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Planning the DEPARTURE

Takeoff performance myths and methods

BY PATRICK CHILES

On July 16, 2003, the flight crew of a Boeing 737-800 planned a reduced-thrust takeoff based on performance calculations for the full runway distance at Manchester, England. They had not read a notice to airmen advising that available runway distance was reduced for removal of rubber deposits. The aircraft was close to rotation speed when the crew noticed vehicles and repair equipment at the departure end of the runway. They decided to continue the takeoff, which surely must have gotten the workers' attention when the aircraft cleared their vehicles by about 50 ft. The crew had correctly determined that there was not enough stopping distance remaining; nevertheless, an engine failure at that moment would almost certainly have been disastrous.[1]

Four months later, on the night of Nov. 11, 2003, a Cessna Citation Excel was being taxied for takeoff after a quick turnaround at Wheeling, Illinois, U.S. "Short runway, full fuel, with a stab[ilizer] that is not moving," the captain mused. "This could get interesting." As the aircraft was taxied onto the runway, annunciator lights likely warned that the horizontal stabilizer was not configured properly. The configuration warning horn sounded as the first officer advanced the power levers for takeoff. However, the flight crew did not take action to reject the takeoff until the first officer found that he could not rotate the aircraft. The Citation was substantially damaged when it overran the 5,000-ft (1,524-m) runway, but the pilots and their three passengers were not injured. Investigators found that, due to an electrical fault, the stabilizer could not be moved from the cruise position to the takeoff position.[2]

These events illustrate the need to clearly understand the nuances of takeoff performance, because assumed margins frequently are incorrect.

The U.S. Federal Aviation Administration (FAA) *Takeoff Safety Training Aid* notes that studies of 74 accidents and serious incidents involving rejected takeoffs (RTOs) showed that more than half occurred after the takeoffs were rejected at airspeeds greater than V_1 — which, simply stated, is the maximum speed at which a crew must take action to reject the takeoff. Most of the accidents were overruns after RTOs were initiated at "high speed," defined as 120 kt or more.[3]

The FAA has been working with Europe's Joint Aviation Authorities (JAA), which now is transferring many of its functions to the European Aviation Safety Agency (EASA), to harmonize regulations affecting takeoff performance, focusing on certification standards, wet and contaminated runways, obstacle analysis, runway lineup distance, 10-minute thrust time limit, and operating standards.

The Basics

Five factors affect every takeoff: field length, tire speed, brake energy, climb performance

and obstacle clearance. They create a variety of policy choices for the operator. Some examples are:

- An unbalanced field length policy;[4]
- Improved climb or "overspeed," using excess field length to improve climb gradient;
- Obstacle avoidance procedures, which a flight management computer (FMC) cannot duplicate without an internal obstacle database;
- Flap retraction heights above the 400-ft regulatory minimum;
- Increased takeoff thrust time limit; and,
- Runway lineup distance.

These choices are reflected in dispatch performance-calculation software or runway analysis tables, but they could be unknown to the end user — the pilot or dispatcher — or unavailable in the aircraft's FMC. Thus, FMC-derived takeoff "V-speeds" may not match dispatch performance calculations or provide adequate terrain/obstacle clearance. Any takeoff policy choices that may not be duplicated aboard the aircraft should be explained to crewmembers in the event they need to rely solely on FMC calculations.

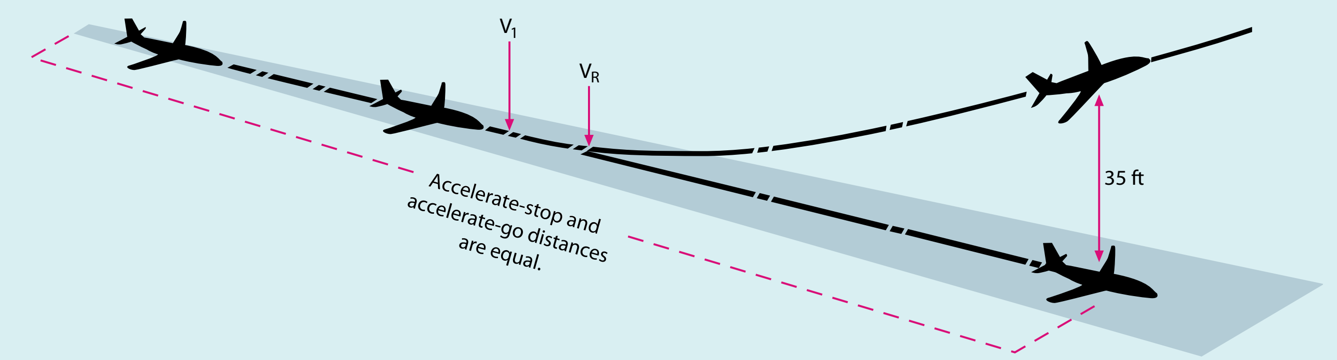
V_1 Conundrum

Despite almost 10 years of efforts to eliminate a common misconception about V_1, it is still widely referred to as "takeoff decision speed." To emphasize that V_1 is *not* a decision speed, the FAA and JAA in 1998 introduced the following two-part definition:

- "V_1 means the maximum speed in the takeoff at which the pilot must take the first action (e.g., apply brakes, reduce thrust, deploy speed brakes) to stop the airplane within the accelerate-stop distance; [and,]
- "V_1 also means the minimum speed in the takeoff, following a failure of the critical engine at V_{EF} [the speed at which the critical engine is assumed to fail during takeoff], at which the pilot can continue the takeoff and achieve the required height above the takeoff surface within the takeoff distance."

Most pilots know that, during certification, manufacturers of transport category airplanes typically designate V_1 airspeeds that result in balanced field lengths, or equal accelerate-stop and accelerate-go distances (Figure 1, p. 28). Takeoff configuration, weight, altitude and temperature are among the factors that must be considered by the manufacturer when designating

Balanced Field Length



Source: Adapted from SimuFlite Learjet 55 Cockpit Reference Handbook

Figure 1

V_1 speeds — and by the pilot or dispatcher when selecting the appropriate airspeed from among the data published in the airplane flight manual (AFM).

Accident and incident reports, however, show that misconceptions about V_1 linger. Of course, the pilot-in-command has the authority in an emergency to do whatever is necessary for safety. But consider that a typical jet transport accelerates at 4 to 6 kt per second; if a no-go decision is made at V_1, it may already be too late to bring the aircraft to a stop on the runway. In almost all cases, action to reject a takeoff must be taken no later than reaching V_1.

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It is important to remember, however, that V_1, accelerate-stop, accelerate-go, etc., are based on an *engine failure*. Many operators specify lower maximum airspeeds — 80 kt or 100 kt, for example — at which action to reject a takeoff should be made in response to malfunctions or abnormalities such as a blown tire or a warning light. Conversely, some training materials and company standard operating procedures (SOPs) specify limited but dire conditions — a control system failure or a fire warning, for example — in which a post-V_1 RTO is justified.

What Is New

One result of the FAA/JAA harmonization was refinement of takeoff performance certification standards. This has resulted in subtle changes that are keys to understanding the basis of the data in the AFM. For instance, it is now allowable to take credit for thrust reversers in calculating takeoff performance on a wet runway.

Other changes have affected the certification allowance for pilot reaction time and whether continued acceleration or a constant speed is assumed during this period. A specific aircraft model undergoing significant design evolution, resulting in separate certification tests, could have subtly different assumptions underlying the takeoff performance data.

Another result of harmonization is FAA Advisory Circular (AC) 120-91, *Airport Obstacle Analysis*. In draft form for several years before its publication in 2006, the AC already had become a commonly accepted resource for developing procedures to comply with takeoff limitations specified in regulations. One effect of the new guidance is clarification of obstacle clearance margins during an engine-out takeoff; the FAA margins now are more closely in line with those of JAA and the International Civil Aviation Organization (ICAO).

The specific wording in U.S. Federal Aviation Regulations (FARs) Part 135, for charter operators, and Part 121, for airlines, requires only that the engine-out net takeoff flight path must clear any obstacles by 35 ft vertically in an obstacle accountability area (OAA) defined as

200 ft (approximately 60 m) laterally — that is, 200 ft on each side of the intended track — from the end of the runway to the airport boundary, and 300 ft (90 m) laterally outside the airport boundary.

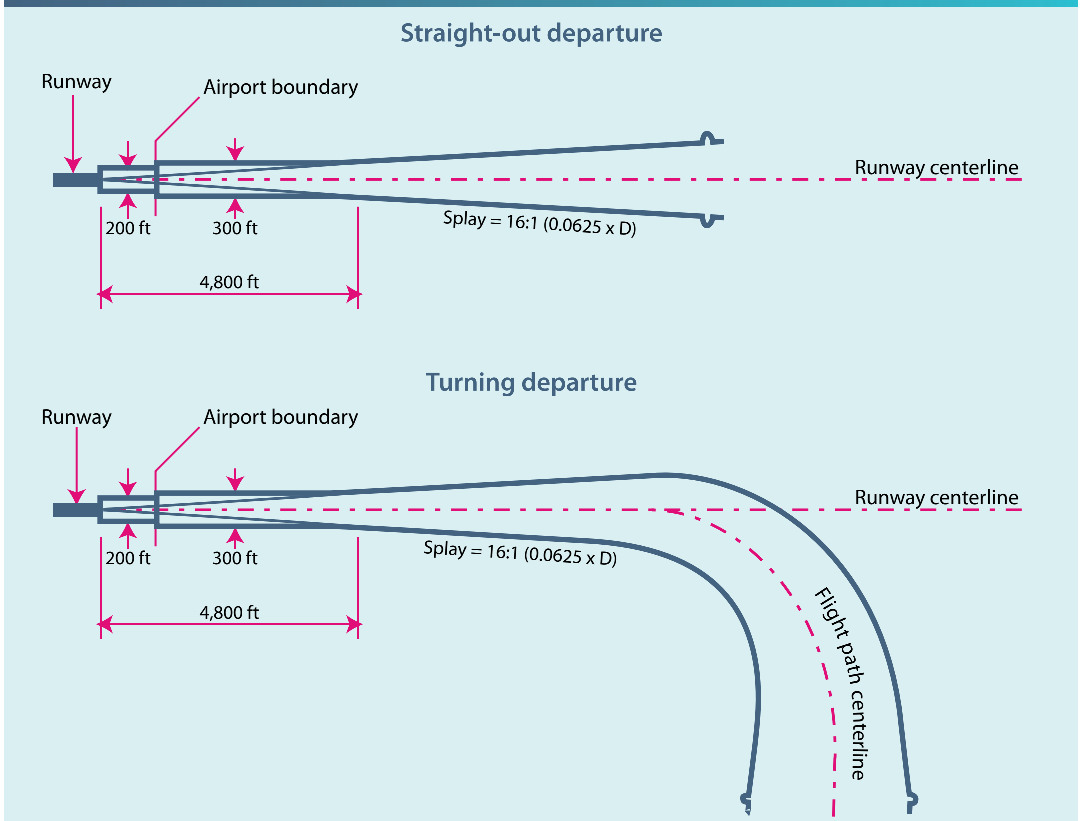
In contrast, the JAA/ICAO standard is a "splay" — an increasingly wider OAA — that begins at 90 m at the runway end and increases by an 8-1 ratio to a maximum width of 600 m (about 2,000 ft). Although this splay makes takeoff performance analysis more rigorous, it offers a sound safety margin because it recognizes that the effects of wind or course guidance errors tend to increase with distance.

In AC 120-91, the FAA recommends an increasing OAA similar to the JAA/ICAO splay beginning 4,800 ft (1,463 m) from the end of the runway (Figure 2). Thus, there now is some difference between the FARs standards and the acceptable compliance methods spelled out in the AC; but it can be understood that the 200/300-ft margin is a minimum width at which the OAA splay begins. Within this lateral path, all obstacles must be cleared by at least 35 ft vertically. There is also a more involved flight track analysis method that must include consideration of wind and course guidance error. This allows for a smaller OAA and can be used for procedures based on required navigation performance (RNP).

For either method, there are two fundamental obstacle-clearance techniques. The simplest is to continue climbing at V_2 — takeoff safety speed, or the minimum airspeed at which the aircraft can maintain the required climb gradient with one engine inoperative — straight out on the runway heading. However, if obstacles are sufficiently high or close to the runway, it may be advantageous to create a turning procedure to avoid them. While there is some loss of performance in the turn, it can be offset by a shallower gradient. When turns are planned, they should not begin until after the aircraft is at least 50 ft above the runway end, and they should not exceed 15 degrees of bank.

In general, V_2 provides stall protection to only 15 degrees of bank. To design an obstacle-clearance procedure for a more steeply banked turn, V_2 must be increased to provide

Obstacle Accountability Areas



D = distance (ft) along runway or flight path centerline from departure end of runway

Source: U.S. Federal Aviation Administration

Figure 2

an equivalent stall margin. One method is to use the following formula, in which V_2 is knots true airspeed and Φ, the Greek letter *phi*, is bank angle in degrees:[5]

$$V_2\Phi = V_2/\sqrt{\cos\Phi}$$

For either method, an accurate source of obstacle data is required. There are a number of government and commercial sources, and it is the operator's responsibility to use the best data available for its specific needs.

Gradients Vary

Although some corporate and charter operators use published standard instrument departure (SID) procedures for obstacle clearance in the absence of other information, the intent of an engine-failure obstacle-clearance path is not necessarily the same as meeting the climb gradient specified by a SID.

AC 120-91 states that "one-engine-inoperative procedures do not need to meet TERPS [*United States Standard for Terminal Instrument Procedures*] requirements," upon which SIDs are designed. The AC also says that meeting a SID climb gradient "does not necessarily assure that one-engine-inoperative obstacle-clearance requirements are met."

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U.S. TERPS, and ICAO *Procedures for Air Navigation Services–Aircraft Operations* (PANS-OPS), are intended for normal, all-engine operations. The minimum 3.3 percent (200 ft per nm) climb gradient required for a published departure procedure is a constant angle. However, transport category airplane certification standards are based on engine-out conditions and result in the climb performance data provided in the AFM.

Further, certification standards require that a two-engine aircraft, for example, be capable of maintaining at least a 2.4 percent gross climb gradient at the beginning of the second segment of the departure — theoretically, when the aircraft is 35 ft above the end of the runway, clearway or stopway, and after the landing gear is retracted. Unlike the TERPS climb gradient requirement, this is a "point in space" gradient taken at the beginning of the segment and not a constant angle. Nor could it be. Engines lose thrust with altitude, and if a constant speed is held throughout the climb, the climb gradient typically decreases with altitude and resembles a decaying curve. To account for this, certification standards specify net takeoff flight paths that provide an increasingly greater margin over distance against the gross takeoff flight path.

While there is an obstacle-clearance consideration in SIDs of 48 ft per nm, it assumes normal all-engine performance. An engine-out takeoff is certainly not a normal condition and takes precedence over any SID or other departure procedure.

Both U.S. and European regulators encourage the examination of SIDs in mountainous regions to plan for engine failures at later stages in the climb, specifically after the point at which an emergency engine-out flight path may diverge from the charted procedure. The question becomes: If the aircraft is committed to the SID, will it be able to maintain adequate terrain clearance with a post-V_2 engine failure, or will it need some escape path? This type of analysis can be arduous and requires all-engine performance data in addition to the AFM data.

Defining Contaminants

The recent 737 runway overrun at Chicago Midway International Airport, among other things, refocused attention on common definitions of runway contaminants.[6] The JAA already requires manufacturers to supply "advisory information" that must be considered in dispatch performance calculations. The information can be derived from flight tests or from existing certification data, and must include runway contaminants such as compacted snow, slush or standing water, and the different definitions of braking action.

The FAA has yet to formally define runway contaminants. The regulatory language in Part 135 and Part 121 only allows the use of approved AFM data for landing on dry, wet or "slippery" runways. There is no definition of what constitutes a slippery runway, and there is no guidance on how to legally dispatch an aircraft when runway conditions are known to be worse than just wet.

No consensus was reached during efforts to harmonize the definitions and requirements for takeoff and landing on contaminated runways, in part due to the complexity of runway contamination and the potentially severe performance penalties posed by some contaminants. Slush, for example, significantly increases drag on the landing gear and, when thrown up onto the airframe, can severely affect the aircraft's aerodynamics. One manufacturer likened the combined effects of slush to having an extra engine, operating at reverse thrust.

The FAA's Aviation Rulemaking Advisory Committee studied various methods to mitigate the performance penalties and economic penalties associated with contaminated runway operations, but no satisfactory solution was found. Among options that a majority of the group supported was to fully harmonize the FARs to the JAR-OPS 1 standard or to use the JAA contaminant definitions and base takeoff-performance calculations on an all-engines-operating condition.[7]

In the meantime, the FAA has allowed manufacturers to provide the European advisory data to U.S. operators with the same aircraft types in their fleets. The FAA has deemed the data acceptable to use as supplemental information while further action is taken to define contaminants and performance calculation methods. However, U.S. operators should be aware that this type of information, being "advisory" and not "approved," does not include the same distance factors applied to the AFM data, such as credit for the use of thrust reversers.

Performance Monitoring

Much of this discussion has concerned preflight predictions of takeoff performance. But, during the actual takeoff roll, is there any protection from an unanticipated mechanical failure or simple human error?

The MK Airlines 747 accident in Nova Scotia, Canada, illustrated that calculation methods may be perfect but offer no protection if they are based on incorrect assumptions. The Boeing Laptop Tool software for calculating the 747's takeoff performance data worked as designed, but it had no way of detecting that the flight crew had mistakenly carried over a lower payload weight from their previous leg (*ASW*, 10/06, p. 18).[8] There was no cockpit display to advise the crew that their thrust-to-weight ratio was insufficient to lift off the runway, a terrible fact realized too late to stop.

This accident renewed interest in on-board takeoff performance monitoring. The U.S. National Aeronautics and Space Administration's Langley Research Center demonstrated a takeoff performance monitor in a 737 in the late 1980s, and there has been other research work. However, no organization has taken a leading role in developing the concept, and there are as yet no commonly accepted methods, algorithms or cockpit displays.

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The MK Airlines accident prompted the Transportation Safety Board of Canada to recommend a requirement that transport category aircraft be equipped with a takeoff performance monitoring system. In response, Transport Canada said that it cannot require installation of a system that does not exist. However, the two organizations have agreed to work together on preliminary research to determine if a system could be designed to give flight crews an "accurate and timely indication of inadequate takeoff performance" (*ASW*, 5/07, p. 8).

Going Forward

There has been substantial movement, particularly in the last 10 years, toward harmonization of U.S. and European requirements and standards for takeoff performance calculation. Efforts to standardize wet runway takeoff performance, RTO time sequences, brake wear and use of 10-minute takeoff thrust have been completed. Obstacle clearance methods now have a more common basis, although some minor differences remain.

Efforts to define runway contaminants continue, and some significant changes in takeoff performance calculations may be presented to U.S. operators when rule making is under way.

Despite progress in these areas, full harmonization has yet to be realized. Common sense tells us that what works for the European Union should likewise work in the United States: Airplanes are airplanes, runways are runways, and terrain is terrain. But with anything technical or regulatory, the devil lies in the details. ●

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Notes

1. U.K. Air Accidents Investigation Branch report no. 3/2006.
2. U.S. National Transportation Safety Board (NTSB) report no. CHI04FA031. NTSB said that the probable causes of the accident were "the flight crew's intentional operation with known deficiencies in the aircraft and their delay in aborting the takeoff when a no-takeoff warning was presented."
3. U.S. Federal Aviation Administration (FAA). *Takeoff Safety Training Aid*. Section 2, "Pilot Guide to Takeoff Safety." <www.faa.gov/pilots/training/>.
4. An unbalanced field length policy allows consideration of extra distance provided by clearways and stopways, in addition to available runway length, in calculating takeoff performance. Thus, accelerate-stop and accelerate-go distances might not be equal.
5. Allen, Carl (Alaska Airlines). "One Airline's Method for Calculating Engine Failure Turn Procedures." A presentation to the Boeing Performance and Flight Operations Engineering Conference, Seattle, Washington, U.S., September 2003.
6. NTSB report no. DCA06MA009. The preliminary report said that snow was falling Dec. 8, 2005, when the landing aircraft slid off the runway and came to a stop on a road. None of the 103 aircraft occupants was injured; one person on the ground was killed, and 12 others received minor injuries.
7. Stimson, Don (FAA). "Harmonization of FAR/JAR Airplane Performance Requirements: Status and Future Plans." A presentation to the Boeing Performance and Flight Operations Engineering Conference, Seattle, Washington, U.S., September 2003.
8. Transportation Safety Board of Canada. *Reduced Power at Takeoff and Collision With Terrain, MK Airlines Limited, Boeing 747-244SF 9G-MKJ, Halifax International Airport, Nova Scotia, 14 October 2004*. Aviation Investigation Report A04H0004.

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