AIAA SciTech Forum
8–12 January 2018, Kissimmee, Florida
2018 AIAA Aerospace Sciences Meeting

10.2514/6.2018-0285

Optimal Piloting Approaches For Obstacle Clearance Limited Standard Instrument Departures

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All commercial aircraft certified under Part 25 of the Code of Federal Regulations must meet or exceed minimum climb performance requirements. Per 14 CFR § 25.121, two-engine aircraft are expected to perform to a climb gradient of at least 2.4% for second segment and at least 1.2% for fourth segment under the critical engine inoperative scenario. While this regulation ensures continued flight safety in that the aircraft has some residual climb capability under this adverse condition, many standard instrument departure (SID) procedures require a climb gradient much greater than what 14 CFR § 25.121 dictates; this becomes problematic in the fact that an aircraft certified to the bare minimum becomes "climb gradient"-limited, precluding use of many SID procedures when using a traditional four-segmented dispatch profile. However, there exists a practical, inexpensive solution that relies solely on an operational change: the extended second segment dispatch profile. Prior literature demonstrates that using an extended second segment dispatch can increase an aircraft's climb gradient capability without any modification to the power plant or airframe. Here, we examine how useful this technique is for real-world dispatch problems. The results of this study indicate that while the extended second segment climb procedure is a viable alternative that makes challenging departures possible, it is more of a convenience to the pilot as opposed to a required maneuver, except for niche scenarios in which the aircraft must depart from airports characterized by high rate of climb minimums.

Nomenclature

a = speed of sound (nM/hr)
AGL = above ground level (ft)
α = angle of attack (°)
ALT = altitude (above sea level) (ft)
AR = wing aspect ratio
CFR = Code of Federal Regulations
C_D = coefficient of drag
C_{D_i} = coefficient of induced drag
C_{D_0} = coefficient of zero-lift drag
C_L = coefficient of lift
DP = departure procedure
d_{fan} = engine fan diameter (ft)

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$\Delta C_{D_{RE}}$ = coefficient of drag increment due to Reynolds number (altitude & Mach) effects
$\Delta C_{D_{ENG}}$ = coefficient of drag increment due to jammed engine
$\Delta C_{D_{FLAPS}}$ = coefficient of drag increment due to flap deflection
$\Delta C_{D_{TRIM}}$ = coefficient of drag increment due to trim
ΔV = excess speed (nM/hr)
e = Oswald's efficiency factor
EDET = Empirical Drag Estimation Technique
E-M = Energy-Maneuverability
FAA = Federal Aviation Administration
K = corrective factor for rate of climb
KIAS = knots indicated airspeed (nM/hr)
KTAS = knots true airspeed (nM/hr)
M = Mach number
NPSS = Numerical Propulsion System Simulation
n_{eng} = number of engines
PLA = power lever angle
q = dynamic pressure (lbf/ft^2)
ROC = rate of climb (ft/min)
SET = specific excess thrust (climb gradient)
SID = standard instrument departure
S_{ref} = wing planform reference area
T = thrust (lbf)
TERPS = Terminal Instrument Procedures
TODR = takeoff distance required (ft)
V_{FTO} = final takeoff speed (nM/hr)
V_{LOF} = lift-off speed (nM/hr)
V_{MC} = minimum control speed (nM/hr)
V_{SR} = reference stall speed (nM/hr)
V_2 = second segment speed (nM/hr)
V_4 = fourth segment speed (nM/hr)
W = aircraft weight (lbm)
WAT = Weight, Altitude, Temperature

I. Introduction

THE Federal Aviation Administration (FAA) is the sole authority which regulates aircraft design and operation in the United States. Prior to its maiden flight, aircraft designers must produce evidence which demonstrates that their design can both withstand expected flight loads as well as provide a minimum level of performance in the critical engine inoperative state. This effectively regulates which commercial aircraft can fly, ensuring that they are safer than ever before, for only aircraft that possess a current airworthiness certificate can take flight.

Airworthiness certification requires compliance to many different criteria, including the incorporation of factors of safety and required redundancy. Commercial aircraft designers are expected to abide by Title 14 of the Code of Federal Regulations,[1] Section 25, should they want their design to pass airworthiness certification. For example, 14 CFR § 25.303 requires all commercial aircraft design engineers to incorporate "a factor of safety of 1.5 … applied to the prescribed limit load which are considered external loads on the structure," unless there is another regulation which essentially overrides this; one such example of this is the factor of safety for fittings: a "fitting factor" of at least 1.15 must be applied to each part, as dictated by 14 CFR § 25.625(a). Evidence of following these design regulations are typically, for means of certification, backed up with a test to destruction.

Additional to the design standards set forth by the FAA, there are operational limits that pilots must abide by for safe flight. To avoid accidental stall during aircraft operation, 14 CFR § 25.107(g) requires that the final takeoff speed, V_{FTO}, must be selected so that it produces at least the gradient of climb prescribed by 14 CFR § 25.121(c); for two-engine commercial aircraft, 14 CFR § 25.121(c) requires the steady gross climb gradient to be no less than 1.2% at

V_{FTO}. When selecting V_{FTO}, it cannot be less than 1.18 times the reference stall speed, V_{SR}, and must be high enough to provide the aircraft with the maneuvering capability specified in 14 CFR § 25.143(h).

Two-engine aircraft are expected to be safely operable with only one engine operating. In this condition, a steady gross climb gradient which is no less than zero is expected at V_{LOF} per 14 CFR § 25.121(a), and a steady gross climb gradient of no less than 2.4% at V_2 is expected per 14 CFR § 25.121(b). 14 CFR § 25.149(b) also dictates that under these conditions, this aircraft is expected to maintain straight flight at the minimum control speed, V_{MC}, with a bank angle of 5 degrees or less. Furthermore, 14 CFR § 25.149(g) requires that the critical engine-inoperative aircraft can roll through an angle of 20 degrees away from the failed engine in no more than 5 seconds. Indeed, the FAA expects that multi-engine aircraft are capable of—in the critical engine-inoperative case—safely climbing, flying level, and turning.

To ensure aircraft are operated in a safe manner, the FAA allows the use of an approved evidence-based pilot's operating handbook developed by the manufacturer. For dispatch personnel and pilots alike, this book is used for mission planning and execution purposes, providing important cue speeds, the "*V* speeds", for safe operation. The manufacturer also provides maximum dispatch weight guidance charts—"*WAT limit*" charts—as functions of airfield altitude and temperature; these are used to ensure that the minimum-required climb gradient performance is achieved in the critical engine-inoperative condition, so long as the aircraft is flown to the prescribed cue speeds.

The FAA, in fact, is so invested in safety that it created a regulation which requires that dispatch uses these WAT limit charts for takeoff procedure planning; that regulation is 14 CFR § 121.189(a),[2] which dictates 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". Essentially, this regulation prevents an aircraft leaving the ground at a weight greater than what is allowed in these WAT limit charts.

When considering the aircraft dispatch problem, planners are required to consider an aircraft's *net* flight path. This is distinctly different from considering an aircraft's *gross*, or actual, flight path. Regulation 14 CFR § 25.115(b) dictates that "the net takeoff path flight data must be 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". In other words, an aircraft's *net* flight path is simply the *gross* flight path derated by a climb gradient of 0.8%. This essentially creates a "margin of safety" similar to "factors of safety" used in aircraft design.

On the topic of safety, the FAA has also established guidelines that regulate aircraft operation. For example, 14 CFR § 121.189(d)(2) requires that all aircraft on takeoff can clear all end-of-runway obstacles by at least 35-ft. Additionally, 14 CFR § 91.119[3] mandates that once an aircraft is outside an airport's boundaries, it must not fly any lower than 500-ft AGL; this essentially means that the FAA expects all aircraft can clear all downrange obstacles by a 500-ft margin.

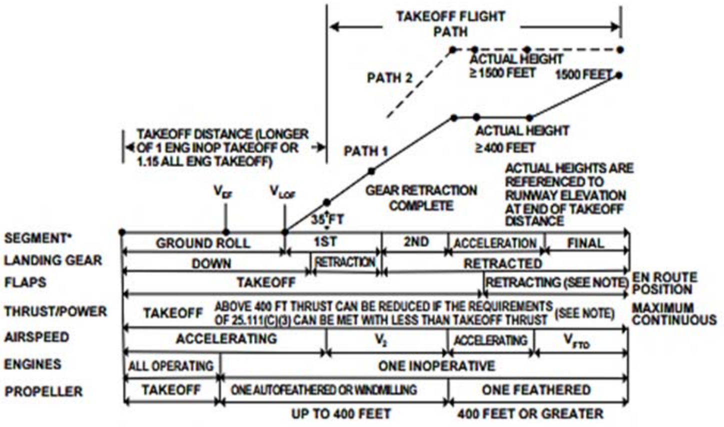

Figure 1. Typical takeoff profile. *Upon end of the second segment climb, that being at 400 ft AGL or higher, the aircraft levels off and picks up speed for the fourth (final) segment climb. Note that takeoff procedures are planned with the critical engine inoperative case in mind, as evidenced by this figure.*

Regulation 14 CFR § 25.111[4] implies that all takeoff procedures are separated into four segments, as represented in Figure 1. For a two-engine aircraft in the critical engine inoperative state, the first segment climb—characterized by the aircraft being in the takeoff configuration—must be performed with a positive steady gross climb gradient at V_{LOF} per 14 CFR § 25.121(a).[5] Once the landing gear is fully retracted, second segment climb begins, which for the two-engine aircraft in the critical engine inoperative state, a steady gross climb gradient of no less than 2.4% at the V_2 speed is expected until reaching 400-ft AGL, per 14 CFR § 25.121(b). While the aircraft designer is free to pick a V_2 of their liking, regulation 14 CFR § 25.107(b) requires that it is no less than 1.13 times V_{SR} or 1.10 times V_{MC}, whichever value is greater.[6] Third segment acceleration is initiated when the aircraft attains an altitude of at least 400-ft AGL, at which the vehicle may level off and accelerate to the flap retraction safety speed. Following this is fourth segment climb, which 14 CFR § 25.107(c) requires the steady gross climb gradient for a two-engine aircraft in the critical engine inoperative state must be no less than 1.2% at V_{FTO}.[6] While the aircraft designer is free to choose V_{FTO}, regulation 14 CFR § 25.107(g) requires that it must be selected so that it abides by the previous regulation and is no less than 1.18 V_{SR}, as well as providing the maneuvering capability outlined in 14 CFR § 25.143(h).[6, 7]

In addition to regulations governing climb gradient, airports have takeoff minimum climb slopes which are often greater than the climb gradient minimums so that aircraft do not accidentally fly into high obstacles such as buildings or mountains in the event the critical engine inoperative state occurs. Terminal Instrument Procedures—also known as TERPS—defines a minimum vertical barrier underneath the aircraft's planned flight path which must not be penetrated by obstacles such as trees, radio towers, and tall buildings, as well as terrain such as tall mountains.[8]

For airports which are not riddled with tall mountains or buildings, these takeoff minimums are often equivalent to the climb gradient minimums. For example, executing the PERCH TWO departure procedure of Los Angeles, CA (KLAX) which points west towards the ocean, pilots are only required to observe minimum climb gradient as everything to the west is essentially flat terrain; that is, the aircraft is expected to maintain a gross climb gradient of at least 2.4% at the V_2 speed in the critical engine inoperative case to safely perform the departure.[5]

Other airports that are riddled with obstacles and high terrain, such as Burbank, CA (KBUR) are expected to have takeoff minimums that are greater than the minimum climb gradient. As this airport is located within a valley, the nearby mountains must be avoided on flyout, so scheduled climb performance needs to be steep enough to avoid them. For the ELMOO EIGHT departure procedure out of KBUR, flight out of runway 33 requires a climb rate of 550-ft per nM to 2,600-ft AGL; this correlates to a *net* climb gradient of approximately 9.85%. Recall that per 14 CFR § 25.115(b), "the net takeoff path flight data must be 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." This implies that the rigorous 9.85% net climb gradient is actually a yet more rigorous 10.65% gross climb gradient, which is much in excess of the minimum 2.4% OEI gross climb gradient set forth by 14 CFR § 25.121 for a two-engine aircraft. The minimum net climb gradient for runways 8, 15, and 26

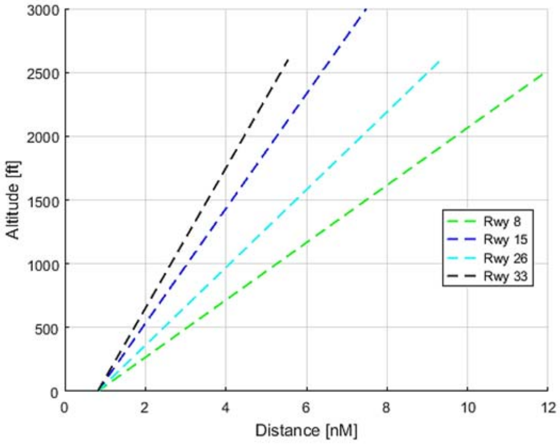

Figure 2. Burbank, CA (KBUR) – ELMOO EIGHT takeoff minimums. *Nominal takeoff distance of 4,970 ft included. The dashed lines, the intersection of which resides at the point of liftoff, represent an imaginary "barrier" at or above which the aircraft must fly to safely overcome obstacles. The minimum required climb gradient depends on the choice of runway.*

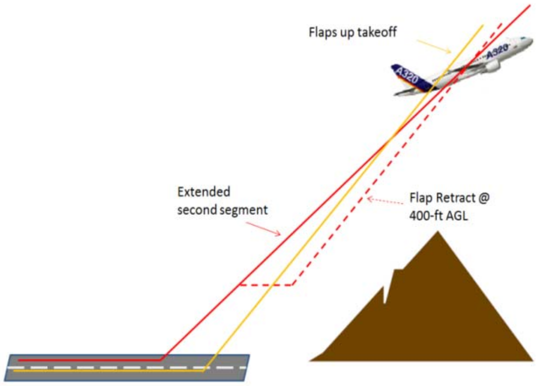

Figure 3. Schematic of E2S climb profile. *While a flaps up takeoff may provide the best climb gradient, the penalty of increased TODR and the need of close-in obstacle clearance needs to be considered. An E2S climb profile seeks to climb as efficiently as possible to clear close-in obstacles while minimizing the penalty on increased TODR.*

are approximately 4.50%, 8.21%, and 5.82%. As these numbers demonstrate, an aircraft that is certified to just meet 2.4% gross climb gradient under the critical engine inoperative condition will have difficulty executing this departure procedure.

For aircraft that cannot meet the required vertical separation as defined by the takeoff minimums, the aircraft must turn away from the obstacle to avoid it. For the airport in the previous example, aircraft departing to the south need to avoid mountains collinear to the flight path; aircraft that do not have sufficient climb gradient to overcome the obstacle must turn to the west to avoid it.

Little scholarly work has been published to-date regarding the relevant modelling and simulation fundamentals needed to fly a standard instrument departure under critical engine inoperative conditions. In our literature review, we found only one conference paper, *Diverging Engine Failure Paths on Standard Instrument Departures*,[9] that addressed this topic. These authors note that many aircraft are incapable of flying the standard instrument departure profile under engine inoperative conditions. They note that engine inoperative SIDs are "not published." They correctly note that performance engineers must develop a substantially different flight path to either 1) clear necessary obstacles or 2) circle back to the departure airport and land (under a potentially overweight situation).

In our previous manuscript, *Revisiting Takeoff Obstacle Clearance Procedures: An Argument for Extended Second Segment Climb*,[10] we produced a model of the Airbus A320 which was calibrated to best match climb gradient data in its AFM. Having simulated multiple dispatch profiles, we found that this aircraft could increase its obstacle clearance performance simply through not an expensive modification to airframe or power plant, but through a simple operational change: instead of using a traditional four-segmented profile on dispatch, one could implement an extended second segment climb to better overcome obstacles in an aircraft's predicted flight path.

While we did learn that this aircraft benefits in climb gradient from some flavor of an extended second segment climb, is it necessarily an appreciable improvement such that it is viable for real-world problems? To answer this question, we took our reverse-engineered A320 model and compared the takeoff climb data to challenging standard instrument departure procedures out of Phoenix Sky Harbor (KPHX), Bob Hope (KBUR), and La Guardia (KLGA). KPHX – Phoenix Sky Harbor Airport, KBUR – Bob Hope Airport, and KLGA – La Guardia.

II. Mathematical Foundation

This study uses the same method of data allocation as did our previous manuscript.[10] For the sake of understanding, we will repeat the equations mentioned there, but in a briefer form. The performance equations herein come from Takahashi's text, *Aircraft Performance and Sizing*.[11]

As climb gradient is largely regulated within the Code of Federal Regulations and by the takeoff minimums in departure procedures, this is a variable that we need to track carefully to ensure an accurate model calibration. Climb gradient is proportional to specific excess thrust (SET), which is succinctly expressed as,

$$SET(ALT,M) = \frac{T_{\max}(ALT,M) - D(ALT,M)}{W} \tag{1}$$

this is the difference of aircraft thrust and drag, the value of which is divided by weight. Eqn. (1) is best expressed as a percentage as 14 CFR § 25.121 expresses minimum climb gradients as percentages.[5]

To get a good grip on the A320's calibration, four tools were necessary: (A) EDET, (B) NPSS, (C) *SKYMAPS*, and (D) *MISSION*, all of which are discussed briefly below.

A. Enhanced Drag Estimation Technique (EDET) & Further Aerodynamic Modelling

A drag estimation technique developed by Feagin and Morrison, the "Delta Method … [estimates] the clean wing drag polar for cruise and maneuver conditions up to buffet onset".[12] This method was codified into a program—later enhanced by Takahashi using more complex form factor equations for drag estimation found in Takahashi, German, et al.—which accepts an input file which details the physical parameters of the aircraft and outputs estimated drag polars for a variety of operating conditions.[13] As all real aircraft have "imperfections" such as fasteners, ridges, and flap tracks which are collectively difficult to account for, EDET includes a “crud drag” correction, which adds drag on top of the nominal count to obtain a better match to reality. For the curious reader, our A320 model incorporates a 35% crud drag correction.

An aircraft flying with a jammed engine is penalized with additional drag counts. In our study, we assume that when an engine fails, it is jammed, creating a sort of “barn door” drag. While we would assume the expression of the additional drag penalty due to an engine inoperative is of the following form,

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

We have found that this estimate is slightly too high, creating a model that is too draggy would could not match the climb gradient values implied by the AFM. So while Eqn. (2) suggests approximately 167 drag counts, we desire a model which better matches published data; through multiple trade studies, we identified that approximately 135 drag counts best fits our model – implying that the AFM must have used a windmilling engine for their inoperative engine model.

Additionally, aircraft flying with a jammed engine experience a yawing moment that is induced by the asymmetric thrust. This yawing moment causes the aircraft to turn away from the centerline; this is countered by use of rudder and aileron deflection, but this induces a small drag penalty. This drag penalty associated with rudder and aileron deflection is estimated as,

$$\Delta C_{D_{TRIM}} \cong 0.0010 \tag{3}$$

As all commercial aircraft are only certified to takeoff using flaps, a drag penalty associated with flaps deflection needs consideration. For our A320 model, we estimated the drag addition associated with leading-edge and fowler flap deflection as,

$$\Delta C_{D_{FLAPS}} \cong 0.0210 \tag{4}$$

This is our drag estimation for the “Flaps 2” setting on the A320 model that enabled it to best-match estimated climb gradients at the prescribed book speeds in its AFM.

As EDET only provides induced drag corrections for the “clean wing” setting, we used the following classic equation for drag-due-to-lift estimations with “Flaps 2” engaged,

$$C_{D_i} = \frac{C_L^2}{\pi\, AR\, e} \tag{5}$$

As the span efficiency factor, e, is a free variable that is not defined in the AFM, we had to run trade studies to get a good estimate on it. Parameter e was picked so that the model’s climb gradients at V_2 and V_4 came close to those suggested by our resource. The value which was found to give the model best fidelity was $e \cong 81.72\%$.

B. Numerical Propulsion System Simulation (NPSS)

While possession of an aerodynamics model on-hand is nice, a propulsion model is also required. NPSS,[14] a physics-based engineering tool, provides us usable five-column data through feeding it key engine parameters such as maximum turbine inlet temperature, reference bypass ratio, reference fan pressure ratio, etc. Using this program, we generated a propulsion model of the V2527-A5 engine that is used by the A320.

C. SKYMAPS

An eloquent name for a VBA code programmed in Microsoft EXCEL, *SKYMAPS* produces plots of key performance parameters as a function of flight speed and altitude. This tool uses the aerodynamics profile provided by EDET and the propulsion model from NPSS for calculations, as well as all corrective drag terms produced in subsection A of this discussion. This point performance code truncates unrealistic points of data, such as where the required lift coefficient exceeds maximum lift coefficient, or where total drag exceeds maximum thrust.

D. MISSION

Although *SKYMAPS* provides performance data at a particular weight setting, this tells us very little about how the aircraft performs when performing flight. Another tool is required to understand how the A320 performs *over time and distance*, especially in response to decisions in cue speeds and takeoff profile.

MISSION is an explicit point-mass simulation tool in which the power lever angle, aircraft flight speed, and altitude are principal state variables. This tool is equipped with multiple "modes" which are used to shape the flight trajectory; only three of them are of interest to us: (1) ground run, (2) constant KIAS climb, and (3) level acceleration. The ground run mode simulates takeoff from rest up until the aircraft reaches V_2 (used in absence of V_{LOF}). Upon reaching V_2, the code switches to constant KIAS climb mode to simulate second segment climb. For modeling a "Flaps 2" extended second segment climb, this climb is carried up to 5,000-ft AGL. For a traditional four-segment profile implied by CFR,[4] this climb is cut off at or above 400-ft AGL; after this commences third segment acceleration, commanded by the level acceleration mode in *MISSION*. Third segment acceleration terminates at V_4 and is followed by fourth segment climb which is commanded by the constant KIAS climb mode, which is carried to 5,000-ft AGL.

Our prior manuscript compared and discussed of how "Flaps 2" extended second segment and its clean wing counterpart compared to traditional takeoff profiles.[10] The notable limitations from that study should be repeated here for clarity. That is, in each *MISSION* simulation, the aircraft starts from rest with one engine inoperative (as opposed to forcing an engine failure at or past V_1). Consequently, this produces pessimistic TODR values but does not affect overall climb performance as the aircraft commences climb at V_2, which we assume is similar to V_{LOF}. As such, we will neglect TODR values and assume that the A320 can takeoff on all runways used in the current study. To simplify the discussion, we will neglect any tire speed rating and brake energy limitations in our analysis, as well as any short-term "takeoff thrust" power restrictions; all simulations imply flight at maximum takeoff thrust.

III. Comparison of Aircraft Performance & Takeoff Minimums

For this study, we examined the SNOBL FIVE departure options out of KPHX, KLGA's JUTES THREE, and KBUR's ELMOO EIGHT departures and compared them to the net flight path takeoff data we procured for our reverse-engineered A320 model. The purpose of this examination is to identify if a simple operational change on takeoff will yield enough additional climb performance to abide by the rigorous takeoff minimums of these airports. To simplify the analysis, we will neglect any climb gradient degradation due to turning; ergo, we treat each dispatch profile as though they are collinear with the runway.

The SNOBL FIVE departure out of KPHX is one of the more challenging departure procedures as it requires an initial climb rate of 500-ft/nM (9.03% net), irrespective of runway choice. For departure out of runways 7L/R and 8, this climb rate is extended to 1,640-ft AGL. This initial required climb rate is quite high as the first waypoint, waypoint SPRKY, is a "mountain" which measures approximately 263-ft above the runway. Following this, a minimum climb of 230-ft/nM (4.59% net) to 10,000-ft AGL is required if one departed from runways 7L/R, otherwise a minimum climb of 300-ft/nM (5.74% net) to the aforesaid altitude is required if the departure occurred on runway 8. For departures out of runways 25L/R, a minimum climb rate of 500-ft/nM (9.03% net) must be maintained for up to 2,140-ft AGL.

KLGA's JUTES THREE departure is also a challenging one as departure from runway 22 requires a high minimum climb rate of 501-ft/nM (9.05% net) to 540-ft AGL. This is then followed by a climb of 356-ft/nM (6.66% net) to 3,000-ft AGL, then a climb of 374-ft/nM (6.96% net) to 5,000-ft AGL. Despite KLGA being situated in New York, New York—a densely-packed place of high buildings—only runway 22 has a serious laundry list of takeoff obstacles that need be avoided.

As mentioned previously, KBUR's ELMOO EIGHT departure comes with variable difficulty, depending on runway choice (see Figures 4 and 5). The easiest departure using this SID procedure is on runway 8, where the aircraft is expected to maintain a minimum climb rate of 225-ft/nM (4.50% net) to 2,500-ft AGL. Taking off on runway 26 requires a minimum climb of 305-ft/nM (5.82% net) to 2,600-ft AGL. Alternatively, one can choose to take off on runway 15, which calls for a minimum climb rate of 450-ft/nM (8.21% net) to 3,000-ft AGL. The most challenging departure of this lot takes place on runway 33, which requires a minimum climb of 550-ft/nM (9.85% net). Referring to Figure 4, we can observe the significant mountainous terrain found just north of the airport. Figure 5, a panoramic photograph taken on the ramp just adjacent to runway 8-26 highlights the terrain found just east of the airport.

Figure 4. View from end of runway 33 at KBUR. *Picture taken facing north.*

Figure 5. Panoramic view of surroundings at KBUR. *Picture taken facing east.*

Recalling that 14 CFR § 25.121 dictates a second-segment climb gradient minimum of 2.4% gross (which implies 1.6% net climb gradient) in the critical engine inoperative case for a two-engine aircraft, and since aircraft dispatches are planned with the worst-case scenario (one engine inoperative) in mind, aircraft which have the minimum-required OEI climb gradient capability at MTOW will very likely be unable to execute any of the aforementioned departure procedures without needing to turn away from the obstacle. To make up for the lack of climb gradient, a reduction in aircraft weight is necessary – this often correlates to a reduction in fare-paying passengers or payload, which implies a reduction in per-flight profits. Obviously, this is an unfavorable choice to make for commercial carriers, so any other alternative that does not include loss of revenue (such as an operational change which yields enough climb gradient to meet the takeoff minimum) is preferred.

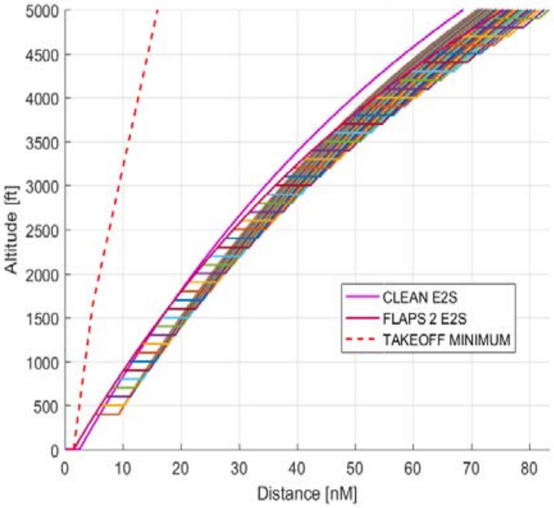

Figure 6. Comparison of KPHX – SNOBL FIVE (Rwy 8) takeoff minimums and A320 OEI net takeoff performance at $W = 172,800$ lbm. *Despite the additional obstacle clearance capability given by the extended second segment procedure, the A320 is still unable to meet the takeoff minimum for a direct departure.*

We will first investigate how the A320 fares departing out of KPHX on the SNOBL FIVE departure at MTOW. Taking this departure out straight out of runway 8 is nothing but impossible due to the required takeoff minimums, as denoted by the red dashed line in Figure 6. While we can see quite clearly that an extended second segment profile will increase obstacle clearance capability, in this case it is not enough to meet the minimum. At this point, we would have to inspect other opportunities departing from other runways, such as 7L/R, 25L/R, and 26. However, after doing so, it is clear that the A320's critical engine inoperative climb gradient performance simply is not enough to meet the required takeoff minimums from any of these runways – even if we choose to execute an extended second segment climb. As such, if we were forced to execute this challenging departure and truly needed enough climb gradient to meet the takeoff minimums, the only remaining option to recover some climb gradient capability is to decrease the aircraft weight through reducing the number of fare-paying passengers, payload, or fuel amount.

A story of a similar theme appears upon inspection of the JUTES THREE departure out of KLGA. The comparison of the takeoff minimum out of runway 22 and the A320's OEI climb performance data at MTOW is displayed in Figure 7. Just as we have observed before, the takeoff minimum required by this departure is way more than what the A320 can provide in the critical engine inoperative case, irrespective of our choice of using a traditional dispatch or one that incorporates an extended second segment climb – thus if the A320 had to execute this procedure as-is, it would have to turn away from the obstacle, burning additional fuel and adding to overall flight time. Assuming we were restricted to using this runway only (as the other has no takeoff minimum), the only solution to recovering climb gradient for this aircraft is, again, a reduction in its takeoff weight through the means described in the previous paragraph.

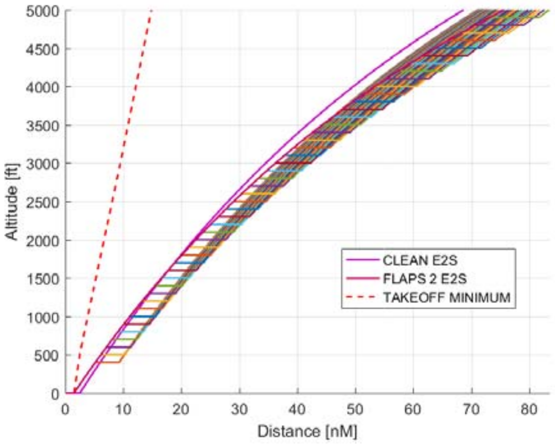

Figure 7. Comparison of KLGA – JUTES THREE (Rwy 22) takeoff minimums and A320 OEI net takeoff performance at $W = 172,800$ lbm. *Like the previous case, the A320's climb performance falls far from the takeoff minimum.*

Investigating the "easiest" ELMOO EIGHT departure out of KBUR against the A320's OEI climb performance data, we turn to Figure 8. Just like the previous cases, again we see that the A320 is so limited in climb gradient at MTOW for the one engine inoperative condition that, irrespective of our chose of traditional flyout profile or one which incorporates an extended second segment, the aircraft is unable to match the required takeoff minimum. As this aircraft cannot meet the required takeoff minimum for ELMOO EIGHT on what is the easiest runway, there is no point in investigating attempts at this dispatch on alternative runways.

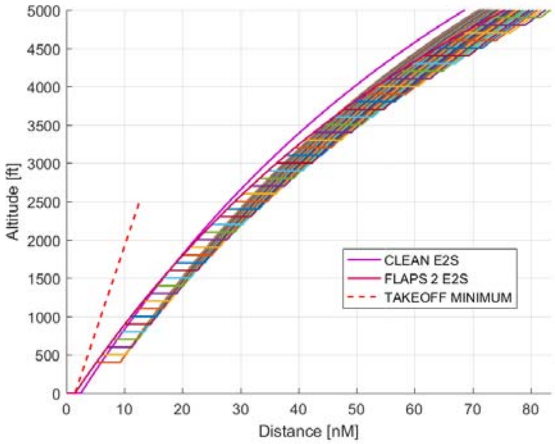

Figure 8. Comparison of KBUR – ELMOO EIGHT (Rwy 8) takeoff minimums and A320 OEI net takeoff performance at $W = 172,800$ lbm. *Even the "easiest" dispatch of those studied in this paper cannot be performed at this weight, irrespective of choice to use an extended second segment climb or not.*

Evidently, it is impossible for this aircraft to meet any of the required takeoff minimums for these challenging departures at the maximum takeoff weight. We are not implying that the A320 was a poorly-engineered plane – bear in mind that we are examining the one engine inoperative scenario, a case which essentially halves the total thrust of the aircraft and adds marked amounts of drag penalties; this aircraft could easily perform these dispatch procedures if no failure would occur on takeoff. The fact of the matter is that all commercial aircraft certified under Part 25 of Title 14 of the CFR are required to have at least a bare-minimum climb gradient capability in the critical engine inoperative scenario to ensure that flight safety is not precluded under such an adverse scenario; in other words, this regulation requires just the bare minimum on climb performance. For the A320, and all other two engine aircraft, this bare minimum is a 2.4% climb gradient for second segment climb, a figure that falls far from the required takeoff minimums for these challenging departure procedures.

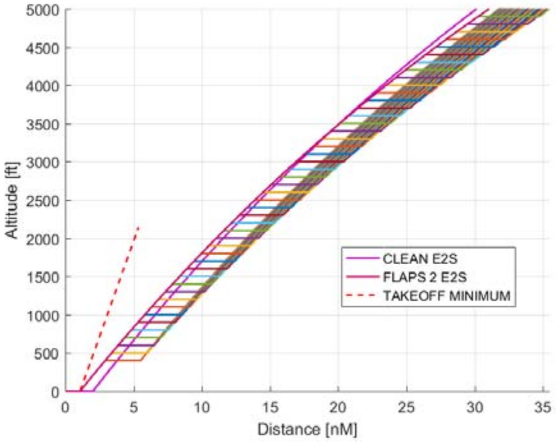

Figure 9. Comparison of KPHX – SNOBL FIVE (Rwys 25L/R, 26) takeoff minimums and A320 OEI net takeoff performance at $W = 152,800$ lbm. *While some climb capability is recovered from flying the aircraft at a reduced weight, the OEI performance still is not strong enough to match the takeoff minimum.*

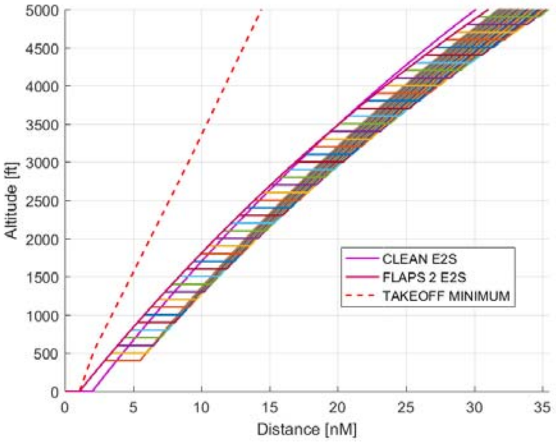

Figure 10. Comparison of KLGA – JUTES THREE (Rwy 22) takeoff minimums and A320 OEI net takeoff performance at $W = 152,800$ lbm. *Again, we observe that despite the additional climb performance capability, it still is not not enough to meet the required takeoff minimum.*

We want to note that all data presented thus far was generated using the nominal cue speeds in the AFM. In our prior manuscript,[10] we found that use of cue speeds that correlated to speeds yielding maximized climb gradient added to overall obstacle clearance performance for the A320 for some dispatch profiles. In combining the extended second segment climb—that yields additional obstacle clearance capability over traditional four-segmented takeoff profiles—with cue speeds maximizing climb gradient, we found additional obstacle clearance performance for some cases. Testing these cases against the challenging dispatch profiles for this study, we found that, unfortunately, even then the A320 still lacks the climb performance to meet any of the takeoff minimums dictated by these SIDs.

Since the A320 is unable to directly complete any of these departure procedures at such a heavy weight, we now inspect how the aircraft will perform at $W = 152{,}000$ lbm. Repeating the process, we begin again by inspecting the SNOBL FIVE departure out of KPHX; a comparison is readily available in Figure 9 (above). Taking the runway which has the "easiest" takeoff minimums, we can see that while the A320 has procured some additional climb performance due to the reduction in takeoff weight, it still regrettably does not have enough performance to match the required minimum for this departure, irrespective of if we chose to perform an extended second segment climb or not. What this really comes down to is reducing the overall aircraft weight until it recovers an appreciable amount of climb gradient potential such that it can match the takeoff minimum under the critical engine inoperative case. Again, a straight-out SNOBL FIVE departure on runways 25L/R and 26 is not feasible, and as this was the "easiest" pick of the runway choices, it makes no sense to examine the other cases in the interest of brevity.

Now examining the JUTES THREE departure out of KLGA for this weight, we refer to the results displayed in Figure 10. Just as we have observed for each case before this one, while some climb gradient capability was recovered due to a reduction in aircraft weight, the amount regained was not enough at all to match the required takeoff minimum, irrespective of choice of extended second segment climb out or otherwise. Therefore, a straight-out departure is infeasible due to lack of obstacle clearance capability. An aircraft executing this departure procedure on this runway will be required to turn away from its current flight path in the event of critical engine inoperative.

By this point, it seems that the aircraft is still a little too heavy to have an appreciable amount of climb performance that is equivalent to the takeoff minimum for this dispatch profiles. As these studies were rendered using book speeds taken from the AFM, we applied cue speeds which were optimized to maximize climb gradient, as we have observed previously that using such speeds increases the obstacle clearance capability of the A320 – and even more so when combined with an extended second segment climb. Unfortunately, though, our results demonstrated that the increase in obstacle clearance capability was not appreciable enough to meet the required takeoff minimum of the previously discussed SIDs.

Even the departures from KBUR using ELMOO EIGHT are plagued with the problem of lacking obstacle clearance performance. For example, Fig. 11 compares the A320's OEI takeoff performance to the ELMOO EIGHT departure using runway 8. Here, we can clearly see that the takeoff minimum comes close to the "Flaps 2" E2S flyout path of the A320, but then it diverges as altitude increases. The drop-off of obstacle clearance capability is best explained by the fact that climb performance degrades the higher the aircraft flies (hence why the flight path data presented tends to "curve" towards the horizontal as opposed to remaining linear). Referring back to Eqn. (1), which is an expression for specific excess thrust (and essentially climb gradient, as these two quantities are directly proportional), we can see that it is a function of both thrust and drag, both of which are functions of altitude. As air density is at a maximum at sea level, we observe that the aircraft drag and thrust are at a maximum (hence the term "sea level" static thrust). Flight at higher altitudes implies the air will be less dense at such conditions, resulting in the thrust and drag terms decreasing. However, thrust is a much more sensitive term than is drag; that is, the thrust term will decay faster than will drag (hence why there is a maximum altitude at which thrust can oppose drag – at higher altitudes, the drag term overcomes maximum possible thrust, making flight there infeasible). Therefore, when planning flyouts, the dispatcher needs to carefully consider the aircraft's climb performance degradation—especially at higher flight levels—when checking if the aircraft is within compliance of the takeoff minimums to ensure a straight-out departure in case of critical engine inoperative.

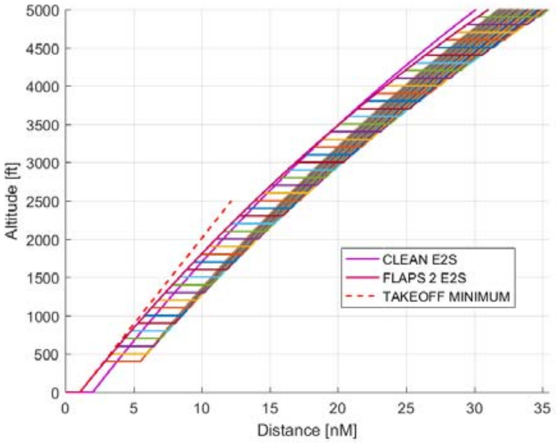

Figure 11. Comparison of KBUR – ELMOO EIGHT (Rwy 8) takeoff minimums and A320 OEI net takeoff performance at $W = 152{,}800$ lbm. *While the "Flaps 2" E2S departure comes close to abiding by the takeoff minimums, reduced thrust capacity at higher altitudes causes this flight profile to diverge from the requirement.*

Thus, as the A320 is incapable of performing a straight flyout from any of the studied airports at $W = 152{,}800$ lbm, we are still required to reduce the aircraft weight further yet. Repeating the analysis again for $W = 132{,}800$ lbm, we look to a more limiting case of the SNOBL FIVE departure from KPHX, a representation of which is provided in Figure 12. While we can clearly see that none of the simulated takeoff profiles will meet the takeoff minimum, it would appear on initial inspection that the takeoff minimum and flight profiles do not "diverge" away from each other as altitude increases; this may seem true, but physics dictates otherwise. Upon closer inspection, we can see that the slope of the flight path is greater than that of the takeoff minimums, in particular around the 5-nM mark. As flight altitude increases, the aircraft's thrust output is reduced at higher altitudes, thus climb rate is not as strong – this correlates to a decrease in the climb slope, which is more noticeable around the 15-nM mark. Indeed, while the A320's climb rate is greater than that required by the takeoff minimums at approximately 5-nM, this actually means nothing for not only does it sit below the required altitude as dictated by the takeoff minimums, but the short duration of climb rate greater than dictated by the takeoff minimums is not strong enough to overcome the altitude limit. Abiding by the takeoff minimums comes at increased difficulty at increased altitudes due to reduced thrust output. Even on application of enhanced cue speeds—those that maximize climb gradient—we still find the A320 lacks the climb performance to meet the takeoff minimums here, as the

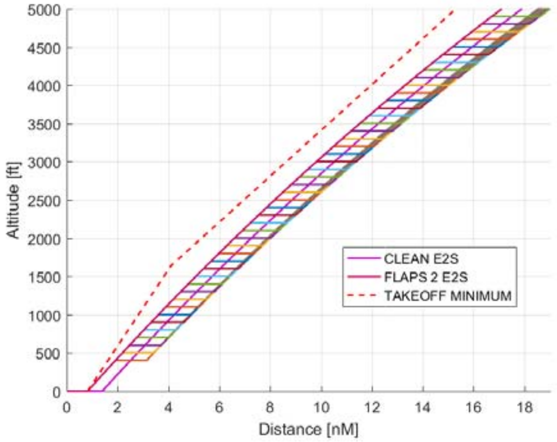

Figure 12. Comparison of KPHX – SNOBL FIVE (Rwy 8) takeoff minimums and A320 OEI net takeoff performance at $W = 132{,}800$ lbm. *While the A320's climb slope is greater than that of the takeoff minimums at approximately 5-nM, this performance parameter diminishes at increased altitude; it is not strong enough to overtake the takeoff minimums downwind.*

increase from implementing these cue speeds was not so much appreciable. Ergo, a straight flyout here is infeasible; the aircraft must turn away from all upcoming obstacles in the event of an engine failure.

We now investigate the JUTES THREE departure from KLGA using a dispatch weight of $W = 132{,}800$ lbm. As usual, the comparison between the takeoff minimums and A320 takeoff performance is provided here and displayed in Figure 13. Unsurprisingly, we still find the aircraft is yet still incapable of performing a straight flyout of this dispatch procedure. By now, it is abundantly clear that irrespective of the plethora of runway options available to the A320, it will likely not be able to abide by the takeoff minimums on departure at moderate to heavy weights. These takeoff minimums are incredibly difficult for commercial aircraft to successfully fly out in the critical engine inoperative scenario; so far, all we have observed is that in order for this to happen, we need to decrease the aircraft's dispatch weight further than $W = 132{,}800$-lbm for these DP's.

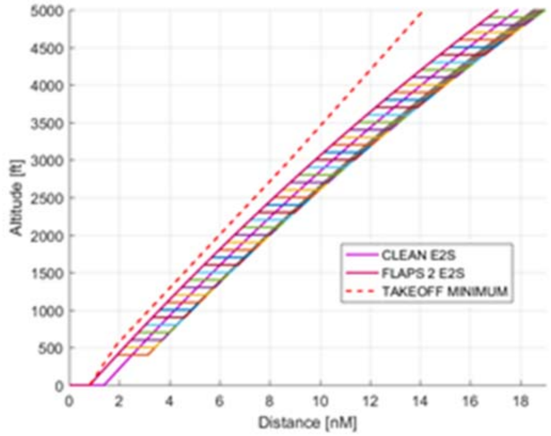

Figure 13. Comparison of KGLA – JUTES THREE (Rwy 22) takeoff minimums and A320 OEI net takeoff performance at $W = 132,800$ lbm. *Here, the divergence between the takeoff minimums and flight profiles is much more pronounced, in particular at higher altitudes.*

However, this is not the case for KBUR as ELMOO EIGHT's takeoff minimums are not as rigorous as the other two departure procedures we are studying. The comparison between runway 26's takeoff minimums and the A320's climb performance is provided in Figure 14. We can immediately see here that the A320 has a good amount of flight profiles that can be used to execute this departure procedure. For example, a dispatch which includes a third-segment acceleration for flap retraction is capable of executing this departure procedure, so long as the flap retraction is scheduled for an altitude at or greater than 2,600-ft AGL in order to avoid transgressing the takeoff minimum climb slope. Alternatively, the A320 can perform a "Flaps 2" extended second segment climb, as this flight profile satisfies both close-in and far-out obstacle clearance needs. Furthermore, the advantage of this profile is that the pilot need not worry about when to "nose over" the aircraft in order to enter the third-segment acceleration. Not only does this simplify the procedure for pilots, but it also ensures a larger vertical safety margin which can be used as a buffer zone of sorts in the event of a catastrophic emergency. In addition to runway 26 being available for straight flyout, we note that runway 8 also opens up at this weight setting; a traditional profile "nosing over" at 800-ft AGL or greater, or a "Flaps 2" extended second segment climb procedure are viable operational methods which abide by the imposed takeoff minimums for that runway.

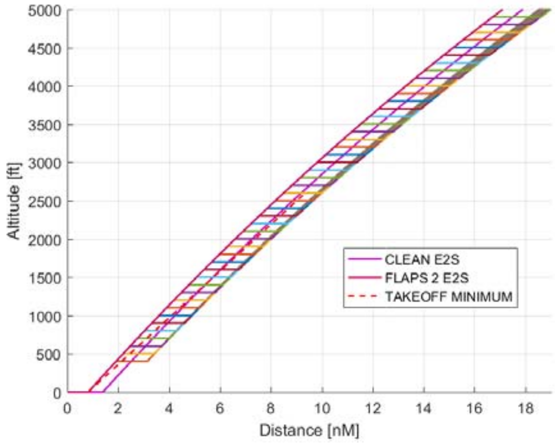

Figure 14. Comparison of KBUR – ELMOO EIGHT (Rwy 26) takeoff minimums and A320 OEI net takeoff performance at $W = 132,800$ lbm. *Using the four-segmented flight profile implied by 14 CFR § 25.111 means that the aircraft must hold flap retraction up until 2,600-ft AGL to abide by the takeoff minimum.*

Looking through our datasets, we note that at $W = 122{,}800$ lbm, we find that the A320 is nearly capable of performing a straight-out departure out of KPHX using SNOBL FIVE on runways 7L&R and 8. For the purpose of comparison, we have produced the takeoff minimums for runway 8 and plotted it with the A320's climb performance data in Figure 15 (overleaf), but we do want to note that both of these runways share the same first-segment takeoff minimum climb slope requirement. As the astute reader might note, the aircraft is slightly insufficient in climb capability in the first segment of the takeoff minimum climb slope, most noticably around the 4 nM mark. What this really indicates to us as engineers is that at this weight setting, the A320 comes very close to having the capability of meeting this takeoff minimum using a "Flaps 2" extended second segment climb procedure. Alternatively, the pilot may also use a typical four-segmented flight profile implied by the CFR,[5] but this requires the flap retraction to be scheduled for an altitude at a rather high altitude. The takeaway from this is that the A320 needs to takeoff at a weight slightly lighter than 122,800 lbm in order to perform a straight flyout for both runway 8 and runways 7L&R. Conversely, if the A320 using a "Flaps 2" extended second segment climb experiences an engine failure at 6-nM away from the point of liftoff (which is approximately 2,400-ft AGL), the pilot may choose to continue the departure and fly over the upcoming obstacles, as the aircraft will still have sufficient climb capability to maintain succincct vertical separation defined by the takeoff minimums.

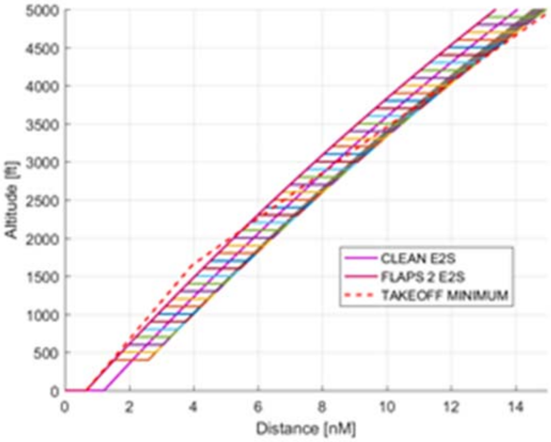

Figure 15. Comparison of KPHX – SNOBL FIVE (Rwy 8) takeoff minimums and A320 OEI net takeoff performance at $W = 122{,}800$ lbm. *This plot really shows that the A320 is slightly incompliant with the first segment of the takeoff minimum climb slope, but this indicates is that the aircraft needs to be not too much lighter to meet this requirement.*

A trend similar to that of the previous figure is noted when we examine KLGA's JUTES THREE dispatch at $W = 122{,}800$ lbm. Just as we had noted with the previous analysis, Figure 16 demonstrates an A320 which is just barely insufficient in its climb performance with respect to the takeoff minimum, particularly around the 2 nM point. This indicates, again, that the A320 technically must turn away from the obstacle as opposed to flying straight over it as it does not have enough climb capability to consider the maneuver "safe". Figure 12 does indicate to us, though, that the optimal weight at which the climb performance meets the takeoff minimum is rather close – in which case, the only viable manuever here is the "Flaps 2" extended second segment dispatch. This is largely due to the stricter takeoff minimum climb slope, which makes sense as there are a number of buildings which need be avoided on takeoff. We note here that no four-segmented profile implied by 14 CFR § 25.111 is viable here, even if the flap retract schedule is delayed! This is because the third segment acceleration will always intersect with the takeoff minimum climb slope, which is problematic. Hence, the only solution here would be to execute an extended second segment climb with "Flaps 2", carrying it all the way to 5,000-ft AGL, as the restriction on minimum climb slope ends at this particular altitude, assuming that the engine failure occurs past the 2-nM point (at which the A320 is incompliant with the flight path dictated by the takeoff minimums).

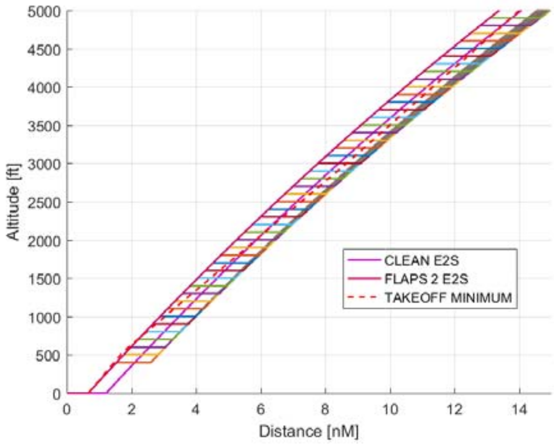

Figure 16. Comparison of KLGA – JUTES THREE (Rwy 22) takeoff minimums and A320 OEI net takeoff performance at $W = 122{,}800$ lbm. *Similar to Fig. 11, we can see the A320 is slightly incompliant with the first segment of the required minimum climb slope, but not significantly; thus, the correct dispatch weight is not too far lighter.*

For departure options out KBUR using the ELMOO EIGHT dispatch procedure, we oberserve that at this departure weight, some secondary runway choices have opened up in addition to runways 8 and 26, which were available at $W = 132{,}800$ lbm. Our results suggest that an ELMOO EIGHT dispatch procedure from runway 15 is possible at a highly reduced weight of $W = 117{,}800$-lbm (see Figure 17). Similar to the dispatch on runway 26, we see here that the aircraft is somewhat restricted in flight profile choices due to the takeoff minimums. However, unlike the dispatch on runway 26, we see that if the pilot desired to use a four-segmented traditional profile which incorporates an clean up on the flaps, the flap retraction must be held until 3,000-ft AGL or greater, otherwise the third segment acceleration would directly intersects the takeoff minimum climb slope, making a straight-out departure impossible. At the pilot's convenience, he/she may also consider executing a "Flaps 2" extended second segment climb, which also serves as an acceptable operational technique which nets the A320 enough climb performance to abide by the takeoff minimums.

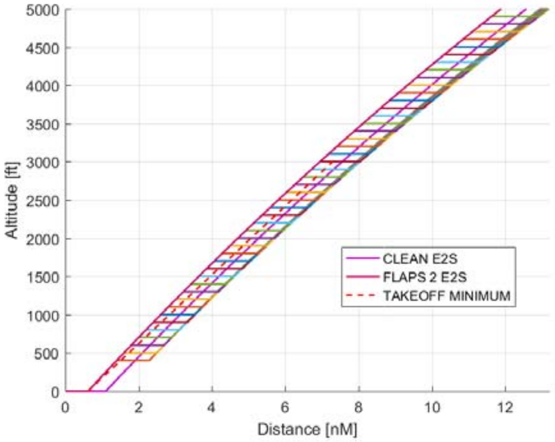

Figure 17. Comparison of KBUR – ELMOO EIGHT (Rwy 15) takeoff minimums and A320 OEI net takeoff performance at $W = 117{,}800$ lbm. *Flight profiles which incorporate the third-segment acceleration procedure must hold flap retraction until 3,000 ft AGL to abide by the takeoff minimum climb slope.*

IV. Discussion

For clarity, we should note to the reader that just because an aircraft does not meet or exceed the takeoff minimum climb slope mandated by a dispatch procedure does not preclude it from taking off. Indeed, the only rules which preclude takeoff are, assuming tire speed limits and brake energy are not limiting factors, the takeoff distance available, as well as aircraft's climb gradient potential under the critical engine inoperative condition. Since we know for a fact that the A320 has sufficient climb gradient performance to meet 14 CFR § 25.121(b), this aircraft is free to depart from any runway which succinctly long enough to satisfy TODR.

That being said, there comes an issue when the A320 takes off and then experiences an engine failure: what happens next? As the aircraft will have enough performance to limp home, there is one obvious option: circle back to the departure airport and land overweight. However, since the aircraft will land heavier than expected, the runway distance required for landing should also be longer than expected; this can potentially give rise to the problem of where a runway is long enough for takeoff, but not long enough for an overweight landing (with no credit given to use of reverse thrust or lift-dumping devices). If the surrounding terrain is favorable—that is, free of obstacle problems—the pilot may consider flying to a nearby airport that has a longer runway. For example, an A320 that experiences an engine inoperative emergency going out of KLGA has the option of limping over to KJFK; similarly, an emergency going out of KBUR has the option of limping over to KVNY. Note that the option of diverting to an alternative airport may not be available if the aircraft is present in an area where the surrounding terrain is plagued with obstacles; if the A320 flies too heavy such that its climb gradient is lower than that implied by the takeoff minimums for the dispatch procedure, it must turn away from the upcoming obstacles. On the other hand, if the A320 has enough climb potential to overcome obstacles, this opens up further options yet in terms of airports at which the A320 may perform an emergency landing.

After this thorough analysis of departure procedures, it seems that while the concept of the extended second segment climb seems promising, the data appears to suggest that there really is only a limited set of cases where it truly makes a difference with respect to increasing obstacle clearance capability without reducing the aircraft weight (which subsequently reduces number of fare-paying passengers, payload and/or fuel amount).

For example, at the maximum takeoff weight ($W = 172{,}800$ lbm), it was quite evident that the A320 could not directly dispatch from any of the three airports—KPHX, KLGA, KBUR—using their respective departure procedure which we had studied carefully under the critical engine inoperative case. Of course, arriving at such a result is not so much surprising – after all, two-engine aircraft are certified to a minimum of 2.4% second segment climb gradient in the one engine inoperative condition as per 14 CFR § 25.121(b), as well as a 1.2% fourth segment climb gradient for the same condition per 14 CFR § 25.107(c) at the maximum takeoff weight. While this ensures that safe flight is not precluded in the event of a bird strike which renders one engine inoperative, these low OEI climb gradients are noncompetitive with the high climb rate requirements of obstacle-challenged airports; in other words, in the event of an engine failure at the maximum takeoff weight at an airport which is riddled with obstacles, the aircraft is forced to turn away from the obstacle as opposed to flying over it as it will be unable to maintain succinct vertical separation between itself and any potential obstacles. This was observed to be the end result, irrespective of choice of a traditional four-segmented flight profile or one that incorporates extended second segment, as well as if we decided to utilize optimized cue speeds or not on dispatch.

Since extended second segment was not a viable alternative which appreciably increased the obstacle clearance capability of the A320 so that it matched the takeoff minimum climb slope, a reduction in dispatch weight is necessary. Thus, we surveyed and compared dispatch procedures to the climb performance of the A320 at $W = 152{,}800$ lbm. All of the analyses demonstrated the same result as we saw before, with the A320 having significant difficulty executing most of these departure procedures – thus the aircraft would have to turn away from the obstacle as opposed to attempting to overcome it; the same can be said even for cases where idealized cue speeds were utilized.

A further reduction in dispatch weight opens up two runway possibilities for KBUR’s ELMOO EIGHT. At $W = 132{,}800$ lbm, we find that the A320 has enough climb performance to dispatch on runway 26, although Fig. 14 suggests that the aircraft can potentially depart at a slightly heavier weight as the climb performance exceeds—not necessarily “just meets”—the takeoff minimums. Continuing with this dispatch weight, to make a straight-out departure on KBUR’s runway 26 a reality using the ELMOO EIGHT dispatch procedure, the pilot must either (1) hold the flap retraction until 2,600-ft AGL if using a traditional four-segmented takeoff profile, or (2) use a “Flaps 2” extended second segment profile. At this point, we also found that dispatch off of runway 8 was possible; valid maneuvers which abide by the takeoff minimums include executing a “Flaps 2” extended second segment climb or a traditional profile which cleans up on the flaps at 800-ft AGL or greater.

The dispatch out of KPHX’s SNOBL FIVE on runways 7L&R and 8 proved to be quite challenging. A departure weight of somewhere less than $W = 122{,}800$ lbm is required for the A320 to meet the high rate of climb requirement on the initial climb out as dictated by the takeoff minimums. For the more-challenging runway 8, assuming that the A320 does not experience an engine failure up until 6-nM away from the runway, a “Flaps 2” extended second segment climb will ensure the aircraft continues to remain above the flight path dictated by the takeoff minimums. A traditional climbout which implements flap retraction may also be considered, however, flap retraction must be held until a high altitude – approximately 4,800-ft AGL. For runways 7L&R, the same operational techniques are viable, except that flap retraction for traditional climbouts may be held until 2,600-ft AGL.

The departure out of KLGA’s runway 22 using JUTES THREE was also particularly challenging, for the required minimum rates of climb are particularly high. Like the previous case, we find that a departure weight of somewhere less than $W = 122{,}800$ lbm is needed to provide the A320 with enough climb performance to meet the takeoff minimums. Unlike the last case, however, there really is only one operational technique that is acceptable here: using a “Flaps 2” extended segment climb. Attempting to use a four-segmented traditional takeoff profile is infeasible as there is no proper altitude at which the pilot can retract the flaps; that is, the third segment acceleration for flap retraction directly intersects with the minimum climb slope at all altitudes—as seen in Fig. 14—thus making such a procedure require the pilot to turn away from upcoming obstacles if an engine fails.

Finally, a straight-out departure on KBUR’s runways 15 and 26 using ELMOO EIGHT was found to be possible at $W = 117{,}800$ lbm. Analyzing the more-difficult runway 15, we found that viable procedures which provide the A320 sufficient enough climb performance to overcome the climb slope minimums includes (1) holding the flap retraction altitude to 3,000-ft AGL if using the traditional four-segmented takeoff profile, or (2) executing an extended second segment climb while holding “Flaps 2”.

We briefly did mention executing simulations that incorporated “optimized” cue speeds, speeds that maximized the climb gradient of the A320. Unfortunately, for all of the surveyed cases, we found no cases in which use of speeds which maximized climb gradient made any appreciable difference in obstacle clearance capability such that the A320 could execute the departure procedure or not. While in our previous manuscript we found increases to obstacle clearance capability using these optimized cue speeds for particular profiles, it would seem that implementation of such speeds serves no practical purpose.

V. Conclusion

The obstacle clearance problem is not a rudimentary “academic exercise” by any means – it is a real-world problem in which the FAA is heavily invested. It would be problematic for the aviation industry and passengers alike if the thought of aircraft plowing into the side of a mountain due to lacking obstacle clearance capability is commonplace. Fortunately, the FAA has regulations in place to prevent such disasters from occuring.

While the climb gradient minimums prescribed by the FAA are “safe” in that they ensure safe flight is not precluded in the critical engine inoperative case, some standard instrument departures require a climb gradient which is greater than the minimum. This can be problematic when considering the dispatch problem. For an aircraft whose climb gradient is limited by weight, airfield altitude, or temperature, a reduction in passengers or payload is necessary in order to meet the climb gradient required by the standard instrument departure; this correlates to a loss of revenue for the commercial carrier, which is obviously an unfavorable outcome.

In our thorough analysis, we put the concept of the extended second segment climb to the test against real-world problems. For some departure procedure/runway combinations, we found the extended second segment climb technique to be a viable procedure which allots the A320 enough climb performance to meet the minimum climb slope. For these same cases, we also found that a traditional four-segment takeoff profile is also capable of overcoming the prescribed takeoff minimums, so long as the flap retraction is delayed to higher altitudes. The only case in which extended second segment was the *only* option which made a straight-out departure possible was for the case presented in Fig. 16, which is characterized by tall buildings and thus, high minimum rate of climb requirements all the way to 5,000-ft AGL. However, these operational techniques only become viable after a significant decrease to the dispatch weight via a reduction in fare-paying passengers, payload, or fuel capacity. As the authors of reference 9 correctly note, many aircraft are incapable of flying standard instrument departure profiles in the critical engine inoperative case, for the imposed takeoff minimums are not published with the engine inoperative case in mind. In no case did we find that use of optimized cue speeds combined with a traditional or extended second segment profile making a difference in which the A320 could perform a particular departure procedure or not.

The results of this study imply that, indeed, while the extended second segment dispatch procedure provides superior obstacle clearance capability over a traditional four-segmented profile through bypassing the “inefficient” (with respect to obstacle clearance) third segment acceleration, there are niche cases in which this operational techinque is absolutely a necessity; these cases are characterized by tall obstacles which are both nearby the point of liftoff as well as far downstream, such as the buildings within the vicinity of LaGuardia Airport. These tall close-in and far-out obstacles lead to highly restrictive takeoff minimum climb slopes, sometimes all the way to 5,000-ft AGL, as is the case for the aforesaid airport. However, as not all airports are as obstacally-challenged as this one, this implies that the option of executing an extended second segment climb will more often than not be at the convenience of the pilot in command, not necessarily a required manuever to overcome challenging obstacles and maintain the required vertical separation defined by TERPS.

Acknowledgements

This manuscript derives from work Mr. Beard performed in partial fulfillment of the degree requirements for obtaining his M.S. in Aerospace Engineering from Arizona State University. This work was sponsored by DragonFly Aeronautics LLC under Contract No. FP00006911. Mr. Beard was a part time research assistant on this project. Professor Takahashi serves both as a consultant for DragonFly Aeronautics LLC and as the Research Investigator at Arizona State University. Professor Lenore Dai serves as Principal Investigator at Arizona State University.

References

[1] 14 CFR § 25, *Code of Federal Regulations*, *Title 14*, *Aeronautics and Space*, *Parts 1 to 59*, 1 January 2012.

[2] 14 CFR § 121.189, "Airplanes: Turbine engine powered: Takeoff limitations", *Code of Federal Regulations, Title 14, Aeronautics and Space*, 1 January 2012.

[3] 14 CFR § 91.119, "Minimum safe altitudes: General", *Code of Federal Regulations*, *Title 14*, *Aeronautics and Space*, 1 January 2012.

[4] 14 CFR § 25.111, "Takeoff path", *Code of Federal Regulations*, *Title 14*, *Aeronautics and Space*, 1 January 2012.

[5] 14 CFR § 25.121, "Climb: One-engine-inoperative", *Code of Federal Regulations*, *Title 14*, *Aeronautics and Space*, 1 January 2012.

[6] 14 CFR § 25.107, "Takeoff speeds," *Code of Federal Regulations*, *Title 14*, *Aeronautics and Space*, 1 January 2012.

[7] 14 CFR § 25.143, "General," *Code of Federal Regulations, Title 14, Aeronautics and Space*, 1 January 2012.

[8] "Terminal Instrument Procedures (TERPS)," Williams *Aviation Consultants.* Available: http://www.wacaz.com/services/obstruction-evaluation/terminal-instrument-procedures-terps/.

[9] Masson, B., Bain, M. and Page, J., "Diverging Engine Failure Paths on Standard Instrument Departures," AIAA 2015-1309, 2015.

[10] Beard, J. E., and Takahashi, T. T., "Revisiting Takeoff Obstacle Clearance Procedures: An Argument for Extended Second Segment Climb", *17th AIAA Aviation Technology, Integration, and Operations Conference*, Jun. 2017.

[11] Takahashi, T. T., *Aircraft Performance and Sizing*, Momentum Press, 2016.

[12] Feagin, R. C., and Morrison, W. D., "Delta Method, an Empirical Drag Estimation Buildup Technique", NASA CR 151971, Dec. 1978.

[13] Takahashi, T. T., German, B. J., Shajanian, A., Daskilewicz, M. J., and Donovan, S., "Form Factor and Critical Mach Number Estimation for Finite Wings," *Journal of Aircraft*, vol. 49, 2012, pp. 173–182.

[14] NPSS, Numerical Propulsion System Simulation, Software Package, Ver. 2.3.0.1, Ohio Aerospace Institute, Cleveland, OH, 2010.