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Revisiting Takeoff Obstacle Clearance Procedures: An Argument for Extended Second Segment Climb

John E. Beard[1]

and

Timothy T. Takahashi[2]

Arizona State University, Tempe, AZ, 85281

To safely dispatch, commercial aircraft must meet or exceed minimum climb performance requirements. Flight operations must check that aircraft meet certain minimum theoretical climb gradients (WAT limits) as well as be able to clear all obstacles under the intended flight path even with one engine inoperative. While typical flight manuals optimize aircraft for operation on short runways, we believe that this "one size fits all" approach is not the way to go; a simple modification to the takeoff procedure can yield additional climb capability. By extending second segment climb until all obstacles are overcome as opposed to using a "scheduled" flap retract altitude, engine inoperative obstacle clearance performance is optimized.From the perspective of the airline, excess climb capability achieved using this technique may allow the aircraft to carry additional payload or fuel, thus increasing per-flight profits.

Nomenclature

AEO	=	all engines operative
AGL	=	above ground level (ft)
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
d_{fan}	=	engine fan diameter (ft)
$\Delta C_{D_{ENG}}$	=	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
E2S	=	extended second segment
FAA	=	Federal Aviation Administration
K_{KIAS}	=	corrective factor for rate of climb

[1] M.S. Candidate, Aerospace Engineering, School of Engineering Matter Transportation & Energy, Student Member AIAA.
[2] Professor of Practice, Aerospace Engineering, School of Engineering Matter Transportation & Energy, Associate Fellow AIAA.

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
OEI	=	one engine inoperative
PLA	=	power lever angle
ROC	=	rate of climb (ft/min)
SET	=	specific excess thrust (climb gradient)
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 the Air Commerce Act of 1926 marked the beginning of federal regulation of aircraft design and operation. This act provided the-secretary of Commerce the ability to "issue airworthiness certificates for aircraft and major aircraft components."[1] The power to issue airworthiness certificates now resides with the Federal Aviation Administration (FAA), thus aircraft are much safer than what they used to be pre-1926. This act and its descendants effectively regulate which aircraft are today allowed to fly. Only those with a valid pilot's license and airworthiness certificate can take to the sky.

Indeed, the Federal Aviation Administration takes aircraft safety very seriously. An airworthiness certificate requires proof of compliance to many different criteria, including the incorporation of factors of safety and required redundancy. These requirements are detailed within Title 14 of the Code of Federal Regulations,[2] a resource the aircraft designer must religiously abide by should they want their design to pass airworthiness certification. For example, per 14 CFR § 25.303, commercial aircraft produced by the designer must include "a factor of safety of 1.5 … applied to the prescribed limit load which are considered external loads on the structure," unless otherwise specified by another regulation (such is the case for fittings – those require at "fitting factor" of at least 1.15 applied to each part, per 14 CFR § 25.625(a)). During the certification process, evidence of abiding by this regulation is typically backed up with a test to destruction.

In addition to mechanical design standards, the FAA specifies operational limits which pilots must abide by for safe flight. To prevent accidental stall when operating the aircraft, 14 CFR § 25.107(g) dictates that V_{FTO}, the final takeoff speed, must be selected so that it produces at least the gradient of climb prescribed by 14 CFR § 25.121(c), but may not be less than 1.18 times the reference stall speed, V_{SR}, and such that the aircraft has the maneuvering capability specified in 14 CFR § 25.143(h). For two-engine aircraft, 14 CFR § 25.121(c) requires the steady gross climb gradient to be no less than 1.2% at V_{FTO}.

There are further regulations which require that the aircraft must be safely operable under the critical engine failure condition. For two-engine aircraft, this means flight must be possible with only one engine operating. In the critical engine failure condition, two-engine aircraft are expected to maintain a steady gross climb gradient of no less than a positive gross climb gradient at V_{LOF} per 14 CFR § 25.121(a), and 2.4% at V_2 as per 14 CFR § 25.121(b). This same aircraft, as per 14 CFR § 25.149(b), is expected to maintain straight flight at the minimum control speed, V_{MC}, with a bank angle of no more than 5^{o}. Diving deeper into this regulation, 14 CFR § 25.149(g) mandates that the aircraft must retain sufficient lateral control so that it may roll through an angle of 20^{o} away from the inoperative engine in no more than 5 seconds. Surmising these regulations together, the FAA expects multi-engine aircraft to be capable of safely climbing, flying level, and turning, all in the critical engine failure condition.

To help facilitate the safe operation of aircraft, the FAA approves the contents of a manufacturer developed, evidence-based pilot’s operating handbook. This book is used by dispatch and pilots for mission planning purposes. It provides important cue speeds, or “V speeds,” for safe operation. There are also provided maximum dispatch weight guidance charts, otherwise known as WAT limit charts, as functions of airfield altitude and temperature, to ensure that regulation imposed minimum critical-engine-inoperative climb performance can be attained so long as the aircraft is flown to the prescribed cue speeds.

In fact, the FAA requires dispatch to use WAT limit charts for takeoff procedure planning, so much so that there’s a regulation which requires its use. Per 14 CFR § 121.189(a), “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”; that is, an aircraft may not legally leave the ground at a weight greater than what is specified by the WAT limit chart out of the interest of safe operation.

In addition to abiding by the guidelines specified by the WAT limit charts, 14 CFR § 121.189(d)(2) states that all aircraft are required to takeoff in a manner where they clear all close-in (end-of-runway) obstacles by at least 35-ft. Furthermore, per 14 CFR § 91.119, once an aircraft is outside of the airport boundaries, it is expected to never fly lower than 500-ft AGL. Since the FAA expects all commercial aircraft to fly safely in the critical engine inoperative case, the pilot needs to plan on clearing all downrange obstacles by a 500-ft margin.

Flight manuals developed to meet the minimum FAA-prescribed content and procedure contain only rudimentary information for climb. They may well omit detailed general climb performance (climb gradient) data. What is known is that the cue speeds at the very least will provide the minimum CFR-mandated climb gradient for takeoff provided by the WAT limit chart.

Neglecting ground roll, the takeoff procedure is separated into four distinct segments, as represented in Figure 1. Per 14 CFR § 25.121(a), during first segment climb where the aircraft is in the takeoff configuration while in the critical engine inoperative state, a two-engine aircraft must be able to produce a positive steady climb gradient with just one engine at the lift-off speed, V_{LOF}. Upon achieving V_{LOF}, the landing gear is stowed, the successful completion of which signals the beginning of second segment climb. Per 14 CFR § 25.121(b), the two-engine aircraft, in the critical engine inoperative state, is expected to produce a steady gross climb gradient of no less than 2.4% at the V_2 speed until reaching 400-ft AGL. Note that, per 14 CFR § 25.107(b), V_2 may not be less than 1.13 times V_{SR} for turbojet aircraft or 1.10 times V_{MC}, whichever is greater. Upon reaching 400-ft AGL, the aircraft may level off and accelerate to the flap retraction speed, at which the flaps can be stowed. Continuing into the fourth segment in the cruise configuration, 14 CFR § 25.121(c) dictates that the steady gross gradient of climb for a two-engine aircraft in the critical engine inoperative state may be no less than 1.2% at V_{FTO}. Note that V_{FTO} is defined in 14 CFR § 25.107(g); it must be selected so that it provides at least this climb gradient and is no less than 1.18 V_{SR} and provides the maneuvering capability detailed in 14 CFR § 25.143(h).

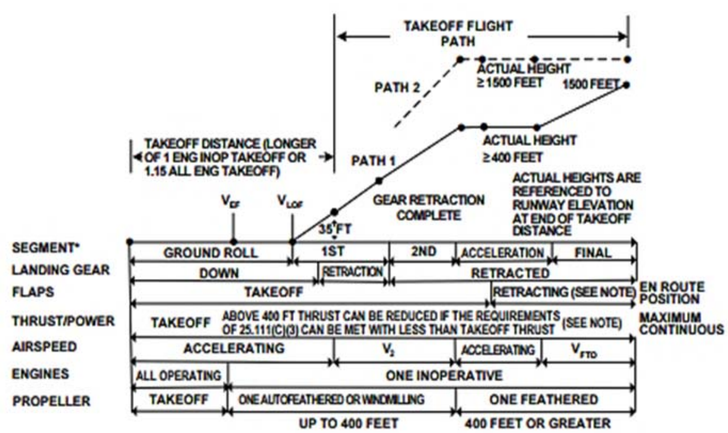

Figure 1. Typical takeoff profile. *Upon end of the-second segment climb, that being at 400-ft AGL or higher, the aircraft levels off and picks up speed for the fourth (final) segment climb. Note that takeoff procedures are planned with the critical engine inoperative case in mind, as evidenced by this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

The takeoff procedure is intricate because it is governed by many CFR regulations. The cue speeds prescribed by the CFR provide the minimum speed to attain at least the minimum absolute climb gradient. In practice, we may find better performance when the aircraft flies at speeds above the minimum statutory speed. To find the best flight profile, we studied "calibrated" models of real-world aircraft for take-off climb flying them at "book" speeds and at alternative speeds. From these trade studies, we could determine if the FAA's standard engine inoperative departure procedure: take-off climb to 400-ft AGL followed by flap retraction is the best practice when flying out of challenging (obstacle clearance) airports.

Pilots must ensure that their aircraft do not accidentally fly into terrain. This is not a pressing concern for airports which lack close-in obstacles. For example, Phoenix AZ (KPHX) is located on essentially flat terrain; departing on runway 25R, pilots must only pay attention to a 416-ft tall antenna, located 17,582-ft from runway, 600-ft left of centerline. To ensure aircraft will have some climb capability, all two-engine aircraft must attain a minimum gross climb gradient of 2.4% at the V_2 speed with a critical engine inoperative case.[3]

For other airports, such as Burbank CA (KBUR) nestled within a valley, nearby mountains must be accounted for. This is where Terminal Instrument Procedures (TERPS) comes into play.[4] TERPS defines a minimum vertical barrier around the planned aircraft flight path which must not be penetrated by any obstacle (mountain, tall building, radio tower, etc.). Thus, scheduled climb must be steep enough to avoid all obstacles within an aircraft's foreseeable flight path.

If the aircraft cannot meet the minimum required vertical separation, the aircraft must turn to avoid the obstacle. One such example of this is for Burbank CA (KBUR): for southwards departures on runway 15, there are nearby mountains which need be avoided. Here, the aircraft must turn to the west to avoid the obstacle. In addition, to clear the valley, the FAA standard instrument departure requires a climb gradient of 335-ft/nM (5.5%) through 2300-ft.

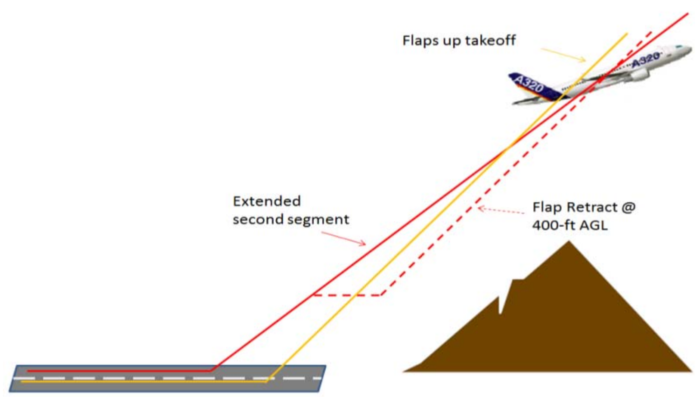

Figure 3. Schematic of E2S climb profile. *While a flaps up takeoff may provide the best climb gradient, the penalty of increased TODR and the need of close-in obstacle clearance needs to be considered. An E2S climb profile seeks to climb as efficiently as possible to clear close-in obstacles while minimizing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

FAA rules imply a standard departure procedure (see Figures 2 and 3), where the pilot begins flap retraction when the aircraft exceeds 400-ft AGL.[5] second segment climb performance is only guaranteed to this elevation. Recall that by 14 CFR § 25.121(b), the two-engine aircraft which has one engine inoperative is expected to produce a steady gross climb gradient of no less than 2.4% at the V_2 speed until reaching 400-ft AGL. Therefore, at altitudes greater than 400-ft AGL, the climb gradient is not regulated by the CFR and thus may be less than 2.4%.

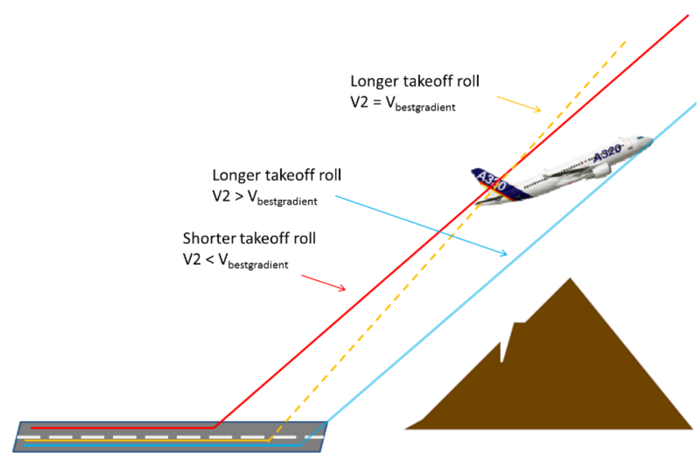

Figure 2. Repercussions of V_2 choice for E2S climb. *Available runway distance is a critical factor in takeoff planning. While takeoff speed can be traded for runway distance, there is an associated effect on the aircraft's climb efficiency which needs consideration.*

Bays & Halpin evaluated the takeoff performance of a C-130H using alternative flight-path profiles.[6] (Note that the C-130 is a military airplane, not flown to strict FAA rules; it also has a very comprehensive flight manual, C130J-1-1, that is more detailed than the typical commercial transport or executive jet.)[7] They discovered that an extended second segment (E2S) procedure, where the flaps are left in the take-off setting for a considerable period of time, provides a more favorable climb gradient which increased the aircraft's obstacle clearance capability. What is intriguing here is that this performance benefit stems from a change in piloting procedure; no modification to the airframe or powerplant were necessary.

By eliminating the low altitude third segment (an acceleration to flap retraction speed at 400-ft AGL), the effective close-in obstacle clearance capability increases. Flying this basic profile at a faster airspeed (i.e. beginning second segment climb at $V_2 + \Delta V$), further increases far-out obstacle clearance capability at the expense of additional takeoff distance and a decreased close-in obstacle clearance height. Either way, the authors thoroughly demonstrated that use of an E2S climb profile allows for additional climbing capability to existing aircraft without the need of expensive modifications to the airframe or powerplant. Pilots may use this improved performance to accommodate additional aircraft weight (i.e. more fuel or payload).

This work seeks to extend and generalize Bays & Halpins' work to see if E2S is a favorable procedure for any arbitrary turbofan powered commercial aircraft. Per the CFR, commercial aircraft are expected to reach V_2 35-ft above the runway, then typically level off after a short climb and accelerate to V_4 approximately 400-ft above the runway – but is this the best procedure for optimal aircraft performance with regards to obstacle clearance? If it is not the best practice, then when should this level off occur (if at all), and at what airspeed should the second and fourth segments be flown at to maximize an aircraft's obstacle clearance capability?

In order to answer these questions, we developed a "calibrated" model of the A320 to simulate its takeoff climb. Using this model, we will first identify if the A320 is scheduled to operate at airspeeds which maximizes its climb gradient performance. Following that, we will then determine if the FAA standard of takeoff climb to 400-ft AGL followed by flap retraction is really the best policy for obstacle-challenged airports.

II. Mathematical Foundation

Means of calculating interesting performance parameters is required to allocate any meaningful data. For this, we refer mainly to Takahashi's text, *Aircraft Performance and Sizing*,[8] which has a plethora of useful equations at disposal. Climb gradient and rate-of-climb are the most important performance parameters for obstacle clearance work.

The climb gradient is directly proportional to the specific excess thrust (SET),

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

which is simply the difference between thrust and drag, divided by aircraft weight. It is typical to express this value as a percentage, for 14 CFR § 25.121 establishes OEI minimum climb gradients as percentages.[3]

We may also calculate the rate of climb of the aircraft. For the pilot who wishes to hold a constant indicated airspeed, their climb rate may be calculated as,

$$ROC_{KIAS}(ALT, M) = 101.33 \;\; K_{KIAS}(ALT, M) \;\; SET(ALT, M) \;\; KTAS(ALT, M) \tag{2}$$

where the correction factor $K_{KIAS}(ALT, M)$ varies in expression, depending on the aircraft's altitude relative to the tropopause. For constant indicated airspeed climb below the tropopause, the calibration factor K_{KIAS} is expressed as,

$$K_{KIAS}(ALT \leq 36{,}089 \text{ - ft}, M) = \frac{1}{1 + 0.7 \;\; M^2} \tag{3}$$

As we are interested in carefully analyzing the A320's takeoff performance between a traditional climbout and an E2S climbout, a couple of tools are necessary for this task: (A) *EDET*, (B) *NPSS*, (C) *SKYMAPS*, and (D) *MISSION*, which we discuss below.

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

Developed by Feagin and Morrison from a careful analysis of nineteen subsonic and supersonic military aircraft and fifteen advanced or supercritical airfoil configurations, the "Delta Method … [estimates] the clean wing drag polar for cruise and maneuver conditions up to buffet onset, and up to approximately Mach 2.0".[9] *EDET* accepts an input file of pertinent physical parameters of an aircraft, and outputs estimated drag polars. An *EDET* model requires broad knowledge of wing characteristics, fuselage, horizontal and vertical tail geometry. Where precise data could not be found in the open literature, we made careful estimates using three-view line drawings. We used an enhanced version of *EDET*, that extends basic *EDET* mathematics with more complex form factor equations found in Takahashi, German, et al., to develop our aerodynamic database.[10] Because real aircraft have some "imperfections", such as fasteners and ridges, as well as flap tracks, *EDET* incorporates a "crud drag" correction; this adds extra drag onto the nominal drag count to better match reality. We adjusted this parameter so that the model's climb gradient at the V_2 and V_4 speeds closely reflect those suggested by the airplane flight manual. Using this *EDET* model, we will simulate takeoff climb cases with one engine inoperative (OEI).

For the OEI case, there are additional drag penalties to consider. When an engine fails, it not only stops producing thrust, it also develops additional airframe drag. We may approximate the additional drag penalty of an inoperative engine as,

$$\Delta C_{D_{ENG}} = n_{eng_{inop}} \frac{\pi\left(\frac{d_{fan}}{2}\right)^2}{S_{ref}} \tag{4}$$

Furthermore, there is a second drag penalty associated with the trim drag arising from the inoperative engine. When an engine fails, thrust and drag asymmetries induce a yawing moment that causes aircraft to "turn" away from the centerline. These moments must be counteracted through deflected rudders and ailerons. We estimate the drag addition associated with trim as,

$$\Delta C_{D_{TRIM}} \cong 0.001 \tag{5}$$

A typical takeoff procedure involves flap deflection to keep the TODR, and subsequently the *V* speeds, low. This comes with an associated drag penalty. For our purposes, we estimate the drag addition associated with leading-edge and fowler flap deflection as,

$$\Delta C_{D_{FLAPS}} \cong 0.021 \tag{6}$$

and this, as we found, holds best for the "Flaps 2" setting. Note that these additional drag counts are automatically applied on top of the AEO-calibrated *EDET* model drag polars for an OEI takeoff simulation.

For operation at high lift conditions, with deployed flaps, we will supersede the *EDET* drag-due-to-lift model with a simple quadratic formula,

$$C_{D_i} = \frac{C_L^2}{\pi\, AR\, e} \tag{7}$$

We calibrate the "Flaps 2" e so that the model's climb gradients at V_2 and V_4 matched those suggested within the corresponding pilot's manual. A degree of judgement and rationality is necessary when iterating e; it is easy to produce an unreasonable model of incredibly low crud drag and high induced drag. For this study, we found that an efficiency factor of $e \cong 81.72\%$ allowed the model to best-match the AFM data.

B. Numerical Propulsion System Simulation (NPSS)

To model performance, we also need a calibrated propulsion model; this is where *NPSS* comes into play.[11] This physics-based engineering tool models key engine parameters, for example: maximum turbine inlet temperature, reference bypass ratio, reference fan pressure ratio, etc. to produce five-column (thrust and thrust-specific fuel consumption as a function of speed, altitude, and throttle setting) propulsion data which can subsequently be used in our simulations.

C. SKYMAPS

This tool produces plots of key performance parameters, such as climb gradient and rate-of-climb. These plots express point performance for a specific aircraft configuration and weight as a function of flight speed and altitude. Our code utilizes an aerodynamics profile generated by *EDET* modified as necessary depending on the flap setting and engine-inoperative status, as well as five-column propulsion data from *NPSS*. Our point performance *SKYMAPS* plots are truncated to eliminate solutions where the required lift coefficient exceeds the maximum lift coefficient, or the engine thrust exceeds estimated drag.

D. MISSION

While *SKYMAPS* can provide point-performance information for an aircraft configuration, it is not capable in of itself of producing the actual flight path. In addition to visualizing how an aircraft's climb gradient or rate of climb is affected by the choice of V_2 or V_4, we need to visualize how an aircraft performs *over time and distance* due to choices in cue speeds and takeoff profile.

In an explicit point-mass simulation, the power lever angle (PLA), the aircraft flight speed (in Mach or-KIAS) and altitude are the principle state variables the engineer uses to shape the trajectory. At each integration step, the computer program updates the other implicit simulation variables: the simulated elapsed flight time, the actual distance flown, the actual altitude, the actual speed, the actual flight weight, the actual amount of fuel consumed, and the actual angle-of-attack. Rate of climb and rate of acceleration are byproducts of the simulation command structure.

Our takeoff simulation employs three "modes" which can be executed in sequence. They are: (1) ground run, (2) constant-KIAS climb, and (3) level acceleration. For our purposes, the ground run begins at rest and continues until the aircraft reaches V_2. While V_2 is officially defined as the speed at which an aircraft is 35-ft AGL off the ground, this value was used in absence of V_{LOF}, which was not present in the A320 flight manual used in this study.[12] At V_2, we switch the *MISSION* code to the constant-KIAS climb mode to simulate the second segment climb. For building an E2S profile, this constant-KIAS climb is carried all the way to 5,000-ft AGL. For a traditional climbout profile which incorporates segments two through four, this constant-KIAS climb continued until the aircraft reached a specified altitude. Here, the simulation begins a level acceleration until the aircraft reaches the V_4 speed. At this point, the flaps are retracted and the constant-KIAS climb mode is activated once again to simulate fourth segment climb which continues all the way to 5,000-ft AGL. All modes were executed with the power lever angle fully forward (i.e., at max throttle).

To thoroughly investigate and compare how a traditional takeoff profile performs against the E2S profile, we created multiple traditional four-segment profiles for flap retraction altitudes starting from 400-ft AGL to 4,900-ft AGL. Similarly, we created two E2S profiles: one for the "clean wing" configuration and one for takeoff with deployed flaps.

The reader should note the limitations of this study; as V_{LOF} speeds were not reported in the AFM used for this exercise, we chose to do the following: (1) for the clean E2S departure, V_4 was used in place of V_{LOF}, and (2) for the traditional and "Flaps 2" E2S profiles, V_2 was used in place of V_{LOF}. Furthermore, the reader should note that the simulation starts at rest with one engine inoperative, as opposed to forcing one engine to fail at the V_1 speed. These limitations come at the expense of longer ground roll, so TODR values reported here are *very* pessimistic in nature.

For the sake of discussion, we will neglect any runway distance, tire speed rating, and brake energy limitations in our analysis. We also disregard any short term "takeoff thrust" power restrictions.

III. Analysis

In our pursuit of generalizing and expanding upon the work of Bays & Halpin,[4] Beard's thesis work examined three contemporary aircraft: (A) Airbus' A320, (B) Boeing's B737-500, and (C) Bombardier's CL-600.[13] In this paper, we will restrict our discussion to our reverse-engineered Airbus A320 model, which was calibrated to best match climb gradient data supplied in a certified airplane flight manual (AFM).[12]

A. Determining Optimum Flight Speed for Climb Gradient

In Figures 4 and 5, we demonstrate how climb gradient is affected by the choice of flight speed and airport altitude. We restrict our performance estimates for flight at standard pressure and temperature conditions.

With all aircraft, one can expect it to perform better the lighter it becomes; that is to say that performance parameters such as climb gradient and rate of climb should improve with a reduction in weight. This conclusion is readily available upon a comparison of Figures 4 and 5.

In Figure 4, which represents climb gradient performance at MTOW, we can see that the yellow band represents the region in which the critical-engine inoperative A320 with "Flaps 2" may attain a gross climb gradient greater than 2.1%. As the aircraft increases in altitude, the climb gradient diminishes. Similarly, flying faster or slower than 171-KIAS reduces the aircraft's climb potential.

Now referring to Figure 5, which represents climb gradient performance at a much lighter weight, we note that the aircraft can fly over a much wider range of airspeed and climb to a much greater altitude thanks to the reduction in weight. The yellow region—the region of optimum climb gradient—has shifted to the left, with the maximum occurring at 149-KIAS. Indeed, the lighter the aircraft, the lower the flight speed required to maximize climb gradient.

To identify the speed at which maximum climb gradient occurs, we ran our point performance tools at a wide variety of weights, speeds and altitudes. We plot the locus of best performance points which are defined by speed and weight. Plotting up these results produces Figures 6 and 7.

Now investigating the relationship between cue speeds and climb gradient, we note that for a "Flaps 2" departure at $W = 172{,}800$-lbm, the book suggests $V_2 = 153$-KIAS. This corresponds to the yellow

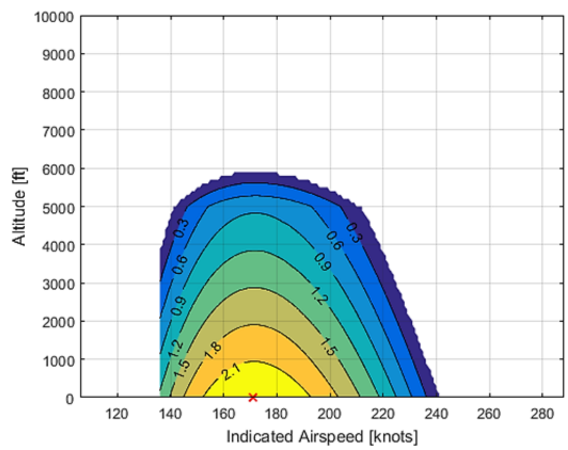

Figure 4. A320, $W = 172{,}800$-lbm OEI "Flaps 2" climb gradient data. *The most efficient climb gradient resides near sea level, as denoted by the yellow region. Climb gradient is maximized at 171-KIAS, marked by the red X. Contour values presented as a percentage.*

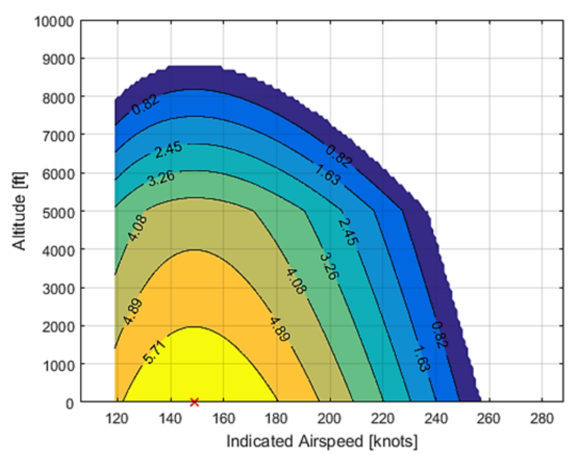

Figure 5. A320, $W = 132{,}800$-lbm OEI "Flaps 2" climb gradient data. *Due to its lighter weight, the region of optimum climb gradient has shifted to a lower speed. Here, maximized climb gradient resides at 149-KIAS, marked by the red X. Contour values presented as a percentage.*

region in Figure 4, on the far left; at that point, $SET \cong 2.13\%$. Per the aforesaid figure, we can maximize the climb gradient simply by introducing an overspeed (i.e., $V_2 + \Delta V$ to obtain best climb gradient at the red X). Indeed, the best climb gradient at the heaviest weight is $V_2 + 18 = 171$-KIAS, with $SET \cong 2.40\%$. By introducing an overspeed, the climb gradient of the A320 increases by 0.27%. While overspeeding from V_2 to a $V_2 + \Delta V$ can maximize climb gradient, do note that there is an associated penalty to required takeoff distance (TODR) for which we must pay.

For a $W = 132{,}800$-lbm with "Flaps 2" and critical-engine inoperative departure, the book recommends $V_2 = 133$-KIAS, so $SET \cong 6.26\%$ from Figure 5. This resides within the yellow region in the aforesaid figure, but it is not as close to the center (where maximum climb gradient resides) as we would like. Introducing an overspeed to obtain the best climb gradient, we calculate $V_2 + 16 = 149$-KIAS, where $SET \cong 6.52\%$. Thanks to the overspeed, the A320's climb gradient increases by 0.26%.

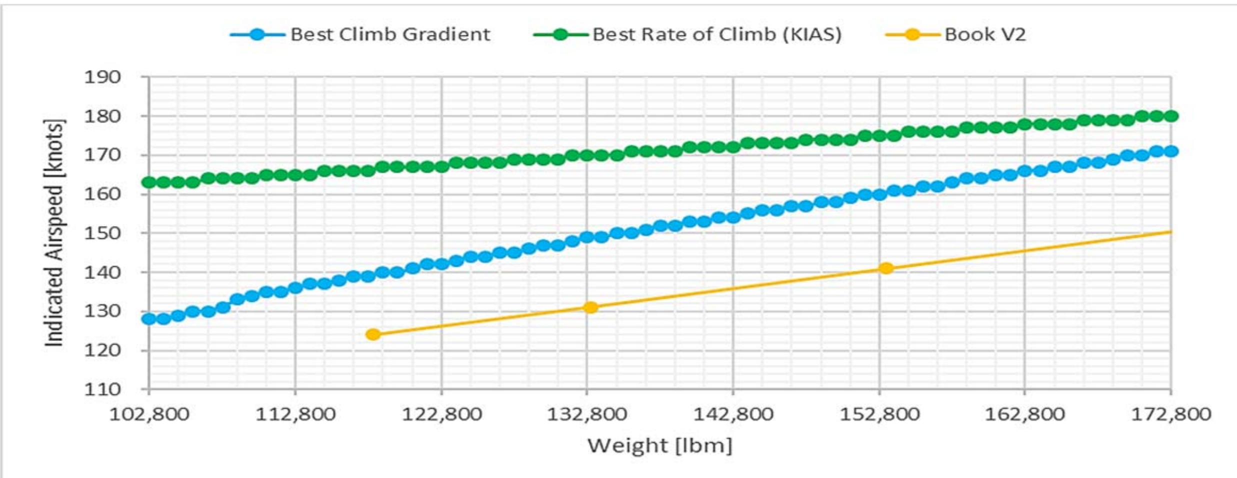

Figure 6. Airbus A320, OEI "Flaps 2" performance data. *A $V_2 + \Delta V$ takeoff procedure would help close the gap between the published V_2 speed and that which maximizes the aircraft's climb gradient capability.*

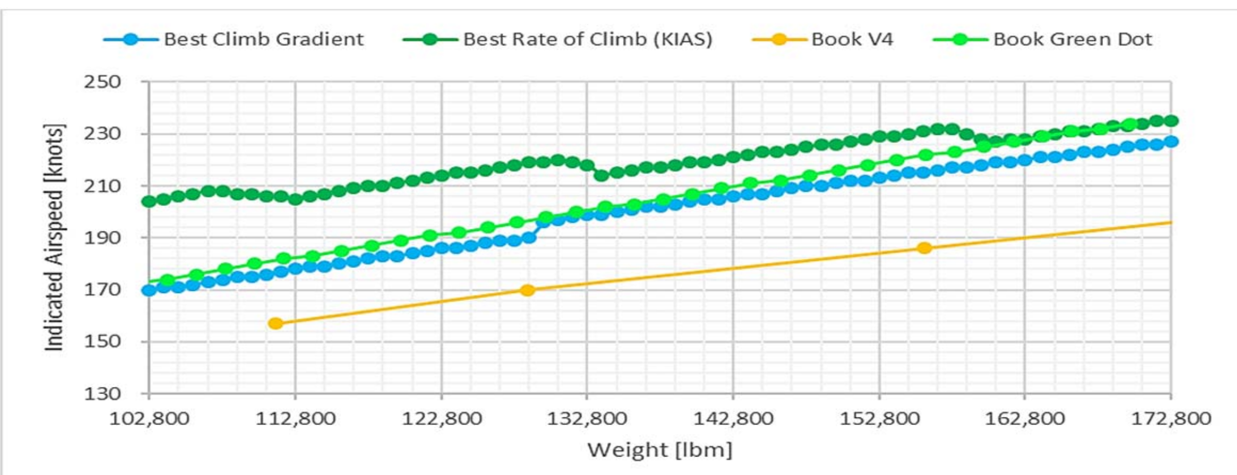

Figure 7. Airbus A320, OEI cruise performance data. *Evidently, the green dot speeds for this aircraft correlate strongly to the SKYMAPS-estimated best speed for optimal climb gradient.*

Based on these preliminary results, we observe at high gross weights that an elevated V_2 yield a tangible increase in climb performance. At these heavy weights, it appears that a larger overspeed is necessary to obtain best climb gradient; however, this comes at the penalty of increased TODR. Similarly, the required overspeed in order to achieve best climb gradient at a lighter weight seems to be smaller; thus, a smaller associated TODR penalty is expected. Therefore, the aircraft weight, required overspeed, and TODR penalty are all proportional to each other, the latter of which is an important consideration in the aircraft dispatch problem.

Interestingly enough, Airbus likes to advocate for a $V_2 + 10$ takeoff when all engines are operative and the runway distance available allows it.[14] Based on the evidence presented in the previous figures, we can say that this practice makes sense. Our reverse-engineered model suggests that a $\Delta V = 10$-KIAS does *not* provide enough overspeed achieve the ideal gradient, it *will* provide some improvement compared to climb at V_2 – after all, runway distance can be a limiting factor and hence ΔV can only be elevated so much before takeoff ground roll becomes excessive.

In addition to advocating for a $V_2 + 10$ takeoff when able, Airbus has listed V_{FTO} cue speeds, otherwise known as "Green Dot" speeds—the recommended best climb speed for the clean wing, OEI case—within the pilot's manual.[14] These speeds are compared to the experimental data in Figure 7. We believe that these speeds are well-chosen because we found strong correlation between "Green Dot" speeds and the best climb gradients predicted with our reverse-engineered model.

The analysis of takeoff flight paths requires one to "derate" the gross flight path into a net flight path. Quoting the relevant regulation, "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" as per 14 CFR § 25.115(b). This regulation creates a "margin of safety" of sorts by forcing the dispatcher to assume that the aircraft has 0.8% less climb capability than it actually has when planning the dispatch procedure. Ergo, while all discussion up to this point was in terms of gross gradient, we are pressured to also address how the flight path appears as in terms of net climb gradient.

Aircraft designers may also be aware that there exists another "derate" which must be applied to en route flight paths. Quoting the regulation directly, "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", as per 14 CFR § 25.123(b). This regulation only applies when the aircraft is in the en route configuration (i.e., flaps stowed and gear up) at a speed no less than V_{FTO}, as defined in 14 CFR § 25.123(a). As we are interested in comparing how the A320's climb performance fares when best climb gradient cue speeds (or "idealized" cue speeds) are applied, some might wonder if said idealized speeds qualify as V_{FTO} cue speeds, as they align quite closely to the "Green Dot" speeds per Fig. 7; thus, is the 1.1% derate to the climb performance necessary? While one may argue that our calculated idealized speeds should be considered as V_{FTO} speeds as models have a slight margin of error associated, another may argue that a strict application of 14 CFR § 25.123(a) (i.e., at a speed no less than V_{FTO}) precludes application of 14 CFR § 25.123(b). We stick to the latter argument, believing that a uniform 0.8% climb gradient derate for all studied flight profiles is easier for our readers to digest than presenting plots which have a mixed 0.8% and 1.1% climb gradient derate. Therefore, all net climb gradient profiles presented herein are derated by 0.8% as per 14 CFR § 25.115(b).

B. Identifying Profiles Which Maximize Obstacle Clearance

Understanding how the choice of cue speed affects climb gradient, the astute reader might ask "so, what?" While it is nice knowing how overspeeds play into maximizing the aircraft's climb gradient, we still have learned nothing on how this (and how extended second segment) affects overall obstacle clearance. Ergo, we are faced with the need of simulating the takeoff profile in order to identify which procedure maximizes obstacle clearance.

Utilizing *MISSION* to accomplish this task, we simulated multiple variations of traditional takeoff profiles (with the altitude at which third segment begins varying). Additionally, we simulated extended second segment climbs, one which incorporated flaps deployed as well as one with a strictly clean wing. All cases were ran using a set of "book cue speeds" from the AFM as well as "optimized cue speeds" predicted by *SKYMAPS* which maximized the climb gradient. Plotting up the results, Figs. 8 and 9 represent various takeoff profiles at the heavy weight case, plotting altitude as a function of distance; the former was generated using book speeds while the latter was created using optimized speeds. In similar fashion, we also present Figs. 10 and 11, which represent various takeoff profiles at the light weight case. Note that all four of these figures and the discussion accompanying them are presented in terms of gross climb gradient.

First inspecting Figure 8, which represents all studied takeoff profiles performed at book speeds, we can immediately that an E2S is superior in maximizing the A320's obstacle clearance capability compared to a traditional profile. Take the 8-nM mark, as an example; while the A320 will still be completing the third segment acceleration at 400-ft AGL, it can very well be at approximately 890-ft AGL with a clean E2S profile or at 1000-ft AGL using a "Flaps 2" E2S profile. For close-in obstacles, "Flaps 2" E2S maximizes obstacle clearance for this aircraft. However, a clean E2S profile maximizes far-out obstacle clearance, albeit this comes with a TODR penalty, increasing the overall required runway distance to roughly 15,800-ft. Note that both profiles are equivalent in obstacle clearance 22.60-nM out from the runway, at approximately 2,824-ft AGL. Indeed, the extended second segment departure is worth consideration in the fact that it makes use of an aircraft's existing capabilities and simply utilizes a procedureal change to maximize obstacle clearance.

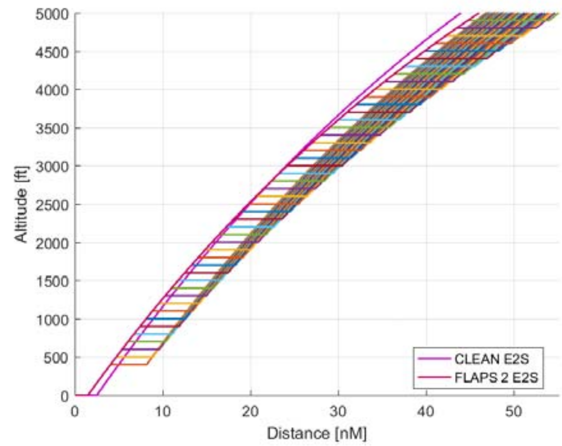

Figure 8. A320, OEI, $W = 172,800$-lbm, gross takeoff profiles using book speeds. *Either flavor of an extended-second segment climb produces greater obstacle clearance than a traditional profile.*

Using a traditional profile with transition altitude of 400-ft AGL as a reference, we note the travel time to be approximately 895-sec, with 2,643-lbm of fuel burned. For the takeoff flaps E2S profile, the travel time requires 1,066-sec, with 3,098-lbm of fuel burned; this correlates to a fly time *increase* of 2.84 minutes and an additional 455-lbm of fuel burn. The clean E2S profile provides minimal flight time and fuel burn at 822-sec and 2,418-lbm, which is a savings of 73.8 seconds and 225-lbm of fuel compared to the baseline. Evidently, per Figure 8, this profile is best used for far-out obstacle clearance, but this does come at the cost of a marked increase in TODR. When comparing our reference profile with others of higher transition altitudes, we note that time to complete the manuever and fuel burn increase – thus rationalizing the concept of an "early cleanup". However, we do want to note to the reader that these changes in flight time and fuel burn are not significant, as seen in this analysis.

Per the results displayed in Figure 8, we note that if we compare the traditional profiles alone, a dispatch with a 400-ft AGL transition altitude has relatively poor close-in obstacle clearance, but excels at far-out obstacle clearance, completing the climb to 5,000-ft AGL in the shortest distance. Conversely, a late cleanup on the flaps such as at 4,900-ft AGL provides for increased close-in obstacle clearance, but can potentially hurt far-out obstacle clearance, with this one completing the climb to 5,000-ft AGL last.

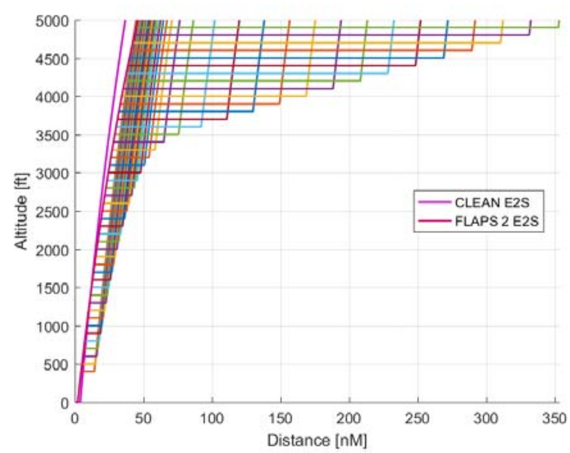

Figure 9. A320, OEI, $W = 172,800$-lbm, gross takeoff profiles using optimized speeds. *Utilizing overspeeds which maximizes climb gradient can benefit clean E2S and profiles which cleanup early on the flaps, but severely hurt those profiles which implement a late cleanup.*

Summarizing the information thus far, we can see that from the perspective of minimizing fuel burn for this aircraft, it is best to clean up early; minimum fuel burn and climb time resides with a clean-wing extended second segment. From the persepective of obstacle clearance, the best profile choice depends on the positioning of the obstacles in an aircraft's flight path. For a dispatch with nearby obstacles, a late cleanup or flaps-out E2S will increase close-in obstacle clearance. Conversely, for distant obstacles, an early cleanup or clean-wing E2S will increase far-out obstacle clearance. For situations where TODR precludes the use of a clean E2S profile, a “Flaps 2” profile may be used in substitution as this provides obstacle clearance capability greater than that provided using a traditional dispatch.

Indeed, we can increase the obstacle clearance capability of the A320 simply by implementing an operational change which extends the second segment climb. But how is the performance of the A320 affected when we implement this and make use of cue speeds optimized for maximum climb gradient? Applying cue speeds optimized for best climb gradient, we produce flight path results in Figure 9. Similar to what was seen in Figure 8, there is a crossover point at which the clean E2S and “Flaps 2” E2S profiles are equivalent in obstacle clearance; this occurs at approximately 11.65-nM out from the runway, with an altitude of 1,436-ft AGL. Curiously, there appears to be another crossover point at which the “Flaps 2” E2S and traditional profile with cleanup at 400-ft AGL intersect – this point is approximately at 41.98-nM out from the runway, at an altitude of 4,688-ft AGL. Also similar to what was observed previously, we note that a “Flaps 2” E2S profile maximizes clearance capability for obstacles closer than 11.65-nM from the point of liftoff, whereas a clean E2S profile maximizes far-out obstacle clearance capability past that point.

Cue speed choice is a significant factor in the resulting flight profile, as observed from the odd appearance of Figure 9. Upon close inspection of this figure, we note that thanks to the use of optimized cue speeds, the clean-wing E2S profile produces even more obstacle clearance than previously, completing the trip to 5,000-ft AGL in 36.77-nM, down from 43.98-nM using book speeds. The flaps-out E2S profile has slightly increased obstacle clearance capability, albiet not so much that it is appreciable. Early cleanup profiles also have some increase to far-out obstacle clearance (completing the trip to 5,000-ft AGL with savings up to 2-nM for the earliest cleanup), but at the expense of reduced close-in obstacle clearance. This phenomenon of exchanging close-in obstacle clearance for increased far-out obstacle clearance by overspeeding was observed by Bays & Halpin in their work.[4] However, clearly there is a limit where overspeeding hurts the overall flight profile; in particular, for profiles with a later cleanup on the flaps, a larger distance is required in order to meet the V_4 speed, ultimately hurting far-out obstacle clearance capability (this is perhaps due to the heavy aircraft weight, thus requiring higher V_4 speeds). That is to say, overspeeding really only works for early cleanup or clean E2S profiles to increase far-out obstacle clearance, the former of which trades close-in obstacle clearance and the latter of which trades TODR. For the reader’s interest, *MISSION* reports a TODR of 23,393-ft for the clean E2S dispatch – which again can preclude use of such a profile; in this case, a “Flaps 2” E2S dispatch will maximize mid-range obstacle clearance capability (up to 41.98-nM), past which a traditional profile cleaning up at 400-ft AGL provides marginally better clearance capability.

In light of the extremly soggy performance for particular profiles displayed in Figure 9, it would seem that our discussion regarding optimized cue speeds is garbage. We contend this is not completely the case; recall that our optimized cue speeds aim to maximize the climb efficiency, not necessarily the rate of climb. Recall our baseline profile, that being a traditional profile with transition altitude at 400-ft AGL (using book speeds); the time traveled is approximately 895-sec, with 2,643-lbm of fuel burned. With a clean-wing E2S profile using optimized cue speeds, climb time and fuel burn are 608 seconds and 1,813-lbm, respectively, which are down from 822 seconds and 2,418-lbm of fuel burn using book speeds. Note that the clean-wing E2S profile provides minimum flight time and fuel burn out of the lot of profiles studied for this trade. Using a traditional profile with cleanup at 400-ft AGL but using optimized cue speeds, we note a flight time of 759-sec and fuel burn of 2,279-lbm. Later cleanups on the flaps results in increased flight time and fuel burn. The exception to this is the flaps-out E2S profile, which with optimized cue speeds results in a climb time of

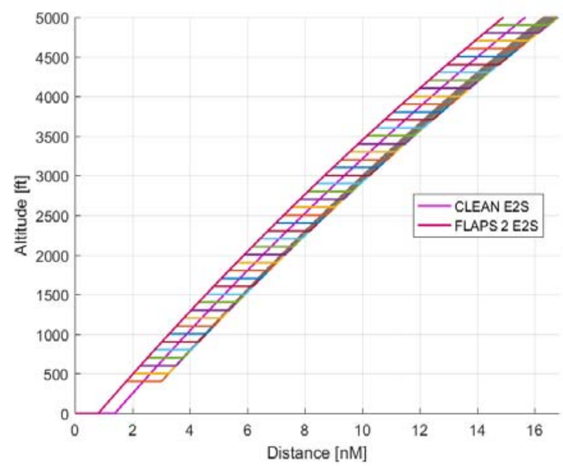

Figure 10. A320, OEI, $W = 132,800$-lbm, gross takeoff profiles using book speeds. *Due to the much lower weight, we can see the aircraft’s obstacle clearance capability has greatly increased.*

959-sec and fuel burn of 2,800-lbm, but only slightly reduced from the 1,066-sec and 3,098-lbm of flight time and fuel burn using book speeds. As noted before, these reductions are not terribly significant given that an aircraft who loses an engine during take-off climb is unlikely to continue to its originally scheduled final destination.

Therefore, we conclude that the A320 can, at the maximum takeoff weight, maximize its obstacle clearance simply by using some flavor of the E2S takeoff profile alone (with book speeds), which comes with collateral savings in travel time and fuel. For close-in obstacles, a flaps-out E2S profile is best; conversely, for far-out obstacles, a clean-wing E2S profile is best, but this comes with a TODR penalty. Application of cue speeds optimized for maximizing climb gradient can be applied to maximize the clean-wing E2S profile's obstacle clearance capability, but this further hurts TODR. Traditional profiles can also take advantage of the overspeed to increase their far-out obstacle clearance capability while trading close-in obstacle clearance capability instead. Maximizing clean-wing time appears to give savings in flight time and fuel burn.

Investigating the lighter weight cases now, Figure 10 represents all studied takeoff profiles calculated using book speeds. While we can see here that, indeed, an extended second segment climb increases obstacle clearance over traditional profiles, only one flavor makes sense; that is, the flaps-out E2S profile maximizes obstacle clearance capability for both close-in and far-out obstacles. This result is different than that we observed for the heavyweight case; there, we saw the choice of E2S profile depends on the placement of obstacles, for the flaps-out E2S profile performed best at overcoming close obstacles whereas the clean-wing E2S profile did well at overcoming far obstacles. Indeed, there is a careful interplay of aerodynamics and weight that affects the overall flight profile and which E2S profile is best for the mission at hand.

Looking into the numbers that accompany Figure 10, we note that, expectedly, the clean-wing E2S minimizes flight time and fuel burn at 344-sec and 1,013-lbm, respectively. Just as before, we also note that an early cleanup on the flaps reduces climb time and fuel burn; the exception to this rule of thumb is flaps-out E2S, which is moderate in flight time and fuel burn at 407-sec and 1,184-lbm, respectively.

Investigating the takeoff profiles using a lighter A320 and optimized cue speeds, the results of which are given in Figure 11, we can see that the obstacle clearance capabilities of all profiles are somewhat *reduced*, with the exception here being the clean-wing E2S dispatch. Unlike the idealized speed case presented in Fig. 9, we see that the penalty of applying overspeeds at a lighter weight implies a reduction in time spent executing the third segment acceleration – a segment which can be seen as "wasteful" to the overall climb efficiency in the fact that that segment is not used for climb. Similar to the idealized speed case presented in Fig. 9, here we observe that the climb slope of the clean E2S profile is greater than the flaps-out E2S profile. This indicates that if the second segment climb was extended further than 5,000-ft AGL, a clean E2S departure would likely overtake a flaps-out E2S departure in terms of far-out obstacle clearance capability. For this study, though, the flaps-out E2S profile is superior in maximizing obstacle clearance – to 5,000-ft AGL, at least.

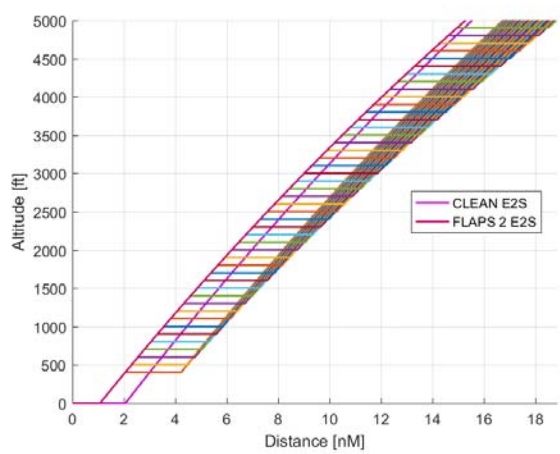

Figure 11. A320, OEI, $W = 132{,}800$-lbm, gross takeoff profiles using optimized speeds. *Interestingly, the obstacle clearance performance with optimized speeds is soggier than that using book speeds at this weight; the takeoff flaps E2S profile still provides the best obstacle clearance out of the profiles surveyed here, though, as expected.*

Inspection of the numbers behind Figure 11 reveals that, unsurprisingly, the clean-wing E2S profile provides for minimized flight time and fuel burn at 302-sec and 897-lbm, respectively. Similarly, as with all of the previous outcomes, we see that an early cleanup on the flaps leads to reduced climb time and fuel burn, the exception to this being the flaps-out E2S profile, which has a moderate flight time of 337-sec and fuel burn of 1,102-lbm. As always, in the context of this analysis, these figures are not significant.

While having the capability to visualize an aircraft's true, gross climb performance capability is useful with respect to aircraft design, in reality, this information is never used for dispatch purposes. Indeed, per 14 CFR § 25.115(b), those individuals planning the dispatch procedure must consider the aircraft's net climb performance capability; an aircraft's net climb performance capability is simply the gross climb gradient minus 0.8%. For example, an achievable 1.2% fourth-segment gross climb gradient is equivalent to a 0.4% fourth-segment net climb gradient. As stated previously, this essentially provides a pessimistic outlook of an aircraft's climb performance, which is particularly important for abiding by the takeoff minimums dictated by standard instrument departure procedures. While that topic falls outside of the scope of this paper, what we will do is provide the net flight path comparisons to the gross flight paths studied thus far.

While Fig. 8 presented the A320's flight profiles at $W = 172{,}800$-lbm in terms of gross climb gradient, Fig. 12 presents them in terms of net climb gradient. The effect of the 0.8% degradation is quite apparent upon a quick comparison of the distance scales between these two figures. On an examination of the gross flight path profiles, we see that all of these dispatches complete in no more than approximately 55-nM; however, when derating these gross flight path profiles by a factor of 0.8%, these net flight paths can require up to approximately 84-nM to fully complete! Indeed, the application of a degradation to already-soggy climb gradient performance hurts our perspective of this aircraft's OEI performance. While in Fig. 8, we found that use of "Flaps 2" E2S maximizes close-in obstacle clearance capability and that a clean-wing E2S flyout maximizes far-out obstacle clearance capability, we can see that the trends suggested here are somewhat the same. For example, in Fig. 8, we saw that at distances closer than 22.60-nM, "Flaps 2" E2S is an excelleng choice in maximizing obstacle clearance capability. Conversely, for obstacles further than 22.60-nM, a clean-wing E2S dispatch will provide optimum obstacle clearance capability. A similar story can be told for Fig. 12. For all obstacles closer than 18.27-nM, a "Flaps 2" E2S dispatch will maximize clearance over those obstacles. Conversely, for obstacles which reside further than 18.27-nM, a clean-wing E2S flyout will maximize far-out obstacle clearance capability. Should an infeasibly high TODR preclude the execution of a clean E2S dispatch, a traditional dispatch with flap retraction at 400-ft AGL can be substituted to provide optimal clearance for obstacles past 46.28-nM, with a "Flaps 2" E2S dispatch providing better close-in obstacle clearance capability for obstacles nearer than 46.28-nM.

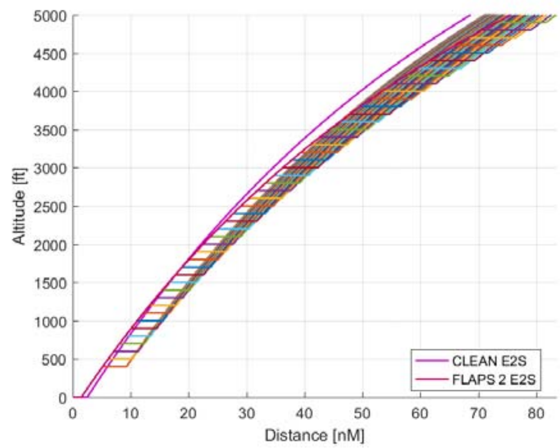

Figure 12. A320, OEI, $W = 172{,}800$-lbm, net takeoff profiles using book speeds. *Unlike in Fig. 8, here we see the "Flaps 2" E2S dispatch provides maginal far-out obstacle clearance capability when compared to traditional profiles which clean up early on the flaps. All profiles also take a significantly longer distance to complete the climb.*

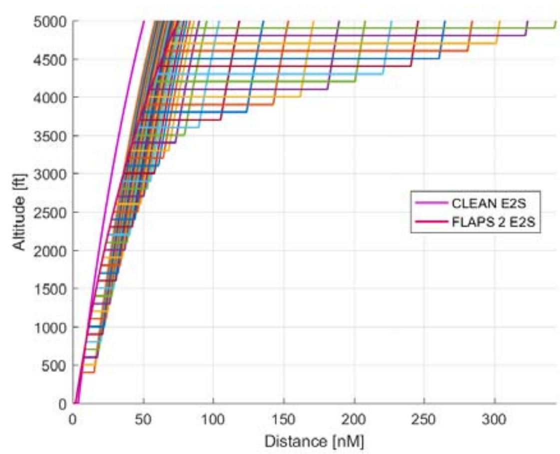

Figure 13. A320, OEI, $W = 172{,}800$-lbm, net takeoff profiles using optimized speeds. *Curiously, it seems that the traditional dispatch with flap retract at 4,900 ft-AGL profile completed in a shorter distance here than in Fig. 9. This was an odd result, considering that all climb profiles here are derated by 0.8%; one would expect all flight profiles to take longer to complete as the climbing capability is technically diminished.*

Also presenting the idealized flight profiles in terms of net climb gradient, we produce Fig. 13, which plots the A320's net flight path at a dispatch weight of $W = 172{,}800$-lbm. Of course, the immediate and obvious conclusion of this plot is that all of these flight profiles are "drawn out" similar to Fig. 9. Naturally, this is due to the fact that the V_4 cue speed is remarkably high, so a long third-segment acceleration is required to reach this cue speed. Then again, none of that is new and interesting information for we already knew this from an earlier discussion. What is different here is that, as the climb gradient is derated by 0.8%, the “crossover point” at which the E2S profiles are equivalent in obstacle clearance capability is different. For example, in Fig. 9, we find that for obstacles closer than 11.64-nM, “Flaps 2” E2S provides superior obstacle clearance capability; conversely, for obstacles which reside further than 11.64-nM, a clean-wing E2S dispatch provides best clearance capability. While we can say that there exists a crossover point here as well, the location of this point has shifted slightly, as we saw in the prior case. Here, in Fig. 13, we see that the clean-wing E2S and “Flaps 2” E2S profiles intersect at approximately 9.37-nM, which correlates to an altitude of approximately 795-ft AGL. Therefore, for all obstacles which are closer than 9.37-nM, a “Flaps 2” E2S dispatch provides the best chance of successfully overcoming those obstacles; conversely, for all obstacles which reside further than 9.37-nM, a clean-wing departure provides optimal obstacle clearance performance. In the event that TODR precludes the use of a clean-wing E2S dispatch (which will likely happen), a traditional profile which incorporates an early cleanup on the flaps serves as an acceptable substitution. These two profiles cross at approximately 36.17-nM away from the liftoff point on the runway; so while a “Flaps 2” profile provides optimum close-in obstacle clearance capability for obstacles nearer than that distance, those which reside further than 36.17-nM are best overcome using a profile which incorporates an early cleanup on the flaps, such as at 400-ft AGL. This case assumes that use of a clean-wing E2S dispatch is precluded due to a TODR constraint.

As we noted in that short exercise of comparing the gross and net flight profiles at a dispatch weight of $W = 172{,}000$-lbm, the visible trends are still the same. For example, at this particular weight configuration, it is not ideal to pursue the use of cue speeds which maximize climb gradient as that results in a significantly long third-segment acceleration. Sticking with the case that uses book cue speeds, we see that both extended second segment climb profiles can provide additional obstacle clearance capability where traditional profiles cannot, although it is apparent the “Flaps 2” E2S profile looks slightly more soggier due to the 0.8% derate – there are additional options which provide better far-out obstacle clearance capability. What has changed, really, is the location of the “crossover point” which drives one’s selection of climbout profile which provides maximized obstacle clearance capability.

Do these findings between net and gross flight paths necessarily relate to all weight settings? To find out, we will also examine the net flight paths of the A320 at $W = 132{,}800$-lbm. The net flight paths of the aircraft at this weight setting using book cue speeds is provided in Fig. 14. Compared to its gross counterparts in Fig. 10, we can see that all net flight profiles require a longer distance to complete the climb to 5,000-ft AGL – an expected outcome, as the climb gradient is derated by 0.8% on each simulated flyout. However, as far as differences between these two figures go, that appears to be it. As we had observed in Fig. 10, a “Flaps 2” E2S flyout provides superior close-in and far-out obstacle clearance capability due to the weight reduction; we come to the same conclusion here. Therefore, irrespective of analyzing the gross or net climb gradients, at lighter dispatch weights we can expect end result of the analysis to point to the idea that the “Flaps 2” E2S flyout provides the best obstacle clearance capability at all altitudes through 5,000-ft AGL.

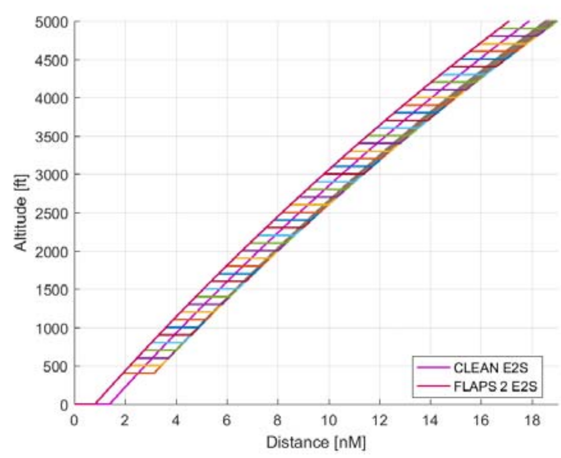

Figure 14. A320, OEI, $W = 132{,}800$-lbm, net takeoff profiles using book speeds. *Bearing the resemblance of Fig. 10, we see here that the “Flaps 2” E2S dispatch provides optimum obstacle clearance capability.*

Comparing the net flight paths presented in Fig. 14 to their “idealized” counterpart which uses optimized cue speeds, we refer to Fig. 15. Unsurprisingly, this figure bears the resemblence of the idealized gross flight paths presented in Fig. 11 as the current figure only implements a 0.8% derating on the climb segments; consequently, due to this pessimistic outlook on climb performance, we can see that the distance required to complete all flyouts has increased slightly – yet another unsurprising finding. Recall that in Fig. 11, we found that from the perspective of idealized gross flight paths, that the climb slope of the clean-wing E2S profile was greater than that of the “Flaps 2” E2S flyout. This leads to the conclusion that at some point, the clean-wing E2S dispatch will provide better far-out obstacle clearance than will the “Flaps 2” E2S climb. In the idealized net flight paths, we can see this is definitely the case; at approximately 17.06-nM from the point of liftoff on the runway—which correlates to approximately 4,885-ft AGL, the clean-wing E2S dispatch overtakes the “Flaps 2” E2S climbout. This means that at distances further than 17.06-nM, the clean-wing E2S flyout will provide optimum obstacle clearance capability; conversely, at distances closer than this point, a “Flaps 2” E2S climbout is best in providing maximized obstacle clearance. In the likely event that the clean-wing E2S’s TODR becomes a limiting factor, a “Flaps 2” E2S dispatch provides second-best obstacle clearance capability.

Evidently, from our short exposée in comparing gross and net flight paths, while general, overarching trends tend to remain the same despite the 0.8% derate in climb performance, specific points at which one E2S flyout is “better” than the other tends to shift. For example, at heavier dispatch weights, we have observed that a “Flaps 2” E2S dispatch provides optimum close-in obstacle clearance capability, whereas a clean-wing E2S flyout provides better far-out obstacle clearance capability. This overarching trend was visible between Figs. 8 and 12. Between these two figures, we can easily see that the overlap point of the “Flaps 2” and clean-wing E2S profiles differs in distance and altitude. In the event a clean-wing E2S dispatch is precluded due to a limiting TODR, a gross flight path analysis shows that a “Flaps 2” E2S dispatch should be used for far-out obstacle clearance capability; however, a net flight path analysis says a traditional profile which retracts the flaps at 400-ft AGL is a better choice. At lighter weights, the gross and net flight path analysis indicates that a “Flaps 2” E2S dispatch is best for both close-in and far-out obstacle clearance capability. Analyzing the idealized gross flight path also leads to the above conclusion, but using an idealized net flight path analysis indicates the existance of a “crossover point” at which the clean-wing E2S dispatch overcomes the “Flaps 2” E2S flyout in terms of obstacle clearance. In other words, while there are general, overarching trends which can appear in either the gross or net flight path analysis, the results which the engineer may observe in a net flight path analysis may not necessarily “match” those observed in a gross flight path analysis. This is because the 0.8% degradation to climb performance adds a level of pessimism in the case that the aircraft does not climb as advertised.

IV. Discussion

The intricate interplay between weight and aerodynamics makes the practice of predicting the aircraft’s response to various takeoff profiles a complicated one. As we observed in our analysis, while the A320 flies lighter over time, some trends noted at the heavyweight case were different than those seen for the lightweight case. A careful operations analysis of the aircraft is necessary in order to identify procedures which maximizes the aircraft’s performance potential.

Synthesizing the results, we can see that the A320 maximizes its obstacle clearance capability via the use of some flavor of an extended second segment procedure – this is true regardless of dispatch weight and choice of “book” or “optimized” cue speeds. At the heavyweight case, the choice of extended second segment type strictly depends on the distance of the problem obstacle(s) from the runway. While a flaps-out extended second segment provides enough lift to overcome nearby obstacles, a clean-wing extended second segment profile gives best far-out obstacle clearарance by maximizing clean wing climb time (albeit TODR may preclude use of this dispatch). The transition point at which these two profiles are equivalent appears to not be clearly defined, as it as a function of the cue speeds. We also saw for the lightweight case that the choice of extended second segment procedure is very much clear: flaps-out E2S can maximize obstacle clearance capability for both close-in and far-out obstacles.

Use of cue speeds which are optimized to maximize climb gradient appears to only be advisable for particular situations. For example, at a heavyweight dispatch, we noted that an overspeed provides additional obstacle clearance capability to dispatch procedures which use a clean-wing E2S or that which incorporates an early retraction on the flaps. For the clean-wing E2S profile, additional obstacle clearance capability comes from adding to TODR. Profiles which utilize an early cleanup on the wings trade close-in obstacle clearance to far-out clearance due to overspeed implementation. At a lightweight dispatch, again it only seemed that the clean-wing E2S dispatch truly benefits from an overspeed. If using a clean-wing E2S flyout, use of an overspeed is advisable to maximize any takeoff operation’s obstacle clearance capability, so long as the tire speed rating, brake energy, and TODR are nonlimiting factors. Otherwise, the appreciability of applied idealized cue speeds appears to be quite little – especially considering that the clean-wing E2S flyout tends to be preempted due to a TODR restriction.

While the savings in flight time and fuel burn are not radically different in this study, the trends observed in these parameters are at the very least worth mention. For all simulated dispatches, the general trend appears to be that a clean-wing E2S profile minimizes climb time and fuel burn. Furthermore, an early cleanup on the wings also helps to reduce climb time and fuel burn. The flaps-out E2S profile typically has mediocre flight time and fuel burn, more than that of a traditional profile which cleans up on the flaps at 400-ft AGL, likely due to carrying the flaps up to 5,000-ft AGL.

It is not unreasonable to think that the A320 would dispatch at the maximum takeoff weight sometimes. Recall that at our heavyweight case, we observed that the clean E2S and flaps-out E2S profiles provided equivalent obstacle clearance at a particular distance from the liftoff point. This point would change if we applied optimized cue speeds; that is, this point where the two takeoff profiles are equal appear to be a function of speed and dispatch weight. Indeed, there is no obvious “rule of thumb” that can be used to predict where exactly this “crossover” point occurs; this lends importance to the process of operations analysis, which examines how an aircraft’s operation relates to its achievable performance. The astute engineer should perform thorough trade studies—similar to those done in this analysis—in order to identify which procedure (clean E2S or flaps-out E2S) which provides the best obstacle clearance capability for all obstacles in the aircraft’s predicted flight path.

From our results, we believe that the traditional “one size fits all” procedure set forth by the FAA does provide some means of far-out obstacle clearance capability, a simple change in the takeoff procedure can maximize obstacle clearance to the best of the aircraft’s capability, without any expensive modification to the wing planform or powerplant. The caveat to this is that the extended second segment dispatch is, of course, not a “one size fits all” solution – it requires a careful flight path analysis which considers all obstacles in an aircraft’s predicted flight path. From knowing the placement of the obstacles and the aircraft’s dispatch weight, one can quickly simulate a batch of takeoff procedures, including simulations of a clean-wing E2S or flaps-out E2S climb; from these results, the profile which provides best obstacle clearance over the considered obstacles should be selected, provided that the tire speed rating, brake energy, and TODR are nonlimiting factors.

V. Conclusion

The FAA’s primary mission always has been ensuring safety for all. While it is the responsible authority for approving the four-segment takeoff procedure,[5] a procedure which has been tried multiple times and proved to provide the minimum required amount of climb gradient for aircraft and passenger safety, we contend that this procedure can be improved so as to increase operative efficiency.

An increase to operative efficiency is important to both dispatch planners and airlines alike, although for obviously different reasons; increasing an aircraft’s climb gradient efficiency allows the dispatch planner more leeway in obstacle avoidance when planning the takeoff procedure, while the airline enjoys a reduction in fuel cost thanks to the more efficient climb. The climb gradient is an important aircraft performance parameter to consider on takeoff, as due to TERPS and the criteria given for departure procedures, aircraft are required to maintain a minimum required obstacle clearance so it does not accidentally impact said obstacle. Increasing the climb gradient capabilities of an aircraft simply by tweaking the V_2 cue speed increases its obstacle clearance capabilities, assuming brake energy, tire speed rating, and additional required runway distance not limiting. From the perspective of the airline, this increased climb capability can be traded for additional fuel (hence additional range) or additional payload so long as the minimum required obstacle clearance is met.

While the standard practice of leveling off at 400-ft AGL works, this “one size fits all” approach is not necessarily the most efficient, as extending the second segment further than 400-ft AGL allows the aircraft to better overcome obstacles at various distances. Indeed, for the A320, we noted that at the lightweight case, a flaps-out E2S profile provides obstacle clearance capability that is superior to a traditional early cleanup profile for both close-in and far-out obstacles. At the heavyweight case, a “Flaps 2” E2S departure maximizes close-in obstacle clearance performance, whereas a clean-wing E2S dispatch maximizes far-out obstacle clearance. As there is an intricate interplay between an aircraft’s weight, aerodynamics, and cue speed choice, we note that the trends observed for the A320 may not necessarily be equivalent to those observed for another aircraft. The diligent engineer needs to perform a thorough takeoff flight path analysis to identify what sort of climb procedure maximizes the aircraft’s obstacle clearance capability, and if this procedure correlates to that which minimizes overall flight time and fuel burn.

For the A320, the use of speeds optimized for maximized climb gradient typically yields reductions in flight time and fuel burn while trading for additional required runway distance, it would appear that this does not necessarily imply maximized obstacle clearance capability; therefore, this implies that climb gradient is not the parameter which maximizes obstacle clearance capability, but rather rate-of-climb. Regardless, from this study it was found that application of cue speeds optimized for climb gradient provided appreciable increases to the clean-wing E2S climbout (and at heavier weights, some traditional profiles which schedule an early flap retraction). However, one needs to carefully consider the tire speed, brake energy, and runway distance limits when implementing an overspeed dispatch to ensure these are truly nonlimiting factors.

It is up to the dispatch planner to utilize the appropriate overspeeds which provides for the optimal climb gradient in the extended second segment, all while ensuring the minimum required obstacle clearance is met. Thus, it is in the hands of aircraft manufacturers to include the relevant climb gradient data within the handbook to help dispatch planners formulate a takeoff strategy which safely abides by the TERPS departure procedure and maximizes the aircraft's climb performance. Indeed, while modification to the existing cue speeds and departure procedure would likely incur the need for recertification, maximizing an aircraft's climbing ability without expensive modifications to the powerplant or airframe makes extended second segment worth serious consideration.

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