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THE PREPARATION OF THIS DATA ITEM

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CALCULATION OF GROUND PERFORMANCE IN TAKE-OFF AND LANDING

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CALCULATION OF GROUND PERFORMANCE IN TAKE-OFF AND LANDING

1. NOTATION AND UNITS

		SI	British
F_N	net thrust of turbo-jet or turbo-fan engine	N	lbf
g	acceleration due to gravity	m/s ²	ft/s ²
H^Σ	resultant angular momentum	kg m ² /s	slug ft ² /s
$I_x; I_y; I_z$	moments of inertia with respect to x-axis; y-axis; z-axis	kg m ²	slug ft ²
$I_{xy}; I_{yz}; I_{zx}$	products of inertia with respect to x- and y-axes; y- and z-axes; z- and x-axes	kg m ²	slug ft ²
$J_x; J_y; J_z$	components of angular momentum of rotating parts of aircraft or engines about x-axis; y-axis; z-axis	kg m ² /s	slug ft ² /s
L	rolling moment	N m	lbf ft
M^Σ	resultant moment	N m	lbf ft
M	pitching moment	N m	lbf ft
m	mass	kg	slug
N	yawing moment	N m	lbf ft
$p; q; r$	angular velocity components about x-axis (rate of roll); y-axis (rate of pitch); z-axis (rate of yaw)	rad/s	rad/s
R^Σ	resultant external force	N	lbf
s	ground run distance	m	ft
t	time	s	s
$u_K; v_K; w_K$	components of V_K in x-direction; y-direction; z-direction	m/s	ft/s
V	air-path velocity (true airspeed or resultant velocity with respect to air)	m/s	ft/s
V_{EF}	engine failure speed	m/s	ft/s
V_K	flight path velocity (resultant velocity with respect to Earth)	m/s	ft/s
V_{LOF}	lift-off speed	m/s	ft/s
V_{MBE}	maximum brake energy speed	m/s	ft/s
V_{MC}	minimum control speed (in the air)	m/s	ft/s
V_{MCG}	minimum control speed on the ground	m/s	ft/s
$V_{MCL}, V_{MCL-1}, V_{MCL-2}$	minimum control speeds in landing approach	m/s	ft/s

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V_{MU}	minimum unstick speed	m/s	ft/s
V_{NWLO}	nose-wheel lift-off speed	m/s	ft/s
V_R	rotation speed	m/s	ft/s
V_S	stall speed	m/s	ft/s
V_{screen}	screen speed for landing	m/s	ft/s
V_{TD}	touch-down speed	m/s	ft/s
V_W	wind speed	m/s	ft/s
V_1	take-off decision speed	m/s	ft/s
V_2	take-off safety speed	m/s	ft/s
$X^\Sigma; Y^\Sigma; Z^\Sigma$	components of R^Σ in x-direction; y-direction; z-direction	N	lbf
$x; y; z$	body-axes co-ordinates in x-direction; y-direction; z-direction	m	ft
$\Delta t_{a_1}, \Delta t_{a_2}$	demonstrated time intervals between successive activations of deceleration devices, see Sketch 3.1	s	s
Δt_{rec}	demonstrated engine-failure recognition time, see Sketch 3.1	s	s

2. INTRODUCTION

This Item deals with all aspects of aircraft ground performance and gives a guide to topics which are common to take-off, accelerate-stop and landing. No particular emphasis is given to the class of aircraft, powerplant, surface or type of operation. A very wide range of technical and operational aspects of ground-performance is considered and the implications of the various airworthiness and operating requirements are included.

The Item has the following detailed objectives.

- To give guidance regarding the forces and moments to be considered for the widest-possible range of ground performance calculations.
- To provide a common background to the ground-performance aspects of Data Items giving examples of field-performance calculation methods, as follows.

Data Item No. 87018 (Reference 48), "Example of take-off field length calculations for a civil transport aeroplane".

Data Item No. 87037 (Reference 49), "Take-off performance of vectored-jet-thrust V/STOL aircraft".

- To provide numerical information for topics not considered elsewhere in the Performance Series.
- To direct the user to sources of detailed information relevant to ground performance given in ESDU Performance, Aerodynamics and Wind Engineering Series.

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3. PRACTICAL ASPECTS OF AIRCRAFT GROUND PERFORMANCE CALCULATIONS

The primary objectives of ground-performance calculations are to find the distance and time taken to accelerate to, or decelerate from, a speed, and to rotate to, or de-rotate from, flight attitudes, for specified aircraft and powerplant configurations and runway surface and atmospheric conditions. The need to consider the possibility of engine failure, and other emergencies during take-off or landing, requires calculation of special cases such as the “accelerate-stop” (or “abandoned”, or “aborted”, or “rejected” take-off) and investigation of the defining manoeuvres for minimum control speeds.

3.1 Scheduled Performance Data

Most aspects of take-off and landing performance are governed by the various civil and military airworthiness requirements and operating regulations, see References 1 to 10. In civil air transport, the term **“scheduled performance data”** denotes the minimum performance standard to which an aircraft may be operated. These data are presented in the aircraft’s **“flight manual”**, must be used in conjunction with the appropriate operating regulations and are legally enforceable to extents that differ between countries. If an aircraft type is certificated in several countries, the manufacturer may have to provide several sets of scheduled data to ensure compliance with the different national airworthiness and operational codes. One effect of the various codes is to introduce different limitations on the range of design features, assumed operating techniques and calculation methods for which the manufacturer may be allowed to take **“performance credit”** when preparing the scheduled data.

To meet the various certification requirements the aircraft manufacturer must demonstrate the ability to calculate the actual aircraft performance reliably. Typically, for a large transport or major combat aircraft, this requires the verification by “flight” tests of a detailed mathematical model of all phases of take-off and landing performance. For this purpose the equation(s) of motion are integrated numerically using “step-by-step” methods while incorporating the relevant forces and moments in such a way as truly to represent the approved techniques. Once verified, this model is used to generate scheduled data.

For smaller aircraft, or cases where only limited amounts of scheduled data are required, it may be acceptable either

- (i) to conduct tests at or near the extreme operating conditions and weights and use relatively simple theoretical or parametric methods to “reduce” and interpolate the results, (see Reference 43), or
- (ii) to test over a more limited range of conditions than (i) and use simple but conservative methods to extrapolate the data to other conditions and weights.

Flight tests are required to demonstrate and validate all critical aspects of aircraft handling and controllability associated with take-off and landing but such well-established effects as headwinds and runway gradients may be determined by calculation alone.

3.2 Calculation of Ground Run in Segments

All but the simplest estimation methods (see References 44 to 46) divide the take-off or landing into segments, within each of which the aircraft configuration is essentially constant. For each segment the resultant aircraft acceleration(s) are estimated so that the distance travelled, speed reached and time taken may be obtained by integration. For some segments, especially those of short duration, mean values based on initial and final conditions may suffice. However, when this is done, the calculated distance is in error if the actual variation of acceleration in the segment is non-linear; if, in addition, the acceleration is near zero for part of the segment, this error can become large.

The beginnings and ends of the various segments correspond closely to the major control inputs and associated speeds and/or the manual or automatic activation of retardation devices. Each such “event” might be represented in the calculation method by a realistic time for pilot reaction or equipment actuation coupled with appropriate rates of change of forces. Alternatively, these times might be used in conjunction with step changes in the forces, provided the overall effect is conservative. An example of the former approach is the modelling of the complete take-off rotation as a single segment. In contrast, the landing de-rotation and ground run might be represented by segments defined only by the times from touchdown to deployment of lift spoilers, effective operation of wheel brakes, *etc.*, with step changes in retarding forces assumed to act at the ends of each interval or at some agreed, mean times. In the calculation of operational data, time delays are introduced between successive pilot actions to allow for the range of likely pilot reaction times to an engine failure or other unscheduled event.

3.3 Speeds Affecting Ground Performance

The usual method of scheduling take-off and landing performance is to identify to the pilot the (indicated) airspeeds at which particular actions are taken. The corresponding true speeds must be used in calculations and in many cases these coincide with changes from one segment to another in the calculation method. The various speeds are discussed in Sections 3.3.1 to 3.3.3.

3.3.1 Limiting speeds for aircraft components and equipment

Operating speed limits on components and equipment (usually maxima, but occasionally minima) affect the retardation forces available and can limit the scheduled speeds for aircraft operations. These speeds are essentially under the control of the aircraft manufacturer.

Tyres: An upper limit to true ground speed in any ground operation is imposed by the maximum permitted tyre speed. This tyre “critical” speed is established from the tyre manufacturers’ dynamometer tests so as to avoid tread separation and to permit only brief periods of operation during which tread instability (standing waves) is present. The speed is associated with the onset of a rapid increase of heat generation within the tread and carcass.

Brake energy limit: Each brake unit is rated according to the energy it may absorb. Separate ratings are assigned to cover “normal” (landing) and “maximum” or “rejected take-off” cases and it is usual for the latter to be associated with some acceptable level of damage – see Reference 101. The total “installed” brake energy capacity imposes upper limits on the combinations of aircraft mass and brake application speed or “maximum brake energy speed”, V_{MBE} , (defined in terms of true ground speed). On some military aircraft this occasionally results in a significant interval between touchdown and brake application, while for civil aircraft it may impose an upper limit on V_1 .

Brake torque limit: The maximum available brake torque imposes an upper limit on the achievable wheel braking force – regardless of wheel normal load and tyre-ground coefficient of friction. The lower the available torque, the higher is the forward speed at which the brakes become “torque limited” during any braked ground run (see Reference 101).

Powerplants: Use of reverse thrust is limited to speeds in excess of that at which exhaust gases and/or debris are liable to be ingested into the intake – see Section 6.3. Similar considerations apply to the use of vectored thrust. In addition, for STOL aircraft, any thrust vectoring is likely to be scheduled on a speed basis to achieve an optimum combination of powerplant and wing lift while minimum-speed restrictions may be imposed from ground erosion considerations.

Braking Parachutes: Upper speed limit (equivalent airspeed) is likely from considerations of aircraft structural damage or controllability or to avoid canopy “squidding” (see Section 7.2). A different cross-wind limit from that applicable to other operations is likely to apply to landings with a braking parachute.

3.3.2 Limiting aerodynamic speeds for take-off and landing

The various airworthiness requirements define speeds which limit the manner in which an aircraft may be operated in take-off and landing. These speeds are defined in terms of calibrated airspeed and on the basis of aircraft aerodynamic and control considerations. Tables 13.1 and 13.2 list and define the speeds appropriate to civil transport aeroplanes (References 1, 2, 5) and describe how they relate to one another – although many of the terms used have wider applications. The “nose-wheel lift-off speed” is included in Table 13.1 because of its implications for c.g. position. For precise definitions and associated numerical factors the user should consult References 1 to 9. Some of these speeds are part of the scheduled data in the aircraft’s flight manual so that values must be presented in a form consistent with the flight-deck instrumentation, *i.e.*, in the case of a pressure-sensing airspeed indicator, as indicated airspeeds.

3.3.3 Optimised speeds for take-off

Most of the “component and equipment” limiting speeds in Section 3.3.1 are maximum values and lower values are used as required. For some of the “limiting aerodynamic” speeds in Table 13.1 there is a unique value for a given aircraft configuration, weight and c.g. position. For others a particular value may be the minimum permissible for the given aircraft configuration, weight and c.g. position and higher values may be used, particularly in optimising take-off performance – provided that the speed limits in Section 3.3.1 are not infringed. For example, to maximise aircraft weight for a particular flap setting and a given runway length, it may be advantageous to use an “overspeed” take-off with $V_2 > (V_2)_{min}$ so as to satisfy the take-off climb requirements. Ideally, the optimum is attained with a combination of weight and speeds (V_1 , V_R , V_2) so that the field length and either obstacle or “WAT” climb limits are just satisfied concurrently. In practice it is usual to obtain a close approximation to this.

3.4 Take-off Ground Run

The take-off ground run traditionally begins at brakes-release or when powerplant thrust exceeds maximum static braking force. However, for civil-transport operations “rolling starts” are used extensively – commencing on the runway or from the adjacent taxi-way. Typically, such take-offs begin at a relatively low power setting, *e.g.* a fan speed of about 40% of maximum. Development of the expected take-off thrust must be confirmed subsequently (at between 50 to 80 knots) for the take-off to proceed. Rolling take-offs offer several benefits – particularly when contrasted with attempts to “hold maximum thrust on the brakes” – as follows,

- avoidance of excessive undercarriage structural loads and airframe flexing (and consequent passenger discomfort),
- avoidance of engine surge – especially in crosswinds,
- avoidance of engine damage due to ingestion of runway debris,
- avoidance of longitudinal control problems such as nose wheel lift-off at high power settings and low forward speeds,
- avoidance of directional control problems on wet or contaminated runways, especially in crosswinds.

Investigations of take-off performance, including effects of thrust build-up, may be required to demonstrate that the correction for rolling take-offs on achieved take-off performance is small.

The ground run ends when the aircraft lifts off the runway or water surface at V_{LOF} , having begun the take-off rotation a few seconds earlier at the rotation speed, V_R (see Table 13.1 for speed definitions). For conventional land planes V_R is chosen to satisfy the criteria listed in Table 13.1. Average rotation rates for large transport aircraft are about 3 deg/s, although higher values are used by some transports, some combat types and STOL aircraft. Data Item No. 87018 (Reference 48) provides examples of more detailed pitch-rotation schedules.

The use of excessively high rotation rates can in some instances lead to a risk of ground impact by the aft end of the aircraft or nacelles or of exceeding the target angle of attack at take-off. The latter effect is accentuated if there is a large change in pitching moment between “ground” and “free-air” conditions as, for example, may occur when vectored thrust is used. High rotation rates imply large tailplane down loads and these can lead to excessive peaks in the normal loads imposed on the tyres of the main undercarriage during rotation.

In the case of a continued take-off following an engine failure at speed V_{EF} , both the loss of thrust and any consequent increases in drag must be allowed for, see Sections 6.4 and 7. A conservative approach is to assume that all thrust on the failed engine is lost instantaneously at V_{EF} , although other methods may be acceptable.

For civil transport aircraft a **take-off run** is defined which, in the specific case where a “clearway” is available at and beyond the end of the runway, may determine the maximum take-off weight for the available runway length. That take-off run is made up of the actual ground run plus half[†] the airborne distance from lift-off to the screen and is factored by 1.15 in the all-engines-operating case. No factor is applied in the engine-failed case (examples are given in Data Item No. 87018 (Reference 48)).

3.5 Landing Ground Run

The landing ground run commences at touch-down and includes the subsequent “de-rotation” and deceleration until the aircraft stops or reaches some arbitrary low speed (Reference 5 quotes 3 kn for landings on water). For performance calculations the landing impact and absorption of kinetic energy associated with the aircraft’s vertical velocity is assumed to take place without affecting aircraft retardation. Table 13.1 includes definitions of the various aerodynamic speeds relevant to landing ground run calculations. Table 13.6 gives values of touch-down speed relative to screen speed from certification tests.

Section 3.6 discusses deceleration techniques in general terms, while descriptions of the various means of retardation are given in Sections 6, 7 and 9. References 46 and 47 contain information on the deceleration levels achieved once “effective” braking has been established – these data correspond to the flight manual scheduled performance of a wide range of transport aeroplanes. For the period from main wheels touch-down until “effective” braking is established, Table 13.4 gives typical values of times taken while Figure 1 gives guidance on the likely levels of deceleration.

[†] Reference 6 (now superseded by Reference 5 for new designs) uses a different definition of the scheduled take-off run.

3.6 Deceleration Techniques

Deceleration techniques during a landing or an accelerate-stop depend on the aircraft characteristics, on the means of deceleration used and on the friction properties of the runway surface – see References 1 to 8 for civil requirements (or Reference 46 for a brief summary). For most aeroplanes, wheel braking is the most effective means of deceleration and the shortest stopping distances are achieved when as much weight as possible is transferred to the braked wheels and the brakes applied at the earliest possible moment. Retardation from wheel brakes depends largely on the normal (to runway) loads carried by the braked wheels, the available tyre-runway coefficient of friction and the efficiency of the anti-skid system. It may be limited by the maximum brake torque and further reduced as energy is absorbed. However, even for wet or icy-runway conditions, wheel braking is usually preferable to the use of maximum aerodynamic drag – see Section 7. The retardation produced by aerodynamic drag, including airbrakes and parachutes, decreases as speed is reduced and some variation with speed occurs with all forms of powerplant-generated retardation forces, see Section 6.

For landing, the use of retardation devices during de-rotation is acceptable, provided the nose wheel can be lowered in a controlled manner. If this option is not taken up, time must be allowed in calculations for aircraft de-rotation in addition to the times for successive activations of lift spoilers, wheel braking, reverse thrust *etc.* – see Table 13.3.

3.6.1 Automatic activation of retardation devices

Modern aeroplanes make considerable use of automatic lift spoilers and/or wheel braking and, to a lesser extent, of automatic deployment of flaps to a final high-drag, lift-dump setting so that significant retardation forces can be achieved prior to nose wheel touch-down.

For landing, these systems may be brought into operation at touch-down by wheel(s) spin up, undercarriage leg compression, bogie tilt or by combinations of these. During an accelerate-stop the selection of reverse thrust may also activate spoilers and/or wheel brakes, although a faster response is likely if throttle closure is used for this purpose.

Automatic braking systems usually permit selection either of “maximum braking”, limited only by brake torque and energy and by anti-skid efficiency, or of lower fixed deceleration levels (the latter may result in reduced wheel braking effort when reverse thrust is applied). Data Item No. 92021 (Reference 50) provides examples of analysis of measured data for fixed auto-brake settings.

3.7 Accelerate-Stops

Consideration of accelerate-stops is a major part of the preparation of scheduled performance data for transport and many other types of aircraft. The decision to continue or abandon a take-off is made by the pilot on the basis of whether or not the aircraft is above or below the scheduled decision speed, V_1 , when the reason for having to make the choice is recognised. The scheduled decision speed is **applicable to any emergency** occurring during the take-off run which could seriously hazard a continued take-off. Different distances for the accelerate-stop result, depending on whether a powerplant failure occurs or all engines are operating throughout. The two cases are considered separately in Sections 3.7.1 and 3.7.2; the **scheduled accelerate-stop distance** is always the greater of these two and is unfactored. For all emergencies V_1 must be greater than V_{MCG} , and less than or equal to V_{MBE} and V_R (see Section 3.3.1 and Table 13.1 for speed definitions).

In scheduling accelerate-stop distances, the airworthiness requirements assume that decisions to abandon take-offs from speeds approaching V_1 are very rare (and so the distances may be unfactored). In practice, stopping performance is very variable, and there are significant increases in accelerate-stop distance if the

need for immediate and full retardation is not appreciated by the pilot(s), or if the acceleration up to that point has been less than normal, or if the available retardation is reduced, for example, by the state of the runway.

3.7.1 Accelerate-stop with a single engine failure

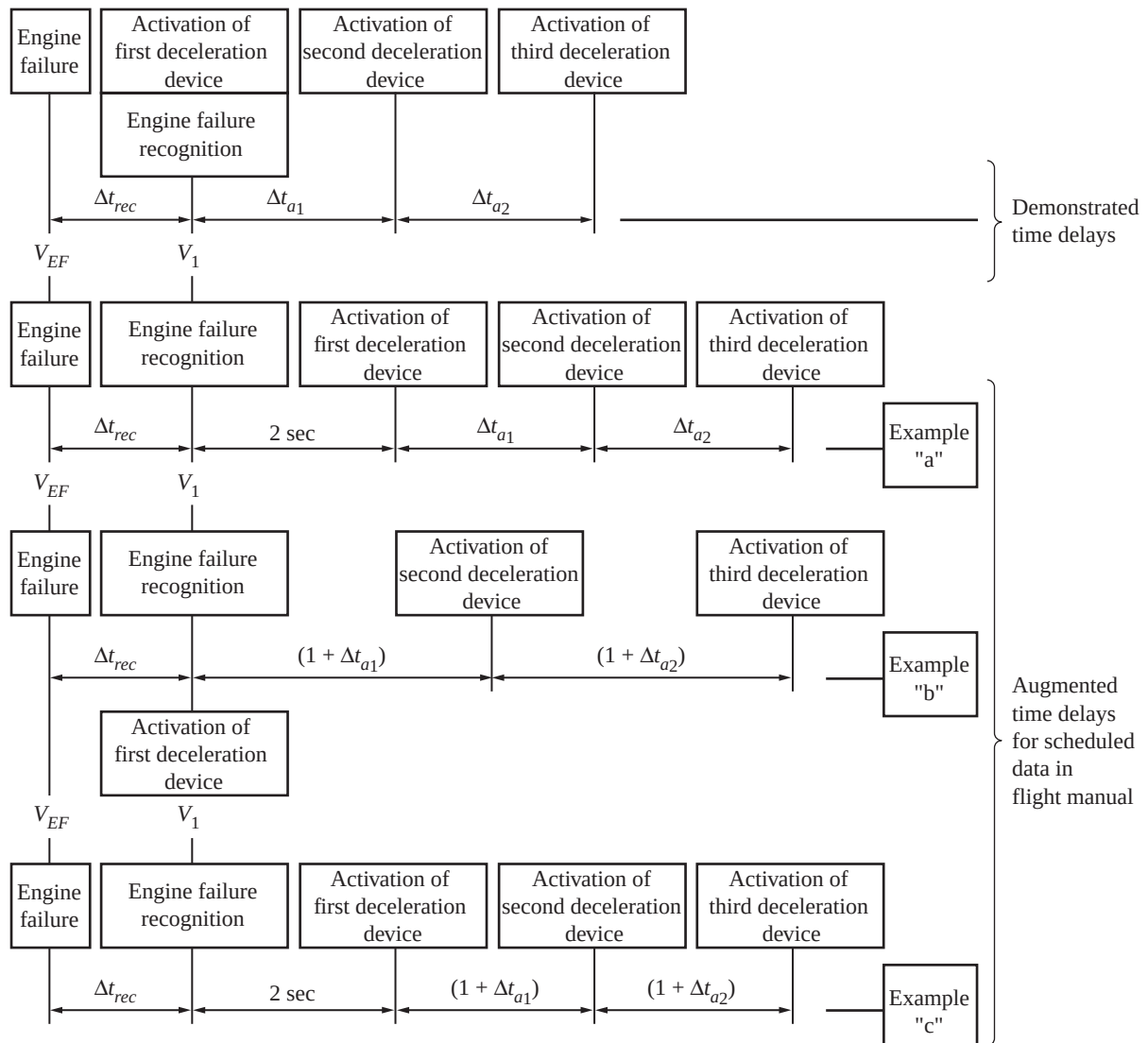
For the case of an accelerate-stop following an engine failure, values of the decision speed, V_1 , are defined on the basis that a powerplant fails at some lower, engine-failure speed, V_{EF} , and since $V_{EF} \geq V_{MCG}$, this further limits the range of possible values of V_1 . For civil certification of transport aircraft, the precise relationship between V_1 and V_{EF} is determined from “flight” tests as follows,

“ V_1 must not be less than V_{EF} plus the speed gained during the time interval between the instant at which the critical engine is failed, and the instant at which the test pilot recognises and reacts to the engine failure, as indicated by the pilot’s application of the first retarding means during accelerate-stop tests”.

This definition of V_1 is depicted in the upper portion of Sketch 3.1 which shows the sequence of “pilot-reaction” times demonstrated in a test where an engine is failed and the take-off abandoned. In Sketch 3.1 the value of Δt_{rec} defined by “flight” tests depends on the type of aircraft, the type of failure and the cues available to the pilot; in practice values of $\Delta t_{rec} < 1$ second are unlikely to be acceptable for certification. This part of the Sketch also includes demonstrated time delays, Δt_{a_1} and Δt_{a_2} , between successive activations of three deceleration devices.

The lower portion of Sketch 3.1 includes three examples, “a”, “b”, “c”, to show how the value of V_1 defined above may be incorporated into the scheduled flight-manual performance. Examples “a” and “b” each include a 2 second delay, allocated on the basis of 1 second for each of the measured values Δt_{a_1} and Δt_{a_2} . This additional delay is to allow for the spread of reaction times between pilots in actual operations; if appropriate, a further 1 second delay is added to the measured value of Δt_a for each succeeding deceleration device activated, in excess of three pilot actions. To some extent sequences “a” and “b” are used interchangeably – although small differences inevitably result in the calculated performance. (For certification of some older aircraft only the values of Δt_a may have been used and no distinction made between V_1 and a V_{EF} .) When a greater margin of conservatism is required in the calculated distances, this might be introduced by increasing the time allowed for pilot reaction – as illustrated by the further 2 seconds delay in Example “c” in Sketch 3.1.

The event labelled, “activation of first decelerating device” in Sketch 3.1 is likely to be either the cutting of power on the live engine(s) or the selection of wheel braking. In either case the thrust decay of the live engine(s) must be realistically modelled in calculations – see Section 6.4.1. Subsequent actions such as the selection of spoilers and reverse thrust depend on the aircraft and the certification requirements used; in any event the forward speed inevitably rises above V_1 before retardation is achieved.



Δt_a is the demonstrated time interval between activation of
 first and second deceleration devices (Δt_{a1})
 second and third deceleration devices (Δt_{a2}).

For each additional deceleration device (above three), a time interval equal to the measured Δt_a plus one second must be allowed for flight-manual calculations.

Sketch 3.1 Accelerate-stop delay times after engine failure

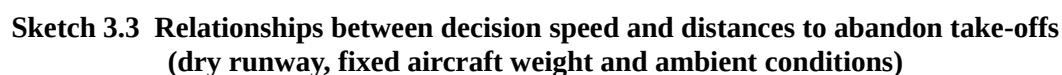
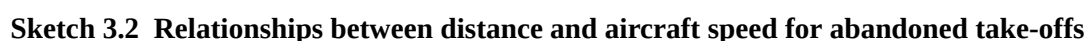
Examples of accelerate-stops following engine failure are shown as the broken lines in Sketches 3.2 and 3.3 (Data Item No. 87018 (Reference 48) gives further examples, in much greater detail). Sketch 3.2 shows the broad sequence of events as plots of runway distance travelled against aircraft true velocity, while Sketch 3.3 shows the variation of accelerate-stop distances for a range of values of decision speed (disregarding V_{MCG} and V_R limits). In practice both the absolute and relative magnitudes of these accelerate-stop distances vary considerably depending on:

- (i) aircraft weight,
- (ii) availability of, and cut-off speed, for reverse thrust,
- (iii) runway surface condition,
- (iv) availability of other means of retardation.

3.7.2 Accelerate-stop with all engines operating

Consideration of the accelerate-stop with all engines operating is included in the airworthiness requirements to take some account of emergencies other than engine failure in determining the minimum acceptable runway length. From the decision point and speed (again denoted V_1) the sequence of events is similar to that shown in Sketch 3.1 and described in Section 3.7.1, although with all engines operating the aircraft accelerates beyond V_1 to a considerably greater extent than in the engine-failed case. Examples of accelerate-stop performance with all engines operating are included as the solid lines in Sketches 3.2 and 3.3. (See Data Item No. 87018 (Reference 48) for further examples, in much greater detail).

As indicated in Section 3.7 a decision to abandon a take-off from speeds approaching V_1 must be the result of an emergency which could seriously hazard the continued take-off. For the all-engines-operating case the identification of such emergencies is left to the pilot. (Depending on particular circumstances these might include tyre failures, loss of forward vision or failure of the aircraft to maintain the configuration required for safe flight.)



3.8 Take-Off and Landing Certification on Wet and Contaminated Runways

3.8.1 Wet-runway accountability

No use is made of actual wet or otherwise contaminated runways in **performance tests** for take-off and landing certification of civil-transport aeroplanes although various proposals for such tests have been made. See Reference 5 or 6 for details of a now-disused technique for wet-runway testing and associated methods of scheduling landing and accelerate-stop performance. See References 126, 128 and 130 for examples of proposals.

Where “wet-runway accountability” is required for landing of current civil-transport aeroplanes, the scheduled field lengths are calculated in most cases as factored values of measured dry-runway landing distances (from 50 ft screen), see References 1 to 8 and see Reference 46 for a summary of factors used.

One approach to the calculation of stopping distances on wet runways is to use an assumed relationship between the effective coefficient of friction in wet and dry conditions, where the effective coefficient of friction is:

$$\mu_{eff} = \frac{\text{total retarding force on aircraft attributable to braked wheels}}{\text{total normal load on braked wheels}}.$$

In general, this would require tests to establish values of $(\mu_{eff})_{wet}/(\mu_{eff})_{dry}$ for an aircraft for a range of runway friction conditions. However, the approach has received a level of acceptance in the certification of accelerate-stop performance (Reference 5) with tests carried out on dry runways to validate the manufacturer’s mathematical model and wet-runway stopping distances calculated with values of $(\mu_{eff})_{wet}/(\mu_{eff})_{dry}$ which are agreed with the certification authority. One very simple method uses $(\mu_{eff})_{wet}/(\mu_{eff})_{dry} = 0.5$ although a preferable and less arbitrary approach includes the possibility of reduced values of $(\mu_{eff})_{wet}/(\mu_{eff})_{dry}$ at high forward speeds.

Another approach (see References 1 and 13) to the certification of accelerate-stop performance in wet conditions specifies the use of friction data taken from Data Item No. 71026 (Reference 102) combined with appropriate values of anti-skid system efficiency.

3.8.2 Contaminated runways

In civil aviation a “contaminated runway” is one that is covered in a relatively deep layer of water, slush, loose snow, ice or compacted snow.

The direct effects on aircraft performance of such contaminants are as follows.

- (i) Tyre-generated sprays from water- or slush-covered runways may be ingested by the engines – with consequent thrust loss or engine failure. Data Item No. 83042 (Reference 104) gives methods for predicting such sprays.
- (ii) Drag forces on tyres due to displacement and/or compression of water, slush or snow, see Section 9.6.1.
- (iii) Drag forces on the airframe due to impingement of water or slush sprays generated by the tyres, see Section 9.6.2
- (iv) Severely-reduced tyre-runway friction which affects both stopping performance and ground handling (the latter, especially, in crosswinds) see sections 9.3 and 9.5.

While the extent to which the “performance” effects of surface contaminants are considered depends on the particular certification authority, all aircraft expected to operate in such conditions must undergo tests to demonstrate the effect, if any, of tyre spray on the powerplants and other critical areas (*i.e.* item (i)).

To obtain certification to operate on contaminated runways, Reference 5 requires the scheduled performance data to take account of the effects of items (i) to (iv) above. If the drag forces identified as items (ii) and (iii) are not defined by suitable ground-run tests, estimated values may be used but are liable to substantial factoring. Reference 5 also imposes upper limits on

- contaminant depths for which take-off performance may be scheduled on the basis of estimated data only,
- the extent to which results from tests on water-covered surfaces may be extrapolated to greater depths of lower-density slush contaminant.

Besides considering the effects of contaminated surfaces on take-off distances, it may be necessary to provide information on the latest point for a decision to abandon a take-off and the earliest point for a decision to continue the take-off with one engine inoperative. For example, while Reference 5 allows credit to be taken for fluid-drag forces during the deceleration in an accelerate-stop, no such credit is allowed in calculating the scheduled landing performance.

Braking performance on contaminated runways is characterised by relatively low levels of runway coefficient of friction. In the past an effective coefficient of friction (for an aircraft) of 0.05 was often assumed. Other default values are given in Reference 5 while the methods of Data Item No. 05011 (Reference 114) are available for more precise systematic estimates.

3.9 Operational Aspects of Aircraft Performance on Wet and Contaminated Runways

There is wide recognition of a need to take more detailed account of adverse runway conditions in aircraft ground operations than is implied by the use of the scheduled performance data described in Section 3.8. However, to take account of “day-to-day” variations in conditions requires reasonably reliable methods for:

- (i) determination of actual runway conditions,
- (ii) transmission of information on runway conditions to the pilot – preferably using a standardised reporting system,
- (iii) interpretation of the information on runway conditions in terms of aircraft performance and/or pilot actions.

As in Section 3.8, the discussion is separated into methods applicable to wet runways (water less than 3mm deep) and methods applicable to contaminated runways.

3.9.1 Wet runways

To accomplish item (i) in Section 3.9, a number of runway friction measuring devices have been designed and built; many are described in Reference 11. Unfortunately, for the purposes of item (ii), each device operates with its own (usually small, low pressure) tyre and measures runway “friction” in a different way from all the others. Examples of friction parameters[†] measured by different machines are

- locked-wheel coefficient of friction,
- coefficient of friction at prescribed tyre “slip” conditions,
- maximum coefficient of friction at optimum tyre “slip” conditions,
- side force coefficient of friction for free rolling at prescribed tyre yaw angle.

Regarding item (iii) in Section 3.9, numerous tests of the various machines’ capabilities in predicting stopping performance of individual aircraft have been reported, see for example the References in Section 12.7, and further tests are likely. For any one combination of aeroplane, friction measuring device and runway, tests frequently show a reasonable and direct correlation between aeroplane stopping distance and the “reading” of the friction device. Difficulties invariably arise, however, when a “universal” and direct correlation is sought for a given combination of aeroplane and friction measuring device which is applicable to all runways.

Operational examples of the use of runway friction measurements as a direct guide to stopping distances do exist, although most relate to combat aircraft. For civil-transport operations there is international agreement only on the use of friction measuring devices to identify the properties of icy runways, see Reference 11. For wet runway conditions, the operational interpretation of readings of friction measuring devices is left to the operator together with such advisory information as each manufacturer is prepared to supply.

A resolution of the difficulties described above is accomplished by the methods of Data Item No. 99015 (Reference 110).

Data Item No. 99015 provides a method for representing – and, if necessary, relating – the braking performance of aircraft and ground-test machines in wet conditions. The method is essentially statistical and implies that there is a clearly-defined level of probability that can be deduced from test runs of an aircraft (or ground-test machine) in a given set of wetness conditions on a particular runway. If the runway macro-texture depth is known, then the parameter that defines the variation of effective coefficient of braking friction in the given conditions can be readily calculated from a pre-determined *Friction Data Base*.

If the method of Data Item No. 99015 is to be used to *relate* the braking performances of a given combination of aircraft and ground-test machine, the procedure is comprised of two distinct phases. The first is the establishment of separate *Friction Data Bases* for the aircraft and for the ground-test machine. The second is to predict operational braking performance of the aircraft from day-to-day measurements from the ground-test machine.

Procedures are also given in Reference 110 for interpreting existing *Friction Data Bases* (summarised in the Item) for use in predicting performance of aircraft or machines for which no wet-runway test data are available.

[†] See Reference 114 for definitions of these terms.

Examples of the construction of *Friction Data Bases* are given in a sequence of three further Data Items, Nos 99016, 99017, 00018 (References [111](#), [112](#), [113](#)). The first example, for a Boeing 727-100QC aircraft, given in Data Item No. 99016, considers a case where an extensive set of test data is available. The second example, in Data Item No. 99017, is for an aircraft where only a limited set of data is available. In the third example (Data Item No. 00018) very extensive sets of data for a ground-test machine are analysed. Because of the availability of so much data, including cases where the machine was operated in “self-wetting mode”, it is possible to show the effects on the derived *Friction Data Bases* of tests conducted in more and less extensive ranges of runway wetness conditions.

3.9.2 Contaminated runways

For contaminated runways the use of ground-test machines has been restricted to identifying the friction properties of runways covered in ice or compacted snow. More extensive use of ground-test machines on such surfaces implies the need to identify separately the effects of:

- tyre-runway friction,
- contaminant drag.

Data Item No. 05011 (Reference [114](#)) provides a, “Comprehensive method for modelling performance of aircraft type tyres rolling or braking on runways contaminated with water, slush, snow, ice”.

The simplest application of the model is to provide values of tyre braking and drag forces for inclusion in aircraft performance calculations. (It has been established already that the model performs in a manner that is consistent with currently-accepted methods used by manufacturers.)

However, the reliable use of such performance data (for take-off, accelerate-stop and landing distances) depends on aircraft and airport operators having up-to-date information on runway conditions (*i.e.* runway texture and contaminant type, depth and relative density). In many cases these data are not available and it becomes necessary to make conservative assessments of the runway state so as to ensure safe operations. If ground-test machines become available which can identify the separate effects of tyre-runway-friction and contaminant drag, then a different situation arises. The model of Item No. 05011 can then be combined with ground-test machine measurements made on the *operational runway* to permit reliable calculations of aircraft performance *for those runway conditions*.

3.10 Other Operational Factors Affecting Ground Performance

Other factors directly affecting ground performance, which are taken into account in the scheduled data, are head and tail winds and runway gradient. Simple methods of adjusting distances for both of these effects are given in Item Nos EG 5/1 and RG 2/1 (References [41](#) and [43](#)). For winds, credit is allowed for only 50 per cent of the reported head wind, whereas 150 per cent of any reported tail-wind component must be assumed.

When the runway length for landing is clearly not critical, the amount of tyre and brake wear may be an economic factor to be considered. Delayed brake action, reduced brake effort, or the use of reverse thrust instead of wheel brakes might be considered in such cases. Although unlikely to be acceptable practice for civil-transport operations, a prolonged “flare” before touchdown and/or high angle of attack during the ground run might be used to reduce the loads on and wear of tyres and brakes while providing a relatively high level of aerodynamic drag. See Section [7.1](#) regarding the levels of deceleration and possible control difficulties associated with such techniques.