

The Assumed Wind Procedure to Increase Dispatch Safety for VMCA Limited Aircraft

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Aircraft must comply with weight, runway and climb gradient limits in order to safely dispatch. Certified multi-engine aircraft must always fly fast enough to have aerodynamic control surfaces that can generate forces and moments to trim out sudden One-Engine-Inoperative (OEI) conditions without creating other safety hazards. In this paper, we propose a dispatch work-around procedure to provide pilots with additional minimum-control-speed (VMCA) speed margin without compromising other safety-of-flight issues.

I. Introduction

MULTI-ENGINE AIRCRAFT are designed to takeoff, fly and land with a malfunctioning or inoperative engine. When an engine fails, it can no longer develop its share of thrust used to propel the airplane or power its control systems. Thus, engine failure impacts climb performance; it reduces the specific excess thrust. Once an engine fails, pilots need to aerodynamically control the airplane in a situation where there is appreciable thrust asymmetry. Pilots will apply rudder, aileron and elevator to orient the aircraft in a manner where the aircraft retains its intended speed, altitude and heading. In our predecessor paper, we showed that conventional configurations can demonstrate a more troubling problem; unless the pilot banks the aircraft to elevate the wing with the failed engine they may not be able to safely trim at flight speeds that seemingly far exceed the published *VMC* values. [1] In this work, we will show an operational work-around that can ensure safe dispatch if the operator wishes to elevate the scheduled obstacle-clearance speed (*V2* or *VOBS* depending on the certification basis) to give pilots additional trim margin.

Takeoff performance is an extremely important responsibility for dispatch. Operational safety requires pilots to observe a variety of speed targets (*V1*, *VR*, *V2*) and speed limits (*VMCG*, *VMCA*, *VMU*), which are all a function of aircraft weight, airfield pressure altitude (*PA*) and outside air temperature (*OAT*). Payload / range capability be seriously reduced by maximum weight limitations imposed by takeoff runway or climb gradient requirements. If the circumstances dictate a significant reduction in maximum dispatch weight from the aircraft's certified maximum takeoff weight, the operator may find themselves limited by a fuel load insufficient to fly their intended payload over the mission.

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Consider the Boeing 737-500; the Payload / Range chart may be seen as FIGURE 1. [2] If this aircraft has an OEW of 75,000-lbm and the operator desires to carry 20,000-lbm 1,750-NM, we can see that the aircraft needs to dispatch at 124,500-lbm; i.e. with 29,500-lbm fuel on board. Thus, so long as the runway, ambient conditions and terrain permit dispatch at or above 124,500-lbm we can operate this flight. If circumstances limit takeoff weight to 115,000-lbm, we would need to refuel at an airport no further than 1,100-NM from origin or we would have to nearly halve our payload (i.e. dispatch with 12,000-lbm payload).

In the most general case, maximum takeoff weight can never exceed the certified MTOW. If the runway is short, its useable length often imposes the most stringent limits on takeoff weight. Regulatory minimum engine-out climb performance (the WAT limit), may also come into play – particularly for airports at high elevations on hot days. Close-in obstacle clearance or the need to maintain a minimum climb capability to fly a standard-instrument-departure (SID) may also limit takeoff weight. Some aircraft may find themselves in situations where the maximum takeoff weight is limited by tire speed limits or by brake-energy limits in the event of a rejected takeoff (RTO). All of these flight parameters are functions of pressure altitude, outside air temperature, wind velocity, runway slope, runway condition, surface covering, flap setting and power setting.

Some aircraft, such as the Boeing 737, offer manufacturer scheduled takeoff performance for a variety of flap settings and a variety of fixed engine de-rate schedules. Boeing handbooks also produce “Improved Climb Performance Field Length Plots;” where dispatch can easily schedule operations with V_1 , V_R and V_2 speeds elevated above the nominal “book values;” see FIGURE 2. [2] In this figure, we see that these corrections allow improved climb performance (and hence a greater obstacle clearance limited weight) at the expense of restricting field (i.e. runway) limited weights.

Depending upon the aircraft and the operator, pilots may be insulated from dispatch. In Wood, Takahashi & Bays, we published the results of an line pilot survey. [3] To quote a line pilot: “Measure with a micrometer. Mark with a grease pencil. Cut with an axe. That about sums up the way aircraft performance works.” [3]

Military transport aircraft may have an aircraft flight manual (AFM) with predicted takeoff ground roll, all-engines-operating as well as critical-field-length (CFL); accel-check speeds and times; predicted liftoff as well as rotation speed, we found that many commercial manuals were alarmingly vague. A 2000+ hour CRJ pilot tells us that “our performance data really doesn't inform us of items such as CFL or expected rates of climb. It is designed to meet the regulatory requirements for runway performance and obstacle clearance, but beyond that we don't get any more useful information.” [3]

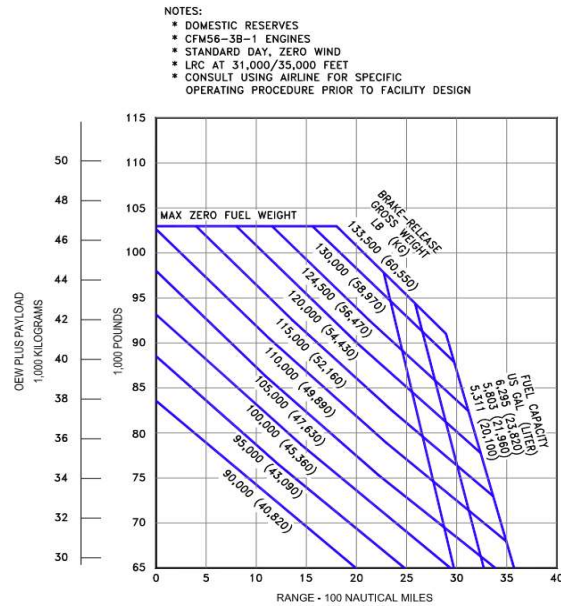


FIGURE 1 – Boeing 737-500 Payload/Range Chart [2]

Improved Climb Field Length Limit
 Flaps 5 and 15

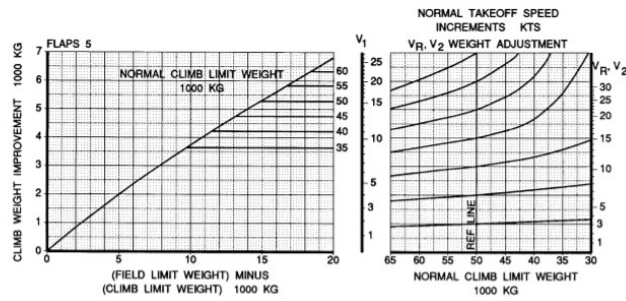


FIGURE 2 – Boeing 737-500 Improved Climb Takeoff Performance Adjustment Chart [2]

Takeoff Field Limit (18.5K Derate)

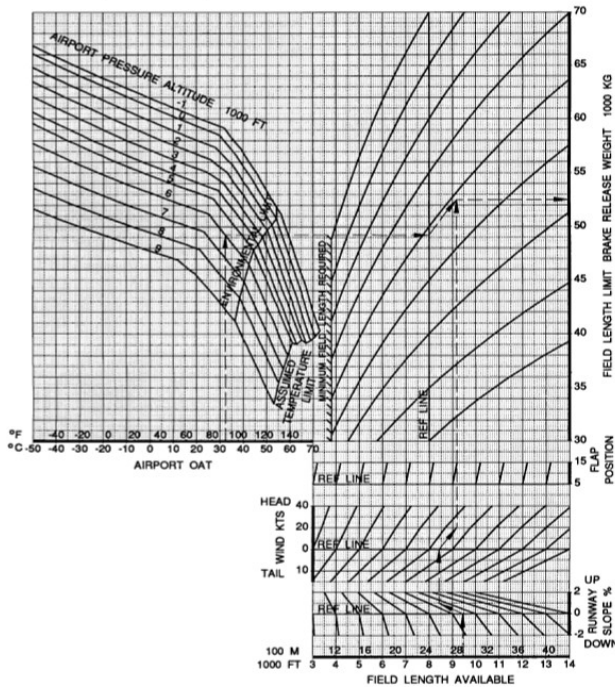


FIGURE 3 – Boeing 737-500 Takeoff Field Limit Chart [2]

We can see in FIGURE 3 that the Boeing books for the B737-500 are set up to compute performance in terms of a Field Length Limited weight. [2] Dispatch enters the chart on one side with airport altitude and temperature and on the other side with an available runway length, wind and flap setting; where the lines intersect, you read off the maximum dispatch weight. This explains the viewpoint of a 2000+ hour CRJ and B737 pilot who wrote that “company dispatch software governs aircraft performance. If it provides numbers for a given runway and aircraft configuration, it is legal ... All I worry about is flying the airplane according to company profile and rotating at the proper point in time.” [3]

This paper seeks to provide insight to develop dispatch planning advice for aircraft whose flight manuals do not provide manufacturer provided tables for elevated VR and V2 speeds.

II. Introducing the Minimum Control Speed

Modern U.S. Federal Regulations 14 CFR § 25.107 [4], 25.125 [5], 25.143 [6], 25.145 [7], 25.147 [8], 25.171 [9] and 25.175 [10] introduce specific requirements that transport category aircraft must meet in order to guarantee safe flight in all (including adverse) weather conditions. Modern Canadian and European regulations are essentially similar.

Civilian regulations require positive lateral and directional trim capability under all flight conditions, including the cruise condition (flaps stowed) and in any takeoff, approach, or landing configuration (drag brakes, flaps, or gear deployed) including flight in turbulent air. [8] Lateral and directional control must be maintained in clear weather and under icing conditions. [8] Aircraft must demonstrate sufficient lateral-directional control power to compensate for yawed flight (in sideslip) that are expected in “normal operation” which include both flight in crosswinds and “crabbed” flight that results from the “sudden failure of [a] critical engine.” [9][11]

The United States Military does not operate in a vacuum; like the civilian regulations, military standards have evolved throughout the years. Since 1969, MIL 8785B [12] introduced minimum control speed for takeoff climb modelled upon then current civilian requirements of 14 CFR § 25.149. [1] To comply with this standard, pilots shall “without a change in [aerodynamic] configuration” be able to retain control after “a sudden asymmetric loss of thrust from the most critical” engine and “maintain straight flight throughout the climb-out.” [12] Commentary to the changes to MIL-8785B states that since “the pilot must have at least 25% excess roll control power ... MIL-F-8785 ... is more stringent than the” corresponding civilian regulation. [13]

VMCA is the “minimum airborne speed with maximum thrust where the engine, most critical to control, can fail and directional control can be maintained” subject to other regulatory limitations. [14]

For civilian aircraft certified before 2002, [15] the scheduled second-segment climb speed for takeoff, V_2 , is governed by:

$$V_2 = \max(120\% V_{Stall}, 110\% VMCA) \quad (1)$$

Whereas under current civilian regulations, [4][16] the scheduled second-segment climb speed for takeoff, V_2 , is governed by:

$$V_2 = \max(113\% V_{stall}, 110\% VMCA) \text{ for turbojet / 2 and 3-engine propeller powered} \quad (2)$$

Thus, a civilian aircraft should never be scheduled to fly any slower than 110% $VMCA$.

For military aircraft certified under pre-1977 MIL rules, [12] the second-segment takeoff climb speed is:

$$VOBS = \max(120\% V_{Stall}, VMCA) \quad (3)$$

U.S. MIL C-5011B (June 1977) [14], revises these speeds somewhat and explicitly introduces the concept of minimum control speed. It calls for the second-segment climb speed to be:

$$VOBS = \max(115\% V_{stall}, VMCA) \quad (4)$$

MIL 8785C [17] from 1980 does not materially change the definition of minimum control speed involving lateral-directional control with asymmetric thrust.

The current MIL-STD-3013 (February 2003) [18] requires scheduled performance to comply with further revised speeds. Today, obstacle climb out speed should be:

$$VOBS = \max(120\% V_{Stall} \text{ power-off}, 105\% VMCA) \quad (5)$$

Civilian aircraft certified under AC 25-7C requires the airframe manufacturer to demonstrate $VMCA$ using flight test. $VMCA$ compliance requires flight at a “constant heading is maintained without exceeding a 5-degree bank angle.” [19] These will be carefully rehearsed flights, where pilots perform their tests at a very light weight so that the aircraft will can achieve lateral-directional trim at the predicted $VMCA$ while still flying comfortably above stall speed.

Modern MIL 1797A reiterates the verbiage of the earlier MIL 8785 standard and requires analysis to predict (and flight test to confirm) lateral-directional trim with asymmetric thrust with the 5-degree bank limit and 75% of available lateral control power. [20][17]

Thus, we can see that both civilian and military agencies have set the speed floor for scheduled flight to be between 13 to 20% above the certification demonstrated stall speed and 0% to 10% above the published minimum control airspeed.

III. How does VMC Impact Aircraft Performance?

Minimum control speeds conceptually exist to promote safe flight. We, as engineers, must remember the purpose of their presence, they do not exist just to “check the box” for regulatory compliance.

Pilots should never unintentionally fly their aircraft slower than the minimum control airspeed. So long as they do so, in the event of sudden engine failure, the pilot will neither lose control due to control saturation nor lose an ability to command heading.

A speed floor for operational flight impacts takeoff performance in two ways:

1. If $VMCA$ elevates the climb speed, it will also increase the takeoff rotation speed. These faster cue speeds lead to the pilot holding the aircraft on the ground longer during takeoff. This will extend the takeoff ground roll, and may consequently lead to a need for a longer runway for safe departure.

- Many times the speed for best-rate-of-climb and best-angle-of-climb are considerably faster than the stall speed. If $VMCA$ elevates the scheduled climb speed, it may actually improve aircraft climb performance.

Here, we show how flight at or near $VMCA$ is less uncommon than we might suspect. Consider military and commercial training flights, as well as some post-COVID pandemic commercial flights where dispatch schedules takeoff at a weight much closer to OEW than to MTOW.

We can infer from the flight manuals the basic stall-speed / weight schedule for a variety of common airframes. [2][21][22][23][24] We can also infer that $VMCA$ for a B737-500 is ~111-KEAS; an A320 is ~115-KEAS and a Lockheed C-130H/L-100 is ~110-KEAS. Turning next to FIGURES 4,5 and 6, we can plot the schedule takeoff speed schedule as a function of weight for these three aircraft.

For the B737-500, with a typical FLAPS 15 dispatch $VMCA$ limits apply to flights within 10,000-lbm of OEW; see Figure 4. Not only does Boeing provide elevated V_2 speed dispatch corrections, we can see that worrying about flight at or near the $VMCA$ floor is moot.

For the EMB-120, with a typical FLAPS 15 dispatch at sea-level on a standard-day, $VMCA$ limits apply to the rotation speed. Because of substantial excess thrust during lift-off, the aircraft will overshoot the nominal 1.2 V_s climb speed. As a consequence, the second segment climb speed, V_2 , is a peculiar function of weight. Nonetheless, at many dispatch weights takeoff climb speeds are dictated by minimum control speeds.

For the A320, with a typical CONF 2 takeoff, we see that $VMCA$ limits apply over a wide range of weights; see FIGURE 5. The Airbus published $VMCA$ speed is a logical complement to the intended use of the aircraft. The minimum control speed floor impacts dispatch under 140,000-lbm; with typical landing fuel reserves of ~5,000-lbm and a fuel consumption of ~0.08-nM/lbm, [1] this would correspond to a dispatch for an ~500-nM flight with ~150 passengers and their luggage; this represents a 79% to 100% load-factor depending upon the airline. Under typical airline utilization, the aircraft would climb-out at speeds above $VMCA$. Because load factors under 50% may become common in the post-COVID world, A320 operational safety may benefit from increased V_2 speeds.

For the Lockheed C-130-H/L-100 airframe, we can see that for any operating standard (older military, newer military or civilian) the aircraft is quite likely to dispatch on the $VMCA$ speed floor; see FIGURE 7 (overleaf). The older military standard schedules second segment climb at 120% V_S not less than $VMCA$; [12][14] the newer military standard schedules second segment climb at 120% V_S no less than 105% $VMCA$; [18] the civilian standard schedules second segment climb at 120% V_S not less than 110% $VMCA$. [4][15] The range of $VMCA$ weights is broadest under the civilian operating standard; 110% $VMCA$ limits V_2 speeds

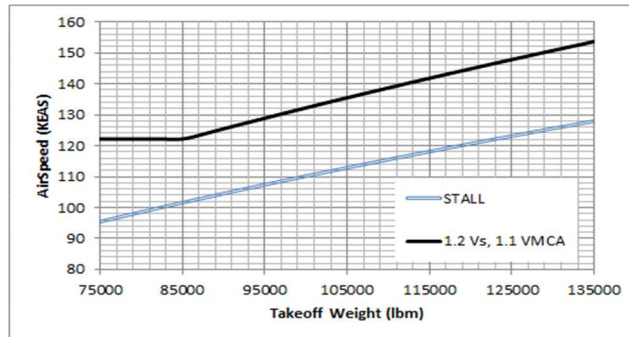


FIGURE 4 - B737-500 **FLAPS 15** Takeoff V_2 speeds [2]



FIGURE 5 - EMB **FLAPS 15** Takeoff Speeds [24]

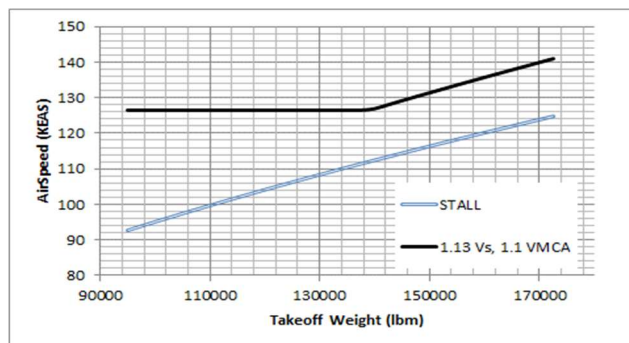


FIGURE 6 - A320 **CONF 2** Takeoff V_2 speeds [22]

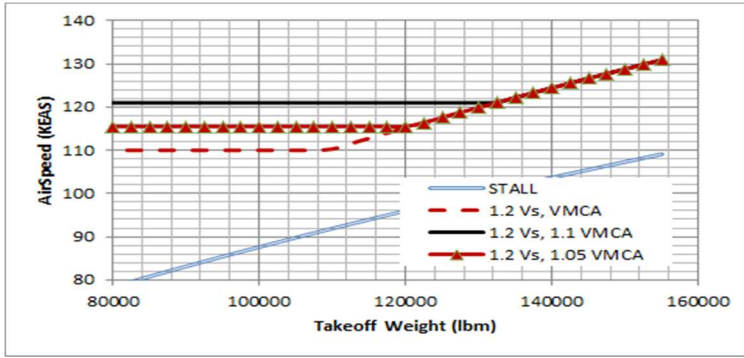


FIGURE 7 – C-130-H / L-100 **FLAPS 50** Takeoff VOBS Speeds for Differing Certification Basis [1]

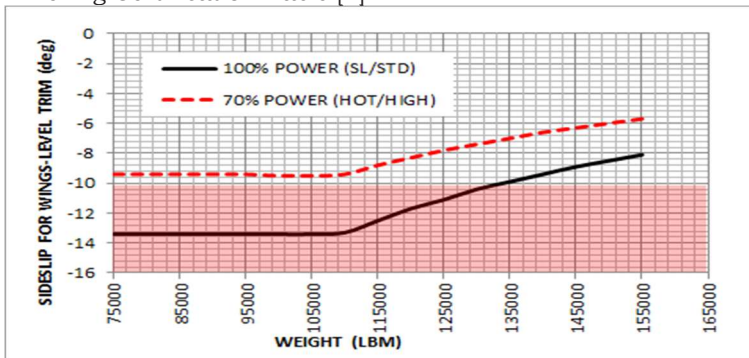


FIGURE 8 – C-130-H/L-100 Predicted Sideslip with Wings Level Trim – older military standard speed schedule [1]

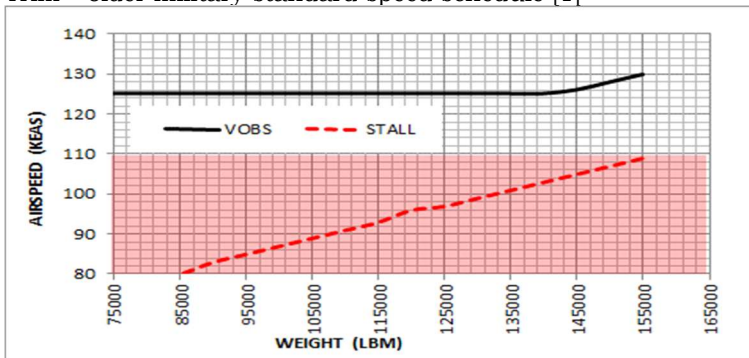


FIGURE 9 – C-130-H/L-100 Suggested Revised VOBS/V2 speed schedule

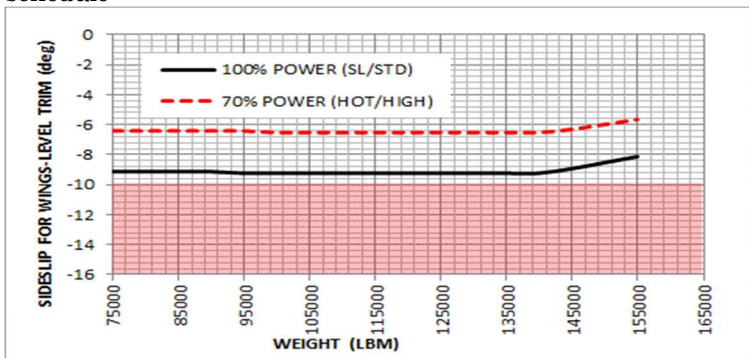


FIGURE 10 – C-130-H/L-100 Predicted Sideslip with Wings Level Trim – 125-KEAS minimum flight speed schedule

up to ~135,000-lbm (nearly 40,000-lbm above OEW). The range of VMCA limited weights is narrowest under the older military operating standards, but these standards schedule dispatch right at VMCA. Turning to FIGURE 8, we can see that if the pilot attempts to trim an inoperative engine with wings level at speeds less than 125-KEAS, he will crab the aircraft to a sideslip where $\beta \geq +10$ -deg. This may lead to rudder pedal force anomalies and other issues that can impact safety of flight.

For operational safety, we can consider a revised speed schedule. Turn next to FIGURE 9, where we define a speed schedule where VOBS can never fall below 125-KEAS. Using the methods from Takahashi & Perez [1], we can see that this corresponds to a wings level OEI trim at high power settings with $\beta < 10$ -deg; see FIGURE 10.

For this aircraft we are tasked with finding safe work-around for dispatch to use existing charts to support elevating the obstacle clearance speed by up to ~15-knots (for an aircraft flown under the older military standards)

IV. Introduction to Takeoff Dispatch Charts

Prior to flight, dispatch is required to ensure that the departure runway is equal to or longer than that required by the aircraft.

In this section we will introduce schematic representations of various dispatch charts and lay the theoretical framework to apply “corrections” to the data.

A. Assumed Temperature Derate Process

When aircraft weight, and runway conditions indicate that the aircraft has excess performance using full power, dispatch may advise use of a lower-power engine setting in order to reduce engine wear and address community noise issues.

The ASSUMED TEMPERATURE method is a common technique used by dispatch to achieve a part-power takeoff. This procedure “fools” the FADEC (Full Authority Digital Engine Controller) by having pilots input a fictitious temperature into the flight management system (FMS) computer.

For example, the Boeing 737 Classic Flight Crew Training manual describes the “Assumed Temperature Method” de-rate as one where “reduced takeoff thrust is achieved by selecting an assumed temperature higher than the actual ambient temperature.” [25] Because jet engines produce less thrust as the ambient air temperature increases, this trick effectively tells the computer to limit the turbine-inlet-temperature (TIT) and rpm (NI) of the engine. Under this procedure, pilot cue speeds ($V1$, $V2$, VR) and minimum control speeds ($VMCA$ and $VMCG$) are set by the full power takeoff thrust levels of the engine because “at any time during takeoff, thrust levers may be advanced to the full rated takeoff thrust” setting. [25] Dispatch “chases-the-charts” at the elevated temperature; so goes the logic - if the scheduled performance on the above ambient day is legal then surely the performance with the “fooled” FADEC will be adequate.

Airbus also utilizes this approach; they call it a “FLEX TEMP” takeoff. [26] A number of aircraft incidents and accidents have occurred when the flex temp was incorrectly calculated. The most serious accident occurred to an Emirates Airlines A340-500 departing Melbourne, Australia. [27] Pilots used an incorrect FLEX TEMP setting due to an erroneous estimate of aircraft flight weight. With greatly reduced thrust, the aircraft approached the end of the runway far below rotation speed. [27] The pilots over rotated in an attempt to get airborne. The aircraft struck several structures at the end of the runway. [27]

B. The ASSUMED WIND Process in Schematic Form

We present a novel method modelled on the concept of the assumed temperature de-rate procedure designed to substantiate dispatch with elevated $V2$ speeds using the existing paper or electronic flight manual.

The kernel of the idea is two fold. First, that climb gradients are not degraded by a modest increase in $V2$ or $VOBS$ speeds because $V2$ is slower than or not substantially greater than VX (the speeds corresponding to best climb gradient). Second, that the existing runway utilization charts already include elevated ground speeds as part of the headwind / tailwind correction process. Thus, we may provide safe (often called “conservative”) estimates for dispatch performance if we selectively apply a fictitious tail wind to the existing charts. We will demonstrate that both of these ideas are correct in **Section VI**.

The one confusing part of this process relates to the headwind / tailwind adjustments found in the various flight manuals. Both the US Military and the FAA establish a required process to “factor” the headwinds and tailwinds used to plan takeoff and landing. They account for the presence of gusts and turbulence by taking one-half the theoretical credit for performance improvements resulting from headwinds and taking 150% of the theoretical credit for performance degradations resulting from tailwinds. The US Military manuals requires dispatch to factor the winds before “chasing the charts;” the MIL charts have true headwind / tailwind correction factors. Civilian aircraft, per 14 CFR § 25.105(d) requires the factors to be “pre-applied” in the scheduled performance; “the takeoff data must include ... not more than 50 percent of nominal wind components along the takeoff path opposite to the direction of takeoff, and not less than 150 percent of nominal wind components along the takeoff path in the direction of takeoff.” [28]

Dispatch’s primary responsibility is to ensure that pilots do not takeoff above the maximum “safe” takeoff weight for conditions. Provided that the aircraft is loaded to less than the maximum “safe” weight, pilots must then establish “cue speeds,” $V1$, VR and $V2$ (or $VOBS$) at the actual dispatch weight.

In this next section we will propose the ASSUMED WIND method.

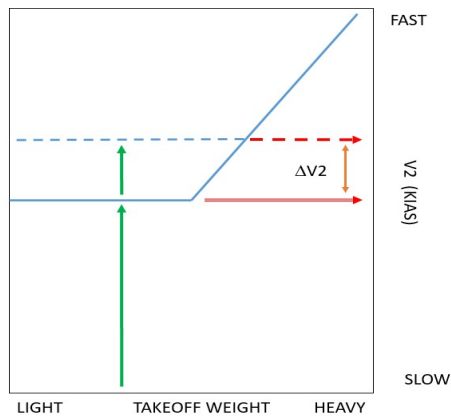


FIGURE 11 – Schematic of a Second Segment Climb Speed (V_2 or $VOBS$) Chart

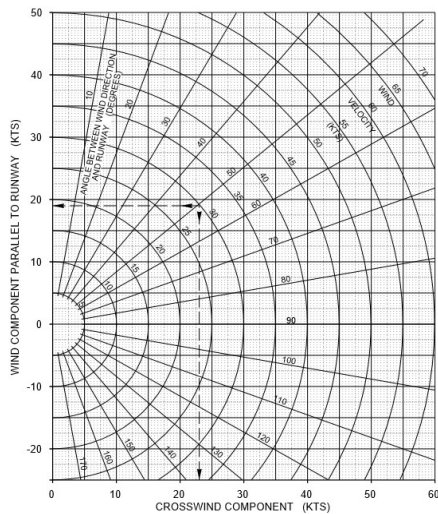


FIGURE 12 – Headwind / Crosswind Chart

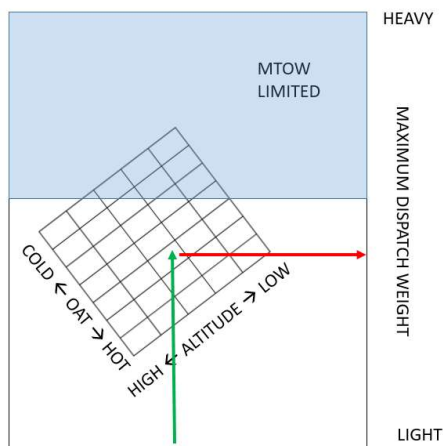


FIGURE 13 – Schematic of a WAT Limit Chart

To begin, we must find the maximum dispatch weight for the conditions (airport elevation, temperature, runway and terrain).

Step 1: for the initial planned dispatch weight and flight conditions (flap settings, temperature and altitude), use the basic flight manual (see FIGURE 11) to find the planned second segment climb speed; V_2 for civilian operators, $VOBS$ for military operators. Refer to a second chart that contains the revised speed schedule (shown as the dashed blue line in FIGURE 10). Subtract the original speed from the revised speed to establish the required speed increase, ΔV .

Step 2: Use the manufacturer supplied headwind / tailwind / crosswind chart (see FIGURE 12) to identify wind components. If the crosswind exceeds the manufacturers stated limits, dispatch cannot be authorized. Remember the HEADWIND and TAILWIND components as they will be used in the next step.

Step 3: Find the ASSUMED HEADWIND or TAILWIND component based upon the actual HEADWIND and TAILWIND reported and the required speed increase. This formula will differ depending upon whether dispatch is supposed to manually factor the winds (i.e. US MIL 5011 rules) or if the scheduled performance pre-factors the winds (i.e. US Civilian rules).

Step 4: Find the maximum dispatch weight compliant with the minimum regulatory climb performance for the planned takeoff flap setting associated with airfield conditions (pressure altitude and outside air temperature); refer to FIGURE 13 to see a cartoon of a typical WAT limit chart. The WAT limit sets an upper bound to dispatch weight, even on a very long runway located far from any terrain. WAT limit charts are not wind dependent.

Step 5: Find the brake energy limited takeoff weight (if the manuals feature this limit) associated with airfield conditions (pressure altitude and outside air temperature) using the ASSUMED HEADWIND / TAILWIND; see FIGURE 14. The solid line represents the basic HEADWIND we would normally use for dispatch; the dashed line represents the ASSUMED TAILWIND which will lead to a lower brake energy limited dispatch weight associated with the elevated ground speeds. The BRAKE ENERGY limit sets potentially sets a more restrictive bound to dispatch weight, even on a very long runway located far from any terrain.

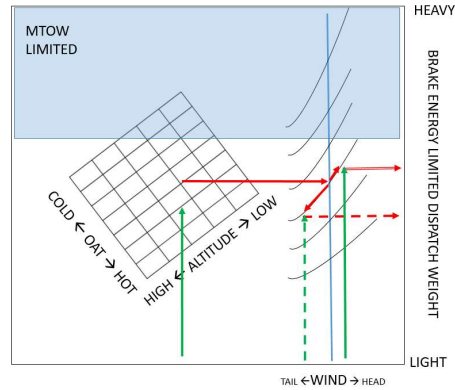


FIGURE 14 – Schematic of a BRAKE ENERGY Limit Chart

Step 6: Find the OBSTACLE CLEARANCE limited takeoff weight associated with airfield conditions (pressure altitude and outside air temperature) using the ASSUMED HEADWIND / TAILWIND. To do this we begin with the Obstacle Clearance chart to find the required engine-inoperative climb gradient based upon the geometry implied by any close-in obstacles; see FIGURE 15. Once we identify the required minimum gradient, dispatch must chase the climb gradient chart (see FIGURE 16) from left and right to intersect in the middle at the weight correction grid. This is how we determine the maximum flight weight that supports the gradient. For an airport with extensive terrain, the OBSTACLE CLEARANCE limit may restrict dispatch weight.

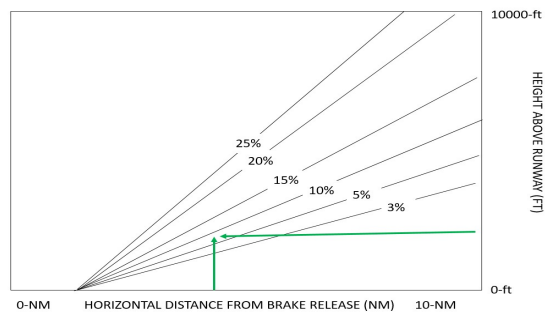


FIGURE 15 – Schematic of Obstacle Clearance Chart

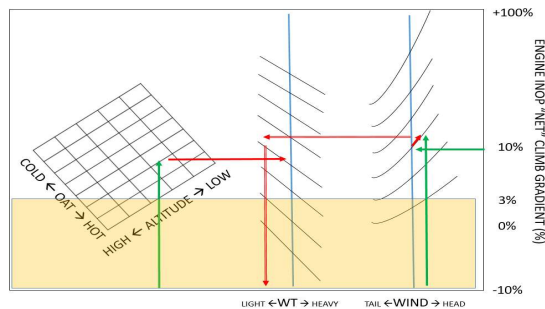


FIGURE 16 – Schematic of Climb Gradient Chart

Step 7: Find the FIELD LENGTH LIMITED takeoff weight associated with a given runway and airfield conditions (pressure altitude and outside air temperature) using ASSUMED HEADWIND / TAILWIND. Dispatch must chase the field length chart (see FIGURE 17) from left (pressure altitude and outside air temperature) and right (back chasing the runway condition (friction) rating (RCR), the ASSUMED WIND and the runway slope) to intersect in the middle at the weight correction grid. This is how we determine the maximum flight weight that supports the available length runway.

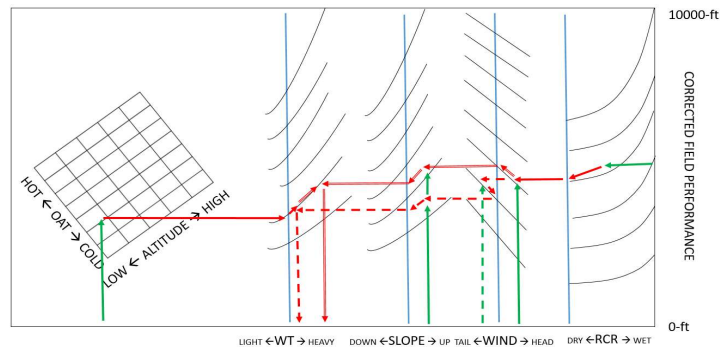


FIGURE 17 - Schematic of a Field Length Chart

Step 8: We can now identify the critical dispatch weight.

$$MAX_WT = \min(WAT\ LIMIT, BRAKE\ ENERGY\ LIMIT, OBSTACLE\ LIMIT, FIELD\ LENGTH\ LIMIT) \quad (6)$$

If the planned dispatch weight is less than the critical dispatch weight, we may proceed.

Step 9: Moving Forwards, we may now establish our actual cue speeds. Chase the appropriate charts with pressure altitude, outside airfield temperature and weight to establish our Baseline $V1$, VR and $V2$; see FIGURE 18.. Increment all of these speeds by ΔV .

$$V1 = V1_{BASELINE} + \Delta V \quad (7a)$$

$$VR = VR_{BASELINE} + \Delta V \quad (7b)$$

$$V2 = V2_{BASELINE} + \Delta V \quad (7c)$$

These are our new “cue” speeds.

Step 10: Chase the ACCELERATION CHECK TIME takeoff planning chart (if present) using the baseline winds (HEADWIND or TAILWIND). Because the acceleration check speed is far below VMCG, the elevated decision speed will not impact the solution.

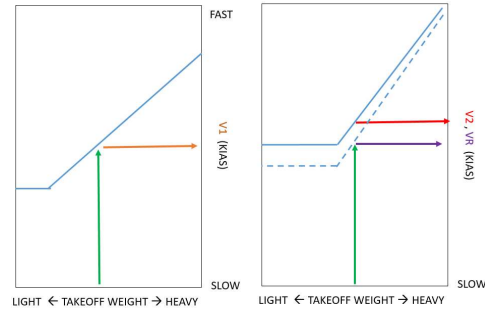


FIGURE 18 – Schematic of the forward solution for Baseline $V1$, VR and $V2$ speeds

V. Worked Example

A. Civilian Manual with Pre-Factored Headwinds

Example EMB 120. MTOW = 25,300-lbm.

Let us say, that for enhanced operational safety we would like to limit $V2$ speeds to be no less than 118-KIAS.

Consider a takeoff from Carlsbad, CA (KCRQ). Runway 24 (actual heading 245) has declared distances of TORA (Takeoff Run Available) = TODA (Takeoff Distance Available) = ASDA (Accelerate-Stop Distance Available) =4,897-ft. The runway has negligible slope. Consider weather where the airfield pressure altitude is at PA=500-ft and the temperature is OAT= 25°C. We plan dispatch at W=23,000-lbm. Flaps 15. Winds 12-knots from 275°. We also plan a “Pilots Convenience Takeoff” with $V1=VR$; thus $V1/VR=1.0$.

Step 1: Obtain Nominal $V2$.

Reading FIGURE 20, we see $V1min = 98$ -KIAS; $V1 = VR = 108$ -KIAS; $V1/VR=1.0$; $V2 = 110$ -KIAS. Thus, to elevate $V2$ to 118-KIAS, $\Delta V = 8$ -knots

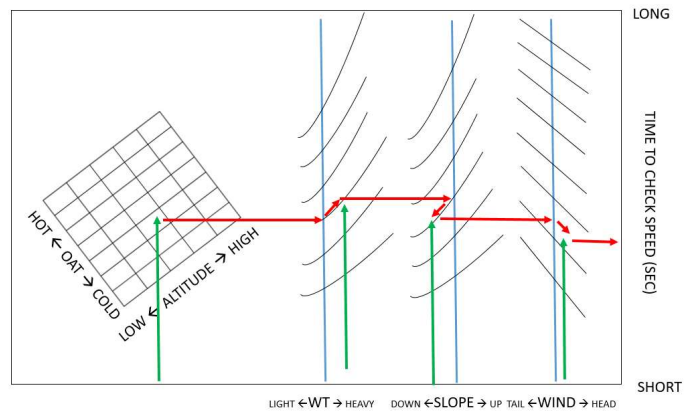


FIGURE 19 - Schematic of a ACCELERATION CHECK TIME Chart

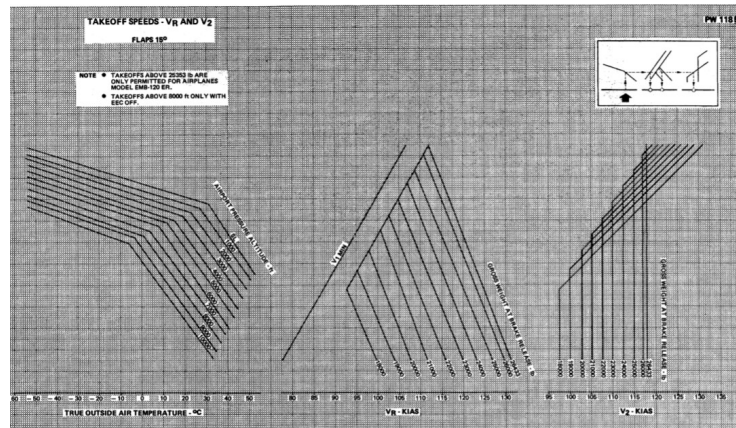


FIGURE 20 – Takeoff Cue speeds for EMB-120 [24]

Step 2: Compute actual headwind / tailwind / crosswind.

HEADWIND = $\cos(275^\circ-245^\circ) * 12 \approx 10$ -knots; CROSSWIND = $\sin(275^\circ-245^\circ) * 12 \approx 6$ -knots. Crosswinds are legal.

Step 3: Estimate assumed headwind / tailwinds

For an FAA manual, the dispatch chart performance for a 10-knot posted headwind represents true aircraft performance with a 5-knot posted headwind. [28] Similarly, the scheduled performance with a 5-knot posted tailwind represents true aircraft performance with a 7.5-knot posted tailwind.

Thus, to properly account for the increased groundspeeds associated with the V2 bump, we must use the following logic:

$$PERFORMANCEWINDS = HEADWIND/2 - TAILWIND*1.5 \tag{8}$$

Thus, to properly introduce the increased ground speed we must apply to ΔV to the performance winds and then unfactor them for entry into the flight manual pages. To ensure safe dispatch, we apply 1.5 ΔV .

$$ZWIND = PERFORMANCEWINDS - \Delta V * 1.5$$

If $ZWIND \geq 0$ then

$$ASSUMED_HEADWIND = ZWIND * 2$$

else

$$ASSUMED_HEADWIND = - ZWIND / 1.5 \tag{9}$$

Thus, for our example:

$$PERFORMANCEWINDS = 10/2 = 5 \text{ kts}$$

$$ZWIND = 5 - 8*1.5 = -7$$

$$ASSUMED_HEADWIND = -5 \text{ kts}$$

Thus, to account for the elevated V2 speeds we have turned a true headwind of 10-knots into a 5-knot “assumed tailwind.”

We may formalize this mathematical transformation into a simple plot for pilot’s reference; see FIGURE 21.

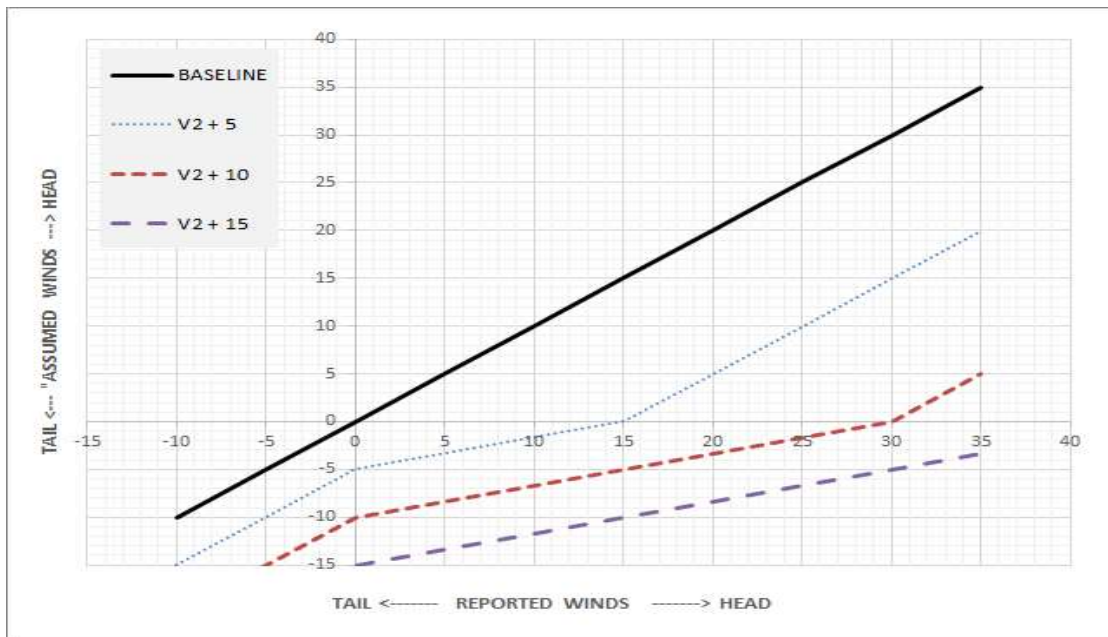


FIGURE 21 – FAA Dispatch “ASSUMED WIND” Reference Graph

Step 4: WAT Limit

Read the WAT limit chart for PA=500-ft, OAT=25°C; see FIGURE 22. WAT limit is > 27,000-lbm (above MTOW).

Step 5: Brake Energy Limit

Read BKE limit chart for PA=500-ft, OAT=25°C, 5-knot ASSUMED TAILWIND, 0 slope, $V1/VR=1.0$; see FIGURE 23. We see that the BKE limit weight is > 27,000-lbm (above MTOW).

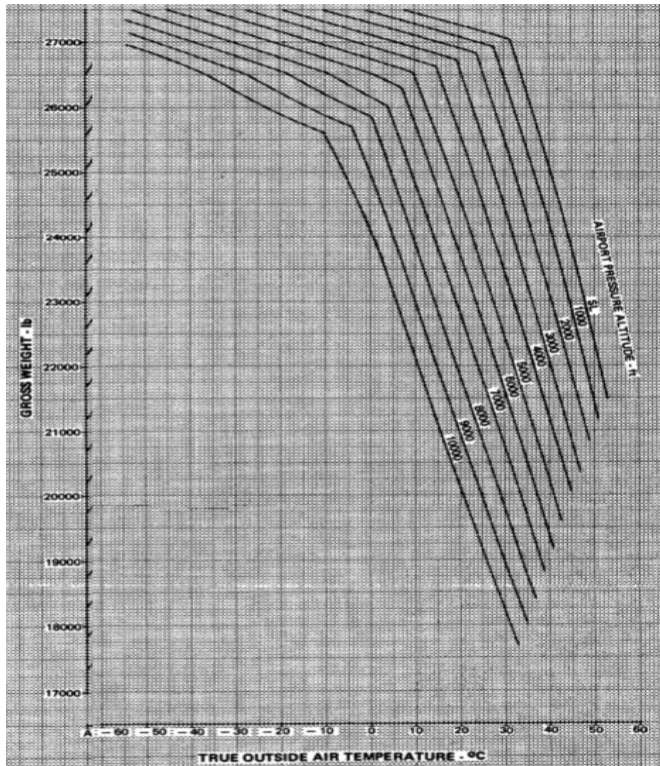


FIGURE 22 – WAT LIMIT CHART [24]

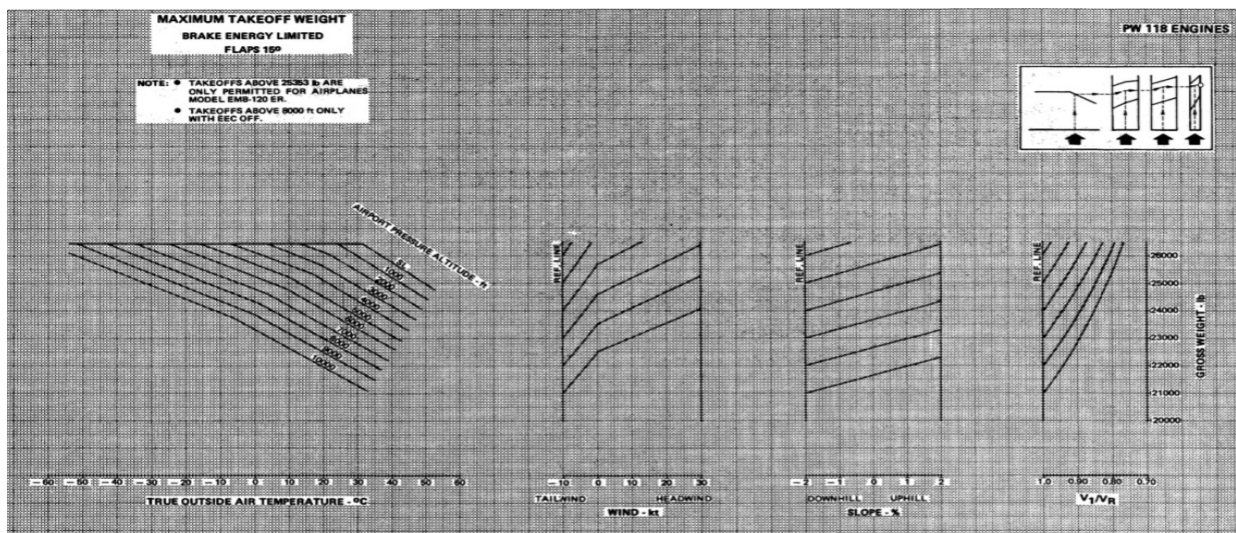


FIGURE 23 – BRAKE ENERGY LIMIT [24]

Step 6: Find Obstacle Clearance Limit

Let us say that we have a need to clear an obstacle 200-ft above the runway, located 9,000-ft from the reference zero. If we enter FIGURE 24, we can use the wind correction table to adjust the required still air climb gradient.

For dispatch at nominal V_2 , we would apply the 10-knot headwind correction to obtain a required ~2.0% climb gradient.

Using the ASSUMED WIND correction for dispatch at elevated V_2 , we would apply a 5-knot tailwind correction to obtain a required ~2.4% climb gradient for obstacle clearance. Thus, the elevated climb speed requires an +0.4% increase in net climb gradient.

We next chase FIGURE 25 (overleaf) entering the chart on the bottom left with OAT=25°C and PA=500-ft and on the right with 2.4% net gradient to find that our Obstacle Clearance Limited Weight is ~23,500-lbm. If we were to use the required climb gradient arising from true winds, we would find that our Obstacle Clearance Limited Weight is ~25,000-lbm.

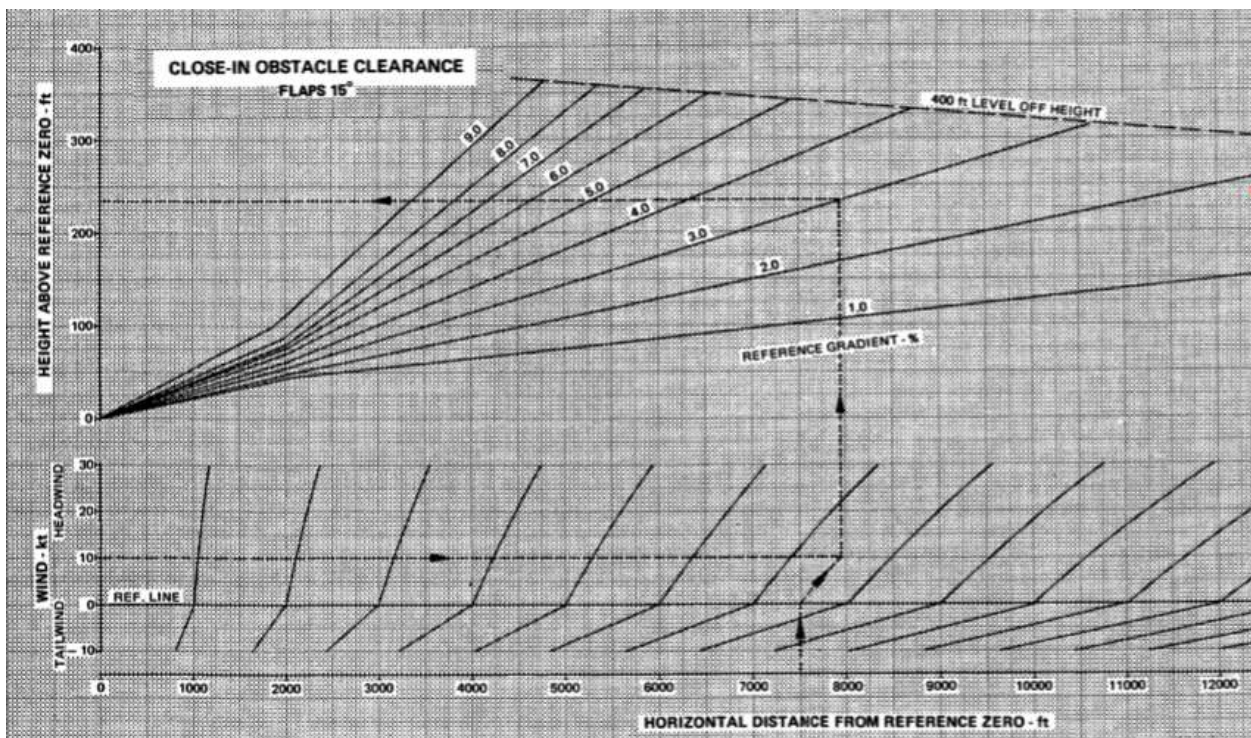


FIGURE 24 – OBSTACLE CLEARANCE GRADIENT ADJUSTMENT [24]

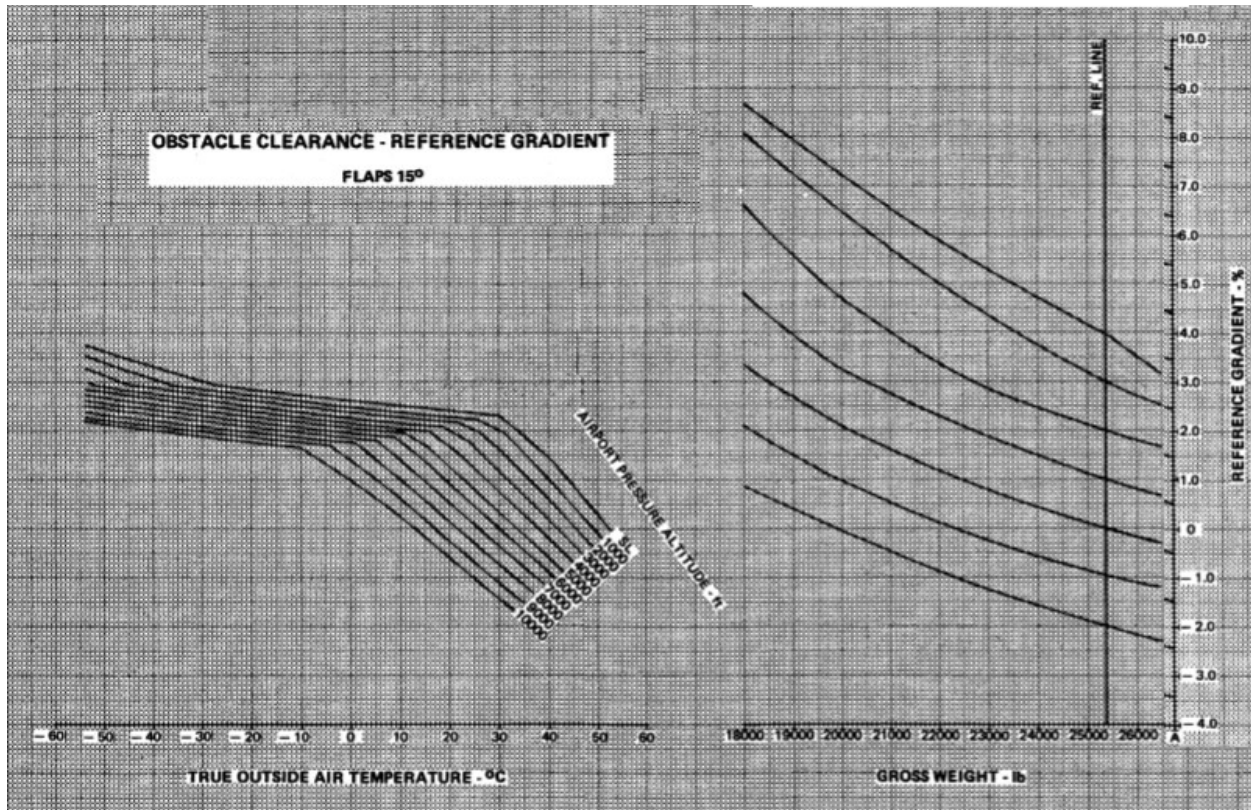


FIGURE 25 – OBSTACLE CLEARANCE SECOND SEGMENT “NET” CLIMB GRADIENT CHART [24]

Step 7: Field Length Limited Weight

Finally, to obtain the field length limited weight we must use the charts in FIGURE 24. Enter FIGURE 26a with the 4,897-ft runway, zero slope and 5-knot ASSUMED TAILWIND. We get a corrected Takeoff Length of ~4,300-ft. Enter FIGURE 26b with the 4,897-ft runway, zero slope and 5-knot ASSUMED TAILWIND. We get a corrected Accelerate-Stop Length of ~4,400-ft. We then enter FIGURE 26c with these distances and $V1/VR=1$, $PA=500$ -ft and $OAT=25^\circ\text{C}$ to determine a FIELD LENGTH LIMITED WEIGHT of ~23,250-lbm.

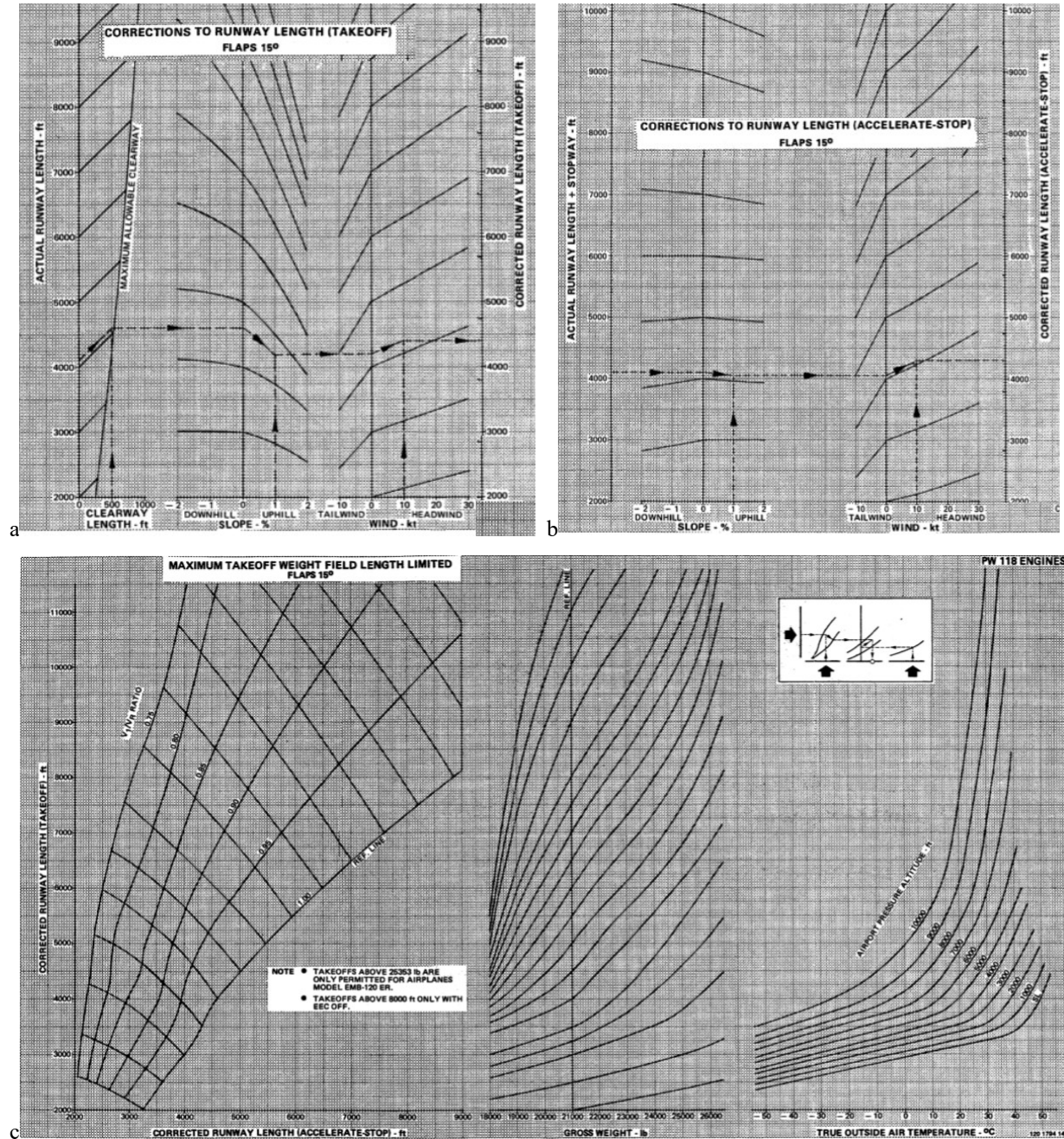


FIGURE 26 – FIELD LENGTH LIMITED WEIGHT CHARTS [24]

Step 8: Determine the CRITICAL DISPATCH WEIGHT

The Critical Dispatch Weight is $\min(>27000, >27000, 23500, 23250) = 23,250\text{-lbm}$.

We see that our takeoff is permissible because the planned dispatch weight of 23,000-lbm is less than the 23,250 field-length-limited critical dispatch weight and less than the 25,300-lbm maximum takeoff weight.

Step 9: Revise cue speeds:

$$VI = VI_{\text{BASELINE}} + \Delta V = 108 + 8 = 116\text{-KIAS} \quad (\text{a } 7.6\% \text{ increase in speed})$$

$$VR = VR_{\text{BASELINE}} + \Delta V = 108 + 8 = 116\text{-KIAS}$$

$$V2 = V2_{\text{BASELINE}} + \Delta V = 110 + 8 = 118\text{-KIAS} \quad (\text{a } 7.2\% \text{ increase in speed})$$

B. Military Manual with User Factored Headwinds

For an aircraft like a C-130-H, we propose dispatch where VOBS speeds shall not be less than 125-KIAS.

Step 1: Obtain Nominal V2.

If basic dispatch calls for VOBS=VMCA=110-KIAS and we are to elevate VOBS to 125-KIAS, $\Delta V = 15\text{-kts}$.

Step 2: Compute actual headwind / tailwind / crosswind.

Step 3: Estimate assumed headwind / tailwind..

A MIL manual expects the pilot to manually factor reported winds before chasing the performance charts.

Thus, to properly introduce the increased ground speed we must apply to ΔV to the true winds and then factor them for entry into the flight manual pages.

If HEADWIND ≥ 0 then

$$FACTORED_WIND = HEADWIND/2 - 1.5 * \Delta V$$

else

$$FACTORED_WIND = HEADWIND*1.5 - 1.5 * \Delta V \tag{11}$$

For example, if we had a 30-knot headwind and a 5-knot ΔV : $FACTORED_WIND = 30/2 - 1.5*5 = +7.5\text{-kts}$.

We can plot up this function for simple pilot’s reference; see FIGURE 27.

Steps 4,5,6,7,8 and 9 will all follow the civilian example.

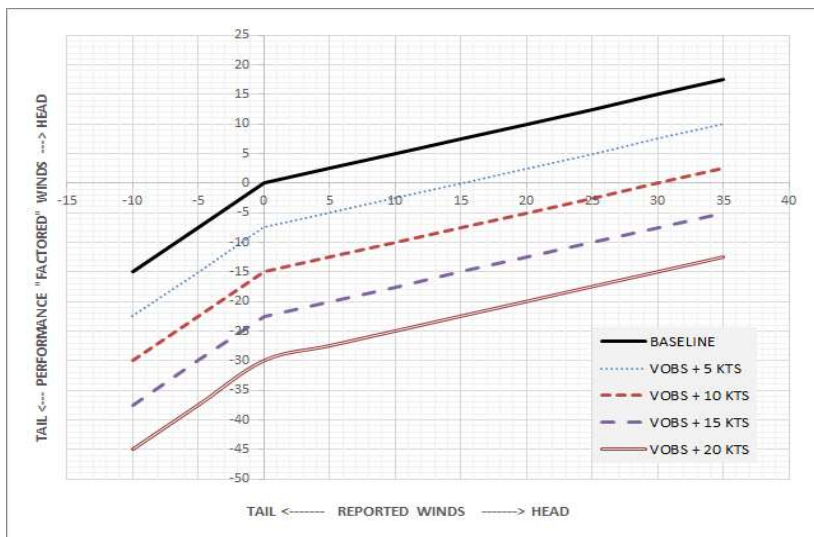


FIGURE 27 – MIL Dispatch “ASSUMED WIND” Reference Graph

VI. Substantiation of the ASSUMED WIND Process

The “ASSUMED WIND” Method produces safe (i.e. “conservative”) dispatch data in the event that the airplane satisfies several conditions. First, we must show that climb gradients are not degraded by a modest increase in V_2 or $VOBS$ speeds. Second, we must show that the peak kinetic energy of the aircraft in the event of a rejected takeoff at elevated V_1 speed is no greater than the peak kinetic energy at the nominal V_1 speed in the presence of the ASSUMED WIND. Third, we must show that the critical field length with elevated V_1 , VR and V_2 speeds is no greater than the critical field length in the presence of an ASSUMED WIND at nominal V_1 , VR and V_2 speeds. This section will work through each of these situations using a reverse engineered EMB-120 as the exemplar model.

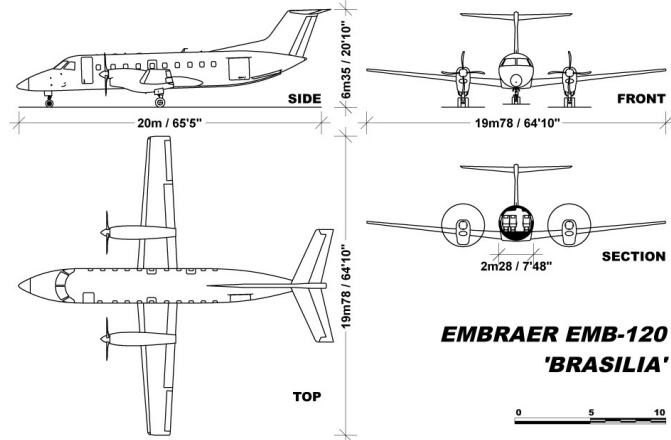


FIGURE 28 – EMB 120 – THREE VIEW DRAWING

FIGURE 28 provides a three-view rendering of the EMB-120. TABLE 1 shows key reference parameters.

TABLE 1 – EMB-120 BASIC SPECIFICATIONS

EMB 120 “Brasilia”	
MTOW	26,433-lbm
SREF	424 sq. ft.
Span	64.92 ft
AR	9.94
CD0	~0.0425 (gear up, take off flaps, engine failed)
CLmax	1.9 (FLAPS 15)
Propulsion	1700 eSHP (~3750-lbm static thrust)

From this publicly available information, we provide the following estimated aerodynamic and propulsive performance estimates.

Return to FIGURE 25. The flight manual chart provides a “net” second segment climb gradient for sea-level, standard-day conditions at a flight weight $W=25,000$ -lbm of +2.5% gradient at $V_2 = 115$ -KIAS and +3.5% gradient at $W=23,000$ -lbm. Because 14 CFR § 25.115(b) the flight manual includes a 0.8% “gross-to-net” derate; [29] the true climb performance under these conditions is +3.3% @ 25,000-lbm and +4.3% @ 23,000-lbm.

The calibrated model has the following thrust-speed lapse under sea-level standard-day conditions; see FIGURE 29 (overleaf). It also has the basic low-speed polar with takeoff flaps deployed including the drag associated with the inoperative engine; see FIGURE 30 (overleaf).

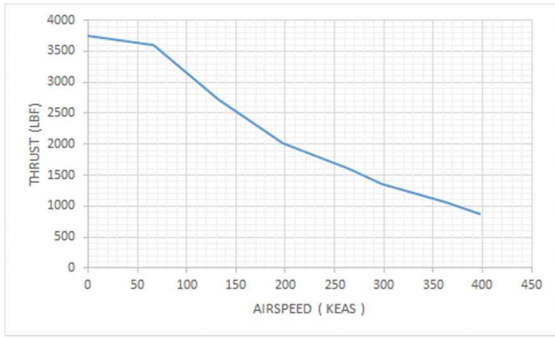


FIGURE 29 – Estimated Sea-Level / Standard-Day Thrust Lapse for the Turboprop Engine on the EMB-120

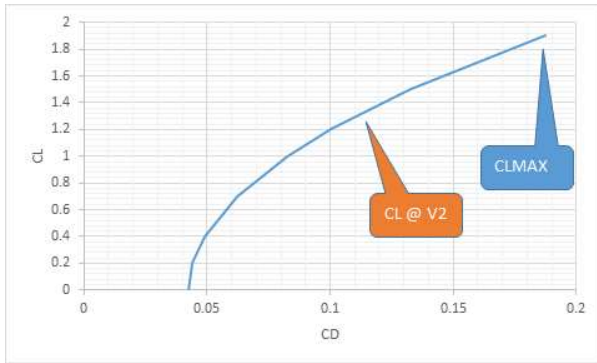


FIGURE 30 – Estimated Drag Polar for the EMB-120 – TAKEOFF FLAPS with Trim & Engine Inoperative Drag

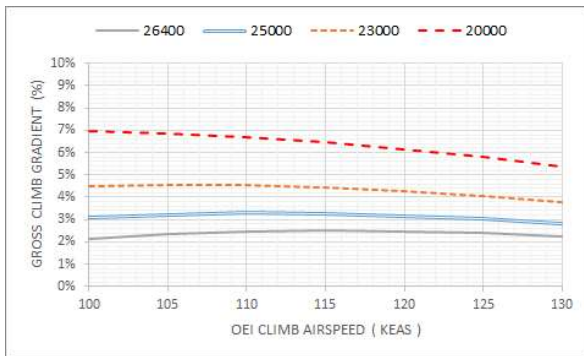


FIGURE 31 – Reverse Engineered EMB-120 Performance. OEI Gross Climb Gradient as a function of Climb Speed

A. Do Assumed Winds Used In the Obstacle Clearance Chart Provide a Conservative Solution?

To show that the ASSUMED WIND method is safe (i.e. “conservative”) we must show that the climb degradation associated with modest increases in V_2 speeds do not degrade climb performance above and beyond the wind corrections found in the obstacle clearance charts. Recall from our worked example, that the assumed winds technique applied to the EMB-120 had an 8-knot increase in V_2 speed associated with a need for +0.5% greater climb gradient on the baseline chart. In other words, to be safe an 8-knot increase in V_2 speed should degrade the reference climb performance by less than 0.5% gradient.

To substantiate this, let us turn to the small-angle approximation for climb gradient:

$$GRADIENT = 100\% * (THRUST - DRAG) / WEIGHT \quad (12)$$

Where:

$THRUST$ is a function of airspeed; see FIGURE 27

$DRAG = CD q SREF$; see TABLE 1

$LIFT = WEIGHT = CL q SREF$; see TABLE 1

$$q \sim (KIAS / 660.8)^2 * 1481 \text{ lbf/ft}^2$$

$$CL \sim (WEIGHT / SREF) / q$$

The above aerodynamic and propulsion models substantiate the gross climb gradient OEI as a function of weight and climb speeds shown in FIGURE 31. Since the handbook provides climb gradients of +3.3% @ 25,000-lbm and +4.3% @ 23,000-lbm both flown ~115-KIAS and the model predicts +3.3% and 4.4% gradients respectively, we can see that the model has been calibrated to closely match the scheduled performance. At the heaviest analyzed flight weight, 26,400-lbm, the nominal 115-KIAS climb speed corresponds to V_X , the speed for best climb gradient; an 8-knot climb speed increase from the nominal 115-KIAS has a 0.2% loss in theoretical climb capability. At the nominal weight, 23,000-lbm an 8-knot increase leads to a 0.4% loss in theoretical climb capability. Since the ASSUMED WIND technique predicted a need to account for a loss of 0.5% in climb gradient it is safe.

B. Does the WAT Limit Chart Provide a Conservative Solution?

For an aircraft where the scheduled V_2 speeds are slower than the V_X speed for best gradient (i.e. the B737-500), the WAT limit charts are inherently safe.

For an aircraft like the EMB-120, where the scheduled V_2 speeds are faster than the V_X speed for best gradient, the WAT limit charts are not inherently safe. Thus, we must always plan dispatch with a minimum close-in-obstacle representing the spirit of the WAT limit.

Regulation 14 CFR § 25.121 (b) controls the minimum second segment gradient. [30] It requires at least 2.4% gradient true climb capability critical engine operative at the V_2 speed. Combining this requirement with 14 CFR § 25.115, which requires the obstacle clearance charts to include a 0.8% gradient degradation (for two-engine aircraft), we realize that to ensure compliance with the WAT limit we must always plan around a minimum close-in obstacle clearance gradient of 1.6%.

C. Do assumed winds used in the Brake Energy Charts Provide a Conservative Solution?

To show that the ASSUMED WIND method is safe (i.e. “conservative”) we must show that the total kinetic energy of the aircraft associated with modest increases in V_2 speeds does not overwhelm the capacity of the brake system.

The peak kinetic energy the brake system is expected to dissipate is associated with a rejected-takeoff (RTO) performed at the decision speed (V_1).

Kinetic energy is proportional to the aircraft mass and the square of its ground speed; $KE = \frac{1}{2} M V^2$.

However, cue speeds are given in terms “indicated airspeed.” The two are related by the following relationship.

$$GROUND_SPEED = TRUE_AIR_SPEED - HEADWIND \quad (13)$$

Under still winds circumstances 100-knots ground speed equals 100-knot true airspeed; under a 10-knot true tailwind 100-knots airspeed implies 110-knots ground speed; under a 10-knot factored tailwind 100-knots airspeed implies 115-knots ground speed.

Thus, to ensure a safe dispatch within the thermal limits of the brake system we must match or overpredict ground-speeds when using the brake energy charts. If the ground-speeds are identical, so must the kinetic energy. If we adjust the headwind by 1.5x the ΔV , we will increase the ground-speed at the moment of the rejected takeoff above the nominal value. If we properly adjust the winds, the ground-speeds will be identical. Our method intentionally adjusts the winds to over-predict the ground speed with ASSUMED WINDS. Because identical kinetic energy must follow identical ground speeds and a greater kinetic energy follows increased ground speeds, the ASSUMED WINDS method provides a safe solution to protect against a high-energy dispatch that exceeds brake system capacity.

D. Do Assumed Winds used in the Takeoff Field Length Chart Provide a Conservative Solution?

To show that the ASSUMED WIND method is safe (i.e. “conservative”) we must show that the takeoff critical field length of the aircraft for modest increases in V_2 speeds can be captured by the method. Here, we reverse engineered the takeoff field performance of the EMB-120 using Takahashi’s method [31]. Since these physics-based methods have been well calibrated against the Airbus A320 in other work, we consider the model to be fundamentally accurate and captures all certification-timing related issues. [32][33]

The most strenuous test of the ASSUMED WIND method will be to model a “Pilot’s Convenience” $V_1=VR$ takeoff. This simulation will stress the differences between a true elevated VR speed takeoff and a takeoff at nominal VR , but with a tailwind. In both circumstances, the true ground speed at VR will be identical. However, with the tailwind the aircraft will be operating at a lower airspeed. Because the drag coefficient on the runway is not a function of the takeoff procedure, a lower airspeed will result in slightly less drag. As noted in FIGURE 29, thrust lapses considerably with airspeed; thus the elevated V_2 simulation will develop slightly more lift and drag than the tailwind simulation at identical ground speeds. Lift will reduce the rolling resistance; drag will slightly diminish the ground phase acceleration. In addition, aerodynamic lift will slightly reduce braking capacity (through a reduction of weight on wheels) and will slightly increase the RTO stop distances. On the other hand, these same effects that worsen acceleration for the elevated V_2 simulation also reduce the speed overshoot between engine-failure and the pilot’s recognition of the engine failure. Because our simulation takes all of these factors into consideration, we can use it to validate our proposal to “adjust” the flight manual.

Turning to FIGURE 32, we can compare the predicted “Pilot’s Convenience” $V_1=VR$ critical field length of the EMB-120 at sea-level standard conditions. You can see that our model closely matches the scheduled performance of the actual aircraft. If we return to FIGURE 26, and chase the charts for a departure from a 5,000-ft runway with zero-slope at sea-level, standard-day under still winds we find the field length limited takeoff for $V_1=VR$ to be ~26,000-lbm; the acceleration-stop case limits CFL. With a 2°-sec rotation rate and a braking $\mu=0.5$, the simulation shows CFL governed by a OEI accelerate-stop at 5,000-ft for a takeoff weight of 26,000-lbm. Thus, for the baseline configuration our model closely matches the flight manual.

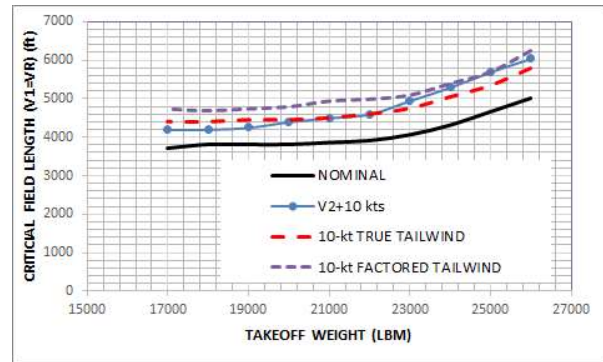


FIGURE 32 – Critical Field Length Estimates. $V_1=VR$. Sea-Level. Standard-Day. Time-Step Integration Simulation for Reverse Engineered EMB-120.

Returning to FIGURE 32, we can examine the predicted performance with an across the board 10-knot V_2 bump in comparison to solutions with a 10-knot true tailwind or a 10-knot factored tailwind (15-knot true tailwind). In all circumstances the CFL is accelerate-stop limited, distances lengthen by up to ~1,000-ft over the baseline. At higher weights (and, hence, higher airspeeds) the residual lift hinders the braking effect to the point where distances stretch up to 250-ft longer than required with the 10-knot true tailwind. Thus, we see that a 10-kt factored tailwind trend is a conservative substitute for the V_2+10 -knot schedule.

VII. Conclusions

In this work we proposed the ASSUMED WINDS technique to permit safe dispatch of aircraft at elevated V_1 , VR and V_2 speeds using an existing flight manual.

In our review, we show how $VMCA$ limits associated with commercial and military certification can and does impact takeoff performance at low dispatch weights. Many aircraft, particularly at light weights, operate at or near the $VMCA$ “floor” for takeoff climbout. Enhanced operational safety may be obtained if aircraft fly substantially faster than $VMCA$ although most flight manuals (the B737 being a commercially successful “exception that proves the rule”) do not provide sufficient advisory information to directly plan for high speeds. Since, $VMCA$ limited takeoff does not have weight dependent cue speeds, dispatch planning at a pessimistic weight does not provide relief from the problem.

For an aircraft like the A320 under pre-COVID airline utilization the defined weights and speeds do not severely limit the aircraft takeoff performance. But at light load factors, it becomes $VMCA$ limited.

$VMCA$ limits many other aircraft, like the EMB-120 and C-130, across a wide range of operational weights.

The ASSUMED WINDS technique, described above, provides a work around to enable safe dispatch including Brake Energy and Close-In Obstacle Clearance for aircraft if the operator would like to reschedule takeoff climb at an elevated V_2 speed.

Acknowledgements

The authors wish to acknowledge and thank the Directorate of Technical Airworthiness and Engineering Support (DTAES) at Canada’s Department of National Defence (DND) for supporting this research (Grant #18485SK110-04).

References

- [1] Takahashi, T.T. and Perez, R.E., “On the Operational Implications of Traditional Design Rules for Minimum Controllable Airspeed,” AIAA 2020-0749, 2020.
- [2] *737 Airplane Characteristics for Airport Planning*, Document Number D6-58235-6, BOEING BOEING, Sept. 2013.
- [3] Wood, D.L., Takahashi, T.T., and Bays, L.V., “Experimental Investigation of Typical Aircraft Field Performance versus Predicted Performance Targets,” AIAA 2017-3276, 2017.
- [4] 14 CFR § 25.107 “Takeoff speeds.” (2019)
- [5] 14 CFR § 25.125 “Landing” (2019)
- [6] 14 CFR § 25.143 “Controllability and Maneuverability - General” (2019)
- [7] 14 CFR § 25.145 “Longitudinal Control” (2019)
- [8] 14 CFR § 25.147 “Directional and Lateral Control” (2019)
- [9] 14 CFR § 25.171 “Stability - General” (2019)
- [10] 14 CFR § 25.175 “Demonstration of Static Longitudinal Stability” (2019)
- [11] 14 CFR § 25.149 “Minimum Control Speed” (2019)
- [12] MIL 8785B (August 1969)
- [13] Chalk, C.R., Neal, T.P., Harris, T.M., Pritchard, F.E. and Woodcock, R.J. “Background Information and User Guide for MIL-F-878B(ASG) “Military Specification – Flying Qualities of Piloted Airplanes,” AFFDL TR6972, August 1969.
- [14] MIL C-5011B (June 1977)
- [15] 14 CFR § 25.107 “Takeoff speeds.” (2001)
- [16] 67 FR 70826 (2002) See: <https://www.govinfo.gov/content/pkg/FR-2002-11-26/pdf/02-29667.pdf#page=16> (accessed June 10, 2019)
- [17] MIL 8785C (1980)
- [18] MIL STD 3013 (Feb 2003)
- [19] Federal Aviation Administration, Flight Test Guide for Certification of Transport Category Airplanes, Advisory Circular AC-25-7C, U.S. Department of Transportation, Washington, D.C., Oct 16, 2012.
- [20] MIL 1797A (Dec 1997)
- [21] *Airbus Industrie A320 Model A320-212 Flight Manual, approved by DGAC*, Airbus Industrie, Blagnac, France, 1990.
- [22] *Lockheed C130 Low-Speed Handling Qualities*. Lockheed Aeronautical Systems Co. (N.D.)
- [23] *Consolidated Aerodynamic Substantiating Data Report for C-130 Airplanes Having T56-A-17 Engines – Redacted*, US01-100005-626, July 2017. (Redacted copy of LG85ER0135 for public release).
- [24] *EMBRAER EMB-120 Brasilia Airplane Flight Manual, Section V, Performance, Rev. 30*, EMBRAER, December 17, 1991.
- [25] 14 CFR § 25.125 “Landing” (2001)
- [25] *Boeing 737 CL Flight Crew Training Manual*, Document Number FCT 737CL, BOEING, Rev. July 29, 2009.
- [26] Fueri, M., “Flex Temperature: Choice of Takeoff Configuration,” Airbus 14th Performance & Operations Conference, April 4-8, 2005, 2005.
- [27] *Tailstrike and Runway Overrun. Melbourne Airport, Victoria, 20 March 2009*, Australian Transport Safety Report ATSB A0-2009-012, 2009.
- [28] 14 CFR § 25.105 “Takeoff” (2019)
- [29] 14 CFR § 25.115 “Takeoff Flight Path” (2019)
- [30] 14 CFR § 25.121 “Climb: One Engine Inoperative” (2019)
- [31] Takahashi, T.T., *Aircraft Performance & Sizing, Vol. II: Applied Aerodynamic Design*, Momentum Press, New York, NY, 2016. 276 pages. ISBN-13: 978-1606509456
- [32] Takahashi, T.T., Wood, D.L. and Bays, L.V., “An Introduction to the Impact of Pilot Techniques Upon “Certified” Field Performance,” AIAA 2017-0007, 2017.
- [33] Beard, J. E., “Takeoff Obstacle Clearance Procedures: The Feasibility of Extended Second Segment Climb,” Thesis, Arizona State University, 2017.