Performance Margins

Article **10**

Paul Schmid
Boeing Aerodynamics Engineering

When an aircraft is dispatched in accordance with certification and operational regulations, there are some inherent margins included in the calculated takeoff and landing performance. Although it is not permitted to take advantage of these margins in order to increase the aircraft performance limit weight, it is of interest to be aware of the magnitude of these margins. This paper quantifies some of the margins in accelerate-stop distance, takeoff distance, minimum rate of climb, obstacle clearance, and landing distance on a 737-800, 747-400, and 777-200.

Takeoff performance requires the consideration of a critical engine failure, the airport pressure altitude and ambient temperature, the runway slope, and the wind component along the runway (50% of the headwind or 150% of the tailwind).

Accelerate-Stop Distance

Prior to FAR Amendment 25-42 (JAR 25 Change 14) and FAR Amendment 25-92 (JAR 25 Change 16), the AFM accelerate-stop distance only considered an RTO associated with an engine failure on a dry runway, and no credit for the use of reverse thrust was permitted. The first amendment introduced the requirement to consider an RTO with all engines operating. The second amendment introduced the requirement for wet runway accountability. However, the wet runway accelerate-stop distance can take credit for reverse thrust.

Figure 1 outlines the calculation basis for the accelerate-stop distance. A mandatory 1-second interval between engine failure speed V_{EF} and V_1 is assumed, followed by a transition segment of approximately 3 seconds during which brakes are applied, throttles retarded, and the spoilers extended. The total time for this transition segment consists of the flight test-demonstrated pilot actions plus 2 seconds. If

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reversers are used in the calculation, a 1-second delay is assumed for the selection of the reversers followed by the demonstrated time for the reverser to deploy and to spin up to the commanded reverse thrust. The reverser deployment and spin-up time is airframe-engine dependent but is in the order of 5 to 8 seconds. Furthermore, it is assumed that reverse thrust is reduced to idle between 60 knots and 30 knots.

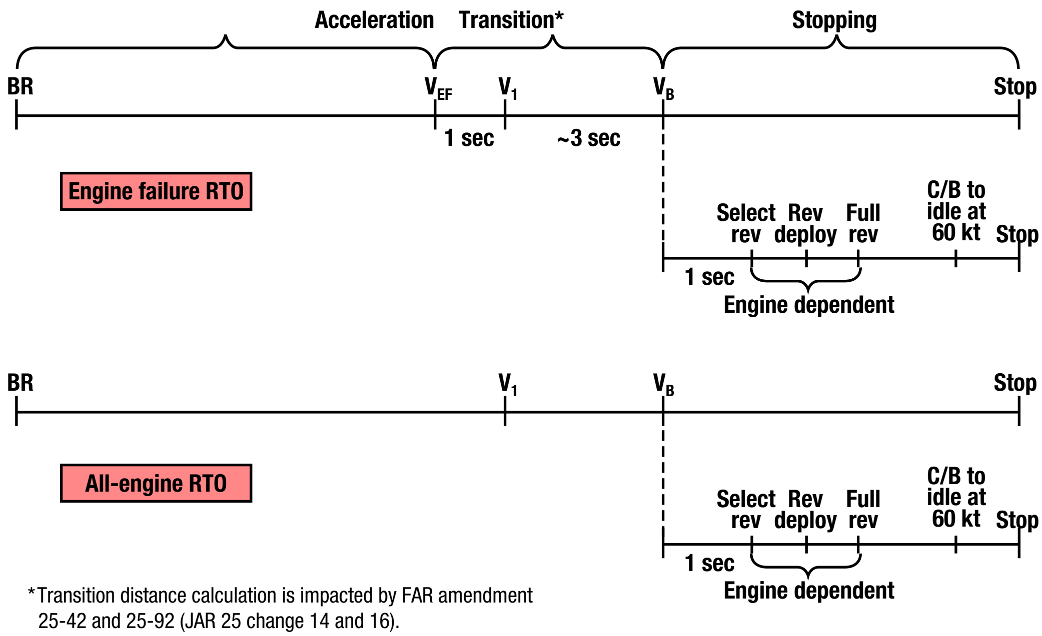

Figure 1. Accelerate-stop distance calculation basis

The manner in which the additional 2 seconds of time in the RTO transition segment has been accounted for has changed over time and is summarized in Figure 2. Prior to 1981 one second was added to the second and third demonstrated pilot action (throttle cut and spoiler extension respectively), during which time the aircraft decelerated. In 1981 the FAA clarified that the intent of their policy was to provide a two-second distance allowance at the speed reached at the end of the demonstrated transition (V_B). In Amendment 25-42 this distance allowance was redefined to be 2 seconds of continued acceleration after V_1. The current certification regulations reflect Amendment 25-92 in which the distance allowance has become equal to 2 seconds at the V_1 speed. The distance associated with this 2 seconds time for the 737-800, 777-200, and 747-400 is approximately 500 to 600 feet.

The requirement to factor the headwind by 50% and the tailwind by 150% in takeoff performance calculations is intended to provide a margin for the possible variation of wind speed and direction during the takeoff. The magnitude of the accelerate-stop distance margin associated with factoring a 10 knot headwind or tailwind is illustrated on Figure 3 for the 737-800, 777-200, and 747-400 at their respective maximum takeoff weight and sea level/30°C conditions. Relative to the scheduled AFM distance, shown in parenthesis, the actual distance is reduced by 5 to 6%. It is not uncommon for operators to conservatively use zero wind performance when operating into a headwind; this practice increases the distance margin to 10 to 12%.

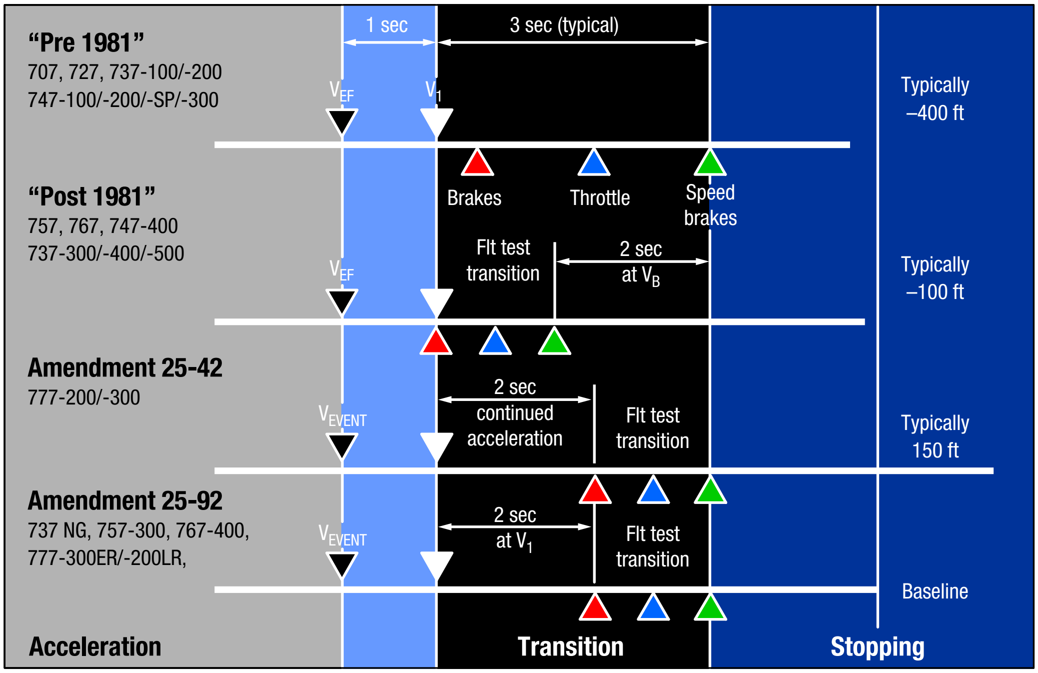

Figure 2. Accelerate-stop transition segments

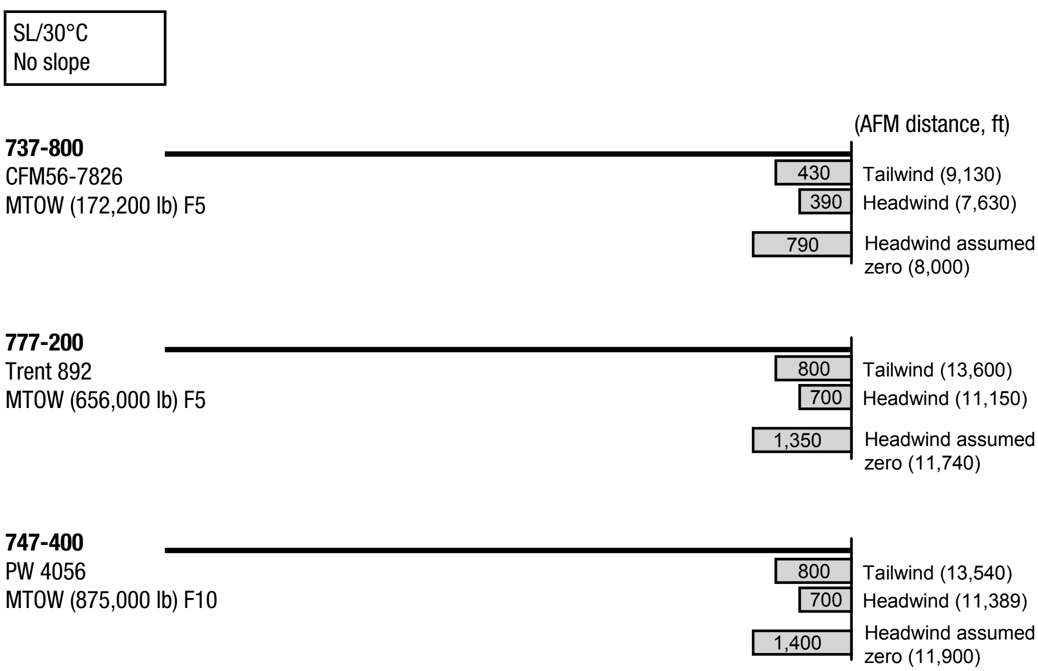

Figure 3. Accelerate-stop margins; wind accountability (10 knots), dry runway

As stated earlier, the regulations do not allow credit for the use of reverse thrust in determining the required accelerate-stop distance on a dry runway. The distance margin provided by the use of idle or maximum reverse thrust relative to the scheduled AFM distance on a dry runway is illustrated in Figure 4. For the 737-800 the effect of detent reverse is also included. The distance margins are 2 to 3% with idle reverse and 4 to 7% with maximum reverse. Note that the scheduled distance for the 737-800 and 777-200 is defined by the all-engine RTO, whereas the scheduled distance for the 747-400 is defined by the engine-failure RTO because the certification basis for the 747-400 did not require the consideration of an all-engine RTO.

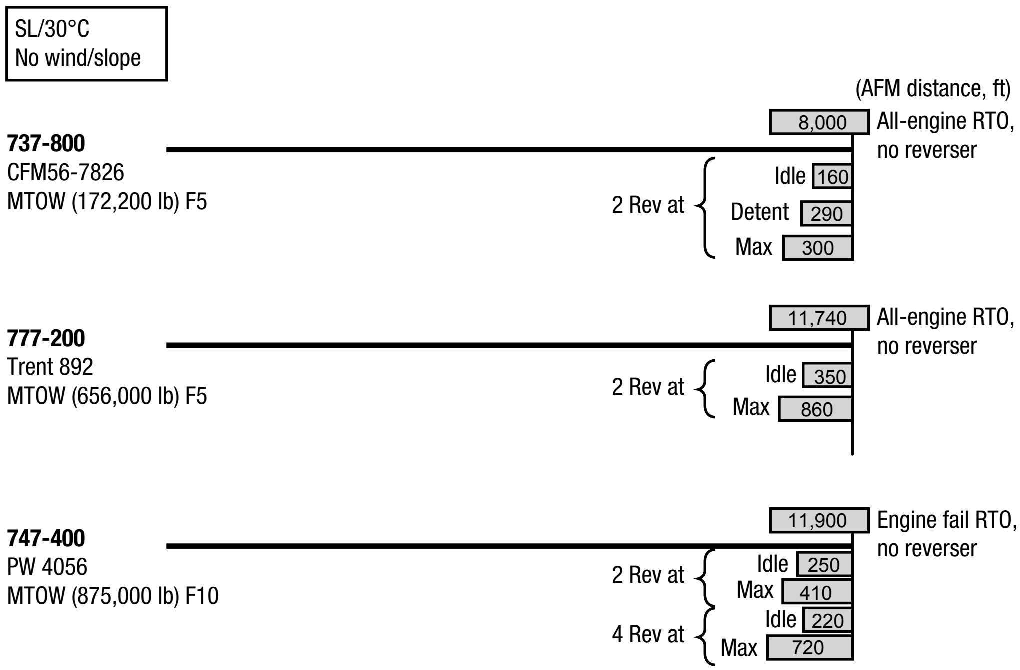

Figure 4. Accelerate-stop margins; thrust reversers, dry runway

On a wet runway, reverse thrust may be used to determine the accelerate-stop distance, but the calculated distance may not be less than the dry runway distance without reverse thrust. The effect of reverse thrust on the wet runway accelerate-stop distance is illustrated in Figure 5. Note that the scheduled AFM distance for the 737-800 and 777-200 is defined by an engine-failure RTO and assumes credit for one reverser. The distance margins shown are therefore applicable only if there is no engine failure during the RTO. For the 747-400, the scheduled accelerate-stop distance is defined by the dry runway distance, and distance margins relative to that dry runway distance are provided for an engine-failure RTO (two symmetric reversers) and all-engine RTO (four reversers) on a wet runway.

By regulation the takeoff analysis must assume that the RTO occurs at V_1. However, a high-speed RTO (greater than 100 knots) is rare and the decision to abort a takeoff earlier results in significant distance margins. Figure 6 illustrates that the accelerate-stop distance is reduced by approximately 13% when the takeoff is aborted 10 knots prior to V_1.

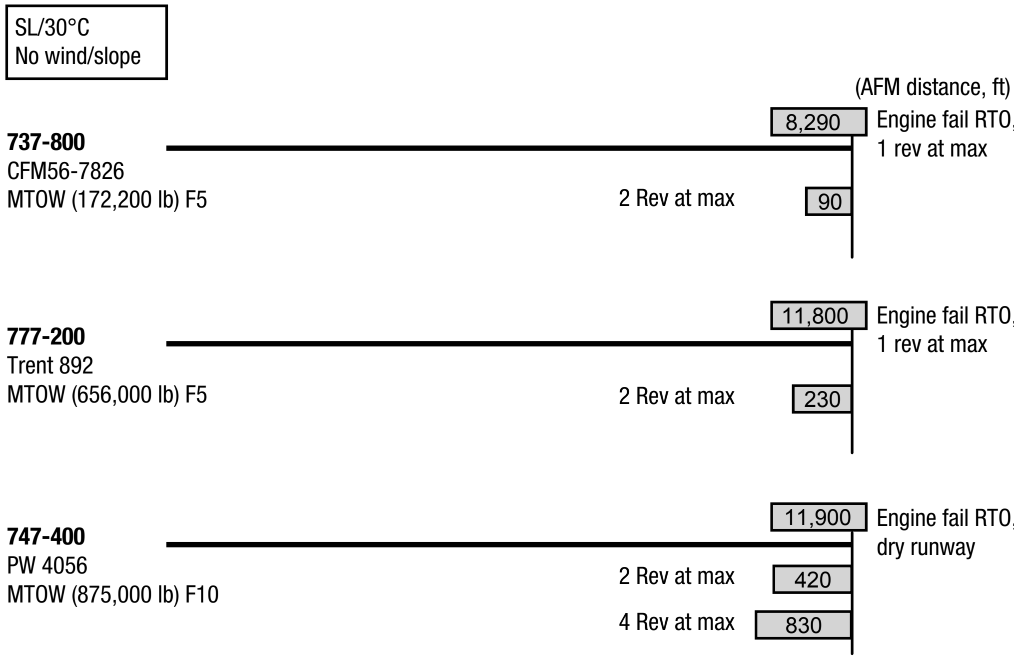

Figure 5. Accelerate-stop margins; thrust reversers, wet runway

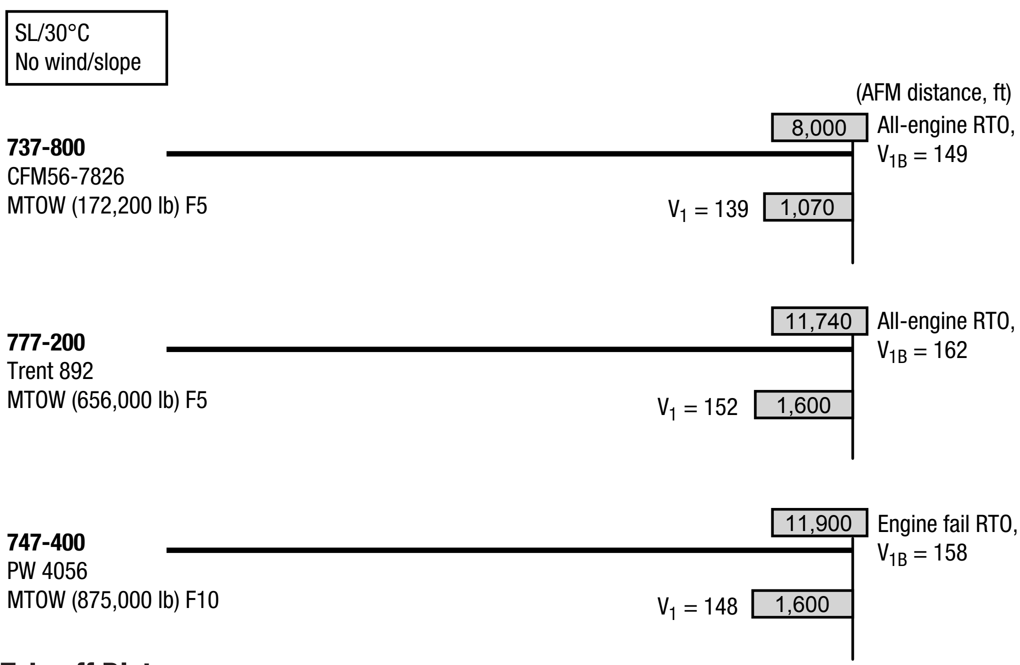

Figure 6. Accelerate-stop margins; RTO 10 knots prior to V_{1B}, dry runway

Takeoff Distance

FAR Amendment 25-92 (JAR 25 Change 16) introduced the requirement to consider a wet runway for takeoff performance analysis. With an engine failure, the takeoff distance on a wet runway is defined to a 15-ft screen height rather than a 35-ft screen height. However, the wet runway takeoff distance cannot be less than the dry runway takeoff distance. Furthermore, with an engine failure the takeoff run is equal to the takeoff distance (i.e., no clearway credit).

The requirement to factor the headwind and tailwind provides similar margins in takeoff distance as was shown for the accelerate-stop distance. Figure 7 illustrates that the wind factors provide approximately a 4% distance margins for a 10-knot headwind/tailwind. If zero wind conditions are conservatively used to represent 10-knot headwind conditions, the margin doubles to approximately 8%.

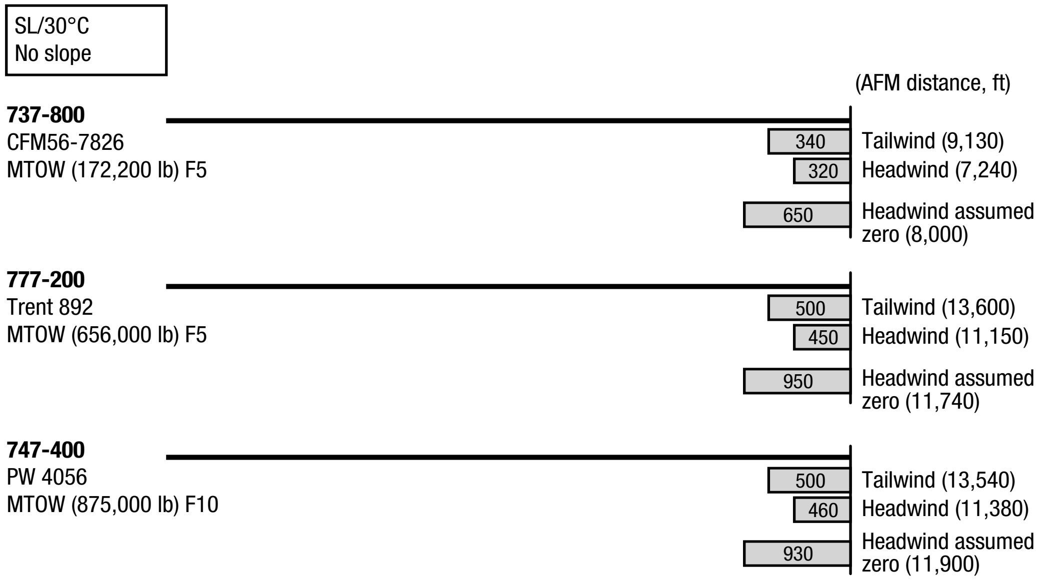

Figure 7. Takeoff distance margins; wind accountability (10 knots), dry runway

Minimum Rate Of Climb

The minimum climb capability of an aircraft during the takeoff phase is generally established by the regulatory minimum climb gradient at V_2 speed with the critical engine inoperative and gear retracted (second segment). These minimum required gradients are 2.4, 2.7, and 3.0% for two-, three-, and four-engine aircraft respectively.

Figure 8 quantifies the rate of climb for the 737-800, 777-200, and 747-400 at maximum takeoff weight, an ambient temperature of 30 °C, and the pressure altitude at which they reach the minimum climb gradient. The left column for each model quantifies the rate of climb with the critical engine failed and V_2 speed. The higher rate of climb for the 747-400 reflects the higher minimum gradient requirement for a quad (3%) versus a twin (2.4%). The second column illustrates the improvement in rate of climb if the critical engine fails sometime after V_1 by which time the speed has increased to V_2+15. The third column illustrates the rate of climb achieved without an engine failure. The relatively large increase in rate of climb of the twins relative to the 747-400 reflects a doubling of thrust rather than only a 33% increase in thrust.

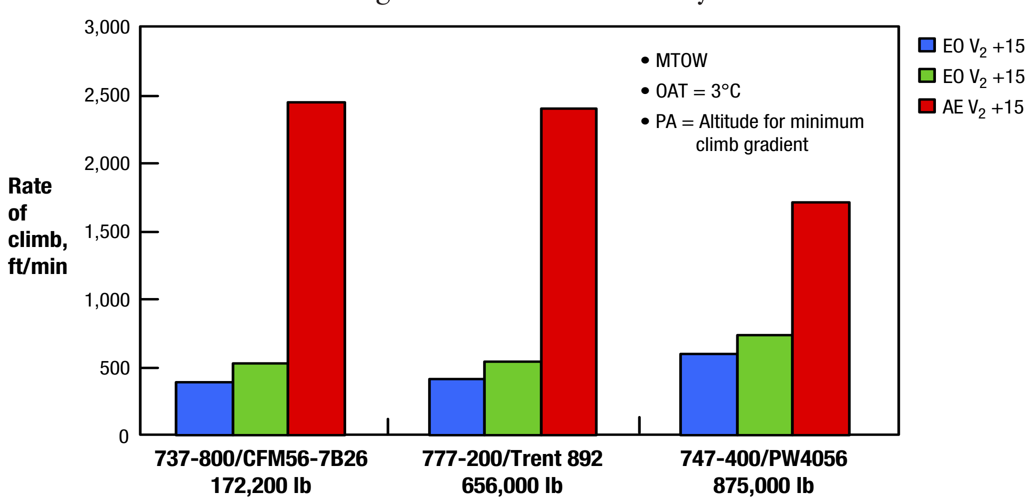

Figure 8.Rate of climb capability second segment limit

Obstacle Clearance

By regulation the net flight path, which begins at 35 ft above the takeoff surface, must clear all obstacles by 35 ft. This net flight path is the actual flight path reduced by a climb gradient equal to 0.8%, 0.9%, and 1.0% for two-, three-, and four-engine aircraft respectively.

The difference between the gross and net flight path provides an ever increasing obstacle clearance margin with distance from brake release. This is illustrated for a 737-800 in Figure 9. If the engine were to fail 10 knots after V_1 the gross flight path would improve as indicated. The gross flight path without an engine failure is also shown.

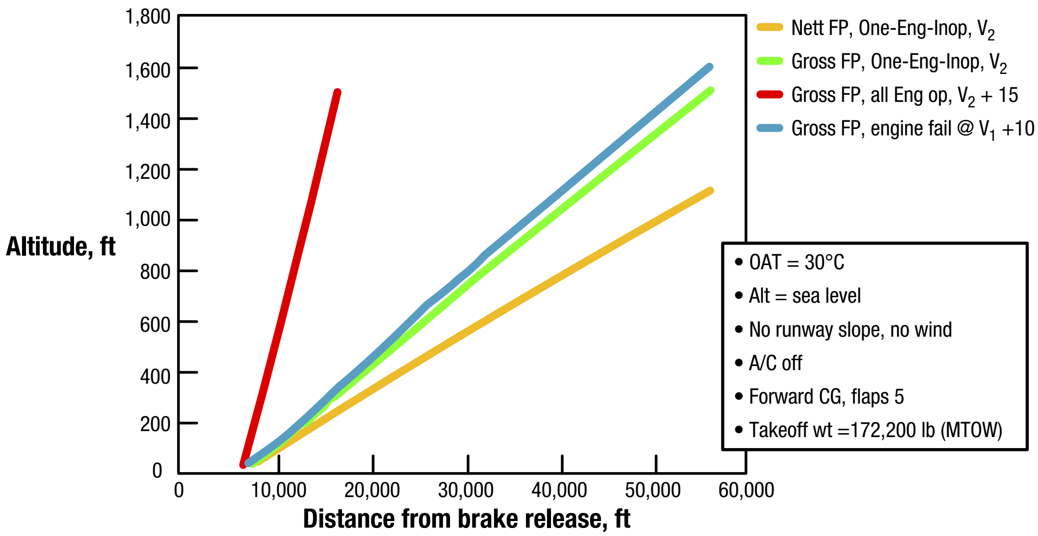

Figure 9. 737-800/CFM56-7B26 takeoff flight path

The increased obstacle clearance margin provided by factoring a 10-knot headwind is illustrated in Figure 10.

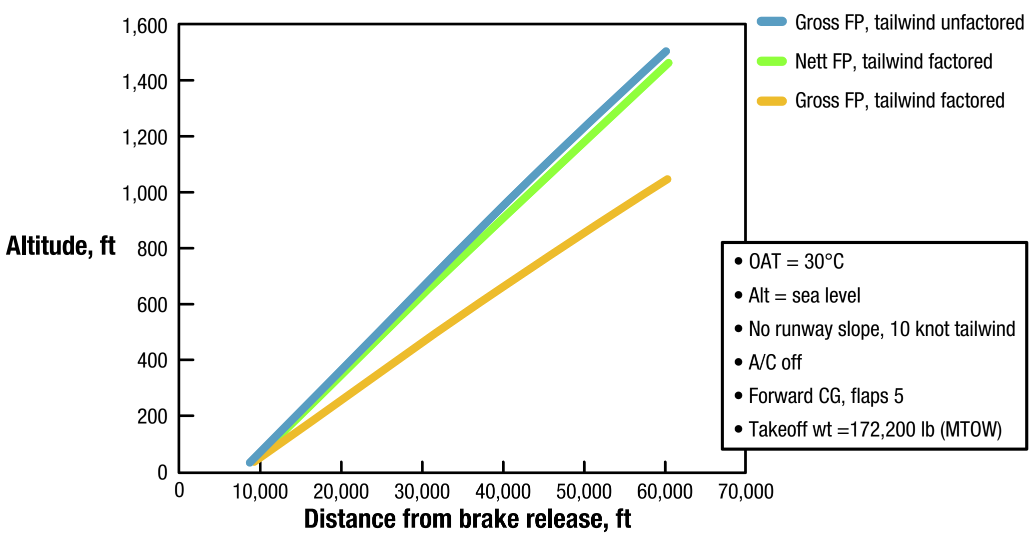

Figure 10. 737-800/CFM56-7B26 takeoff flight path

Note that on a wet runway, the takeoff distance may be defined by the engine-failure takeoff distance to a 15-ft screen height. In such a condition the obstacle clearance will be reduced by 20 ft.

Landing Distance and Runway Length Required

The landing distance is defined by FAR/JAR 25.125 to be the horizontal distance to come to a complete stop from a point 50 ft above the landing surface, assuming

- Airspeed at the runway threshold is VREF.
- A level, smooth, dry, and hard surfaced runway.
- Airport altitude and standard day temperature.
- 50% of the headwind or 150% of the tailwind.
- Maximum manual braking.
- No reverse thrust.

If the runway at the destination is forecast to be dry at the time of dispatch, FAR 121.195(b) and JAR-OPS 1.515(a) specify that the aircraft must come to a stop within 60% of the available runway length. Therefore, the dry runway length required is 1.67 (1/0.6) times the landing distance calculated per FAR/JAR 25.125. The landing distance provided in Boeing AFM/AFM-DPI includes this operational factor.

If the runway at the destination is forecast to be wet at the time of dispatch, FAR 121.195(d) and JAR-OPS 1.520(a) specify that the runway length required is 115% of the required dry runway length. The landing distance provided in Boeing AFM/AFM-DPI includes this operational factor. Note that FAR 121.195(d) and JAR-OPS 1.520(c) provide for a reduction in the 115% factor subject to additional flight test and operational approval on wet runways.

The FAR do not differentiate between wet and slippery runway length requirements at the time of dispatch. However, JAR-OPS 1.520(b) specifies that the runway length be the greater of the required wet runway length or 115% of the contaminated runway landing distance.

Figure 11 outlines the calculation basis for determining landing distance and the required runway length. The landing distance includes the flare from a 50-ft threshold to touchdown, a transition segment during which brakes are applied and spoilers extended, and a stopping segment. A flare time of approximately 4.5 seconds, established by flight test, results in a flare distance of 1,000 to 1,200 ft. A transition time of 1 second is assumed when the auto spoilers are armed, and 2 seconds if the spoilers are extended manually. The deceleration during the stopping segment assumes the maximum manual braking coefficient demonstrated in flight test on a dry runway. As discussed previously, the required runway length for a dry and wet runway are respectively 1.67 and 1.92 (1.67*1.15) times this calculated landing distance. When reverse thrust is used in the calculation of advisory landing distance, a 1 second delay to engage reversers is assumed, followed by the time it takes the reverser to deploy and spin up to the selected level. Furthermore, it is assumed that reverse thrust is reduced to idle between 60 knots and 30 knots.

Figure 12 shows how the calculated landing distance for the 737-800 at maximum landing weight is affected by airplane braking coefficient (related to runway friction capability) and the use of reverse thrust, and how this distance compares to the scheduled AFM dry and wet landing field length. The 737-800 demonstrated an airplane braking coefficient of 0.38 on a dry runway, and a braking coefficient of

0.20 is typical for a wet smooth runway. Boeing associates braking action reports of Good, Medium, and Poor with airplane braking coefficients of 0.20, 0.10, and 0.05 respectively. It is very evident from this data that a significant distance margin relative to the scheduled AFM distance is available for dry runway conditions. When the runway is wet (or braking action is good) the distance margin is less when no reversers are used, but is approximately the same as on a dry runway if reverse thrust is used. However, as the runway becomes more slippery, the distance margin ceases to exist even with credit for reverse thrust.

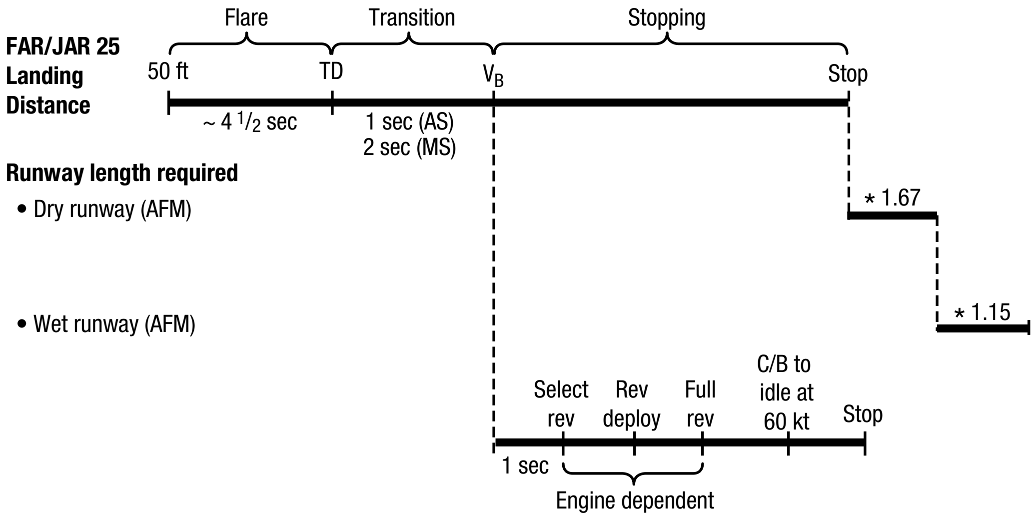

Figure 11. Landing distance calculation basis

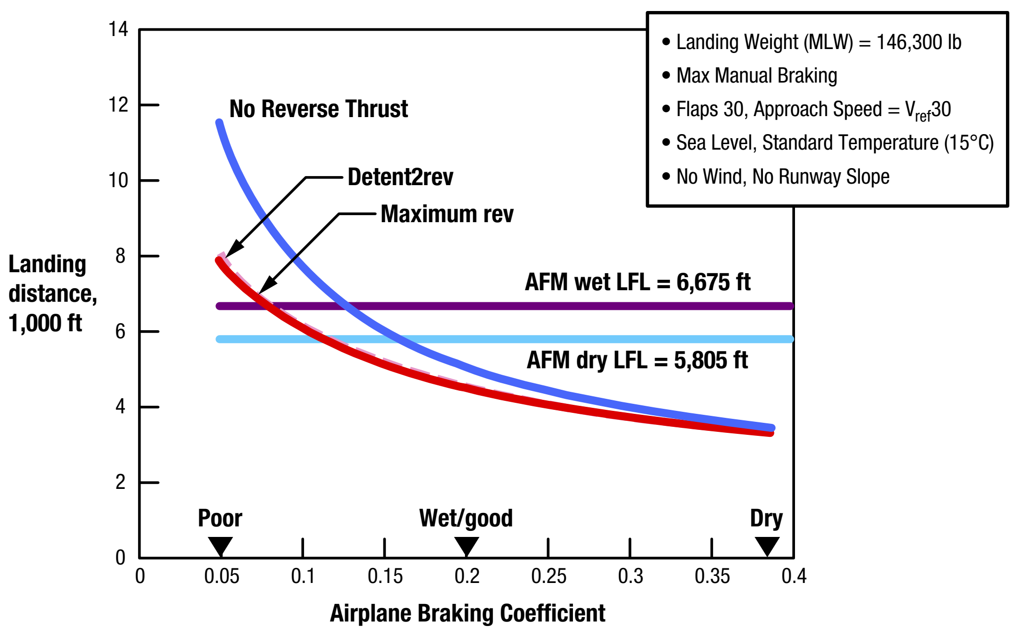

Figure 12. Landing distance, 737-800

Figure 13 quantifies the distance margins for the dry and wet runway conditions depicted on the previous figure. This presentation highlights the fact that some of the potential distance margin provided by the 1.67 and 1.92 factors must accommodate the adverse effects of higher approach and landing speed, ambient temperature above standard day, and negative runway slope, which are not included in the AFM landing distance. Nevertheless, adequate distance margins remain for dry and wet runway conditions.

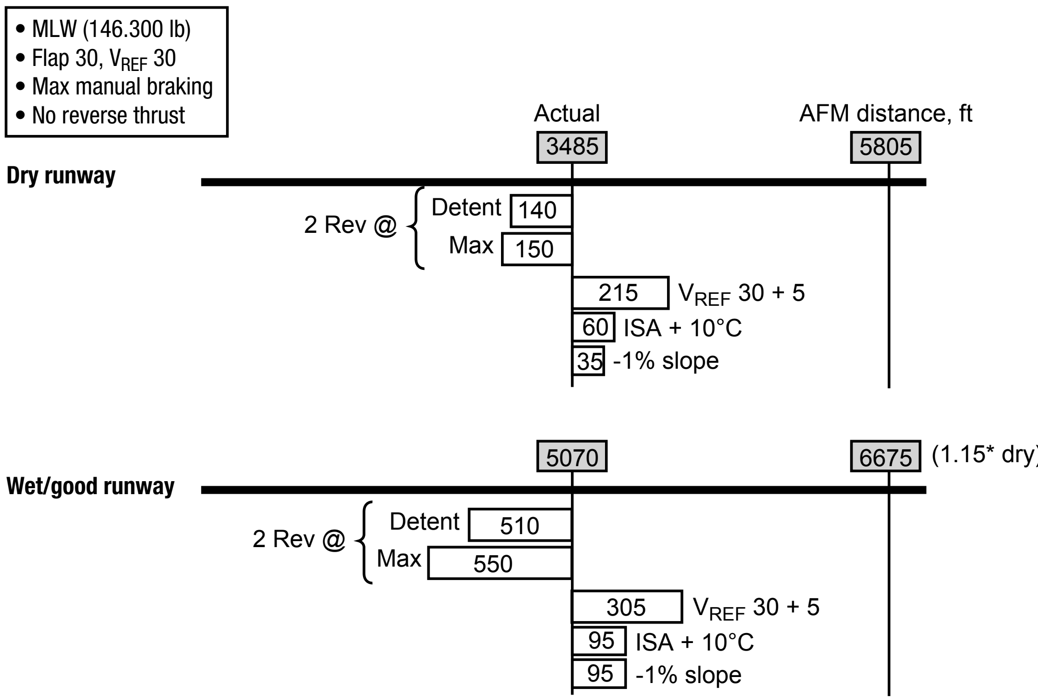

Figure 13. Landing distance margins, 737-800