

ESTIMATION OF AIRBORNE PERFORMANCE IN LANDING

1. NOTATION AND UNITS

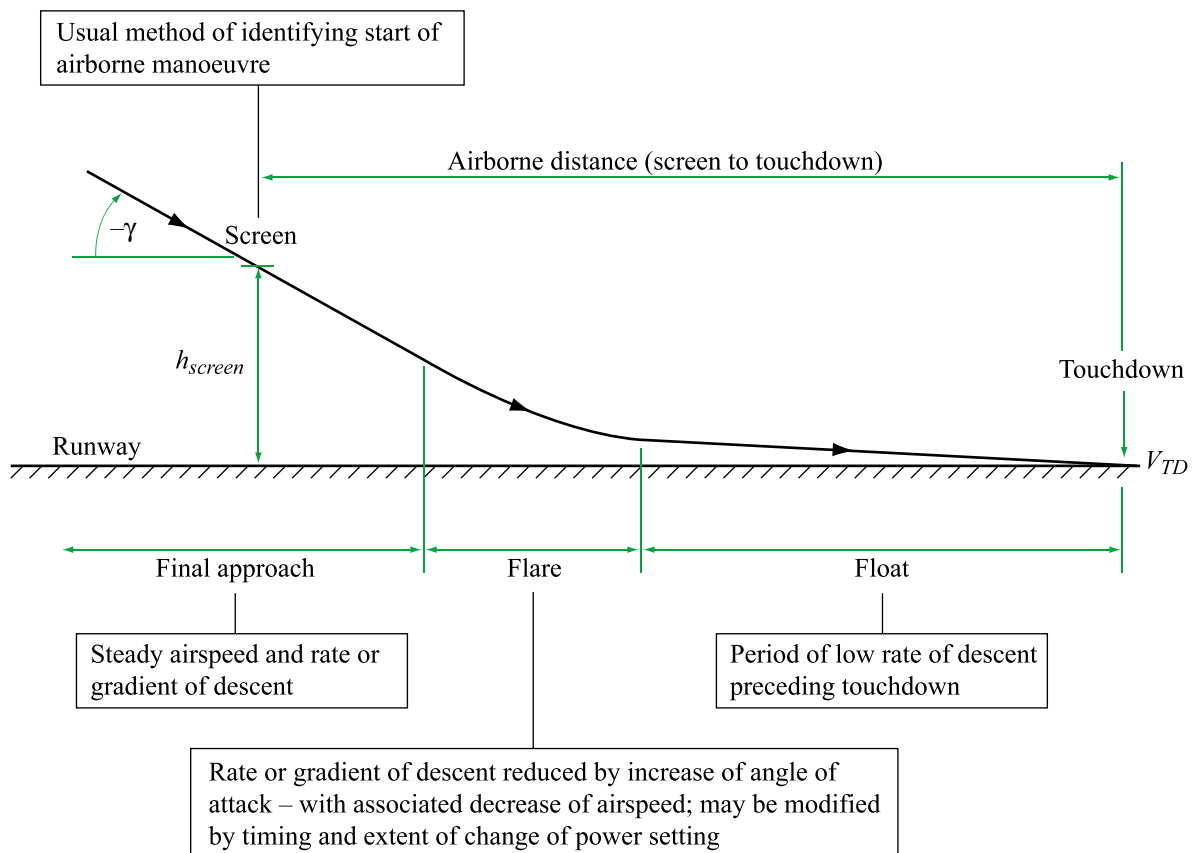
		<i>SI</i>	<i>British</i>
A	aspect ratio, b^2/S		
b	wing span	m	ft
C_{D-F}	coefficient of drag-minus-thrust, $(D - F)/qS$		
C_L	lift coefficient, L/qS (usually taken as W/qS when calculating $C_{L_{screen}}$ and $C_{L_{TD}}$, but see Section 7.4)		
D	airframe drag	N	lbf
F	thrust component along flight path, per aircraft	N	lbf
F_L	thrust component in lift direction	N	lbf
g	acceleration due to gravity (taken as 9.806 65 m/s ² , 32.174 0 ft/s ²)	m/s ²	ft/s ²
H, H_1, H_2, H_3	heights above touchdown	m	ft
H_{power}	height at which engine power is reduced	m	ft
h_{screen}	screen height, see Section 4.3 for definitions	m	ft
h_w	wing height above ground ("static" value, taken at aerodynamic mean chord of gross wing, with aircraft stationary)	m	ft
k_1	parameter in Equation (6.3)		
k_2	parameter in Equation (6.3)		
L	lift	N	lbf
m	aircraft mass	kg	slug
n	normal load factor, $(L + F_L)/W$		
q	kinetic pressure, $\rho V^2/2$	N/m ²	lbf/ft ²
$[R/S]_{screen}$	rate of sink at screen ($= -[dH/dt]_{screen}$)	m/s	ft/s
$[R/S]_{TD}$	rate of sink at touchdown ($= -[dH/dt]_{TD}$)	m/s	ft/s
R^Σ	resultant external force acting on aircraft	N	lbf
r	radius of circular path, $V^2/(n - \cos \gamma)g$	m	ft

S	wing reference area (gross wing)	m ²	ft ²
s	horizontal distance travelled	m	ft
s_a	horizontal distance travelled from screen to touchdown, in still air	m	ft
s'_a	distance along path followed by aircraft, in still air	m	ft
t	time	s	s
t_a	time taken from screen to touchdown	s	s
$t_{a\text{datum}}$	datum time for airborne manoeuvre, <i>i.e.</i> value of t_a if steady approach continued to touchdown (= $h_{\text{screen}}/[R/S]_{\text{screen}}$)	s	s
V	true airspeed	m/s	ft/s
V_c	calibrated airspeed	m/s	ft/s
V_g	true groundspeed	m/s	ft/s
V_{MS}	stall speed (calibrated airspeed) defined in Section 4.4	m/s	ft/s
$V_{S_{1g}}$	one-g stall speed (calibrated airspeed) defined in Section 4.4	m/s	ft/s
V_W	wind component along runway, headwind positive	m/s	ft/s
$V_{W_{av}}$	average headwind component along runway, taken as value between $(h_{\text{screen}} + h_w)$ and h_w	m/s	ft/s
W	aircraft weight, mg	N	lbf
z_0	terrain roughness parameter used in Equation (8.3)	m	ft
γ	inclination of flight path to horizontal, positive for climb ($\tan\gamma = (dH/dt)/V_g$)	deg	deg
ΔC_L	change in value of C_L between screen and touchdown, = $C_{L_{TD}} - C_{L_{\text{screen}}}$		
$\Delta[C_L^2]$	change in value of C_L^2 between screen and touchdown, = $[C_{L_{TD}}^2 - C_{L_{\text{screen}}}^2]$		
$\Delta[C_{D-F}]$	change in value of C_{D-F} between screen and touchdown		
$\Delta k_{1\text{config}}$	contribution to k_1 due to airframe configuration change during landing manoeuvre		
Δk_{1ge}	contribution to k_1 due to ground effect		
Δk_{1power}	contribution to k_1 due to engine power reduction during landing manoeuvre		

Δs_a	reduction in airborne distance due to headwind component along runway, see Section 8.1	m	ft
θ_r	runway average slope (positive uphill)	deg	deg
ρ	density of air	kg/m ³	slug/ft ³

Subscripts

a	denotes value applicable to whole of airborne manoeuvre
$horiz$	denotes value for horizontal runway
$screen$	denotes value at screen
TD	denotes value at (mainwheels) touchdown
0	denotes value at sea level in International Standard Atmosphere, ISA (except in parameter z_0 – adopted from Wind Engineering Series)
$1, 2, 3 \dots$	denote values at successive points during airborne phase of landing



Sketch 1.1 Terminology for airborne manoeuvre divided into three phases
(level runway; see Section 4.3 for significance of runway gradient)

2. INTRODUCTION

This Data Item gives methods for estimating distance in the airborne part of the landing manoeuvre for fixed-wing aircraft. In all cases the principle is to estimate separately the time taken for the manoeuvre and the speed loss incurred. Methods applicable to several categories of landings are listed in **Section 3**.

Section 4 describes the various categories of landing airborne manoeuvre and the factors affecting them. Sketch 1.1 illustrates the terminology used.

Section 5 gives methods for estimating airborne time. The main emphasis, in Section 5.1, is on an empirical method for estimating values of airborne time for landings where no significant “float” succeeds the flare. The method is directed particularly at civil-transport-certification style landings usually adopted when seeking compliance with the requirements of References 1, 3, 5, 6, 7, 9. Section 5.2 provides advice on airborne time for landings where there is a significant float phase.

Section 6 gives a general method, based on energy considerations, for estimating the relationship between time taken and change in speed in the airborne manoeuvre. It is based on analyses of measured performance for a wide range of aircraft types – primarily, but not exclusively, from a 50 ft (15.24 m) screen. The theoretical background is given in **Appendix A**.

Section 7 provides guidance on the use and applicability of the methods and includes information on the ranges of aircraft types and flight conditions for which measured data were available.

Section 8 presents methods of adjusting distances in still-air for the effects of wind and wind gradient.

Section 10 contains three examples to illustrate the use of the estimation methods. Section 10.1 predicts the (Reference 9) certification performance of a large transport aircraft; Section 10.2 considers the effects of a wide range of approach and touchdown conditions for a small transport aircraft; Section 10.3 predicts the initial flare heights for a low L/D glide aircraft.

Appendix B gives the geometric relationships that result if the airborne path is prescribed as some combination of circular-arc and straight-line segments.

3. ESTIMATION METHODS FOR AIRBORNE DISTANCE IN LANDING

Airborne distance in landing is the horizontal projection of the flight path from some initial point to touchdown, so that

$$s = \text{airborne distance} = [\text{mean true ground speed}] \times [\text{time}]. \quad (3.1)$$

For most aircraft it may be assumed that the flight-path inclination in the landing airborne manoeuvre is small enough for its horizontal projection to be taken as equal to the path length, so that for *still-air* conditions,

$$s_a \approx s'_a = \frac{(V_{screen} + V_{TD})}{2} t_a. \quad (3.2)$$

Effects of wind and wind gradient on airborne distance are considered in Section 8.

Equation (3.2) is the basis of all distance estimates in this Data Item. The following Table lists the methods available for separately estimating time taken and speed change in several categories of landing manoeuvre.

Category of landing manoeuvre	Method of estimating airborne time, t_a	Method for estimating speed change, $(V_{screen} - V_{TD})$
Landing from defined height speed and approach angle; “without significant float”.	Section 5.1; Figure 1 or 2 (Figures 3, 4 give upper limits for zero-float).	Section 6, Figures 6 to 10. Use Figures 9, 10 for “without significant float” case.
Reference 9 certification-style landing manoeuvre.	As above, with $[R/S]_{TD} = 8$ ft/s.	As above.
“Reference landing distance” method of Reference 6.	See Reference 6, Appendix to Chapter D2-5, “Performance – Landing”.	Section 6, Figures 6 to 10. Use Figures 9, 10 for “with significant float” case.
Landing from defined height, speed and approach angle; “with significant float”.	Section 5.2.	As above.
Landing from undefined initial height; speed and approach angle known.	Appendix B.	Section 6, Figures 6 to 10.

4. THE AIRBORNE MANOEUVRE IN LANDING

To obtain exact agreement between calculated and measured airborne performance in landing, step-by-step computational methods* are needed to take full account of aerodynamic and powerplant characteristics, possible control inputs and the resulting aircraft motion. However, the limited ranges of combinations of control inputs likely to be made (whether in flight tests or operationally) mean that simpler calculation methods may be satisfactory for *predicting* landing performance when only the initial conditions (weight, speed, height, approach gradient) can be specified with any certainty, but the piloting technique used varies in detail from landing to landing.

For such performance predictions, the limitations placed on the type, or style, of landing manoeuvre considered must be reflected in the choice of calculation method. Ways of defining the airborne manoeuvre are described in Sections 4.1 and 4.2. Suitable estimation methods are listed in Section 3.

4.1 Certification Landings – Different Concepts

The need to provide acceptable levels of safety and performance has led to several philosophies for establishing the landing performance of fixed-wing aircraft and these tend either to define, or to invite the use of, particular types of landing manoeuvre.

- (i) For large civil transport aircraft, References 1, 5, 6, 9 define limiting approach and touchdown conditions within which flight tests may be used to establish the best (shortest) landing performance in the most favourable conditions (test pilot, calm air). A relatively large “field length factor[†]” is then applied when calculating the scheduled landing field length. In this Data Item, such landings are termed, “**Reference 9 certification-style landings**”.
- (ii) An alternative philosophy to (i) is to establish, by flight tests, an acceptable landing technique for a particular aircraft and to make allowance for operational deviations from that technique. One certification method in Reference 6 (the “Reference Landing Distance”) requires such tests to be made using an artificially high approach speed but imposes a relatively small field length factor. The use of this method has been discontinued for new aircraft. For combat aircraft[‡], flight tests again tend to be used to establish an acceptable landing technique for individual aircraft types.
- (iii) For automatic landing systems both flight measurements and computer simulations are used to establish the dispersion of touchdown conditions likely to be obtained over a wide range of practical operating conditions. Pre-flight estimates of performance are usually made using computer simulations with step-by-step calculation procedures. Flight tests with automatic landing systems are primarily directed towards the validation of the computer simulation, although the method of analysis used in Section 6 is still applicable.
- (iv) A final possibility, which is not relevant here, is to consider the airborne element of landing only from the points of view of handling and the establishment of a representative touchdown speed for the calculation of ground stopping performance.

* For a complete modelling of the airborne manoeuvre, it is necessary to solve the equations of motion (both translational and rotational) with full account taken of all relevant forces and moments and a realistic means of representing control inputs. The calculation methods are, essentially, the same as those described for take-off in Data Item No. 87018 (Reference 21) for “conventional” aeroplanes and, in Data Item No. 87037 (Reference 22), for vectored-jet-thrust V/STOL aircraft.

[†] Values of landing field length factors – applicable to both air and ground parts of the landing – are summarised in Table 11.1.

[‡] Where a civil transport aircraft (say) is adapted for military purposes, the civil certification may be accepted, possibly with modifications, to avoid duplication of effort.

4.2 Other Landings

To make estimates for landings which are in some sense “typical”, it is necessary to establish one or more combinations of “typical” values of those parameters used to define the airborne manoeuvre. Possible methods are as follows.

- (i) Measurements of flight-test or even operational landings can provide a basis for selecting average values of airborne time and screen and touchdown speeds for use in Equation (3.2). The scatter in such measured data (particularly operational landings) is likely to be large.
- (ii) Customary values of speed loss and/or airborne time may be selected, based on experience or deduced using data given in Sections 5.2 and 6.
- (iii) The geometry of the airborne manoeuvre may be specified in such a way that airborne time or distance can be deduced using the methods of Appendix B (although the speed change may still be obtained from Section 6). These methods also provide a means of investigating the effects on landing performance of different assumptions regarding the three elements of the manoeuvre shown in Sketch 1.1, for example, to estimate and to optimise the height for flare initiation and the *average* normal load factor required in the flare. (The effect of *actual* variations in normal load factor can only be investigated fully using computer simulation methods or flight test.)

4.3 Landing Initial Conditions and Screen Height

The landing airborne manoeuvre is assumed to start from initial conditions of steady airspeed and approach gradient and, for estimates of airborne distance, a screen height, h_{screen} , is the most common method of identifying the point from which distances and times to touchdown are defined.

For most aircraft types the screen height is passed during the final, steady approach although occasionally it may be necessary to initiate the flare at a greater height. In some cases, however, a fixed screen height may be less relevant and the performance task is to estimate the height (and associated airborne distance) from which a successful manoeuvre can be started as, for example, for unpowered low L/D aircraft (see Section 10.3 and References 11, 14, 17, 19).

The screen height most widely used is 50 ft (15.24 m). For example, the certification requirements of References 1, 3, 5, 6, 7 define the landing distance as, “The horizontal distance necessary to land and come to a complete stop from a point 50 ft above the landing surface”. (Other screen heights are used for particular purposes – one of the methods specified in Reference 6 uses 30 ft while some civil STOL aircraft are certificated using a 35 ft screen for landing.) A “screen” implies that at the start of the airborne distance the lowest point on the aircraft is at a height h_{screen} and, while this is usually the main undercarriage (Reference 9 specifies this), other locations are possible.

For sloping runways the screen has been interpreted as either a fixed height above the touchdown point or a fixed height above the extended runway surface. The difference, Δs_a , between the corresponding airborne distances can be obtained from the following expression.

$$\frac{\Delta s_a}{s_{a_{horiz}}} = \frac{1}{\frac{\tan \gamma}{\tan \theta_r} - 1}, \quad (4.1)$$

where $s_{a_{horiz}}$ is the airborne distance on to a horizontal runway and θ_r , the runway angle to the horizontal (positive for landing uphill). In deriving Equation (4.1) it is assumed that the airborne manoeuvre and touchdown points on a horizontal runway remain fixed in space while the runway surface is rotated about the touchdown point to give θ_r .

For small runway gradients, of order ± 2 per cent, say, current practice (Reference 9) for new civil transport aircraft is to take no direct account of that gradient on the airborne part of the landing (this has not always been the case – particularly when working to the requirements of Reference 6). Any effect of a sloping runway on the airborne distance which is not taken into account in the certification will be limited in actual operations, for the following reasons.

- (i) The effect of operational obstacle clearance criteria on the declared landing distance available.
- (ii) When an instrument landing system (ILS) is used, the system alignment provides for a ground clearance (normally 50 ft) at the runway threshold based on the height of the receiving antenna (whereas the screen assumed for calculation of scheduled distances extends to the lowest point on the aircraft).
- (iii) When an automatic landing system is used in conjunction with an ILS, the declared landing distance available can be reduced to take account of the siting of the ILS transmitter, and/or the scheduled landing distance required is corrected appropriately.
- (iv) The influence of runway slope on the airborne distance would be one of the numerous effects which it is presumed are allowed for by the use of a field length factor.

For large runway gradients, it is essential that the airborne distance take account of that gradient and that the screen be defined as h_{screen} above the (extended) runway surface. Equation (4.1) may be used to estimate a correction to distance to take account of changes in runway slope. In using this equation it may, in some circumstances, be appropriate to use an average runway slope as specified in current airport data while, in other cases, the particular details of the local terrain must be considered.

4.4 Approach Speed

Approach speed is the single most important parameter affecting landing performance.

The effect of the aircraft characteristics on the approach speed are discussed in Data Item EG 6/2, where criteria are given for the limitations on the approach speed imposed by stalling, speed and thrust considerations. However, for all civil aircraft the minimum value of approach speed is defined by the appropriate Airworthiness Requirements (References 1, 3, 5, 6, 7, 8). (Higher values may be scheduled.)

For “conventional” transport aircraft it is customary to take, as a first estimate of approach speed, a value of 1.3 times the stall speed in the landing configuration. However, since for some time two definitions of stall speed* (V_{MS} and $V_{S_{1g}}$ have been in widespread use, two definitions of the calibrated airspeed at the screen, $V_{c_{screen}}$, are also required,

$$\text{either} \quad V_{c_{screen}} \geq 1.3 V_{MS}, \quad (4.2)$$

$$\text{or} \quad V_{c_{screen}} \geq 1.3 \times [0.94 V_{S_{1g}}]$$

$$\text{taken as,} \quad \geq 1.23 V_{S_{1g}}. \quad (4.3)$$

It is anticipated that, in the foreseeable future, the use of Equation (4.3) only will be permitted for new civil transport aircraft.

* A stalling manoeuvre is defined in Reference 5 from which values of stall speed may be derived for each of the following two definitions. V_{MS} is the minimum calibrated airspeed obtained when the aeroplane is stalled (or the minimum steady flight speed at which the aeroplane is controllable with the longitudinal control on its stop). $V_{S_{1g}}$ (the one-g stall speed) is the minimum calibrated airspeed at which the aeroplane can develop a lift force (normal to the flight path) equal to its weight whilst at an angle of attack not greater than that at which the stall is identified.

The effects on the approach speed of the differing requirements of visual or instrument conditions, and of carrier operations, are also discussed in EG 6/2. The approach and threshold speeds may be increased to maintain adequate control with asymmetric power; similarly a higher margin over the stall may be necessary right down to touchdown in gusty winds and turbulent air conditions. Use of autothrottle and autoland systems may impose further constraints.

4.5 Other Factors Affecting Airborne Manoeuvre in Landing

The technique for achieving minimum *overall landing distance* is, in general, dependent on both the characteristics of the aircraft and the runway conditions.

For given “threshold conditions” (V_{screen} , γ_{screen}), for most aircraft which are equipped with efficient wheel brake systems, it is advantageous to touch down at the earliest practicable moment and to apply maximum braking immediately, with as much weight as possible on the main-wheels (see, for example, the certification method described in Section 4.1, item (i)). Operational landings for civil transports tend to be governed by the need for relatively “soft” landings – leading to airborne times in excess of the minimum possible.

Where threshold conditions can be varied, while retaining acceptable handling qualities and performance margins, a reduction in V_{screen} invariably reduces the overall landing distance. An increase in approach angle usually results in a reduction in the airborne distance although for most types the effect is one of diminishing returns as γ_{screen} varies, say, from -5 to -10 deg. In particular, for propeller-driven “powered-lift” aeroplanes, as the approach angle is steepened (for a given aerodynamic configuration), the engine power required decreases while the approach speed must be increased if its ratio to the stall speed is to be held constant. In consequence, there is an optimum combination of approach angle and speed at which the air distance is a minimum (assuming handling characteristics are satisfactory).

In some circumstances an acceptably-short airborne distance might be obtainable using a flat approach ($\gamma_{screen} \approx -1$ deg) and an early power-cut – see Section 5.1(c) and Sketch 5.1(c). A relatively high approach power setting is required and the touchdown sink rate may exceed that at the screen. The technique is probably more relevant to propeller-driven aircraft than jets and can be beneficial where visual cues to a manual approach are poor (for example, to a plateau or over water) and for operations on to severely sloping runways.

The flight-path curvature (or load factor) during the flare may be limited by the pitch control response, by the speed margin above the stall and possibly by the throttle response. Angle of attack limits the extent to which an aircraft may be allowed to “float”. With most nose-wheel undercarriage configurations, by virtue of the position of the centre of gravity relative to the main-wheels, combined with a low ground angle of attack, it is possible to eliminate the float by touching down at a speed well above the stall – provided the associated descent rate is acceptable.

For tail-wheel aircraft the touchdown may be carried out in two ways. The aircraft may be landed in a three-point position which in some cases is preceded by a float during which the required attitude is attained, or it may be flown on to the ground on the main-wheels with a low rate of descent, a procedure that will reduce or eliminate the float. The latter method allows the touchdown to be made at a greater speed, giving greater control and higher margin over the stall in gusty wind conditions during the approach and flare. However, it leads to a longer ground run and involves smaller ground clearance for the propeller(s). For some types of tail-wheel aircraft, moreover, the touchdown on main-wheels alone may lead to porpoising, caused by the dynamic characteristics of the undercarriage and aircraft.

5. ESTIMATION OF TIME FOR AIRBORNE MANOEUVRE IN LANDING

5.1 Landings With No Significant “Float” (Including Reference 9 Certification-style Landings)

For landings where there is little or no “float” and where the “flare” is primarily a means of achieving an acceptably-safe sink rate at touchdown, the airborne time may be related to the sink rates at screen and touchdown, *i.e.* $t_a = f([R/S]_{screen}, [R/S]_{TD})$. In particular, for the landing manoeuvre described in Section 4.1, item (i), the use of these two sink rates as independent variables is a recommended method for analysing flight-test data for certification purposes (see Reference 9).

Figures 1 and 2 present data, based on tests for wide ranges of aircraft types, for the airborne time from screen to touchdown for this type of landing manoeuvre. The data are presented as increments, in both time and sink rate, from the values that would apply if the aircraft continued down the approach path to intersect the runway, *i.e.* as

$$(t_a - t_{a_{datum}}) \text{ and } ([R/S]_{screen} - [R/S]_{TD})$$

where

$$t_{a_{datum}} = \frac{h_{screen}}{[R/S]_{screen}} \quad (5.1)$$

In addition, Figures 3 and 4 present upper limits to values of $(t_a - t_{a_{datum}})$ appropriate to “landings with no significant float”. These were evolved during the preparation of Figures 1 and 2 to permit the systematic rejection of those landings which were of a different style – *i.e.* those with a significant “float” phase.

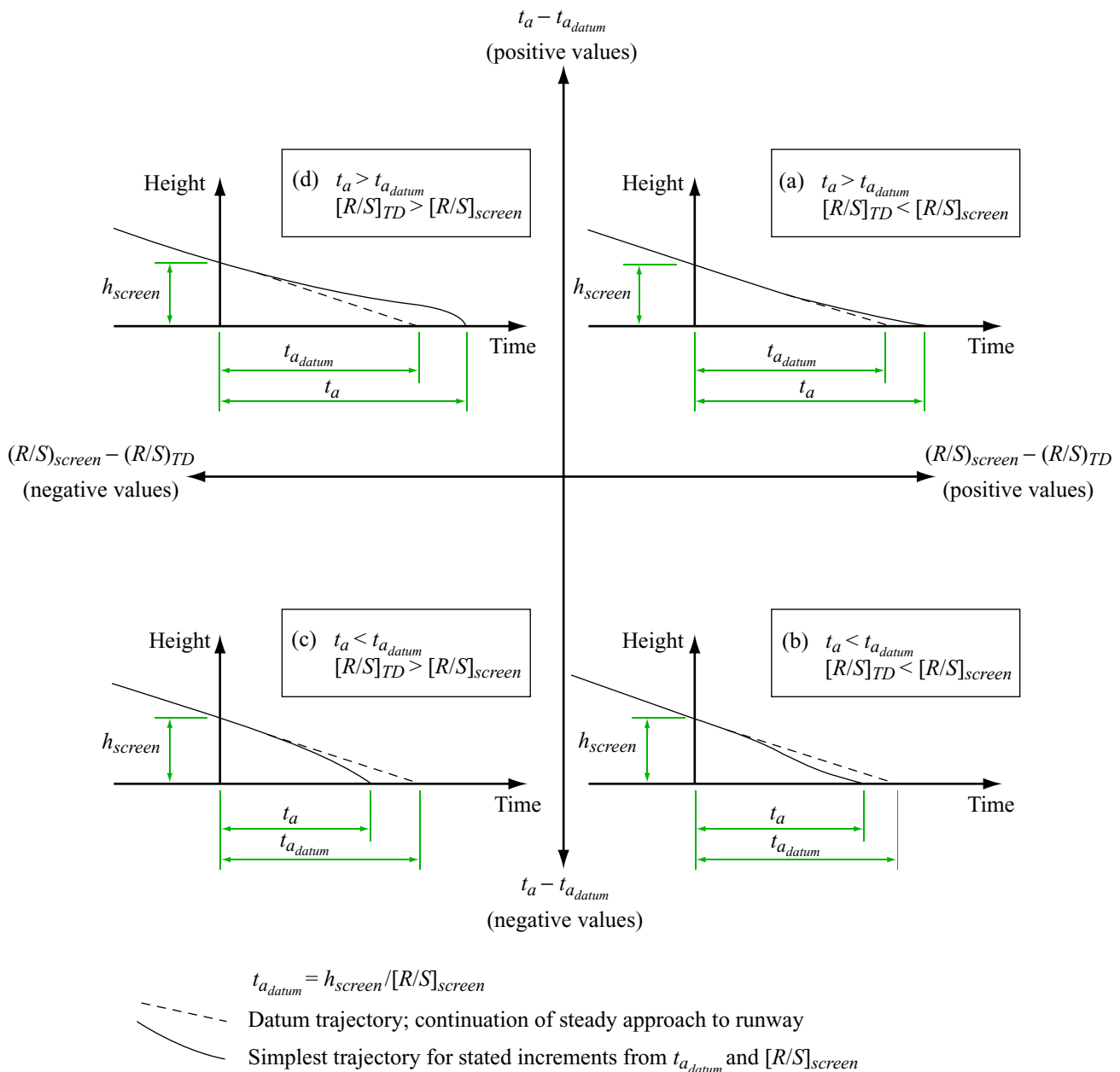
Sketch 5.1 shows schematically the implications, in terms of the simplest-possible trajectories for landings corresponding to each of the four quadrants of Figures 1 and 2. The trajectories arise from different combinations and timings of longitudinal control input and/or engine power cut. Brief descriptions are given below and the “trajectories” are repeated, as insets, in Figures 1 and 2.

- This represents the traditionally-expected trajectory for landings and, as can be seen from Figure 1, the majority of landings for all types of jet- and fan-engined aircraft are of this type. For propeller-driven aircraft, Figure 2 shows that the proportion of landings displaying this sort of trajectory is smaller than with the jets.
- Here the aircraft sinks below the glide slope, but recovers to achieve a touchdown sink rate less than that at the screen. Many landings for propeller-driven aircraft are of this type – particularly where the change in sink rates from screen to touchdown is relatively small (less than about 5 ft/s, say). It is believed that this tendency to sink is associated with the initial loss of propeller slipstream induced lift when power is cut during the landing manoeuvre (and may be accompanied by a change in longitudinal trim and hence in pitch angle).
- These landings tend to be associated with very flat approach paths ($\gamma_{screen} \approx -1^\circ$) and there are a considerable number of them at the higher touchdown sink rates (greater than 8 ft/s, say). In such approaches the aircraft uses a power setting not far removed from that for level flight. The change in flight path angle is all the greater, therefore, when the power is cut. Note, however, that these landings, while taking less time (or distance) than the “datum” value, can be long – because of the initial, (relatively-flat) trajectory.

- (d) Landings in this category, if achieved consistently, tend to be associated with some undesirable aspect of the landing performance of the aircraft. This is particularly so where propeller-driven aircraft are concerned and has been found to be associated with, for example, the following.

An unusually high flight-idle power setting leading to no significant loss of slipstream induced lift when power is cut.

A combination of slipstream and flap configuration which, when close to the ground, tends to cushion the aircraft and leads to the pilot's forcing the aircraft on to the runway.



Sketch 5.1 Simplest possible trajectories for airborne manoeuvres represented by departures from datum (straight-line) time and sink rate in each quadrant of Figures 1 and 2

5.2 Landings with Significant Float

Where landings include a significant float in the airborne manoeuvre, estimation of time taken is, at best, imprecise.

Examination of limited samples of operational landings (taken together with the minimum airborne time of the “Reference Landing Distance” in Reference 6) suggests that for transport aeroplanes having approach speeds in the range 90 to 145 knots an overall average time is represented by $(t_a - t_{a_{datum}}) \approx 5$ s, with 90% of times within ± 3 s of this. The lower end of this range overlaps with the limiting values of $(t_a - t_{a_{datum}})$ given in Figures 3 and 4 – implying only that some operational landings have no float.

An alternative is to construct an airborne manoeuvre based on a combination of straight line and circular arc segments – see Appendix B. However, there remains the problem of deciding at what height the flare finishes and the constant sink rate phase begins. See also Section 7.3.

5.3 Reference Landing Method (Reference 6)

Reference 6 (discontinued for new aircraft) defines a minimum time for the landing airborne manoeuvre. The original definition was based on a maximum screen speed – expressed in knots as $V_{screen} = (1.3 V_{S_{lg}} + 15)$ – and gave $t_a \geq (13 - 0.045 V_{screen})$ but a lower limit, $t_a \geq 7$ s, was imposed subsequently. It can be shown that, for $\gamma_{screen} = -3$ deg and for $70 \leq V_{screen} \leq 200$ kn, the combined effect of these limits can be represented by $t_a \geq (t_{a_{datum}} + 5)$ s, to within ± 0.5 s.

6. ESTIMATION OF SPEED LOSS FOR AIRBORNE MANOEUVRE IN LANDING

6.1 Energy Relationships Between Distance, Time and Speeds

For a screen height, h_{screen} , energy considerations can be used to relate s_a , V_{screen} and V_{TD} as follows

$$s_a = \left(\frac{W}{D - F} \right)_a \left[h_{screen} + \frac{(V_{screen}^2 - V_{TD}^2)}{2g} \right]. \quad (6.1)$$

Alternatively, by combining Equations (3.2) and (6.1), values of t_a , V_{screen} and V_{TD} can be related as

$$t_a = \left(\frac{W}{D - F} \right)_a \frac{2}{(V_{screen} + V_{TD})} \left[h_{screen} + \frac{(V_{screen}^2 - V_{TD}^2)}{2g} \right]. \quad (6.2)$$

In Equations (6.1) and (6.2), $[W/(D - F)]_a$ is the mean value for the whole airborne manoeuvre from screen to touchdown.

Figure 5 presents Equation (6.2) in graphical form for $h_{screen} = 50$ ft to give an overall guide to the relative significance of the variables.

Appendix A gives the derivation of Equations (6.1) and (6.2) and presents (as Equations (A1.4) and (A1.5)) alternative expressions relating the quantities s_a , t_a and V_{screen} but eliminating V_{TD} .

6.2 Estimation of Speed Loss

For given screen conditions, a relationship between speed loss and time* in the airborne manoeuvre can be deduced from Equation (6.2), provided values of $[W/(D - F)]_a$ are available for the particular aircraft. Sections 6.2.1, 6.2.2, 6.2.3 deal, respectively, with the principles of this method, the procedure for estimating $[W/(D - F)]_a$ and the practicalities of obtaining solutions to Equation (6.2) for V_{TD} in terms of t_a .

6.2.1 Representation of measured values of $[W/(D - F)]_a$

Values of $[W/(D - F)]_a$ derived (using Equation (6.2)) from flight-test measurements for the landing airborne manoeuvre may be represented as the linear variation of $\Delta[C_{D-F}]$ with $\Delta[C_L^2]$, see Sketch 6.1,

$$\Delta[C_{D-F}] = k_1 + k_2 \Delta[C_L^2]. \quad (6.3)$$

In Equation (6.3), $\Delta[C_{D-F}]$ represents the increase in the value of the coefficient, C_{D-F} ,

$$\begin{aligned} \Delta[C_{D-F}] &= [C_{D-F}]_a - [C_{D-F}]_{screen}, \\ &= \left[\frac{D - F}{qS} \right]_a - \left[\frac{D - F}{qS} \right]_{screen}, \\ &\approx C_{L_{TD}} \left[\frac{D - F}{W} \right]_a - C_{L_{screen}} \tan(-\gamma_{screen}) \end{aligned} \quad (6.4)$$

* A similar relationship between speed loss and distance can be deduced from Equation (6.1) but, for consistency with Section 5, it is convenient here to work in terms of airborne time.

In Equation (6.4) the $\approx$ sign is used since C_{LTD} is not a mean value for the airborne manoeuvre.

The parameter k_1 in Equation (6.3) is made up of three contributions representing ground effect, the timing and extent of engine power reduction, and any aerodynamic configuration change,

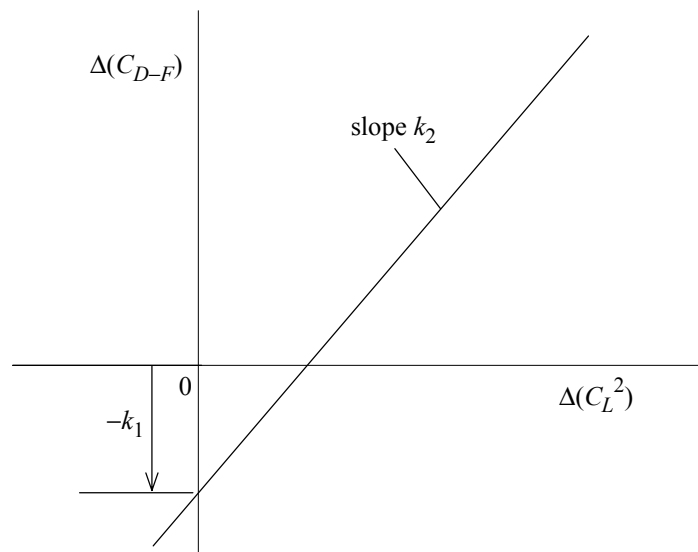
$$k_1 = \Delta k_{1_{ge}} + \Delta k_{1_{power}} + \Delta k_{1_{config}}. \quad (6.5)$$

Values of $\Delta k_{1_{ge}}$ are given in Figure 6. Values of $\Delta k_{1_{power}}$ are given in Figure 7 for turbo-jet and turbo-fan engined aircraft and in Figure 8 for propeller-driven aircraft.

For most aircraft landings the term $\Delta k_{1_{config}}$ has no significance and so is not considered further here – but see Section 7.4.3.

The parameter k_2 in Equation (6.3) represents the change in lift-dependent drag between screen and touchdown. Values are given in Figure 9 for turbo-jet and turbo-fan engined aircraft and in Figure 10 for propeller-driven aircraft.

The parameter $\Delta[C_L^2]$ is the increase in C_L^2 , as determined by the decrease in airspeed between screen and touchdown – see Section 7.4.1.



Sketch 6.1 Illustration of relationship defined by Equation (6.3)

6.2.2 Calculation procedure for $[(D-F)/W]_a$

Data given in Figures 6 to 10 may be used to deduce values of $[(D-F)/W]_a$ for the airborne manoeuvre for a wide range of aircraft configurations (represented by wing aspect ratio and (static) height), screen conditions (represented by lift coefficient and approach gradient) and power-cut timing (represented by H_{power}/h_{screen}). The calculation procedure is as follows.

- (i) A value of $\Delta k_{1_{ge}}$ is deduced from the definition,

$$\Delta k_{1_{ge}} = \frac{C_L^2}{\pi A} \left[\Delta k_{1_{ge}} \frac{\pi A}{C_L^2} \right]_{\text{Fig. 6}}, \quad (6.6)$$

where the quantity in brackets is read from Figure 6 for the appropriate wing height, h_w , (static value, taken at aerodynamic mean chord of gross wing). The value of C_L is taken as $C_{L_{screen}}$.

- (ii) A value of Δk_1 is read from Figure 7, for turbo-jet or turbo-fan engined aircraft, or from Figure 8 for propeller-driven aircraft. Advice regarding the selection of the power-cut height parameter, H_{power}/h_{screen} , is given in Section 7.6.1.
- (iii) The value of k_1 is given by Equation (6.5).
- (iv) A value of k_2 is read from Figure 9 or 10 for the appropriate wing aspect ratio, $A (= b^2/S)$, with S taken as gross wing area). Note these Figures give data for “no float” and “with float” cases.
- (v) Values of $\Delta[C_{D-F}]$ are calculated using Equation (6.3) with

$$\Delta(C_L^2) = C_{L_{TD}}^2 - C_{L_{screen}}^2 \quad (6.7)$$

For most purposes $C_L = W/qS$, but see Section 7.4.1.

- (vi) Values of $[(D-F)/W]_a$ are calculated from

$$\left(\frac{D-F}{W}\right)_a = \frac{\Delta[C_{D-F}] + [C_{L_{screen}} \tan(-\gamma_{screen})]}{C_{L_{TD}}} \quad (6.8)$$

or, if Equations (6.3), (6.7) and (6.8) are combined,

$$\left(\frac{D-F}{W}\right)_a = \frac{k_1 + k_2 C_{L_{screen}}^2 \left[\frac{V_{screen}^4}{V_{TD}^4} - 1 \right] + C_{L_{screen}} \tan(-\gamma_{screen})}{C_{L_{screen}} \frac{V_{screen}^2}{V_{TD}^2}} \quad (6.9)$$

See Sections 7.4 and 7.5 regarding the sensitivity of the solutions of Equations (6.2) and (6.9).

6.2.3 Inverse solution of Equations (6.2) and (6.9)

For given screen conditions, Equations (6.2) and (6.9) can be solved directly to give airborne time as a function of touchdown speed. A particular solution is then obtained by interpolation at the value of t_a predicted from Section 5 (or elsewhere). The form of solution is demonstrated graphically in Sketch 10.1 of the Example of Section 10.1. The explicit solution of Equations (6.2) and (6.9) to obtain V_{TD} as a function of t_a is not possible although such solutions are desirable because of the availability of values of t_a from Section 5. In consequence, most check calculations have been made using iterative techniques available through Reference 23. It is recommended that these or comparable techniques be used where rapid results are required and particularly if a range of initial screen conditions is to be considered – as in the Example of Section 10.2

See Sections 7.4 and 7.5 regarding the sensitivity of the solutions of Equations (6.2) and (6.9).