Improved Obstacle Clearance Capability of a Legacy Transport Aircraft Using a Modified Climb-Out Flight Profile

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This paper evaluates the effect of alternative flight-path profiles on the scheduled takeoff performance of an existing, operational transport aircraft, the C-130H. An aircraft performance model was reverse-engineered and validated using publicly-available data. New profiles based on an extended climb in the second segment, as commonly used in civilian operations, were evaluated. These profiles improve the gradient and obstacle-clearance capability of the airplane, which increases the range and payload capability and expands the number of accessible runways. Significantly, the revised profiles take advantage of the existing capability of the airplane and require no changes to the airframe or engines. Additional options such as an extension of the time limit for takeoff power and dynamic overspeeds may incur non-recurring certification and/or development costs, but would further enhance the performance capabilities of the airplane.

I. Nomenclature

\begin{align*}
  AEO & = \text{all engines operating} \\
  CFR & = \text{Code of Federal Regulations} \\
  CG & = \text{climb gradient} \\
  DER & = \text{departure end of runway} \\
  DOSC & = \text{dynamic overspeed climb} \\
  DP & = \text{departure procedure} \\
  E2S & = \text{extended second segment climb} \\
  ERA & = \text{excess runway available} \\
  FPNM & = \text{feet per nautical mile} \\
  g & = \text{gravitational constant, 32.174 ft/sec}^2 \\
  h & = \text{geometric height} \\
  k & = \text{energy split, actual rate-of-climb / available rate-of-climb} \\
  MCP & = \text{maximum continuous power} \\
  MTP & = \text{maximum takeoff power} \\
  OCS & = \text{obstacle clearance surface} \\
  OEI & = \text{one engine inoperative} \\
  OSPD & = \text{overspeed} \\
  P_s & = \text{specific excess power} \\
  RC & = \text{rate of climb} \\
  SDP & = \text{special departure procedure} \\
  SID & = \text{standard instrument departure} \\
  TERPS & = \text{terminal instrument procedures} \\
  USAF & = \text{United States Air Force} \\
  V & = \text{true airspeed} \\
  V_{LO} & = \text{liftoff speed} \\
  V_{OBS} & = \text{obstacle clearance speed (V_2)}
\end{align*}

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II. Introduction

The C-130, Figure 1, is a four-engine turboprop military transport produced by Lockheed Martin Aeronautics Company. First flown in 1954, it has been updated several times, and remains in production today as the C-130J. Older models of the aircraft remain in service around the world, most notably the C-130H. Due to budget constraints, there is interest in modernizing the avionics and propulsion systems of older C-130s to keep the airplanes functional, relevant, reliable, and economically useful for decades to come. With this in mind, the authors explored operational performance improvements to increase the economic utility of the existing aircraft. Such improvements, when available, are cheaper than physical modifications to the aircraft. In particular, the performance flight manual for the aircraft, or its electronic equivalent, is used to determine, or “schedule,” the maximum takeoff weight for the airplane from the departure airfield. Among the constraints in the performance manual are structural limitations, minimum climb gradient limitations, brake energy limitations, runway length limitations, and obstacle clearance limitations. It is this latter consideration, the obstacle-clearance flight-path, which the authors found to be a particularly interesting opportunity.

The climb-out flight path for a multi-engine aircraft, whether military- or civil-certified, is based on an engine failure at a critical point in the takeoff ground run. The climb-out flight profile is the continuation of the takeoff within the terminal area using the remaining, operating engines. The legacy C-130 flight manual subdivides the profile into a series of segments defined by transitions in configuration (including landing gear retraction, propeller feathering, and flap retraction), as well as changes in airspeed, and/or power setting. Through several of these segments, the flight path prescribed in the legacy flight manual splits the excess power of the airplane between climb and acceleration. Unfortunately, diverting excess power into acceleration reduces the available climb gradient near the ground, and diminishes the maximum takeoff weight in obstacle- and gradient-limited conditions. This reduction in takeoff weight decreases the available payload and range from some airfields, and curtails access to other airfields altogether.

An alternative profile called an “extended second-segment climb,” abbreviated as “E2S” in this paper, is in widespread use in the civilian world to increase the maximum takeoff weight in obstacle-limited takeoff conditions. Unlike the legacy C-130 profile, the civilian profile from which the E2S is derived is split into segments where the airplane is either climbing at fixed calibrated airspeed, or is accelerating at constant altitude. Procedurally, these profiles are easier to fly and produce repeatable performance.

The E2S profile is effective not only in improving clearance of defined obstacles in the flight path, but in ensuring compliance with the fixed gradients specified with standard instrument departures (SIDs) or departure procedures (DPs). SIDs and DPs prescribe an imaginary, sloping plane anchored at the end of the runway that must not be penetrated. Such a surface may exist for reasons other than obstacle clearance, such as noise or air traffic management. DP’s are defined as “normal” procedures, and are not intended for the “abnormal” condition of an engine failure. However, USAF operating instructions dictate that flight crews schedule performance to comply with DPs with an engine failure, in both IFR and VFR conditions. On the C-130H, this requirement may pose the most stringent limitation on the takeoff weight, particularly in conjunction with the energy-split of the legacy climb-out profile.

To evaluate the operational impact of a modified, second-segment profile on the C-130H, a flight-test expansion model was constructed. Aerodynamic and propulsion characteristics for the C-130H, obtained using classical methods, were used to reverse-engineer publicly-available data and populate the performance model. The model was adapted to reproduce the results of reference 2, and then modified to produce an extended second-segment profile, including several variations. One variation would allow continuation of the second-segment climb at maximum continuous power (MCP) after expiration of the current 5-minute limit for maximum takeoff power (MTP). Another variation of the E2S explores the change to performance if the MTP time limit were extended to 10 minutes. For comparison purposes, alternative profiles were computed with a minimum, 400-foot acceleration altitude. Finally, a novel profile was developed in which excess climb capability during the initial climb is “banked” as extra speed, and exchanged for additional gradient at the end of the climb.

Figure 1. The C-130H. Image courtesy of Jimmy Van Drunen.
III. Analysis

After takeoff, the airplane must transition from the speed and configuration for takeoff to the speed and configuration for efficient climb to the cruise altitude. During this transition, the flaps and landing gear are retracted, the power is transitioned from the takeoff setting to a lower, maximum continuous setting, and the speed is increased from \( V_{ OBS} \) (\( V_2 \)) to the speed for enroute climb. It is also during this portion of flight that clearance of any obstacles in the flight path must be assured (usually with some margin determined by the certification authority), both with all engines operative (AEO) and with one engine inoperative (OEI). Likewise, consideration must be given to DPs and SIDs, which define an imaginary surface with a climb gradient (CG) emanating from the departure end of the runway (DER) that must not be penetrated at any point in the flight path, up to a specified height. Figure 2 depicts the climb-out problem in the context of distinct obstacles and SIDs/DPs.

![Figure 2. Obstacle clearance with distinct obstacles in the flight path and with SIDs/DPs.](image)

The present analysis is predicated on standard atmospheric conditions, runways with zero wind and zero slope, and climbs that commence from sea-level altitude. In addition, for SIDs/DPs, no adjustment to the required climb gradient is taken for the excess runway available (ERA), defined as the distance between the screen height and the DER. Typically, the airplane will achieve the screen height prior to the DER, and the resulting ERA can be used to relax the required gradient needed to comply with the SID/DP. Adequately accounting for the ERA requires a consideration of runway slope, among other factors, and is beyond the scope of the present analysis. The use of zero ERA serves as a conservative approximation.

A. Legacy Profile

The legacy C-130H climb-out flight-path profile is specified by the flight manual\(^2\), and is reproduced in Figure 3. The military regulations\(^8,9\) are relatively mute on requirements for the climb-out flight path, and the legacy profile is of unknown origin. The profile is unusual in specifying segments of combined climb and acceleration (increasing KCAS) between the gear-up point and flap-retraction speed, and between flaps-up and the best climb speed. The exact split of excess power has a profound effect on the height-versus-distance relationship of the profile. Assuming the energy split is constant throughout these segments, the exact value of the energy split can be determined without the aerodynamic or thrust characteristics of the airplane. The rate-of-climb during the segment is determined as a fraction, \( k \), of the total excess power according to Eq. (1).

![Figure 3. Segmentation of the legacy C-130H takeoff flight path (from TO 1C-130H-1-1\(^2\)).](image)
\[ RC = k P_s \]  

(1)

Since rate-of-climb is equivalent to \( P_s \) divided by the acceleration factor (i.e., \( 1 + (V/g) \frac{dV}{dh} \)), the energy split can be related to the change in speed with altitude via Eq. (2).

\[ dh = \left( \frac{k}{1-k} \right) \frac{V}{g} dV \]  

(2)

Solving for the constant \( k \) yields Eq. (3), where the subscripts “f” and “i” refer to the final and initial conditions for the segment, respectively.

\[ k = \frac{1}{\left( \frac{V_f^2-V_i^2}{2g(h_f-h_i)} + 1 \right)} \]  

(3)

Extracting the speeds and altitudes from the OEI flight path chart of reference 2 and applying Eq. (3) yields the results of Figure 4. The values suggest an energy split of \( \frac{1}{2} \) was used to construct the profile. This energy split was used to re-construct the legacy flight-path seen in Figure 5 using the reverse-engineered performance expansion model. The reconstructed profile serves as a reasonable facsimile of the one in reference 2, and serves as a baseline for evaluating other profiles generated with the expansion model.

### B. Extended Second Segment Profile

The first alternative profile evaluated was a classic extended second-segment climb using the existing 5-minute MTP limit. The regulations of 14 CFR § 25.111, § 25.115, and § 25.121 describe four segments, as illustrated in Figure 6. In contrast to the legacy C-130H profile, the segments in the civilian profile consist of either constant calibrated airspeed or constant altitude. Consequently, the civilian profile can be flown with greater accuracy and repeatability than the segments of combined acceleration and climb found in the legacy profile. As seen in Figure 6, the E2S profile corresponds to “Path 2” and consists of climb with gear retracted and flaps extended to an altitude at which the airplane can level-off and accelerate to the final takeoff speed (taken here as the best speed for climb, as published in reference 2) within the 5-minute MTP limit. While the second segment is permitted to end as early as 400 feet, it may extend to greater heights for obstacle clearance.
Figure 7 shows the results for three representative weights for the C-130: 100,000 lb (light), 140,000 lb (medium), 180,000 lb (heavy). The E2S results are superimposed with those of the legacy profile. Part (a) of Figure 7 shows the profile for close-in obstacles, while part (b) of the figure shows the profile for distant obstacles.

The charts show the significant benefit of the E2S profile. For example, given a 140,000 lb airplane at 3 nm, the legacy profile puts the airplane at about 750 feet, while the E2S profile puts the airplane at over 1,000 feet. An airplane flying the legacy profile would have to reduce its weight about 13,000 lb to achieve the same height as the E2S profile at that distance. After level-off and acceleration to the flap retraction speed \((V_{LO} + 20)\), the heights of the two profiles become closer. In contrast to the legacy profile, which transitions to lower power after quickly achieving the best climb speed, the E2S profile uses the full 5-minutes of available takeoff power. The combined effect of the early transition to MCP and the energy split renders the legacy profile inferior to the E2S at all conditions, except for a heavyweight airplane at very distant obstacles.

Because a SID or DP may be more limiting than defined obstacles in the flight path, the effective gradient, defined simply as the height/distance at any point along the climb-out, was evaluated at the three aircraft gross weights. Figure 8 illustrates the superior performance of the E2S profile in the context of a SID/DP. For example, given a 140,000 lb airplane, the E2S profile would comply with a 400 ft/nm DP up to a height of 4,000 ft, while the legacy profile would be capable of no greater than 300 ft/nm over the same height. The legacy profile would require a 12,000 lb reduction in takeoff weight to achieve the same minimum gradient as the E2S profile over the interval.

### C. Extended Second Segment with Overspeed

Figure 9 depicts the excess power characteristics of the airplane, as well as the speeds for best angle of climb. The figure indicates that improved gradients may be possible at speeds greater than the normal, minimum \(V_{OBS}\) for aircraft weights above 108,000 lb. This may be accomplished via an “overspeed” on takeoff, in which \(V_{OBS}\) is increased to achieve greater climb capability at the expense of increased takeoff distance. For validation, the expansion model was executed with a 10-knot increase in \(V_{OBS}\), resulting in the profiles in Figure 10. By increasing the distance from liftoff to brake release, the overspeed diminishes the close-in obstacle-clearance capability, particularly at lightweights where the overspeed does not improve the climb angle. However, at all weights, the increased climb rates from the overspeed result in greater acceleration heights. For example, at 11 nm, a 140,000 lb airplane with a 10-knot overspeed achieves 300 ft greater height (4,350 ft) compared to the baseline E2S profile (4,050 ft), and 660 ft greater height compared to the legacy profile (3,690 ft). For reference, at 11 nm, an airplane flying the legacy
profile would reduce its weight 9,300 lb to achieve the same height as the E2S with overspeed, or 5,200 lb to achieve the same height as the baseline E2S. Thus, for a narrow range of obstacles, a significant increase in clearance capability is enabled by overspeed.

Figure 11 shows the effective gradient of the overspeed profile. The overspeed slightly reduces the effective gradient at low heights at light weights, but the increase in acceleration height increases the achievable heights for a narrow range of climb gradients at all weights. For example, given a 100,000 lb airplane, the baseline E2S supports a gradient of 800 ft/nm to a height of 7,750 ft, but the overspeed E2S supports the same gradient to a height of 8,170 ft.

D. Extended Second Segment with 10-Minute Limit

Both the baseline and overspeed E2S profiles can be implemented without changes to the airframe or engines. Both profiles are predicated on the current 5-minute MTP limit. An extension of the MTP time limit, such as the 10-minute limit of the Boeing 78712, would permit greater gradients to higher acceleration heights, but would require certification effort. The significant in-service experience with the T56 engine may help reduce this effort. The dashed red lines of Figure 12 and Figure 13 indicate the improvement available with the “E2S-10min” profile at climb heights beyond the level-off height of the baseline E2S profile. For example, at 11 nm, a 140,000 lb airplane on the 10-minute E2S profile achieves 360 ft greater height (4,420 ft) than the baseline E2S, and 730 ft greater height than the legacy profile. An airplane on the legacy profile would need to reduce its weight 10,200 lb to achieve the same height as the 10-minute MTP E2S at 11 nm. For SID/DP performance at 140,000 lb, the 10-minute MTP E2S would support a gradient of 400 ft/nm to about 7,050 ft height, while the baseline E2S would support the same gradient to only 4,050 ft.
E. Extended Second Segment with Continuation at MCP

As an alternative to extending the MTP time limit, or conducting a level acceleration at the expiration of the MTP limit, a profile in which the airplane transitions to MCP after the 5-minute MTP limit, but maintains $V_{ OBS }$, may produce comparable benefits at less cost.

Results for such an “E2S-MCP” profile are shown by the dashed blue lines on Figure 12 and Figure 13. The figures show that the E2S-MCP falls somewhere between the baseline E2S and 10-minute MTP E2S profiles in terms of performance. For example, at 11 nm, a 140,000 lb airplane on an E2S-MCP profile achieves 310 ft greater height (4,360 ft) than the baseline E2S profile, and 60 ft less height than the 10-minute MTP E2S profile. An airplane flying the legacy profile would reduce its weight 9,400 lb to achieve the same height as the E2S-MCP profile at 11 nm. For a 140,000 lb airplane flying a 400 ft/nm SID/DP, the E2S-MCP profile would support a height of 5,380 ft, compared to the baseline E2S that would support a height of 4,050 ft, and the 10-minute MTP E2S that would support a height of 7,050 ft.

Given the normal thrust-lapse with altitude, it may be necessary to provide additional charts to ensure sufficient capability exists for the enroute climb at the end of the takeoff flight path, consistent with 14 CFR § 25.121(c).10

F. Acceleration at 400 feet

All of the new profiles explored so far involve some form of an extended 2nd segment. These profiles tend to accelerate at the highest available altitude. At the opposite end of the spectrum is a climb profile that accelerates to the final takeoff speed at the minimum allowable altitude, which is 400 ft in 14 CFR § 25.111.10 In concept, accelerating and transitioning to the lowest-drag configuration soon after lift-off diminishes the capability to clear...

Figure 12. E2S profile with 10-minute MTP and continuation at MCP. Close-in is unchanged.

Figure 13. Effective gradient surface for E2S using 10-minute MTP and continuation at MCP.

Figure 14. Profile for minimum acceleration altitude. Transition to MCP (Min400") and continuation of MTP up to the 5-minute limit (Min400'-MTP5min) at the end of the level acceleration.
close-in obstacles, but improves the capability to clear distant obstacles. Figure 14 shows profiles for two scenarios: one in which power is transitioned to MCP immediately at the end of the level acceleration at 400 ft, and one in which the power is transitioned to MCP at the expiration of the 5-minute limit. At heavy weights, both "Min-400'" profiles cross the baseline E2S profile at the acceleration height. Thus, the min-accel profile provides the expected benefit, at least for heavy aircraft at very distant obstacles. On the other hand, the Min-400’ profiles do not match the capabilities of the 10-minute E2S or E2S-MCP profiles. Figure 15 shows that the Min-400' profiles are suitable for small SID/DP climb gradients only, due to the greatly diminished effective gradient during the initial climb.

G. Reduced Flap Setting

The above profiles are based on the normal takeoff flap setting for the C-130 (50% flap extension). Typically, increased gradient capability is available via reduced flap deflection, at the cost of increased takeoff distance. Assuming the runway length permits this trade, and that other factors, such as brake energy and tire-limit speeds do not become limiting, Figure 16 and Figure 17 show that additional improvements are available via flaps-up takeoff. For example, at 11 nm and 140,000 lb, the flaps-up E2S achieves 550 ft greater height (4,600 ft) than the baseline E2S, and 910 ft greater than legacy. The same airplane at 11 nm on the legacy profile would reduce its weight 12,600 lb to achieve the same height as the flaps-up E2S. While flaps-up take-off offers the greatest climb capability, an intermediate flap setting may provide the optimal compromise between field-length and climb requirements.

Figure 15. Effective gradient surface, height/distance, for min-accel profile. Transition to MCP (Min400’’ and continuation of MTP Min400’-MTP5min).

Figure 16. E2S profiles with flaps up. Legacy and E2S with flaps 50% shown for comparison.

Figure 17. Effective gradient surface, height/distance, for E2S profiles with flaps up.
H. Dynamic Overspeed Climb

In the absence of specialized departure procedures (SDPs), SIDs/DPs may assume a prominent role in establishing maximum takeoff weights, particularly in the context of an engine failure. With this in mind, a climb profile was sought to maximize the height to which a required gradient can be maintained. Revisiting Figure 9, it is evident that excess power for a given weight is most abundant at the starting height for the climb, and the available climb gradient may be in excess of a required DP at the start of the climb. However, the excess power diminishes with altitude, and drops discontinuously at the acceleration height, such that the available climb gradient may become inadequate near the final height of a DP. One strategy to maintain a minimum gradient to a greater height is to maintain only the minimum gradient at the start of climb, and “bank” the excess power in the form of speed. The increasing speeds in this “dynamic overspeed” climb profile (abbreviated “DOSC”) produce greater rates of climb. The result is greater height at the expiration of the 5-minute MTP limit, whereupon the banked speed can be exchanged to maintain the minimum gradient until the minimum climb speed is reached.

Two DOSC profiles were evaluated. In the first, the flaps are held in the takeoff position throughout the climb. In the second, flap retraction is initiated once the airplane achieves the minimum flap retraction speed. For both cases, the target is a DP with a 420 ft/nm CG, and climb is assumed to continue at \( V_{OBS} \) and MCP after the 5-minute MTP limit. In the latter scenario, flap retraction reduces drag and increases the rate of acceleration and climb; however, the flap retraction speed becomes a higher minimum speed for the end of the climb, restricting the amount of energy recovery. Figure 18, Figure 19, and Figure 20 show the speed, height, and gradient traces, respectively, for a 140,000 lb aircraft flying a 420 ft/nm DP. Figure 18 shows the DOSC with flap retraction reaches a maximum speed about 12 knots faster during the initial climb at MTP. Both DOSC profiles must reduce speed quickly after the 5-minute MTP limit in order to maintain 420 ft/nm. The profile with flap retraction achieves a much greater height before the time limit, and bleeds-off speed at a lower rate after the limit. The result is a greater final height despite the higher minimum final speed.

Compared to the basic E2S profile, which holds the DP to 4,600 feet, the DOSC profiles hold the DP longer: 5,000 feet without flap retraction, and 5,600 feet with flap retraction. Further development is needed before operational implementation of a DOSC profile. In particular, modifications to the autopilot, or additional indications to the pilot, perhaps via a heads-up display, may be required.

Figure 18. Speed variation for DOSC to maximize climb height for a 420 FPNM CG, gross weight 140,000 lb.

Figure 19. Height profile for DOSC to maximize climb height for a 420 FPNM CG, gross weight 140,000 lb.

Figure 20. Effective climb gradient for DOSC to maximize climb height for a 420 FPNM CG, gross weight 140,000 lb.
IV. Conclusion

This paper shows that significant increases to the operational capability of a legacy transport aircraft are available via simple changes to the climb-out profile in the performance flight manual. Furthermore, no expensive development program is required to unlock this increased capability. The most basic improvement to the climb-out profile, an extended second segment using the existing five-minute limit to takeoff power, requires no changes to the airframe or engines. Since flight manuals are “living” documents subject to regular update, the new profile could be implemented as part of a routine update, using the established flight-test database for the airplane. In contrast, the improvements typically proposed for legacy aircraft, such as retrofitting new engines or winglets, are much more expensive, require a protracted development and test cycle, and may not deliver a return on investment in the limited remaining life of the aircraft.

The more aggressive improvements identified in this paper would incur additional costs beyond those associated with a flight-manual update. An extension of the takeoff power limit from 5 to 10 minutes, for instance, shows significant additional performance benefit, but invites an expensive engine certification effort. However, the extensive operational experience with the T56 engine on the C-130 may mitigate that effort. The dynamic overspeed profile is the most aggressive approach to maximizing performance, but also the most complex. Such an improvement may not be appropriate for an airplane like the C-130H, which lacks a modern avionic infrastructure. However, it might find application on newer aircraft in the fleet, or next-generation airlifters.

Ultimately, the improved climb-out profiles described in this paper will benefit operators every day, by increasing the range and/or payload from airfields that are currently accessible but climb-limited, and by enabling operations from airfield that were previously inaccessible due to climb limits. In addition, the improved payload capability will save fuel by reducing the number of sorties necessary to carry an equivalent tonnage to or from an obstacle-limited airfield. Finally, the proposed changes will improve safety via greater obstacle-clearance capability, and easier-to-fly profiles consisting of segments of either constant calibrated airspeed or constant altitude.

References


3. Advisory Circular (AC) 120-91, Airport Obstacle Analysis, United States Department of Transportation, Federal Aviation Administration (FAA), 5 May 2006.


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