Takeoff Obstacle Clearance Procedures:

The Feasibility of Extended Second Segment Climb

by

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ABSTRACT

To ensure safety is not precluded in the event of an engine failure, the FAA has established climb gradient minimums enforced through Federal Regulations. Furthermore, to ensure aircraft do not accidentally impact an obstacle on takeoff due to insufficient climb performance, standard instrument departure procedures have their own set of climb gradient minimums which are typically more than those set by Federal Regulation. This inconsistency between climb gradient expectations creates an obstacle clearance problem: while the aircraft has enough climb gradient in the engine inoperative condition so that basic flight safety is not precluded, this climb gradient is often not strong enough to overfly real obstacles; this implies that the pilot must abort the takeoff flight path and reverse course back to the departure airport to perform an emergency landing. One solution to this is to reduce the dispatch weight to ensure that the aircraft retains enough climb performance in the engine inoperative condition, but this comes at the cost of reduced per-flight profits.

An alternative solution to this problem is the extended second segment (E2S) climb. Proposed by Bays & Halpin, they found that a C-130H gained additional obstacle clearance performance through this simple operational change. A thorough investigation into this technique was performed to see if this technique can be applied to commercial aviation by using a model A320 and simulating multiple takeoff flight paths in either a calm or constant wind condition. A comparison of takeoff flight profiles against real-world departure procedures shows that the E2S climb technique offers a clear obstacle clearance advantage which a scheduled four-segment flight profile cannot provide.

DEDICATION

To my friends and family: thank you for your support, patience, and believing in me when I needed it the most.

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CHAPTER 1

INTRODUCTION

History of The Federal Aviation Administration

Humanity has always possessed the desire to fly; this is evidenced by the plethora of the test flights which occurred in the early 1900's. As interest in aviation and its technology both grew rapidly post-World War I, governments realized there existed a need to regulate this activity to ensure that all who take to the skies do so in a safe manner. The first steps of Federal Regulation came with the Air Commerce Act of 1926, which was signed into law by President Calvin Coolidge. This act bestowed upon the Secretary of Commerce multiple powers to foster air commerce; two of the more noteworthy powers given to this individual include the ability to (1) license pilots and (2) issue airworthiness certificates for aircraft and major aircraft components.[1] Curiously, among the powers given to the Secretary of Commerce, there was no clause which grants this person the ability to establish operational regulations; so while indeed there was some regulation of who could fly and what could fly, there were no guidelines which specifically dictated *how* an aircraft should be operated.

As many people observed, this measure to ensure safety in the air was not enough at first. Several aviation accidents called into question the effectiveness of the Department of Commerce. To strengthen the federal government's stance on aviation safety, the Civil Aeronautics Act of 1938 was signed by President Franklin Roosevelt. Passage of this act established the independent Civil Aeronautics Authority, which

[1] *FAA Historical Chronology, 1926-1996*, 2017.

inherited the aviation responsibilities of the Secretary of Commerce. The Civil Aeronautics Authority was eventually split into two agencies: (1) The Civil Aeronautics Administration, operating under the Department of Commerce, whose responsibilities included airworthiness certification and pilot licensing, and (2) the Civil Aeronautics Board, one of whose responsibilities included establishing safety regulations. Later, in 1958, another piece of legislation established the Federal Aviation Agency, which inherited the Civil Aeronautics Authority's responsibilities. After the establishment of the Department of Transportation (DOT) in 1967, the Federal Aviation Agency became to the Federal Aviation Administration (FAA), which operates within the DOT.[2] While the FAA retrains many of its powers from when it was an agency, the responsibility of investigating air accidents now resides with the National Transportation Safety Board. However, the FAA still retains the authority of investigating suspected violations of Federal Aviation Regulations, all of which are codified in Title 14 (Aeronautics and Space) of the Code of Federal Regulations (CFR). The agency also has the power to initiate administrative action against violators of these regulations.[3]

While the power to license pilots and issue airworthiness certification for aircraft has changed hands over time, at present, those authorities reside with the FAA. Just as how a pilot may not operate an aircraft without the proper certification, an aircraft may not legally fly without an airworthiness certification. For an aircraft to procure airworthiness certification, aircraft designers must demonstrate that their design can

[2] A Brief History of the FAA, 2017.

[3] Daniel & Pearson, 2015.

withstand expected flight loads and provide a minimum amount of performance when a critical number of engines fail. Both the structural design and performance aspects of aircraft are heavily regulated to ensure safety is not precluded easily. While flight tests demonstrate an aircraft's capability to provide the required performance minimums under a variety of conditions, claims of a design abiding by structural regulations are typically backed up by a test to destruction. As the FAA has strict criteria on who can fly, what can fly, and how aircraft should fly, taking flight in the present is safer than ever before.

Takeoff & En Route Regulations

To understand how flight is safer in present-day, it is necessary to speak briefly on takeoff operations. Federal Regulation 14 CFR § 25.111 implies a standard four-segment takeoff procedure.[4] The total takeoff path is defined as "[extending] from a standing start to a point in the takeoff at which the airplane is 1,500 feet above the takeoff surface, or at which the transition from the takeoff to the en route configuration is completed and V_{FTO} is reached, whichever is higher."[5] That is, the takeoff flight path is defined as the segment of flight from which the aircraft, starting from its standing position on the runway, either (1) attains an altitude of 1,500 feet above ground level (AGL) *or* (2) completes the transition into the en route configuration *and* flies at the final

[4] Takeoff path, 2017.

[5] Ibid.

takeoff speed V_{FTO}, whichever is higher in altitude.[6] Figure 1 provides a visual representation of the nominal four-segment takeoff procedure.

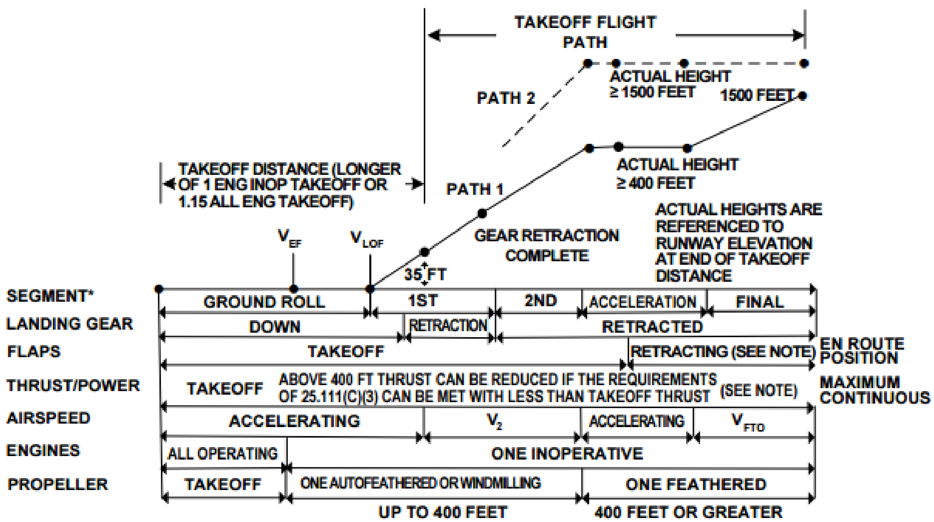

Figure 1. Standard Takeoff Profile. Reprinted from Advisory Circular 25-7C, *Flight Test Guide For Certification of Transport Category Airplanes*. Copyright 2012 by the Federal Aviation Administration.

Because of the FAA's mission to ensure flight is safe for all involved parties, airworthiness certification is only granted to aircraft which have performance capabilities which meet or exceed the minimums imposed by Federal Regulations. It is expected that all two-engine aircraft are safely operable with only one engine operating. The minimum required climb gradient performance expected of an aircraft under the critical engine inoperative condition is published under 14 CFR § 25.121.[7] For the two-engine aircraft taking off with the flaps and gear out with one engine inoperative, the vehicle is expected

[6] The en route configuration is defined as the aircraft having both the flaps and gear retracted. However, this configuration *and* flying at V_{FTO} must be satisfied to consider the aircraft as "en route".

[7] Climb: One-engine-inoperative, 2017. As climb gradient performance is inversely proportional to weight, the aircraft typically performs to the absolute minimum required by the regulation at its maximum takeoff weight (MTOW).

to produce a steady positive gross climb gradient (i.e., greater than zero percent) for first segment climb at the liftoff cue speed, V_{LOF}, as per part (a) of 14 CFR § 25.121.[8] After complete retraction of the landing gear, two-engine aircraft are expected to produce a steady gross climb gradient for second segment climb of no less than 2.4% at the second segment cue speed, V_2, as per part (b) of 14 CFR § 25.121.[9] Fourth segment climb is also regulated; two-engine aircraft are expected to maintain a steady gross climb gradient of no less than 1.2% at V_{FTO}, as dictated by part (c) of 14 CFR § 25.121.[10]

These V speeds, otherwise known as cue speeds, to which the pilot must fly are also federally regulated under 14 CFR § 25.107.[11] For example, part (a) of this regulation deals with the careful selection of V_1, the "stop/go" decision cue speed. This cue speed is what the pilot uses to determine if, when an engine fails during the ground roll on takeoff, whether he/she should continue the takeoff or abort it.[12] Subpart (2) of part (a) in this regulation mandates that V_1 must be selected so that it is no less than the assumed engine failure speed, V_{EF}, plus the speed gained between the time the engine failed and the expected time the pilot recognizes the engine failure and acts upon it.[13]

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[8] Ibid.

[9] Ibid.

[10] Ibid.

[11] Takeoff speeds, 2017.

[12] If an engine failure is observed at a speed of V_1 or greater, the pilot must continue the takeoff procedure. Otherwise, if the engine failure occurs below V_1, the pilot may abandon the procedure by applying brakes and reverse thrust.

[13] Takeoff speeds, 2017.

The V_2 cue speed, according to part (c) of 14 CFR § 25.107, must be chosen so that it produces at least the steady gross climb gradient listed in the previously-discussed 14 CFR § 25.121(b); this cue speed may be no less than (1) $V_{2_{MIN}}$, (2) V_R, the rotation cue speed, or (3) the speed which provides the maneuvering capability outlined in 14 CFR § 25.143(h).[14] Each of these speeds themselves have their own associated Federal Regulations which dictate what their value should be. Summarizing the regulations together, the two-engine aircraft designer must put much thought must go into selecting V_2 so that the vehicle produces a steady gross climb gradient of 2.4% and is capable of rolling into a bank angle of up to 30° without risk of stall at this cue speed.[15]

In similar fashion, part (g) of 14 CFR § 25.107 dictates V_{FTO} should be picked so that at this speed the aircraft can produce the steady gross climb gradient previously discussed in 14 CFR § 25.121(c); this cue speed may be no less than (1) 1.18 V_{SR}, or (2) the speed that grants the aircraft the maneuvering capability outlined in 14 CFR § 25.143(h).[16] Surmising these regulations, the two-engine aircraft designer must carefully select V_{FTO} so that it not only produces the a steady gross climb gradient of 1.2% at this cue speed, but also can bank up to 40° without risk of stall at this cue speed.[17]

Federal Regulation 14 CFR § 25.149 covers the minimum control speed airspeed, V_{MC}, of an aircraft. Part (b) of this regulation requires that at V_{MC} the aircraft is capable

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[14] Ibid. 14 CFR § 25.143(h) specifically calls out maneuvering capabilities expected of an aircraft.

[15] General, 2017.

[16] Takeoff speeds, 2017.

[17] General, 2017.

of maintaining straight flight with a bank angle of no more than 5° under the one engine inoperative condition.[18] While part (c) of this regulation deals with picking the value of V_{MC}, part (d) says that the rudder forces required to maintain control of the engine inoperative aircraft at V_{MC} can be no greater than 150 lbm at full thrust of the remaining operative engines; when recovering from a rudder input, the aircraft may not react in a dangerous way or require extraordinary piloting skill, alertness, or strength to prevent a heading change of greater than 20 degrees.[19] The pilot must not fly the afflicted engine-inoperative aircraft any slower than V_{MC}, else the aircraft will feel nonresponsive to pilot input.

The Dispatch Problem

An approved flight plan must be filed with the FAA prior to flying. Among the many necessities required in a flight plan is a carefully-planned takeoff procedure. To ensure safety for the aircraft and passengers alike, the FAA encourages the use of an approved evidence-based pilot's operating handbook developed by the manufacturer. This handbook contains a plethora of useful information for both pilots and dispatch personnel. Pilots find great use out of this aircraft flight manual because in it contains important cue speeds which indicate important parts of the takeoff procedure. Dispatch personnel heavily use the FAA-approved aircraft flight manual (AFM) because in it contains maximum dispatch weight guidance charts, otherwise known as WAT limit charts. These charts, given as functions of airfield altitude and ambient temperature,

[18] Minimum control speed, 2017.

[19] Ibid.

assist the dispatcher in identifying the maximum-allowable takeoff weight such that the aircraft retains the federally-required minimum amount of climb gradient performance in the event of an engine failure, assuming the aircraft is operated to the prescribed cue speeds. In other words, use of the WAT limit chart ensures that a two-engine aircraft dispatches at a weight such that if an engine failed during the takeoff roll and the pilot chose to continue the takeoff, the aircraft is expected to produce at least a steady positive gross climb gradient at V_{LOF} per 14 CFR § 25.121(a), and a 2.4% gross climb gradient at V_2 per 14 CFR § 25.121(b).[20] To ensure that these WAT limit charts do not go unused, regulation 14 CFR § 121.189(a) requires that "no person operating a turbine engine powered airplane may take off … at a weight greater than that listed in the Airplane Flight Manual for the elevation of the airport and for the ambient temperature existing at takeoff."[21] In other words, it is illegal for an aircraft to take flight at a takeoff weight which is greater than the maximum allowable as advised by the WAT limit charts. This guarantees that aircraft will always be dispatched such that if an engine failure were to occur, the vehicle would retain enough climb gradient capability to safely complete initial climb out.

Many airports have standardized instrument departure procedures available when planning the dispatch. These are provided so that aircraft do not accidentally fly into high obstacles or terrain. Departure procedures (DPs) can be thought of as a set of

[20] Climb: One-engine-inoperative, 2017.

[21] Airplanes: Turbine engine powered: Takeoff limitations, 2017.

instructions the pilot should follow when taking off.[22] Departure procedures typically also impose their own set of takeoff minimums, otherwise known as minimum *net* climb gradient requirements. The values of these minimum net climb gradients are set so that the aircraft may successfully and safely overcome all predicted obstacles within its flight path. The vertical margin of clearance between the obstacle and the aircraft set by a departure procedure is governed by Terminal Instrument Procedures, which requires that no obstacle may penetrate this safety barrier.[23] It is important to note that these takeoff minimum net climb gradients are usually different than the minimum climb gradients imposed by Federal Regulation.

There is a distinction which must be made with respect to the climb gradient. While engineers worry about their design aircraft's actual, *gross* climb gradient performance, dispatch planners are required to consider the aircraft's *net* climb gradient capability when planning a flyout.[24] This is because the CFR calls out an aircraft's *net* flight path capabilities in various regulations under Part 121, which deals with domestic and international operating requirements. Calculating an aircraft's *net* flight path from knowing the *gross*, or actual flight path, is through a simple "derate" applied to the latter. Directly quoting regulation 14 CFR § 25.115(b), "the net takeoff path flight data must be

[22] Pulling data from AirNav for KPHX - Phoenix Sky Harbor International Airport, there are a total of sixteen different departure procedures form which the dispatch planner may choose and file as a part of the flight plan. For example, upon examination of KPHX's SNOBL FIVE departure (Figure A1 in Appendix A), it can be observed that departures to the east must intercept waypoint SPRKY, then waypoint GOALY.

[23] Terminal Instrument Procedures (TERPS), 2017.

[24] The federal regulation which governs minimum climb gradient performance under the critical engine inoperative scenario gives that performance parameter in terms of *gross* climb gradient, hence why engineers worry more about their design's actual climb gradient performance.

determined so that they represent the actual [gross] takeoff flight paths … reduced at each point by a gradient of climb equal to – (1) 0.8 percent for two-engine airplanes."[25] In other words, the dispatcher must assume that the aircraft will produce a net flight path of 0.8% less climb gradient capability than advertised, essentially creating a "margin of safety" when planning the dispatch procedure.

There exists another "derate" which only applies to the en route flight path. Directly quoting regulation 14 CFR § 25.123(b), "the one-engine-inoperative net flight path data must represent the actual [gross] climb performance diminished by a gradient of climb of 1.1 percent for two-engine airplanes."[26] Strictly speaking, part (a) of this regulation dictates that part (b) only applies when the aircraft is in the en route configuration at a speed no less than V_{FTO}.[27] In other words, for the segment of flight where the aircraft has its gear and flaps stowed *and* is flying at V_{FTO} or faster, the dispatch planner must assume the aircraft will produce a net flight path of with 1.1% less climb gradient capability than advertised.

While use of the WAT limit charts ensures that the aircraft will depart at a weight where its performance provides the minimum amount of climb gradient required by Federal Regulation in the critical engine inoperative case, often this climb gradient is too weak to overcome all obstacles within an aircraft's predicted flight path. In other words, while Federal Regulation places an absolute minimum on an aircraft's engine-inoperative

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[25] Takeoff flight path, 2017.

[26] En route flight paths, 2017.

[27] Ibid.

climb gradient performance to ensure safety is not precluded, the climb gradient required by a DP's takeoff minimums are typically much higher than said minimums. This creates an awkward scenario: when a two-engine aircraft is dispatched so heavy that it can only output performance equal to the CFR-minimum of 1.6% *net* climb gradient with an inoperative engine and the takeoff minimum for the particular departure calls for a *net* climb gradient of 9.85%.[28] As the aircraft lacks the climb performance to safely overcome all obstacles within its predicted flight path, the pilot must reverse course, limping the aircraft back to the departure airport to attempt a potentially overweight landing. As evidenced by this short example, there is a severe disconnect between an aircraft's one engine inoperative (OEI) climb gradient capability and published climb gradient minimums for DP's.

[28] This is a realistic net climb gradient figure, especially for airports that are congested with tall nearby obstacles.

CHAPTER 2

BACKGROUND INFORMATION & PRIOR ART

Obstacle Clearance-Constrained Airports

There exist several airports which are riddled with nearby obstacles that requires the departure procedure to utilize high takeoff minimums. These high takeoff minimums are often greater than an aircraft's OEI climb gradient capability insofar that the aircraft simply cannot complete the dispatch procedure if an engine does fail.

Bob Hope Airport (KBUR) in Burbank, CA, is an excellent example of an airport which is obstacle clearance-constrained. While there are no tall buildings or radio antennae to avoid on takeoff, the airport is situated in a valley surrounded by nearby mountains. Figure 2, for example, provides a northward view of the surrounding mountains from the end of Runway 33.

Figure 2. View from End of Runway 33 at KBUR, Facing North..

For departure from this airport, one can expect the climb gradient requirement on takeoff to be quite high so that aircraft do not accidentally fly into the terrain if an engine fails. Taking the ELMOO EIGHT departure procedure, the handout of which is reproduced in Figure A2 of Appendix A, one can note that that the takeoff minimums of this departure vary depending on the choice of runway. Of the options available, the easiest runway from which to take flight is Runway 8, which requires the aircraft to maintain a minimum climb rate of 225 ft/nM up to 2,500 ft AGL; this climb rate correlates to a net climb gradient of 3.70%.[29] The dispatcher may also plan the takeoff on Runway 15, but this calls for a slightly more challenging 450 ft/nM (7.41% net) up to 3,000 ft AGL. Runway 33 also serves as an option for executing the ELMOO EIGHT departure procedure, but requires a steep 550 ft/nM (9.05% net) up to 2,600 ft AGL. Alternatively, Runway 26 is preferable compared to the previous since the required climb rate is a much less rigorous 305 ft/nM (5.02% net) to 2,500 ft AGL. Figure 3 provides a visualization of the takeoff minimums just discussed.

[29] Since climb gradient is in terms of ft/ft (typically presented as a percentage), one can easily convert a climb rate given in ft/nM to this format simply dividing by 6076.12 nM/ft.

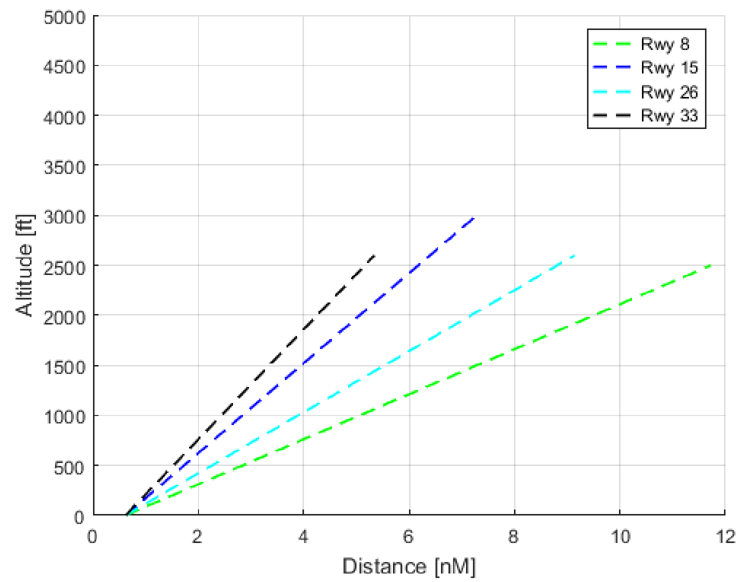

Figure 3. KBUR's ELMOO EIGHT Takeoff Minimums. Includes a nominal 3,761 ft of takeoff distance required (TODR).

Like KBUR, Phoenix Sky Harbor International (KPHX) in Phoenix, AZ, is also nestled in a valley; while close-in mountains do not necessarily surround the airport, there are tall buildings and radio antennae which need be avoided on flyout. While the takeoff minimums vary depending on the choice of runway, the obstacles presented when considering KPHX's SNOBL FIVE departure procedure force higher climb gradient requirements for all runways. Irrespective of runway choice, a departure out of any runway using this procedure requires a high climb rate of 500 ft/nM (8.23% net) up to 1,640 ft AGL. For Runways 25L/R and 26, this climb rate must be maintained up to 2,140 ft AGL. Departures out of Runways 7L/R and 8 require this high climb rate as the first waypoint, waypoint SPRKY, is a "mountain" whose top measures approximately 263 ft above the runway. If departing out of Runways 7L/R, a minimum climb rate of 230 ft/nM (3.79% net) up to 10,000 ft AGL is required after the initial climb. Otherwise, a departure out of Runway 8 requires a climb rate of 300 ft/nM (4.94% net) is needed up to 10,000 ft AGL to abide by the procedure. Figure 4 summarizes all of SNOBL FIVE's takeoff minimums into a tidy visualization.

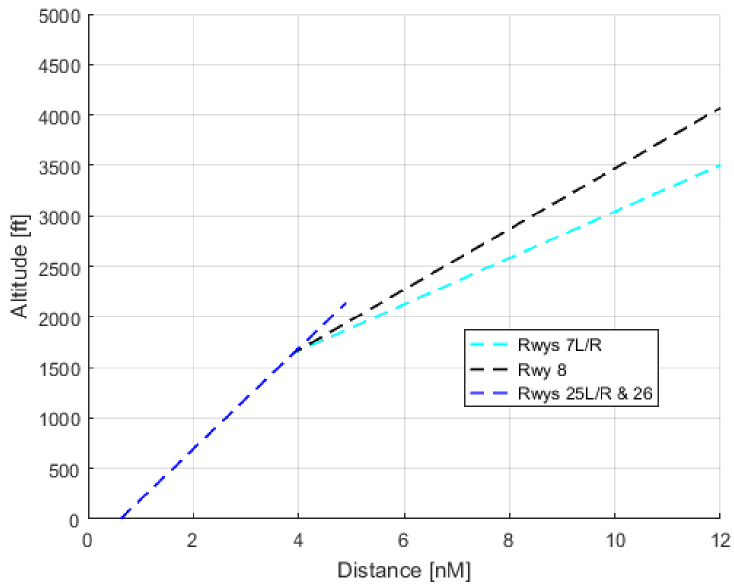

Figure 4. KPHX's SNOBL FIVE Takeoff Minimums. Includes a nominal 3,761 ft of TODR.

While New York, NY is characterized as a city of skyscrapers, when departing from one of the four runways available at LaGuardia Airport (KLGA), only one is imposed with takeoff minimums for the JUTES THREE departure procedure. Referring to the reproduced departure procedure handout in Figure A3 of Appendix A, one can verify that, indeed, Runway 22 is the only one which forces the aircraft to encounter several obstacles on flyout; such obstacles which the aircraft need avoid on takeoff include multiple trees, buildings, a localizer, and a fence. Figure 5 provides a visualization of the takeoff minimums for Runway 22, which comes in three parts: (1) a climb rate of 501 ft/nM (8.25% net) to 540 ft AGL, then (2) a climb rate of 356 ft/nM (5.86% net) to 3,000 ft AGL, and finally (3) a climb rate of 374 ft/nM (6.16% net) to 5,000 ft AGL.

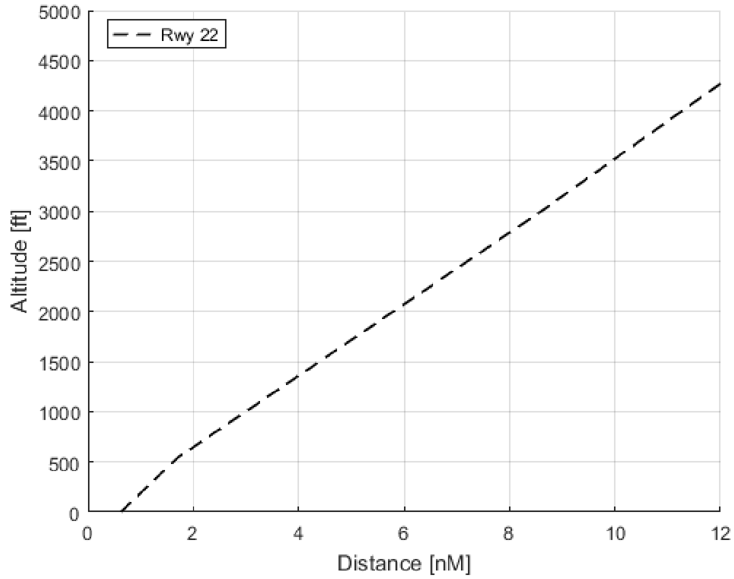

Figure 5. KGLA's JUTES THREE Takeoff Minimums. Includes a nominal 3,761 ft of TODR.

While one could easily just fly this dispatch using the less-restricted runways 4, 13, and 31, it not be unreasonable to think that turbojet aircraft are expected to complete this DP on occasion, especially when the airport is congested with thru traffic.[30]

As observed by investigating select DP's from these airports, all of their net climb gradient minimums are in excess of what is expected by 14 CFR § 25.121(b); that is, with two-engine commercial aircraft designed to perform to a gross climb gradient minimum of 2.4% (1.6% net) with one failed engine at the maximum takeoff weight, this performance is clearly not enough to successfully complete any of the previously studied

[30] While the former three runways are "unrestricted" in terms of takeoff minimums, all two-engine commercial aircraft must maintain at least a steady gross climb gradient of 2.4% during the second segment climb with one engine inoperative, per 14 CFR § 25.121(b).

DP's.[31] Figure 6 compares all studied takeoff minimums on climb gradient and the federally-regulated minimum on climb gradient performance.

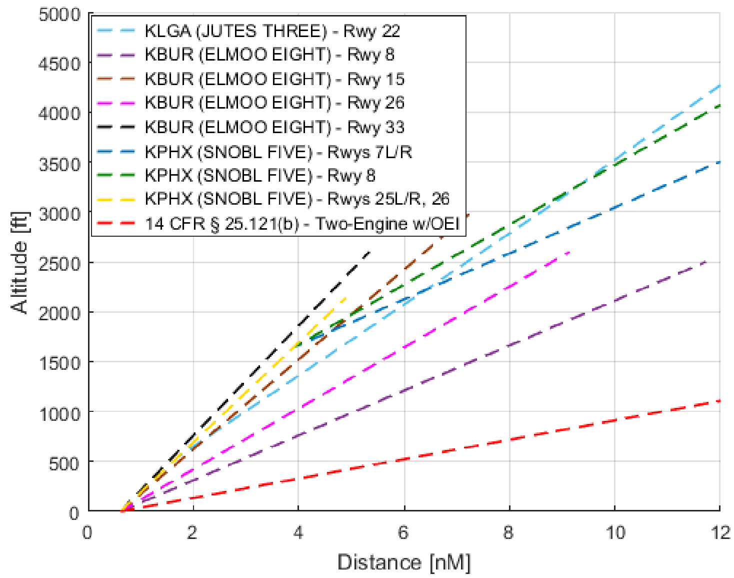

Figure 6. Comparison of DP Takeoff Minimums Against Federal Regulations. Presented in terms of net flight path.

As can be easily noted, all takeoff minimums on climb gradient are more than the minimum set by the CFR.

Prior Art & Motivation to Extend Second Segment Climb

Little scholarly work to date has been published to address the issue of an aircraft's incapability to compete with a DP's rigorous climb gradient minimums when operating under the critical engine inoperative case. Only one conference paper, *Diverging Engine Failure Paths on Standard Instrument Departures*, speaks on this topic.[32] These authors note that several aircraft are incapable of executing existing

[31] Climb: One-engine-inoperative, 2017.

[32] Masson, Bain, & Page, 2015.

departure profiles under engine inoperative conditions because of their high climb gradient requirements; the authors also note that takeoff minimums for engine inoperative conditions are "unpublished", implying that departure profiles are currently calculated with the all-engines-operative case in mind.[33] In other words, there is a need for performance engineers to develop alternative flight paths for engine inoperative conditions so that the aircraft may either (1) clear all predicted upcoming obstacles, or (2) circle back to the departure airport in order to land in a potentially overweight situation, as the authors correctly note.[34] However, until that occurs, the problem then becomes the following: how is one expected to abide by the rigorous takeoff minimums in the one engine inoperative case without reducing the aircraft's takeoff weight beforehand? On the one hand, reducing the dispatch weight beforehand ensures the aircraft will produce enough climb gradient capability to abide by the takeoff minimums in case of engine failure; however, on the other hand, this decrease in weight typically correlates to a reduction in the number of fare-paying passengers or payload, which implies a decrease in per-flight profits. Clearly, this is not a desirable solution for commercial carriers that wish to turn a profit; ergo, a new solution must be sought.

Bays and Halpin, having done extensive studies on the C-130H, a military transport aircraft displayed in Figure 7, found that its obstacle clearance capability can be increased without any expensive modifications to the airframe or powerplant; instead, an operational change which involves delaying the third segment acceleration and extending

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[33] Ibid.

[34] Ibid.

second segment (E2S) climb with the flaps deployed in the takeoff setting provided a more favorable climb gradient which increased the aircraft's close-range obstacle clearance capability.[35]

Figure 7. C-130H "Hercules" Banking Left. Copyright 2013 by the U.S. Air Force.

Indeed, by delaying the "wasteful" low altitude third segment acceleration, the time originally spent executing said segment can instead be put towards climbing, which effectively increases the aircraft's close-in obstacle clearance capability. Bays and Halpin also found that by executing the E2S using overspeeds, far-out obstacle clearance capability increases by at the expense of additional TODR and a decreased close-in obstacle clearance capability.[36] Since use of the E2S profile provides additional obstacle clearance capability, for cases where this increased performance is not necessary to successfully complete the DP, said additional performance can be traded to accommodate

[35] Bays & Halpin, 2015.

[36] Ibid. For example, using overspeeds, the aircraft would execute second segment climb at $V_2 + \Delta V$.

additional fare-paying passengers or payload, thereby increasing a commercial carrier's per-flight profits.

Purpose of Study & Methodology

This study seeks to expand and generalize Bays & Halpin's work to see if the E2S procedure applies to any arbitrary turbofan-powered commercial aircraft. There are five key questions which will be answered in this study:

1. As mentioned previously, Federal Regulation 14 CFR § 25.111 implies aircraft should follow a four-segment takeoff procedure, with third segment acceleration occurring at 400 ft AGL or higher above the runway.[37] However, does this takeoff procedure provide optimal obstacle clearance capability for aircraft?
2. If not, what procedure optimizes an aircraft's obstacle clearance capability?
3. Should overspeed cue speeds be used in dispatch planning in combination with the optimal takeoff procedure to further augment obstacle clearance capability?
4. How viable is this optimal flyout procedure with respect to real-world DP's?
5. Bays & Halpin performed their study assuming calm winds. How does a constant 10 knot headwind or tailwind affect the aircraft's overall obstacle clearance capability with respect to DP's?

To answer these questions, a "calibrated" model of the Airbus A320 was developed, a representation of which is provided in Figure 8.

[37] Takeoff path, 2017.

Figure 8. Computer Render of Airbus A320. Copyright 2012 by Air Charter Service.

This model was first used to identify if the A320 is scheduled to operate at cue speeds which maximizes its climb gradient performance; these such airspeeds will be referred to as “optimized” or “idealized” cue speeds. Following that, simulated missions were performed to answer questions 1 and 2; these dispatches included traditional four-segment takeoff profiles (with the third segment acceleration’s occurrence varying in altitude from 400 ft to 4,900 ft) as well as a “Flaps 2” E2S procedure and a “clean wing” E2S procedure. Figure 9 provides a visual comparison between extended second segment profiles and a traditional four-segment profile.

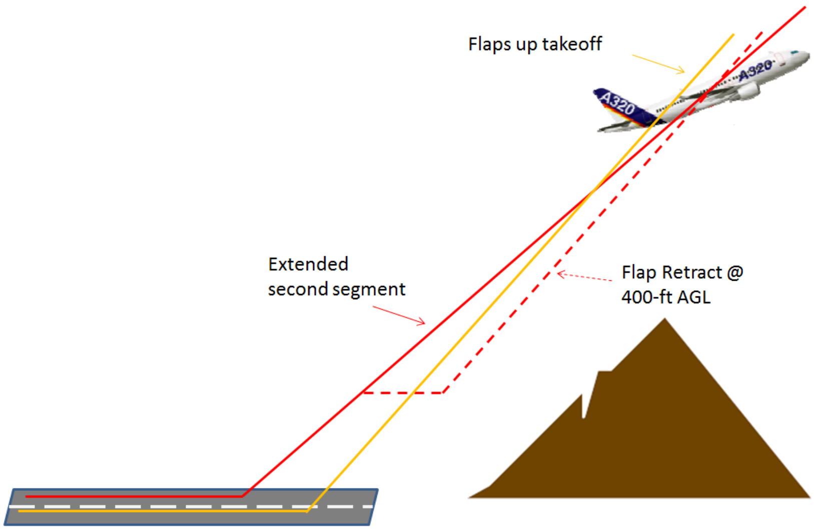

Figure 9. Comparison of Traditional Flyouts Versus E2S Flyouts.

To answer question 3, additional simulated missions were performed as above, but this time scheduling dispatch at the previously identified idealized cue speeds. From knowing the answers to questions 1 through 3, a formulation of the optimal takeoff procedure (or procedures, if more than one) was made. The optimal takeoff procedure, along with other takeoff profiles, was compared against the real-world DP's discussed in the *Obstacle Clearance-Constrained Airports* section of Chapter 1: KPHX's SNOBL FIVE, KLGA's JUTES THREE, and KBUR's ELMOO EIGHT to answer question 4. To answer question 5, additional simulated missions were required; created in the same manner as above (at the prescribed book cue speeds only) but under the influence of a 10 knot headwind or 10 knot tailwind, these flyouts were compared to the real-world DP's utilized in question 4.

CHAPTER 3

MATHEMATICAL & SIMULATION BASIS

Mathematical Foundation

To procure any meaningful data, means of accurately calculating aircraft performance parameters is required. Takahashi's text, *Aircraft Performance and Sizing*, provides the necessary equations which enables calculation of relevant aircraft performance parameters.[38]

Although the text presents equations in terms of altitude, ALT, and Mach number, M, the control variables in this study are altitude and aircraft indicated airspeed, $KIAS$, in units of knots.[39] Fortunately, an aircraft's Mach number can be simply calculated by knowing its indicated airspeed,

$$M(ALT, KIAS) \cong \sqrt{\frac{1481}{\frac{q}{M^2}(ALT)}}\left(\frac{KIAS}{660.8}\right) \tag{1}$$

where the fraction $\frac{q}{M^2}$, which is a function of ALT, can be easily determined via a lookup of a 1976 Standard Atmosphere table; it should go into the equation in units of pounds per square foot for the output to remain dimensionless.

In addition to calculating the aircraft's Mach number, its true airspeed, $KTAS$, may also be calculated from knowing its indicated airspeed. The conversion from indicated airspeed to true airspeed is as follows,

[38] Takahashi, 2016.

[39] Knots, rigorously expressed as one nautical mile per hour, is the standard unit of speed in the aviation industry; in addition to the conduct of "pilot talk" in terms of knots, aircraft flight manuals provide cue speeds in terms of knots, as well.

$$KTAS(ALT, KIAS) = \big(MACH(KIAS)\big)\big(a(ALT)\big)\left(\frac{3600}{6080}\right) \tag{2}$$

where a is the speed of sound, varies with altitude, and can be determined from a quick lookup of the 1976 Standard Atmosphere table. The variable a should go into the equation in units of feet per second so $KTAS$ comes out in units of knots.

Dynamic pressure, q, is an important value which requires calculation as this variable shows up in other equations. This variable can be calculated via the following equation,

$$q(ALT, KIAS) = \left(\frac{q}{M^2}(ALT)\right)\left(M(ALT, KIAS)^2\right) \tag{3}$$

where, as stated before, the fraction $\frac{q}{M^2}$ can be quickly identified by a lookup and interpolation of the 1976 Standard Atmosphere table.

Moving forward with more interesting equations yet, the three-dimensional lift coefficient of the aircraft, C_L, can be calculated as,

$$C_L(ALT, KIAS) = \frac{L}{\big(q(ALT,KIAS)\big)\, S_{ref}} \cong \frac{W}{\big(q(ALT,KIAS)\big)\, S_{ref}} \tag{4}$$

where L is the lifting force acting on the aircraft and S_{ref} is the wing reference area in units of feet squared. Since the lifting force acting on the aircraft is expected to sustain the aircraft's weight, W, we may approximate that the lifting force is equal to the current weight of the aircraft, which should go into the equation in units of pounds (mass), lbm.

Another coefficient of importance is the drag coefficient. The expression for drag coefficient is complicated, for it is composed of many sources. It may be summarized as follows,

$$C_D(ALT, KIAS) = C_{D_0}(KIAS) + C_{D_i}(\alpha, KIAS) + \Delta C_{D_{RE}}(ALT, KIAS) \tag{5}$$

that is, the drag coefficient C_D is the summation of the zero-lift drag C_{D_0} at the reference altitude, induced drag C_{D_i} (which is a function of the angle of attack, α), and incremental drag due to Reynolds number effects $\Delta C_{D_{RE}}$ at the reference altitude.[40] While this appears difficult to do by hand, an easy way to bypass calculating this tedious equation is simply by performing a direct interpolation of tabular drag data for a model.[41] Note that this equation bears no corrections for flaps, or trim, or any other miscellaneous drag sources, which implies that the supplied tabular data must be for a "clean wing" aircraft.

When an engine fails, there are additional drag penalties to consider on top of those presented in Equation 5. For example, a failed, jammed engine will produce additional airframe drag which may be approximated as a cylinder,

$$\Delta C_{D_{ENG}} = n_{eng_{inop}} \frac{\pi\left(\frac{d_{fan}}{2}\right)^2}{S_{ref}} \tag{6}$$

where $n_{eng_{inop}}$ represents the number of failed engines, and d_{fan} represents the fan diameter in feet. Curiously, model calibration revealed that this drag estimation was too high; while Equation 6 suggests approximately 167 drag counts, calibration results implied that approximately 135 drag counts is a better fit for the model. This suggests that the AFM must have used a windmilling engine for their inoperative engine model instead of the highly pessimistic jammed engine model.

[40] The Reynolds number is a dimensionless value associated with flow quality, where a lower number implies better flow quality. A higher Reynolds number implies the flow is turbulent, which correlates to higher drag.

[41] An aerodynamics model which includes tabular drag data can be generated by EDET. More information on this is contained within the *Enhanced Drag Estimation Technique (EDET)* section of this chapter.

Additionally, when an engine fails, there exists a thrust and drag asymmetry which induces a yawing moment which causes the aircraft to “turn” away from the centerline. Trim is typically used to counteract the yawing moment, but comes with an associated drag penalty, which is approximately,

$$\Delta C_{D_{TRIM}} \cong 0.001 \tag{7}$$

On takeoff, deployment of flaps aids in keeping the TODR and cue speeds low by supplementing the aircraft’s lifting capabilities. However, the protrusion of additional aircraft surfaces into the flow creates increased skin friction drag. Furthermore, the supplemental lifting capability created by flap deflection results in increased induced drag for which must be accounted. For this study, the skin friction drag addition associated with leading-edge and fowler flap deflection is estimated as,

$$\Delta C_{D_{FLAPS\,2}} \cong 0.021 \tag{8}$$

which holds only for the “Flaps 2” setting, the only one studied in this review. Estimation of the induced drag with flaps deployed will supersede *EDET*’s induced clean wing drag model with a simple quadratic formula,

$$C_{D_i} = \frac{C_L^2}{\pi\, AR\, e} \tag{9}$$

where AR represents the aspect ratio of the wing, and e represents the Oswald’s efficiency of the wing. While the value of e is not available in open literature, a careful model calibration reveals that $e \cong 81.72\%$ enables the model to best fit drag polar data.

To extract the dimensional drag, D, from a drag coefficient, the following expression can be used,

$$D(ALT, KIAS) = \big(C_D(ALT, KIAS)\big)\big(q(ALT, KIAS)\big)\big(S_{ref}\big) \tag{10}$$

which is, indeed, nothing more than a simple multiplication of variables which are known.

Now stepping into expressions for interesting aircraft performance parameters, the maximum available thrust, T_{max}, of the aircraft is expressed as,

$$T_{max}(ALT, KIAS) = n_{eng_{op}}\big(T(ALT, KIAS, PLA_{max})\big) \quad (11)$$

where $n_{eng_{op}}$ represents the number of operative engines multiplied by the thrust output T, which is a function of altitude, airspeed, and power lever angle. Like how Equation 5 was handled with its complex expression, a simple interpolation of nominal five-column engine data can handle this equation.[42]

The specific excess thrust, SET, is a performance parameter succinctly expressed as,

$$SET(ALT, KIAS) = \frac{T_{max}(ALT, KIAS) - D(ALT, KIAS)}{W} \cong \text{Still Air Climb Gradient} \quad (12)$$

which is simply the difference between maximum thrust and drag, the value of which is divided by weight. This performance parameter represents the linear acceleration capability of an aircraft. Incidentally, this expression can be used to approximate an aircraft's gross, or actual, climb gradient performance in still air.[43] The climb gradient of an aircraft is best thought of as a measure of climb efficiency; it tells of the climb rate of

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[42] A propulsion model which includes tabular data on power lever angle, thrust, and fuel flow as functions of altitude and Mach number can be generated by NPSS. More information on this is contained within the *Numerical Propulsion System Simulation (NPSS)* section of this chapter.

[43] In work performed after writing this manuscript, it was found that this approximation can break down, especially at high angles of attack. This results in point-performance estimates from *SKYMAPS* which are pessimistic in comparison to performance seen in *MISSION*. It should additionally be noted that this approximation for climb gradient only works in still air conditions, for the presence of wind affects that performance parameter.

the aircraft per unit of distance travelled, often expressed in terms of a percentage.[44] As dispatch personnel are required by Federal Regulation to consider an aircraft's net climb gradient performance as opposed to its gross climb gradient performance, a derate of 0.8% or 1.1% should be applied to Equation 8 where appropriate.[45]

The aircraft's rate of climb is also an interesting parameter for this study. As aircraft can climb at either constant Mach number or constant indicated airspeed, the latter more relevant here as most maneuvers are conducted in terms of airspeed. The rate of climb of an aircraft while holding a constant indicated airspeed is,

$$ROC_{KIAS}(ALT, KIAS) =$$

$$103.33\left(\left(K_{KIAS}(ALT, KIAS)\right)\left(SET(ALT, KIAS)\right)\left(KTAS(ALT, KIAS)\right)\right) \qquad (13)$$

where all variables expressed in the equation are known, apart from K_{KIAS}, a corrective factor. The expression of this corrective factor varies as it is sensitive to the aircraft's altitude relative to the tropopause. Since the problem, by its nature, is an examination of low altitude cases, only one expression is of relevance; the corrective factor for a constant indicated airspeed climb at an altitude below the tropopause is expressed as,

$$K_{KIAS}(ALT \leq 36{,}089 \text{ ft}, KIAS) = \frac{1}{1 + 0.7\, M(ALT, KIAS)^2} \qquad (14)$$

which holds so long as the aircraft flies at an altitude at or below 36,089 ft AGL.

[44] Takahashi, 2016. For example, a gross climb gradient of 2.4% implies a climb rate of 0.024 nM (approximately 145.83 ft) for every 1 nM of distance travelled.

[45] Recall that the 1.1% derate of the climb gradient, as per 14 CFR § 25.123(b), only applies when the aircraft is *both* (1) in the "en route" configuration and (2) flying at a speed of V_{FTO}. Otherwise, 14 CFR § 25.115(b) requires a derate of only 0.8% to the climb gradient.

Simulation Basis

In preliminary aircraft design work, aircraft models can be tested using computer code. An aircraft performance model comprises of three parts: (1) aerodynamics, (2) propulsion, and (3) weight. *EDET*, a program whose abbreviation stands for the Enhanced Drag Estimation Technique, can be used to generate a comprehensive aerodynamics profile of an aircraft given input geometry. A numerical code such as *NPSS*, Numerical Propulsion System Simulation, simulates the powerplant performance at a variety of Mach numbers and altitudes to produce comprehensive five-column propulsive data.

With a completed aerodynamics and propulsion models, weight can be incorporated into computer codes such as *SKYMAPS* or *MISSION* to reasonably gauge an aircraft's performance capabilities. *SKYMAPS* is a point-performance code, capable of calculating the values of interesting performance parameters at a weight and engine configuration. *MISSION*, on the other hand, is useful for evaluating how an aircraft design performs over time given several pilot inputs. A comprehensive review on all the aforesaid tools follows.

Enhanced Drag Estimation Technique (*EDET*). Developed by Feagin and Morrison after a careful analysis of nineteen subsonic and supersonic military aircraft and fifteen advanced or supercritical airfoil configuration, the Delta Method is capable of estimating the clean wing drag polar for a variety of cruise and maneuver conditions up to stall or buffet onset.[46] Codified into a program, *EDET* accepts input geometry of an aircraft to

[46] Feagin & Morrison, 1978.

produce estimated drag polars; relevant input geometry required by *EDET* includes various wing characteristics, fuselage, horizontal and vertical tail geometry. Additional geometry such as flap tracks may be fed into *EDET* for increased accuracy in drag estimations. Open literature provided accurate measurements for various parts of the A320's geometry; in cases where precise data was not readily available, careful estimations were made using three-view line drawings. The version of *EDET* used in this study is enhanced by Dr. Takahashi, extending the basic mathematics contained in the program with more complex form factor equations contained in Takahashi, German, et al.[47]

As real aircraft have "imperfections" such as fasteners and ridges, *EDET* incorporates a user-specified "crud drag" correction; that is, additional drag is added on top of the nominal drag value to better-match reality. After many preliminary tests, a crud drag addition of approximately 35% was found to give the model the closest match of abiding by a set of real climb gradient data supplied from the AFM, as represented in Figure 10.[48]

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[47] Takahashi, German, et al., 2012.

[48] *Airbus Industrie A320 Model A320-212 Flight Manual*, 1990.

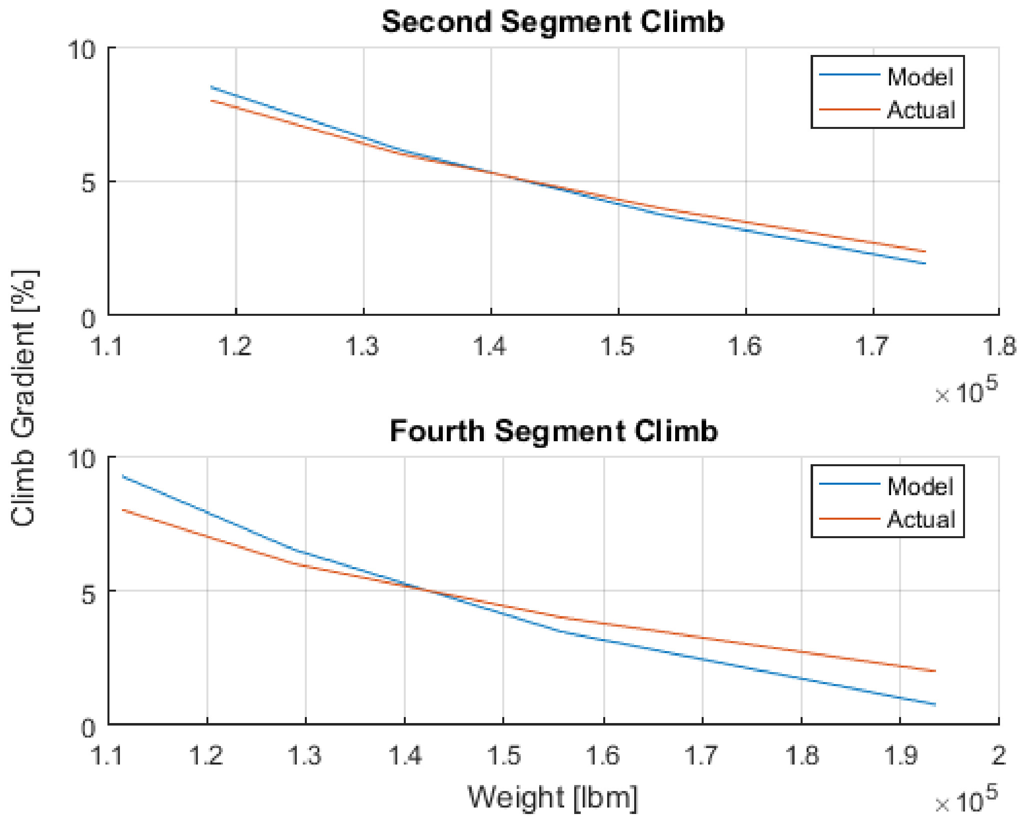

Figure 10. A320 Model Calibration Results. After thorough calibration to minimize the difference between modeled gross performance and real-world gross performance, second segment climb appears to be modeled reasonably well, with larger deviations observed for fourth segment climb.

Combining *EDET* with supplemental drag Equations 6 through 9 to enhance *SKYMAPS* enables simulation of takeoff climb cases with one engine inoperative (OEI), which is required when planning dispatch for the two-engine A320.

Numerical Propulsion System Simulation (*NPSS*). A physics-based engineering tool, *NPSS* accepts key engine parameters such as maximum turbine inlet temperature, reference bypass ratio, reference fan pressure ratio, etc., to produce realistic propulsion data which can be applied to aircraft models. This output data is presented in five-columns; output thrust and thrust-specific fuel consumption is given as a function of aircraft speed, altitude, and throttle setting. For engine parameters not explicitly called out in literature which were required by *NPSS*, informed estimations were made to produce a powerplant model which is as faithful to that of the A320's as possible.

SKYMAPS. A tool capable of combining the aerodynamics and propulsion profiles provided by *EDET* and *NPSS*, *SKYMAPS* can plot point-performance parameters as a function of altitude and aircraft speed; useful information can be identified upon inspection of the "thumbprint", which allows for informed engineering decisions.[49] For this study, *SKYMAPS* was used to identify overspeed cue speeds which maximizes the A320's climb gradient performance, in preparation for responding to key question 3. For example, while the A320 is scheduled at $\boldsymbol{V_2 = 153}$ KIAS when dispatching at MTOW, Figure 11 suggests that maximized climb gradient performance resides at an idealized cue speed of $\boldsymbol{V_2 + \Delta V = 171}$ KIAS.

[49] Officially coined as "Energy Maneuverability Plots", work on this method of data presentation was initially started by Kaiser in Germany, then expanded upon by Boyd & Christie in the United States. With Christie's assistance, Boyd developed the Energy Maneuverability Theory, which was initially used to rank the relative combat performance of aircraft and identify operating points at which these aircraft perform their best. For further information, refer to Merrit, Cliff, & Kelley, 1985, and Boyd & Gibson, 1996.

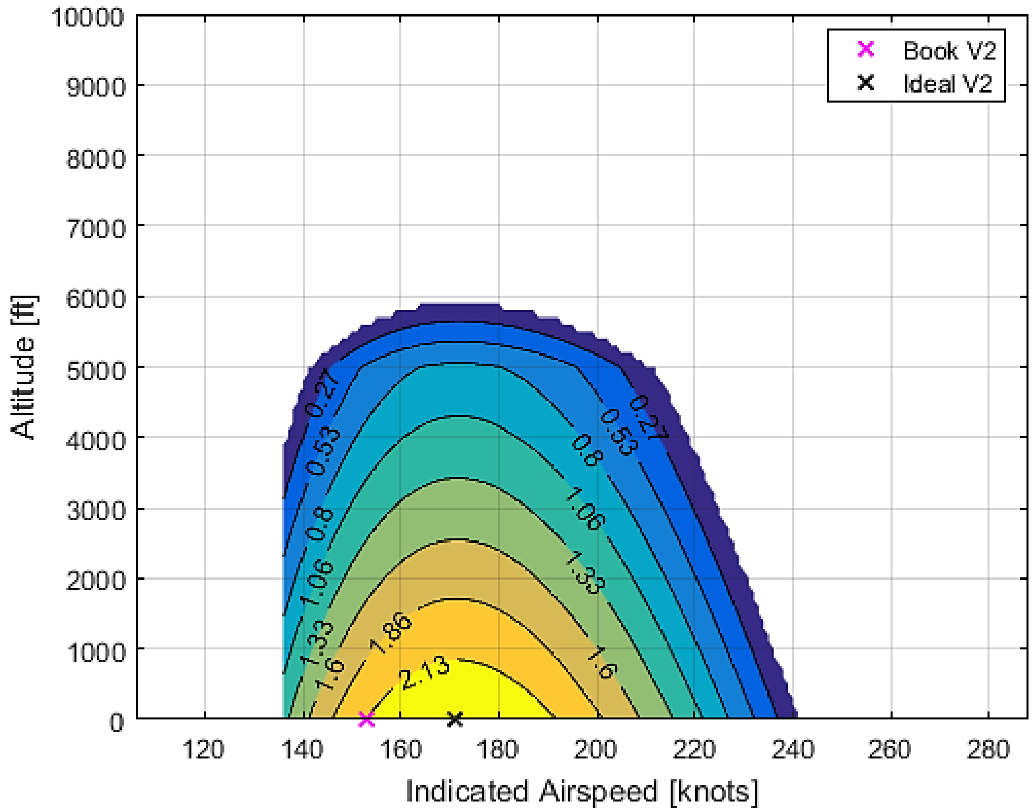

Figure 11. Contour Plot of A320 Gross Climb Gradient w/OEI at $W = 172{,}800$ lbm. Flaps and trim drag included. Contours presented as a percentage.

These plots are truncated to eliminate solutions which do not abide by physics, such as points where required lift coefficient exceeds the wing's maximum lift coefficient, or where engine thrust exceeds drag. This tool is enhanced with the additional drag Equations 6 through 9 to accurately model engine inoperative performance.

MISSION. An explicit point-mass simulation tool which employs a large flight path angle approximation, the power lever angle, aircraft flight speed, and altitude are all principal state variables which can be controlled to shape the takeoff procedure. The code updates implicit state variables at each integration time step, variables such as the elapsed time, distance flown, current altitude, current speed, aircraft weight, and current fuel consumption. *MISSION* was the primary tool which produced various takeoff simulations which were analyzed to answer the key questions of this study. Figure 12 provides a visual representation of a nominal mission simulated by this tool.

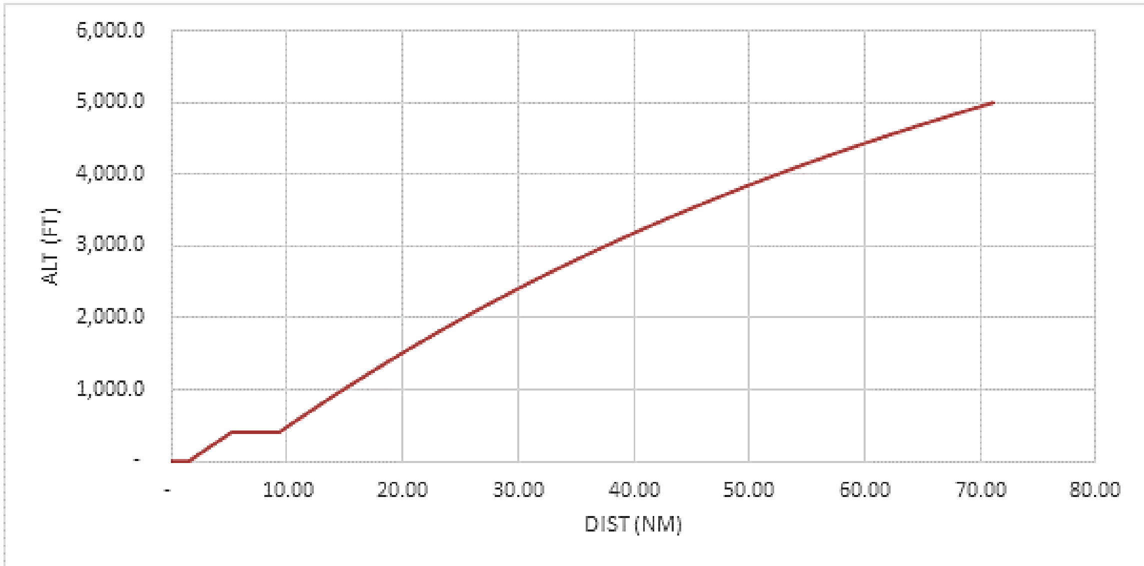

Figure 12. A320 Net Flight Path, OEI at $W = 172{,}800$ lbm. Flaps and trim drag included where applicable. Third segment acceleration executed at 400 ft AGL. Uniform 0.8% climb gradient derate applied.

This tool employs three "modes" which are executed in sequence to mimic a real-world takeoff procedure: (1) ground run, (2) constant KIAS climb, and (3) level acceleration. For the purposes of this study, the ground run mode implies the aircraft begins at rest with OEI, flaps deployed and trim in use; the aircraft accelerates down the runway until V_2, which was used in absence of V_{LOF}. At V_2, the aircraft is considered airborne, at which point *MISSION* switches into constant KIAS climb mode. Here is where the simulation routine differs depending on the type of flyout executed:

- For traditional flyouts which are separated into four distinct segments, this climb continues until the aircraft reaches an altitude of 400 ft AGL or greater. Upon attaining the altitude, *MISSION* switches into level acceleration mode, at which the aircraft discontinues climb and accelerates horizontally until the V_4 speed is attained. At this speed, level acceleration is discontinued and *MISSION* switches back to constant KIAS climb mode to mimic fourth segment climb. This climb is continued until 5,000 ft AGL.

- For a "Flaps 2" E2S flyout, this second segment climb continues to 5,000 ft AGL, with no retraction on the flaps.
- For a "clean wing" E2S flyout, this second segment climb continues to 5,000 ft AGL; notable differences from the general procedure includes no flap deflection on takeoff, and with ground run continuing until the aircraft reaches V_4, at which the aircraft is considered airborne.

To accomplish these segments of flight, *MISSION* is loaded with several advanced equations of motion. For example, the ground distance covered is calculated as,

$$dist_{new} = dist_{old} + \frac{\big((a)(MACH)(dt)(\cos(\gamma)) - (winds)(dt)\big)}{6080} \tag{15}$$

which is simply the summation of the previously-calculated distance and the contributive horizontal part of the distance travelled. Note that, in this formulation, a headwind implies that $winds$ is positive, thereby reducing covered ground distance; conversely, a tailwind implies that $winds$ is negative, thus adding to covered ground distance. Also note that the flight path angle, γ, is expressed through a simple geometrical relation,

$$\gamma = \operatorname{asin}\left(\frac{dh}{(a)(MACH)(dt)}\right) \tag{16}$$

where dh is the change in height, and the output is to be expected in units of radians. For calculating the change in altitude so the value of total altitude can be updated in the next time step, *MISSION* uses the following equation,

$$dALT = (k_0)(a)(MACH)(SET)(dt) \tag{17}$$

where k_0 is a scaling factor whose value depends on the altitude and flight speed of the aircraft, and specific excess thrust is either representative of the aircraft's gross performance or that minus a "derate" specified by the user. As a highly intricate and complicated code, *MISSION* is, indeed, a comprehensive flight path analysis tool.

There are distinct limitations to this study which must be acknowledged. As previously mentioned, in absence of V_{LOF}, V_2 was used in place for all flyouts except the "clean wing" E2S dispatch. This approximation results in a slightly longer TODR which has no impact on the focus of this study. Additionally, this approximation implies the aircraft will attain liftoff at a speed slightly greater than that expected in the real world; a negligible positive impact on climb performance results from this. Another limitation of this study is that it is assumed the aircraft *begins* with OEI at rest; realistically, this never happens – completed OEI takeoffs are performed with the engine failing at or above V_1. While this has a significant detrimental impact on TODR, field performance is not the focus of this study. Similarly, neglecting to model gear drag in these simulations favorably benefits TODR—which again is not in the scope of this study—and negligibly benefits climb rates to all studied takeoff profiles.

While all TODR values reported here are pessimistic in nature and require further study for a more accurate value, limitations on available runway distance at KPHX, KBUR, and KLGA, as well tire speed rating and brake energy capabilities of the A320 will be neglected in the analysis. Additionally, any short-term "takeoff thrust" power restrictions are neglected – it will be assumed that the engines operate to 100% capacity for the entirety of the takeoff procedure.[50] All performance estimates are restricted to flight at standard pressure and temperature conditions, with takeoffs beginning at sea level.

[50] In the real world, use of the "takeoff thrust" power setting is restricted to a maximum of five minutes. This limitation is in place in attempt to extend engine life and reduce the frequency of engine maintenance.

CHAPTER 4

ANALYSIS

Optimal Flight Speed for Maximum Climb Gradient

Like many other aircraft performance parameters, choice of speed and altitude affects climb gradient strength; there exists a “sweet spot” at which the aircraft’s climb gradient performance parameter is at a maximum – flying too high, too fast, or too slow results in less than optimal performance. The dispatch weight of the aircraft also affects the strength of climb gradient performance.

Recalling Figure 11, it can be noted that the “thumbprint” is rather small; this is because the high dispatch weight of $W = 172{,}800$ lbm limits climb gradient performance. At the $V_2 = 153$ KIAS, *SKYMAPS* predicts the A320’s gross second segment climb gradient as approximately 2.13%. *SKYMAPS* also identifies that a stronger gross climb gradient of 2.40% can be procured at an idealized cue speed of $V_2 + \Delta V = 171$ KIAS. By introducing an overspeed, the A320 gains an additional 0.27% (16.41 ft/nM) to its gross climb gradient capability.

A reduction in dispatch weight benefits any aircraft’s climb gradient performance, as demonstrated in Figure 13; in addition to stronger climb gradient performance, there now exists additional altitude and flight speed combinations at which the aircraft can fly.

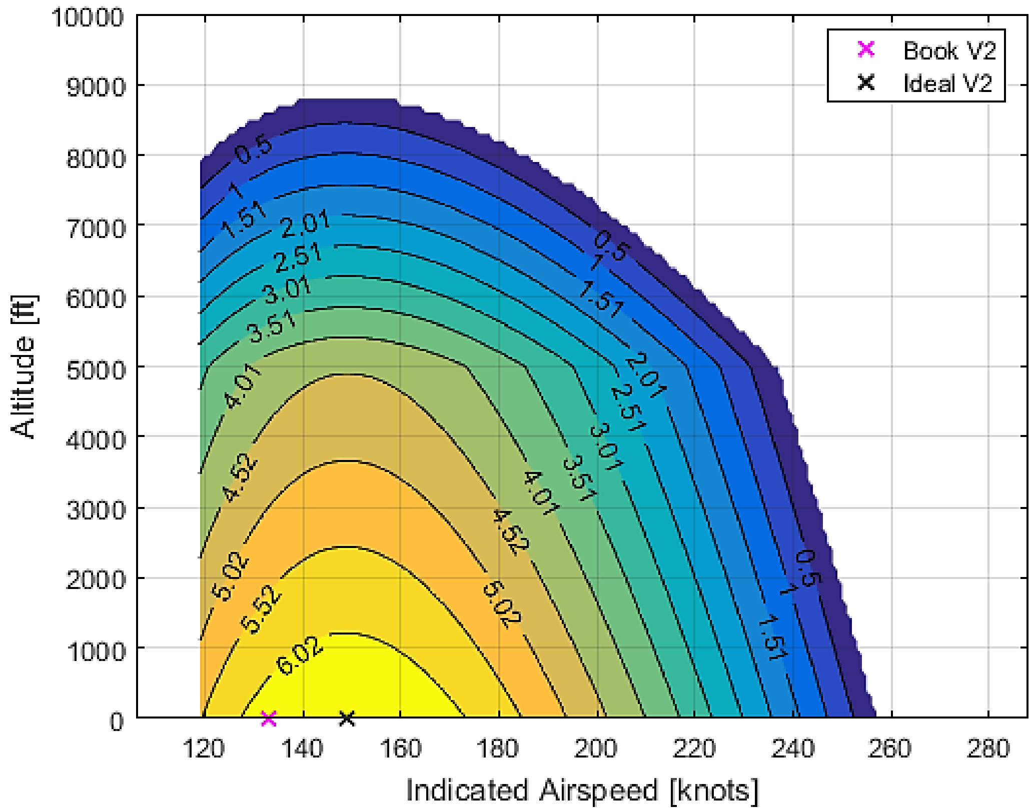

Figure 13. Contour Plot of A320 Gross Climb Gradient w/OEI at $W = 132{,}800$ lbm. Flaps and trim drag included. Contours presented as a percentage.

For a dispatch weight of $W = 132{,}800$ lbm, the aircraft flight manual recommends a cue speed of $V_2 = 133$ KIAS; at this cue speed, *SKYMAPS* predicts a gross second segment climb gradient of approximately 6.26%. The strongest gross climb gradient possible on the map is 6.52%, which is attained when the aircraft flies at $V_2 + \Delta V = 149$ KIAS. Introduction of an overspeed results in the A320 gaining an additional 0.26% (15.80 ft/nM) in gross climb gradient capability.

This process of identifying the speed which maximizes performance was repeated for various weight settings, in increments of 1,000 lbm, for both second segment and fourth segment climb. The locus of best performance points was plotted as a function of speed and weight; Figure 13 gives a comparison of V_2 speeds suggested by the book and those which maximize climb gradient or climb rate, whereas Figure 14 is a comparison of V_4 speeds suggested by the book and those which maximize climb gradient or climb rate.

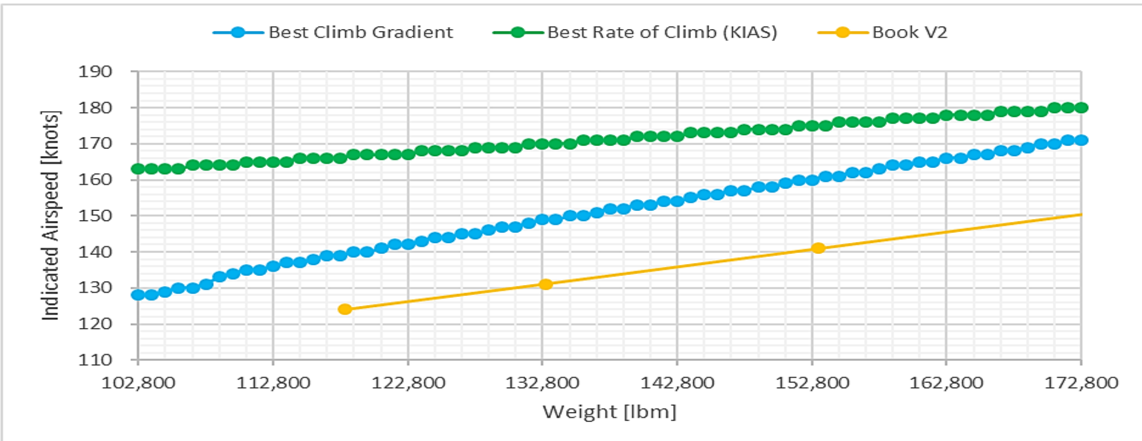

Figure *14*. Airbus A320, OEI "Flaps 2" Performance Data. Evidently, the A320 is never scheduled at a V_2 which maximizes climb gradient.

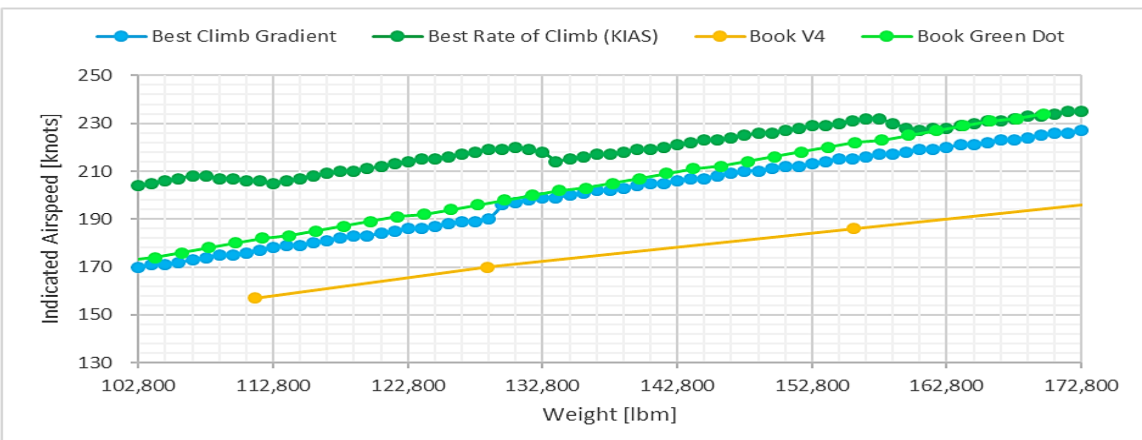

Figure 15. Airbus A320, OEI Cruise Performance Data. There is a significant correlation between the *SKYMAPS*-predicted best climb gradient speed and the "Green Dot" speed given by the flight manual.

These preliminary results suggest that, indeed, some climb gradient may be recovered simply by introducing an overspeed; this adds to the A320's overall obstacle clearance performance but comes at the cost of increased TODR. Both Figures 14 and 15 suggest that at heavier weights, a larger overspeed is required to maximize climb gradient performance, hence the TODR penalty is larger; conversely, at lighter weights, a smaller overspeed is required to do the same, which results in a smaller TODR penalty. This trend suggests that the aircraft dispatch weight, required overspeed to maximize climb gradient performance, and TODR penalty are all proportional to each other, the latter of which is an important consideration should this potentially find application to real-world dispatches.

Unsurprisingly enough, Airbus encourages performing a $V_2 + 10$ KIAS takeoff when all engines are operative and the takeoff distance available permits it.[51] The evidence presented in the previous figures support this practice. Irrespective of the fact that the reverse-engineered A320 model does not suggest a $\Delta V = 10$ KIAS overspeed is enough to achieve maximized climb gradient performance, it will at the very least provide some additional climb gradient capability. It makes sense that Airbus advocates for a general overspeed of no more than 10 knots because runway distance is a limiting factor; ergo, ΔV can only be elevated so much before TODR exceeds available takeoff distance.

In the aircraft flight manual, Airbus also listed V_{FTO} cue speeds, otherwise known as "Green Dot" speeds, which are the recommended best climb speeds for when the aircraft is in the en route configuration with one engine inoperative. Referring to Figure 13, one can observe that, indeed, there is a strong correlation between these Green Dot speeds and those which maximize climb gradient performance predicted by the reverse-engineered model.

[51] *Flight Operations Briefing Notes: Takeoff and Departure Operations*, 2017.

Before simulating departure procedures, there remains an issue which must be resolved beforehand. Recall that Federal Regulations require dispatch planners to consider an aircraft's net flight path. For the entirety of takeoff procedure, a 0.8% climb gradient detriment should be applied to the aircraft's gross climb gradient performance to procure the net flight path.[52] Similarly, for the en route portion, which is characterized by the aircraft being in the en route configuration and flying at V_{FTO}, a 1.1% climb gradient detriment applies to the aircraft's gross climb gradient performance to produce the net flight path.[53] The issue at hand here is the following: for simulations which utilize idealized cue speeds, should $V_4 + \Delta V$ be considered as equivalent to the "Green Dot" V_{FTO}, in light of the strong correlation presented in Figure 13? If yes, then the 1.1% derate should apply to the fourth segment climb because the conditions which signify the aircraft is "en route" are satisfied, with a 0.8% derate applied to all other parts of the flight path. If no, then the 0.8% derate applies to all parts of the flight path. Strictly speaking, 14 CFR § 25.123(b), the 1.1% derate on en route gross climb gradient performance, only applies when the aircraft's speed is no less than the Green Dot V_{FTO}, per 14 CFR § 25.123(a).[54] Since these idealized cue speeds are lesser than the set of Green Dot speeds at all weight settings, a strict interpretation of Federal Regulations precludes the application of a 1.1% derate to the simulations using these optimized cue speeds.

[52] Takeoff flight path, 2017.

[53] En route flight paths, 2017.

[54] Ibid.

Optimal Piloting Procedure for Maximum Obstacle Clearance

Now equipped with a set of cue speeds recommended by the book and another which maximizes the A320's climb gradient performance, *MISSION* comes into play by simulating the multiple variations of takeoff profiles previously mentioned. For the sake of making clear the impact of considering the net flight path and not an aircraft's gross flight path when planning the departure procedures, both will be presented here. The first data package consists completely of gross takeoff profiles, comprised of traditional four-segment flyouts, a "Flaps 2" E2S takeoff, as well as a "clean wing" E2S takeoff. In similar fashion, the second set will consist completely of net takeoff profiles, comprised in the same manner as before. Within each of the two data packages, simulations performed using the cue speeds recommended by the book (book speeds) will contrast to those performed at speeds which maximize obstacle clearance (idealized or optimized cue speeds). Flyouts will not be compared to the takeoff minimums of aforesaid airports as that is not the focus of this section.

First inspecting the book speeds of the gross flight profile set, Figure 16 represents flyouts performed at the maximum takeoff weight, $W = 172{,}800$ lbm.

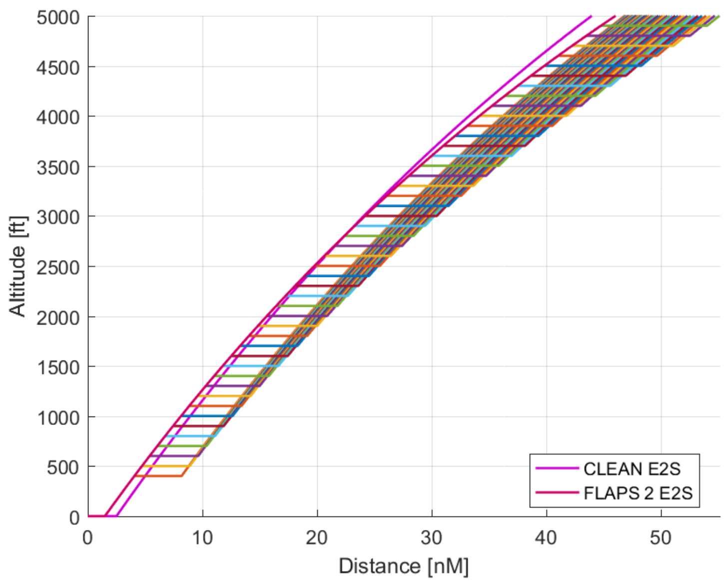

Figure 16. A320, OEI, $W = 172{,}800$ lbm, Gross Takeoff Profiles w/Book Speeds.

As can be observed, traditional four-segmented flight profiles were simulated with the third segment acceleration altitude varying from 400 ft AGL to 4,900 ft AGL and are not notated on the legend. The two dominant flight profiles which maximize obstacle clearance capability are clearly the “Flaps 2” E2S takeoff procedure (rose line) and a “clean wing” E2S takeoff procedure (magenta line). For example, on inspection of the 8 nM mark, the A320 could still be completing third segment acceleration at 400 ft AGL if a four-segment takeoff procedure was utilized; conversely, the aircraft could attain an altitude of approximately 890 ft AGL if a clean E2S profile was used, or up to 1,000 ft AGL if a “Flaps 2” dispatch was planned. Interestingly, both E2S profiles are equivalent at approximately 22.60 nM away from the runway, at an altitude of approximately 2,824 ft AGL. This suggests that while one E2S profile is not necessarily best for everything, a variation on the flaps setting using this procedure can either maximize close-in (with flaps out) obstacle clearance capability or far-out (with no flaps) obstacle clearance capability. It may be worthwhile noting that the clean E2S simulation requires a runway distance of roughly 15,800 ft to perform; while TODR values are indeed pessimistic in nature and need to be reexamined closely, not every airport in the United States is equipped with runways this long, potentially precluding the use of a clean E2S flyout. Assuming this does not, it appears that, indeed, the extended second segment climb procedure is worth consideration as it maximizes the A320's obstacle clearance capability without the need for expensive retrofit to the aircraft's airframe or powerplant.

The data from this set of simulations indicate that a traditional four-segment profile with transition altitude of 400 ft AGL as a reference requires a flight time of 895 sec, with 2,643 lbm of fuel burned. The "Flaps 2" E2S climb requires a travel time of approximately 1,066 sec, with 3,098 lbm of fuel burned; in other words, execution of this profile results in an additional 2.84 minutes of flight and additional 455 lbm of fuel burned. On the other hand, a clean wing E2S climb provides minimal flight time and fuel burn at 822 sec and 2,418 lbm, respectively, which correlates to a savings of 73.8 sec in flight and 225 lbm of fuel burned when compared to the reference profile; these results make sense given that a clean wing configuration is one of minimal drag, improving flight efficiency. When comparing the reference profile to other four-segment profiles with a higher third segment transition altitude, it is evident that flight time and fuel burn increase as the transition altitude for third segment increases. Ergo, while these values for flight time and fuel burn are insignificant by themselves, there is some evidence here that provides rationale to the concept of an "early cleanup" on the flaps when possible.

On a comparison of the traditional profiles alone, Figure 16 shows that a dispatch using a transitional attitude of 400 ft AGL has poor close-in obstacle clearance capability, but has the best far-out obstacle clearance capability. Conversely, a dispatch using a late cleanup on the flaps—such as a third segment acceleration occurring at 4,900 ft AGL—has better close-in obstacle clearance capability, but not so when considering the far-out case. Indeed, it starts to seem that the notion of the four-segment profile with an early flaps cleanup at 400 ft AGL is no longer a "one size fits all" approach.

Closing out the analysis on Figure 16, it appears so far that from the perspective of maximizing aircraft efficiency, it is best to schedule flap retraction early to minimize fuel burn and flight time, with the absolute minimization of these two parameters comes from a clean wing E2S flyout. However, from the perspective of obstacle clearance, this may not necessarily be the best practice; in fact, the best profile choice depends on the location of the obstacles within the aircraft's flight path. For example, avoidance of close-in obstacles is best done using a "Flaps 2" E2S profile as that provides optimal nearby obstacle clearance capability; conversely, a clean wing E2S flyout provides best far-out obstacle clearance capability, and thus is best suited for situations where the aircraft needs to overcome distant objects. If a clean wing E2S climb out is precluded due to TODR restrictions, a "Flaps 2" E2S provides second-best obstacle clearance capability up to 5,000 ft AGL.

The evidence of Figure 16 reveals that, indeed, obstacle clearance performance can be improved through a simple operational change which extends second segment climb, providing some means of answering key questions 1 and 2. However, as per key question 3, is obstacle clearance performance improved when an E2S climb out *and* optimized cue speeds are used in dispatch? To produce some evidence in answering this question, Figure 17 represents the same heavyweight case, but this time with idealized cue speeds executed in the simulation.

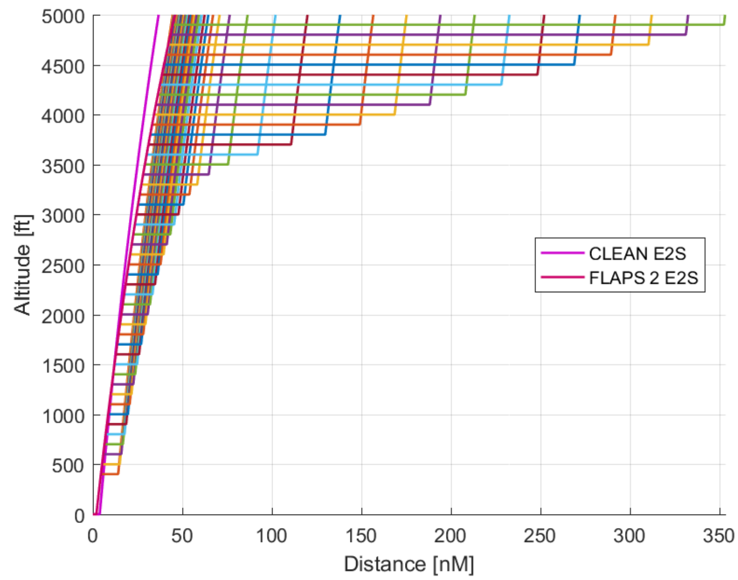

Figure 17. A320, OEI, $W = 172{,}800$ lbm, Gross Takeoff Profiles w/Ideal Speeds. Clean E2S and early cleanup profiles gain some obstacle clearance capability, but those with a late flaps cleanup are adversely affected.

An immediate observation reveals that cue speed choice is a significant factor which molds the shape of the resulting flight profile. A closer inspection of this figure reveals that the clean wing E2S profile produces slightly more obstacle clearance performance than before, completing the climb to 5,000 ft in 36.77 nM when using idealized speeds, down from 43.98 nM if using book speeds. The “Flaps 2” E2S climb also procured some additional obstacle clearance capability, albeit not in an appreciable amount worthy of mention. Traditional four-segment profiles which implement an early cleanup on the flaps can save up to 2 nM in distance when implementing idealized cue speeds, thereby increasing far-out obstacle clearance capability, but at the expense of close-in obstacle clearance performance due to a longer third segment acceleration. Unsurprisingly, Bays & Halpin also observed in their work that close-in obstacle clearance performance for the C-130J can be traded for additional far-out obstacle clearance by overspeeding.[55]

However, obviously there is a limitation to the use of idealized cue speeds; specifically, Figure 17 implies that profiles which utilize a late cleanup on the flaps require a longer third segment acceleration to attain the $V_4 + \Delta V$ speed. This is best explained by the fact that the thrust performance of aircraft engines is reduced at higher altitudes due to a reduction in air density; thus, the higher the altitude, the longer of a thrust duration is necessary to attain the desired speed. Then again, if using idealized cue speeds maximizes far-out obstacle clearance capability, it makes no sense to apply these speeds to profiles which excel at providing better close-in obstacle clearance performance. Thus, use of overspeeding only makes sense for flight profiles which implement an early cleanup on the flaps or a clean wing E2S profile to maximize far-out obstacle clearance performance, with the first trading close-in obstacle clearance capability and the latter trading TODR. It may be worth mentioning that in this case, *MISSION* reports a TODR of 23,393 ft for the clean E2S dispatch when using idealized cue speeds; this can potentially preclude use of such a profile since no runway in the United States is long enough to accommodate this field length requirement, but then again, further research is necessary to produce a more accurate estimation of TODR. If the clean wing E2S dispatch is precluded by a TODR restriction, a “Flaps 2” E2S

[55] Bays & Halpin, 2015.

dispatch can be substituted to provide maximized close to mid-range obstacle clearance performance up to 41.98 nM, past which a traditional four-segment profile with flaps cleanup at 400 ft AGL provides somewhat better clearance capability.

An application of idealized cue speeds seems to also provide reductions in flight time and fuel burn for a handful of profiles; this makes sense, given that a maximized climb gradient implies maximized climb efficiency. Recall the baseline profile before, a four-segment flyout with a third segment transition at 400 ft AGL using book speeds; there, the flight time was approximately 895 sec, with 2,643 lbm of fuel burned. Using this same profile but with optimized cue speeds leads to a flight time of 759 sec and fuel burn of 2,279 lbm, which correlates to a reduction of 2.27 minutes in flight time and 364 lbm of fuel burn. A clean wing E2S profile with optimized cue speeds requires a climb time of 608 seconds and fuel burn of 1,813 lbm, which are down from 822 seconds and 2,418 lbm if using book speeds. A "Flaps 2" E2S climb using optimized cue speeds results in a climb time of 959 sec and fuel burn of 2,800 lbm, but only slightly reduced from 1,066 sec and 3,098 lbm of flight time and fuel burn using book speeds. Unsurprisingly, the clean wing E2S flyout once again provides minimizations to both flight time and fuel burn, with profiles implementing an early cleanup on the flaps also seeing reductions to both parameters when idealized speeds are used; profiles with a late cleanup on the flaps observe longer climb times and higher fuel burn when idealized speeds are applied. While the figures in of themselves are insignificant, the trends are at the very least interesting to note.

Synthesizing the results from the last two figures, it is apparent that the A320 can, even at the maximum takeoff weight, procure some additional obstacle clearance capability through use of an E2S climb profile, which only requires a simple operational change on the pilot's end. For close-in obstacles, a "Flaps 2" E2S climb is best; conversely, far-out obstacles are best overcome using a clean-wing E2S profile, albeit the TODR penalty is one which cannot be neglected in a real-world application. Applying idealized cue speeds adds to the obstacle clearance capability of both profiles, the latter more so than the first, but this comes with a TODR penalty. In the case that a clean wing E2S climb out is precluded due to a TODR limitation, a "Flaps 2" E2S can provide second-best obstacle clearance capability up to 5,000 ft AGL.

Moving on to the light weight case, Figure 18 represents a book speeds dispatch at $W = 132{,}800$ lbm.

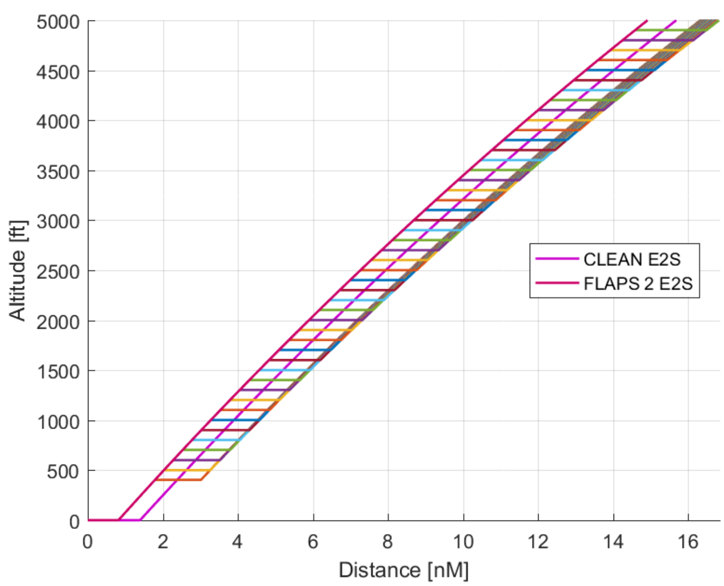

Figure 18. A320, OEI, $W = 132{,}800$ lbm, Gross Takeoff Profiles w/Book Speeds. The reduction in aircraft weight improved the obstacle clearance performance of all profiles.

One obvious conclusion here is that the obstacle clearance capability of the A320 has increased significantly, very much due to dispatching at a lighter weight. Because of this additional performance to all profiles, the trends which were previously observed at the height weight case are not the same here; that is, where previously it was observed that a "Flaps 2" E2S flyout gives best close-range obstacle clearance performance and a clean wing E2S flyout gives best long-range obstacle clearance performance, Figure 18 suggests that *only* a "Flaps 2" E2S climb provides *both* best both close- and long-range obstacle clearance performance for a climb up to 5,000 ft AGL. Indeed, there exists a careful interplay of aerodynamics and weight which affects the aircraft's performance, subsequently affecting which E2S profile is best for the mission at hand.

A quick inspection of the numbers accompanying Figure 18 reveals that, unsurprisingly, a clean wing E2S climb minimizes flight time and fuel burn at 344 sec and 1,013 lbm, respectively. In similar fashion, a "Flaps 2" E2S climb requires a moderate amount of flight time and fuel burn at 407 sec and 1,184 lbm, respectively. Profiles which implement an early cleanup on the flaps reap reduced flight time and fuel consumption, as usual.

Investigating how the application of optimized cue speeds affects the lightweight dispatch, Figure 19 provides a similar, although not identical story to that observed in Figure 18.

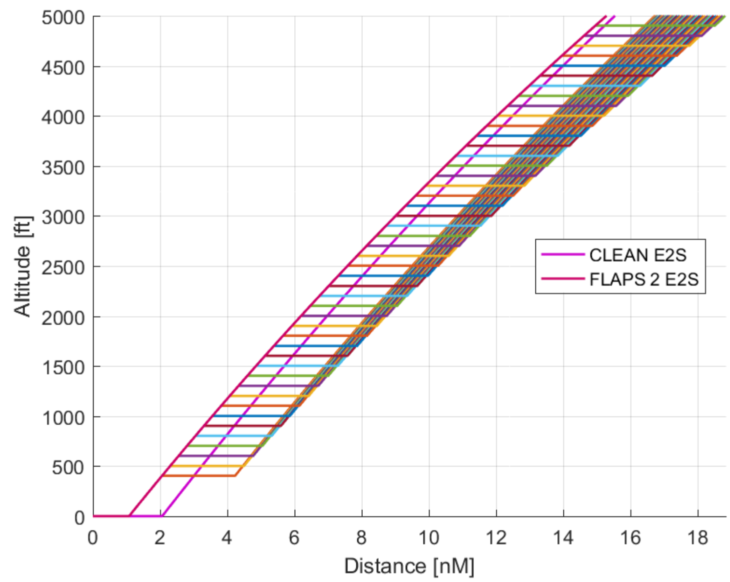

Figure 19. A320, OEI, $W = 132{,}800$ lbm, Gross Takeoff Profiles w/Ideal Speeds. Except for the clean wing E2S climb, all other profiles found reduced obstacle clearance performance upon application of cue speeds maximizing climb gradient.

Surprisingly, it seems that the application of optimized cue speeds here *reduced* the obstacle clearance performance of all profiles, with the exception being the clean wing E2S climb. Regardless, this figure implies that the “Flaps 2” E2S climb provides best close- and long-range obstacle clearance performance for a climb up to 5,000 ft AGL. Due to the increased slope of the clean wing E2S profile, if the second segment climb was extended further than 5,000 ft AGL, then this profile would likely overtake the “Flaps 2” E2S climb in terms of long-range obstacle clearance performance.

The numbers behind Figure 19 provide no surprise; the clean wing E2S climb provides minimum flight time and fuel burn at 302 sec and 897 lbm, respectively. Similarly, profiles which implement an early retraction on the flaps reap reduced flight time and fuel burn. The “Flaps 2” E2S climb requires a modest climb time of 337 sec and a fuel burn of 1,102 lbm. Of course, in the context of a short 5,000 ft climb, these figures are not significant.

With all the gross flight profiles thoroughly examined, net flight profiles will now be provided as a comparison; as a reminder, these flight profiles come with a derate of 0.8% in climb gradient, as a sort of "margin of safety" necessary for dispatch planning.

Inspection of the high weight net flight path case presented in Figure 20 reveals flight trends like those observed when inspecting the gross flight paths in Figure 16, yet somewhat different. The obvious difference here is that all flight profiles provided in Figure 20 are "soggier" in terms of obstacle clearance performance due to the 0.8% reduction to climb gradient performance.

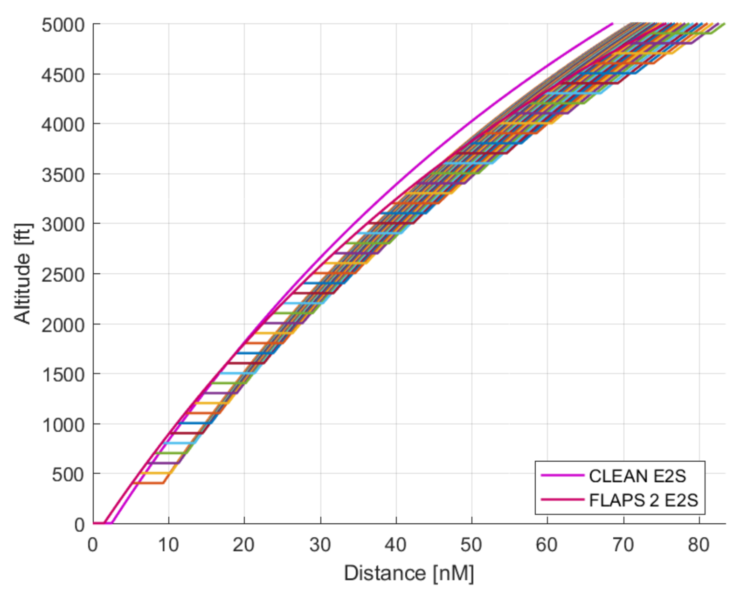

Figure 20. A320, OEI, $W = 172{,}800$ lbm, Net Takeoff Profiles w/Book Speeds. Unlike previously observed, a "Flaps 2" E2S climb provides somewhat more marginal long-range obstacle clearance performance.

Whereas all gross flight path profiles completed the climb to 5,000 ft AGL in 55 nM or less, these net flight path profiles can require up to 84 nM to fully complete the same climb – an increase of 29 nM due to the 0.8% reduction to climb gradient. Like Figure 16, where it was observed that a "Flaps 2" E2S maximizes obstacle clearance for objects nearer than 22.60 nM, and a clean wing E2S climb maximizes obstacle clearance for objects further than 22.60 nM, the trend suggested here in Figure 20 is somewhat the same. Obstacles which are nearer than 18.27 nM from the liftoff point in the takeoff path are best overcome by the "Flaps 2" E2S climb; those which reside further than 18.27 nM in the takeoff path are best overcome by a clean wing E2S climb. While a "Flaps 2" E2S dispatch can typically be substituted for the clean wing E2S climb if TODR precludes execution of the latter profile to get second-best obstacle clearance performance, this claim only holds true up to 46.26 nM, where then traditional profiles which implement an early cleanup on the flaps (such as at 400 ft AGL) provide better long-range obstacle clearance performance.

Also presenting the aircraft's heavy weight net flight path using optimized cue speeds, it can be observed that this Figure 21 is similar to its gross flight path with optimized cue speeds presented in Figure 17.

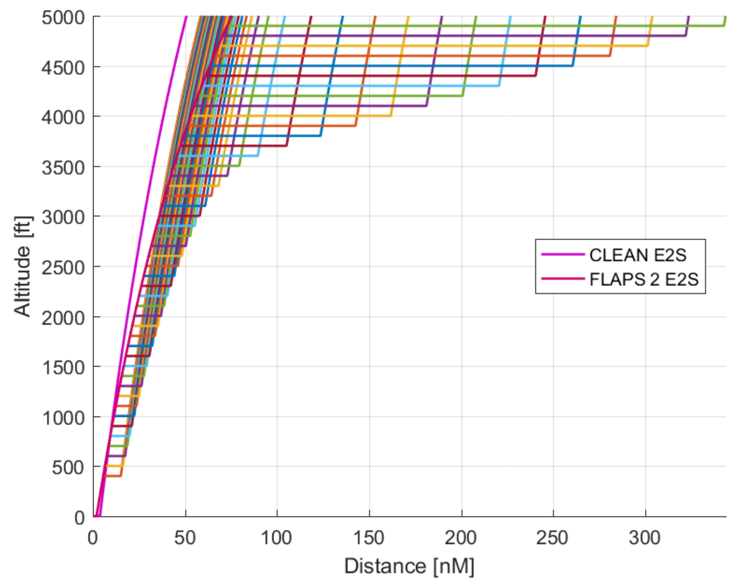

Figure 21. A320, OEI, $W = 172{,}800$ lbm, Net Takeoff Profiles w/Ideal Speeds. An odd, unexpected result here was the 4,900 ft AGL flap retract profile completing in a shorter distance than its gross counterpart – one would expect the opposite to be true.

Between these two figures, one similarity is that these flight profiles are "drawn out" unnecessarily, out of the consequence of the need for a long third segment acceleration due to high $V_4 + \Delta V$; of course, this revelation is nothing new and exciting. What is different and interesting between these two profiles is that the "crossover point" at which the E2S profiles are equivalent in obstacle clearance performance has moved. For example, Figure 17 implies that this crossover point resides at 11.64 nM – where a "Flaps 2" E2S and clean wing E2S provide an equivalent amount of obstacle clearance. A crossover point exists here in Figure 21, but it has shifted closer towards 9.37 nM. Thus, for obstacles which reside closer than this point, a "Flaps 2" E2S climb provides maximized obstacle clearance performance; conversely, obstacles residing further from this point are best overcome with a clean wing E2S climb. In the likely event a clean wing E2S climb is precluded due to an insatiable TODR, a "Flaps 2" E2S climb can be substituted to provide second-best obstacle clearance capability, at least up until 36.17 nM away from the runway – past that point, a profile which implements an early flap retraction (such as at 400 ft AGL) will provide second-best obstacle clearance performance.

Between the heavy weight gross and net flight profiles, the trends observed were still largely the same. For example, it would be ill-advised to pursue the use of cue speeds which maximize climb gradient performance because in either way of looking at it (net or gross), a prolonged, wasteful third segment acceleration is required. Between the net and gross book speeds cases, both E2S profiles can provide better obstacle clearance performance where traditional profiles cannot. When considering the net flight path, the "Flaps 2" E2S profile looks slightly soggier than traditional profiles which implement an early cleanup on the flaps, despite the uniform 0.8% climb gradient derate – likely since the aircraft climbs better clean than with the flaps out; thus, there exists additional options which provides better long-range obstacle clearance performance when considering the net flight path (although the actual, gross flight path contradicts this!). Between the gross and net flight paths, a consistent change noticed is the "crossover point" which drives the selection of which E2S profile provides maximum obstacle clearance performance.

Moving back to an inspection of the light weight cases, this time investigating the net flight paths, Figure 22 represents a story which is nearly identical to that told by Figure 18.

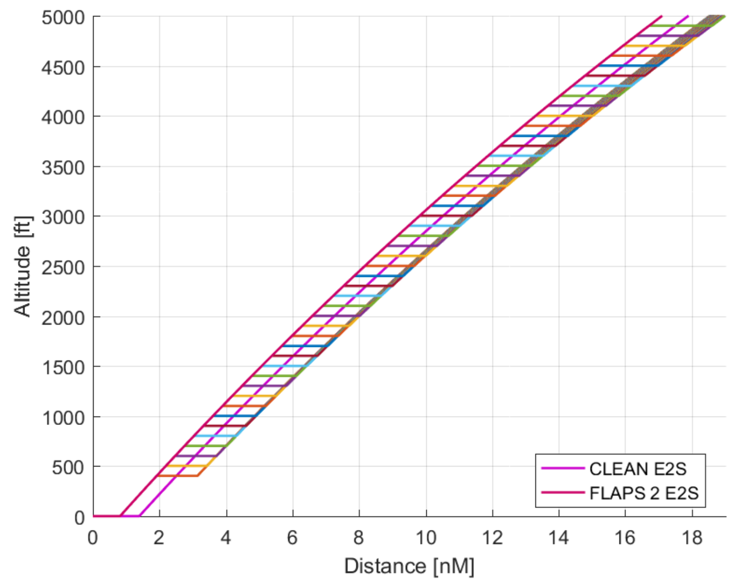

Figure 22. A320, OEI, $W = 132{,}800$ lbm, Net Takeoff Profiles w/Book Speeds.

Compared to the gross flight paths, those presented here required a longer distance to complete the climb to 5,000 ft AGL; again, this is an expected outcome thanks to the 0.8% decrement to climb gradient performance. Otherwise, that appears to be the only difference between these two figures. Between these two, a "Flaps 2" E2S climb provides superior close-range and far-out obstacle clearance performance due to the weight reduction adding to climb performance. Ergo, irrespective of analyzing the gross or net flight path, analysis at lighter dispatch weights will point to a "Flaps 2" E2S climb providing best obstacle clearance performance up to 5,000 ft AGL.

Figure 23 represents the above case, but with an application of optimized cue speeds.

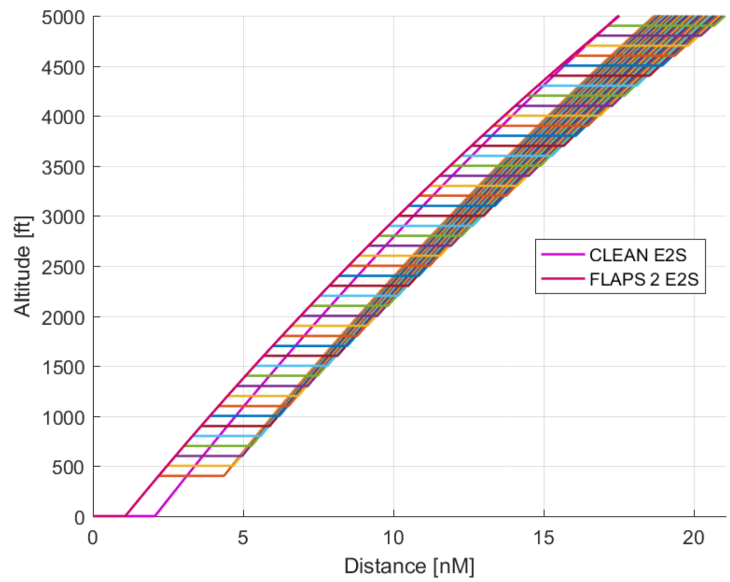

Figure 23. A320, OEI, $W = 132{,}800$ lbm, Net Takeoff Profiles w/ Ideal Speeds.

Compared to its gross counterpart Figure 19, these two figures bear an unsurprising resemblance to each other; for example, both figures imply that a clean wing E2S climb will eventually overtake the “Flaps 2” E2S climb in terms of obstacle clearance performance at some altitude. That is exactly the case here – at approximately 17.06 nM away from the liftoff point, which correlates to an altitude of 4,885 ft AGL, the clean wing E2S climb provides equivalent obstacle clearance performance compared to the “Flaps 2” E2S climb. Thus, at distances further than 17.06 nM, a clean wing E2S climb is recommended for optimal obstacle clearance, though its TODR may be a limiting factor; in this case, a “Flaps 2” E2S dispatch provides second-best obstacle clearance performance.

From this short investigation in comparing the gross and net flight paths to identify the “best” operating procedure which maximizes obstacle clearance performance, it appears that the general, overarching trends observed tend to remain the same, irrespective of the 0.8% derate in climb performance; while this 0.8% decrement to climb gradient affects the performance of all simulated profiles, the results suggested that some variant of an extended second segment climb provides better obstacle clearance capability over the traditional four-segment profiles, with little to no additional appreciable obstacle clearance performance gained due to the application of idealized cue speeds; this is consistent with the results gathered from the gross flight profiles. For example, a heavyweight dispatch finds best close-range obstacle clearance performance with a “Flaps 2” E2S climb, whereas a clean wing E2S climb provides best long-range obstacle clearance performance. The definition of “close-range” and “long-range” varies, dependent upon if one chooses to analyze the gross (actual) or net (actual minus 0.8% climb gradient performance) flight path. In the event a clean wing E2S climb is precluded due to an insatiable TODR, a gross flight path analysis shows a “Flaps 2” E2S climb should be used for second-best long-range obstacle clearance performance; however, a net flight path analysis implies that a traditional profile which schedules flap retraction at 400 ft AGL is a better choice. For a lighter dispatch weight, both the gross and net flight path analysis indicates that a “Flaps 2” E2S climb gives best obstacle clearance performance everywhere for a climb up to 5,000 ft AGL. In other words, while there exist overarching trends which appear in both a gross and net flight path analysis, the results which stem from one analysis may not necessarily exactly match that of the other; in layman’s terms, the “best” operational procedure which maximizes obstacle clearance performance from a dispatch personnel’s net flight path analysis may not necessarily truly be the best when applied to an aircraft as it performs its actual, gross flight path.

Feasibility of Extended Second Segment Climb for Departure Procedures

While it is exciting to see that some variant of an extended second segment climb can extend the A320's current performance capabilities into producing additional obstacle clearance, there remains the test of seeing if there is truly some appreciable, practical aspect of this technique. Recall the obstacle clearance problem: while aircraft are certified to an absolute minimum on climb gradient which the FAA deems as "safe enough", the takeoff minimums imposed by standard instrument departures often exceed the federal minimums. If the aircraft's AEO climb performance is satisfactory enough to meet the takeoff minimums, it may attempt to perform the entire DP – but if an engine fails and the aircraft's OEI climb performance falls below the takeoff minimums, the climb out must be aborted; thus, the aircraft is expected to circle back to the airport and attempt a potentially overweight emergency landing. The unfavorable solution is reducing the aircraft weight before takeoff to ensure its OEI climb performance meets or exceeds the imposed takeoff minimums, which correlates to a reduction in fare-paying passengers or payload, which implies a reduction in revenue. This is where the net flight path results gathered in the previous section are applied to a handful of rigorous takeoff minimums found at KPHX, KLGA, and KBUR to test if the E2S climb technique is a viable solution to the obstacle clearance problem. Note that due to expected infeasibility in the real world, the clean wing E2S profile will not be considered in these analyses.

First investigating if dispatches can be performed at a takeoff weight of $W = 172{,}800$ lbm, Figure 24 compares the takeoff minimums of KPHX's SNOBL FIVE departure on Runway 8 to the A320's possible net flight path profiles.

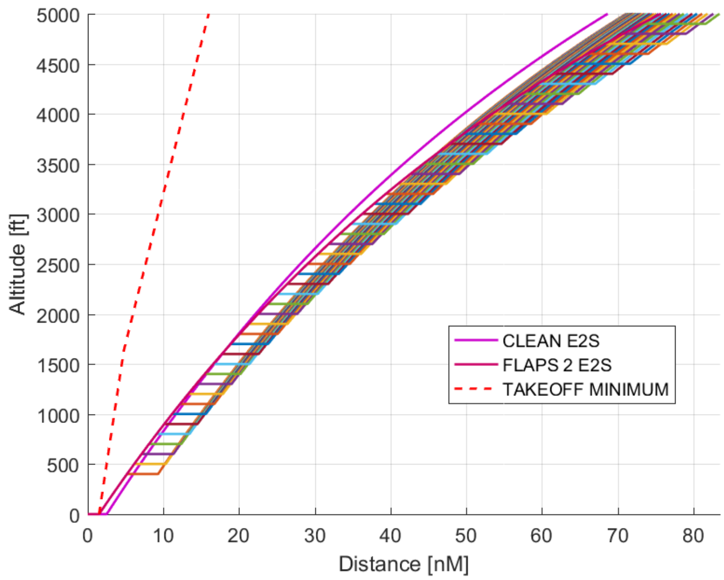

Figure 24. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 172{,}800$ lbm.

Unsurprisingly, the aircraft is so heavily limited in climb gradient performance at this dispatch weight that it is simply incapable of performing the departure procedure, even if an E2S climb was executed. While Runways 7L/R, 25L/R, and 26 have separate sets of takeoff minimums, simulations performed on those runways reveal the same result; the A320's engine inoperative climb gradient performance is simply insufficient in meeting any of the takeoff minimums imposed by a SNOBL FIVE departure procedure. If constrained to this departure procedure and set of runways only, the only remedy to low climb gradient is to decrease the aircraft weight through a reduction in the number of fare-paying passengers, payload, or fuel amount.

Inspecting the JUTES THREE departure out of KLGA reveals the same story as the previous figure. That is, Figure 25 demonstrates the takeoff minimums imposed by this departure procedure are more than the A320's engine inoperative climb performance capability, irrespective of one's choice to perform an extended second segment climb or not.

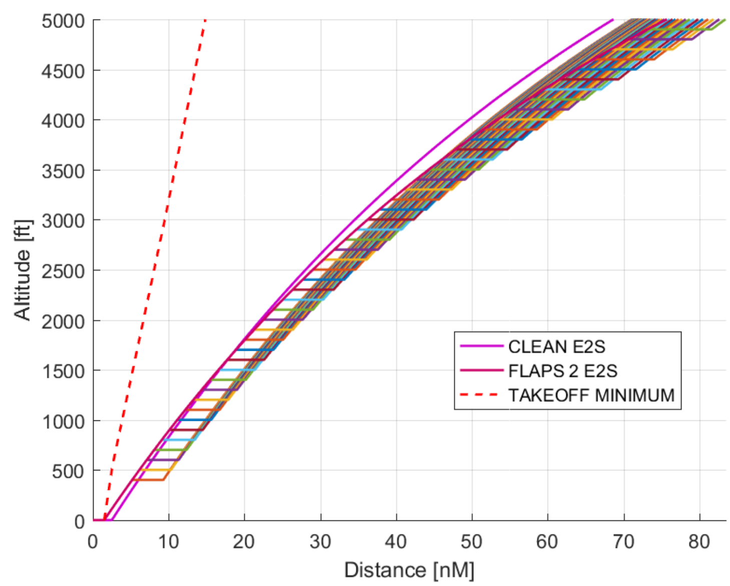

Figure 25. Comparison of KLGA – JUTES THREE (Runway 22) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 172{,}800$ lbm.

Thus, if the A320 experienced an engine failure at this dispatch weight during the takeoff climb, the pilot would have to turn away from the current flight path and back to the departure airport for an emergency landing, expending fuel and more if fuel dumping is permitted.

Figure 26 gives the "easiest" ELMOO EIGHT departure out of KBUR, compared against the A320's OEI net flight path data.

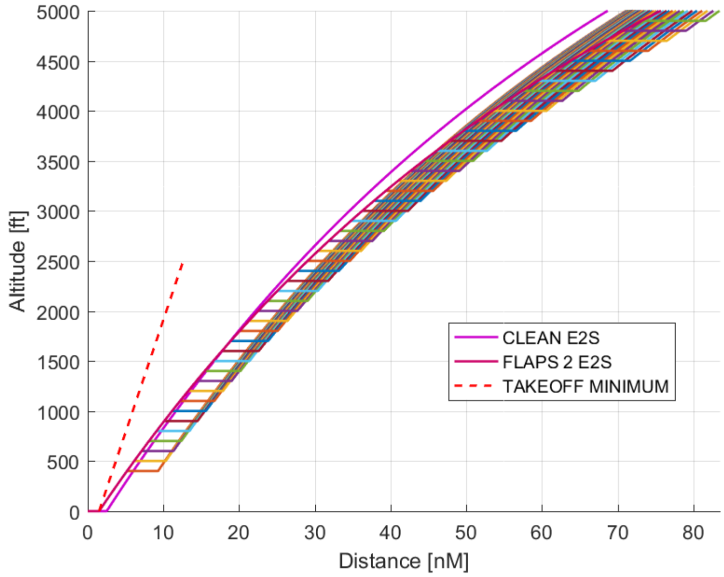

Figure 26. Comparison of KBUR – ELMOO EIGHT (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 172{,}800$ lbm.

Like the previous cases, the A320 is so heavily limited in climb gradient performance at MTOW that it cannot compete with the takeoff minimum imposed here, irrespective of whether the pilot executes an E2S climb or otherwise. Since this was the easiest runway available for the ELMOO EIGHT departure, it makes no sense to waste time analyzing further attempts at this dispatch on alternative runways. Evidently, when considering the previous three figures, it seems that an A320 which dispatches at MTOW with AEO will be incapable of satisfying the takeoff minimums with OEI, even if an E2S climb was planned.

Would these results be different if optimized cue speeds were applied on takeoff? In the previous section, it was observed that while the “Flaps 2” E2S’s obstacle clearance performance was largely unaffected, the clean wing E2S climb did see some tangible improvement. Applying the optimized cue speeds for a heavyweight dispatch, the simulations revealed that, unsurprisingly, no appreciable amount of climb gradient was recovered such that any of the takeoff minimums studied above were satisfied; this confirms that the A320 really faces no solution other than a weight reduction if a successful completion of any of the above DP's in the OEI case is desired.[56]

Now inspecting how the A320's net flight path at $W = 152{,}800$ lbm compares to the real world, Figure 27 displays KPHX's SNOBL FIVE takeoff minimums on Runways 25L/R and 26, which are the "easiest" compared to those imposed on other runways.

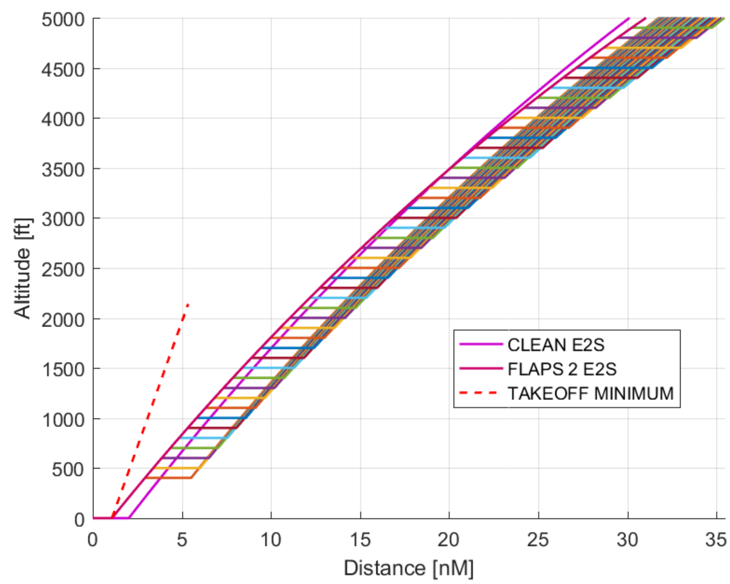

Figure 27. Comparison of KPHX – SNOBL FIVE (Runways 25L/R, 26) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 152{,}800$ lbm.

Evidently, some climb gradient performance is recovered thanks to the reduction in aircraft dispatch weight; however, the aircraft still does not possess enough OEI climb performance to match the required minimum for this departure, regardless of if an E2S climb out was planned or otherwise. As a straight flyout of the SNOBL FIVE departure

[56] Optimized cue speeds were also applied to the following lighter weight cases to see if it made the difference between incompliance and compliance of takeoff minimums when flying with OEI, but to ultimately no benefit for the A320.

under the OEI condition is impossible, the pilot must abort the takeoff procedure and circle back to the airport for an emergency landing in the event of an engine failure. As the takeoff minimums imposed upon Runways 25L/R and 26 were the "easiest" of the lot, it makes no sense to examine this DP applied on other runways in the interest of time.

Unsurprisingly, yet another similar story appears when comparing KLGA's JUTES THREE takeoff minimums against the A320's net flight path performance at this dispatch weight in Figure 28.

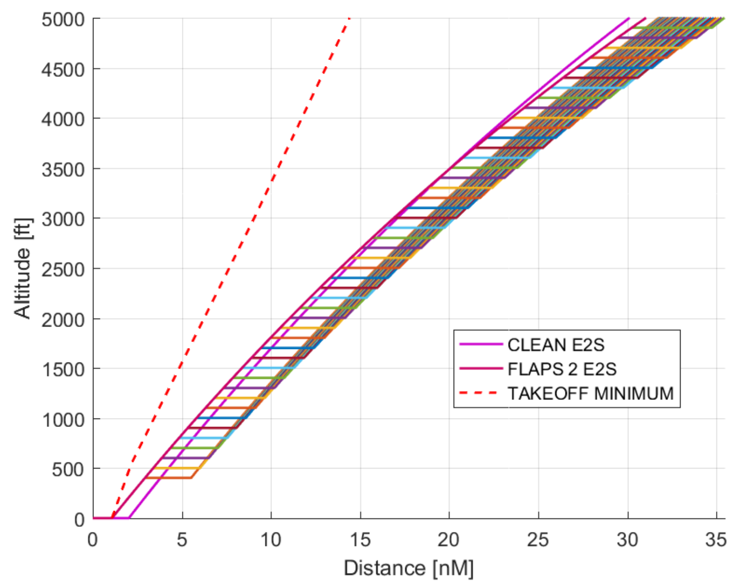

Figure 28. Comparison of KLGA – JUTES THREE (Runway 22) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 152{,}800$ lbm.

The recovery in climb gradient performance thanks to a dispatch weight reduction is regrettably still not enough to satisfy the takeoff minimums imposed by this departure procedure, even if an E2S climb was planned. Just as before, the pilot of the A320 will be obligated to turn away from the takeoff flight path if an engine failure occurs because the OEI climb performance falls below the recommendation set forth by the takeoff minimums.

Even the dispatches from KBUR on an ELMOO EIGHT departure are plagued with the issue of lacking obstacle clearance performance, as presented in Figure 29.

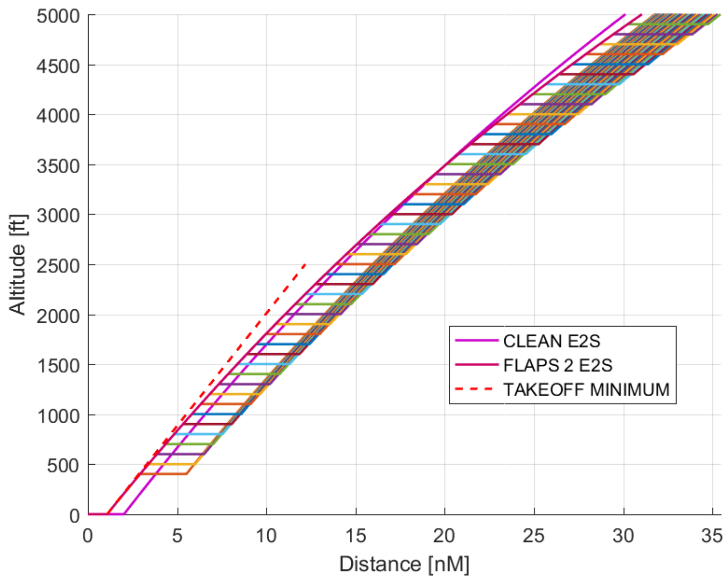

Figure 29. Comparison of KBUR – ELMOO EIGHT (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 152{,}800$ lbm.

While the A320's net flight path in the second segment climb appears to meet the takeoff minimums early in the procedure, the flight path eventually deviates below the takeoff minimums. This drop-off in obstacle clearance capability is due to the consequences of physics: as the aircraft flies higher, its thrust capabilities are reduced due to the decrease in air density, hence why the aircraft's flight paths appear curved (especially at heavier weights – not so much on the lighter end) as opposed to remaining linear. This is why performance equations such as climb gradient and rate of climb, Equations 12 and 13, respectively, are functions of aircraft altitude – these performance parameters are a maximum at sea level, they decrease as the aircraft altitude increases. Ergo, the dispatch planner is faced with carefully considering the aircraft's climb performance degradation to check for compliance with all parts of the takeoff minimums, especially at higher altitudes. In this case, and like the others before, the pilot must abort the takeoff climb if an engine fails, limping the aircraft back to the departure airport for an emergency landing in a potentially overweight situation.

Evidently, yet another weight reduction is necessary as the A320 is incapable of meeting the takeoff minimums under OEI conditions for the cases described above. Taking the A320's net flight profiles at a dispatch weight of $W = 132{,}800$ lbm, Figure 30 compares them to KPHX's SNOBL FIVE on Runway 8.

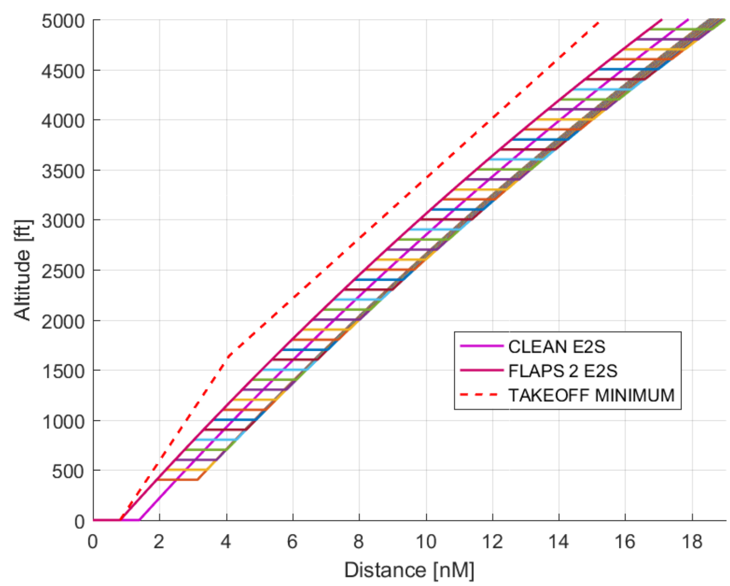

Figure 30. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 132{,}800$ lbm.

While, again, the A320 is incapable of meeting the takeoff minimums in the OEI case, irrespective of choice to implement an E2S climb or otherwise, one peculiar feature of this figure is that the net flight profiles appear linear – not so. Physics dictates that an aircraft's thrust output, hence climb performance, is reduced as altitude increases due to a decrease in air density. On a closer inspection of Figure 30, in particular at the 5 nM mark, it seems that the climb slope of the net flight profiles is greater than that of the takeoff minimums; however, as altitude increase, the climb slope decreases, so the flight paths start to diverge away from the takeoff minimums, which is most noticeable at the 15 nM mark. As always, an aircraft which has insufficient OEI climb performance to meet the recommendation set forth by the takeoff minimums must abort the takeoff climb if an engine fails mid-climb.

Inspection of KLGA's JUTES THREE departure procedure in Figure 31 tells a story which is like that of Figure 30.

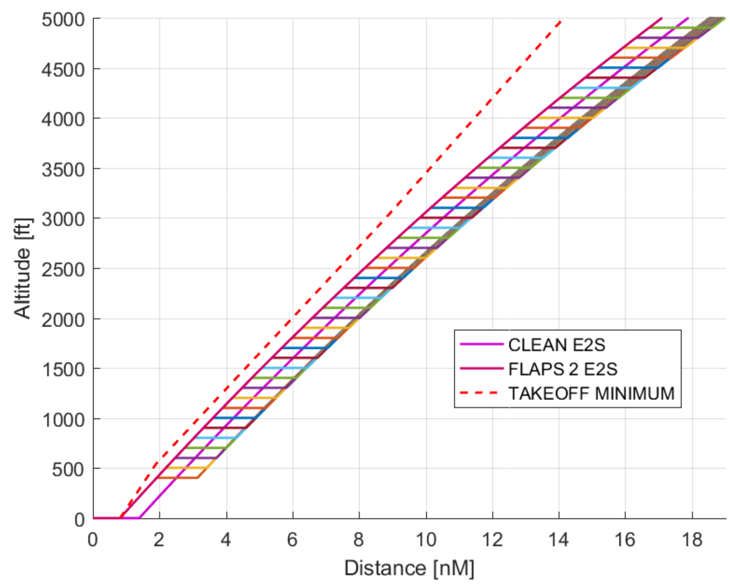

Figure 31. Comparison of KGLA – JUTES THREE (Runway 22) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 132{,}800$ lbm.

Of course, it is no surprise to find that once again the A320 is insufficient in its climb performance with respect to the takeoff minimums of this departure procedure. With all the cases studied so far, it is evident that the A320, as well has other commercial aircraft, have an incredible amount of difficulty attempting to abide by rigorous departure procedures. Even after shedding roughly half of its weight capacity, this aircraft comes close to, but not enough to overcome, the takeoff minimums of this departure procedure.

A further weight reduction on the A320 is necessary to recover enough climb gradient to overcome the takeoff minimums imposed here to fully complete a OEI dispatch, further reducing the per-flight profits of the carrier.

However, said weight reduction is no longer required for a dispatch from KBUR's Runway 26 using ELMOO EIGHT, as indicated by Figure 32.

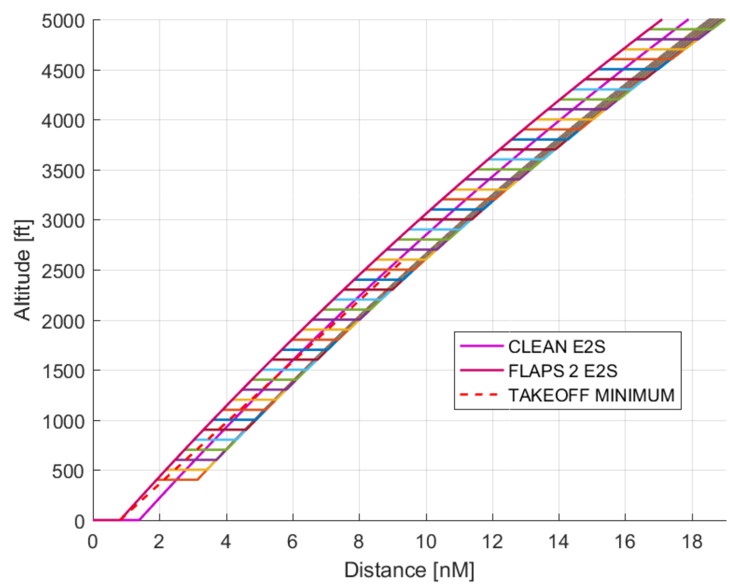

Figure 32. Comparison of KBUR – ELMOO EIGHT (Runway 26) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 132{,}800$ lbm.

Indeed, finally the A320 has a handful of flight profiles which can be utilized to execute this departure procedure under the OEI condition. For example, any of the traditional four-segment takeoff profiles are valid candidates for performing this DP so long as the flap retract altitude is delayed to 2,600 ft AGL or greater to avoid transgressing the takeoff minimum climb slope. Alternatively, a "Flaps 2" extended second segment climb is also a viable option here for that procedure also avoids transgressing the takeoff minimum climb slope. An advantage of the E2S profile is that the pilot needs not worry about when to "nose over" the aircraft for third segement acceleration; this simplifies the procedure for pilots, freeing up valuable cognitive resources which can be dedicated elsewhere. At this dispatch weight, Runway 8 at KBUR also opens up as a viable possibilitiy for an OEI DP if Runway 26 is occupied by traffic; for that runway, viable operational techniques include a four-segment profile which holds the flap retract until 800 ft AGL or greater, or a “Flaps 2” E2S climb.

With an additional weight reduction, the A320 can depart from KPHX’s Runway 8 using the SNOBL FIVE departure procedure at a dispatch weight of $W = 117{,}800$ lbm, as seen in Figure 33.

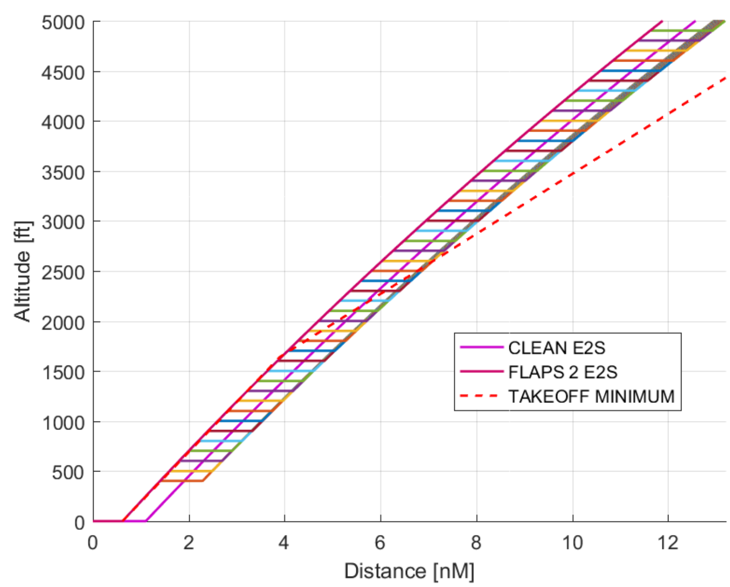

Figure 33. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 117{,}800$ lbm.

Note that this weight is relatively light compared to the maximum of 172,800 lbm and empty weight of approximately 82,079 lbm. Viable techniques include a “Flaps 2” E2S climb or a four-segment profile which holds the flap retract until 2,600 ft AGL or greater. At this dispatch weight, runways 7L&R also open as departure options for fully completing the OEI departure procedure if traffic occupies Runway 8; for those two runways, the flap retract altitude should be scheduled at 2,200 ft AGL or greater, or it can be bypassed entirely by using a "Flaps 2" E2S climb. Runways 25L&R and 26 require a small weight reduction to abide by the takeoff minimums imposed up to 2,200 ft AGL.

At a departure weight of $W = 122{,}800$ lbm, the A320 is nearly strong enough in climb performance to totally abide by the takeoff minimums of KLGA's JUTES THREE, as indicated in Figure 34.

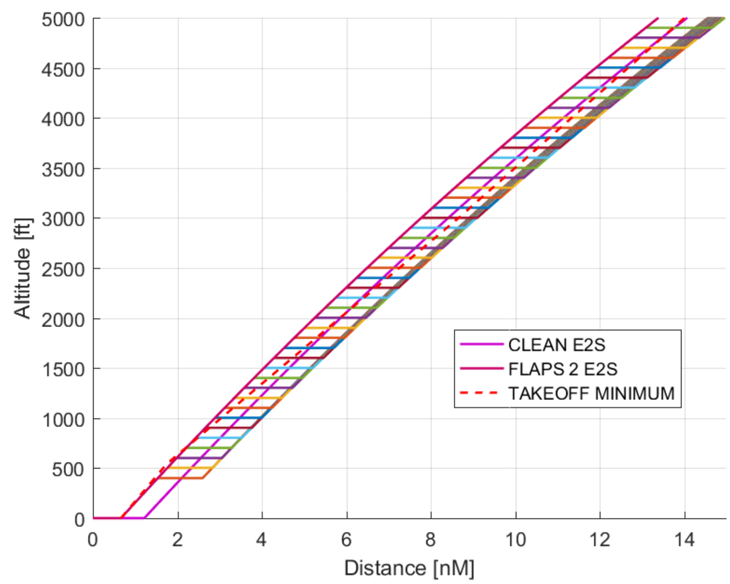

Figure 34. Comparison of KLGA – JUTES THREE (Runway 22) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 122{,}800$ lbm.

The aircraft is just barely insufficient in climb performance—in particular at the 2 nM point—to abide by the recommended minimum climb slope. Technically, this means that the A320 must abort the takeoff and turn away from the climb path in case of engine failure. Fortunately, this plot does indicate that the weight at which the A320 can completely satisfy the takeoff minimums is not too far from $W = 122{,}800$ lbm. Curiously, assuming that the OEI aircraft is compliant with the takeoff minimums of the DP, the only viable technique to abide by the minimum climb slope is the "Flaps 2" extended second segment climb. This is largely due to the rigorous climb slope imposed out of consequence of the need to avoid the tall buildings in the area. It is interesting to note that no four-segment profile is viable here, even if flap retract schedule is delayed up to 5,000 ft AGL; this is because the third segment acceleration will always transgress the takeoff minimum climb slope, which poses safety issues. Ergo, the only solution to this DP (within the context of this problem) would be the “Flaps 2” extended second segment climb carried all the way to 5,000 ft AGL, as the restriction on the minimum climb slope ends there. However, there is nothing that forbids the pilot from executing a four-segment profile and holding the flap retract to an altitude of, say, 5,000 ft AGL or greater.

A departure out of KBUR’s Runway 15 using the ELMOO EIGHT procedure is possible at a dispatch weight of $W = 117{,}800$ lbm, as per Figure 35.

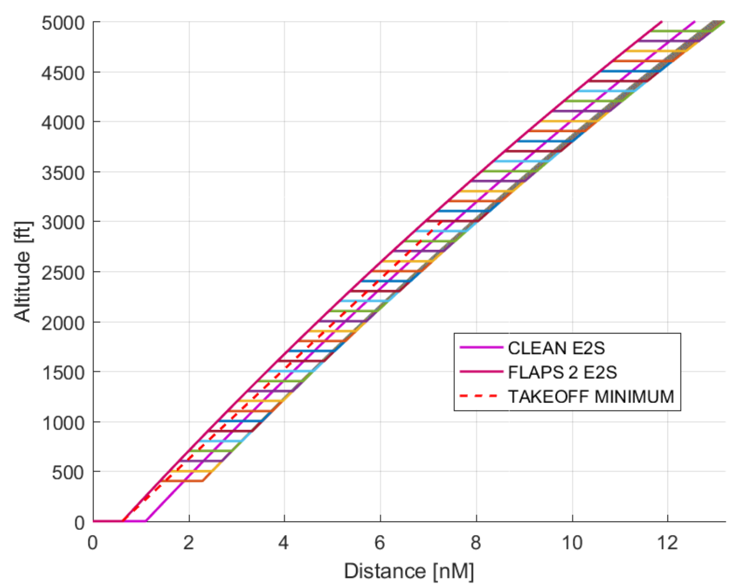

Figure 35. Comparison of KBUR – ELMOO EIGHT (Runway 15) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 117{,}800$ lbm.

For this DP, a four-segment profile must hold the flap retract to an altitude of 3,000 ft AGL or greater, otherwise the third segment will transgress the minimum climb slope.

Alternatively, at the pilot's convenience, a "Flaps 2" E2S climb may be utilized, as that technique also provides enough climb performance to overcome the takeoff minimums of this departure. Data inspection reveals that Runway 33, which has the most rigorous set of takeoff minimums, cannot be performed at a reduced weight of $W = 112{,}800$ lbm; hence, another slight reduction to weight would be necessary, albeit with the other runway choices available for the OEI DP, this is inadvisable.

Effects of Wind on Takeoff Performance

Evidently, the above analyses reveal that the "Flaps 2" E2S technique is not so much an obligation to make an OEI departure procedure possible; in fact, it is more of a "pilot's convenience" than anything. However, those simulations were all based on scenarios which had calm winds; how would the presence of a 10 knot headwind or tailwind affect the A320's flight profiles? To solve this, the same procedure utilized in the above section was repeated, but these simulations were reproduced in the presence of either a 10 knot headwind or 10 knot tailwind. Additionally, in the interest of brevity, only the SNOBL FIVE dispatch out of KPHX's Runway 8 will be evaluated.

An initial look over the results confirms that, indeed, the presence of a wind slightly alters the obstacle clearance performance of the A320; this comes as no surprise for the presence of a headwind is expected to increase the effective airspeed of the aircraft, whereas the presence of a tailwind is expected to reduce the effective airspeed of the aircraft. As was discussed previously, altering the vehicle's airspeed can either worsen or benefit its performance, for there exists an optimal speed which maximizes a performance parameter such as climb gradient.

Beginning the inspection at a dispatch weight of $W = 172{,}800$ lbm in the presence of a constant 10 knot headwind, Figure 36 represents the takeoff minimums of Runway 8 compared to the A320's flight path.

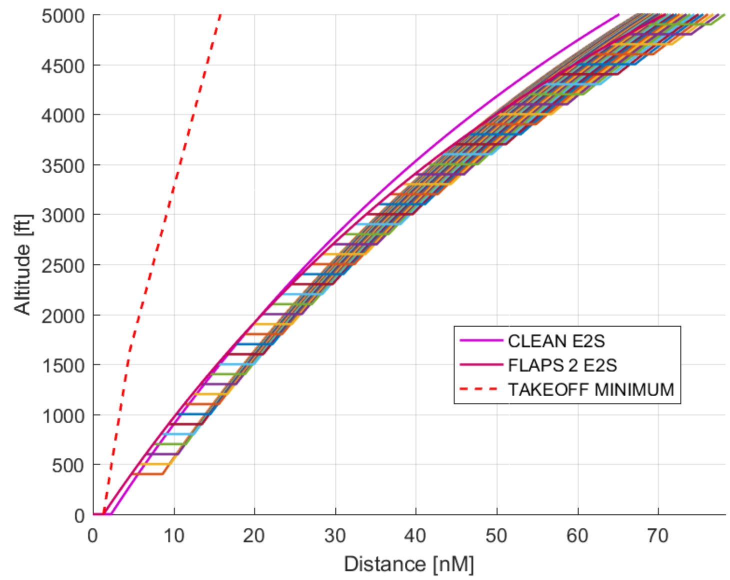

Figure 36. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 172{,}800$ lbm, 10 Knot Headwind.

Unsurprisingly, even under the presence of a 10 knot headwind, the aircraft is vastly incapable of abiding by the takeoff minimums for this departure procedure. Comparing this with Figure 24, which presented this case in a calm winds condition, it can be observed that under the presence of a 10 knot headwind, obstacle clearance performance has increased slightly, albeit not so much to make an appreciable difference. For example, if using a "Flaps 2" E2S takeoff in the presence of a constant 10 knot headwind, at 10 nM downwind the aircraft is at an altitude of 965 ft AGL, and 3,079 ft AGL when

35 nM downwind from the runway.[57] Note that, under the no wind condition, at 10 nM and 35 nM away from the runway, the A320 attains an altitude of 890 ft AGL and 2,917 ft AGL, respectively. Ergo, in the presence of a 10 knot headwind at this weight setting, the aircraft gains an additional 75 ft in altitude when 10 nM downwind of the runway, and 162 ft when 35 nM downwind.

Now applying a 10 knot tailwind to the simulation instead, Figure 37 displays how the A320's flight profiles are affected under such an operating condition.

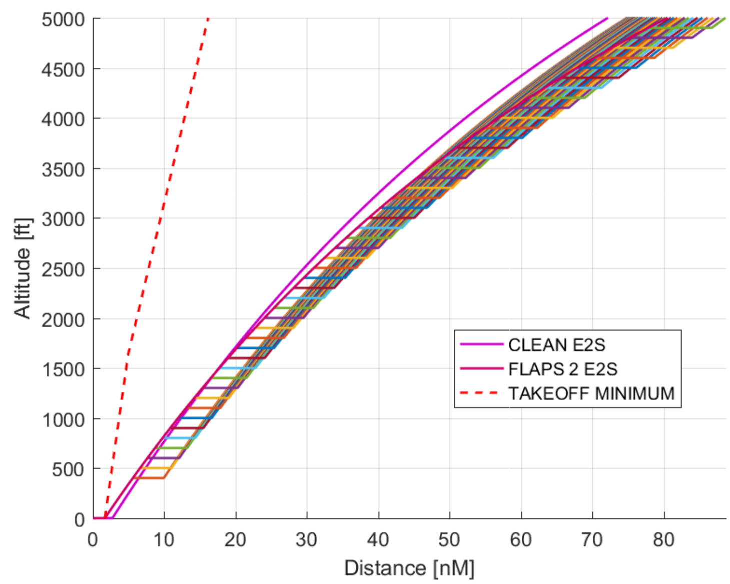

Figure 37. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 172{,}800$ lbm, 10 Knot Tailwind.

When compared to the calm winds case presented in Figure 24, it can be observed that the obstacle clearance performance of the A320 was slightly reduced, albeit it was not the sole driving factor here which made the A320 non-compliant with the minimum climb slope; the fact of the matter is that commercial aircraft which dispatch at the maximum

[57] Unless otherwise indicated, the "Flaps 2" E2S flight profile will be used as points of reference.

takeoff weight will unlikely have enough climb performance in the engine inoperative condition to successfully complete a departure procedure which imposes minimums on climb gradient greater than those dictated by Federal Regulations – even under the influence of a favorable 10 knot headwind. The numbers behind Figure 37 reveal that when 10 nM and 35 nM downwind of the runway, the A320 will attain an altitude of 822 ft AGL and 2,769 ft AGL, respectively, in the presence of a 10 knot tailwind. Comparing this to the no wind condition, it can be noted that there is a loss of approximately 68 ft and 148 ft at 10 nM and 35 nM downwind of the liftoff point, respectively, when the aircraft is subject to a constant 10 knot tailwind.

Indeed, while the presence of a roughly constant headwind or tailwind can affect an aircraft's obstacle clearance performance, it appears to have little effect at the heavy weight case. Figure 38 represents a comparison of the takeoff minimums against the A320's flight profiles under a constant 10 knot headwind at $W = 132{,}800$ lbm.

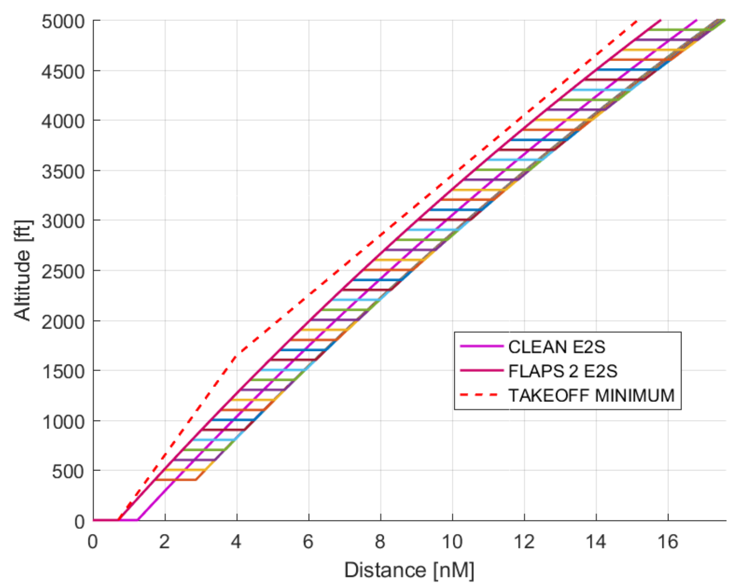

Figure 38. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 132{,}800$ lbm, 10 Knot Headwind.

As expected, when compared to the companion Figure 30, which gave the A320's performance at this weight in a no winds condition, there is a noticeable increase in obstacle clearance performance thanks to the 10 knot headwind; for example, the A320 attains an altitude of 3,305 ft AGL using "Flaps 2" E2S when 10 nM downwind of the runway, fully completing the climb to 5,000 ft AGL at a horizontal distance of approximately 15.82 nM. In the no winds condition, the aircraft fully completed the same climb in a horizontal distance of 17.11 nM, which confirms that, indeed, the presence of a 10 knot headwind benefits obstacle clearance performance. Additionally, when subject to no winds, the A320 attains an altitude of approximately 3,055 ft AGL when 10 nM downwind of the runway. This correlates to an additional 250 ft of obstacle clearance capability at the 10 nM mark when the A320 is subject to a 10 knot headwind at a dispatch weight of $W = 132{,}800$ lbm; this gain in altitude is much greater than what was observed than when the A320 was subject to the same conditions but at a heavier dispatch weight of $W = 172{,}800$ lbm. This points to the possibility that as the aircraft flies lighter, the contribution/detriment of winds to overall obstacle clearance performance is greater.

Examining how the A320 reacts to a 10 knot tailwind at $W = 132{,}800$ lbm, Figure 39 unsurprisingly implies the A320 is incapable of performing the OEI DP.

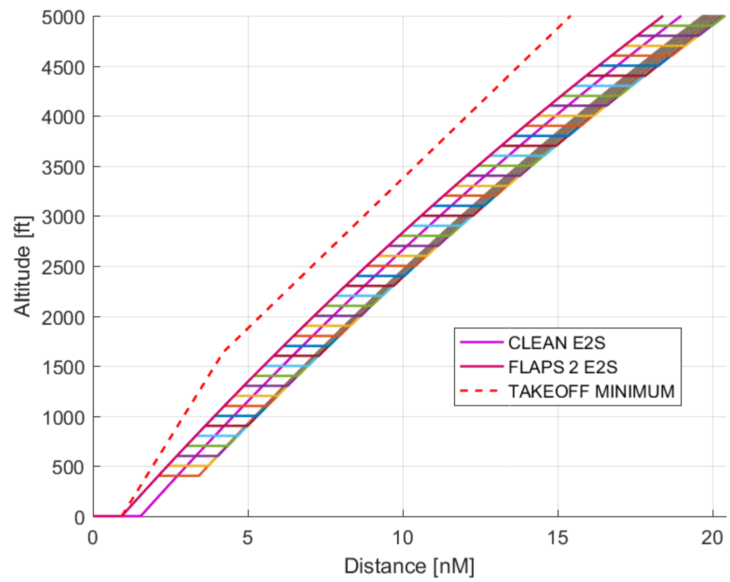

Figure 39. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 132{,}800$ lbm, 10 Knot Tailwind.

Verifying if the aircraft was more influenced by wind effects at this lighter dispatch weight, it can be noted from Figure 39 that the A320 resides at an altitude of 2,837 ft AGL when 10 nM away from the liftoff point on the runway. Recalling that the no winds condition presented in Figure 30 found the A320 at an altitude of 3,055 ft AGL at the same point, this implies that dispatching under a 10 knot tailwind results in a 218 ft loss in appreciable altitude. At a departure weight of $W = 172{,}800$ lbm, the A320 only lost 68 ft of altitude when subject to a 10 knot tailwind; it is seen here that at the lighter dispatch weight, even altitude losses due to tailwinds are higher in magnitude, ergo the wind detriment on obstacle clearance performance is also more contributive at lighter weights.

Evaluating the final set of the series, Figure 40 represents a lightweight dispatch at $W = 112{,}800$ lbm under the presence of a 10 knot headwind.

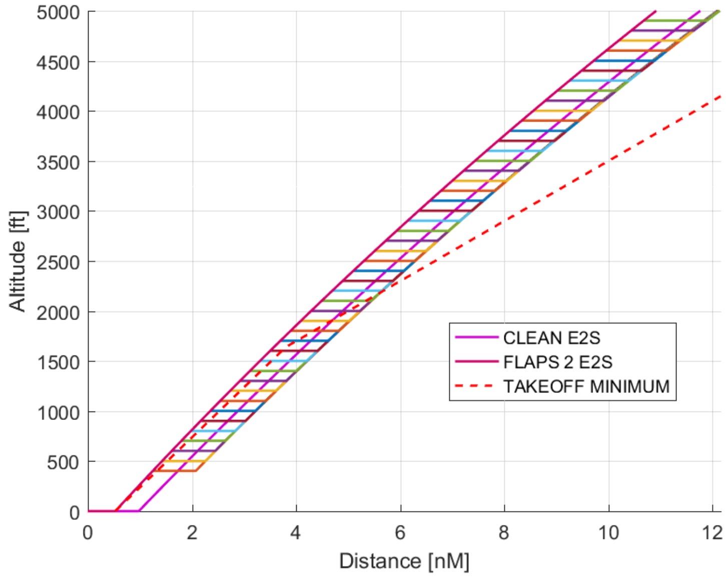

Figure 40. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 117{,}800$ lbm, 10 Knot Headwind.

As expected, there is some additional obstacle clearance performance gained thanks to the contribution of the 10 knot headwind. Comparing to the companion Figure 33, which gives this case in the no winds condition, the A320 is at an altitude of 4,270 ft AGL when 10 nM downwind of the runway, fully completing the climb to 5,000 ft AGL in approximately 11.89 nM. In the presence of a 10 knot headwind, the aircraft completes the climb in a horizontal distance of 10.92 nM, affirming that, indeed, the climb slope has increased thanks to the wind contribution. Additionally, at the 10 nM point, the aircraft is at an altitude of approximately 4,619 ft AGL when flying into a 10 knot headwind. Between these two cases, there is an appreciable altitude increase of 349 ft. Compared to the altitude gains of 75 ft and 250 ft at weights of $W = 172{,}800$ lbm and $W = 132{,}800$ lbm, it is abundantly evident now that the contribution of headwinds to gaining additional obstacle clearance performance becomes stronger the lighter the aircraft flies.

Figure 41 provides the previous dispatch, but simulated under a 10 knot tailwind.

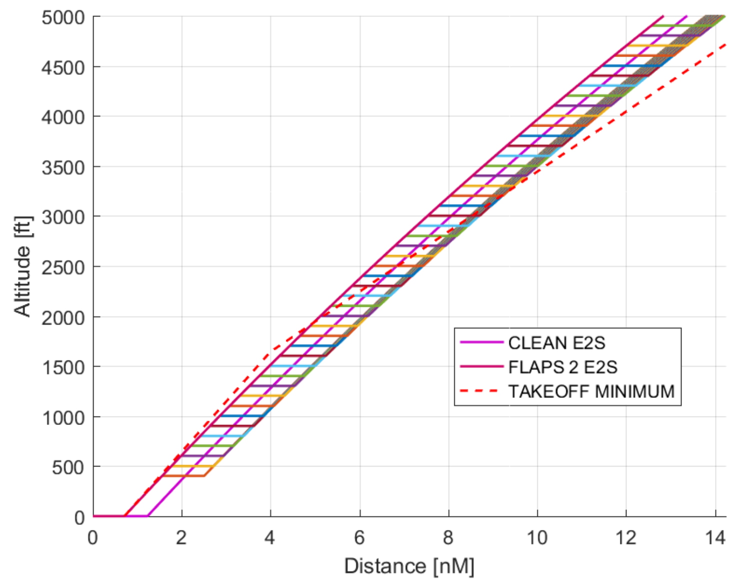

Figure 41. Comparison of KPHX – SNOBL FIVE (Runway 8) Takeoff Minimums and A320 OEI Net Takeoff Performance at $W = 117{,}800$ lbm, 10 Knot Tailwind.

Surprisingly, here it can be seen that the A320 is now non-compliant with the takeoff minimums imposed by the SNOBL FIVE DP; this is quite unlike the no winds condition presented in Figure 33, in which it was found the A320 was compliant with the minimum climb slope for a successful OEI DP. This gives light to the fact that it is very well possible—especially for lighter aircraft—that a tailwind detriment could reduce an aircraft's climb performance below the recommendation set forth by the takeoff minimums; this is especially problematic for engine failure scenarios, as safety can find itself compromised in strong tailwinds that heavily reduce the aircraft's climb performance. Pulling data from this figure, it can be noted that at 10 nM away from the point of liftoff, the A320 is at 3,962 ft AGL in the "Flaps 2" E2S climb, with 12.85 nM of ground distance required to complete the climb to 5,000 ft AGL. This required ground distance is markedly longer than the nominal 11.89 nM in a no winds condition, meaning the required ground distance has increased by 0.96 nM in the presence of a 10 knot tailwind due to a reduced climb slope. Additionally, when compared to the no winds case, an altitude loss of 308 ft is noted. When compared to the altitude losses of 68 ft and 218 ft for dispatch weights of $W = 172{,}800$ lbm and $W = 132{,}800$ lbm, respectively, again the evidence suggests that the effect of wind on the resulting flight profile, whether that effect be beneficial or detrimental, is much stronger when the aircraft flies lighter.

CHAPTER 5

DISCUSSION

Importance of Maximum Climb Gradient

The results gathered from the *Optimal Piloting Procedure for Maximum Obstacle Clearance* section with respect to the feasibility of idealized cue speeds were curious at best. Since the climb gradient performance parameter of an aircraft is analogous to climb efficiency, one would expect that by maximizing climb gradient, the aircraft would achieve maximized climb efficiency.

Indeed, while the aircraft did achieve maximized efficiency in many cases thanks to the implementation of idealized cue speeds, it was inappropriate to assume that these cue speeds would universally benefit obstacle clearance performance. For example, at a dispatch weight of $W = 132{,}800$ lbm, Figure 18 represents various gross flight paths with moderate obstacle clearance performance using nominal book cue speeds; however, upon application of idealized cue speeds, Figure 19 demonstrates that the obstacle clearance performance of many flight profiles has decreased. Similarly, between Figures 16 and 17, which represents gross flight paths using nominal book and idealized cue speeds, respectively, at a dispatch weight of $W = 172{,}800$ lbm, it was found that the application of idealized cue speeds degraded the obstacle clearance performance of many profiles; this resulted in an unreasonably long third segment acceleration which, ironically, likely resulted in a fuel burn which is worse due to use of speeds which were originally meant to maximize climb efficiency.

While it may seem inadvisable to utilize speeds which maximize climb gradient performance, this is exactly what Airbus does when calculating "Green Dot" V_{FTO} speeds for their aircraft so that fuel consumption is minimized. It should be noted that Airbus distinctly calls out a V_4, a fourth segment climb speed, which is entirely separate from V_{FTO}; some aircraft designers like to say $V_4 = V_{FTO}$—and indeed, that is exactly what was attempted in this study by implementing "idealized" cue speeds for fourth segment climb—but given the results in Figure 17, it seems to only be reasonable in cases where the aircraft is relatively light so that the third segment acceleration remains relatively short.[58] But even then, only a handful of flight profiles benefit in obstacle clearance performance from such an implementation of "idealized" cue speeds – notedly those which schedule for an early flap retraction when using a four-segment climb profile to maximize clean wing climb time. However, further simulations revealed that these augmented cue speeds made no appreciable increase to obstacle clearance performance insofar that it enabled an OEI departure procedure to abide by the takeoff minimums.

At the beginning of this research, it was debated whether the "idealized" cue speeds which were to be implemented into the simulations should be based from maximizing the climb gradient or maximizing climb rate with respect to constant indicated airspeed – after all, there does not exist one speed which maximizes both parameters under an engine inoperative scenario. Since it was learned that Airbus's Green Dot speeds correlated with those that maximize the climb gradient parameter, it

[58] In fact, V_4 typically is not explicitly defined in most flight manuals or training guides, thus leading to the assumption that $V_4 = V_{FTO}$. One notable exception to this observation is the HS-125 series Hawker 900XP, whose AFM calls out a V_4 which is different from V_{FTO}.

was incorrectly assumed that maximized climb gradient must be the parameter which could provide appreciable improvements to obstacle clearance when applied to both second and fourth segment climb. However, after chasing maximized climb gradient and simulating flyouts at speeds which achieve just that, the simulations suggest that this was *not* the parameter which should have been studied. Rather, for expeditiously completing the takeoff path with additional obstacle clearance capability, it is theorized that perhaps maximizing the climb rate with respect to constant indicated airspeed is the way to go; while this may result in a more inefficient use of fuel (as the speed which maximizes climb rate is often greater than that which maximizes climb efficiency) and a higher TODR penalty, implementation of such speeds can potentially serve as a solution to the obstacle clearance problem when combined with procedures such as extended second segment climb. Further research is necessary to validate this theory.

Implications of Extended Second Segment Climb

The initial results gathered from the *Optimal Piloting Procedure for Maximum Obstacle Clearance* section very well indicated that the A320 could produce additional obstacle clearance performance through a simple operational change, with no need for expensive modifications to the airframe or powerplant. For heavier dispatches, the data implies that the optimal choice of piloting procedure depends on the distance of the obstacles from the runway – there is not one profile which is the “jack of all trades”. With obstacles that are within proximity to the runway, a “Flaps 2” E2S is advisable as that procedure excels at overcoming these close-range obstacles; conversely, a clean wing E2S climb is best-suited for long-range obstacles which need be avoided. If TODR precludes the use of a clean wing E2S climb, a net flight path analysis implies that viable alternatives include a “Flaps 2” E2S or four-segment profile with flap retract at 400 ft AGL, the first providing reasonable mid-range obstacle clearance performance and the latter providing better long-range obstacle clearance. The definitions of close- and long-range depend on the location where these two profiles intersect – this transition point is not easy to calculate by hand as it appears to be a function of profile cue speed. For the lightweight dispatches, the data suggests that a “Flaps 2” extended second segment climb is very much suitable for both close- and long-range obstacles. In other words, there exists no profile in which “one size fits all” – the optimal profile choice is dependent upon the dispatch weight of the aircraft and the rigor of the takeoff minimums.

While the savings in flight time and fuel burn were not the focus of the study, the trends observed of these two parameters are at least worthy of mention. Of all the simulated dispatches, the general trend appears to be that a clean wing E2S profile provides minimum climb time and fuel burn, with profiles implementing an early cleanup on the flaps finding minimal to moderate flight time and fuel burn; those which clean up late on the flaps end up with mediocre to poor climb time and fuel burn efficiency. Curiously, the “Flaps 2” extended second segment profile typically found itself somewhere in the middle of this spectrum with respect to climb time and fuel burn efficiency, likely due to bypassing the “wasteful” third segment acceleration.

While the results from the previous section held that the extended second segment climb technique showed some promise, data coming from the *Feasibility of Extended Second Segment Climb for Departure Procedures* section gave a serious reality check:

how commercial aircraft will almost always *never* be capable of fully completing a challenging departure procedure under the engine inoperative condition. After a significant amount of trade studies, it was revealed that only after the A320 shedded a little more than half of its usable weight could it be able to abide by some rigorous takeoff minimums; in this case, two feasible options are available to the pilot: "Flaps 2" extended second segment or a traditional four-segment profile.[59] For example, in Figure 32, acceptable piloting techniques which satisfy the takeoff minimums of KBUR's ELMOO EIGHT on Runway 26 when dispatching at $W = 132{,}800$ lbm are either a "Flaps 2" extended second segment climb or a four-segment profile which holds the flap retract until 2,600 ft AGL. Similarly, the same DP can be satisfied on Runway 8 using either a "Flaps 2" extended second climb or a four-segment profile which holds the flap retract until 800 ft AGL. Figure 34, which represents a dispatch out of KLGA using the JUTES THREE departure procedure on Runway 22, suggests that a "Flaps 2" E2S climb or a four-segment profile which schedules a flap retract at 5,000 ft AGL are equally viable solutions.

If the two profiles both provide enough obstacle clearance performance to overcome a set of rigorous takeoff minimums, then what edge does the extended second segment technique have over a four-segment takeoff procedure? After all, the discussion up to this point seems to suggests that these two are the one and the same. However, this is most certainly not the case. While a four-segment takeoff profile is "scheduled" in the

[59] The "clean wing" extended second segment climb is expected be precluded due to an insatiable TODR, despite how overly pessimistic are the TODR values acquired during this study.

fact that second segment climb ceases at a predefined altitude set forth in a flight plan, the extended second segment climb is fluid in the fact that the climb ceases as soon as the aircraft overflies all obstacles. The only case in which these two piloting techniques are the one and the same is if the four-segment takeoff profile schedules the flap retract precisely at the altitude at which all obstacles are passed. However, variations in pilot reaction time, atmospheric conditions (such as wind), and subsequent aircraft performance can make predicting this altitude at which all obstacles are successfully passed hard to do. Extended second segment climb accounts for these variations by simply worrying about continuing the climb until all obstacles are overcome, thus the flap retract can occur at any altitude – that is what gives the "fluid" behavior to this flight profile. Ergo, it is quite clear that the extended second segment climb does, in fact, have a clear advantage over a four-segment takeoff profile. While a four-segment takeoff profile can ensure obstacle clearance by scheduling third segment flap retraction at a high, "safe" altitude, a second segment climb prolonged past all problem obstacles in order to meet the minimum "safe" altitude is wasteful, as that time can be spent accelerating in order to execute the much more efficient fourth segment climb. The extended second segment climb here has the edge here by performing the third segment acceleration as soon as all obstacles are overcome.

Speaking of atmospheric conditions, when studying the effects of wind on the flight profile, the results were overwhelmingly obvious: flight conducted in the presence of a 10 knot headwind will result in additional obstacle clearance performance, whereas a reduction in obstacle clearance performance is noted when flying in the presence of a 10 knot tailwind. Figure 42 represents how climb rate performance improves when the aircraft is subject to a 10 knot headwind (green dashed line) or decrements when subject to a 10 knot tailwind (red dashed line).

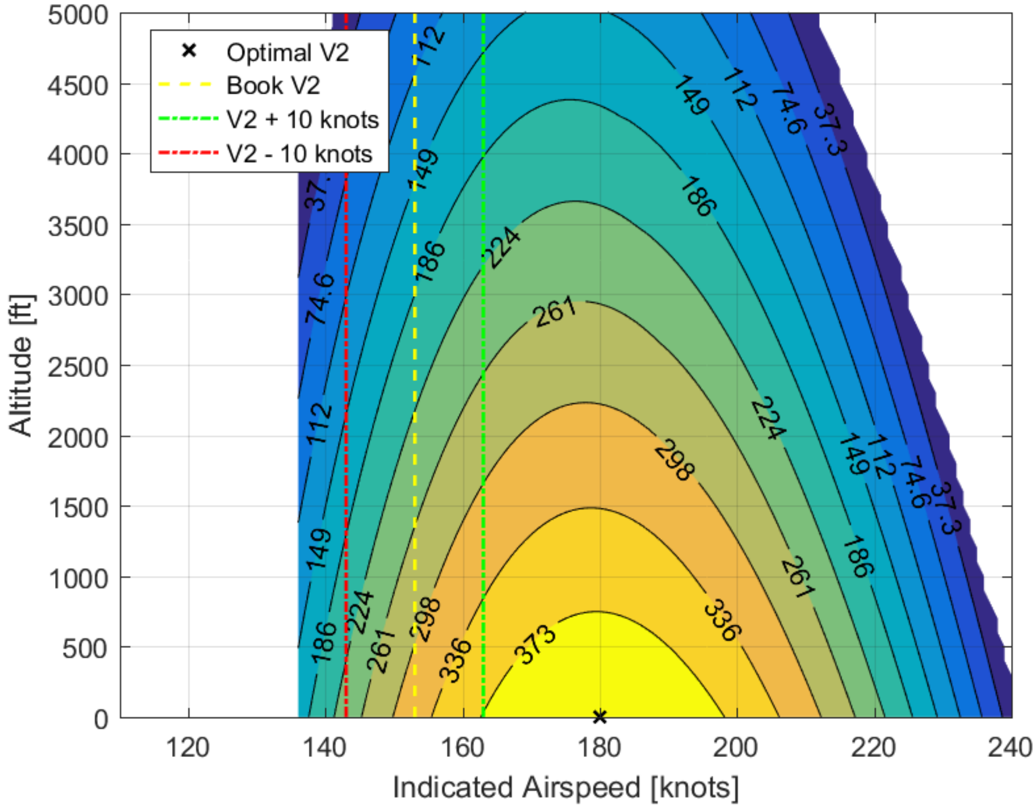

Figure 42. Contour Plot of A320 Climb Rate w/OEI at $W = 172{,}800$ lbm. Climb rate performance is with respect to a constant indicated airspeed climb. Flaps and trim drag included. Best performance attained at sea level, 180 KIAS.

Of course, the effect of wind on the A320's performance increase or detriment become much more obvious when the aircraft flies lighter. This trend makes sense, based on behavior which could be observed in Figure 14, which contrasts the A320's nominal V_2 speeds against those which maximize climb gradient performance. At heavier dispatch weights, a higher overspeed is required to attain best performance; conversely, at lighter weights, a smaller overspeed is required to attain best performance. This is why a 10 knot headwind—which adds to the aircraft's effective airspeed—seems to have little beneficial effect at heavier dispatch weights, whereas the effect is much more pronounced at lighter dispatch weights. As the aircraft's climb performance is much more sensitive to speed changes at lighter weights, this also explains why a constant tailwind much more negatively affects the aircraft when flying light.

Teaching Extended Second Segment Climb

As extended second segment climb with flaps deployed shows an appreciable increase to obstacle clearance performance compared to a traditional four-segment dispatch, some may find interest in teaching the extended second segment climb technique to pilots. Teaching, however, is a practice much deeper than lecturing a group of students or demonstrating an action. To develop an instructional plan that will "stick" when applied to students, it is important to understand two core parts of the learning process: (1) information processing and (2) instructional alignment.

Information processing describes how people handle external stimuli and process the subsequent information. There is a total of five senses from which a person may focus on to draw information from the environment, with three of the most common ones being sound, sight, and touch. When the individual realizes that one of their senses is in the process of drawing information, he/she may choose to focus on it; focusing on the sense enables the person to commit the drawn information to *short term memory* – otherwise, ignoring the sense means that information will not be committed and is lost entirely. Since short term memory only lasts a finite amount of time, information committed to this region will be lost unless a *meaningful learning strategy* is implemented. A meaningful learning strategy is one which makes the teaching experience, for example, (1) relevant, (2) personal, (3) contextual, and/or (4) meaningful to the student.

Instructional alignment is simply aligning the instruction with respect to *learning objectives*. A well-written learning objective includes the level of mastery expected of the student when the learning process is complete – something which is measurable. Some well-written learning objectives appear as, for example: "the learner will describe the four segments of the takeoff profile", or "the learner will calculate an aircraft's net flight profile". Depending on the expected level of mastery, an appropriate verb is required. Bloom's Taxonomy classifies mastery levels into six ascending categories: (1) remember, (2) understand, (3) apply, (4) analyze, (5) evaluate, and (6) create.[60] Bloom's verb charts aid the educator in picking the correct key verb to incorporate into a well-written learning objective; for example, "describe" falls under the understanding category, whereas "calculate" resides in the higher-level apply category.[61] A well-written learning objective helps orient the student to what is expected of him/her after the instruction is complete.

An effective teaching plan takes the form of *Gagné's Nine Events of Instruction*, which incorporates provisions for both instructional alignment and information

[60] Shabatura, 2013.

[61] Ibid.

processing.[62] Of the nine steps, there are three distinct categories: (1) pre-instruction, (2) instruction, and (3) post-instruction.

Pre-instruction begins with gaining the attention of the learner; this step is important so that the learner pays attention and can begin moving information to short-term memory through one or more of their senses. After this, the learner is informed of the well-written learning objective; this prepares the learner with informing him/her of the learning expectations so that information is better received. For topics which build upon prior skills or information, stimulating recall of prior learning assists the learner in remembering what was learned previously; not only does this strengthen the previously-learned skill, but it also better prepares the learner to receive the information.[63]

Instruction entails of presenting the learner with the new material and stressing key elements of it. Following this, guidance should be provided to the learner in the form of examples and explanation; this is where relevant tie-ins, such as providing contextual or personal cues, aids in committal of the information to learner's long-term memory. Providing an opportunity for the learners to perform by practicing the use or application of the new information is highly recommended as this aids in information retention. Any incorrect usage or application of the information should be rectified with immediate feedback from the instructor which is specific, corrective, and positive in nature, for unlearning incorrect information is difficult and time-consuming.[64]

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[62] Gagné's 9 Events of Instruction, 2016.

[63] Ibid.

[64] Ibid.

Post-instruction requires the assessment of learner performance; it is here where it should be determined if the learner's acquisition and application of knowledge abides by the learning objective – hence why it is important to have a well-written learning objective which is measurable. Here, if the learning objective is determined to not be met, then further guidance and instruction for the learner is necessary. Otherwise, if the learner demonstrates that he/she has completed the learning outcome, then information retention and transfer can be enhanced by applying the newfound knowledge to a novel problem.[65]

With respect to teaching experienced pilots how to execute an extended second segment climb, it is advisable that the instruction follows the guidelines set forth by Gagné. The following is an outline of an example learning plan for extended second segment which follows those nine events of instruction, with the successful learner expected to *demonstrate* an extended second segment takeoff profile:

I. Pre-Instruction

  A. Gaining Attention

    1. Show the learner a video of a "dangerous" takeoff from an airport which has close-in obstacles or terrain (Paro International Airport, for example)
    2. Remind the learner that obstacle clearance is an integral part of the takeoff procedure
    3. There exists a method which optimizes obstacle clearance performance, while disregarding the need to abide by a "scheduled" flap retraction altitude

[65] Ibid.

B. Informing the Learner of the Objective

1. Tell the learner that he/she is expected to *demonstrate* an extended second segment takeoff profile at the end of the lesson.

C. Simulating Recall of Prior Learning

1. Remind the student of his/her prior training on takeoff procedure

   (1) Elevate throttles to full when cleared for takeoff

   (2) Pay attention to indicated airspeed

   (3) Four-segments of the takeoff flight path: first and second segment climb, third segment acceleration, and fourth segment climb

2. Remind student of important cue speeds: V_1, V_R, V_2, V_{FUSS}, V_4

II. Instruction

A. Presenting the Content

1. Inform the learner that an extended second segment climb is like a traditional four-segment takeoff procedure, except it delays third segment acceleration and fourth segment climb

2. Inform the learner that flaps are deployed for the whole climb, and only retracted at an altitude where all obstacles are cleared when V_{FUSS} is attained

B. Providing Guidance for the Learner

1. Provide a demonstration/example of an extended second segment takeoff for the learner, verbalizing the steps taken to perform the procedure

C. Eliciting Performance (Practice)

1. Allow the learner to apply the new knowledge by practicing an extended second segment climb takeoff

D. Providing Immediate Feedback

1. Highlight the positives of student performance, and suggest areas for improvement

III. Post-Instruction

A. Assessing Performance

1. Determine if the learner met the learning objective

(1) If the learner has successfully demonstrated an extended second segment climb takeoff, then the learning outcome is achieved.

(2) If the learner did not demonstrate a successful extended second segment climb takeoff, then the learning outcome is not met; the learner should be provided with additional practice and instruction until the learning objective is met.

B. Enhancing Information Retention and Transfer

1. Allow the learner to apply the new skill to novel scenarios. For example, the learner should try executing an extended second segment takeoff:

(1) from an alternative airport

(2) under different conditions (time of day, winds, weather)

Of course, this outline is just a rough example teaching plan. The instructor is free to present their own teaching plan in the way he/she deems fit, though it is highly recommended that it incorporates measurable learning objectives and follows the steps set forth by Gagné for proven improved student learning and training transfer.

CHAPTER 6

CONCLUSION

The obstacle clearance problem is not a rudimentary "academic exercise" – it is a real-world problem which still needs to be addressed. While the FAA has enforced climb gradient minimums by Federal Regulations, this is nothing more than an absolute minimum check on safety to ensure it is not precluded in the event of an engine failure.[66] With respect to the dispatch problem, standard instrument departure procedures already impose their own expectations on climb gradient minimums, often more than those set forth by Federal Regulations, which must be followed for ensured obstacle avoidance. While this can be seen as an additional safety check, Masson, Bain, and Page have correctly noted that these takeoff minimums appear to be published with the AEO case in mind – there exists no set of departure procedures which are specifically tailored to the OEI case.[67] Was this a purposeful action to ensure that aircraft that experience an engine failure will always return to the departure airport for an emergency landing? As there exists no Federal Regulation which requires the critical engine inoperative aircraft to return to the departure airport posthaste, the likely answer is "no" – this is probably more of an oversight. Until performance engineers develop alternative flight paths which consider the engine inoperative case so aircraft can safely clear anticipated obstacles, dispatch personnel are forced to work within the confines of the current "AEO-only" takeoff minimums.

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[66] Takeoff flight path, 2017, and En route flight paths, 2017.

[67] Masson, Bain, & Page, 2015.

As this analysis has demonstrated, the current takeoff minimums are quite rigorous in nature; commercial aircraft which dispatch at heavier weights—while enjoying a strong climb gradient at AEO—may find themselves non-compliant with the climb slope minimums as soon as an engine fails. There currently only exists two solutions to this: (1) dispatch at a lighter weight which ensures the OEI climb gradient still exceeds those established by the takeoff minimums so the takeoff procedure need not be aborted, or (2) dispatch at the heavy weight and hope an engine does not fail during the takeoff procedure – else the pilot is obliged to limp the afflicted aircraft back to the departure airport due to incompliance with the takeoff minimums.

This study examined if there existed a more optimal procedure—or set of procedures—which provides additional obstacle clearance capability without the need for expensive powerplant or airframe retrofit. Indeed, after a thorough analysis of the possible flight paths a pilot could execute to maximize obstacle clearance capability, it is abundantly clear that the traditional four-segment procedure with flap retract scheduled at 400 ft AGL is no “one size fits all” approach. The “optimal” flight profile depends on the placement of obstacles relative to the liftoff point on the runway. The analysis strongly suggested that a “Flaps 2” E2S profile can provide improved obstacle clearance capability for close- to mid-range obstacles. While a clean wing E2S profile can potentially provide improved long-range obstacle clearance performance, it is quite likely that TODR will preclude execution of this profile; in this case, the standard four-segment flight profile with flap retract at 400 ft AGL can provide second-best long-range obstacle clearance performance. It should be noted, however, that these trends are quite generalized for our A320-esque model; when applying extended second segment to real-world aircraft, a separate, careful takeoff operations analysis should take place to ensure the trends observed here also apply to real-world commercial aircraft like this.

While it was thought that pursuing a combination of cue speeds optimized for maximized climb gradient and extended second segment would yield an appreciable improvement in obstacle clearance performance, this only appeared to hold true for the clean wing E2S flight profile, which would very likely be precluded by TODR anyway. It was also discussed previously that, perhaps, pursuing maximized climb gradient is *not* the way to go in the obstacle clearance problem; after all, maximized fuel burn efficiency means nothing when the aircraft is on an impact trajectory with a mountain because of reduced obstacle clearance performance. That said, further research should go into investigating whether the combination of extended second segment and cue speeds which maximize climb rate at a constant indicated airspeed would improve overall obstacle clearance performance.

The results of this research strongly suggest that there are practical advantages associated with the use of a flaps-out extended second segment climb in contrast to use of a four-segment takeoff profile. For example, this climb technique is “fluid” in the fact that it accounts for variances in piloting style, atmospheric conditions such as wind, and resulting aircraft performance in the fact that third segment acceleration only occurs which all obstacles are overcome. The four-segment takeoff profile, in comparison, is not so malleable as there exists a “scheduled” altitude at which flap retract must be executed. If this flap retract altitude is not high enough, the critical engine inoperative aircraft risks non-compliance with the takeoff minimums of a DP; while this can be easily rectified by scheduling this flap retract at a high, “safe” altitude, extra time spent executing second segment climb when all close-range obstacles are already overcome is wasteful, as fourth segment climb is much quicker and efficient with respect to flight time and fuel burn. A flaps-out extended second segment climb ensures optimum obstacle clearance and subsequent climb performance due to the fluidity of when third segment acceleration can be executed.

In the context of the obstacle clearance problem, extended second segment climb is not the “golden solution” which allows the OEI heavy dispatch to abide by rigorous takeoff minimums – at least not until a separate set of departure procedures are published with the engine-inoperative case in mind. However, this study has shown that, indeed, this technique does optimize a commercial aircraft’s obstacle clearance performance through simply delaying the third segment and following fourth segment climb, with no need for expensive airframe or powerplant retrofit. Considering these results, further research should go into the applicability of the extended second segment climb technique across various aircraft types—such as general aviation and light business jets—to better understand the implications of this novel idea.

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APPENDIX A

STANDARD INSTRUMENT DEPARTURE PROCEDURES

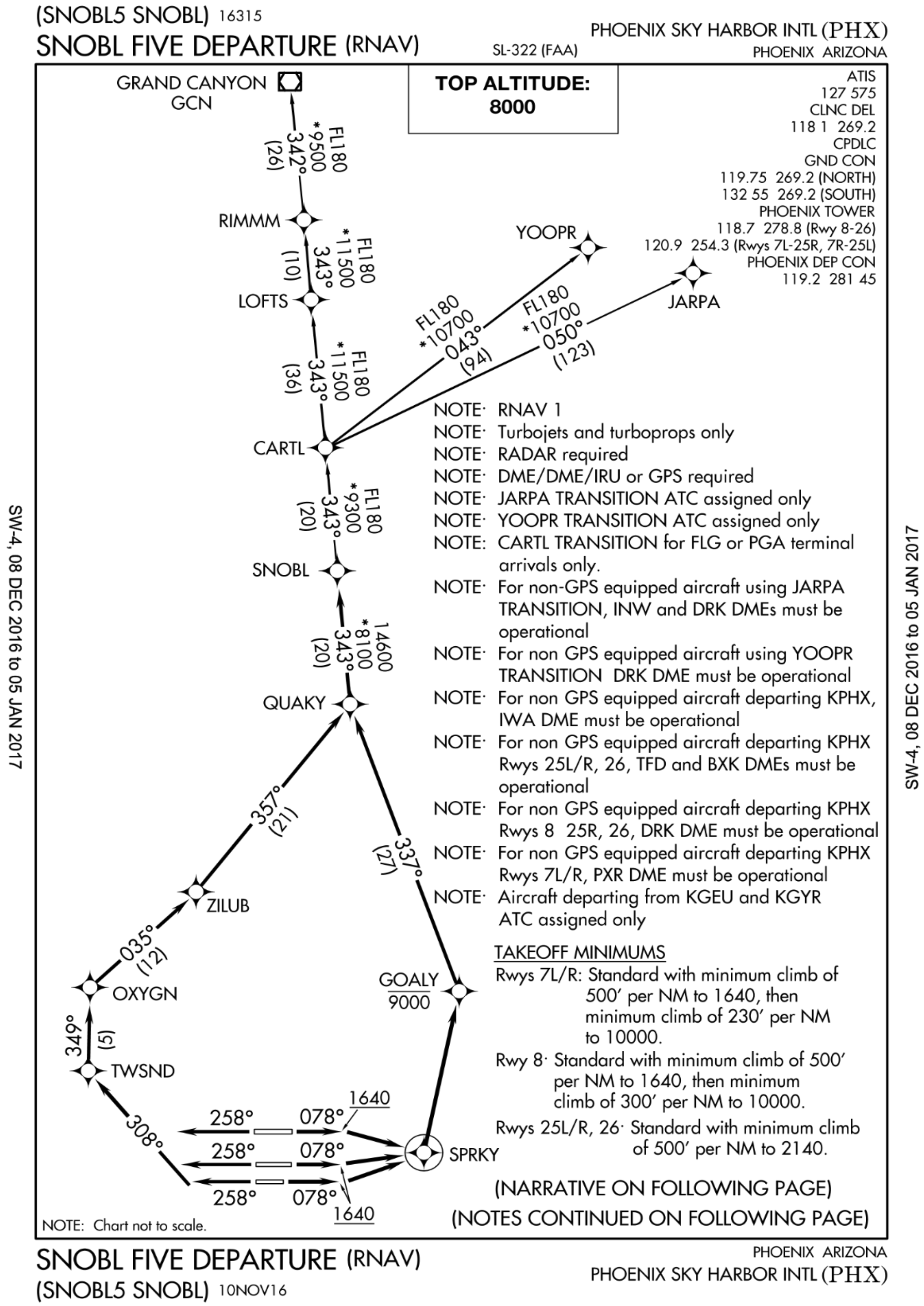
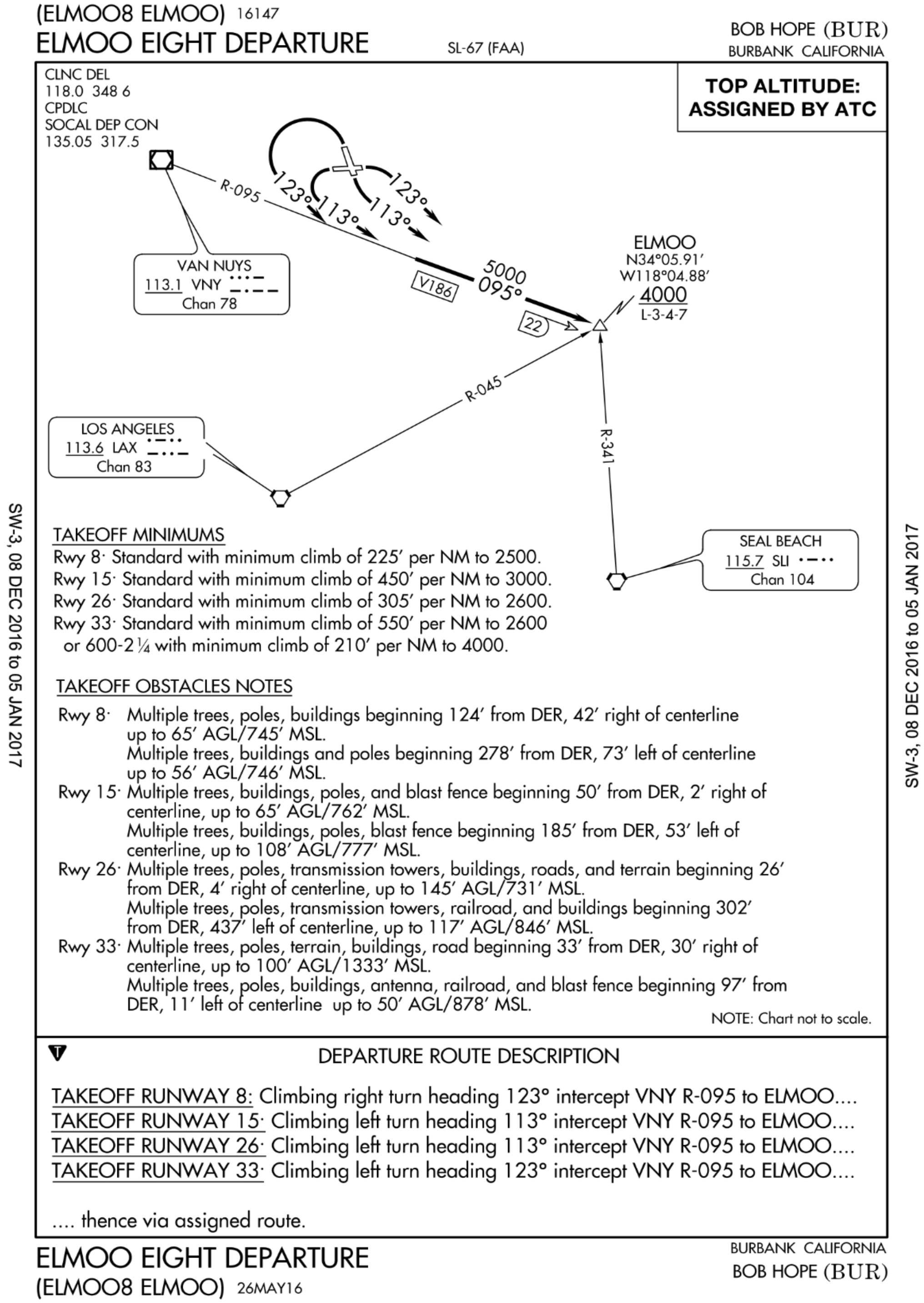


Figure A1. KPHX SNOBL FIVE Departure Procedure, Page One. Reproduced from AirNav: KPHX - Phoenix Sky Harbor International Airport, 2017. Copyright 2016 by the Federal Aviation Administration.


(ELMOO8 ELMOO) 16147

ELMOO EIGHT DEPARTURE SL-67 (FAA)

BOB HOPE (BUR)
BURBANK CALIFORNIA

CLNC DEL
118.0 348 6
CPDLC
SOCAL DEP CON
135.05 317.5

TOP ALTITUDE:
ASSIGNED BY ATC

TAKEOFF MINIMUMS
Rwy 8: Standard with minimum climb of 225′ per NM to 2500.
Rwy 15: Standard with minimum climb of 450′ per NM to 3000.
Rwy 26: Standard with minimum climb of 305′ per NM to 2600.
Rwy 33: Standard with minimum climb of 550′ per NM to 2600 or 600-2 ¼ with minimum climb of 210′ per NM to 4000.

TAKEOFF OBSTACLES NOTES
Rwy 8: Multiple trees, poles, buildings beginning 124′ from DER, 42′ right of centerline up to 65′ AGL/745′ MSL.
Multiple trees, buildings and poles beginning 278′ from DER, 73′ left of centerline up to 56′ AGL/746′ MSL.
Rwy 15: Multiple trees, buildings, poles, and blast fence beginning 50′ from DER, 2′ right of centerline, up to 65′ AGL/762′ MSL.
Multiple trees, buildings, poles, blast fence beginning 185′ from DER, 53′ left of centerline, up to 108′ AGL/777′ MSL.
Rwy 26: Multiple trees, poles, transmission towers, buildings, roads, and terrain beginning 26′ from DER, 4′ right of centerline, up to 145′ AGL/731′ MSL.
Multiple trees, poles, transmission towers, railroad, and buildings beginning 302′ from DER, 437′ left of centerline, up to 117′ AGL/846′ MSL.
Rwy 33: Multiple trees, poles, terrain, buildings, road beginning 33′ from DER, 30′ right of centerline, up to 100′ AGL/1333′ MSL.
Multiple trees, poles, buildings, antenna, railroad, and blast fence beginning 97′ from DER, 11′ left of centerline up to 50′ AGL/878′ MSL.

NOTE: Chart not to scale.

SW-3, 08 DEC 2016 to 05 JAN 2017

DEPARTURE ROUTE DESCRIPTION

TAKEOFF RUNWAY 8: Climbing right turn heading 123° intercept VNY R-095 to ELMOO....
TAKEOFF RUNWAY 15: Climbing left turn heading 113° intercept VNY R-095 to ELMOO....
TAKEOFF RUNWAY 26: Climbing left turn heading 113° intercept VNY R-095 to ELMOO....
TAKEOFF RUNWAY 33: Climbing left turn heading 123° intercept VNY R-095 to ELMOO....

.... thence via assigned route.

ELMOO EIGHT DEPARTURE
(ELMOO8 ELMOO) 26MAY16

BURBANK CALIFORNIA
BOB HOPE (BUR)

Figure A2. KBUR ELMOO EIGHT Departure Procedure, Page One. Reproduced from AirNav: KBUR - Bob Hope Airport, 2017. Copyright 2016 by the Federal Aviation Administration.

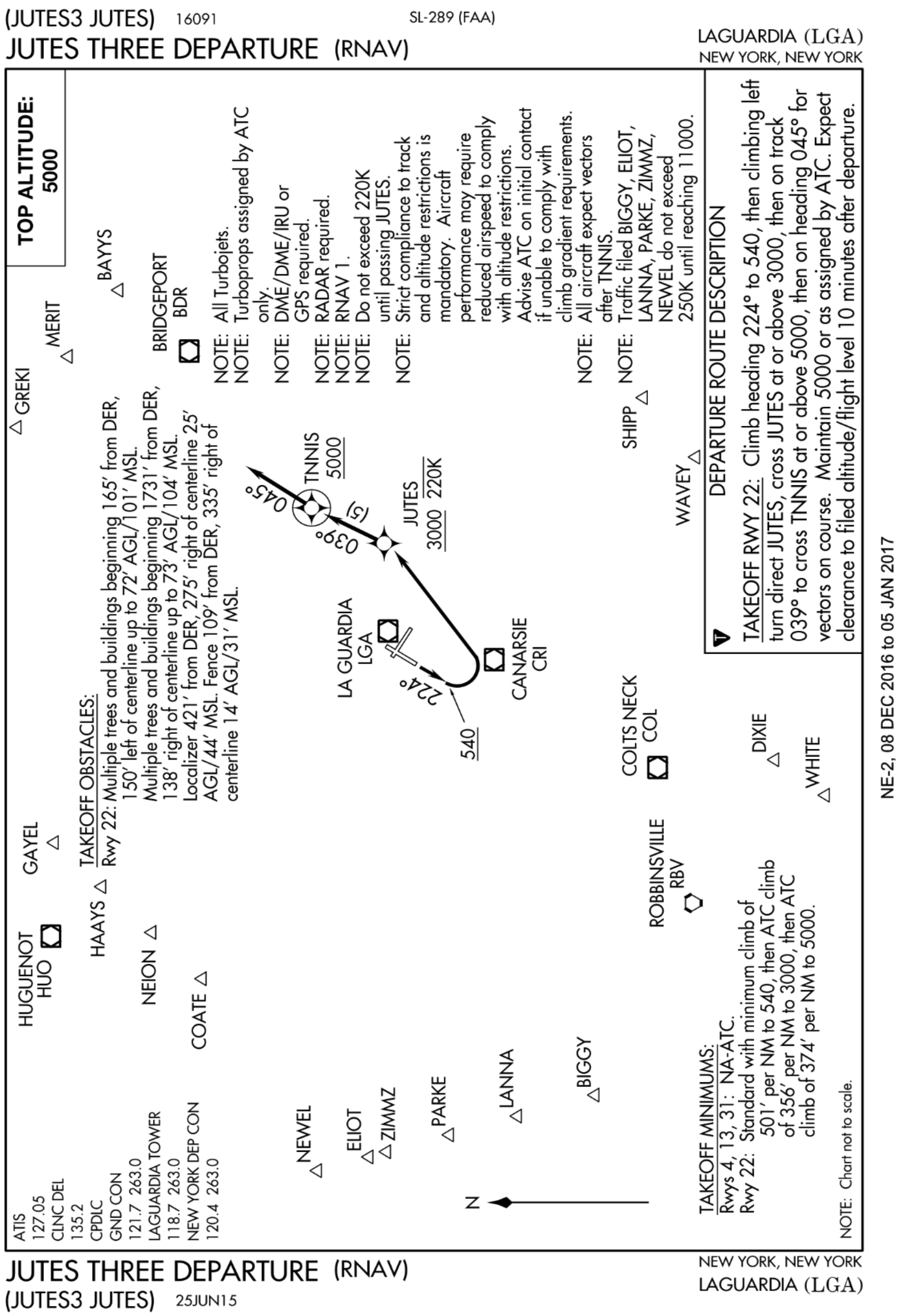


Figure A3. KGLA JUTES THREE Departure Procedure, Page One. Reproduced from AirNav: KGLA - LaGuardia Airport, 2017. Copyright 2015 by the Federal Aviation Administration.