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PROPOSED ANALYTICAL MODEL FOR THE FINAL STAGES OF LANDING A TRANSPORT AIRPLANE

by Maurice D. White

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Moffett Field, Calif.

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SUMMARY

Methods for defining and certifying landing distances and approach speeds of transport airplanes are currently being reviewed. Revisions are being sought that would make the requirements and demonstration procedures account more realistically for operational practices and variables. As an aid in this task, a simple model is proposed for describing the final airborne stages of landing a transport airplane manually. The model separates the maneuver into three distinct phases, an initial flare, a float, and a touchdown. Methods are indicated for estimating the speed changes or lift increments associated with each phase. Assumptions regarding thrust management in the maneuver are shown to be important. The considerations that affect these assumptions are discussed and indicate how the thrust would probably be managed in normal operations. Limited flight data are described which confirm the main elements of the model. Additional refinement of the model is desirable to make it useful in the development of more rational rules for certifying landing characteristics.

INTRODUCTION

The final manual stages of landing an airplane have been regarded as difficult to define explicitly. Large variations of landing trajectories and touchdown conditions result from operational variations. In the current method of certifying landing distance for transport airplanes, a minimum demonstrated distance is increased by a rather large factor (1.67) partly to provide for these inconsistencies in the landing maneuver. Operational experience has shown that in most cases the factor 1.67 effectively accommodates the variations of basic pilot proficiency as well as certain operational variables that are not considered otherwise. Basically, however, this method of defining landing distance is unsatisfactory because of its arbitrary nature; there is no assurance that the 1.67 factor will accommodate advanced transport designs as effectively. Similarly, the former basis for defining a certified approach speed ($V_{ref} = 1.3\ V_{stall}$) is certainly inadequate for airplanes with no clearly defined maximum lift coefficient or with very large drag levels that make it difficult to define the stall speed. In recognition of this situation, regulatory agencies are attempting to develop alternate methods of specifying minimum landing distance and approach speed that will more closely represent actual operational practice. As one step toward meeting these objectives, a simple model of the airborne part of a transport landing maneuver is proposed. This model separates into several discrete phases a maneuver that has generally been treated as one continuous task. In so doing, it sets the stage for more detailed study of the different variables involved in each phase. Hopefully, this will result in more rational definitions of the critical combinations of variables that define required landing distance and possibly approach speed. The successful development of such a model may prove valuable for certification purposes and also in suggesting refinements to landing techniques that would produce more consistent landing performance.

This report describes the proposed model and some preliminary results of its application to specific designs.

NOTATION

a_x	longitudinal acceleration, ft/sec^2
a_z	acceleration normal to flight path, positive upward, ft/sec^2
$C_{L_{app}}$	lift coefficient at approach speed
$C_{L_{max}}$	maximum lift coefficient in ground effect, limited if necessary by ground-attitude geometry
C_{L_1}, C_{L_2}	lift coefficients at the end of Phases I and II, respectively (fig. 4)
L/D	lift-drag ratio
V_{app}	estimated speed required at beginning of landing maneuver
V_{ref}	certified approach speed
V_1, V_2	airspeed at end of Phases I and II, respectively
W/S	wing loading, lb/sq ft
γ	change in flight-path angle
γ_o	initial flight-path angle
$\dot{\gamma}$	rate of change of flight-path angle
$\Delta V_1, \Delta V_2$	speed decrease in Phases I and II, respectively
ρ	air density, slugs/cu ft
$\partial C_L/\partial C_D$	local slope of lift-drag curve, measured at mid-C_L point in Phase I, out of ground effect

PROPOSED FLARE AND TOUCHDOWN MODEL

For analysis purposes, the flare and touchdown are assumed to comprise the following three sequential phases, shown schematically in figure 1:

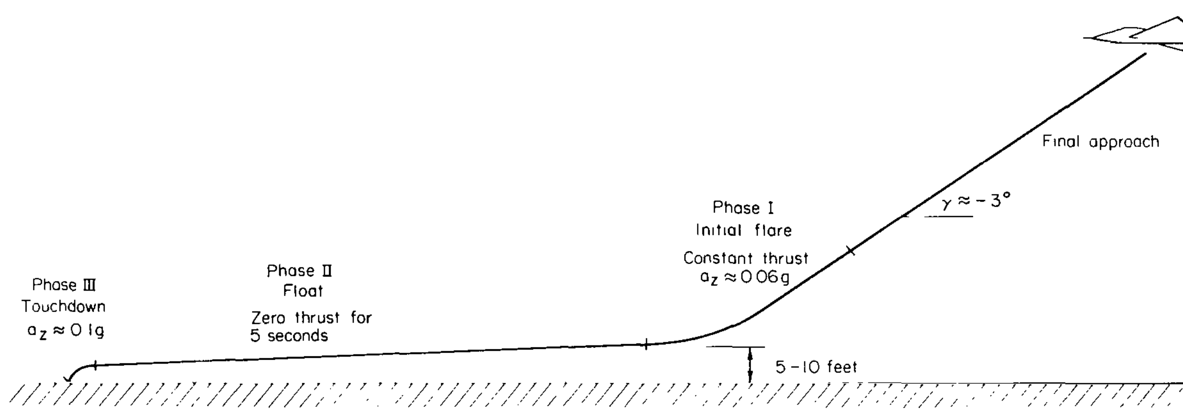


Figure 1.- Schematic diagram of proposed flare and touchdown model.

1. An initial flare to reduce the approach flight-path angle to essentially zero, accomplished at constant load factor, and terminating at 5 to 10 feet above the ground. Thrust is assumed maintained at the value used in final approach on the glide slope.

2. A "float," to ease the airplane down from the 5- to 10-foot height at the end of the flare, accomplished at essentially a 1 g load factor. For the basic model it is assumed that thrust is instantaneously reduced to zero at the beginning of this phase.

3. A touchdown for which the main concern is to provide some load factor margin to check a previously established sink rate.

These three phases are an approximation of the idealized continuous flare to touchdown normally assumed for the maneuver. They were selected to identify the main elements of an inaccurate flare.

In the following sections of this report the assumptions that define these maneuvers quantitatively are developed. As a test of the validity of the assumptions, calculations are made for two specific airplanes to determine whether the approach speed would provide enough speed margin for the cumulative requirements of an inaccurate flare and touchdown. Since the approach speed is usually defined on a completely different basis, results from this approach-speed test cannot be considered to completely confirm or invalidate the proposed model. It will be shown that, on the basis of this test, some of the initial assumptions regarding thrust management need reconsideration. However, the adjustments indicated to be necessary themselves provide useful insight into the mechanism of the landing maneuver, suggesting further the merits of the approach-speed test and the main elements of the model. For this reason, it is considered worthwhile to proceed with a description of the model and its application.

To apply the approach-speed test to the model, the speed losses in the first two phases of the maneuver are first converted into increments in lift coefficient. These are combined with the lift coefficient increment required for the third phase, and the three increments are subtracted from the maximum usable lift coefficient. The resulting lift coefficient defines a required initial speed for the maneuvers, which is interpreted as a minimum final approach speed.

Initial Flare

The characteristic of concern in this phase of the maneuver is the speed loss. It is widely accepted that the initial flare actually is performed with an average incremental vertical acceleration of about 0.06 g (≈ 2 ft/sec^2). This is a comfortable level from a passenger's standpoint, and provides a reasonable time and starting height for completing the maneuver. At 130 knots and an initial flight-path angle of 2-1/2°, 5 seconds would be required to decrease the flight-path angle to zero, and the height loss would be 24 feet.

Thrust management significantly affects speed loss in the initial flare. A wide range of possible thrust adjustments may be used by the pilot, depending on his judgment of the situation. Techniques may range from decreasing thrust at the beginning of the maneuver (if the airspeed is higher or the flight-path angle lower than normal) to increasing thrust at the beginning of the flare for the converse conditions. Even the rate of change of thrust may be a variable. For the present purposes, it is assumed that thrust is held at the approach value throughout the initial flare, with the inference that thrust is varied only to compensate for nonstandard flight conditions. With this assumption, the speed loss in the initial flare, calculated as a function of initial flight-path angle, local lift-drag slope, and airspeed, is shown in figure 2. The derivation of the expression used to calculate the curves of figure 2 is shown in the appendix.

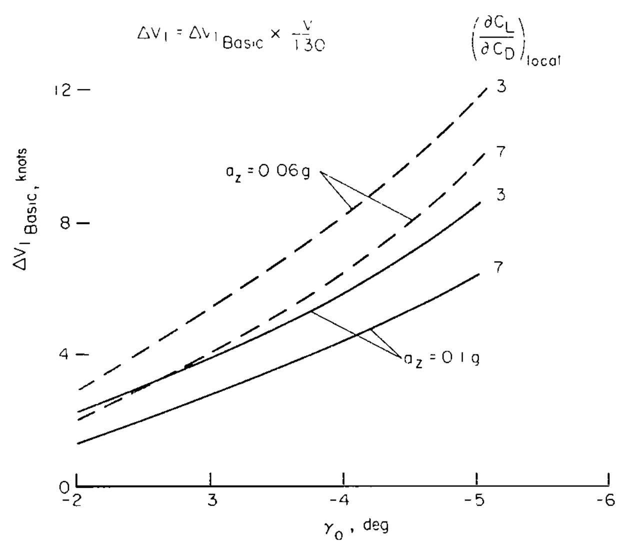


Figure 2.- Speed decrease in constant-thrust flare to $\gamma = 0^\circ$.

The numbers used in the above described maneuver make no allowance for the dynamics of the flare initiation, the effects of variations in starting conditions (height, height rate, or airspeed), the effects of atmospheric variations (wind shears or gusts), or imprecise piloting. All these factors could be expected to contribute to errors in the end conditions of the initial flare and it is these errors that define a requirement for the following phase, called here, the "float."

The Float

The float phase of the landing maneuver is difficult to define quantitatively and, correspondingly is in need of investigation. Limited evidence suggests that air distance to touchdown, or, more basically, air time, may be a reasonable criterion. Lending support to this notion is the observation made by a test pilot during some related simulator studies; i.e., when air times exceeded about 9 to 10 seconds from flare initiation, the pilot became uneasy about the duration of float and made a positive effort to set the airplane down on the runway. In the present analysis, air time in float is assumed to be 5 seconds. The speed loss in float may then be estimated as a function of L/D, from the curve of figure 3. For this estimate aerodynamic characteristics in ground effect are used which may be substantially different from those out of ground effect.

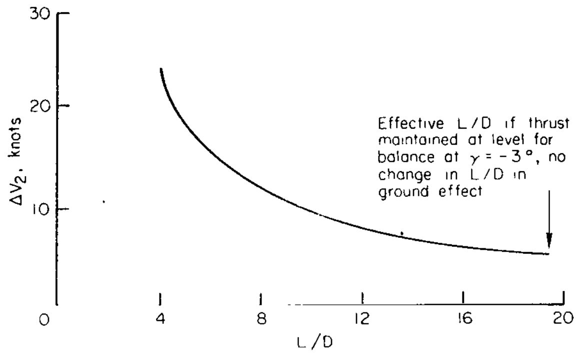


Figure 3.- Speed decrease during power-off float of 5 seconds.

The factors that tend to extend the float phase to the order of 5 seconds merit some discussion. Basically, this phase involves a tight tracking task, accomplished with the aerodynamic longitudinal control, since thrust has been assumed to be reduced to idle at the end of the initial flare. The difficulty in performing this task depends on the location of the center of gravity of the airplane. For the forward center-of-gravity position, as speed is decreased in the float, the elevator deflection required for pitching-moment balance is increased and therefore the longitudinal control power remaining to provide pitching acceleration for maneuvering is reduced. This static balance requirement is one item considered in defining required longitudinal control power, and the problem of providing the necessary additional maneuvering capabilities on very large airplanes is one of the motivations for studies of direct lift control systems (ref. 1).

For the aft center of gravity location longitudinal stability may be so low that tracking in the float would be difficult; this has, in the past, received little attention, partly because the problem had not been identified explicitly, and partly because only recently have transport airplanes been proposed with very low longitudinal stability. There is no positive evidence that this problem lengthens the required float duration, but the question would certainly appear to warrant investigation.

Whether the foregoing factors, further aggravated by the effects of speed variation during the landing, will significantly affect the time duration in the float remains to be established. The assumed float time of 5 seconds will be recognized then as an interim first guess, representative of a moderately inaccurate landing.

The Touchdown

The final phase of the landing maneuver is easing the airplane to the ground from some small height at an acceptably low touchdown rate, say of the order of 2 feet per second. If at the end of an extended float the airplane sink rate is higher than desired for touchdown, the pilot would require a vertical acceleration capability to check this sink rate. This higher sink rate could result from a deliberate effort to set the airplane down, as the pilot realizes the float period is too long, or could result from failure to maintain the proper attitude variation for level flight as speed decreases in the float. In any case, it is assumed that 0.1 g incremental load-factor capability is desired by the pilot for this touchdown maneuver, at the end of the 5-second float; speed loss in this phase would be unimportant. The value of 0.1 g is probably a reasonable approximation of the load factors that are normally used in this phase of flight. Experimental validation of this value might prove very difficult.

Application Procedure

To estimate the approach speed necessary to provide the capabilities defined in the preceding sections it is convenient to consider the three phases in reverse order, as follows:

1. Phase III:

   a. Determine $C_{L_{max}}$ in ground effect, and as limited by ground attitude geometry (if necessary) and divide by 1.1 to determine C_{L_2} (see fig. 4).

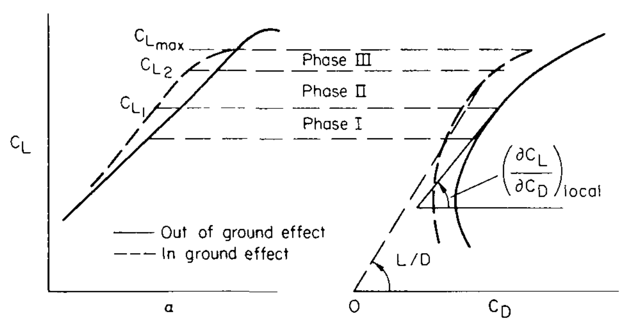


Figure 4.- Representation of the phases in the proposed landing model.

   b. Calculate V_2 from $V_2 = \sqrt{\dfrac{2(W/S)}{\rho C_{L_2}}}$

2. Phase II:

   a. For a C_L range extending from C_{L_2} down to approximately $0.8\ C_{L_2}$, determine an average L/D for the airplane in ground effect.

b. From figure 3, determine the speed decrease during float corresponding to this L/D. Add this increment in speed to V_2 from step 1 above to obtain V_1.

c. Determine C_{L_1} from $C_{L_1} = \frac{2(W/S)}{\rho V_1^2}$. Compare with 0.8 C_{L_2}, and apply an iteration for an adjusted average L/D for the range C_{L_1} to C_{L_2}, if necessary.

3. Phase I:

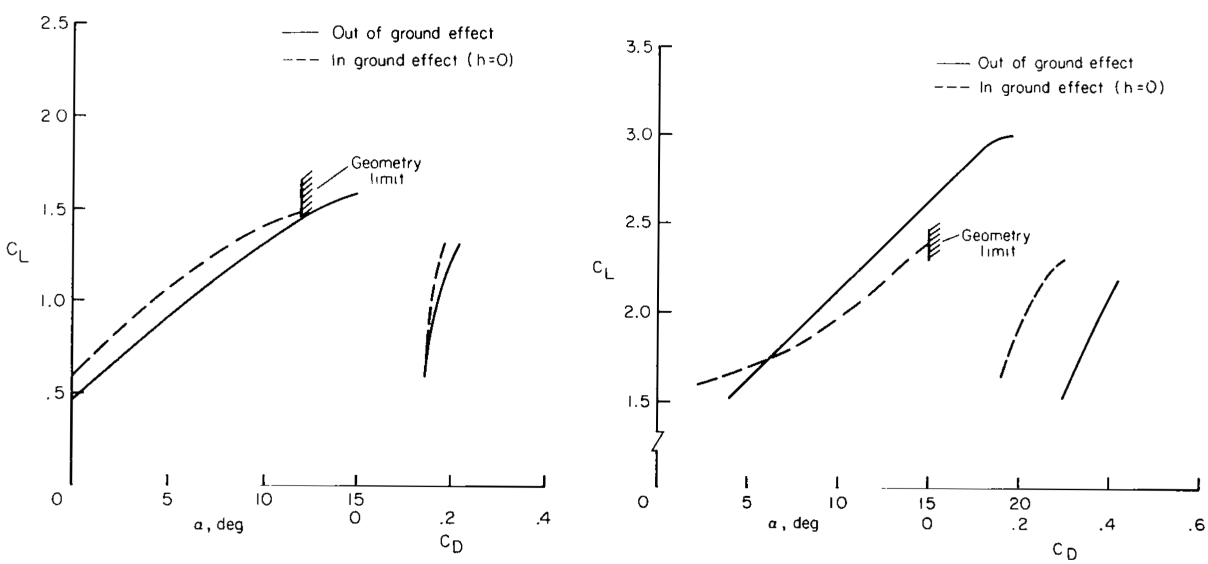
a. For C_L's slightly below C_{L_1}, out of ground effect, estimate the local C_L-C_D slope, $\left(\frac{\partial C_L}{\partial C_D}\right)_{loc}$.

b. Using figure 2, estimate the speed decrease during initial flare for an initial value of $\gamma = -3^\circ$.

c. Add this increment to V_1 as determined from step 2 to determine V_{app}.

APPLICATION TO SUBSONIC TURBOJET TRANSPORTS

The computation methods described earlier have been applied to the estimation of approach speed for two subsonic jet transports. The lift-drag curves for the two airplanes are given in figures 5(a) and 5(b).



(a) Airplane A.

(b) Airplane B.

Figure 5.- C_L-C_D-α curves, trimmed.

Following the calculation procedure outlined earlier, with appropriate designation of each step, the approach speeds are estimated as follows:

Step	Item	Airplane A (W/S = 68)	Airplane B (W/S = 83.3)
1(a)	$C_{L_{max}}$	1.47	2.37
	$C_{L_2} = \frac{C_{L_{max}}}{1.1}$	1.34	2.15
1(b)	$V_2 = 0.592\sqrt{\frac{W}{(1/2)\rho S C_{L_2}}}$, knots	122	107
2(a)	(L/D) (C_{L_2} to 0.8 C_{L_2})	7.0	4.5
2(b)	ΔV_2 (fig. 3), knots	14	19
2(c)	$V_1 = V_2 + \Delta V_2$	136	126
2(d)	C_{L_1}	1.08	1.55
3(a)	$(\partial C_L/\partial C_D)_{loc}$	8.5	5.5
3(b)	ΔV_1 (fig. 2), ($\gamma_o = -3^o$, $a_z = 0.06g$), knots	3	5
3(c)	$V_{app} = V_1 + \Delta V_1$	136 + 3 = 139	126 + 5 = 131
4	V_{ref}	135	120

Reasonable agreement is indicated between estimated and certified approach speeds for airplane A. For reasons that will now be discussed the indicated 11-knot disparity between the predicted and certified approach speeds for airplane B is not considered to invalidate the flare and touchdown model. Setting aside for the moment the possibility that operational pilots might be more prone to use higher approach speeds than are certified for airplane B, consider the model modifications that might be made by way of accommodation. It does not appear likely that the assumptions for either Phase I or Phase III could be altered to improve the correlation between the certified and the estimated approach speeds. If the speed increment from Phase III were eliminated entirely, it would only reduce the estimated approach speed about 5 knots. A similar reduction would result from complete elimination of the increment from Phase I, but since this would (in practice) require the unreasonable technique of consistently increasing thrust during the initial flare, it may be ruled out.

Focussing, then, on Phase II, the float, the adjustments that might be considered would be (1) to retain the thrust during the float, and (2) to shorten the float time. The required decrease in float time to the order of 2 seconds does not seem to allow enough maneuvering time, so the second alternative appears inappropriate. Retaining thrust in the float is a reasonable piloting technique and is apparently the recommended practice for this airplane. It should be noted that while this may be an operational variable on other current turbojet transports, it is generally recognized to be an important requirement for airplane B.

It might be well to review some of the consequences of maintaining thrust through the float. On the favorable side, thrust modulation may be an effective means of limiting the float time or distance, thus improving touchdown precision, and may perhaps compensate for inferior flight-path controllability by aerodynamic means. Experience with fighter airplanes with low L/D has indicated the usefulness of thrust modulation, but thrust-response dynamics would have to be considered in assessing its utility for transports. Moreover, if there are appreciable pitching-moment variations with thrust change, they could compromise the precision of the touchdown maneuver rather than appear as part of a relatively loose initial flare.

There have not been enough quantitative studies in connection with the proposed model to draw definitive conclusions regarding the effect on total landing distance. Qualitatively, some compensating effects can be identified. Consider the alternatives for the airplane B of (1) increasing the initial approach speed to permit a zero-thrust float, or (2) maintaining approach thrust until touchdown. If, as seems reasonable, the touchdown speed is assumed the same in both cases then for case 1, the air distance corresponding to the higher average airspeed would be greater, and for case 2, the time needed to decrease thrust after touchdown would contribute added energy that would increase the ground run. Rough estimates of these effects indicate them to be relatively small, of the order of 100 to 200 feet, and other variables could very well turn out to be much more important in defining landing distance.

To summarize the results of the foregoing analysis, it appears that while the delineation of separate model phases may be reasonable, the detailed assumptions regarding control within each phase need refinement. In one quantitative example, an ambiguity regarding alternative model adjustments (i.e., maintain thrust in the float versus increase approach speed) is partly resolved by the evidence from actual operations where the former technique is recommended. Doubtless, in the general case, the operating characteristics of the airplane in the initial approach at the two speeds in question would influence this selection. From this it may be inferred that the model has some capability for identifying required deviations from a "standard" landing technique, but is inadequate in itself for defining the form of the deviation.

OPERATIONAL FLIGHT DATA

Added confidence in the ability of the model to represent actual operational practice is provided by certain flight data to be described here. The data in figure 6 show the speed decrease in the landing maneuver as a function of distance from the 50-foot height to touchdown. The data were obtained as part of an unreported measurement survey conducted by the FAA on current jet transport landing performance in routine operations at one airfield. The data in figure 6 are representative of 5 types of airplanes: the Douglas DC-8, Boeing 707, 720, 720-B, and the Convair 880 airplanes, and are typical of

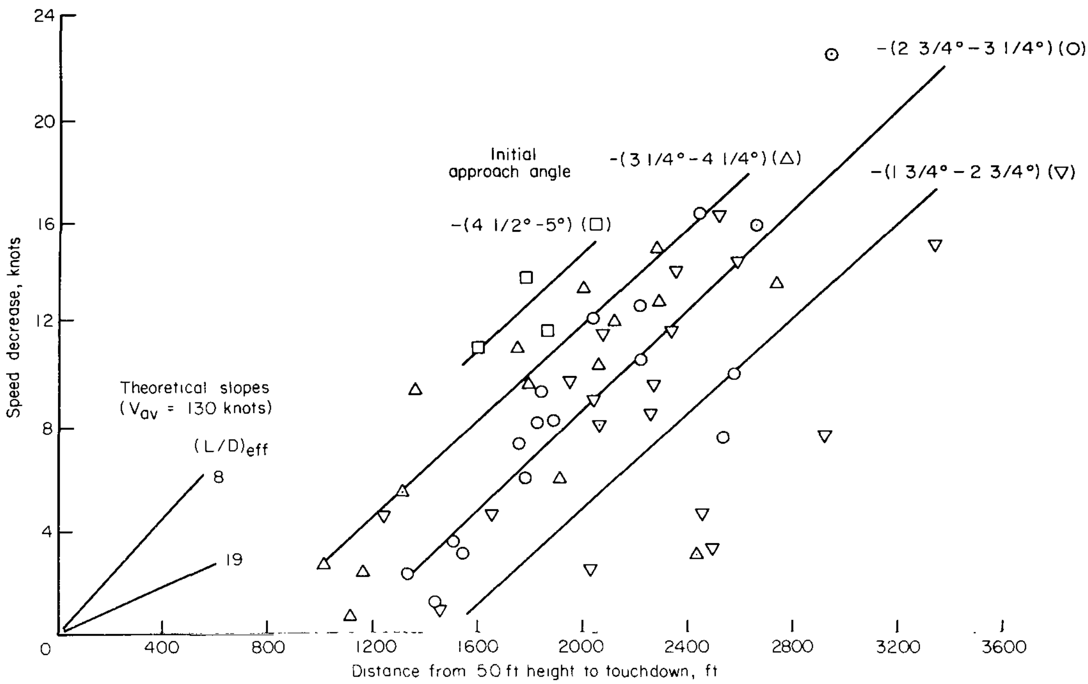


Figure 6.- Typical speed loss in landing maneuver for current subsonic jet transports.

those obtained at four different airfields. The various symbols designate different ranges of approach flight-path angle, and several lines have been drawn to represent the faired variations at given approach flight-path angles. The data indicate the consistency of piloting techniques in operational landing practice by the fact that it was possible to fair lines through the data points from different pilots flying different airplanes, in spite of all the effects of unconstrained operational variables.

The slopes of the curves depend on the effective L/D of the airplane over the interval considered. For comparison, lines are shown on figure 6 for effective lift-drag ratios of 8 and 19, the former being representative of power-off values for this class of airplane in ground effect, the latter being the value if thrust is maintained at approach values through the float. The indications from this comparison are that the variations of speed loss with touchdown distance along a line are associated with differences in the thrust-off float duration (or at least, differences in duration of a power-off flight condition). Emphasis here is on the fact that thrust is off during this time, consistent with the assumption of no thrust in Phase II that was initially proposed.

A trend toward displacement of the various slopes with initial flight-path angle is evident in the data in figure 6. This is indicative that pilots are not adjusting their thrust management to the different flight-path angles. For a given distance to touchdown, increments in speed decrease would be associated with different initial flight-path angles as shown by the curves of figure 2. The spacing of adjacent lines in figure 6 corresponds to increments in speed decrease that would be predicted, on the basis of constant thrust, for about a $3/4^\circ$ shift in γ_o. Actually, somewhat larger increments are indicated by the flight data than predicted, which suggests some reduction of thrust in the initial flare. However, increments are still much closer to the constant-thrust values than they would be to zero-thrust values.

Because of the scatter of the data points in figure 6, these data cannot be offered as definitive validations of the model. On the other hand, the very fact that consistent trends can be identified in data obtained as these were, is considered encouraging evidence that the model represents actual operational practice quite reasonably.

CONCLUDING REMARKS

A simple model is proposed to describe the final airborne stages of manually landing a transport airplane. The applicability of the model has not been confirmed in all details. In particular, the constraints initially suggested for thrust management appear to need adjustment for the characteristics of each airplane design. However, one quantitative application has indicated that the model can be used effectively to show that a modified thrust management is needed to accommodate to approach speeds as currently certified. A broad inference of this finding is that the model may contribute to the development of rules for defining approach speeds and landing distances that would be commensurate with operational piloting techniques. The model would also appear useful for defining approach speeds for airplanes that do not have a well-defined maximum lift coefficient. A rational basis for including the effects of ground geometry limitations and of drag, both in and out of ground effect, is a noteworthy feature of the model. Additional development of the model is needed in order to refine quantitative values for certain parameters included in it.

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National Aeronautics and Space Administration
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APPENDIX

SPEED DECREASE IN CONSTANT-THRUST FLARE

If the thrust balances the combined effects of the drag and the gravity contribution of the inclined flight path just prior to flare initiation, and the thrust remains constant during the flare, then speed is decreased only by the increasing flight-path angle and the increased drag during the flare. Small-angle approximations can be used to express the speed change due to these effects by:

$$\Delta V_1 = \int_0^{T_1} a_x \, dt = -\int_0^{T_1} g \, \Delta\gamma \, dt + \frac{a_z}{(\partial C_L/\partial C_D)_{loc}} \, dt \tag{1}$$

where $\Delta\gamma$ is the change in flight-path angle (from the initial value) at time t, and T_1 is the time required to complete the flare. If a_z is assumed constant during the flare, and the effect of changing V is ignored, $\Delta\gamma$ may be expressed as:

$$\Delta\gamma = \int \dot{\gamma} \, dt = \int \frac{a_z}{V} \, dt = \frac{a_z}{V} t \tag{2}$$

When this value of $\Delta\gamma$ from equation (2) is substituted into equation (1):

$$\Delta V_1 = -\int_0^{T_1} g \frac{a_z}{V} t \, dt + \frac{a_z}{(\partial C_L/\partial C_D)_{loc}} \, dt \tag{3}$$

$$= -\frac{g a_z}{V} \frac{{T_1}^2}{2} - \frac{a_z}{(\partial C_L/\partial C_D)_{loc}} T_1 \tag{4}$$

If the initial flight-path angle is assumed to be reduced to zero in the flare:

$$T_1 = \frac{\gamma_o}{\dot{\gamma}} = \frac{\gamma_o V}{a_z} \tag{5}$$

Then

$$\Delta V_1 = -\frac{g a_z}{2V} \cdot \frac{{\gamma_o}^2 V^2}{{a_z}^2} - \frac{a_z}{(\partial C_L/\partial C_D)_{loc}} \frac{\gamma_o V}{a_z} \tag{6}$$

$$= -\frac{g {\gamma_o}^2 V}{2 a_z} - \frac{\gamma_o V}{(\partial C_L/\partial C_D)_{loc}} \tag{7}$$

REFERENCE

1. Zalovcik, John A.; and Schaefer, William T., Jr.: NASA Research on Noise-Abatement Approach Profiles for Multiengine Jet Transport Aircraft. NASA TN D-4044, 1967.

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