A METHOD FOR DETERMINING LANDING RUNWAY LENGTH FOR A STOL AIRCRAFT

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SUMMARY

The certification method that is presently used by the FAA for determining runway landing lengths for conventional transports and that might be applied to STOL aircraft would require longer STOL runways than those envisioned by designers for a metropolitan STOL-port. During the development and evaluation of an automatic landing system for the Augmentor Wing Jet STOL Research Airplane (AWJSRA) this matter of runway lengths was examined. Based on data obtained from flight tests of the AWJSRA, a new method is proposed for determining the length of the landing runway for powered-lift STOL aircraft. The suggested method determines runway landing length by summing three segments: the touchdown-dispersion distance, the transition distance from touchdown to application of brakes, and the stopping distance after brakes are applied. In addition, it is shown how the landing field length can be reduced either through improved autoland system design or by providing the pilot with appropriate information to allow him to identify a "low probability" long or short landing and to execute a go-around.

INTRODUCTION

STOL aircraft have been envisioned as the main element in a high-speed transportation system connecting metropolitan centers, major hub airports, and outlying communities. Basic to such a system is the requirement for safe routine operation into STOL runways. At the present time, the general basis for determining the landing distance performance of a transport category STOL airplane is the airworthiness requirement of Federal Air Regulations (FAR) Part 25 (ref. 1). The operating rule for determining the landing runway length is contained in FAR Part 121 (ref. 2). However, there are developments that might lead to FAR revisions in this area. For example another method, which has been considered for determining an operational runway length requirement, takes into account a specific aircraft and various runway characteristics. To date this method, known as the rational method, has only been applied to the Concorde supersonic transport (ref. 3). The FAA has recognized the need for new airworthiness standards for powered lift STOL transport category aircraft. Proposed Airworthiness Standards for Powered Lift Transport Aircraft, Part XX (ref. 4) presents a method for determining the required landing runway length based on a variation of FAR Part 25 (ref. 1).

Rational method concepts for determining the landing distance are recommended in reference 5. Airport planning recommendations for metropolitan STOL-ports are presented in reference 6.

In addition to the above developments, flight experience has been accumulated for light-wing-loading as well as powered-lift STOL aircraft. For example, reference 7 presents data for a FAA Twin Otter flight-test program that uses a 549-m (1,800-ft) STOL runway with 30-m (100-ft) safety overruns. These data indicate that the Twin Otter is capable of routine operations into the type of STOL-port recommended in reference 6. Considerable data were collected on the landing performance of a specially equipped Twin Otter in the Canadian Air Transportation Administration, Ministry of Transport demonstration program (refs. 8, 9). Satisfactory operation into a 610-m (2,000-ft) STOL runway with 134-m (440-ft) safety overruns was demonstrated. Since the Canadian STOL demonstration, another light-wing-loading turboprop STOL airplane, the deHavilland DHC-7, has begun service into a high-density hub airport (ref. 10). A proposed "stub" runway concept is being evaluated in which the DHC-7 and conventional takeoff and landing (CTOL) aircraft would be allowed to fly simultaneous approaches; the CTOL airplane would land on the main runway, and the DHC-7 would land on an intersecting runway and then stop short of the main runway. Under special STOL conditions for the DHC-7 certification (ref. 11), the airplane can operate into a 594-m (1,950-ft) runway.

Experience with one powered-lift STOL airplane, the McDonnell Douglas Model 188 (Breguet B.R. 941S) has been reported in references 12 and 13. Reference 12, which describes a demonstration program conducted by American Airlines, presents general performance numbers for the airplane but makes no recommendation about the landing runway length. Reference 13 presents landing distance performance data for 60 landings; it notes the need for special factors to cover the effects of wind disturbances, runway conditions, and landing technique for each type of STOL airplane and recommends that a demonstration procedure for rationally determining landing performance replace the current procedures of FAR Parts 25 and 121.

This paper discusses the present runway length certification methods including FAR Parts 25 and 121, special conditions for the DHC-7, the rational method, and the CTOL autoland certification process. This is followed by a detailed discussion of a proposed method for establishing the runway length for STOL aircraft. The present and proposed methods are then compared, using the example of the propulsive-lift STOL aircraft. The report concludes with a discussion of techniques for reducing runway length requirements for STOL aircraft through high touchdown sink rates, or by using special pilot displays to facilitate go-arounds when the pilot sees an out-of-tolerance situation.

PRESENT RUNWAY LENGTH CERTIFICATION METHODS

The certification method used in FAR Parts 25 and 121 and in the rational method can be characterized as a deterministic method. That is, the manufacturer works with the FAA to conduct a limited number of landings and uses data from those landings to arrive at a certified landing distance. The FAA adopts another method, a statistical method, in certifying automatic landing systems, as discussed in Advisory Circular AC 20-57A (ref. 14). The specification states that no more than a certain percentage of the total number of landings shall be outside a specified touchdown region. An application of the statistical method for autoland certification is presented for the L-1011 in reference 15.

A statistical method that has been proposed for determining the landing distance for a STOL transport is discussed in references 16 and 17. Parameters important to the determination of landing distance, such as approach airspeed, touchdown distance, and stopping distance, are evaluated in terms of probabilities. Safety limits are assigned to each parameter. If the pilot determines that any critical parameter exceeds safe limits, he must either execute a go-around or prepare to engage an emergency arresting gear for stopping. The airplane manufacturer must establish through design and testing that the probability of exceeding safety limits on critical parameters is acceptable to the FAA and operators.

Several key issues emerge from a review of references 1 through 17. A conservative method of determining the landing distance performance for transport aircraft is presently used that requires relatively little flight data, is applicable to existing types of operational aircraft, and yet insures safe operations. For STOL aircraft in which heavy emphasis is on maximizing landing performance, investigators of that performance indicate a preference for the rational method but note the difficulty of evaluating the effects of a wide range of atmospheric conditions, runway conditions, and airplane characteristics. Many flight-test landings, supplemented by considerable simulation work, are needed to investigate the performance of each type of airplane. The probabilistic approach presented in references 16 and 17 provides the tool for determining the landing runway length needed for the STOL airplane.

FAR Part 25

Figure 1(a) outlines the procedure presently contained in FAR Part 25 (ref. 1) for determining the flight manual reference landing distance (RLD). The RLD is determined from maximum-effort flight-test data as the horizontal distance required to land and come to a full stop from a point 15 m (50 ft) above the landing surface. As noted earlier, this method is broadly applied to transport aircraft.

FAR Part 121

FAR Part 121 (ref. 2) provides the operating factors that determine the runway length required at the destination airport before a commercial transport can be dispatched to that destination. As shown in figure 1(a), the destination airport runway length required is RLD/0.6 for a dry runway and (RLD/0.6) × 1.15 for a wet runway.

Special Condition for DHC-7

The deHavilland DHC-7 has been certified in the United States under special conditions developed by the FAA (ref. 11). Under this special condition, the STOL landing distance for the DHC-7 is determined for a 7.5° glide slope from the lowest point of the airplane at an altitude of 11 m (35 ft) to stop. The 0.6 factor for the destination airport dry runway length of FAR Part 121 is retained for the DHC-7.

Rational Method for Concorde

The rational method (ref. 3) was developed for transport certification; however, it has been applied only to the Concorde supersonic transport. This method, outlined in figure 1(b), specifies the separate determination of an air segment, a transition segment, and a stopping segment. The air segment begins with the lowest part of the airplane at an altitude of 15 m (50 ft) on a 2.5° glidepath and ends at the point of touchdown. The transition segment begins at the point of touchdown and ends when a deceleration device is applied. The stopping segment is from the point where the braking device is applied to the point where the airplane comes to a stop. The operating portion of the rational method requires that a multiplication factor of 1.15 be applied only to the stopping segment for determining the dry runway length. A wet runway correction factor, determined for each specific runway, can range from 1 to 4. Figure 1(b) shows that the landing runway length is the sum of the air segment, the transition segment, and the factored stopping segment.

CTOL Autoland Certification Process

The autoland certification process for a CTOL jet transport (from ref. 14) is illustrated in figure 1(c). This autoland process provides the method for determining the touchdown zone requirement that is adopted as part of the proposed procedure described in the next section.

PROPOSED METHOD FOR ESTABLISHING THE RUNWAY LENGTH FOR STOL AIRCRAFT

The new method proposed here for determining the landing runway length for a STOL aircraft is a combination of the statistical method used by the FAA for autoland certification (ref. 14) and the rational method developed for the Concorde landing distance certification (ref. 3). Probabilistic data like those used for autoland certification determine the length of runway that must be reserved to accommodate touchdown dispersions. Deterministic data from the rational method determine the distance from touchdown to brake application and the distance from brake application to point of stop.

The touchdown data from the automatic landing system flight tests provide an example for the application of the proposed method. These tests were conducted by Ames Research Center using a powered-lift STOL airplane. The test airplane, which is referred to as the Augmentor Wing Jet STOL Research Airplane (AWJSRA), is shown in figure 2 and is described in reference 18. These flight tests were conducted using a microwave landing system (MLS). An automatic landing system (described in ref. 19) was utilized in the tests. An operationally oriented flight-director system for flying curved descending approaches (described in ref. 20) has also been flight-tested on the AWJSRA.

General Method

The landing runway length needed for a powered-lift STOL airplane is proposed to be determined as the sum of three segments (fig. 3): a touchdown-probability-dispersion distance, a transition-segment distance, and a factored stopping-segment distance. The touchdown-dispersion distance is determined using the method that is used for automatic landing system certification (ref. 14); it is illustrated in figure 1(c).

The rationale for the use of the transition and stopping segments in the determination of runway landing length is well established in connection with the rational method (ref. 3) and will be adapted for determining the STOL runway landing length. However, the rationale for use of touchdown-probability dispersion requires some explanation.

From the outset, in considering this problem, it appeared that a conservative approach must be used, with emphasis on taking maximum advantage of the capability of an automatic landing system to accurately control the landing touchdown point. As previously noted, it appeared that the "Automatic Landing System Criteria" of reference 14 meet the above requirements. Moreover, enough experience has been gained in the certification of autoland systems for CTOL aircraft, using the criteria of reference 14, to make this approach a credible one.

In essence, the longitudinal touchdown dispersions about a nominal point on the runway must be demonstrated in flight. Sufficient flight-test data are usually obtained to define the $2\text{-}\sigma$ probability landing dispersions. These flight-test results are then backed up by a suitable computer or simulation analysis, which extends the landing dispersion estimate to the $4\text{-}\sigma$ to $5\text{-}\sigma$ level; that is, to the determination of the improbable-event touchdown distance. This latter "dispersion" distance is the third segment, which is summed with the transition and stopping segments to define the proposed landing runway length for STOL aircraft.

The method of determining the touchdown probability distribution is well established for automatic landing systems. Unfortunately, a comparable method applicable to manual landings has not been developed. In order for this proposed method to be useful for a manually flown airplane, a suitable procedure for extrapolating manual flight-test data to account for the improbable event will be needed. Extrapolating flight data on the basis of an assumed probability distribution is the procedure employed in reference 7. Another possible procedure would require the development of a suitable pilot model for use in a high-speed simulation. Still a third possible procedure is to accumulate operating experience from a large number of landings, using instrumented airplanes.

The next four sections will describe the determination of the touchdown dispersion, the transition segment, and the stopping segment from the AWJSRA autoland flight test and simulation data.

Touchdown Dispersion

Figure 4 shows touchdown data presented in the form of a probability distribution plot. The data are plotted on paper on which a normal probability distribution appears as a straight line. These data were obtained from both flight test and high-speed computer simulation for the best performing of several autoland control laws examined (ref. 19). The circles in figure 4 represent the probability distribution data for 31 flight-test automatic landings; the solid line represents more than 10,000 samples of data obtained from high-speed computer simulation. The abscissa shows the touchdown distance measured with respect to the MLS glidepath intercept point (GPIP). The ordinate shows the probability that the touchdown distance will exceed the abscissa value. The shaded vertical band in figure 4 represents the 61-m (200-ft) STOL-port marked touchdown zone shown in figure 2. The touchdown dispersion for any probability level can be read from the simulation data in figure 4. For example, there is a 97.7% (2-σ short landing) probability that the airplane will land longer than 34 m (110 ft) and a 2.3% (2-σ long landing) probability that the airplane will land longer than 157 m (515 ft). The difference between the 2-σ short landing and the 2-σ long landing is the 2-σ touchdown dispersion.

The 31 flight-test landings provide (1) a good estimate of the mean value and the 1-σ performance of the autoland system, (2) a poorer estimate of the 2-σ performance, and (3) no estimate at all of the low-probability performance. The low-probability performance is estimated by first validating the simulation with flight-test data and then using the simulator to generate the low-probability performance. Figure 4 shows agreement between the flight and simulation data, provided differences in the flight and simulation wind disturbances are taken into account. The wind disturbances encountered in flight were less than the reference 14 wind model disturbances used for the simulation. The steeper slope of the flight data probability distribution curve in figure 4 is the result of lighter wind disturbances. The difference in the mean touchdown distance between flight and simulation is the result of a residual modeling discrepancy coupled with the fact that the range was not explicitly controlled in the AWJSRA autoland system. The match between the simulation and flight data is believed to be adequate to establish the validity of the simulation data.

The FAA has allowed 10^{-6} to define the improbable event for a recent autoland certification (ref. 15). Figure 4 shows that the touchdown dispersion for a 10^{-6} probability is 297 m (970 ft); this is the value that will be used later to define the STOL runway landing length. References 16 and 17 present another view on the probability level to use in determining the required runway landing length for a STOL-port. If the pilot had the means of detecting that the airplane would land outside an acceptable touchdown region, a go-around could be executed. References 16 and 17 state that from an airline point of view no more than 1×10^{-3} approaches should result in a go-around. One landing in 1,000 means that the probability of landing short is $1 - (0.5\times10^{-3})$ and the probability of landing long is 0.5×10^{-3}. Using the simulation data from figure 4, the touchdown dispersion for 1×10^{-3} landings is 203 m (665 ft).

Transition and Stopping Segments

Transition and stopping segment time histories are shown in figure 5 for three levels of braking performance: maximum, moderate, and minimum. To execute a maximum-performance stop, the pilot applied the antiskid brakes installed on the main wheels of the AWJSRA as firmly as possible until the airplane came to a stop. It should be noted that the pilots object to maximum antiskid operation because of attendant longitudinal jerk (i.e., rate of change of acceleration).

Figure 5(a) shows a typical maximum-performance time history of longitudinal acceleration and distance from touchdown to stop. A maximum-performance stop is characterized by a rapid change in deceleration from 0 to -0.4 g in 0.5 sec followed by two cycles of antiskid brake operation before a near steady state -0.42 g is achieved.

Figure 5(b) shows a moderate-performance time history. The pilot applied brakes gradually to avoid antiskid brake cycling, taking 10 sec to achieve a steady-state deceleration of -0.42 g. The difference between maximum and moderate performance appears to be the rate of onset of deceleration rather than the steady-state deceleration. A typical time for achieving the steady-state deceleration was 2.5 sec; this onset time will be used for subsequent stopping segment calculations.

Figure 5(c) shows another type of stop that can be denoted either as a minimum-performance stop or as "turn off at the next taxiway" (located beyond the end of the STOL runway markings). In this case, following an initial deceleration, the airplane was allowed to coast until near the second turnoff after the touchdown zone, at which time light braking was applied just before the turn.

Transition segment- During the transition segment, the pilot of the AWJSRA must reduce thrust, lower the nose of the airplane from the 6° pitch attitude, which was commanded by the automatic landing system, and begin applying the brakes.

Figure 6 shows transition-segment data as a function of groundspeed for minimum-performance stops and for maximum- and moderate-performance stops. The transition-segment distance varied randomly from 40 m (131 ft) to 88 m (290 ft) for the maximum- and moderate-performance stops and was beyond 91 m

(300 ft) for the minimum-performance stops. The transition-segment samples obtained during the flight tests do not show a trend with groundspeed; nevertheless, such a trend would be expected. This trend might have become evident if the pilots had been asked to minimize transition-segment distance as well as the overall touchdown-to-stop distance. In any case, the transition-segment distance for the maximum- and moderate-performance landings never exceeded 91 m (300 ft); this number will be used for subsequent determinations of required runway landing length.

Stopping segment- The distance that must be available for stopping an airplane is simply computed by integrating a longitudinal acceleration profile. Figure 7 shows the stopping distance computed for a range of wind speeds and for an assumed moderate longitudinal acceleration profile like that seen in figure 5(b). The braking commences at the end of the transition segment with a typical AWJSRA calibrated airspeed V_c of 55 knots. Accelerometer data recorded during AWJSRA performance landing stops show peak deceleration levels of -0.42 g. However, the -0.35 g deceleration profile curve matches the recorded moderate stopping distance apparently because of reduced average deceleration associated with antiskid brake cycling.

Figure 7 shows that the longest stopping distance occurs in a tailwind. The pilot will generally avoid a tailwind situation, but in rapidly changing wind conditions, a tailwind can develop during the approach. Therefore, a conservative runway landing length should be based on a 10-knot tailwind. For a 10-knot tailwind and a -0.35-g deceleration profile, the dry runway stopping distance is 204 m (670 ft).

References 21 and 22 show that very long stopping distances can occur due to hydroplaning if the runway is flooded. These references also indicate that if the runway is grooved, a flooded runway need only be 10% longer than a dry runway to insure equivalent stopping performance. References 6, 16, and 17 conclude that a grooved and heated runway will be a necessary feature of an all-weather STOL-port. In the comparison of methods of determining runway landing length that follows, a division factor of 0.9 is assumed to be adequate for determining the length of the grooved runway needed in wet conditions.

References 21 and 22 also indicate that a maximum deceleration of -0.55 g is possible if the airplane is equipped with antiskid brakes on the nosewheel as well as on the main wheels. If the AWJSRA had been equipped with antiskid brakes on all wheels, a steady-state deceleration of -0.45 g would probably have been possible. Figure 7 shows that the stopping distance in a 10-knot tailwind with a -0.45-g average deceleration is 169 m (555 ft).

COMPARISON OF METHODS

Figure 8 summarizes the runway landing lengths needed for both the FAR Parts 25 and 121 method and the proposed method. Based on a maximum-performance landing conducted with the AWJSRA, the FAR Part 25

15-m-altitude-to-stop (50-ft-altitude-to-stop) reference landing distance would be near 409 m (1,340 ft). Applying the FAR Part 121 destination-airport factor of 0.6 results in a required dry runway landing length of 680 m (2,230 ft). Applying the 1.15 factor results in a wet runway landing length of 782 m (2,570 ft). Both the dry and wet runway landing lengths exceed the recommended (ref. 6) STOL-port runway length of 457 m (1,500 ft) to 549 m (1,800 ft).

If the 11-m-to-stop (35-ft-to-stop) provision of the special STOL condition for certification of the DHC-7 is applied to the maximum-performance landing of the AWJSRA, the reference landing distance would be 366 m (1,200 ft). The destination-airport factor of 0.6 results in a required runway landing length of 610 m (2,000 ft). This distance also exceeds the runway length recommended in reference 6.

The proposed-method runway landing length is the sum of a touchdown-probability distribution determined as for autoland certification (ref. 14), a transition-segment distance, and a factored stopping-segment distance from the rational method (ref. 3). The 10^{-6} improbable-event touchdown probability distribution of 296 m (970 ft) summed with the 91 m (300 ft) transition segment distance and a factored stopping distance of 204 m (670 ft) results in a dry runway landing length of 622 m (2,040 ft), which still exceeds the recommended STOL-port length. In this case, the stopping distance is based on the main wheel and antiskid brakes installed on the AWJSRA and on the 1.15 factor applied only to the stopping distance as adopted from the rational method. The assumed additional 10% factor for a wet grooved and heated runway increases the runway landing length to 649 m (2,130 ft).

If the airline point of view from references 16 and 17 is adopted (1 out of 1,000 approaches can result in a go-around) and if the airplane is assumed to be equipped with antiskid brakes on all wheels, the runway landing length is within the STOL-port runway length recommended in reference 6. In this case, the dry runway landing length is 488 m (1,601 ft) and the grooved-and-heated wet runway length is 510 m (1,673 ft).

TECHNIQUES FOR REDUCING RUNWAY LENGTH REQUIREMENTS

The touchdown dispersion results presented in this paper were obtained with an automatic landing system that was designed to produce the low touchdown sink rates (near 1 m/sec (3 ft/sec)) found in contemporary CTOL autoland systems, but to do so for a powered-lift STOL airplane flying a 7.5°-glide-slope landing approach. Improved touchdown dispersions can probably be achieved by using a range feedback term in the autoland control law and by accepting higher touchdown sink rates. However, such improvements in automatic landing system design are no aid in reducing the touchdown dispersion for manually flown approaches. There is an acute need to find a way — equally applicable to both automatic and manually flown systems — to reduce touchdown dispersion.

As noted earlier, one way to reduce the runway landing length needed for a STOL airplane is to execute go-arounds for those landing approaches that will be outside a desired touchdown region. The key element in this procedure is a display that will provide the pilot with an indication of the touchdown point.

Some form of cockpit display, perhaps integrated into a head-up display, is needed for approaches in near-zero visibility and ceiling conditions. Two such display concepts have undergone preliminary evaluations on the AWJSRA, which was equipped with an electronic attitude display indicator (EADI) as shown in figure 9 and described in reference 23. The EADI incorporated a perspective runway and a path-deviation box. The perspective runway was intended to provide the pilot with a simple picture of the runway during the approach. This display provides some measure of both range and range rate. The path-deviation box shows glide slope and localizer error on the approach down to the flare height. This sort of raw data information is presently used down to the decision height but not below. For the AWJSRA evaluation the path-deviation window was mechanized to show errors from a reference flare path throughout the flare maneuver, thereby providing the pilot with an indication of a long or short landing. A brief evaluation of this mechanization of the path-deviation window was conducted with the AWJSRA. Although the EADI displays appeared to provide the desired range-error information, the pilot was not inclined to ride through the flare with his head down. Further research in conjunction with a head-up display is needed to determine if the pilot can perceive and react to a range-error display in time to execute a satisfactory go-around maneuver.

CONCLUDING REMARKS

A systematic method for defining the runway landing length for a STOL transport has been developed. In this method the runway length is composed of the sum of three segments: the touchdown-dispersion distance, the transition-segment distance from touchdown to the application of a braking device, and the stopping-segment distance after a braking device is applied. The method combines statistical and deterministic data.

The proposed method appears to determine a safe runway landing length for the STOL application and offers the potential for reducing runway length if great emphasis is placed on a short-runway capability. FAR Parts 25 and 121 appear conservative and suitable for the situation where no great emphasis is placed on reducing the runway length requirement.

Work directed at techniques to shorten the landing runway length requirement is under way. Cockpit displays, which would permit the pilot to reject long or short landings, appear to have the greatest potential for reducing required runway landing lengths.

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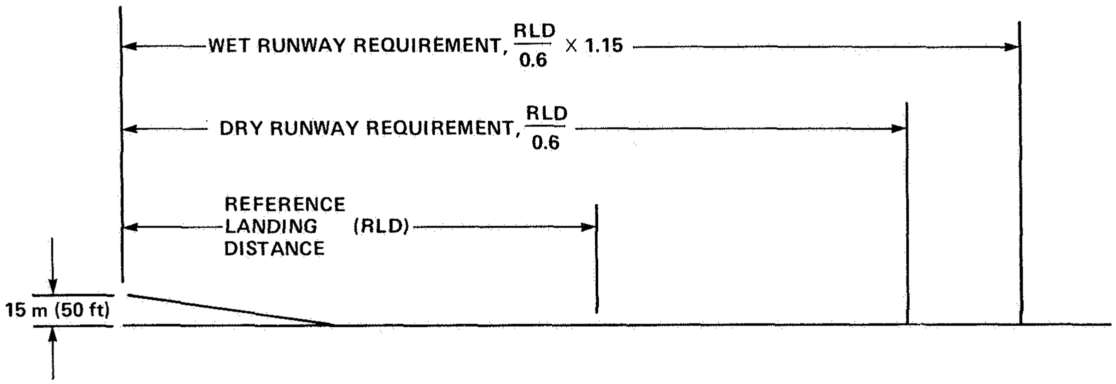
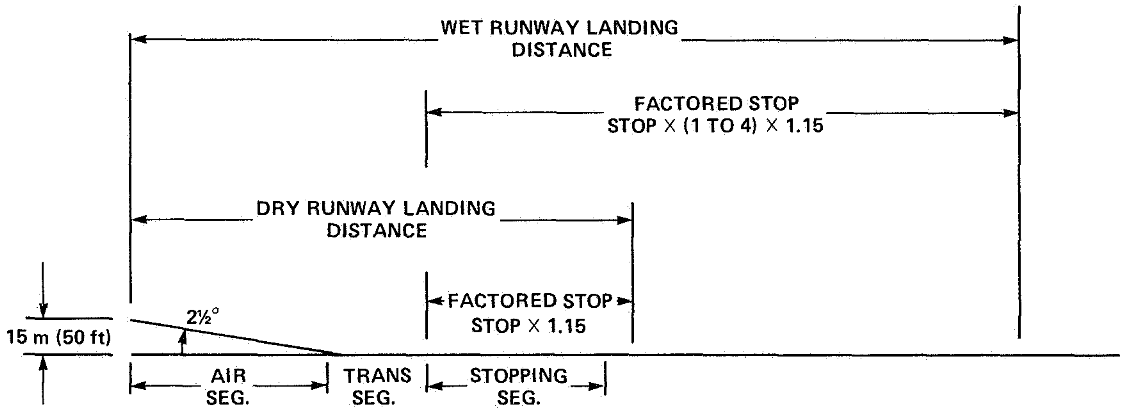
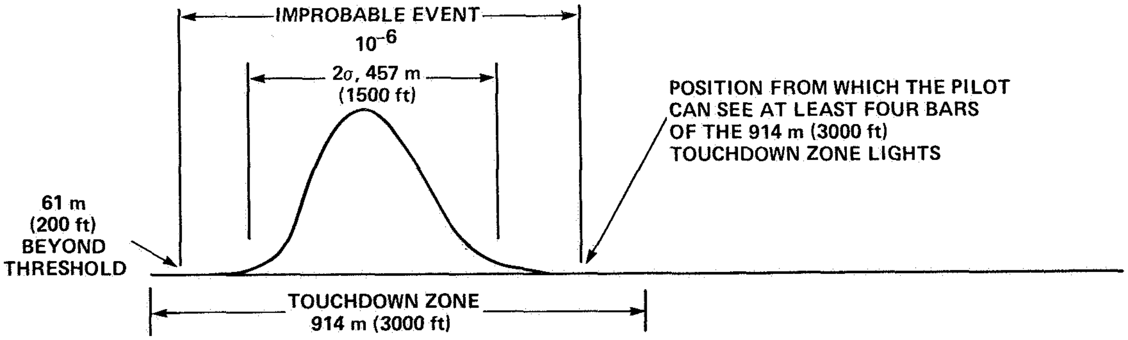


(a) Method of FAR Parts 25 and 121.



(b) Rational method for Concorde.



(c) Autoland requirement.

Figure 1.- Present certification methods.

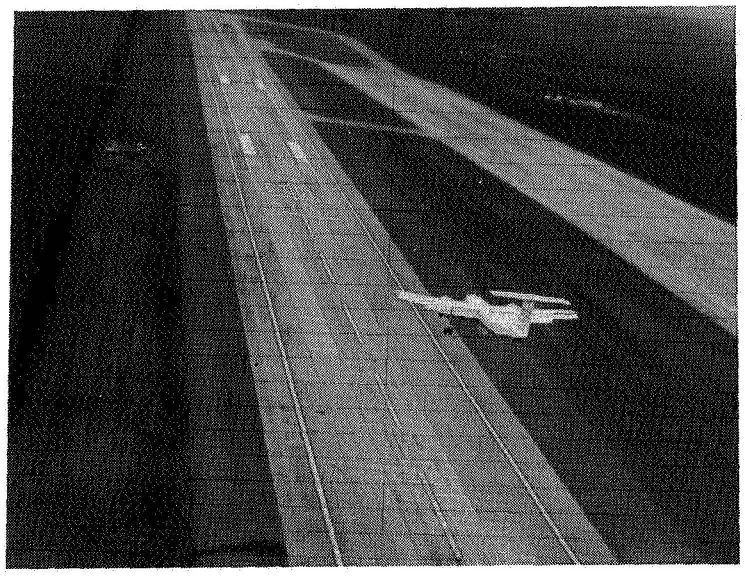


Figure 2.- The Augmentor Wing Jet STOL Research Airplane on an automatic landing approach to a 518-m (1,700-ft) microwave-landing-system-equipped STOL-port located at the Crows Landing Navy Auxiliary Landing Field, California.

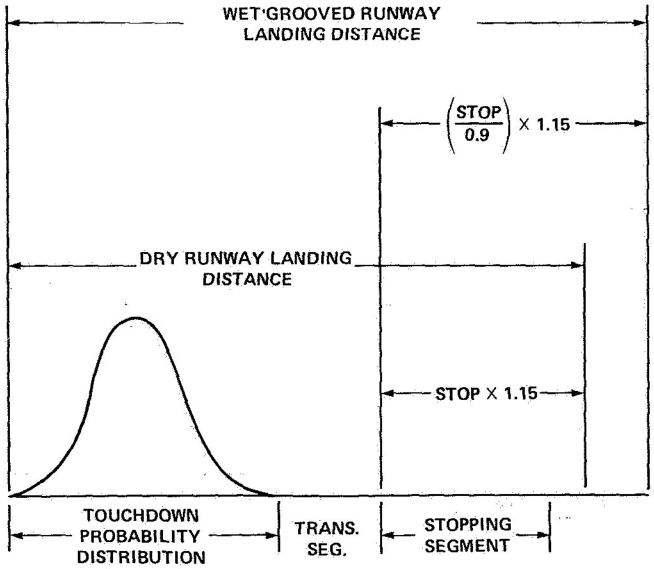


Figure 3.- Proposed method for STOL autoland.

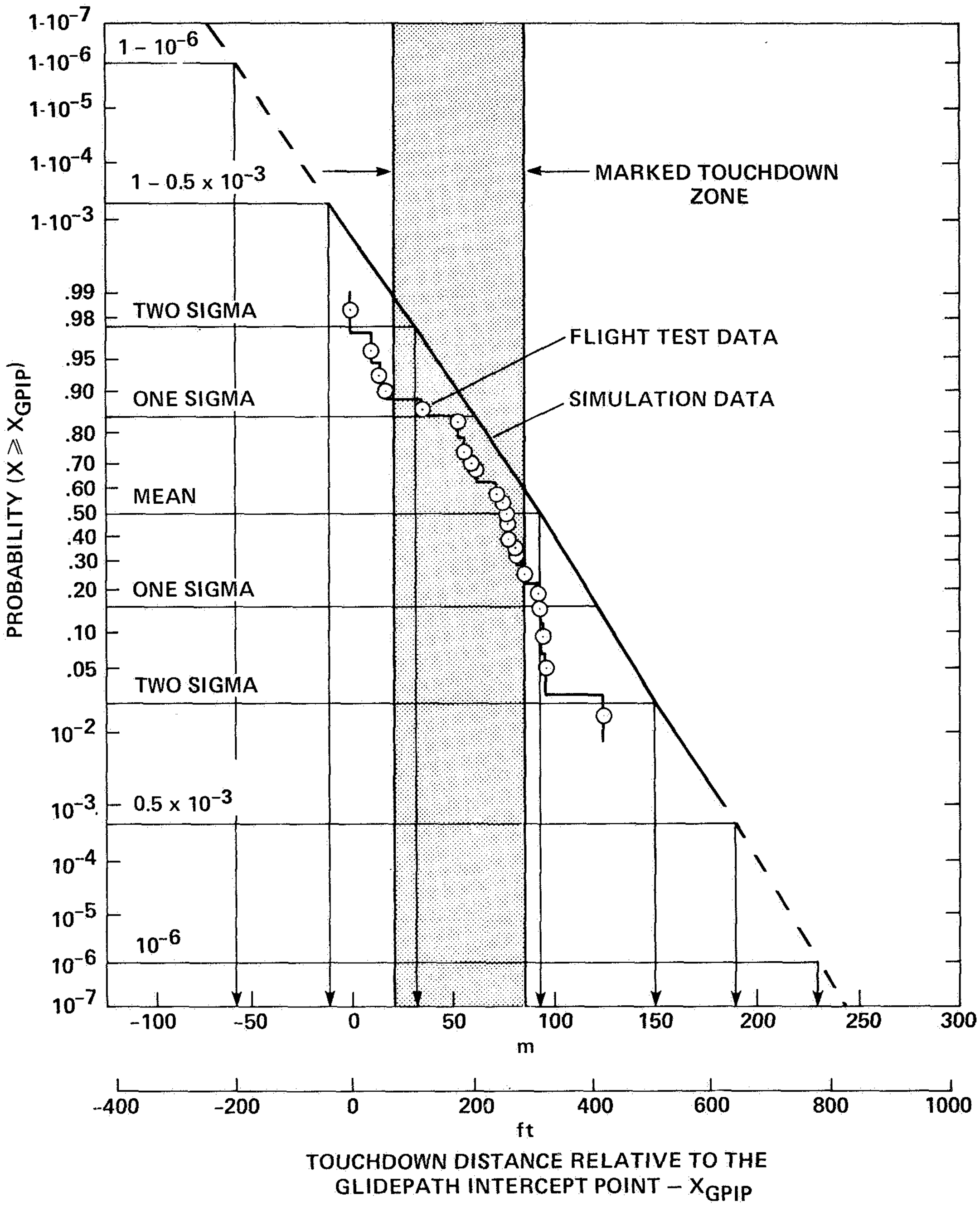
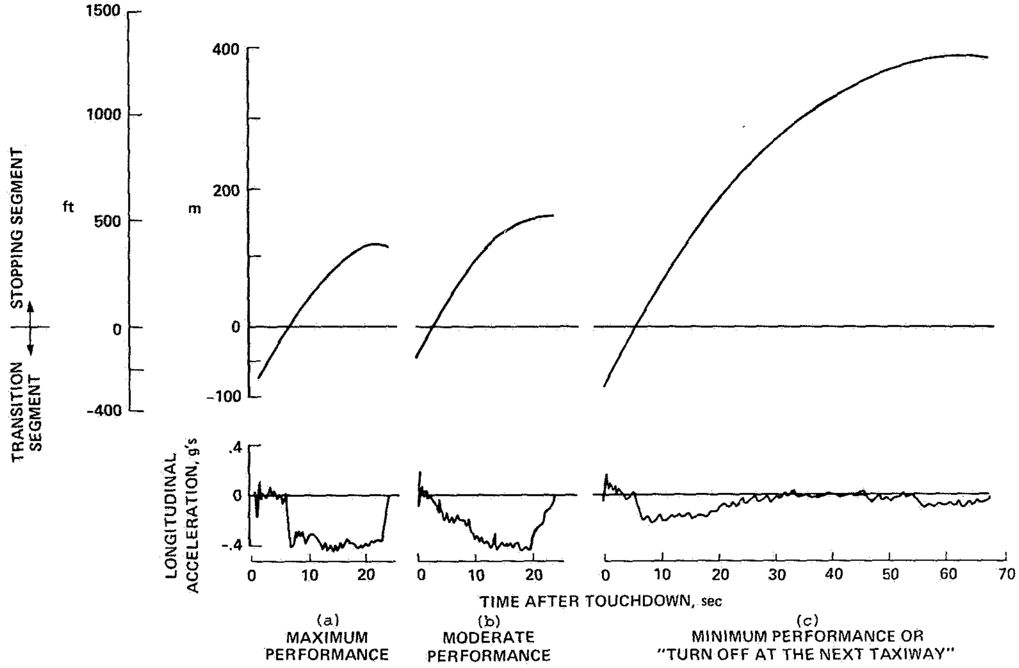


Figure 4.- Touchdown probability distribution for the AWJSRA autoland system.



(a) MAXIMUM PERFORMANCE

(b) MODERATE PERFORMANCE

(c) MINIMUM PERFORMANCE OR "TURN OFF AT THE NEXT TAXIWAY"

Figure 5.- Transition and stopping segment time histories.

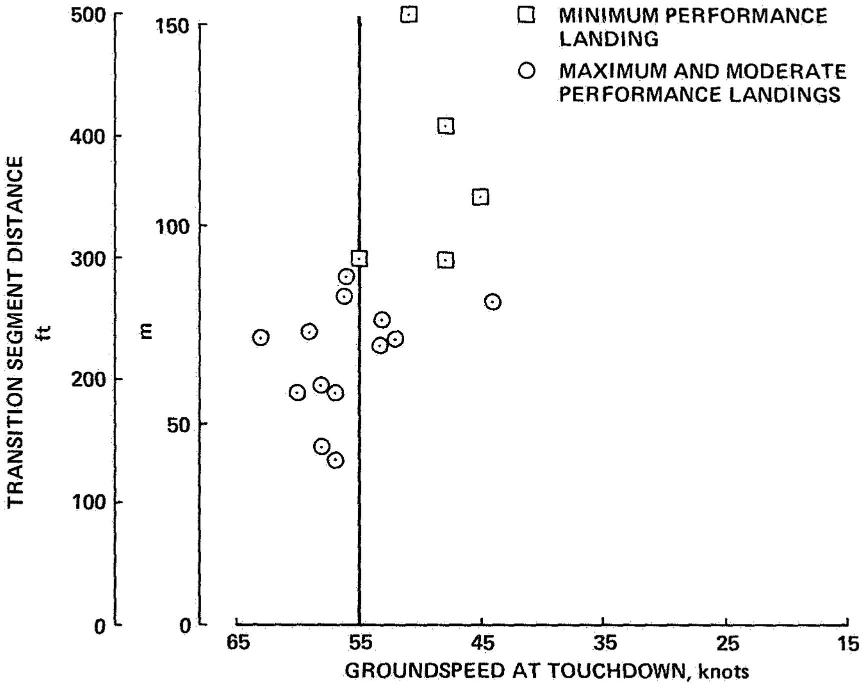


Figure 6.- Transition segment distance as a function of touchdown groundspeed.

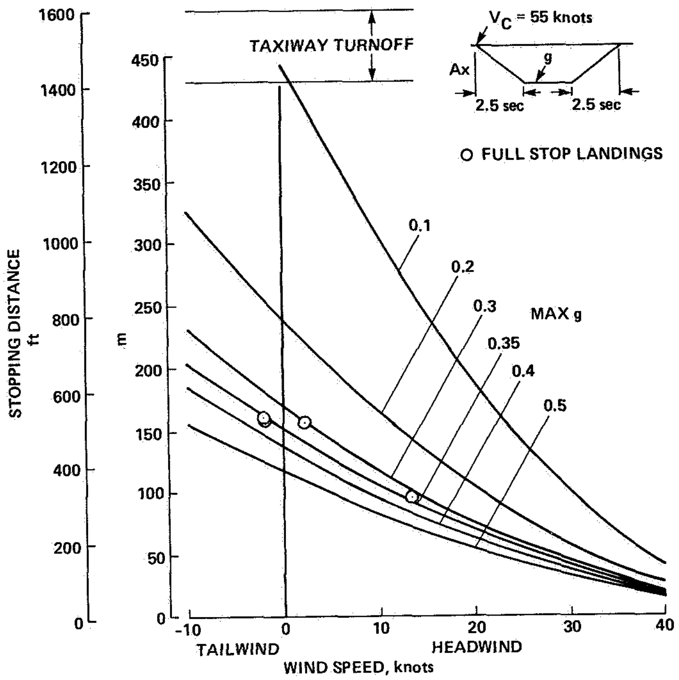


Figure 7.- Moderate-performance stopping distance as a function of windspeed.

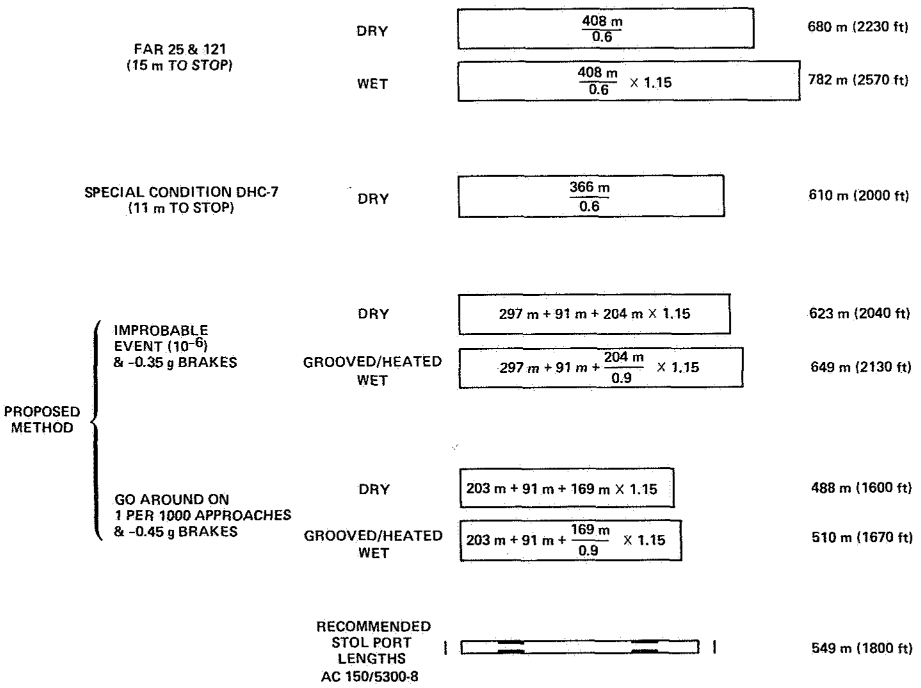


Figure 8.- Comparison of methods for determining landing runway length.

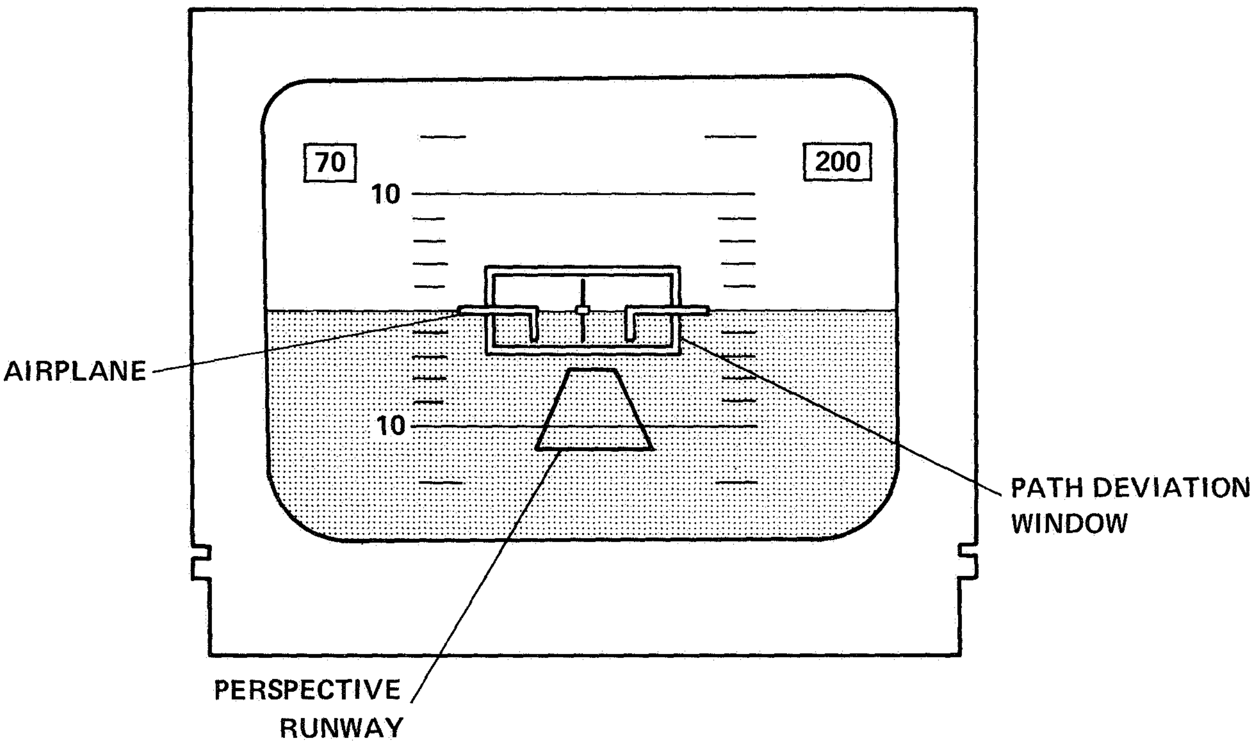


Figure 9.- Electronic attitude director indicator.