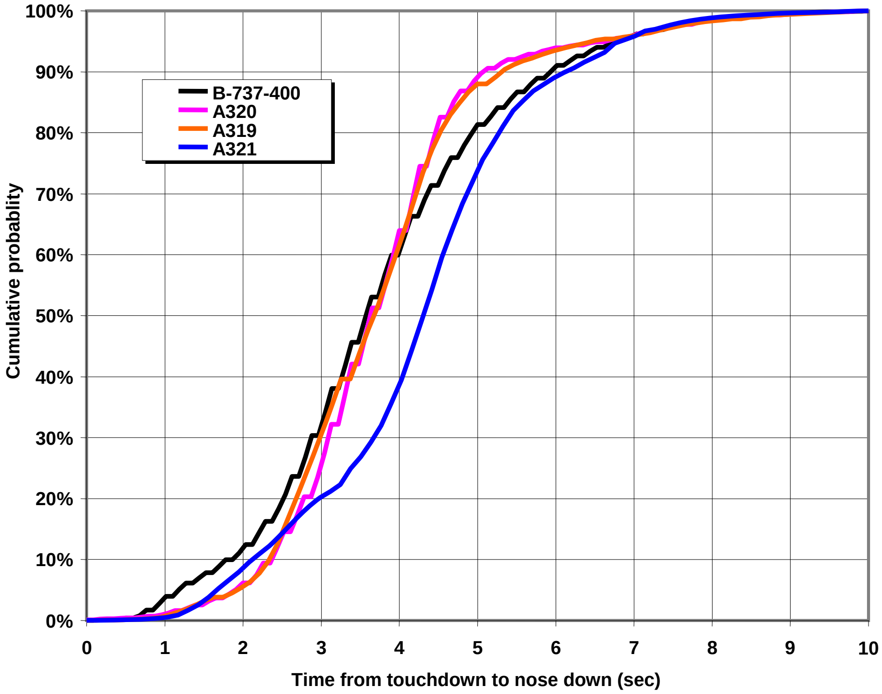

Figure 28. Time From Touchdown to Nose Down

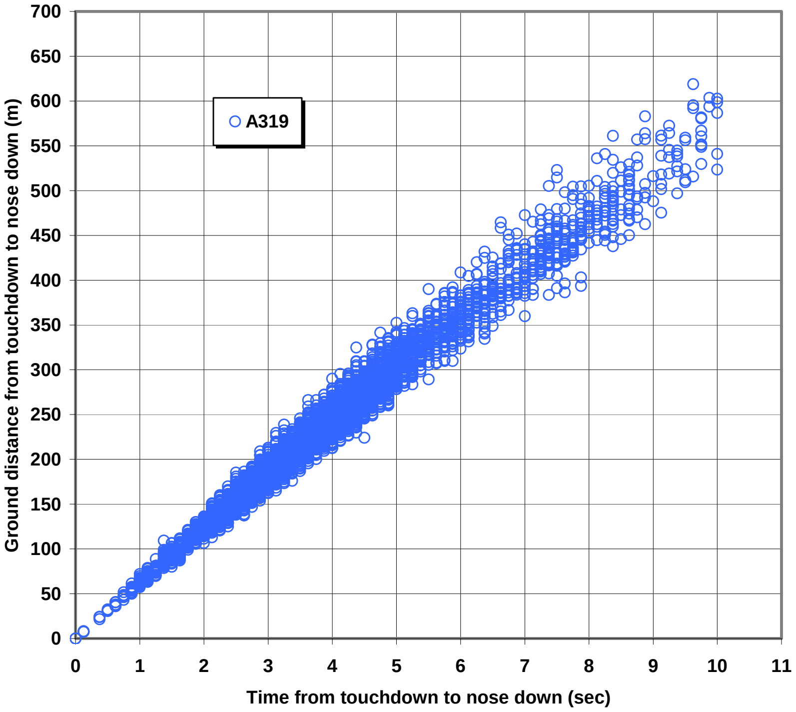

Figure 29. Ground Distance During Nose-Down Rotation as Function of Time

The use of autobrakes can have a significant impact on ground roll distance. Autobrakes decelerate the aircraft with a fixed predefined deceleration. In general, they produce a more consistent deceleration than manual braking by the pilot. Figure 30 shows the effect of autobrake selection on the ground roll distance of the four aircraft analyzed. Clearly, those landings in which no autobrakes were selected show a significantly longer ground distance than when the autobrake was selected. These results do not consider the actual autobrake setting used nor do they reflect situations where maximum manual braking effort is needed. Figure 31 gives an example of the influence of the actual autobrake setting on the ground roll distance for the A320 and the B-737-400. It is clearly shown that the average ground roll distance reduces rapidly from the no autobrake setting to the medium level[6] for the A320 and from no autobrakes setting to setting 3 for the B-737-400[7].

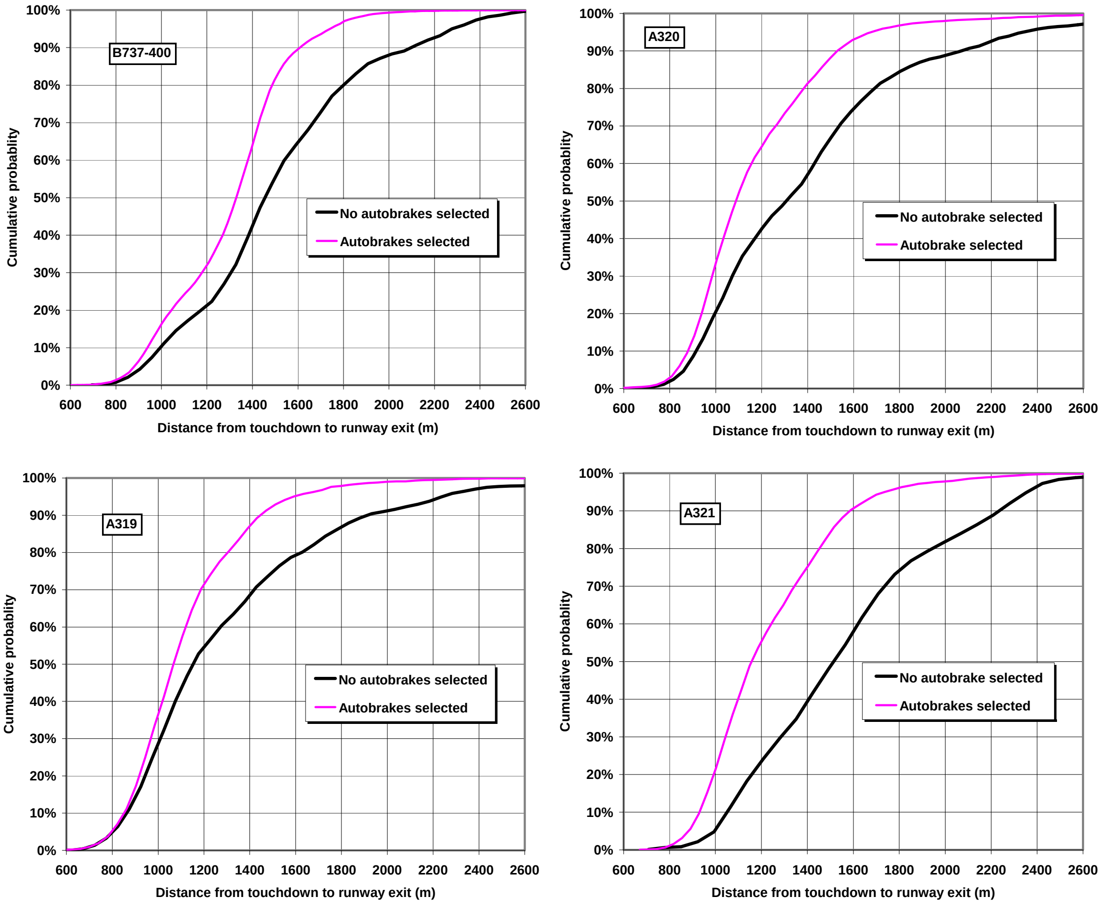

Figure 30. Influence of Autobrake Use on Ground Roll Distance

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[6] The Airbus aircraft have four autobrake settings: no autobrakes, low, medium, and high. Normally, medium is the highest autobrake setting used. The data sample contains only 148 landings with autobrake setting high.

[7] The B-737-400 has five settings for the autobrake available for landing: no autobrakes, 1, 2, 3, and max. The maximum setting is not normally used. The data sample contains only three landings with autobrake setting max.

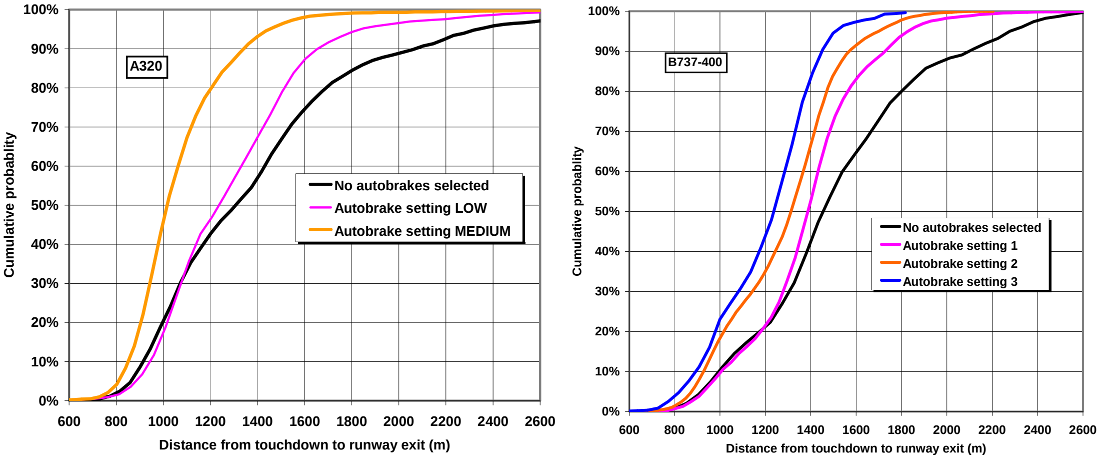


Figure 31. Influence of Autobrake Setting on the Ground Roll Distance of the A320 and B-737-400

Runway condition affects the braking friction between the tires and the runway. Runways covered with water or snow generate lower frictional forces than dry runways. This could result in longer ground distances to stop the aircraft. However, figure 32 shows that, for the data collected for this study, the runway condition had no influence on the ground roll distance. This is partly the result of higher autobrake settings being selected by the pilots that landed on damp, wet, and snow-covered runways. High autobrake settings were used in 35% of the landings on damp, wet, and snow-covered runways compared to the 21% on dry runways.

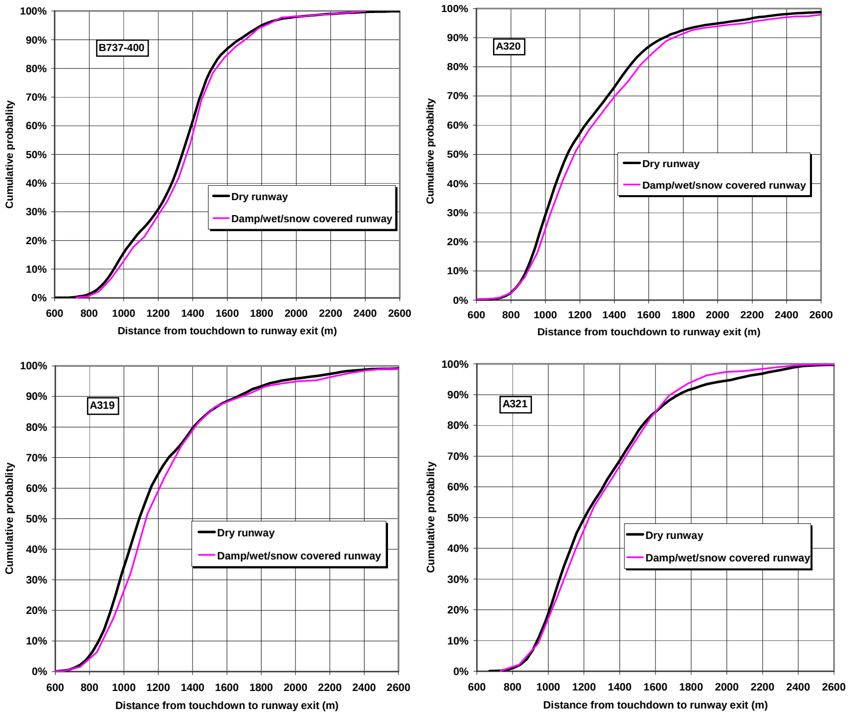


Figure 32. Influence of Runway Condition on Ground Roll Distance

All four aircraft models have thrust reversers installed. Thrust reversers are an effective means for stopping an aircraft on the ground. Thrust reverser efficiency is proportional to the square of the speed. It is therefore recommended to use reverse thrust at high speeds. This means that maximum reverse thrust should be selected immediately after touchdown. This also applies to the four aircraft models considered in this study. The standard operational procedure is to select reverse immediately after touchdown of the main gear. Figure 33 shows the distribution of the time from touchdown to thrust reverser engagement for the four aircraft. All four aircraft show similar pilot performance in selecting the thrust reversers. Figure 34 shows the frequency distribution of the thrust reverser use. The data show a large variation in the time that reverse thrust is used.

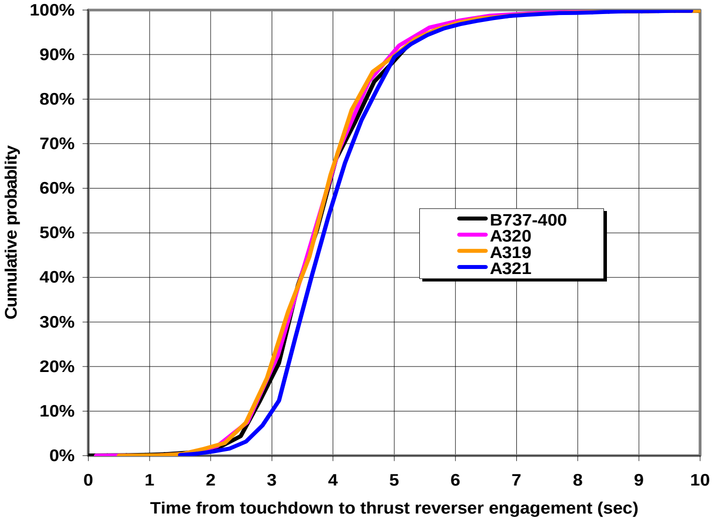


Figure 33. Time From Touchdown to Thrust Reverser Engagement

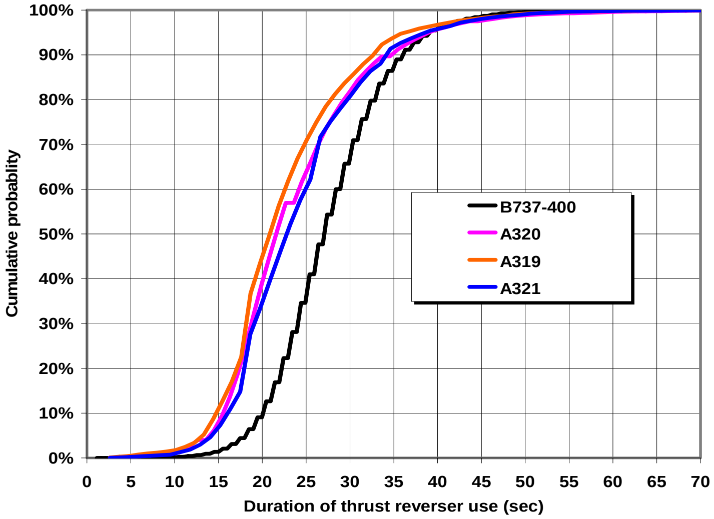


Figure 34. Duration of Thrust Reverser Use

For the A319, A320, and A321, it is recommended to use maximum reverse thrust down to an airspeed of 70 kt (36 m/s), whereas for the B-737-400, an airspeed of 60 kt (31 m/s) is recommended. Figure 35 shows the frequency distribution of the airspeed at which idle reverse is selected for the Airbus aircraft. In a large number of landings, the reverse thrust is used down nearly to the recommended speed.

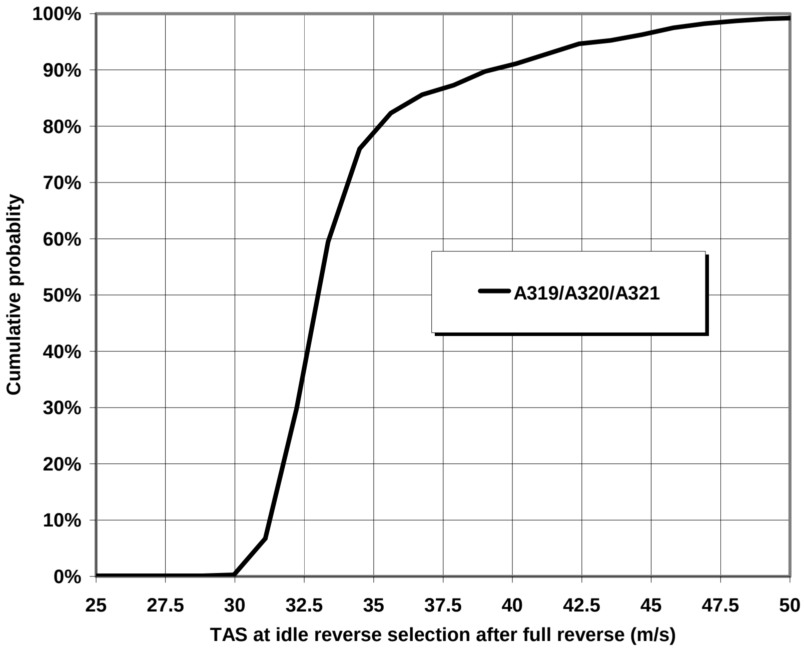


Figure 35. Airspeed at Idle Reverse Selection for the A319, A320, and A321 Aircraft

Although thrust reversers are an important means for stopping an aircraft, the ground roll data analyzed in this study did not show a clear correlation between thrust reverser use and ground roll distance, as shown in figure 36. Clearly, more variables are involved in stopping distance than thrust reverser use.

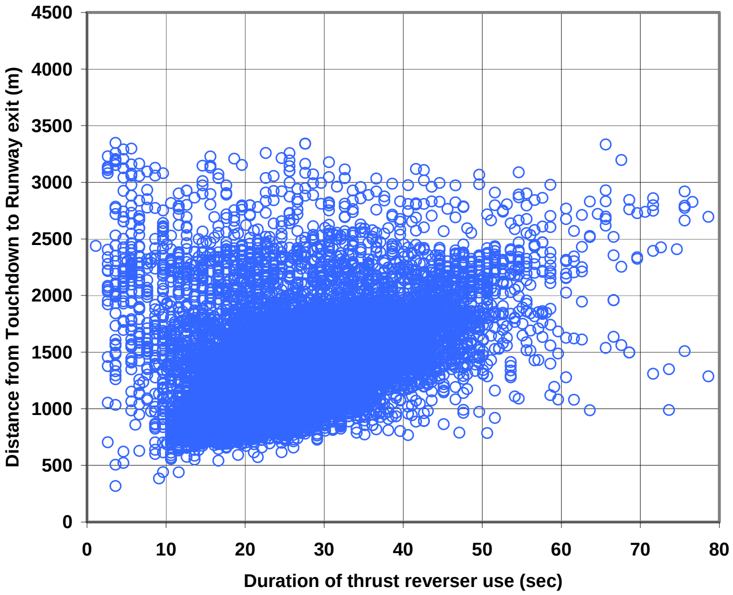


Figure 36. Influence of Thrust Reverser Use on Ground Roll Distance

5. BRIEF DISCUSSION OF THE RESULTS.

5.1 DATA PROCESSING.

The flight data used in the present project were obtained from quick access recordings. These data are retrieved regularly by the airlines for their flight data monitoring analysis. A disadvantage of these recordings is that some parameters are recorded at a low sampling rate. Time-critical recordings, such as touchdown point, can, therefore, not always be obtained directly from the raw data. As part of the present study, algorithms were developed (either based on existing material or newly developed) to overcome some problems of the low sampling rate. Also, data processing algorithms were developed for events during the landings for which no direct recorded parameters were available (e.g., the flare initiation point). The developed data processing algorithms were validated as much as possible. This showed that the algorithms gave credible results.

5.2 RESULTS.

The results presented in this report show that there a large number of variables that influence the overall landing field performance. The results also show that the variation of those variables can be large and that they can be related to each other. The results gave insight into the operational variation of a number of issues such as: autobrake selection, the use of thrust reverse, floating behavior. The following is a summary of the important findings.

- The airborne distance is strongly influenced by the threshold crossing height and the speed loss from flare initiation to touchdown.

- The airborne distance during autolands is, on average, shorter and shows a smaller variation than during manual landings.

- The flare initiation height is lower for the fly-by-wire aircraft than for the non-fly-by-wire aircraft examined.

- Lighting conditions do not affect the airborne distance.

- The ground roll distance is strongly affected by the available landing distance.

- Autobrake setting has a significant influence on the ground roll distance.

- Runway condition did not have a measurable influence on ground roll distance. In general, the reduced braking action on a slippery runway was counteracted by the use of higher autobrake settings. This explains why there appears to be no measurable affect.

Regarding LAHSO, it can be concluded that not all the data analyzed in this report are relevant. The available runway length has a strong influence on the overall behavior of the pilots during landing (e.g., figure 27). It seems, therefore, evident that for the relevance for LAHSO, only landings on the shorter runways should be considered for study. This requires further analysis of the data.

6. CONCLUSIONS.

The following conclusions were made based on the results of the present study.

- Data from quick-access recorders can be used to analyze aircraft performance. During this study, valuable insight and knowledge was gained on using quick access recorded data for aircraft landing field performance analysis.

- Aircraft landing field performance is influenced by many variables. Some variables were found to have a more dominating influence than others. Variables that were found to have a strong influence are height above the threshold, speed loss form flare initiation to touchdown, and the available runway length for landing. However, there is not one single factor that dominates the landing field performance.

- Not all the results presented in this study can be used for the analysis of Land and Hold Short Operations (LAHSO). It follows from the results that the ground roll performance is strongly influenced by the available runway length for landing. Therefore, for LAHSO study purposes, only landings on shorter runways should be considered.

7. RECOMMENDATIONS.

The following recommendations were made.

- It is recommended to collect and analyze flight data during the landing of other type of aircraft, such as small turboprops.
- It is recommended to further analyze the already collected flight data. In particular, operations on short runways should be addressed because they are relevant for use in a LAHSO study. Furthermore, the collected data should be used for other more detailed analyses on issues like the dynamics of the flare, use of manual brakes, etc.

8. REFERENCES.

1. Title 14 Code of Federal Regulations Part 25.125, “Requirements for Landing in Federal Aviation Regulations.”
2. Advisory Circular 25-7A, “Flight Test Guide for Certification of Transport Category Airplane.”

APPENDIX A—EXAMPLE TIME HISTORIES

Figures A-1 through A-8 show example time histories for normal operational flights.

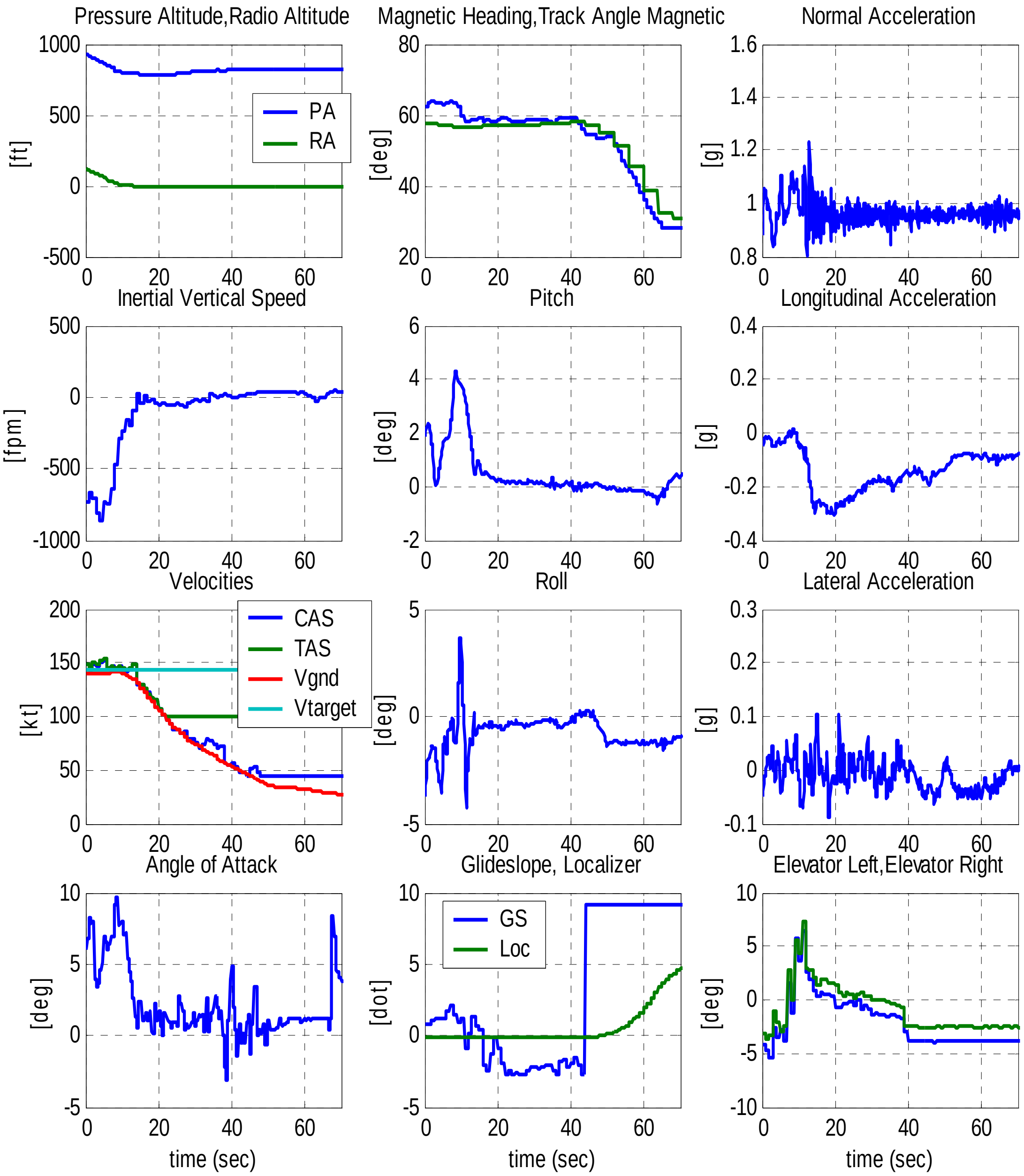


Figure A-1. Example Time Histories B-737-400, Parameter Series 1

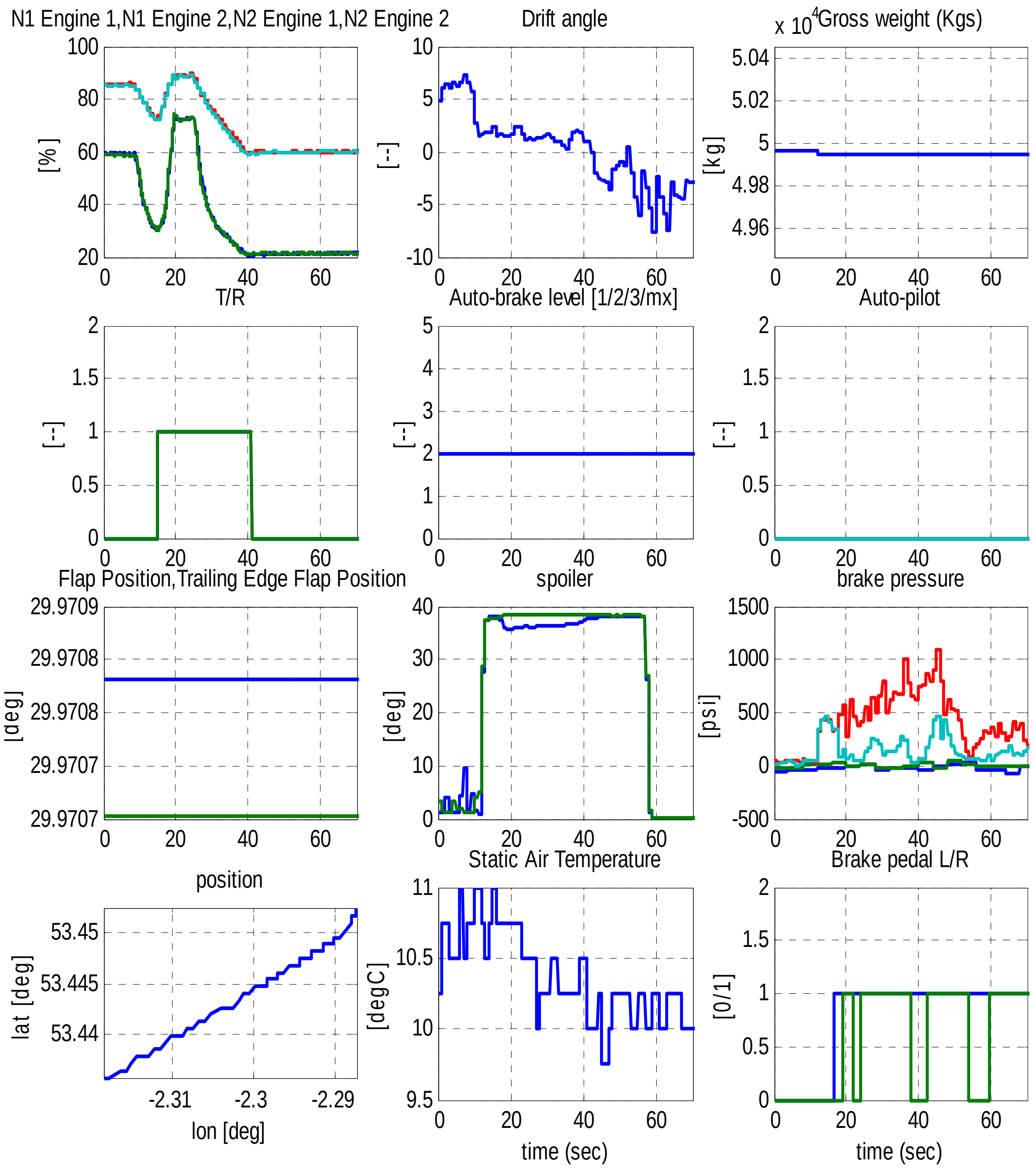


Figure A-2. Example Time Histories B-737-400, Parameter Series 2

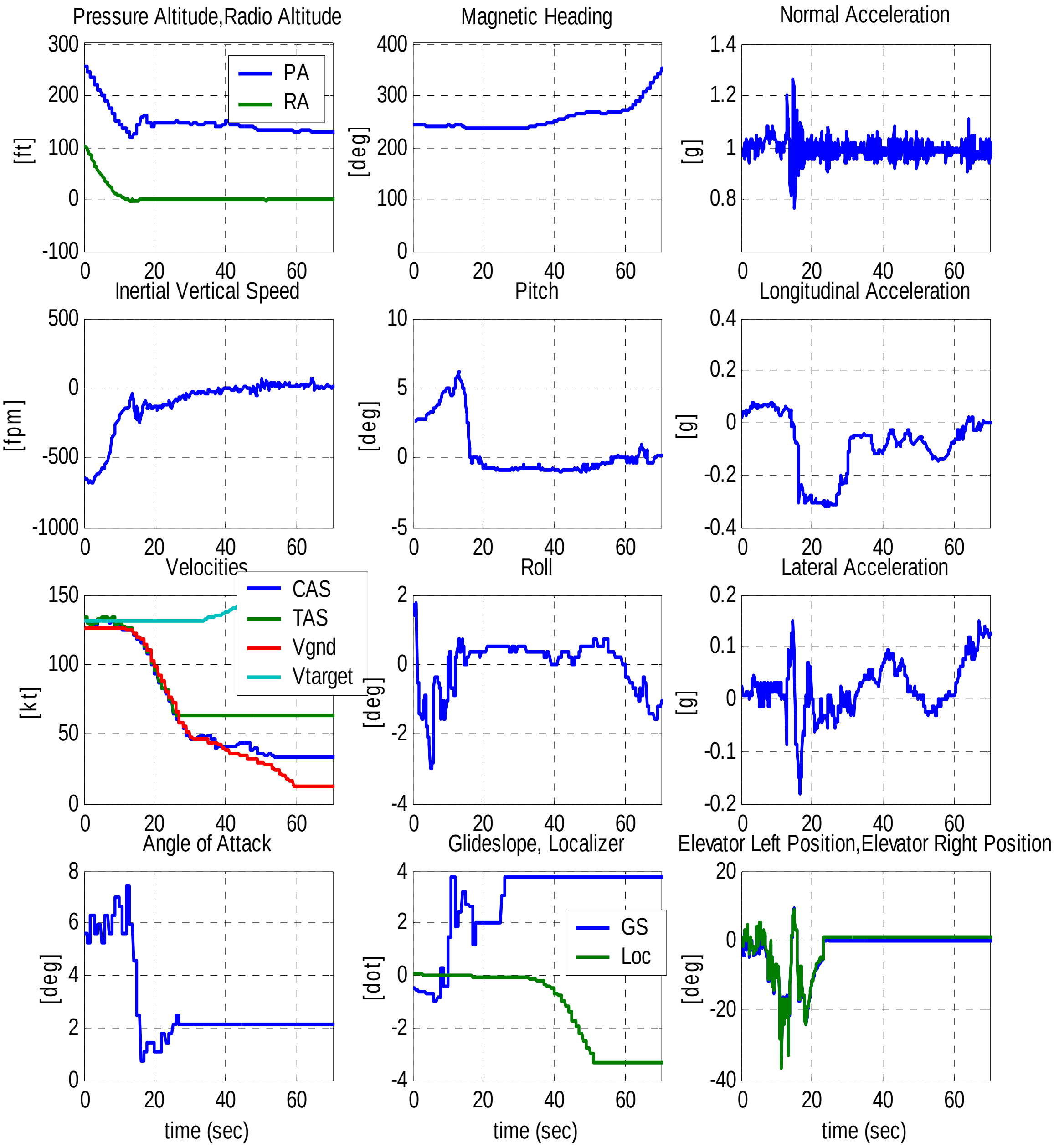


Figure A-3. Example Time Histories A320, Parameter Series 1

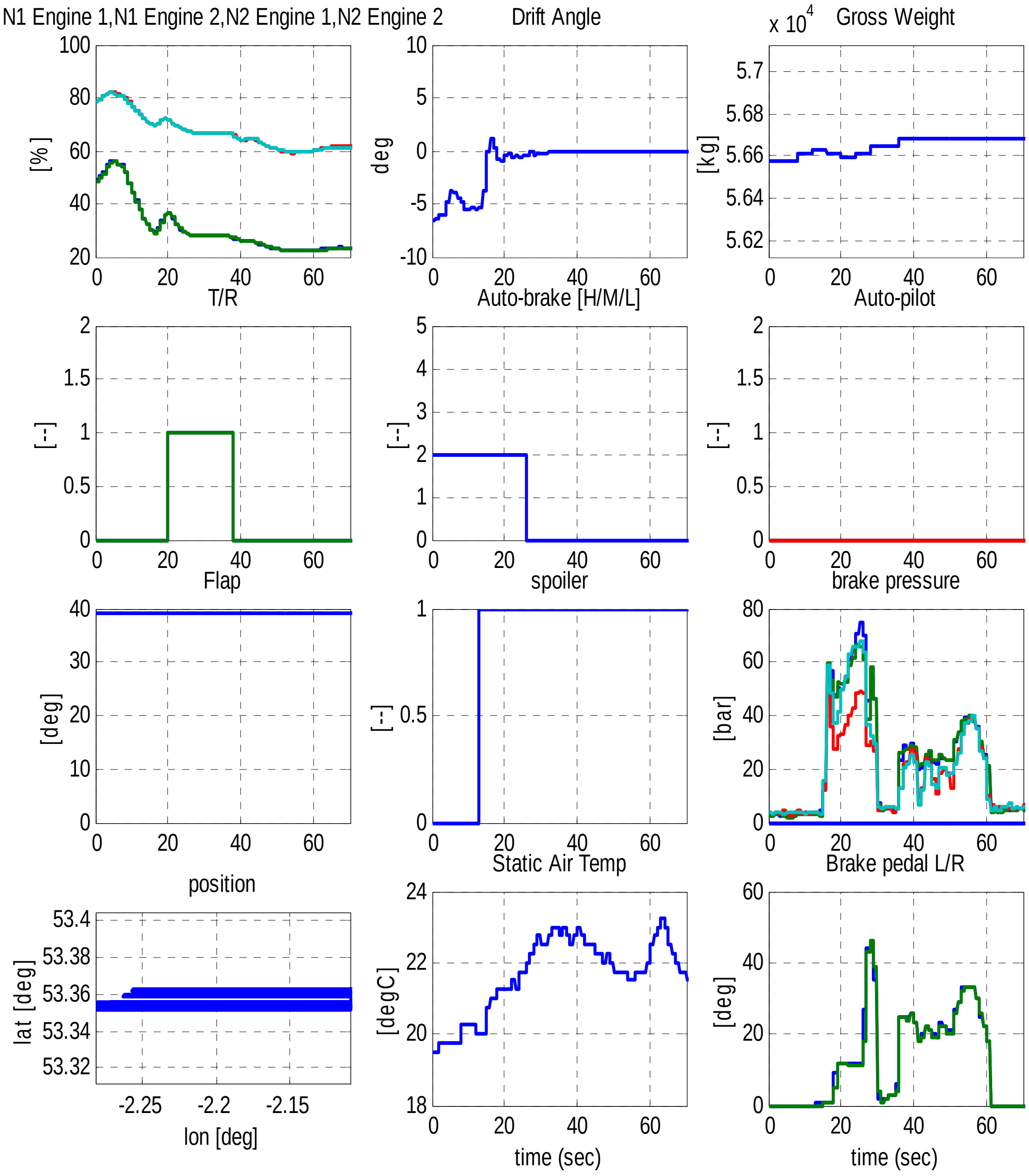


Figure A-4. Example Time Histories A320, Parameter Series 2

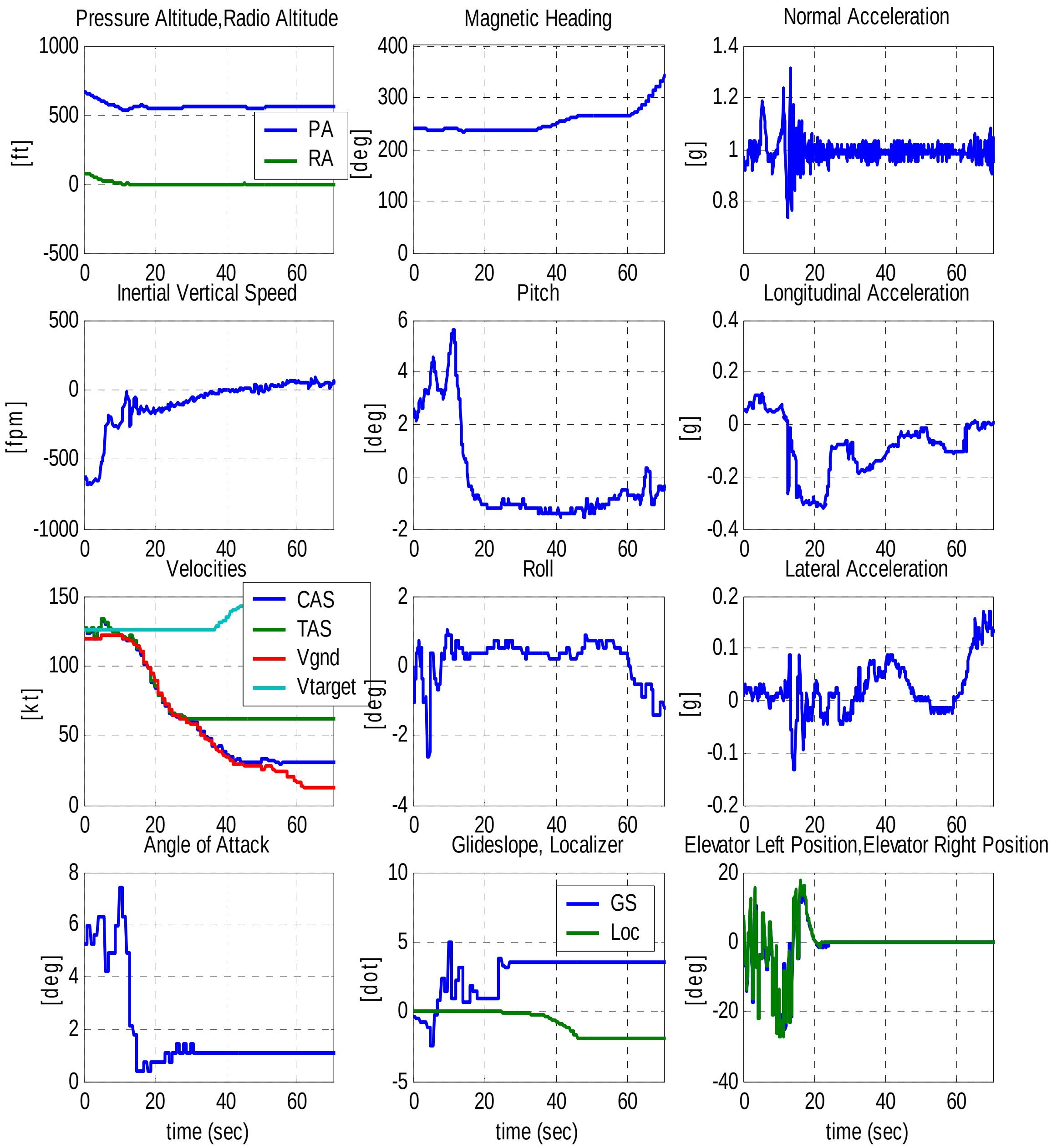


Figure A-5. Example Time Histories A319, Parameter Series 1

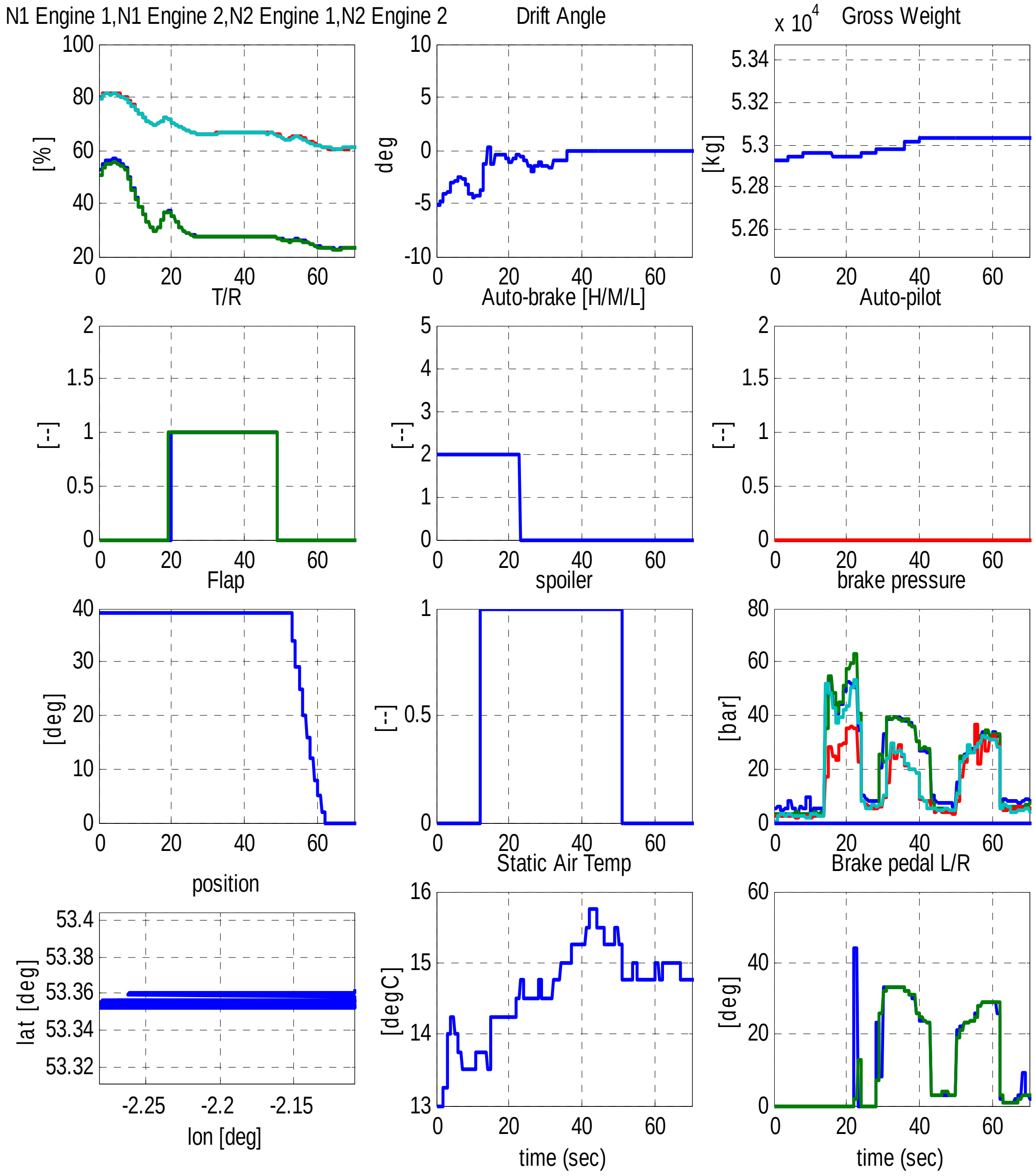


Figure A-6. Example Time Histories A319, Parameter Series 2

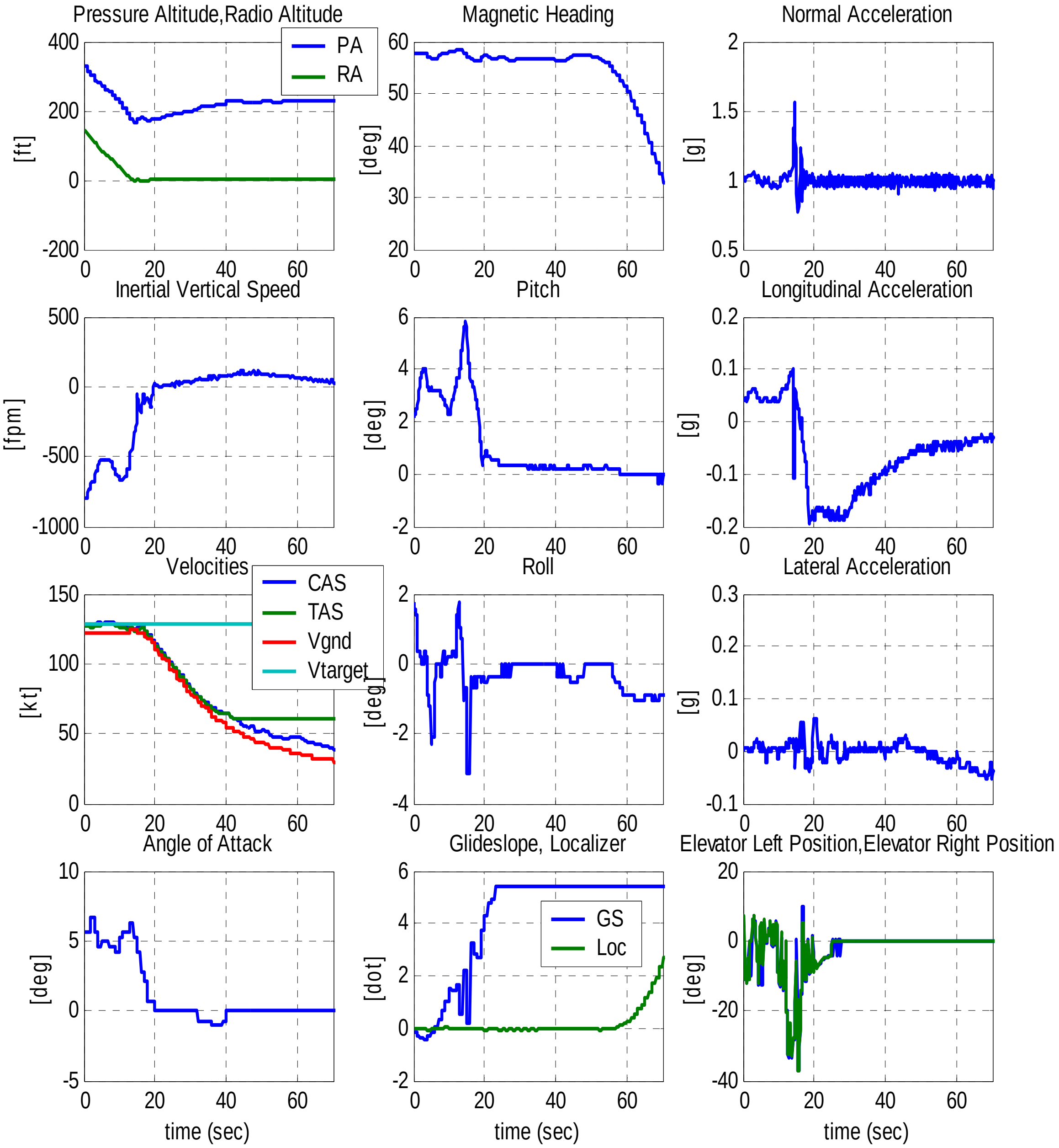


Figure A-7. Example Time Histories A321, Parameter Series 1

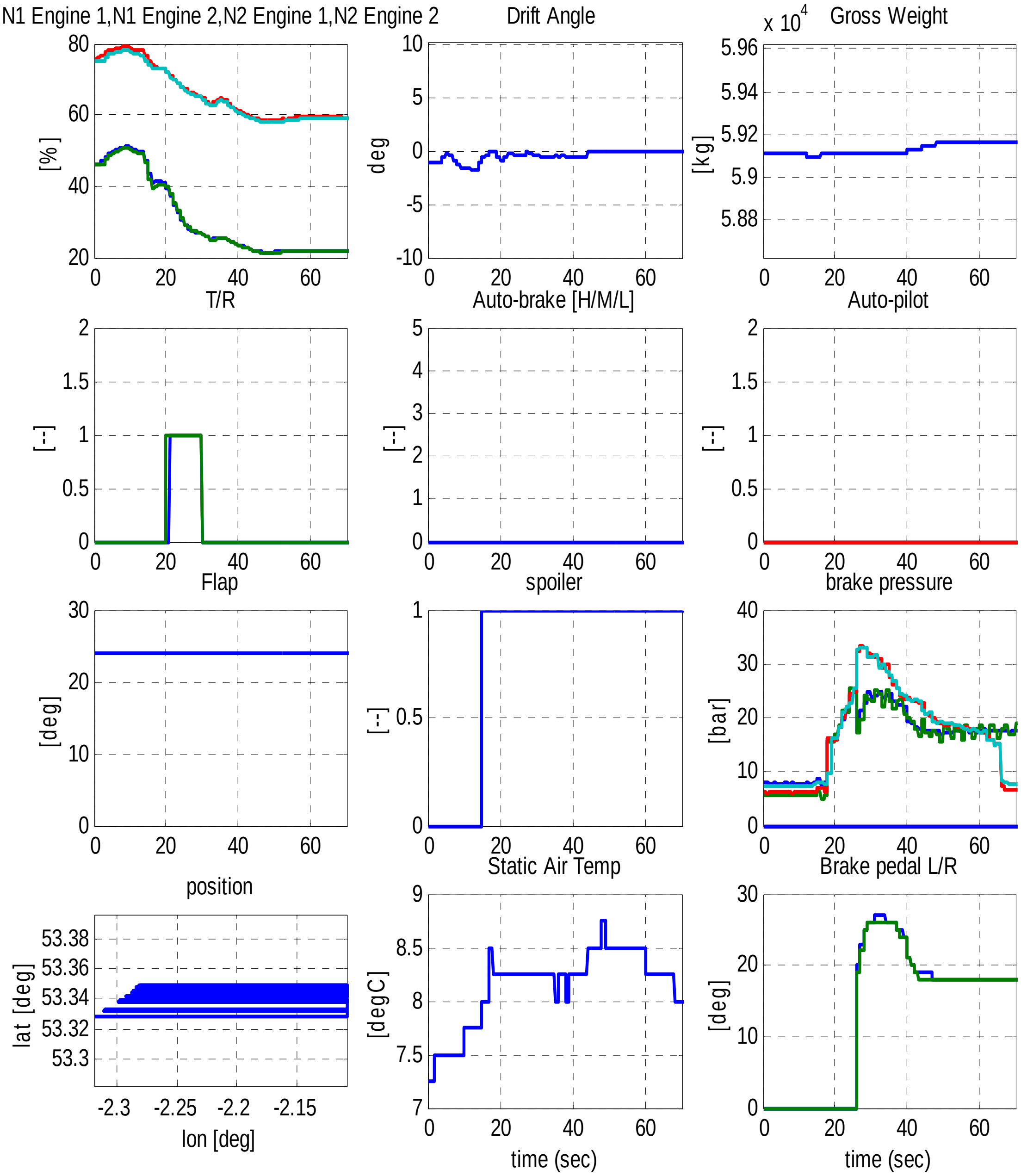
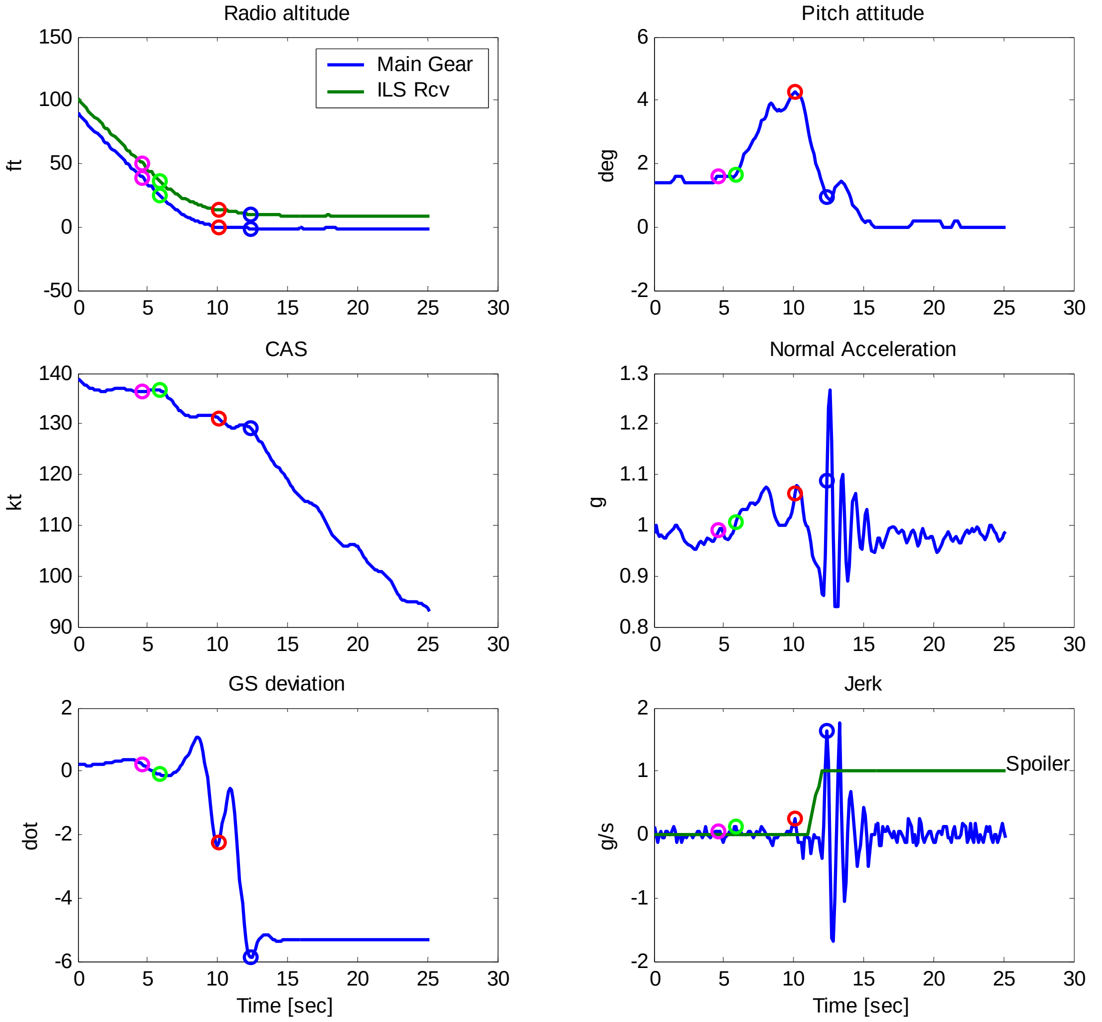


Figure A-8. Example Time Histories A321, Parameter Series 2

APPENDIX B—DEMONSTRATION OF DATA PROCESSING ALGORITHMS

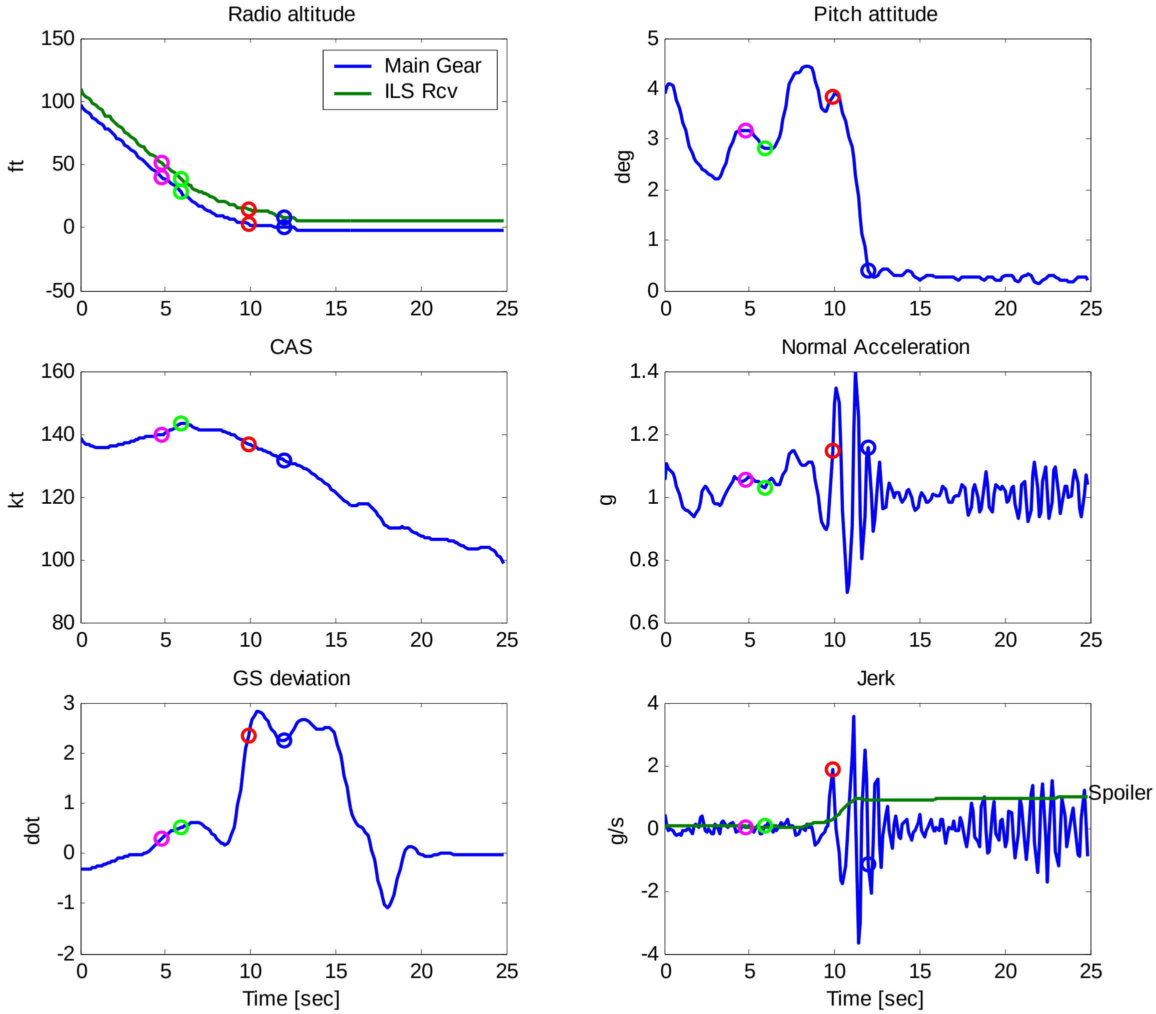
B.1 EXAMPLE CASES WITH SMALL AND LARGE GLIDE SLOPE TRACKING ERROR.

Figures B-1 through B-30 are examples of the data that was collected during normal operational flights.



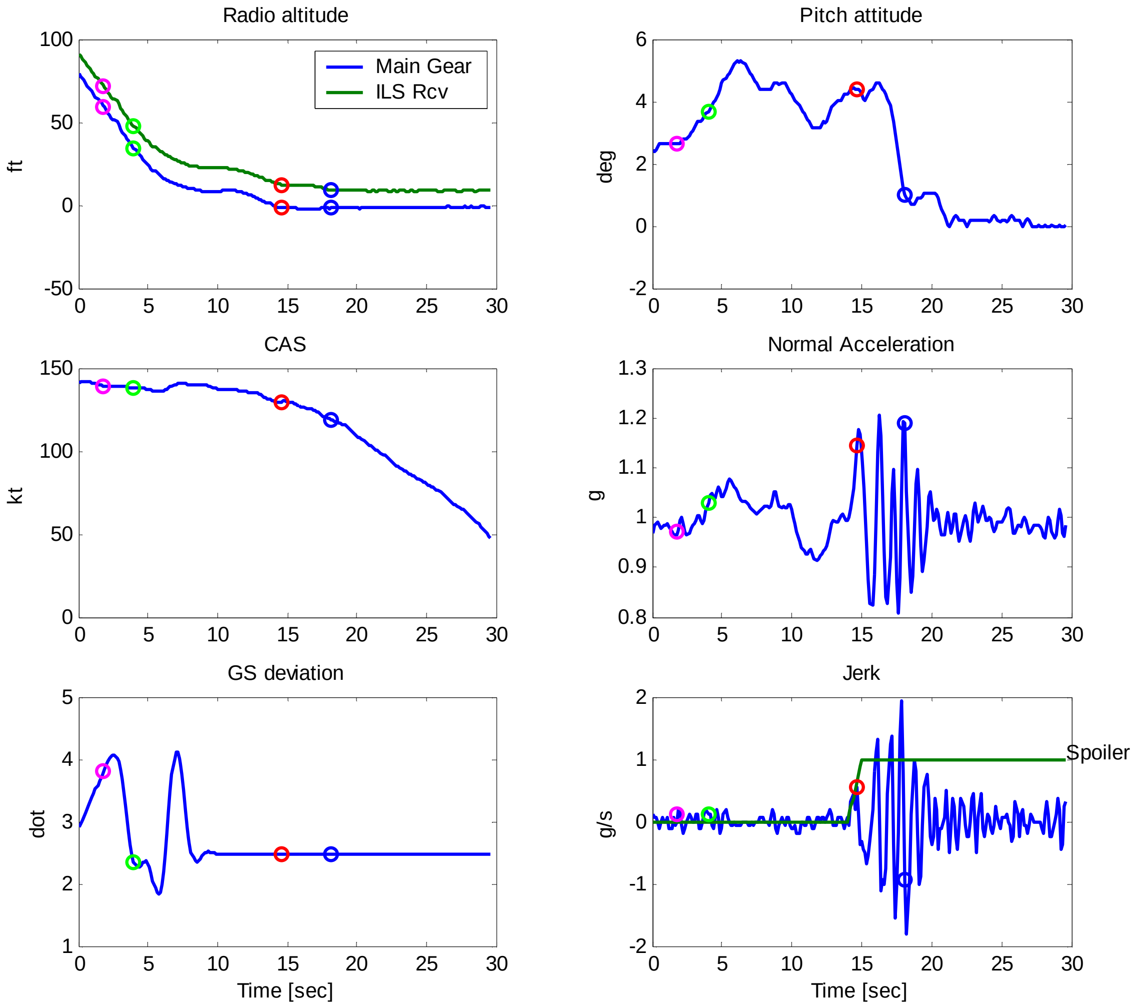
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-1. A320 Nominal Conditions on Glide Slope



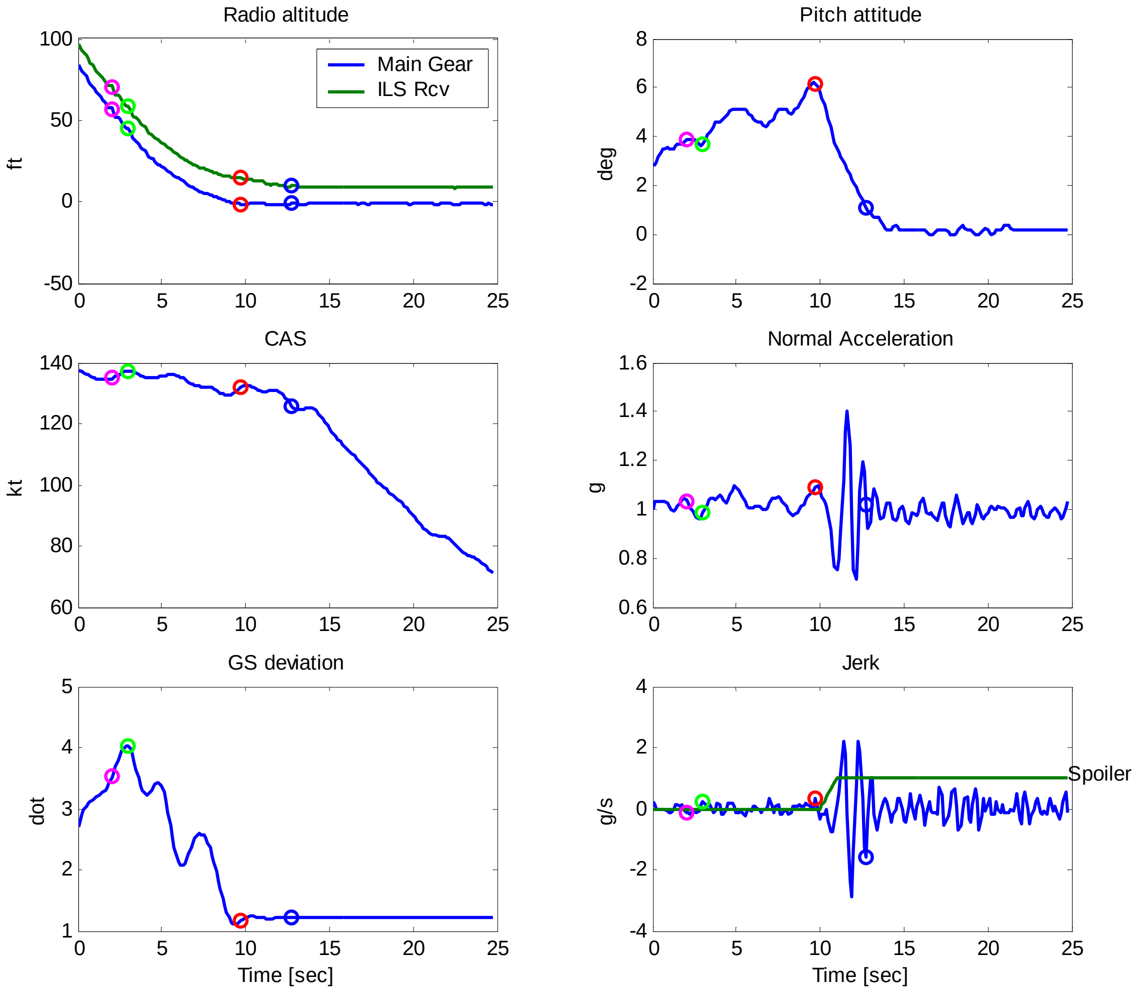
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-2. B-737 Nominal Conditions on Glide Slope



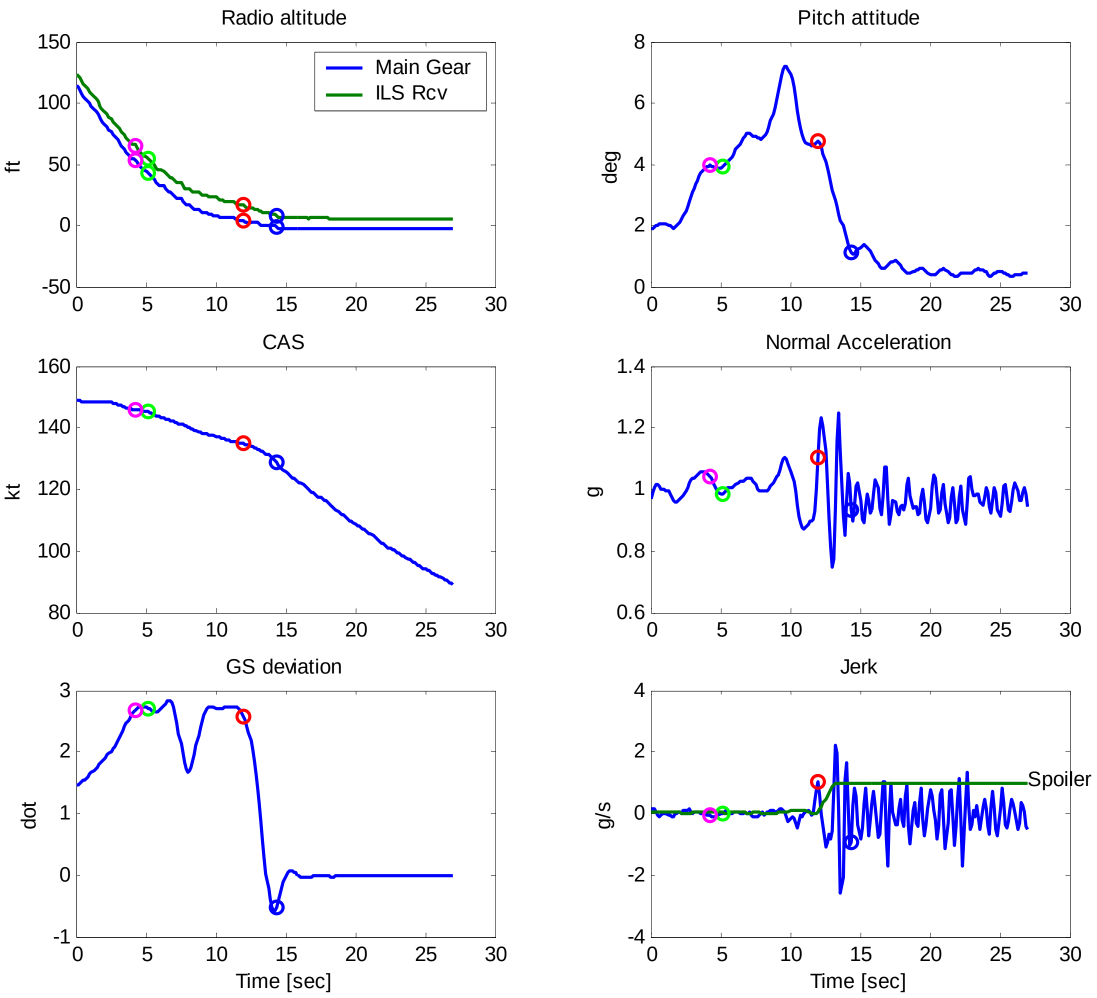
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-3. A320 High THR Crossing



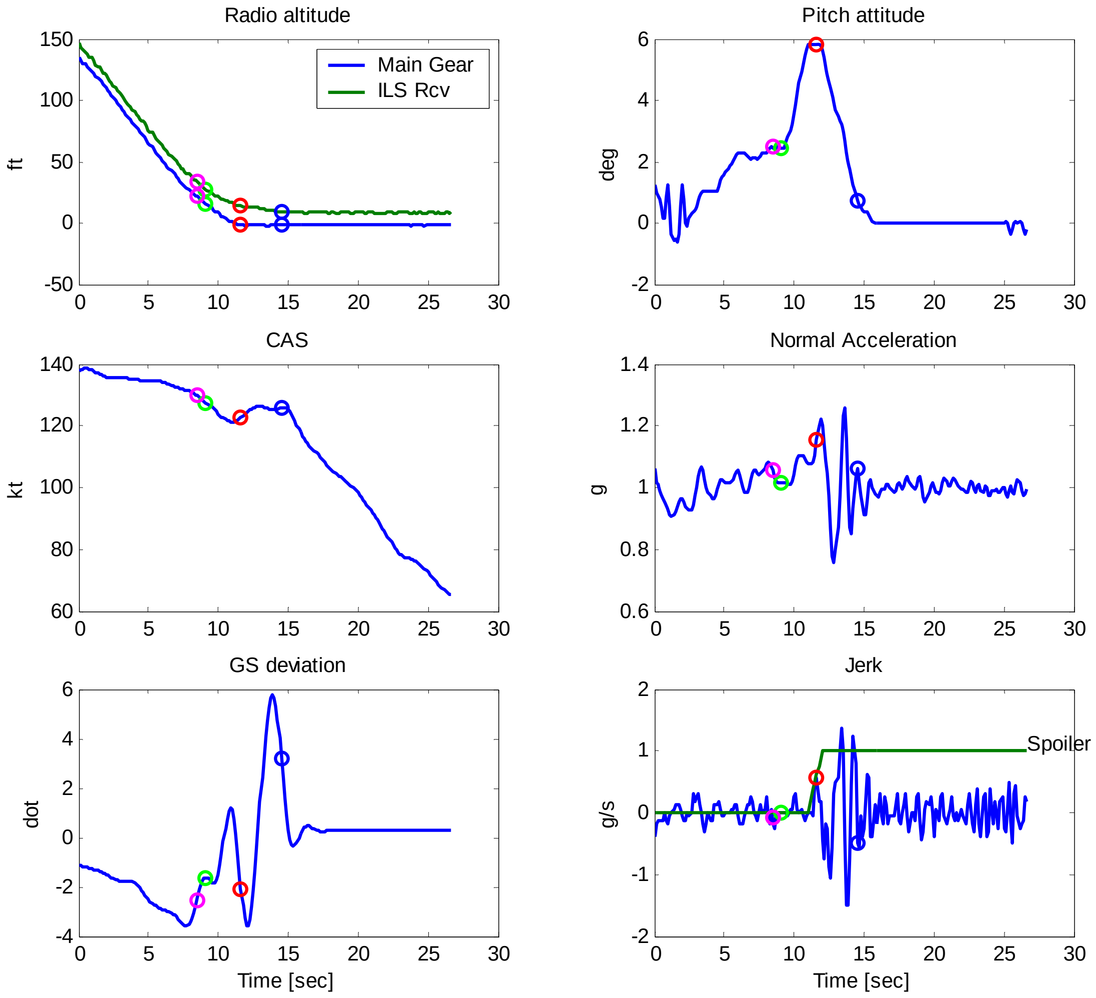
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-4. A320 High THR Crossing 2



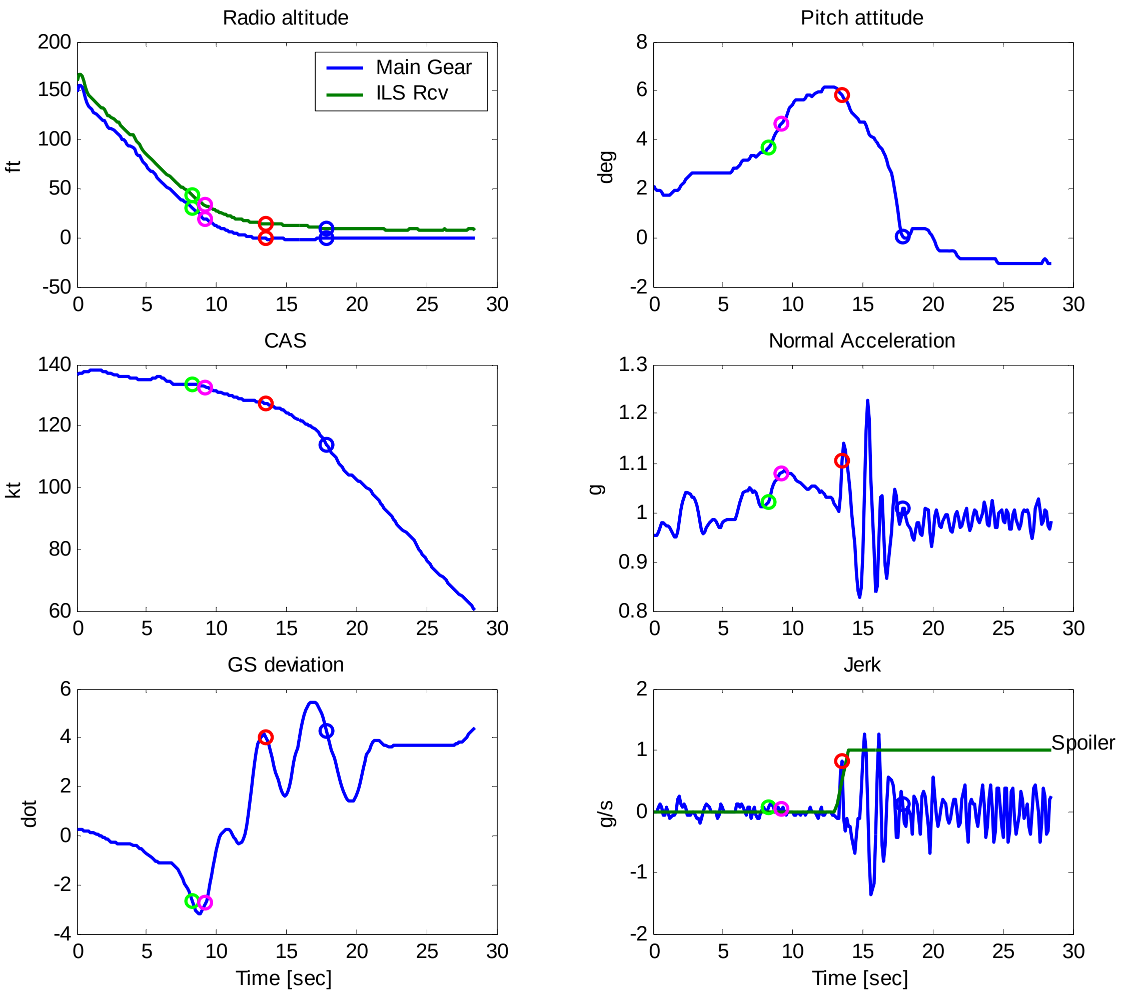
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-5. B-737 High THR Crossing



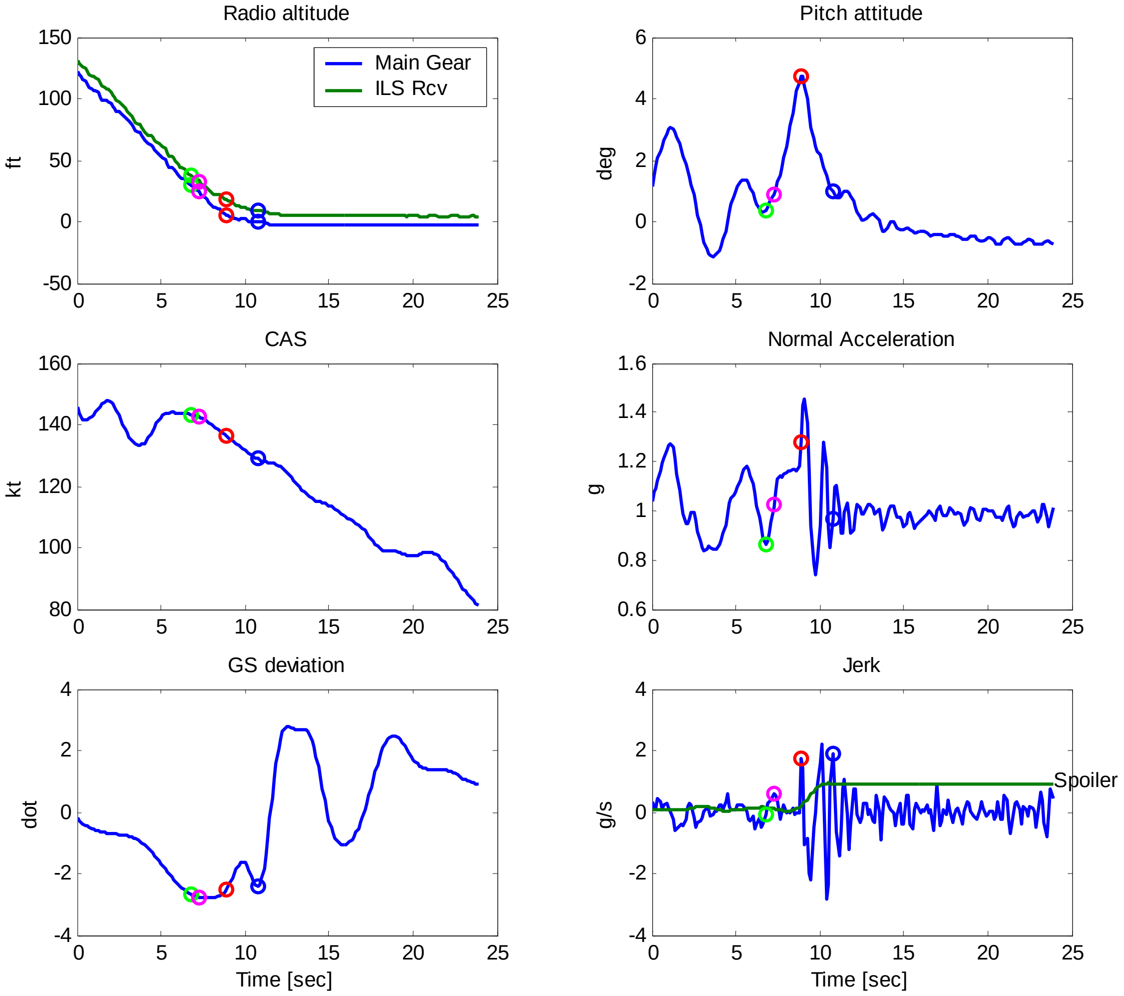
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-6. A320 Low THR Crossing



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

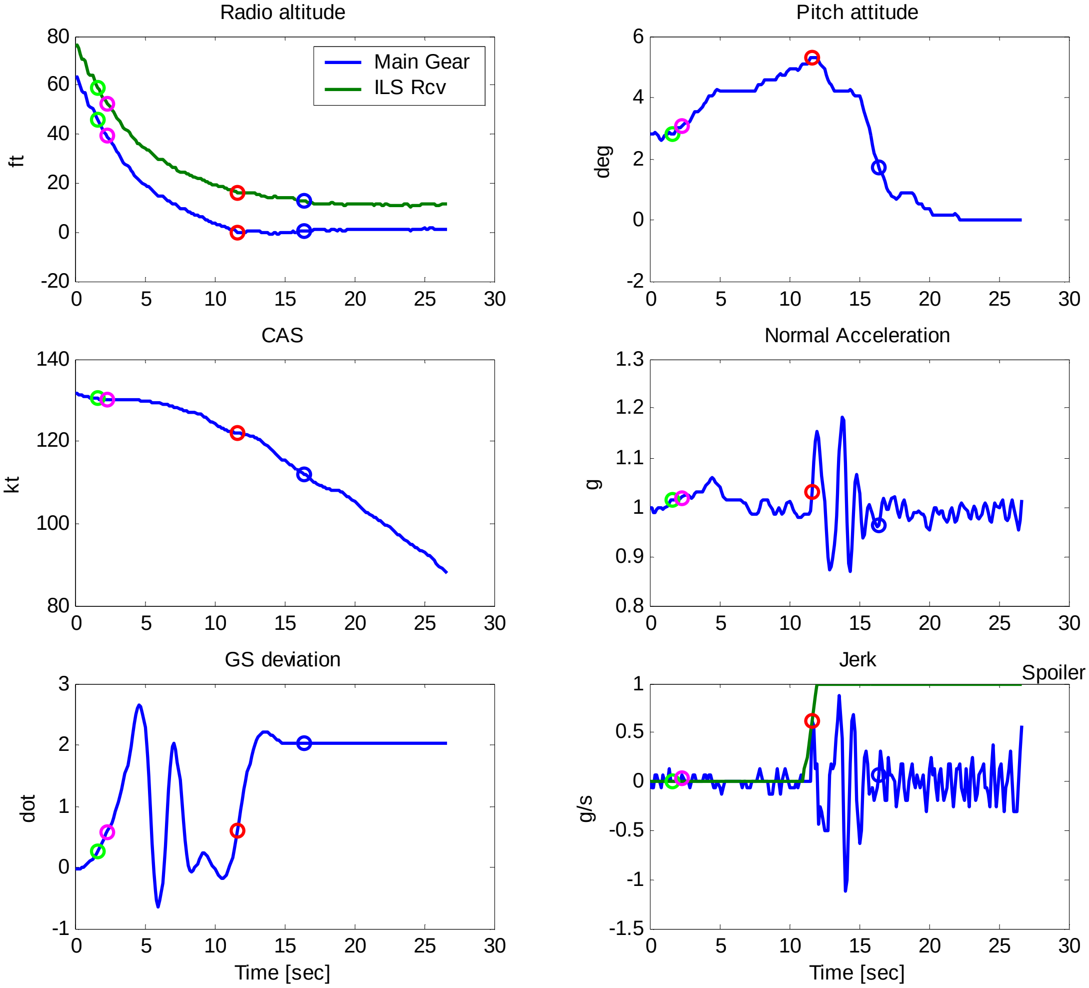
Figure B-7. A320 Low THR Crossing 2



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

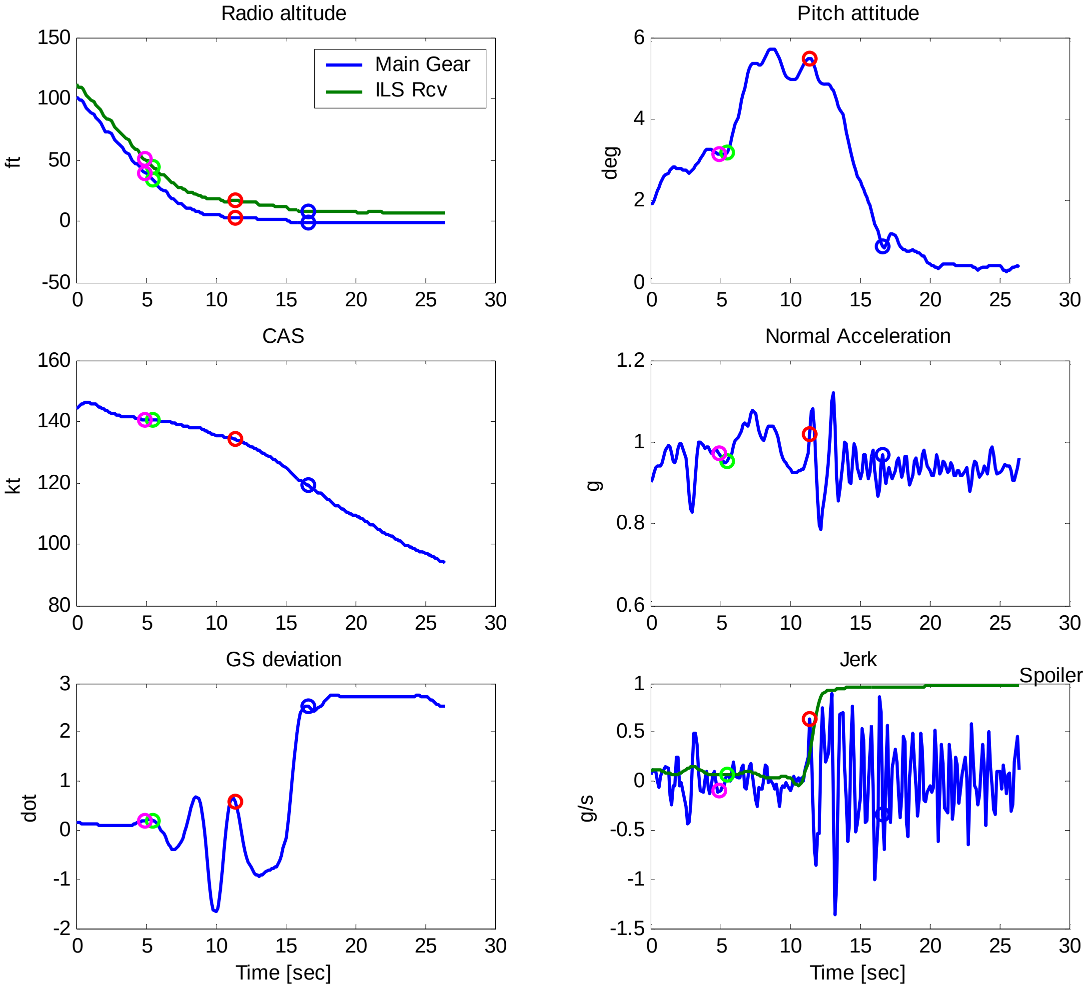
Figure B-8. B-737 Low THR Crossing

B.2 EXAMPLE CASES UNDER CALM WIND, HIGH WIND, AND SEVERE TURBULENCE.



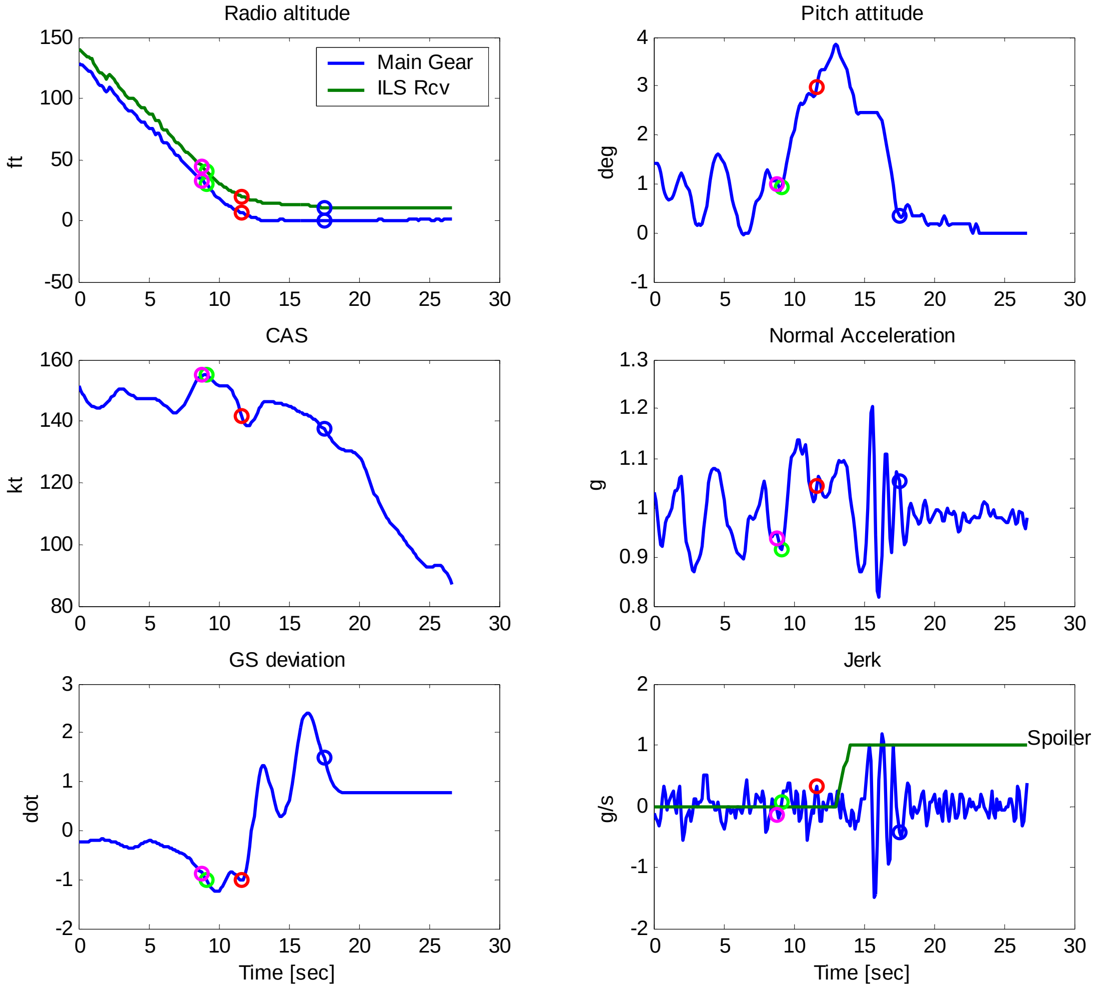
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-9. A321 Calm Wind, no Turbulence



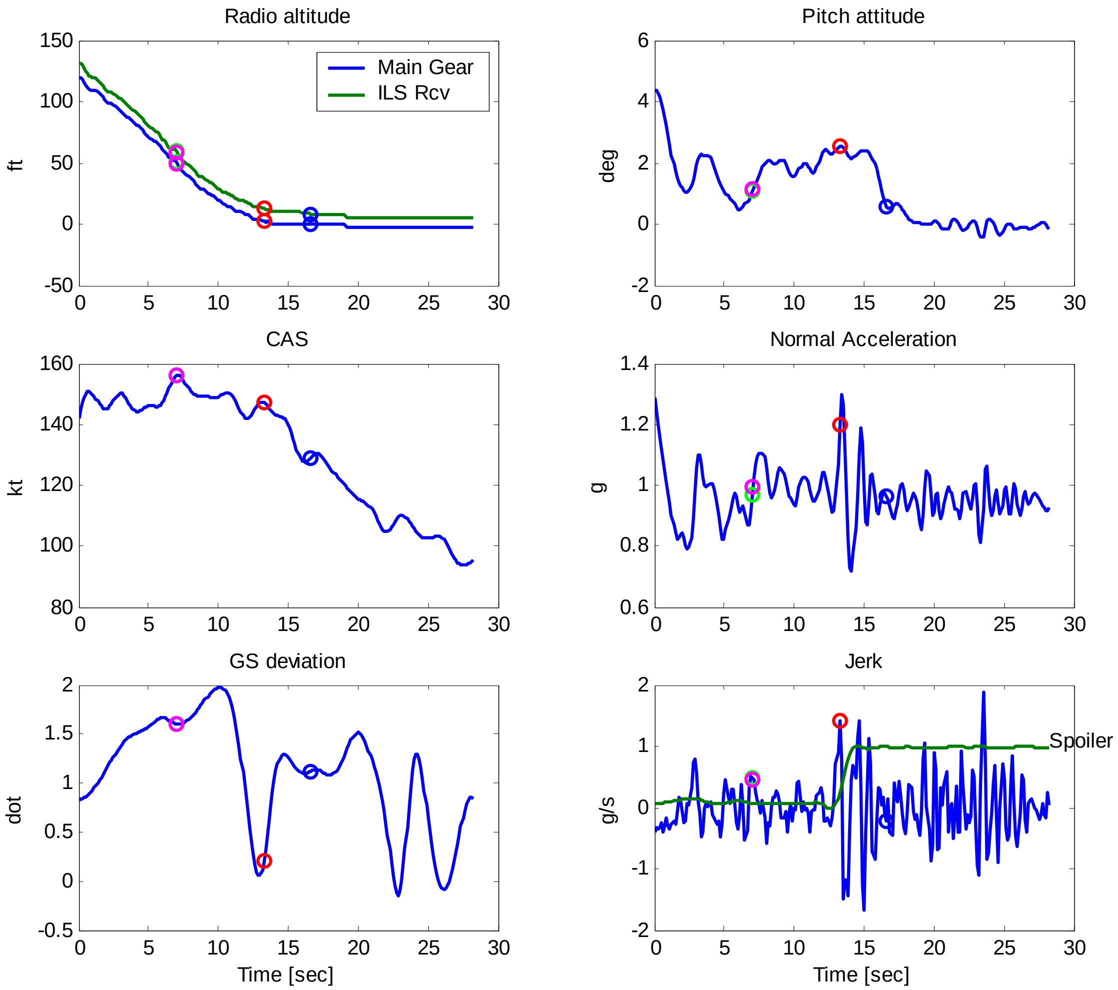
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-10. B-737 Calm Wind, no Turbulence



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

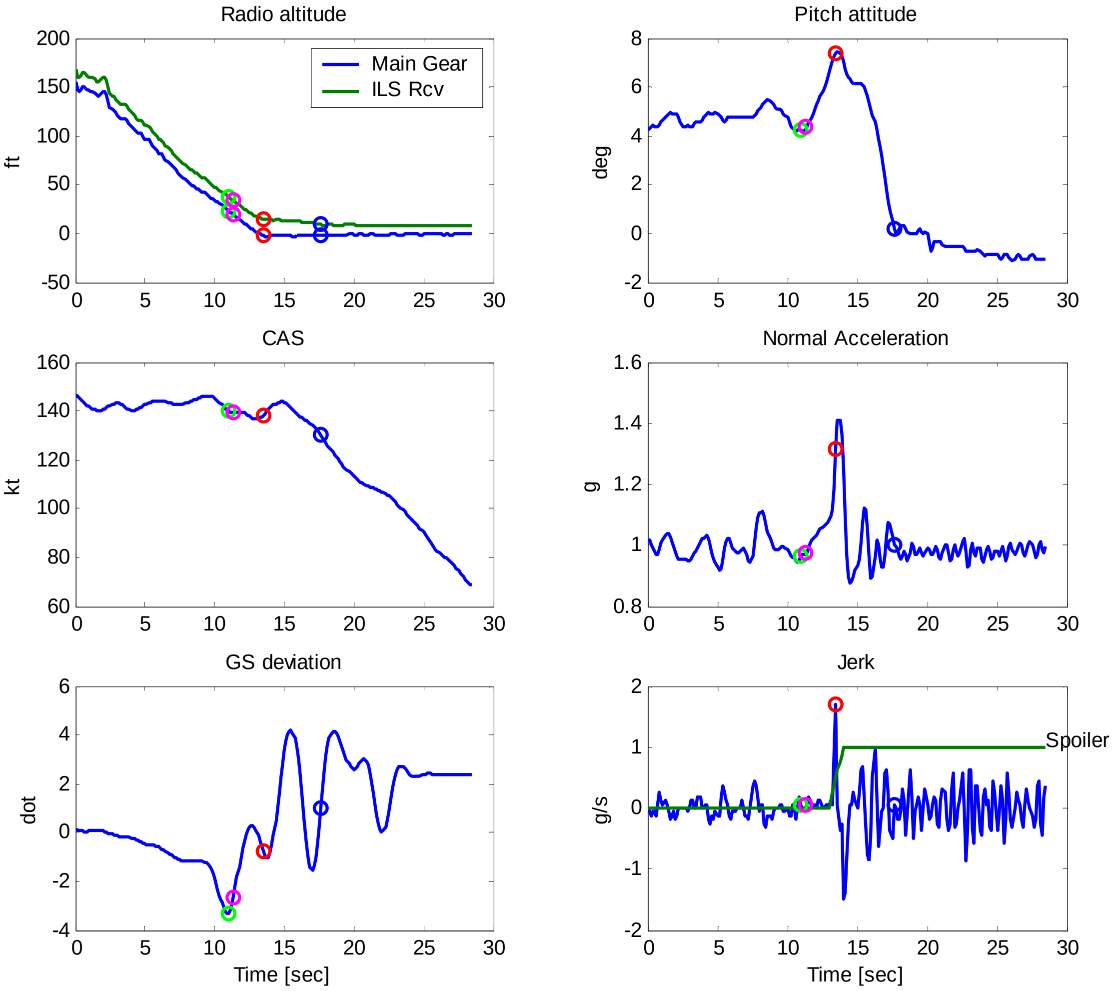
Figure B-11. B-737 Calm Wind, no Turbulence



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

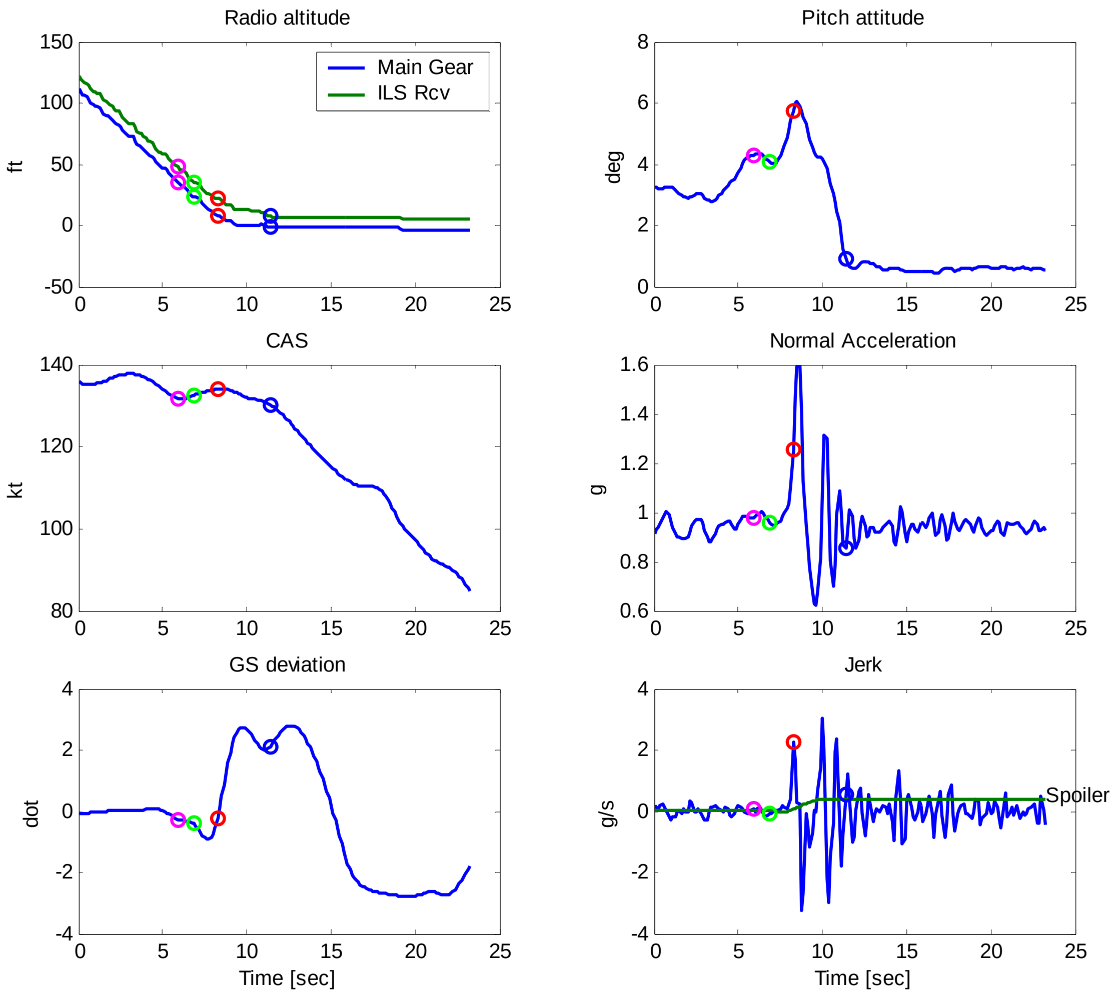
Figure B-12. B-737 Strong Wind (38 kt) and Severe Turbulence (gusting 52 kt)

B.3 EXAMPLE CASES WITH SHORT AND LONG AIR DISTANCE.



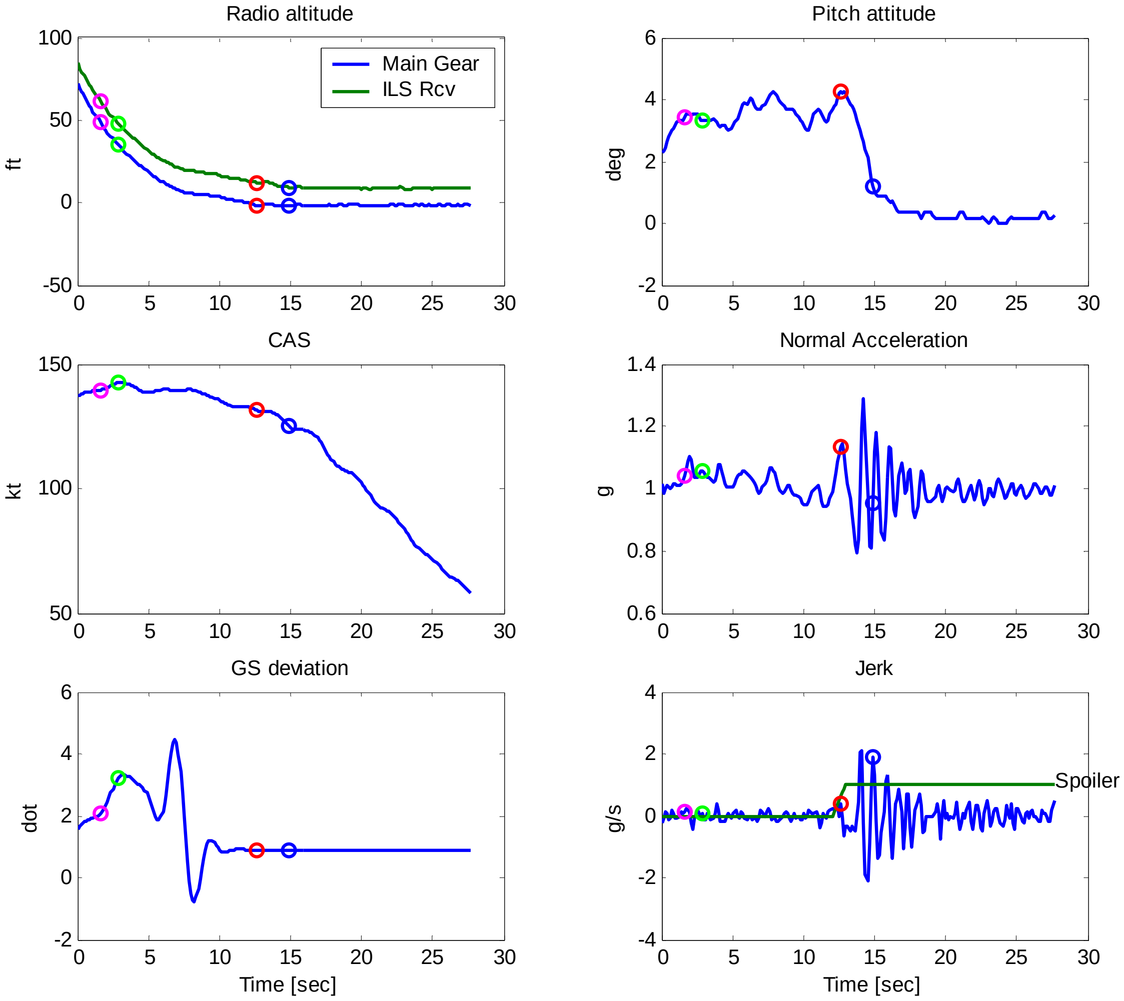
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-13. A320 Short Landing (airborne distance = 463 ft)



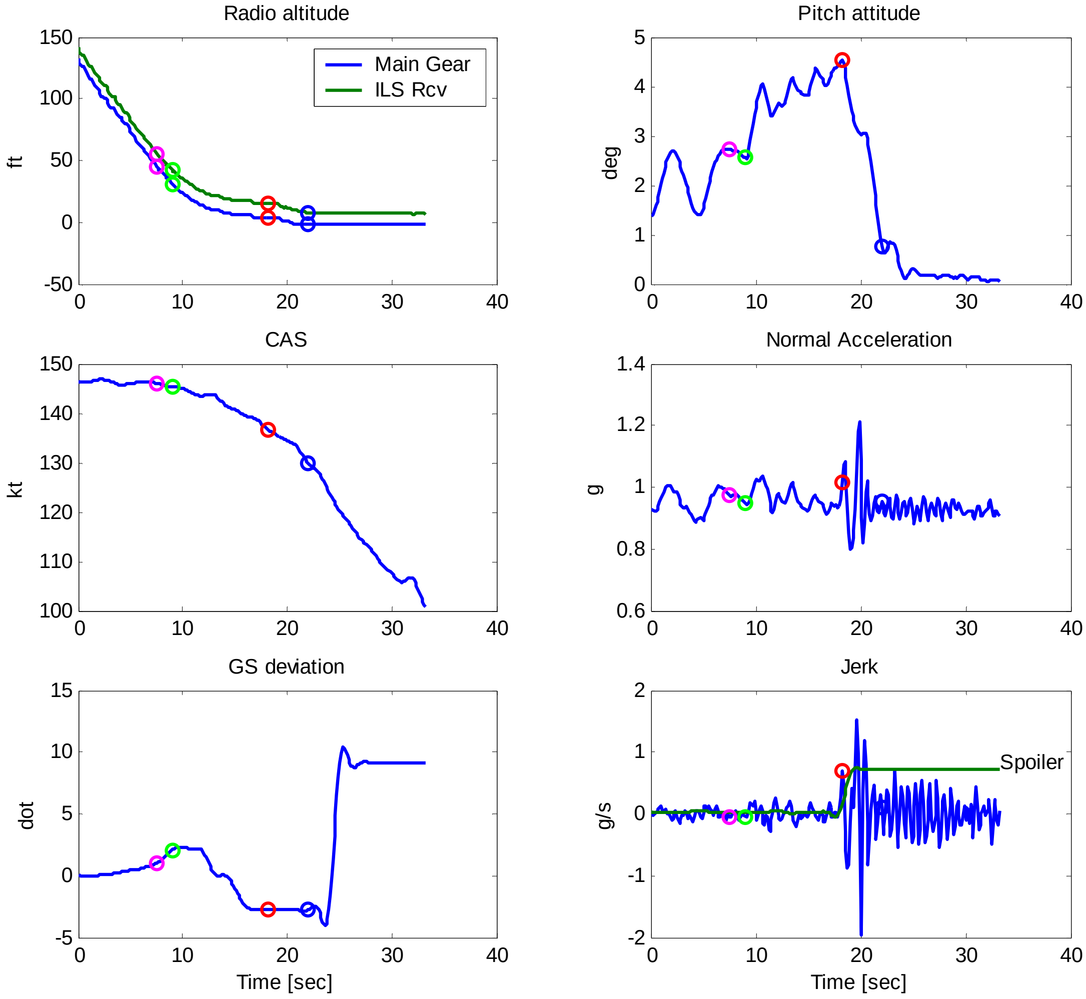
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-14. B-737 Short Landing (air distance = 519 ft)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

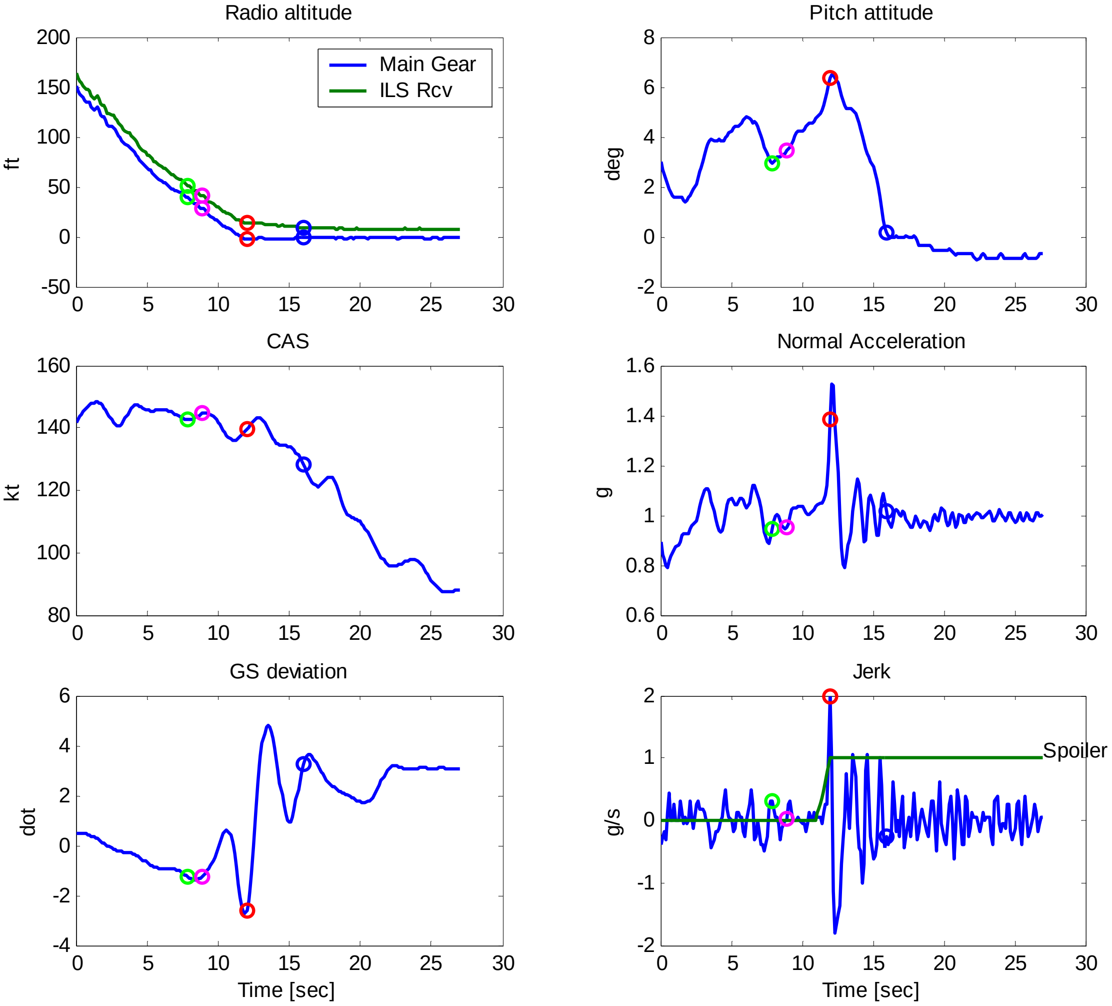
Figure B-15. A320 Long Landing (air distance = 2643 ft)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

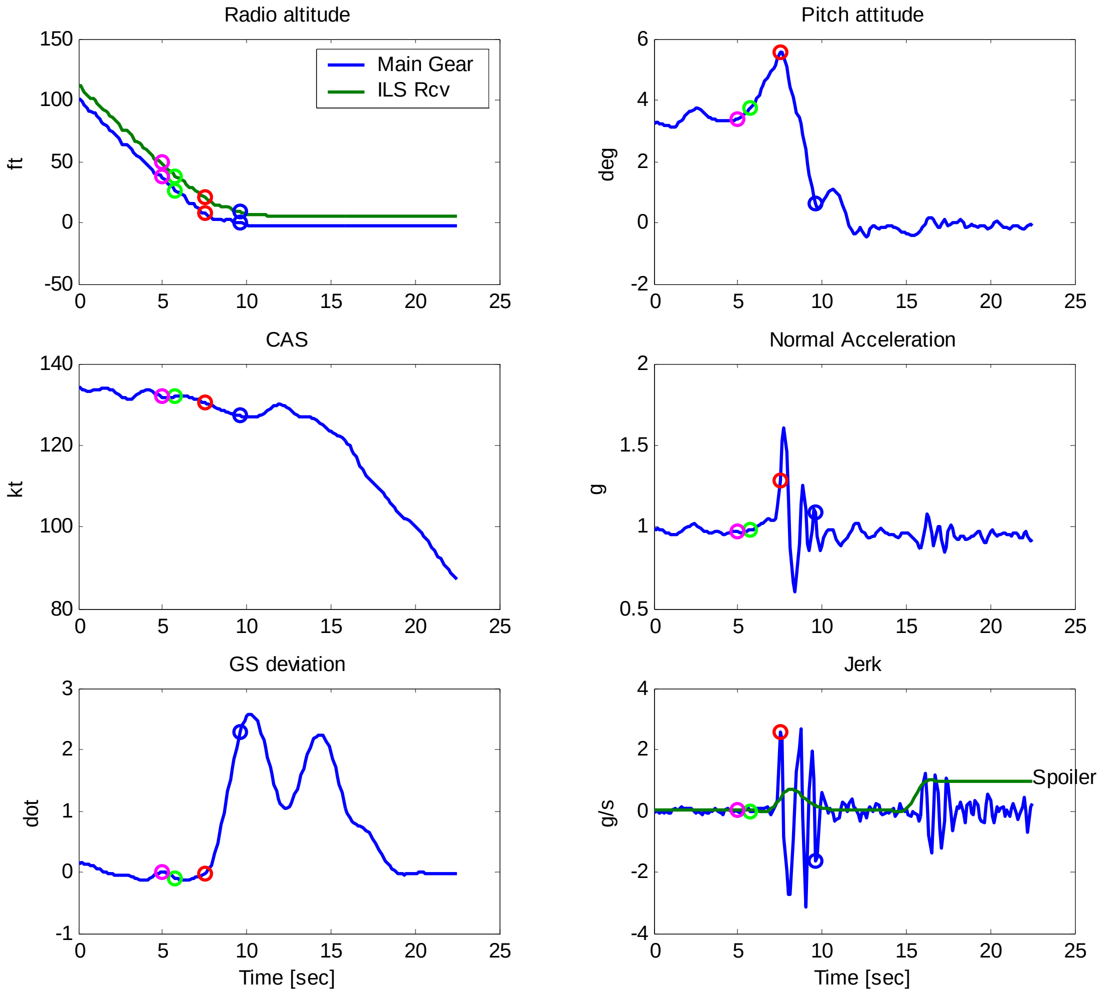
Figure B-16. B-737 Long Landing (air distance = 2642 ft)

B.4 EXAMPLE CASES WITH HARD AND SOFT LANDINGS.



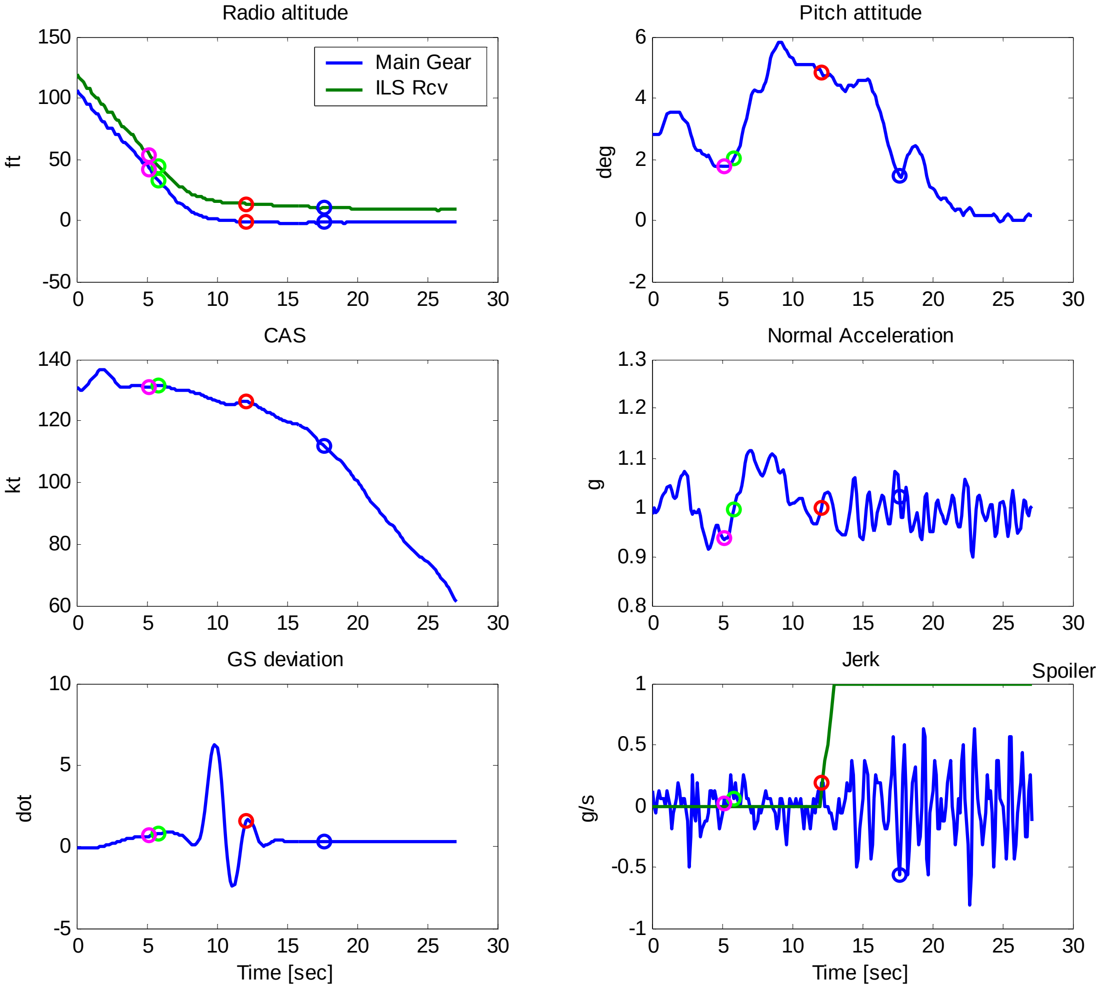
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-17. A320 Hard Landing (air distance = 670 ft)



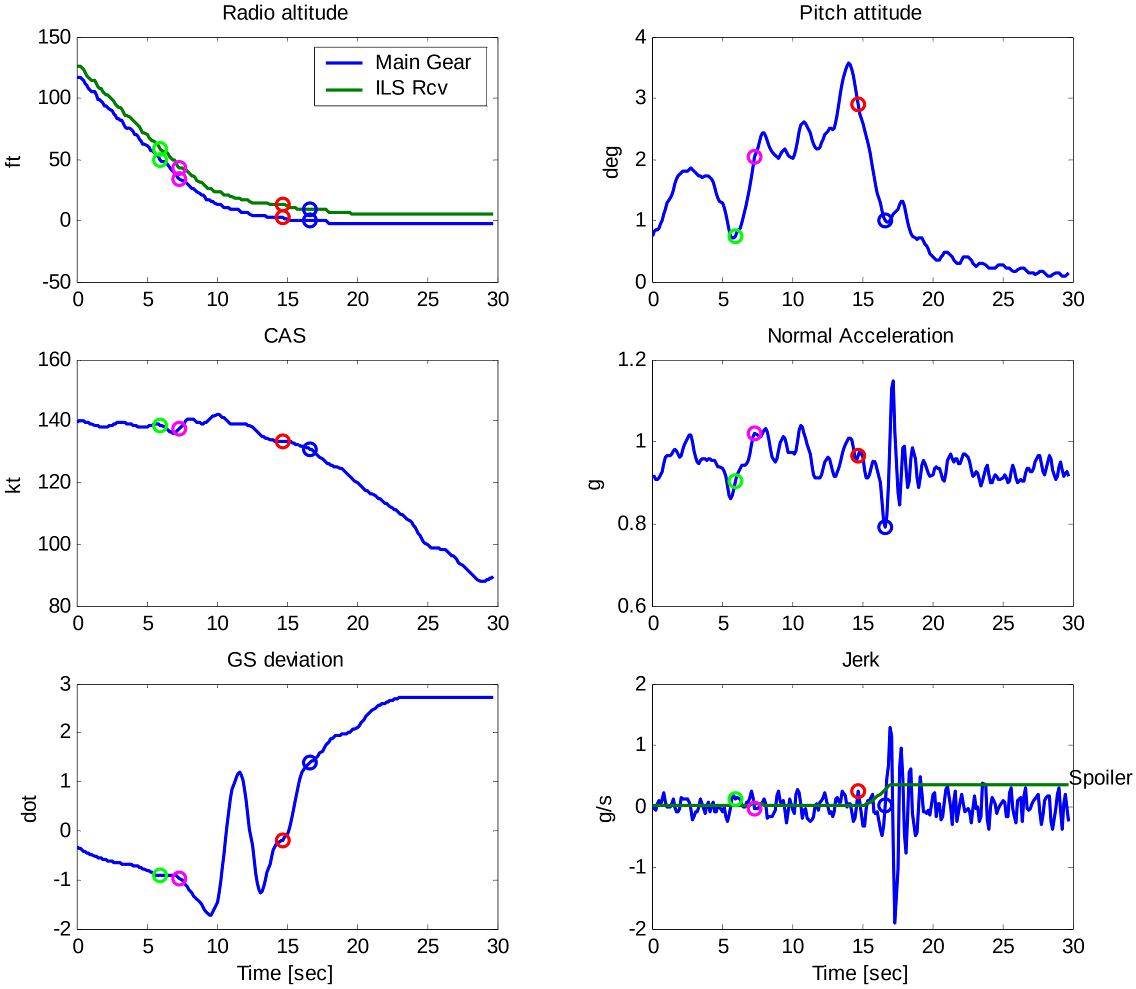
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-18. B-737 Hard Landing (air distance = 552 ft)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

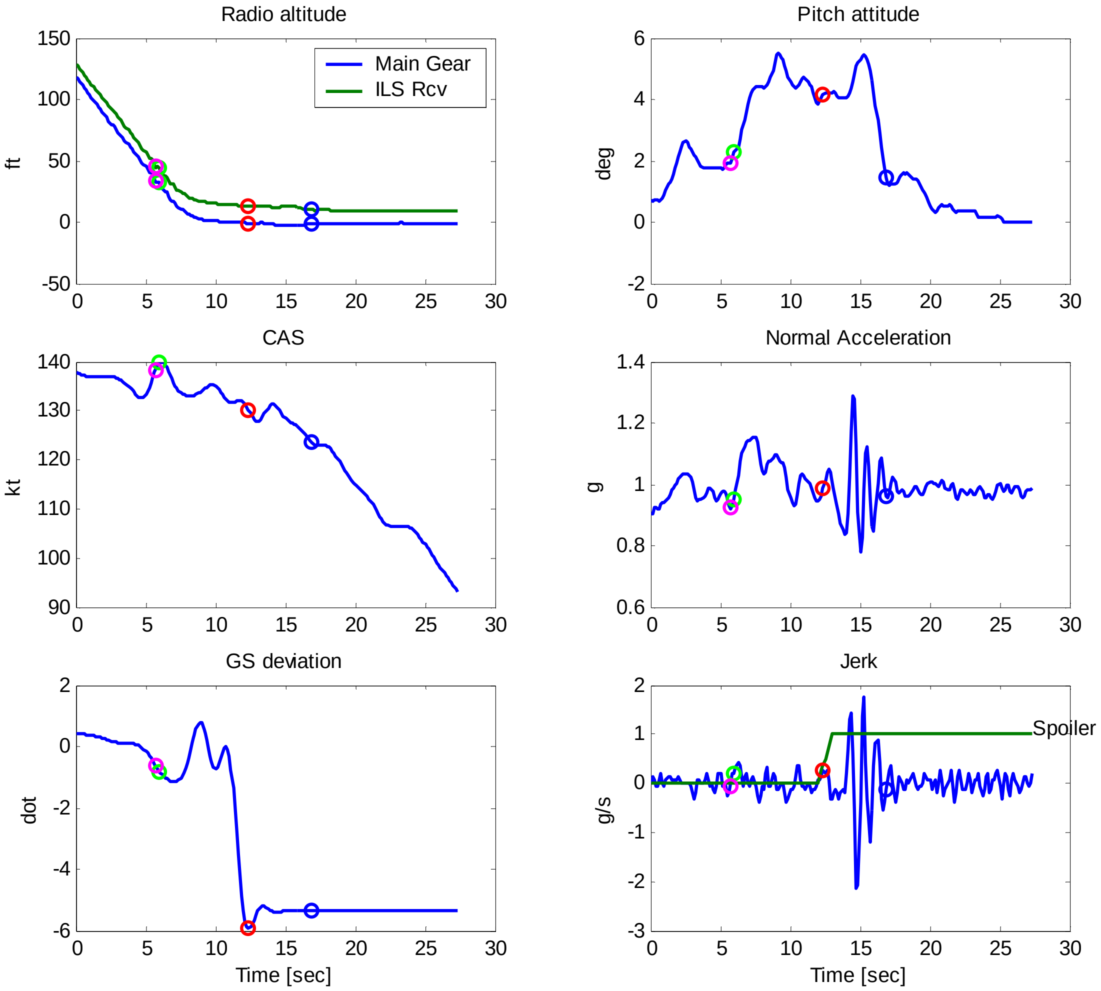
Figure B-19. A320 Soft Landing (air distance = 1607 ft)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

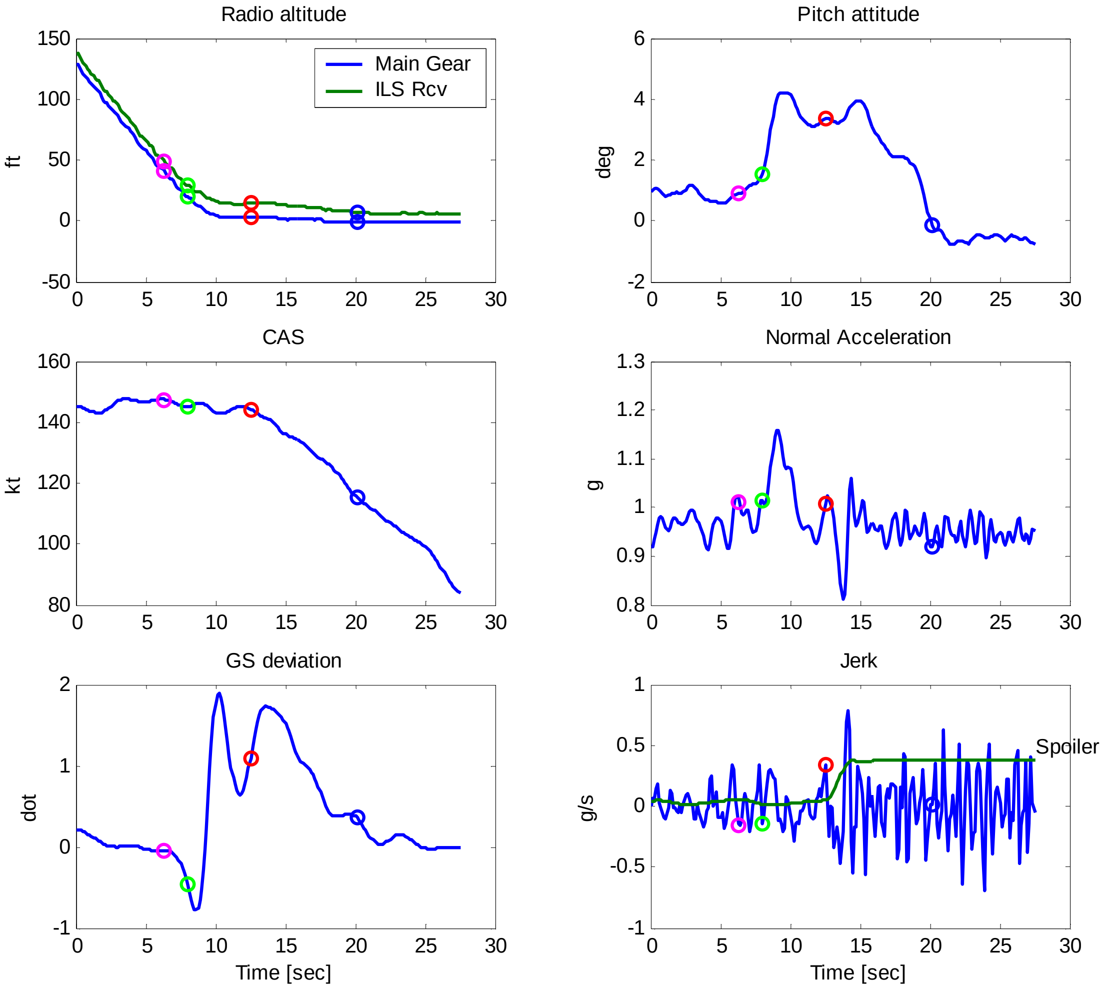
Figure B-20. B-737 Soft Landing (air distance = 1515 ft)

B.5 EXAMPLE CASES WITH HIGH AND LOW DESCENT RATE.



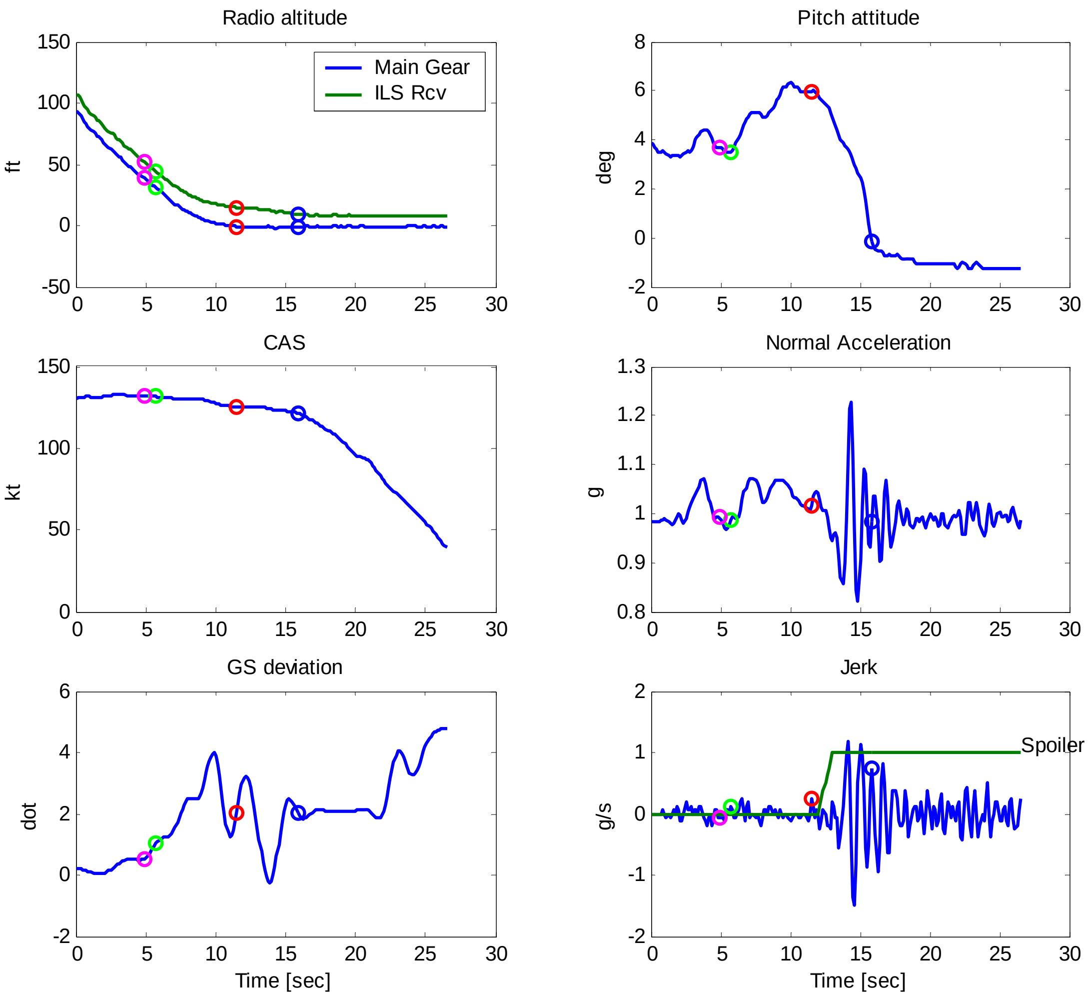
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-21. A320 High Descent Rate at THR (V/S = 870 ft/min, air distance = 1720 ft)



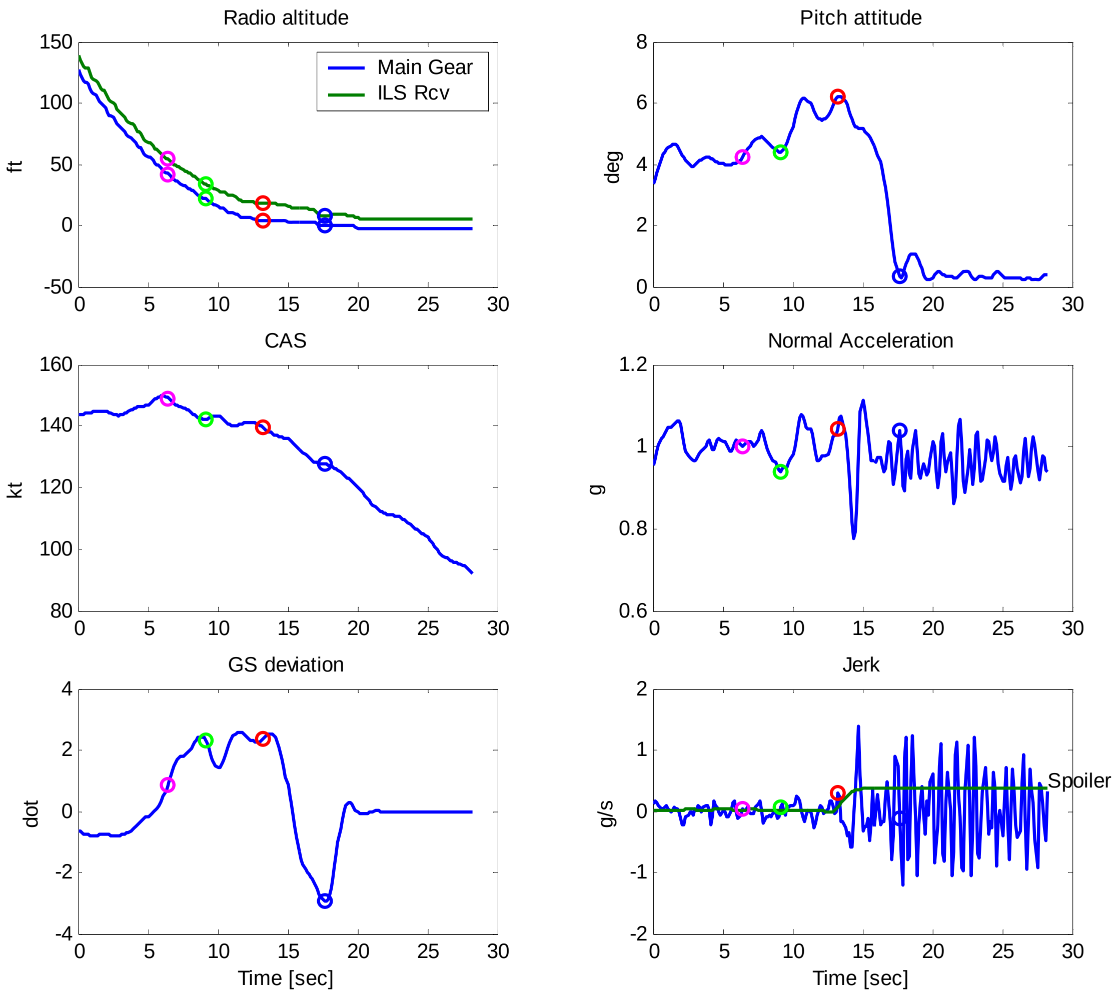
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-22. B-737 High Descent Rate at THR (V/S=859 ft/min, air distance = 1330 ft)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

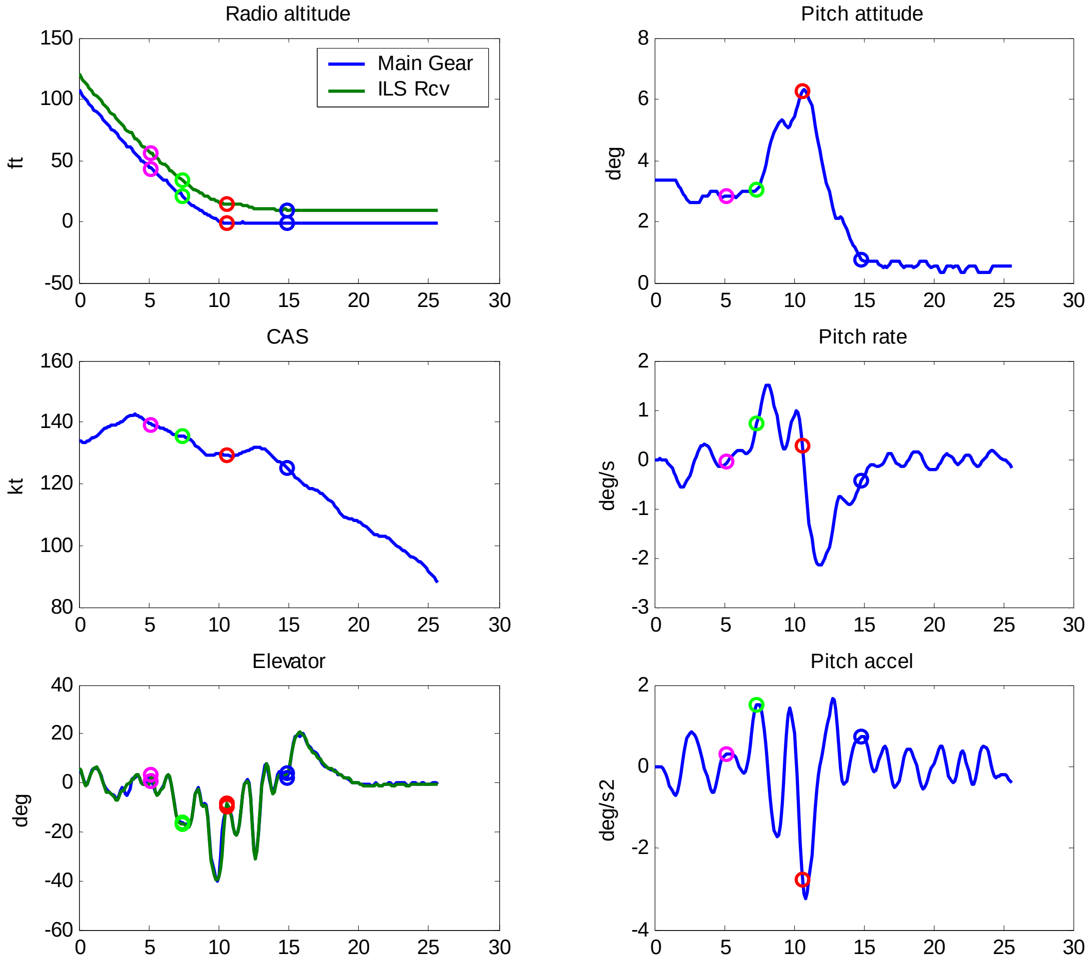
Figure B-23. A320 Low Descent Rate at THR (V/S=160 ft/min, air distance = 1398 ft)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

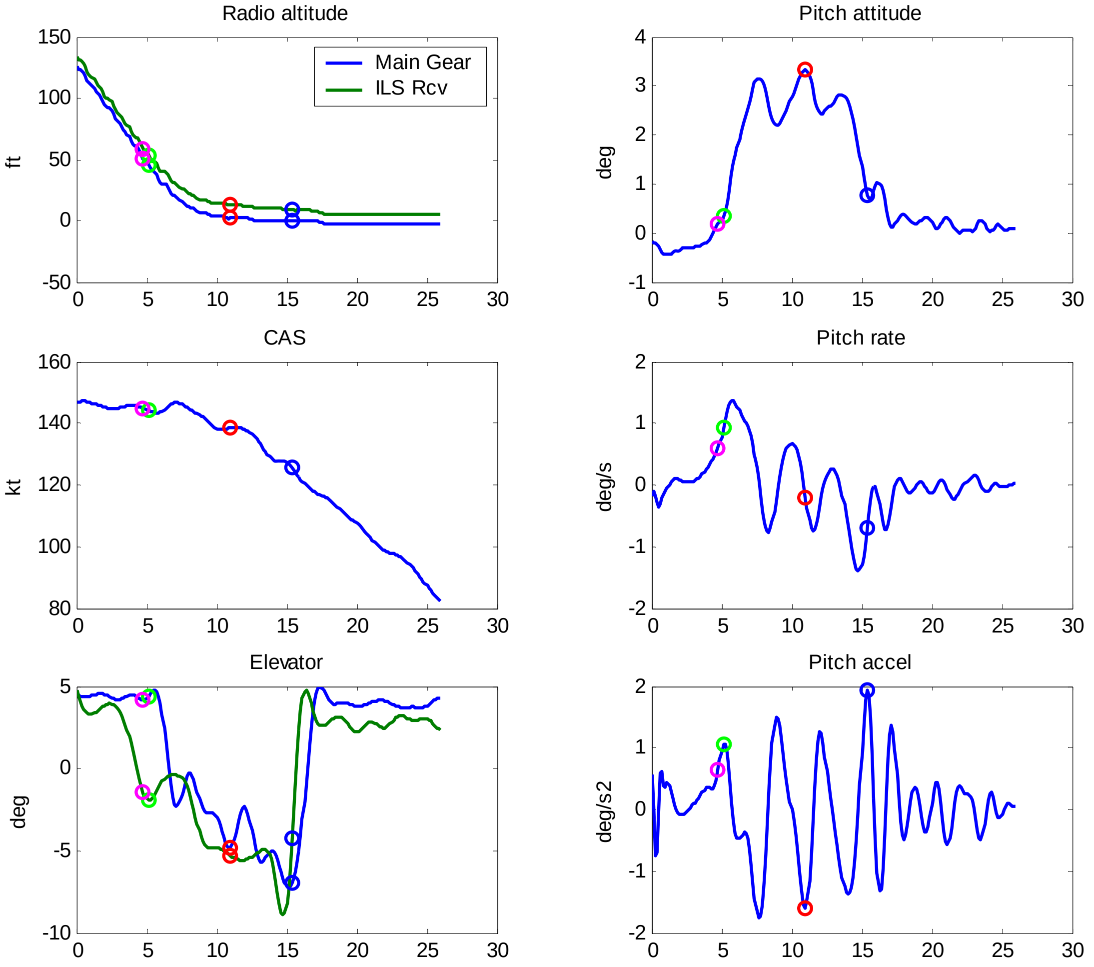
Figure B-24. B-737 Low Descent Rate at THR (V/S=314 ft/min, air distance = 1740 ft), Mean V/S~570 fpm

B.6 EXAMPLE FLARE CASES.



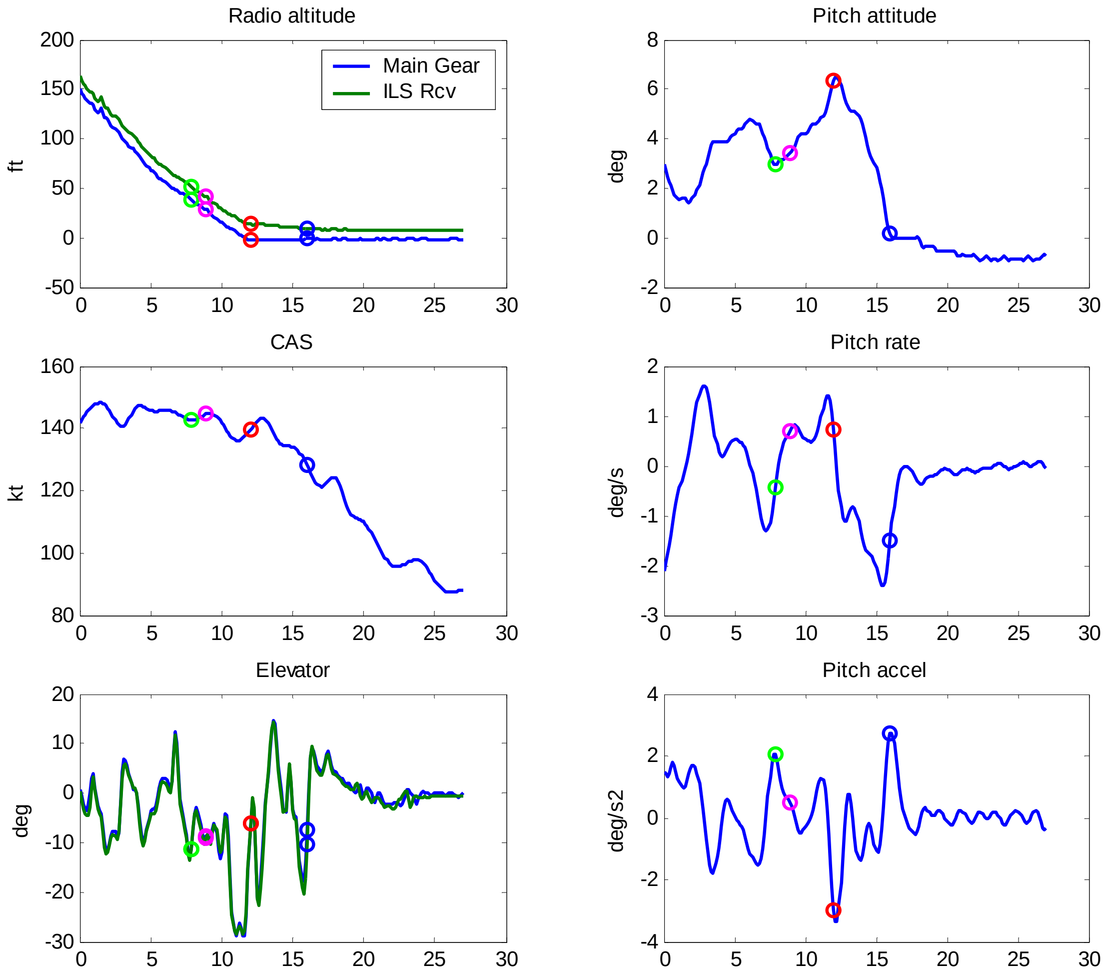
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-25. A320 Normal Flare (NZ = 1.12 g)



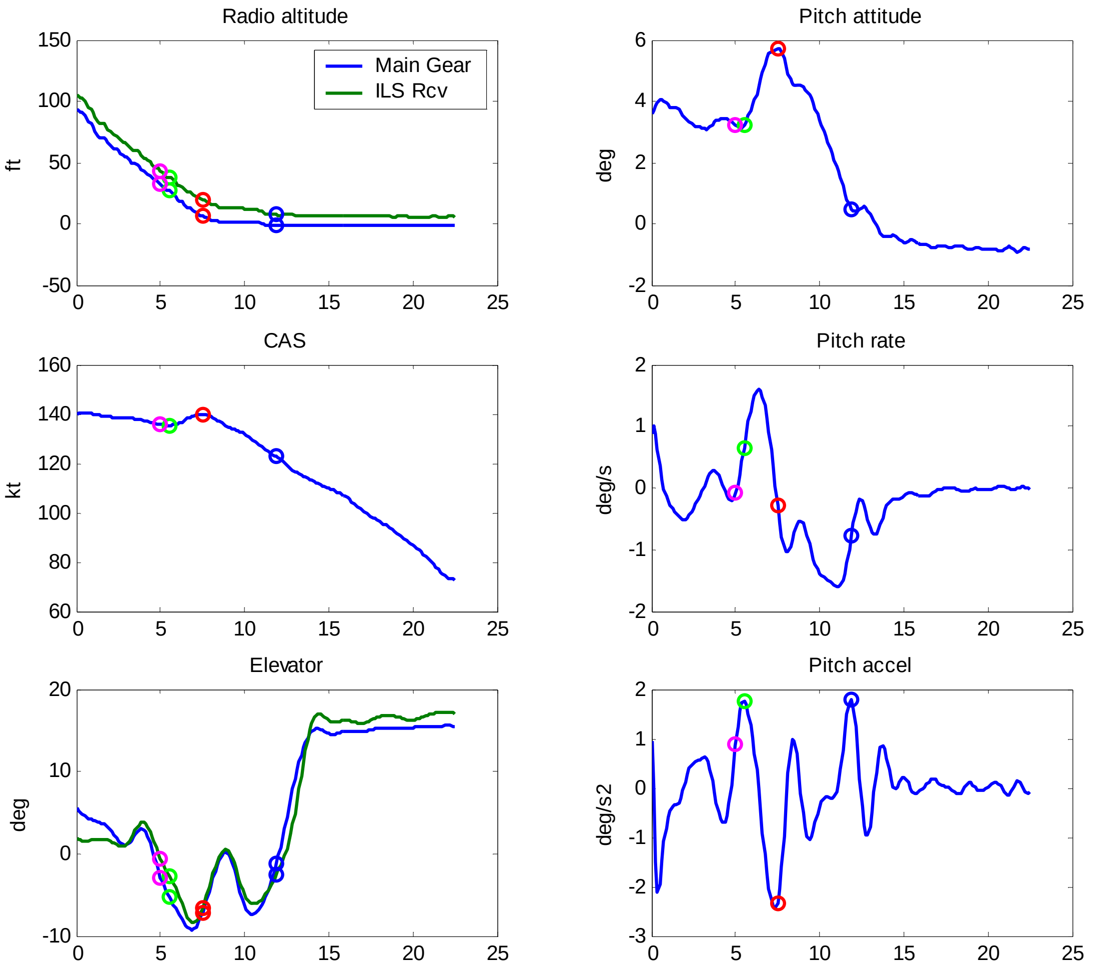
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-26. B-737 Normal Flare (NZ = 1.12 g)



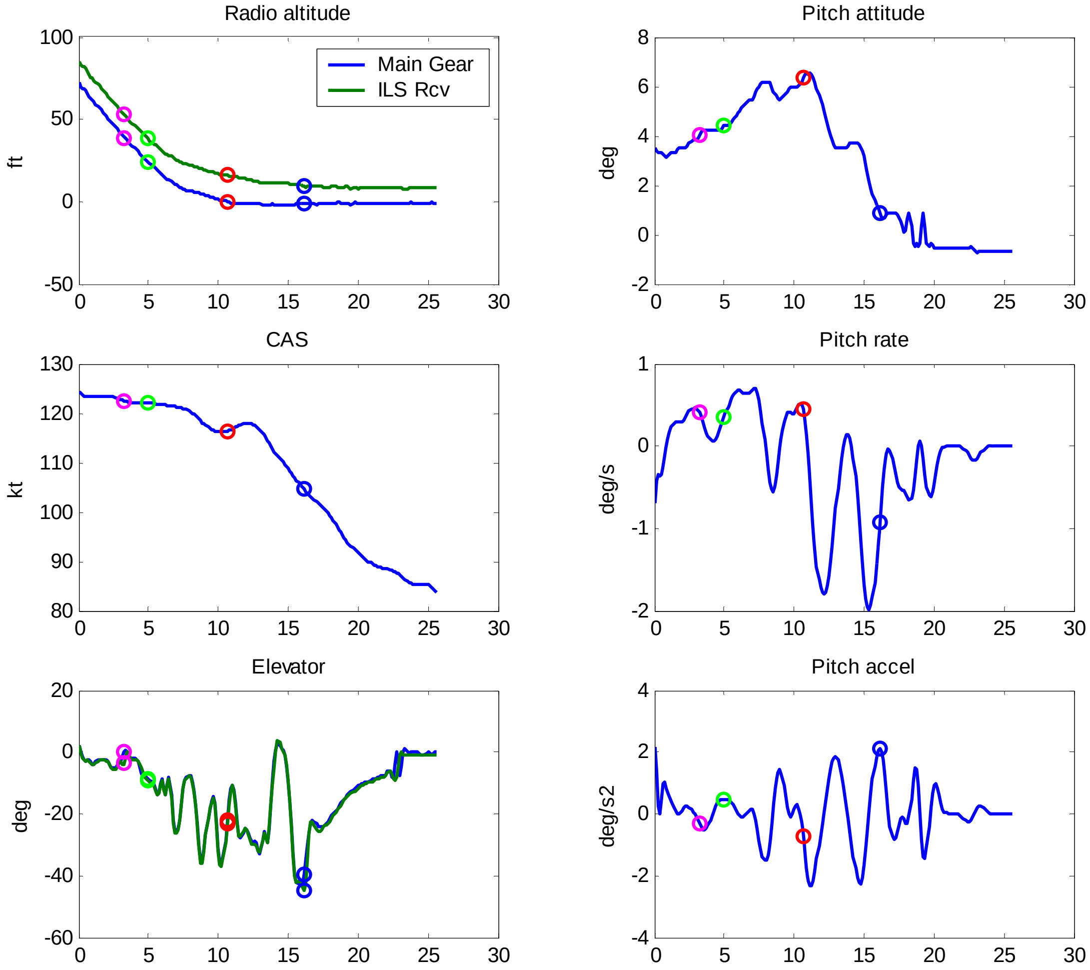
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-27. A320 Aggressive Flare (NZ = 1.38 g)



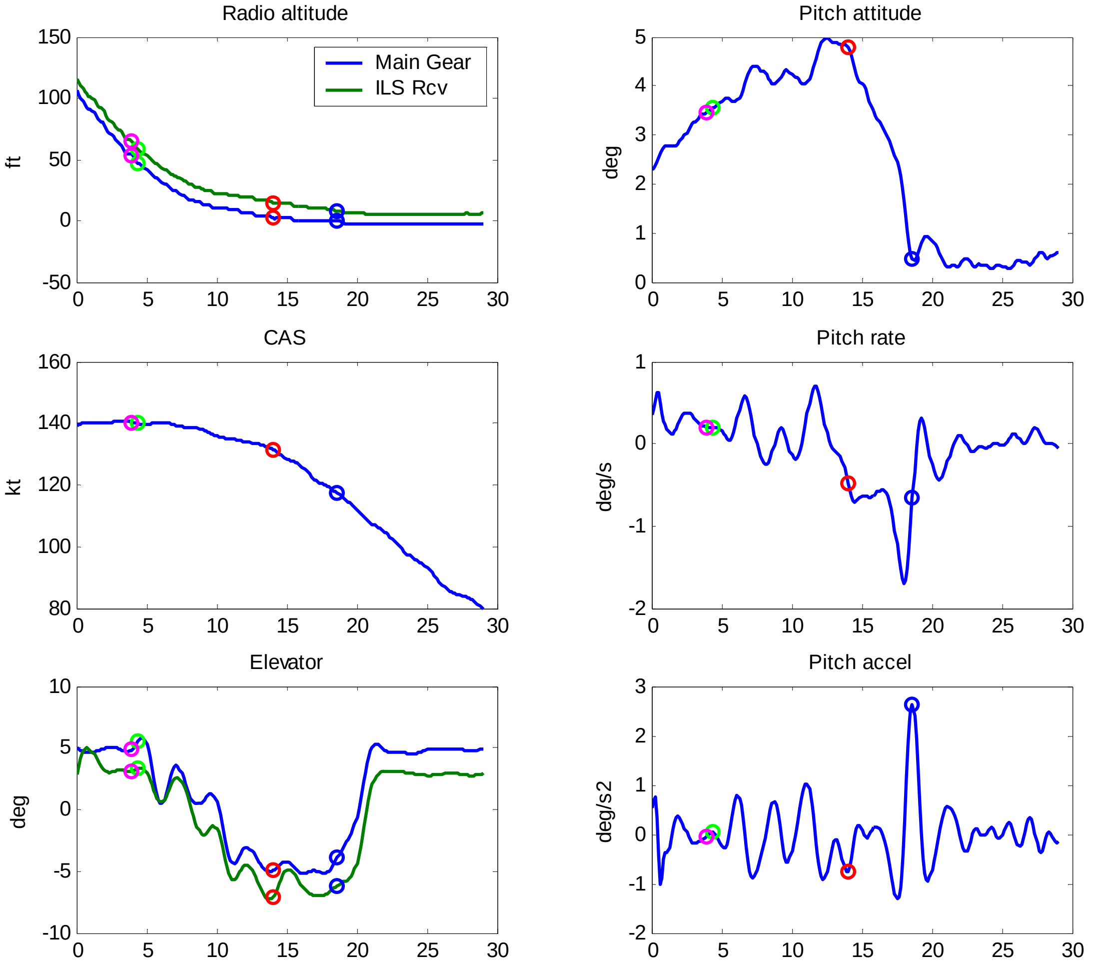
Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-28. B-737 Aggressive Flare (NZ = 1.4 g)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-29. A320 Slow Flare (NZ = 1.05 g)



Legend:
O Threshold crossing
O Flare initiation
O Main gear touchdown
O Nosewheel touchdown

Figure B-30. B-737 Slow Flare (NZ = 1.02 g)

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
National Policy

ORDER
1110.149

Effective Date:
10/12/07

SUBJ: Takeoff/Landing Performance Assessment Aviation Rulemaking Committee

1. Purpose of This Order. This order establishes the Takeoff/Landing Performance Assessment Aviation Rulemaking Committee (ARC) according to the Administrator's authority under Title 49 of the United States Code (49 U.S.C.) § 106(p)(5).

2. Audience. The audience for this order includes employees from the following services within the office of the Associate Administrator for Aviation Safety: Aircraft Certification, Flight Standards, and Rulemaking. Employees of the Office of the General Counsel and the Office of the Associate Administrator for Airports are also part of this order's audience.

3. Where You Can Find This Order. You can access this order through the Flight Standards Information Management System (FSIMS) at http://fsims.avr.faa.gov and https://employees.faa.gov/tools_resources/orders_notices.

4. Background. After any serious aircraft accident or incident, the Federal Aviation Administration (FAA) typically performs an internal audit to evaluate the adequacy of current regulations and guidance information in areas that come under scrutiny during the course of the accident investigation. The Southwest Airlines landing overrun accident involving a Boeing 737-700 at Chicago Midway Airport in December of 2005 initiated such an audit. In addition to the regulations, the FAA evaluated its own orders, notices, and advisory circulars, as well as International Civil Aviation Organization (ICAO) and foreign country requirements, airplane manufacturer-developed material, independent source material, and current practices of air carrier operators.

a. This internal FAA review revealed the following issues:

(1) A survey of Title 14 Code of Federal Regulations (14 CFR) part 121 turbojet operators' manuals indicated that approximately 50 percent of the operators surveyed do not have policies in place for assessing whether sufficient landing distance exists at the time of arrival, even when conditions (including runway used, meteorological environment, runway surface contaminants, airplane weight, airplane configuration, and planned usage of decelerating devices) are different and worse than those planned at the time the flight was released.

(2) Not all operators who perform landing distance assessments at the time of arrival have procedures that account for runway surface conditions or reduced braking action reports.

(3) Many operators who perform landing distance assessments at the time of arrival do not apply a safety margin to the expected actual landing distance. Those that do are inconsistent in applying an increasing safety margin as the expected actual landing distance increased (i.e., as a percentage of the expected actual landing distance).

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(4) Some operators have developed their own contaminated runway landing performance data or are using data developed by third party vendors. In some cases, this data indicate shorter landing distances than the airplane manufacturer's advisory data for the same conditions. In other cases, an autobrake landing distance chart has been misused to generate landing performance data for contaminated runway conditions. Also, some operators' data has not been kept up to date with the manufacturer's current advisory data for contaminated runway operations.

(5) Credit for the use of thrust reversers in the landing performance data is not uniformly applied and pilots may be unaware of these differences. In one case, the operator had given different credit for various series with the same make and model aircraft. The operator's understanding of the data with respect to reverse thrust credit, and the information conveyed to pilots, were both incorrect.

(6) Aircraft Flight Manual (AFM) landing performance data is determined during flight testing using flight test and analysis criteria that are not representative of everyday operational practices. Landing distances determined in compliance with 14 CFR part 25, § 25.125 and published in the FAA-approved AFM do not reflect operational landing distances. Landing distances determined during certification tests are aimed at demonstrating the shortest landing distances for a given airplane weight with a test pilot at the controls, and are established with full awareness that operating rules for fractional ownership, domestic, flag, supplemental, commuter/on-demand operations with large transport category turbine-engine powered airplanes require the inclusion of additional factors when determining minimum operational field lengths. (These factors are required for dispatch, but are used by some operators at the time of arrival as well.) Flight test and data analysis techniques for determining landing distances can result in the use of high touchdown sink rates (as high as 8 feet per second) and approach angles of -3.5 degrees to minimize the airborne portion of the landing distance. Maximum manual braking, initiated as soon as possible after landing, is used in order to minimize the braking portion of the landing distance. Therefore, the landing distances determined under § 25.125 are shorter than the landing distances achieved in normal operations.

(7) Wet and contaminated runway landing distance data (which is advisory data only) is usually an analytical computation using the dry, smooth, hard surface runway data collected during certification. Therefore, the wet and contaminated runway data may not represent performance that would be achieved in normal operations. This lack of operational landing performance repeatability from the flight test data, along with many other variables affecting landing distance, are taken into consideration in the preflight landing performance calculations by requiring a significant safety margin in excess of the certified (unfactored) landing distance that would be required under wet and contaminated landing conditions. However, the regulations do not specify a particular safety margin for a landing distance assessment at the time of arrival. The required safety margin has been left largely to the operator and/or the flightcrew to determine.

(8) Manufacturers do not provide advisory landing distance information in a standardized manner. However, most turbojet airplane manufacturers make landing distance performance information available for a range of runway or braking action conditions using various airplane deceleration devices and settings under a variety of meteorological conditions.

This information is made available in a wide variety of informational documents, dependent upon the manufacturer, and is not part of the FAA-approved AFM.

(9) Most of the data for runways contaminated by snow, slush, standing water, or ice were developed to show compliance with European Aviation Safety Agency (EASA) and Joint Aviation Authority (JAA) airworthiness certification and operating requirements.

b. FAA actions following the internal review:

(1) The FAA published an advanced notice of policy for “Landing Performance Assessments After Departure for All Turbojet Operators.” This notice was published in the Federal Register on June 7, 2006 (71 FR 32877) with a correction notice (71 FR 34856) published on June 16, 2006.

(2) After considering public comments on the advance notice of policy, the FAA issued Safety Alert for Operators (SAFO) 06012 on August 31, 2006. This SAFO, while not being mandatory, urgently recommended all operators of turbojet airplanes to have procedures in place to perform landing performance assessments, and to provide a 15 percent safety margin beyond the actual landing distance. SAFO 06012 also notified the aviation community that the FAA has initiated the rulemaking process to address this issue.

5. Objectives and Scope of the Committee. The Takeoff/Landing Performance Assessment ARC will provide a forum for the U.S. aviation community to discuss the landing performance assessment methods provided in SAFO 06012. Additionally, takeoff performance for contaminated runway operations and issues relevant to part 139, Certification of Airports, will be discussed. These discussions will be focused on turbine powered aircraft including both turbojet and turboprop airplanes operated under parts 121, 135, 125, and 91 subpart K.

6. Committee Procedures.

a. The Associate Administrator for Aviation Safety will issue more specific taskings, including deliverable dates.

b. The committee will provide advice and recommendations to the Associate Administrator for Aviation Safety. The committee will act solely in an advisory capacity.

c. The committee will discuss and present information, guidance, and recommendations that the members of the committee consider relevant to disposing of issues. Discussion will include, but is not limited to, the following:

(1) Operational objectives, recommendations, and requirements.

(2) Recommendations for rulemaking necessary to meet objectives.

(3) Guidance material and the implementation processes.

(4) Global harmonization issues and recommendations.

7. Organization and Administration.

a. The FAA will set up a committee representing the various parts of the industry and Government. The committee may set up specialized work groups that will include at least one committee member and invited subject matter experts from industry and Government, where necessary.

b. The Associate Administrator for Aviation Safety will have the sole discretion to appoint members or organizations to the committee. The committee will consist of members of the aviation community, including aviation organizations of affected airplane manufacturers, operators, and pilot unions of turbine powered aircraft under parts 121, 135, 125, and 91 subpart K. The FAA will provide participation and support from all affected FAA lines-of-business.

c. The Associate Administrator for Aviation Safety will receive all committee recommendations and reports.

d. The Associate Administrator for Aviation Safety is the sponsor of the committee and will select a steering committee from the membership of the committee to act as lead. Also, the Associate Administrator will select the FAA-designated representative for the committee. Once appointed, the steering committee will do the following:

(1) Determine, in coordination with the other members of the committee, when a meeting is required.

(2) Arrange notification to all committee members of the time and place for each meeting.

(3) Draft an agenda for each meeting and conduct the meeting.

e. A Record of discussions of committee meetings will be kept.

f. Although a quorum is desirable at committee meetings, it is not required.

8. Membership.

a. The committee will consist of approximately 40 members, selected by the FAA, representing aviation organizations of affected airplane manufacturers, operators, and pilot unions, of turbine powered aircraft under parts 121, 135, 125, and 91 subpart K, and the FAA.

b. Each member or participant on the committee should represent an identified part of the aviation community and have the authority to speak for that part. Membership on the committee will be limited to promote discussions. Active participation and commitment by members will be essential for achieving the committee objectives and for continued membership on the committee. The committee may invite additional participants as subject matter experts to support specialized work groups.

9. Cost and Compensation. The estimated cost to the Federal Government for the Takeoff/Landing Performance Assessment ARC is approximately $40,000 annually. Non-Government representatives serve without Government compensation and bear all costs related to their participation on the committee. As non-Government representatives, the chair and all non-FAA committee members serve without Government compensation and bear all costs related to their participation on the committee.

10. Public Participation. The Takeoff/Landing Performance and Assessment ARC meetings are not open to the public. Persons or organizations that are not members of this committee and are interested in attending a meeting must request and receive approval in advance of the meeting from the industry co-chairs or the designated Federal representative.

11. Availability of Records. Under the Freedom of Information Act, Title 5 of the United States Code (5 U.S.C.) § 552, records, reports, agendas, working papers, and other documents that are made available to or prepared for or by the committee will be available for public inspection and copying at the FAA Office of Rulemaking, 800 Independence Avenue, S.W., Washington, DC 20591. Fees will be charged for information furnished to the public according to the fee schedule published in Title 49 of the Code of Federal Regulations (49 CFR) part 7.

12. Public Interest. Forming the Takeoff/Landing Performance Assessment ARC is determined to be in the public interest to fulfill the performance of duties imposed on the FAA by law.

13. Effective Date and Duration. This committee is effective October 12, 2007. The committee will remain in existence until October 12, 2009, unless terminated sooner or extended beyond the effective dates of the charter by the Administrator.

ORIGINAL SIGNED by

Robert A. Sturgell
Acting Administrator

APPENDIX Y

FAA Takeoff/Landing Performance Assessment - Aviation Rulemaking Committee - Recommendations. April 9, 2009.

TALPA ARC
Airport/Part 139 Working Group Recommendation
April 9, 2009

Background: Following the overrun of a Boeing 737 at Midway in December of 2005 the FAA found that the current state of the industry practices did not have adequate guidance and regulation addressing the operation on non-dry, non-wet runways, i.e., contaminated runways. As such they chartered an Aviation Rulemaking Committee (ARC) to address Takeoff and Landing Performance Assessment (TALPA) requirements for the appropriate part 23, 25, 91K, 121, 125, 135, and 139 Parts of 14 CFR. In formulating their recommendations it became clear to the ARC that the ability to communicate actual runway conditions to the pilots in real time and in terms that directly relate to expected aircraft performance was critical to the success of the project. While researching current NOTAM processes numerous significant short comings were discovered that hampered this communication effort. This document provides NOTAM formatting recommendations and reporting procedures intended for a digital communication process that would support this major safety initiative and resolve the identified short comings. Without accurate real time information pilots cannot safely assess takeoff or landing performance.

At the core of this recommendation is the concept of using the included **Paved Runway Condition Assessment Table** (the matrix) as the basis for performing runway condition assessments by airport operators and for interpreting the reported runway conditions by pilots in a standardized format based on airplane performance data supplied by airplane manufacturers for each of the stated contaminant types and depths. The concept attempts, to the maximum extent feasible, to replace subjective judgments of runway conditions with objective assessments which are tied directly to contaminant type and depth categories, which have been determined by airplane manufacturers to cause specific changes in the airplane braking performance. However, since the concept is radically different from the traditional practices in this area, several caveats are integral to this recommendation:

> In order to succeed, this concept will require extensive retraining of airport operations personnel, dispatchers and pilots to assure that the application of the matrix is consistent across airports and that interpretation of the results and reporting of braking performance via PIREPs is consistent with the terms of the matrix. Specific training issues requiring attention are identified in Appendix A.
>
> Since the matrix has only been tested at two airports for a portion of the winter of 2008/2009, and some potential discrepancies between the matrix and both airport personnel assessments and PIREPs have been identified under certain conditions, a much more extensive pilot program should be conducted during the winter of 2009/2010. This pilot program should involve 10 – 20 airports and require standardized documentation that can be analyzed in support of refinements to the matrix or the accompanying instructions, if warranted. This pilot program might be conducted under the auspices of the Commercial Aviation Safety Team, using the ASIAS program with its capability of employing FOQUA data to correlate individual airplane stopping performance with runway condition assessment codes in effect at the time. It would also be highly desirable to have airline participation in the pilot program.
>
> During the course of this ARC work effort, numerous cases were identified by the airport/Part 139 working group where various FAA guidance documents use inconsistent

terms or definitions. A thorough harmonization of other guidance documents with this recommendation should be undertaken. The documents identified by the working group are listed in Appendix B.

Advisory Circular 150/ 5200-30 was amended last winter to address the immediate needs of closing a runway upon receipt of a “nil” braking action report and taking specific actions upon receipt of two successive “poor” braking action reports. There is a pressing need to further revise that AC before next winter to clarify the appropriate method of returning a runway to service after a closing due to “nil” braking reports and to address other inconsistencies the working group has identified.

Because of the close interrelationship between performing runway condition assessments and the reporting of those assessments, these recommendations are presented in two sections: each section must be considered as integral to the overall recommendation. The first section addresses runway condition assessment using the matrix and the second section addresses changes to the reporting system that should be incorporated into the revisions to the NOTAM system, currently being designed. While the use of the matrix as the basis for ultimate implementation of runway condition assessment and reporting is the core recommendation of the working group, it must be treated as a “living document” and any changes that result from additional experience gained during the pilot program, or otherwise, must be fully coordinated with all stakeholders and incorporated into both sections of this recommendation.

Section 1 - RUNWAY CONDITION REPORTING

This document is intended to capture necessary runway condition reporting logic to support the Takeoff and Landing Performance Assessment ARC recommendations. This is not a standalone document. These procedures must be incorporated into existing AC and other guidance materials. While there are numerous acceptable methods to accomplish the communication of this information, the specific terms, depths, percentages, thresholds and definitions must not be altered unless such changes are reviewed and approved by the airplane manufacturers' aviation performance engineers and the changes are coordinated with each stakeholder.

Instructions to Airport Operators:

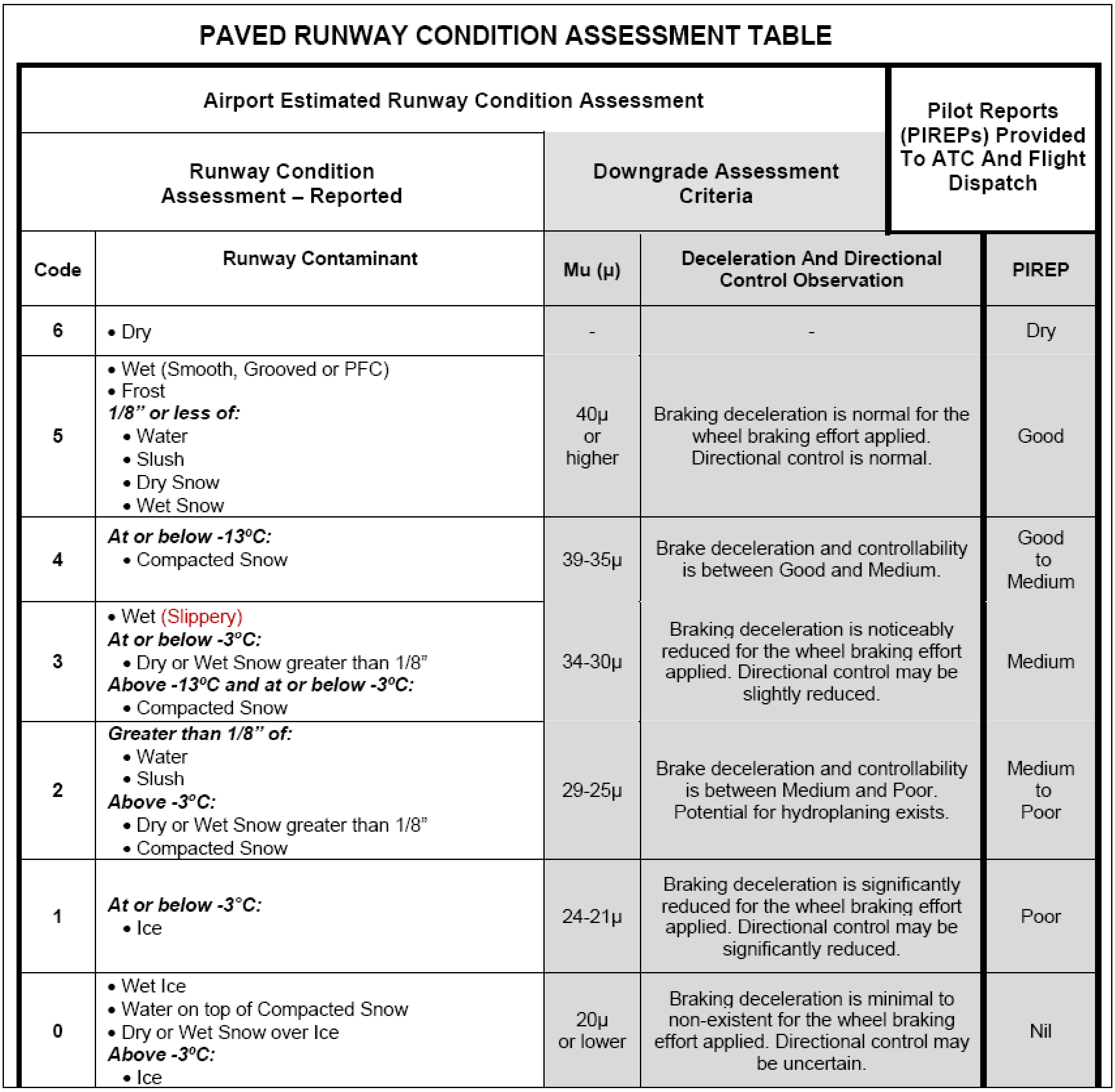
Whenever a runway is not dry the airport operator is responsible for providing current runway surface condition reports. Report runway surface conditions using the runway condition and contamination terms, percentage of runway coverage, contaminant depth, and procedures provided in this document.

During active snow events or rapidly changing conditions (e.g., increasing snowfall, rapidly rising or falling temperatures) airport operators are required to maintain a vigilant runway inspection process to ensure accurate reports.

Downgrade Assessment Adjustments

When data from the shaded area in the table (i.e., CFME/deceleration devices, pilot reports, or observations) suggest conditions are worse than indicated by the present contaminant, the airport operator should exercise prudent judgment and, if warranted, report a lower runway condition code than the contamination type and depth would indicate in the table below. While pilot reports (PIREPs) of braking action provide valuable information, these reports rarely apply to the full length of the runway as such evaluations are limited to the specific sections of the runway surface in which in which wheel braking was utilized. Downgrade assessment criteria may never be used to upgrade contaminant based assessments of condition codes (e.g., from 2 to 3).

Example: *The full length of the runway is covered with ½" wet snow (-4°C) resulting in a 3/3/3 runway condition code. However, if the airport operator finds the last third of the runway is slicker* *than would be indicated by this runway condition code, the airport operator should consider reporting a runway condition code of 3/3/2.*



PAVED RUNWAY CONDITION ASSESSMENT TABLE

Airport Estimated Runway Condition Assessment				Pilot Reports (PIREPs) Provided To ATC And Flight Dispatch
Runway Condition Assessment – Reported		Downgrade Assessment Criteria		
Code	**Runway Contaminant**	**Mu (μ)**	**Deceleration And Directional Control Observation**	**PIREP**
6	• Dry	-	-	Dry
5	• Wet (Smooth, Grooved or PFC) • Frost ***1/8" or less of:*** • Water • Slush • Dry Snow • Wet Snow	40μ or higher	Braking deceleration is normal for the wheel braking effort applied. Directional control is normal.	Good
4	***At or below -13ºC:*** • Compacted Snow	39-35μ	Brake deceleration and controllability is between Good and Medium.	Good to Medium
3	• Wet (Slippery) ***At or below -3ºC:*** • Dry or Wet Snow greater than 1/8" ***Above -13ºC and at or below -3ºC:*** • Compacted Snow	34-30μ	Braking deceleration is noticeably reduced for the wheel braking effort applied. Directional control may be slightly reduced.	Medium
2	***Greater than 1/8" of:*** • Water • Slush ***Above -3ºC:*** • Dry or Wet Snow greater than 1/8" • Compacted Snow	29-25μ	Brake deceleration and controllability is between Medium and Poor. Potential for hydroplaning exists.	Medium to Poor
1	***At or below -3°C:*** • Ice	24-21μ	Braking deceleration is significantly reduced for the wheel braking effort applied. Directional control may be significantly reduced.	Poor
0	• Wet Ice • Water on top of Compacted Snow • Dry or Wet Snow over Ice ***Above -3ºC:*** • Ice	20μ or lower	Braking deceleration is minimal to non-existent for the wheel braking effort applied. Directional control may be uncertain.	Nil

Notes:

Contaminated runway. *A runway is contaminated when more than 25 percent of the runway surface area (whether in isolated areas or not) within the reported length and the width being used is covered by water, slush, frost or snow greater than 0.125 inches (3 mm), or any compacted snow or ice.*

Dry runway. *A runway is dry when it is not contaminated and at least 75% is clear of visible moisture within the reported length and width being used.*

Wet runway. *A runway is wet when it is neither dry nor contaminated.*

Temperatures referenced are average runway surface temperatures when available, OAT when not.

While applying sand or liquid anti ice to a surface may improve its friction capability, no credit is taken until pilot braking action reports improve or the contaminant type changes (e.g., ice to water).

Compacted Snow may include a mixture of snow and imbedded ice.

Compacted Snow over Ice is reported as Compacted Snow.

Taxi, takeoff, and landing operations in Nil conditions are prohibited.

Section 2 - CONCEPT FOR RUNWAY CONDITION NOTAMs

1. The system must allow for all season real time NOTAM dissemination in a manner accessible via typical requests for NOTAMs by any customer. The output should be retrievable in several formats to include clear text, contractions, and machine readable. The system should allow for easy import of NOTAM data into information systems used by air carrier dispatch centers.
2. The input side of the system should:
    a. Allow for secure password protected web access for easy input by airport personnel.
    b. Incorporate simplified drop down input menus and logic to only allow use of the following standardized runway condition and contamination terms, percentage of runway coverage and contamination depths:
        i. Runway Condition and Contamination terms:
            1. Dry
            2. Wet (Smooth)
            3. Wet (Grooved)
            4. Wet (PFC)
            5. Wet (Slippery)
            6. Water
            7. Slush
            8. Wet Snow
            9. Dry Snow
            10. Compacted Snow
            11. Frost
            11. Ice
            12. Wet Ice
        ii. Percentage of runway coverage:
            1. Whenever a runway is not bare and dry, runway condition NOTAMs are to be issued. The menu system should provide options for input of the specific runway condition and contamination terms above, and the depth and percentage of runway coverage per the specifications in this document.
            2. Reported Runway Width: Include a menu option to designate the reported runway width (e.g., cleared, treated, usable) when less than full.
            3. Simple drop down menus should provide the following percentage of runway coverage as it pertains to the full width of the runway, or if the cleared width is reported in the NOTAM, the percentage of coverage of that cleared width:
               10% (Label the drop down tab "10% or less")
               25% (Label the drop down tab "11% thru 25%")
               50% (Label the drop down tab "26% thru 50%")
               75% (Label the drop down tab "51% thru 75%")
               100% (Label the drop down tab "76% thru 100%")
            4. Runway condition codes (see the Paved Runway Condition Assessment Table) are only reported when contaminant coverage exceeds 25 percent of the runway length and width (or cleared width if cleared width is reported in the NOTAM). When contaminant coverage exceeds 25 percent of the runway length and width (or cleared width as noted above), the system should automatically provide an additional menu to capture the data necessary to automatically determine and issue runway condition codes for each third of the runway per the Paved Runway

Condition Assessment Table (e.g., 3/3/2). The data to be captured includes the contamination type and depth present on the full width or cleared width (if so reported) for each third of the runway, and surface or OAT temperature values (see Paved Runway Condition Assessment Table). (Automated capture of temperatures is preferred.) If a cleared width is reported, the runway condition codes pertain to that limited width, not the full width. The contaminants (type and depth) on the uncleared runway edges must also be reported, but without a corresponding runway condition code.

- The output NOTAM should not include contaminant type and depth for each third of the runway as this would cause excessive NOTAM lengths. The by thirds input is solely a means to determine and provide runway surface condition codes for each third of the runway (e.g., 3/3/2).
- Issuing runway conditions codes (e.g., 3/3/2) is the pilots' cue to start using non-dry stopping performance values.
- When multiple contaminants are present assign the runway condition code based on the slickest contaminant condition (type, depth and temperature based on the definitions in the Paved Runway Condition Assessment Table above) that exceeds 10% of the runway third. Runway condition codes should not be based on contaminants with 10% or less of coverage in a given runway third.
- To support data tracking and quality control there should be an input field to capture and track the Mu reading (if obtained) for each third of the runway. This Mu value would not be output in the NOTAM but would help with future reviews of the data and possible improvements in the Matrix logic. Additionally, if the Mu value is worse than defined in the table above, its input could be used to cause the system to automatically downgrade the runway surface condition code.

iii. <u>Contamination depths</u>. When reporting contamination depths, do not report depths for ice, frost, or compacted snow. Report all other levels of contamination depths as follows:

1. 1/8" (Label the drop down tab: "1/8" or less")

2. ¼" (Label the drop down tab: "Greater than 1/8" thru 1/4")
3. ½" (Label the drop down tab: "Greater than 1/4" thru 1/2")
4. ¾" (Label the drop down tab: "Greater than 1/2" thru 3/4")
5. 1" (Label the drop down tab: "Greater than 3/4" thru 1")
6. 2" (Label the drop down tab: "Greater than 1" thru 2")
7. 3" (Label the drop down tab: "Greater than 2" thru 3")
8. 4" (Label the drop down tab: "Greater than 3" thru 4")
9. Note: After 1 inch of accumulation report additional accumulation in whole inches and discontinue the use of fractions. After a depth of 35 inches report the additional amounts in whole feet only. (AC 150/5200-28D)

c. The menu must have an override feature to allow manual (or automatic??) downgrade of assigned runway condition codes (i.e., to assign a lower number) when desired.
   i. Logic should not allow upgrading of the runway condition code (i.e., assigning a higher number).
   ii. From a quality control standpoint, there should be an input field to capture the reason for the downgrade (e.g., click one of the following options: Mu, Pilot or Operations vehicle Braking Action Report and capture the data). This information would help with future improvements in the Matrix logic.

d. The menus should have provisions for entering optional data in a standardized format, such as:
   i. CENTER XXX FEET CLEARED, EDGES (contamination description), or
   ii. FIRST, CENTER or LAST XXXX FEET (contamination description), or
   iii. Use of the "OVER" description (e.g., WET SNOW OVER COMPACTED SNOW, DRY SNOW OVER ICE etc.). When the "OVER" descriptor is used assign the runway condition code based on the slickest contaminant condition (type, depth and temperature based on the definitions in the Paved Runway Condition Assessment Table above) that exceeds 10% of the runway third. Runway condition codes should not be based on contaminants with 10% or less of coverage in a given runway third.

e. The menu needs to include a "Runway Properties" tab where established properties such as the runway number, surface type (i.e., smooth, grooved, PFC or slippery) are pre-designated. These properties should be referenced to auto generate numeric runway options available on the runway condition input menu (e.g., RWY 17, RWY 35 etc.). Incorporate programming logic so that if "wet" is selected as the runway condition, the output NOTAM would automatically include the designated surface type as follows:
   i. WET (SMOOTH), WET (GROOVED), WET (PFC) or WET (SLIPPERY).
   ii. If friction evaluations conducted in accordance with AC 150-5320-12C reveals the average friction level is less than required, downgrade the runway property as appropriate (e.g., SMOOTH or SLIPPERY). Following this downgrade, if "wet" is the reported condition, the system would automatically generate the corrected output NOTAM (e.g., WET (SMOOTH) or WET (SLIPPERY)).
   iii. WET (SMOOTH, GROOVED or PFC) must automatically generate a runway condition code of 5.
   iv. WET (SLIPPERY) must automatically generate a runway condition code of 3.
   v. When a friction failed runway is brought back into proper specifications the airport operator would change the runway property back to its design specification (e.g., GROOVED).
   vi. The SLIPPERY modifier in the properties tab needs to include a location selection breakout such as: FIRST XXXX', LAST XXXX' or ENTIRE, where XXXX' is the designated slippery zone. For example, if the first 3000' of RWY 35 failed a preventive maintenance friction survey and the runway is wet, the output would read "RWY 35 3/5/5 WET (GROOVED), FIRST 3000' WET (SLIPPERY)". (Conversely, if runway 17 is the active runway the output NOTAM would automatically read "RWY 17 5/5/3 WET (GROOVED), LAST 3000' WET (SLIPPERY)".) If the entire runway is slippery, the NOTAM would read "RWY 35 3/3/3 WET (SLIPPERY)".

f. The system logic must only allow a runway third to be reported as "DRY" (code 6) when other sections are wet or contaminated (codes 0 through 5).

i. The code of 6 should only be used if the runway's cleared width is more than 25% wet or contaminated and at least one third of the runway is reportable as DRY (e.g., 6/6/5).

ii. A runway with a cleared width of at least 76% dry would not have any codes assigned; the dry sections would be reported as DRY and the contaminated sections and edges would be reported appropriately.

iii. A runway 100% bare and dry would be reported as DRY (if a runway condition report is issued) and would have no codes assigned. (A code report of 6/6/6 should be inhibited.)

g. The menu should allow for reporting conditions for each specific runway (by number).Report the runway numbers directionally according to the direction of takeoff and landing (e.g., RWY 35).

The output NOTAMs should include the option for retrieval in multiple formats to include clear text, contractions and machine readable. To help clarify the logic and guidance provided in this document, the following examples provide an airport observation and the resulting (clear text) NOTAM:

Scenario 1:

Grand Rapids Airport observed the following conditions for runway 17:

- Average surface temperature -7C
- Mu 32/32/32
- The entire runway was covered with ½" dry snow
- Operations vehicle experienced reduced directional control slightly reduced braking action and no downgrade in condition was recommended.

GRR RWY 17 3/3/3 100% 1/2 INCH DRY SNOW 1512Z 20 JAN 2009

Scenario 2:

Cherry Capital Airport observed the following conditions for runway 28:

- Average surface temperature -4C
- Mu 42/44/46
- The runway had 75% coverage of 1 inch dry snow over 50% coverage of compacted snow
- Operations vehicle experienced significantly reduced braking action and directional control
- The runway condition codes were downgraded from 3/3/3 to 1/1/1 based on the observers judgment given the poor operations vehicle braking action and control.

TVC RWY 28 1/1/1 75% 1 INCH DRY SNOW OVER 50% COMPACTED SNOW 2115Z 20 JAN 2009

Scenario 3:

Denver International Airport observed the following conditions for runway 07:

- Average surface temperature -1C
- Mu 24/31/27
- The runway had 75% coverage of 1/4 inch slush 130 feet wide with compacted snow on the remaining edges. The compacted snow on the remaining edges was not used to determine runway condition codes.
- The operations vehicle experienced noticeably reduced braking action and directional control and no downgrade in condition was recommended.

RWY 07 2/2/2 75% 1/4 INCH SLUSH 130 FEET WIDE REMAINING EDGES COMPACTED SNOW 1420Z 20 JAN 2009

Scenario 4:

Denver International Airport observed the following conditions for runway 35L:

- Average surface temperature -4C

- Mu 32/24/21 (the last 2 numbers were outside approved measuring parameters).
- The first 7000'of the runway was plowed to 60' wide with 50% compacted snow reaining
- The remaining edges of the first 7000' averaged 2 inches of dry snow over compacted snow
- The last 5000' was 75% covered with 4 inches of dry snow over compacted snow and 10% covered with 6 inch dry snow drifts over compacted snow
- The snow banks just off the runway edges was averaging 24 inches high
- Operations vehicle experienced noticeably reduced braking action and directional control and no downgrade in condition was recommended.

DEN RWY 35L 3/3/3 FIRST 7000 FEET 50% COMPACTED SNOW 60 FEET WIDE REMAINDER 100% 2 INCH DRY SNOW OVER COMPACTED SNOW LAST 5000 FEET 75% 4 INCH DRY SNOW 10% 6 INCH DRY SNOW 24 IN SNOWBANKS 1200Z 20 JAN 2009

RATIONALE

- Contaminant terms were harmonized to the maximum extent possible with ICAO. The few differences are due to the ARC’s desire to limit terms to those for which manufactures can provide performance data. Runway surface descriptions such as SMOOTH, GROOVED and PFC were added to WET conditions to allow manufactures to gain improved performance capability when providing such data (as a few currently provide). This descriptor technique made also made it easier to deal with and report when the SLIPPERY condition exists.

- The contaminant coverage threshold of 25% for the total runway (or less with a reported width) for when runway condition codes are to be reported mirrors guidance in existing AC 91-6A (and draft B) for when takeoff performance penalties apply. The issuance of runway condition codes is the signal for pilots to use appropriate non dry landing data. Additionally this threshold was reviewed and recommended by the manufacture performance engineering team represented in the ARC. To prevent a small ice puddle or other minor situation from causing a runway third to be coded slicker than reasonable, the minimum threshold of 10% was established and each runway third should be coded with the slickest condition exceeding this 10% threshold.

- The recommended percent coverage thresholds (e.g., 10%, 25% etc) were designed to provide a reasonable idea of what a pilot can expect without causing unnecessary complication. The smaller 10% threshold provides a means for airports to convey a minor contaminant issue (e.g., a few low spots trapped water and froze) without giving the impression the runway is worse than it is. The 25% or less option conveniently hits just shy of the threshold requiring the reporting of runway condition codes. Vague terms such as PATCHY were eliminated.

- The measurement increments recommended for depth reporting (e.g., 1/8", 1/4" etc) are aligned to correlate with changes in both takeoff and landing performance issues. Vague adjectives such as THIN or TRACE were eliminated.

- Runway condition codes are to be issued per the definitions provided in the Paved Runway Condition Assessment Table. However, because it is occasionally possible for metrological conditions to cause the correlated stopping performance to be less than expected the ability to allow for intervention and a downgraded code must be possible. Code downgrades may be accomplished manually or automatically if reasonable logic constraints are designed and incorporated in the data capture process. Downgraded runway condition codes assessments should be based on all available observations to include Mu, PRIRPs, operations vehicle controllability issues or simply the judgment of the observer. Conversely, for safety reasons it is not desired to allow airport personnel to upgrade a runway condition report from what is defined in the table.

- To prevent confusion and provide ease of understanding runway condition NOTAMs should only report the runway numbers directionally according to the direction of takeoff and landing (e.g., RWY 35). There is no desire to include the word OPEN in the NOTAM. The act of providing a runway condition NOTAM means the runway is open. Closed runways are to be NOTAMed as CLOSED with no condition provided. The runway condition codes were placed in the leading part of the NOTAM to make it easy to scan the list of runways and locate an acceptable runway option.
- It is highly desirable to organize all runway, taxiway and ramp condition NOTAMs by type, together in a single section of the airports NOTAM report (e.g., an airfield condition section).

APPENDIX A – TRAINING ISSUES

Specific needs for Airport Operators' Guidance Identified by the W.G.:

> Clear guidance is needed on the process of when and by how much to downgrade a runway condition code.
>
> Guidance is needed on the frequency with which NOTAMs must be reissued during changing conditions.
>
> Guidance is needed on developing codes for the reported center section vs the edges or the "remainder" of runways.
>
> Guidance is needed on reporting the surface temperatures, differentiating between the use of the average of multiple imbedded runway surface temperature reporting devices ("pucks") and infrared temperature measurements of the surface of any contaminants that may be present.

Specific Needs for Pilots' Guidance Identified by the W.G.:

> General guidance must be developed for pilot training in the use of the matrix – both how to interpret it via their airplane performance data and how to report braking action PIREPs which are consistent with the airplane handling characteristics described in the matrix. Particular emphasis should be placed on the difficulty of interpreting the intermediate braking action categories of "good to medium" and "medium to poor".

APPENDIX B – GUIDANCE DOCUMENTS REQUIRING HARMONIZATION

Amend 150-5200-30, “Winter Safety and Operations” to include contaminant description and braking action portions of the runway safety matrix and to eventually include the entire matrix and associated methodology, to clarify the appropriate method of returning a runway to service after a closing due to “nil” braking reports, to define runway condition assessments, to establish a frequency for conducting runway condition assessments, to place proper emphasis on the use of friction measurement equipment (Mu) to assess runway conditions and to address other inconsistencies the working group has identified.

Amend NOTAM AC 150/5200-28 and Order 7930.2 to reflect changes in matrix (patchy, thin, trace vs. contaminant % coverage, depth, etc).

Amend AC 150/5320-12, “Measurement, Construction, And Maintenance of Skid Resistant Airport Pavement Surfaces”, for consistency with matrix (establish threshold minimum friction value for matrix entry).

Amend AC 150/5200-18 “Airport Safety Self Inspection” to correlate snow and ice section with winter operations AC.

Amend training programs for airport operators, airplane operators, FAA personnel (Order 7110.65, 7110.10, etc.). Harmonize ATC and Airports procedures.

Amend AC 150/5235-4, “Runway Length Requirements for Airport Design” to include 15% safety margin for Snow Belt airports.

Amend the AIP handbook to establish eligibility for runway extensions needed to meet the 15% safety margin.

Amend AC 91-6A, “Water, Slush and Snow on Runway” to be consistent with Winter Operations AC and TALPA recommendations.

TALPA ARC MATRIX PROPOSED REVISION 2010-11

Airport Runway Condition Assessment				Pilot Reports (PIREPs) Provided To ATC And Flight Dispatch
Assessment Criteria		*1.1.1.1.1Downgrade* Assessment Criteria		
Code	**Runway Condition Description**	**Mu (μ)** [1]	**Deceleration And Directional Control Observation**	**PIREP**
6	• Dry		-	Dry
5	• Wet (Includes water 1/8" or less and Damp) ***1/8" or less depth of:*** • Slush • Dry Snow • Wet Snow	40 or Higher	Braking deceleration is normal for the wheel braking effort applied. Directional control is normal.	Good
4	• Frost ***-15ºC and Colder outside air temperature:*** • Compacted Snow	39 to 30	Brake deceleration and controllability is between Good and Medium.	Good to Medium
3	• Wet ("Slippery when wet" runway) • Dry Snow or Wet Snow (Any Depth) over Compacted Snow ***Greater than 1/8" depth of:*** • Dry Snow • Wet Snow ***Warmer than -15ºC outside air temperature:*** • Compacted Snow	29 to 21	Braking deceleration is noticeably reduced for the wheel braking effort applied. Directional control may be noticeably reduced.	Medium
2	***Greater than 1/8" depth of:*** • Water • Slush		Brake deceleration and controllability is between Medium and Poor. Potential for hydroplaning exists.	Medium to Poor
1	• Ice [2]	20 or Lower	Braking deceleration is significantly reduced for the wheel braking effort applied. Directional control may be significantly reduced.	Poor
0	• Wet Ice [2] • Water on top of Compacted Snow [2] • Dry Snow or Wet Snow over Ice [2]		Braking deceleration is minimal to non-existent for the wheel braking effort applied. Directional control may be uncertain.	Nil

[1] *The correlation of the Mu (μ) values with runway conditions and condition codes in the Matrix are only approximate ranges for a generic friction measuring device* ***and are intended to be used only to downgrade a runway condition code.*** *Airport operators should use their best judgment when*

using friction measuring devices for downgrade assessments, including their experience with the specific measuring devices used.

[2] *In some circumstances, these runway surface conditions may not be as slippery as the runway condition code assigned by the Matrix. The airport operator may issue a higher runway condition code (but no higher than code **3**) if Mu values greater than 40 are obtained on all three thirds of the runway by a properly operated and calibrated friction measuring device **and all other observations, judgment, and vehicle braking action support the higher runway condition code. The decision to issue a higher runway condition code than would be called for by the Matrix cannot be based on Mu values alone; all available means of assessing runway slipperiness must be used and must support the higher runway condition code.** This ability to raise the reported runway condition code to a code 3 can only be applied to those runway conditions listed under code 0 and 1 in the Matrix.*

The airport operator must also continually monitor the runway surface as long as the higher code is in effect to ensure that the runway surface condition does not deteriorate below the assigned code. The extent of monitoring must consider all variables that may affect the runway surface condition, including any precipitation conditions, changing temperatures, effects of wind, frequency of runway use, and type of aircraft using the runway. If sand or other approved runway treatments are used to satisfy the requirements for issuing this higher runway condition code, the continued monitoring program must confirm continued effectiveness of the treatment.

> ***Caution: Temperatures near and above freezing (e.g., at -3°C and warmer) may cause contaminants to behave more slippery than indicated by the runway condition code given in the Matrix. At these temperatures, airport operators should exercise a heightened level of runway assessment, and should downgrade the runway condition code if appropriate**.*

Definitions

Dry runway. For airplane performance purposes and use of this Matrix, a runway can be considered dry when no more than 25 percent of the runway surface area within the reported length and the width being used is covered by:

1. Visible moisture or dampness, or
2. Frost, slush, snow (dry or wet), ice, or compacted snow.

Wet runway. For airplane performance purposes and use of this Matrix, a runway is considered wet when more than 25 percent of the runway surface area within the reported length and the width being used is covered by any visible dampness or any water up to 1/8-inch (3 mm) deep.

Contaminated runway. For airplane performance purposes and use of this Matrix, a runway is considered contaminated when more than 25 percent of the runway surface area within the reported length and the width being used is covered by any depth of slush, ice, snow (dry or wet), or frost, or by water more than 1/8-inch (3 mm) deep. Definitions for each of these runway contaminants are provided below:

> **Dry snow.** Snow that can be blown if loose, or that will not stick together to form a snowball using gloved hands.

Wet snow. Snow that contains enough water content to be able to make a well-compacted, solid snowball, but water will not squeeze out.

Slush. Snow that is so water saturated that water will drain from it when a handful is picked up. Slush will splatter if stepped on forcefully.

Compacted snow. Snow that has been compressed into a solid mass such that the airplane tires, at operating pressures and loadings, will run on the surface without significant further compaction or rutting of the surface. Compacted snow may include a mixture of snow and embedded ice; if it is more ice than compacted snow, then it should be reported as either ice or wet ice, as applicable. A layer of compacted snow over ice should be reported as compacted snow.

Frost. Frost consists of ice crystals formed from airborne moisture that condenses on a surface whose temperature is below freezing. Frost differs from ice in that the frost crystals grow independently and therefore have a more granular texture. Heavy frost that has noticeable depth may have friction qualities similar to ice and downgrading the runway condition code accordingly should be considered. If driving a vehicle over the frost does not result in tire tracks down to bare pavement, the frost should be considered to have sufficient depth to consider a downgrade of the runway condition code.

Water. Water in a liquid state.

Ice. Frozen water.

Wet ice. Ice with a layer of water on top of it or ice that is melting.

Slippery when wet runway. A runway where a friction survey, conducted for pavement evaluation/friction deterioration per Advisory Circular 150/5320-12C (or later revision), shows that more than 25 percent of the runway length does not meet the minimum friction level classification specified in Table 3-2 of that AC. The airport operator should assign and report a runway condition code of 3 for all applicable thirds of the runway when wet under this condition. If less than 25 percent of the runway fails the friction evaluation, the airport operator should report runway condition codes of 5 for the applicable runway thirds when the runway is wet, and report the deteriorated condition of the runway through the normal airport NOTAM system.

Braking Action	Current Boeing Airplane Braking Coefficient Used in the QRH Performance Data	Approximate Equivalent Airplane Coefficient based on TALPA ARC Recommendations
Good	0.20	0.18 – 0.22*
Medium	0.10	0.13 – 0.15 (depending on airplane)
Poor	0.05	0.06 – 0.07 (depending on airplane)

*Equivalent to wet runway performance as defined in FAR 25.109, approximately equivalent to a constant airplane braking coefficient of 0.18 – 0.22.

Appendix Z is the “NTSB staff” comments to the AIBN draft report. The only products listed as from the “NTSB” are the Board’s final reports and recommendations, which have gone through the process of being voted on by the 5 members of the government Board.

National Transportation Safety Board
Washington, D.C. 20594
Office of Aviation Safety

October 27, 2010

Mr. Roger Holm
Accident Investigation Board Norway
Sophie Radichsvei 17
2003 Lillestrøm
Norway

Dear Mr. Holm:

The NTSB appreciates the opportunity to examine and comment on the draft of the AIBN report *Winter Operations, Friction Measurements, and Conditions for Friction Predictions.* This report was forwarded to me to review and provide comments, based on my experience and familiarity with the subject area from several past Safety Board investigations of incidents and accidents involving contaminated runway landings, and my comments on behalf of the Safety Board are contained below.

The report details 30 accident and incidents experienced in Norway related to slippery runway conditions in the 10 year period from 1999 – 2009, and as a result of the incidents and accident the AIBN has issued 36 safety recommendations. However, as detailed in the report, the accidents and incidents continue to occur. This extensive and comprehensive report focuses on the general framework and commonalities of the winter operations on contaminated and slippery runways in Norway. The report provides an excellent compilation of the various methods and assumptions used in braking action reports, friction measurements, correlation of friction measurements with airplane braking coefficients, applicability of measurements and braking reports between airplane types, crosswind conditions, and use of reverse thrust in landing calculations and guidelines for winter operations for different airframe manufacturers.

The NTSB shares many of the same AIBN concerns detailed in the report regarding inconsistencies amongst the various guidelines provided by manufacturers and lack of requirements for manufacturers to provide validated stopping distances on contaminated runways. Based on the SouthWest Airlines runway excursion accident in Chicago, IL, the NTSB recommended that landing distance assessments be performed by flight crews en-route based on the best available runway condition information, accurate landing distance information being provided to flightcrews in their AFM, information on the assumptions used to develop the landing distances (speeds, air-distance, reverse thrust, etc.), and issued the following safety recommendations[1] to the FAA:

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[1] See complete details in the accident final report *NTSB AAR-07/06, Runway Overrun and Collision, Southwest Airlines Flight 1248, Boeing 737-7H4, N471WN, Chicago Midway International Airport, Chicago, Illinois, December 8, 2005.*

A-07-058 (Currently Open-Acceptable response):
The National Transportation Safety Board recommends that the Federal Aviation Administration: Require all 14 Code of Federal Regulations Part 121 and 135 operators to ensure that all on board electronic computing devices they use automatically and clearly display critical performance calculation assumptions.

A-07-059 (Currently Open-Acceptable response):
The National Transportation Safety Board recommends that the Federal Aviation Administration: Require all 14 Code of Federal Regulations Part 121 and 135 operators to provide clear guidance and training to pilots and dispatchers regarding company policy on surface condition and braking action reports and the assumptions affecting landing distance/stopping margin calculations, to include use of airplane ground deceleration devices, wind conditions and limits, air distance, and safety margins.

A-07 -061 (Currently Open-Acceptable response):
The National Transportation Safety Board recommends that the Federal Aviation Administration: Require all 14 Code of Federal Regulations Part 121, 135, and 91 subpart K operators to accomplish arrival landing distance assessments before every landing based on a standardized methodology involving approved performance data, actual arrival conditions, a means of correlating the airplane's braking ability with runway surface conditions using the most conservative interpretation available, and including a minimum safety margin of 15 percent.

A-07 -062 (Currently Open-Acceptable response):
The National Transportation Safety Board recommends that the Federal Aviation Administration: Develop and issue formal guidance regarding standards and guidelines for the development, delivery, and interpretation of runway surface condition reports.

A-07 -063 (Currently Open-Acceptable response):
The National Transportation Safety Board recommends that the Federal Aviation Administration: Establish a minimum standard for 14 Code of Federal Regulations Part 121 and 135 operators to use in correlating an airplane's braking ability to braking action reports and runway contaminant type and depth reports for runway surface conditions worse than bare and dry.

A-07-057 (Currently Open-Unacceptable response):
The National Transportation Safety Board recommends that the Federal Aviation Administration: Immediately require all 14 Code of Federal Regulations Part 121, 135, and 91 subpart K operators to conduct arrival landing distance assessments before every landing based on existing performance data, actual conditions, and incorporating a minimum safety margin of 15 percent. (Urgent)

During the Public Hearing for this accident[2], the NTSB had several witnesses from the research and operational communities detail the inconsistencies in runway measurement techniques, and the lack of any verifiable correlation to airplane braking coefficient, echoing the concern expressed in the AIBN's report.

Many of the concerns expressed in the NTSB's report on that accident are echoed in this comprehensive report examining these 30 incidents in Norway. Based on the Safety Board's work during and since that accident investigation, the Safety Board supports the conclusions presented in the draft report regarding the inconsistencies and weak correlation of contaminated runway friction measurements to airplane braking coefficients. The NTSB firmly supports the publication of this report in its entirety, for the factual data, analysis and conclusions detail the current regulatory and operational factors that act to reduce the safety margins when operating on contaminated and slippery runways. This compilation will provide the various regulatory agencies a comprehensive framework for further research and regulation development to increase the safety margins for winter operations. The Safety Board appreciates the opportunity to review and comment on this report.

Grammatical comments:

Page 112, 3rd paragraph: Change "FAFO" to "SAFO"
Page 112, last paragraph: Change "1.9 G" to ".19 G"
Page 112, last sentence: Change "together 1.0 G" to "together 0.1 G"

Regards,

Daniel R. Bower, Ph.D.
Senior Aviation Accident Investigator

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[2] The transcript for the Public Hearing on the SouthWest Airlines accident are available in the Public Docket on our website at http://www.ntsb.gov.