AIAA AVIATION Forum
5-9 June 2017, Denver, Colorado
17th AIAA Aviation Technology, Integration, and Operations Conference

10.2514/6.2017-3420

The Effect of Aerodynamic and Propulsive Uncertainty Upon Certified Takeoff Performance

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This second paper, in a series, explores technical factors that control "certified" takeoff and landing distances obtainable by modern commercial aircraft. Government regulations control the formulation of field length requirements used by manufacturers and operators. To date, the aviation community considers these regulations adequate. This work seeks to clarify ambiguities within both basis data and regulations that can result in large variations between estimated and actual performance. Here, we explore the effects of well-regulated parameters arising from aerodynamic and propulsive data (the stall speed, stick-pusher settings, and minimum control speed) upon distances. We find small and expected sensitivities associated with changes in thrust, drag, maximum lift coefficient and minimum control speeds. We find significant performance sensitivities arising from the aircraft braking system; the effectiveness of the brakes substantially impacts the choice of decision speed and the resulting takeoff distance.

Nomenclature

CFR	= *Code of Federal Regulations*
ASDA	= *Accelerate-Stop-Distance Available*
TORA	= *Takeoff Run Available*
TODA	= *Takeoff Distance Available (beginning of roll to 35-ft obstacle at end of runway)*
TOGR	= *Takeoff Ground Roll*
KIAS	= *Knots Indicated Airspeed*
Vs,Vs0,Vs1,Vsr0	= *Stall Speed (as called out in various parts of the CFR)*
V1	= *Takeoff Go/No-Go Decision Speed (one-engine inoperative)*
V2	= *Takeoff Obstacle Clearance Speed (one-engine inoperative)*
VMCA	= *Minimum Controllable Airspeed (takeoff flap setting) (one-engine inoperative)*

I. Introduction

COMMERICAL aircraft must operate according to standard procedures developed by the Federal Aviation Administration (FAA). In order to promote safety, if an operator chooses to fly these aircraft from airports with shorter runways or close in obstacles, the allowable takeoff weight may be restricted to a value less than the certified maximum. If this is the case, the aircraft must offload either fuel or payload below to restrict takeoff weight. For a given amount of payload, this means that the aircraft has to depart with a limited amount of fuel (potentially reducing range to the point where the

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aircraft would need to make a refueling stop enroute to its final destination). If the operator deviates from published procedure, the aircraft is likely to overrun the runway or crash into an obstacle in the event of an engine failure.

Market pressures to improve operating economy, reduce overall community noise and reduce fossil fuel consumption reward operations that schedule fewer flights of larger aircraft as opposed to more frequent flights of smaller aircraft. Thus, future trends reward operators who can effectively schedule safe and reliable operations of aircraft into otherwise “marginal” airports.

This paper, the second in a series, seeks to document the effect of aerodynamic, weight, braking and propulsive uncertainty to the “certified distances” found in a flight manual as well as the actual performance of aircraft flown with all engines operating. Our first paper, AIAA 2017-0007, given at the 2017 SciTech conference, documented the impact of piloting procedure (pitch rate and reaction times) as well as braking traction upon the “certified distances.”[1]

This paper helps clarify the magnitude of uncertainty in these estimates. For example, how does a one –vs- two second reaction time for engine failure compare to a 25 count uncertainty in zero-lift drag? an extra knot of pessimism when setting *VMCA*? a half-degree extra pessimism when setting a stick-pusher? a 5% reduction in induced drag (from retrofit winglets)? or a 1% degradation in take-off thrust? Or a change in braking μ between the very optimistic ESDU values to the more pessimistic ICAO values? This paper will restrict itself to consider only takeoff problems.

II. Summary of Scheduled Takeoff Performance

The reader should always keep in mind that flight manuals provide reference performance data based upon models that assume that pilots operate aircraft in a specific manner. The FAA and its predecessor agencies have promulgated many rules and regulations to manage the industry of commercial aerospace (found in Title 14 of the Code of Federal Regulations).[2] Field performance comprises the totality of the following tasks related to takeoff and landing (TOLD): the development of procedures, the setting of key speeds, and the computation of distances and flight paths associated with takeoff and landing.

We believe that complications begin to arise in the “real-world” of aircraft operations. Pilots may or may not fly aircraft in a manner consistent with the calculations found in approved flight manuals (the subject of AIAA 2017-0007).[1] Even with superb training, pilots may also operate an aircraft with some degradation in aerodynamic or propulsive performance. Because pilots often fly aircraft based upon pro-forma (as opposed to actual) payload weight, aircraft may takeoff at an actual flight weight somewhat different from that planned by dispatch. Because cue speeds are based on pro-forma as opposed to actual flight weight, these errors may have a compounding effect upon flight performance. We seek to see if these consistencies lead to a significant deviation in the actual field performance of the aircraft compared to the “scheduled performance.”

a. Takeoff Regulations

The takeoff distance is the horizontal distance covered by the aircraft, from the position of the main landing gear at a standing still point, to the same point at which the lowest part of the aircraft is 35 feet off of the runway. The takeoff distance is comprised of two sections: 1) the ground roll section where the aircraft is accelerated until sufficient airspeed is obtained in order to achieve flight, and 2) the airborne distance where the aircraft leaves the runway and achieves 35 feet altitude.

Edited copies of current takeoff regulations[4] are given below:

14 CFR § 25.101 – General

(h) The procedures … must—

  (1) Be able to be consistently executed in service by crews of average skill;
  (2) Use methods or devices that are safe and reliable; and
  (3) Include allowance for any time delays, in the execution of the procedures that may reasonably be expected in service.

14 CFR § 25.107 – Takeoff speeds.

(a) *V1* must be established in relation to V*EF* as follows:

  (1) V*EF* is the calibrated airspeed at which the critical engine is assumed to fail. V*EF* must be selected by the applicant, but may not be less than *VMCG* determined under § 25.149(e).

  (2) *V1*, in terms of calibrated airspeed, is selected by the applicant; however, *V1* may not be less than V*EF* plus the speed gained with critical engine inoperative during the time interval between the instant at which the critical engine is failed, and the instant at which the pilot recognizes and reacts to the engine failure, as indicated by the pilot's initiation of the first action (e.g., applying brakes, reducing thrust, deploying speed brakes) to stop the airplane during accelerate-stop tests.

(b) *V2MIN,* in terms of calibrated airspeed, may not be less than—

  (1) 1.13 *VSR* for—

…

    (i) Turbojet powered airplanes without provisions for obtaining a significant reduction in the one-engine-inoperative power-on stall speed;

…

(c) *V2*, in terms of calibrated airspeed, must be selected by the applicant to provide at least the gradient of climb required by § 25.121(b) but may not be less than—

  (1) *V2MIN*;

  (2) *VR* plus the speed increment attained (in accordance with § 25.111(c)(2)) before reaching a height of 35 feet above the takeoff surface; and

  (3) A speed that provides the maneuvering capability specified in § 25.143(h).

…

(e) *VR*, in terms of calibrated airspeed, must be selected in accordance with the conditions of paragraphs (e)(1) through (4) of this section:

  (1) *VR* may not be less than—

    (i) *V1*;

    (ii) 105 percent of V_{MC};

    (iii) The speed (determined in accordance with §25.111(c)(2)) that allows reaching *V2* before reaching a height of 35 feet above the takeoff surface; or

    (iv) A speed that, if the airplane is rotated at its maximum practicable rate, will result in a *VLOF* of not less than —

      (A) 110 percent of *VMU* in the all-engines-operating condition, and 105 percent of *VMU* determined at the thrust-to-weight ratio corresponding to the one-engine-inoperative condition; or

      (B) If the *VMU* attitude is limited by the geometry of the airplane (*i.e.,* tail contact with the runway), 108 percent of *VMU* in the all-engines-operating condition, and 104 percent of *VMU* determined at the thrust-to-weight ratio corresponding to the one-engine-inoperative condition.

…

  (3) It must be shown that the one-engine-inoperative takeoff distance, using a rotation speed of 5 knots less than *VR* established in accordance with paragraphs (e)(1) and (2) of this section, does not exceed the corresponding one-engine-inoperative takeoff distance using the established *VR*. The takeoff distances must be determined in accordance with §25.113(a)(1).

  (4) Reasonably expected variations in service from the established takeoff procedures for the operation of the airplane (such as over-rotation of the airplane and out-of-trim conditions) may not result in unsafe flight characteristics or in marked increases in the scheduled takeoff distances established in accordance with §25.113(a).

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-38, 41 FR 55466, Dec. 20, 1976; Amdt. 25-42, 43 FR 2320, Jan. 16, 1978; Amdt. 25-92, 63 FR 8318, Feb. 18, 1998; Amdt. 25-94, 63 FR 8848, Feb. 23, 1998; Amdt. 25-108, 67 FR 70826, Nov. 26, 2002; Amdt. 25-121, 72 FR 44665, Aug. 8, 2007][3]

14 CFR 14 § 25.109 Accelerate-stop distance.

(a) The accelerate-stop distance on a dry runway is the greater of the following distances:

(1) The sum of the distances necessary to—

b. Accelerate the airplane from a standing start with all engines operating to VEF for takeoff from a dry runway;

c. Allow the airplane to accelerate from VEF to the highest speed reached during the rejected takeoff, assuming the critical engine fails at VEF and the pilot takes the first action to reject the takeoff at the *V1* for takeoff from a dry runway; and

d. Come to a full stop on a dry runway from the speed reached as prescribed in paragraph (a)(1)(ii) of this section; plus

e. A distance equivalent to 2 seconds at the *V1* for takeoff from a dry runway.

(2) The sum of the distances necessary to—

(i) Accelerate the airplane from a standing start with all engines operating to the highest speed reached during the rejected takeoff, assuming the pilot takes the first action to reject the takeoff at the *V1* for takeoff from a dry runway; and

(ii) With all engines still operating, come to a full stop on dry runway from the speed reached as prescribed in paragraph (a)(2)(i) of this section; plus

(iii) A distance equivalent to 2 seconds at the *V1* for takeoff from a dry runway.

…

(e) Except as provided in paragraph (f)(1) of this section, means other than wheel brakes may be used to determine the accelerate-stop distance if that means—

(1) Is safe and reliable;

(2) Is used so that consistent results can be expected under normal operating conditions; and

(3) Is such that exceptional skill is not required to control the airplane.

(f) The effects of available reverse thrust—

(1) Shall not be included as an additional means of deceleration when determining the accelerate-stop distance on a dry runway; and

(2) May be included as an additional means of deceleration using recommended reverse thrust procedures when determining the accelerate-stop distance on a wet runway, provided the requirements of paragraph (e) of this section are met.

…

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-42, 43 FR 2321, Jan. 16, 1978; Amdt. 25-92, 63 FR 8318, Feb. 18, 1998] [4]

14 CFR § 25.111 Takeoff path

(a) The takeoff path extends from a standing start

…

(3) The airplane must be accelerated on the ground to VEF, at which point the critical engine must be made inoperative and remain inoperative for the rest of the takeoff; and

(4) After reaching VEF, the airplane must be accelerated to *V2*.

(b) During the acceleration to speed *V2*, the nose gear may be raised off the ground at a speed not less than *VR*. However, landing gear retraction may not be begun until the airplane is airborne.

(c) During the takeoff

…

(2) The airplane must reach *V2* before it is 35 feet above the takeoff surface and must continue at a speed as close as practical to, but not less than *V2*, until it is 400 feet above the takeoff surface;

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-6, 30 FR 8468, July 2, 1965; Amdt. 25-42, 43 FR 2321, Jan. 16, 1978; Amdt. 25-54, 45 FR 60172, Sept. 11, 1980; Amdt. 25-72, 55 FR 29774, July 20, 1990; Amdt. 25-94, 63 FR 8848, Feb. 23, 1998; Amdt. 25-108, 67 FR 70826, Nov. 26, 2002; Amdt. 25-115, 69 FR 40527, July 2, 2004; Amdt. 25-121, 72 FR 44666; Aug. 8, 2007] [5]

14 CFR § 25.113 Takeoff distance and takeoff run.

(a) Takeoff distance on a dry runway is the greater of–

(1) The horizontal distance along the takeoff path from the start of the takeoff to the point at which the airplane is 35 feet above the takeoff surface, determined under §25.111 for a dry runway; or

(2) 115 percent of the horizontal distance along the takeoff path, with all engines operating, from the start of the takeoff to the point at which the airplane is 35 feet above the takeoff surface, as determined by a procedure consistent with §25.111.

…

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25–23, 35 FR 5671, Apr. 8, 1970; Amdt. 25–92, 63 FR 8320, Feb. 18, 1998] [6]

b. 14 CFR § 121.189 Certified Takeoff procedure

The regulations reproduced above require the operator to ensure that the pilot can safely dispatch.[3,4,5,6]

This means, through inspection of flight manual data, that: 1) the aircraft departs at a weight where the implied critical field length (CFL) requirement is shorter than the available runway length, and 2) the pilot has been advised of all appropriate "cue" speeds – *V1*, the "go-no-go" speed, *VR*, the rotation speed and *V2*, the second segment climb speed.

That is, the accelerate-stop-distance-available to the pilot must be greater than the accelerate-stop-distance when an engine fails below the *V1* speed or the pilot elects to reject the takeoff at the scheduled *V1* speed.

$$ASDA > max(ASD_{OEI}, ASD_{RTO}) \tag{1}$$

Second, the take-off-distance-available must exceed both the take-off-distance-required under an engine-failure condition where the pilot slavishly follows procedure to elevate the nosewheel for take-off at the prescribed rotation speed, *VR* and 115% of the take-off distance required under normal operating conditions.

$$TODA > max(TODR_{OEI}, 1.15\ TODR_{AEO}) \tag{2}$$

Finally, the runway length available must exceed both the take-off-ground-roll required under an engine-failure condition where the pilot slavishly follows procedure to elevate the nosewheel for take-off at the prescribed rotation speed, *VR* and take-off-ground-roll required under normal operating conditions.

$$RUNWAY > max(TOGR_{OEI}, TOGR_{AEO}) \tag{3}$$

Thus, so long as the runway is longer than the estimated critical field length there is no chance for a crash or ground based excursion in the event of engine failure during takeoff.

The minimum control ground speed, *VMCG*, represents the lowest airspeed during the takeoff run where "when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane using the rudder control alone (without the use of nosewheel steering)."[7] The minimum control airspeed, *VMCA*, represents the lowest airspeed during flight where "when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane … and maintain straight flight with an angle of bank of not more than 5 degrees."[7] The engine failure speed, *VEF*, is the airspeed "at which the critical engine is assumed to fail." [7] The designer has liberty to choose an engine failure speed that may be as slow as the minimum control ground speed (*VMCG*) or as high as the rotation speed (VR).

The takeoff decision speed (*V1*) is selected by the applicant as the "go-no-go" speed for takeoff.[3] If an engine fails above this speed, the pilot must continue onwards and attain flight. Below that speed, the pilot must begin an emergency ground deceleration sequence. The manufacturer may schedule *V1* to be as low as the speed corresponding to the engine failure speed (*VEF*) plus any speed gains attained through two seconds of residual acceleration with one engine rendered suddenly inoperative; it may be as high as the takeoff rotation speed, *VR*. During a rejected-takeoff (RTO) procedure, the pilot, at *V1*, is expected to throttle back, deploy aerodynamic speed brakes and other lift-dump devices and apply full effort to stop using the wheel brakes.

In a rejected takeoff scenario, the FAA suggests, in AC 25-7C,[8] that the manufacturer account for a minimum of a one-second delay per action required by the pilot between engine failure recognition and the beginning of the rejected takeoff braking sequence. Since the typical transport category airplane requires three pilot actions (i.e., brakes-throttles-spoilers) to achieve the final braking configuration, and the FAA requires certification demonstration to credit not less than one second between each action, the typical aircraft must account for not less than a two second delay prior to full brake application. Under Amendment 25-92[9] (implemented 1998) in 14 CFR § 25.109,[4] the manufacturer must also include an additional two-second time period at *V1* in its estimate of the certified rejected takeoff accelerate-stop distance.

The minimum unstick speed (*VMU*) is the minimum airspeed at which "the aircraft can safely lift off the ground."[3] This value is typically determined by test: after accelerating to a modest ground speed, the pilot aerodynamically tips the aircraft back onto its tail using full nose-up elevator control. The aircraft slowly accelerates under part power, often dragging its tail down the runway, until the wheels just leave the ground.

The FAA intends the rotation speed (*VR*) to be the speed at which the pilot initiates action to raise the nose wheel off the ground during the acceleration to flight. The reader should note that FAA does not expressly mandate a minimum or maximum nose-pitch up rate for takeoff. For a critical engine inoperative continued takeoff, rotation at *VR* should enable the aircraft to just attain the obstacle clearance speed, *V2,* at the moment the main gear is 35-ft above the runway surface. Under normal conditions, with all engines operating, the aircraft is expected to overshoot *V2.* 14 CFR § 25 regulations limit *VR* to be no less than the takeoff decision speed (*V1*) or 105% of minimum control airspeed (*VMCA*) or 105% of minimum unstick airspeed (*VMU*). [3]

The lift-off speed (*VLOF*) is the airspeed where the airplane first becomes airborne.[3] Under normal procedures, *VLOF* occurs at a higher airspeed than indicated by *VR* and higher airspeed yet over *VMU.*

Recall that the second-segment climb speed, *V2*, is the target obstacle clearance speed for a failed engine takeoff run. For a modern turbofan powered aircraft, this value may not be less than 113% of the stall speed with the flaps in takeoff position or 110% of the minimum control airspeed, whichever is lower. In other words:

$$V2 = max(1.13\ Vs, 1.1\ VMCA) \tag{4}$$

Where *Vs* is the stall speed with the flaps.

Although basic aircraft flight manual takeoff distances "shall be based on a smooth, dry, hard-surfaced runway, and shall be determined in such a manner that reproduction of the performance does not require exceptional skill or alertness on the part of the pilot,"[10] the CFR does not expressly call out dry runway braking capabilities. For these simulations, we will utilize an aggressive braking traction (μ~0.5) somewhat more conservative than ESDU 71026[11] that seems to best represent the sorts of braking characteristics attained during certification testing of Airbus narrow body aircraft.

III.Numerical Simulations

Key aircraft speeds during both ground and flight phases of takeoff are notated in terms of KIAS. This exists because flight is a function of the dynamic pressure, *q*, that the airplane experiences rather than its physical speed on the ground. On the other hand, the kinetic energy of an aircraft is proportional to its true airspeed, KTAS. Therefore numerical simulations must simultaneously track aircraft speeds in terms of KIAS (for procedural control) as well as KTAS (to satisfy the equations of motion).

A. Overall Description of Takeoff Simulation

Per 14 CFR § 121.189, for takeoff, the simulation must include modules to ensure that:

- The "Accelerate-stop distance must not exceed the length of the runway plus the length of any stopway"[11] (the accelerate-stop-distance-available (ASDA)), and
- "Takeoff distance must not exceed the length of the runway plus the length of any clearway"[12] (the takeoff distance available (TODA))
- "Takeoff (ground) run must not be greater than the length of the runway." [12]

The critical field length (CFL) computation follows regulation 14 CFR § 25.113, that defines the takeoff distance to be the greater of "the horizontal distance along the takeoff path from the start of the takeoff to the point at which the airplane is 35 feet above the takeoff surface … or … 115 percent of the horizontal distance along the takeoff path, with all engines operating, from the start of the takeoff to the point at which the airplane is 35 feet above the takeoff surface" [6]

Thus, for a conventional runway, where the entire runway is paved (no distinct clearway or stopway), we may define the critical field length (reference to Figure 1) as:

$$CFL = max(ASD_{OEI}, ASD_{RTO}, TODR_{OEI}, 1.15\ TODR_{AEO}) \qquad (5)$$

So long as the runway is longer than the estimated critical field length there is no chance for a crash or ground based excursion in the event of engine failure during takeoff.

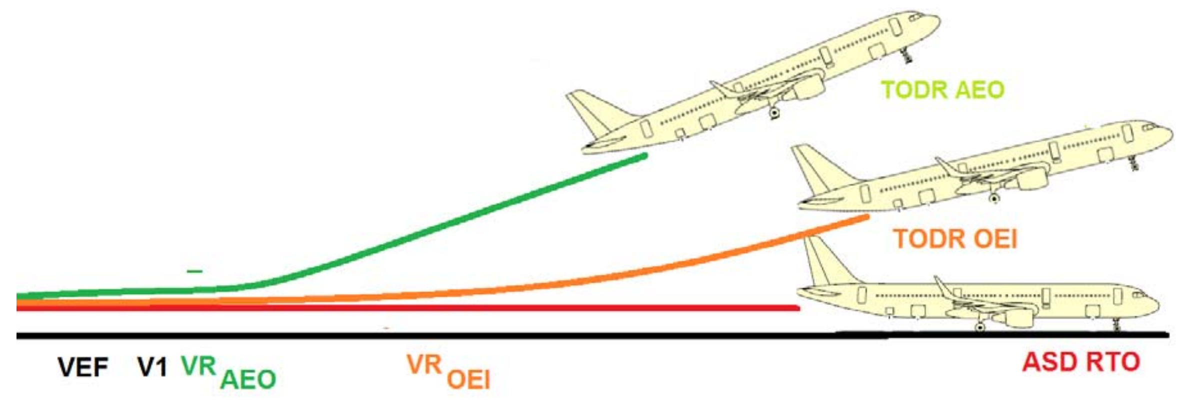


Figure 1 – Schematic of Takeoff Procedure (AEO Accel-Go *Vs* OEI Accel-Go *Vs* RTO)

B. Balanced-Field vs. Pilot's Convenience Critical Field Length

Recall that the aircraft designer has the liberty to select the takeoff decision speed, *V1*, over a wide range of possibilities. Armed with the simulations shown above, the engineer can run trades and examine the actual distances that control the critical field length. Balanced Field conditions occur when the decision speed is selected so that the OEI accel-go distance is exactly the same as the OEI accelerate-stop distance (see Figure 2). This represents the shortest possible runway that can accommodate the aircraft, because the *CFL* is governed by the greater of the accel-stop and OEI accel-go distances. There is no performance benefit to scheduling *V1* so slowly that the aircraft is accel-go limited (although aircraft that have small kinetic energy limited brakes may be forced to do so). Thus, over a wide range of weights, *V1* can be selected to balance the accel-stop and *OEI* go distances.

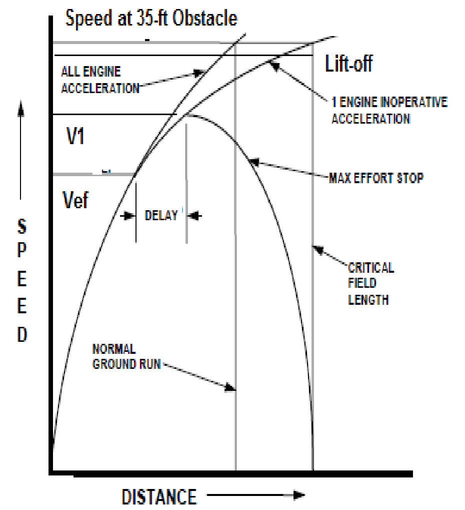


Figure 2 – Balanced Field Length Terminology Chart

However, the engineer must realize that under many flight and airport conditions, typically operations at light weight and/or slippery runways, the aircraft will be accel-stop limited because *VEF* (which governs *V1*) cannot be lowered beneath *VMCG*. Under other flight conditions, typically heavy weight, dry runway conditions, the aircraft may be accelerate-go limited because *V1* cannot be elevated above the rotation speed, *VR*. It is important to understand that the critical field length with *V1* set as slow as possible (*VEF* = *VMCG*), governs short-field runway performance.

When operating out of longer runways, engineers should consider a pilot's convenience critical field length with *V1* set to the nominal rotation speed. Pilots prefer to fly aircraft with *V1* scheduled as fast as possible so that they can perform a rejected takeoff maneuver at any ground speed prior to rotation. If the "go-no-go" speed *V1* is significantly slower than *VR*, the engineer expects the pilot to hold the aircraft on the runway for an extended period of time after an engine failure waiting to attain rotation speed. While many pilots may be able to perform an OEI takeoff in a controlled training exercise, the reality is that a real engine failure would result in a strenuous situation. The normally composed cockpit can quickly become a cacophony of alarms and warnings all while the aircraft is speeding down the runway. This unexpected and sudden onset of warning stimuli can leave the pilot's decision making process prone to the startle effect. This tends to cause the pilot to react instinctively instead of rationally. The initial impulse of the pilot would be to bring the stricken plane to a halt instead of continuing with the flight, even though the amount of runway remaining would not support a safe stoppage of the aircraft. This resulting overconfidence bias in the decision making process would then lead to the disastrous outcome of a runway overrun. Setting *V1* at the same airspeed as *VR* effectively removes the decision making requirement for an aborted takeoff, removing mental workload on a pilot during an emergency situation.

C. Accelerate-Stop Simulation

For accelerate-stop, the simulation will follow regulation 14 CFR § 25.109.[4] It will numerically integrate aircraft time and position history for two scenarios:

- when an **engine fails** at the most inopportune time (recognized by the pilot just as the aircraft reaches its critical go-no-go speed, *V1*) and the pilot must abort the takeoff, and
- when the pilot decides for **any other reason** to abort that takeoff just as the aircraft reaches its critical go-no-go speed, *V1*)

In scenario 1: we compute the total distance covered by the aircraft when it accelerates:

- "from a standing start with all engines operating to *VEF*," [4]
- "from *VEF* to the highest speed reached during the rejected takeoff, assuming the critical engine fails at *VEF* and the pilot takes the first action to reject the takeoff at *V1*" [4]
- travel "a distance equivalent to 2 seconds at the *V1*" [4] speed, and
- "come to a full stop" [4]

In scenario 2: we compute the total distance covered by the aircraft when it accelerates:

- "from a standing start with all engines operating to the highest speed reached during the rejected takeoff, assuming the pilot takes the first action to reject the takeoff at *V1*," [4]
- travel "a distance equivalent to 2 seconds at the *V1* " [4] speed
- "with all engines still operating, come to a full stop" [4]

Note that braking effect is a function of the weight on wheels. Because any residual lift developed by the wing will reduce the effective weight on wheels, an airplane that lifts up at its ground incidence will have a longer stopping distance than one that develops downforce. The residual thrust of the engines at idle also contribute to the stopping distance. Presently, the use of thrust reversers is forbidden by regulation when calculating the dry runway accelerate-stop distance. In an actual rejected takeoff situation, if reverse thrust is available, pilots will use it to help stop the aircraft quickly.

D. Failed Engine Accelerate-Go Simulation

The failed engine accel-go simulation follows regulation 14 CFR § 25.111[5]. It will numerically integrate aircraft time and position history to simulate:

- Acceleration "from a standing start with all engines operating to *VEF*,"[5]
- From *VEF* to the *V1* " go-no-go" speed, with one engine failed, [5]
- From *V1* to the *VR* rotation speed, with one engine failed, [5]
- With one engine failed, have the pilot slowly command a nose-up attitude until the aircraft leaves the runway (where Lift > Weight), [5]

- With one engine failed, allow the aircraft to climb until it reaches a height of 35-ft above the runway surface; *VR* must be selected so that the aircraft attains the scheduled *V2* speed at this point. [5]

The code tracks the one engine inoperative (OEI) takeoff ground roll distance (to the point where the wheels first leave the runway), *TOGR*, as well as the takeoff distance to the 35-ft obstacle height, *TODR*. It also tracks the speed at lift off (*VLOF*) in terms of indicated airspeed and the climb gradient.

E. All Engines Operating Takeoff Simulation

The all-engines-operating (AEO) simulation follows regulation 14 CFR § 25.113[6] to reflect normal operating conditions. It will compute the total distance covered by the aircraft when it accelerates:

- From a standing start with all engines operating to the *VR* rotation speed, [6]
- Command a nose-up attitude until the aircraft leaves the runway (where Lift > Weight), [6]
- Allow the aircraft to climb until it reaches a height of 35-ft above the runway surface; the aircraft is allowed to considerably exceed the scheduled *V2* speed (which is an obstacle-clearance speed target for use only in the event of engine failure during takeoff). [6]

The code tracks the all engines operating (*AEO*) takeoff ground roll distance (to the point where the wheels first leave the runway) (*TOGR*) as well as the takeoff distance to the 35-ft obstacle height(*TODR*).

IV.Trade Studies

This paper will consider the effects of various aerodynamic, propulsive and mass-properties uncertainties upon the takeoff distances of a notional narrow-body twin-engine commercial airliner, reminiscent of an Airbus A320. It will compare and contrast these new results with effects of timing and operational parameters published in AIAA 2017-007.[1] Where AIAA 2017-0007 examined timing and braking effects upon takeoff. Here, we will examine the effects of a variety of other parameters upon the "handbook" performance of an aircraft.

- What are the effects of small changes in takeoff thrust to the "certified" distances? (baseline vs. 1000-lbf static thrust degradation). That is, reporting the takeoff performance for a 27,000-lbf thrust/engine static derate as the performance for engines with 26,000-lbf static thrust. This is less of an issue with modern FADEC equipped engines than it once was.

- What are the effects of excess optimism or pessimism in *VMCA* speed to the "certified" distances?(baseline *VMCA*=110 KIAS vs increased *VMCA*=115-KIAS). In other words, providing additional safety margin by computing the performance as if the minimum control speed were higher than it actually might be.

- What are the effects of excess optimism or pessimism in *VMCG* speed to the "certified" distances?(baseline *VMCG*=115 KIAS vs increased *VMCG*=120-KIAS). This provides additional safety margin by computing the performance as if the minimum control speed were higher than it actually might be.

- What are the effects of small changes in rolling resistance to the "certified" distances? (baseline μ=0.0025, vs higher rolling resistance μ=0.0050)

- What are the effects of small changes in zero-lift aerodynamic drag to the "certified" distances?(baseline CD0=0.0350 vs increased drag CD0=0.0400)

- What are the effects of small changes in lift-induced aerodynamic drag to the "certified" distances?(baseline effective AR=8.5 vs reduced drag effective AR=9.0)

- What are the effects of small changes in maximum ground angle-of-attack to the "certified" distances?(baseline max ground $\alpha=18^{o}$ vs reduced max ground $\alpha=17^{o}$) – here we allow this to impact the *VMU* computation.

- What are the effects of small changes in stick pusher setting to the “certified” distances?(baseline CLmax=2.10 vs reduced CLmax=2.00) – here we allow this to impact the stall speed computation.

- What are the effects of changes in lift dump effectiveness to the “certified” distances? (baseline CL0=0 vs reduced lift dump CL0=+0.30) – aerodynamic lift during ground roll impedes braking action.

- What are the effects of changes in tire traction to the “certified” distances?(baseline μ=0.50 vs reduced μ=0.38)

Since field length requirements are predominantly driven by engine out scenarios, the ability of the aircraft to accelerate and, if need be, come to a stop can greatly affect field length requirements. Acceleration from a standing start is easily predicated and somewhat excluded from pilot human factors, but is sensitive to thrust, mass and various drag losses (aerodynamic and rolling resistance). By varying these parameters we can see the effects on the balanced field length performance. Any factor that reduces acceleration (higher mass, higher rolling resistance, thrust degradation), increases the necessary flight speed (higher *VMU*, *VMCG*, *VMCA*, *V2* speeds) or impedes braking (higher mass, less effective lift dump, reduced tire traction) will degrade field performance.

A. Baseline Aircraft

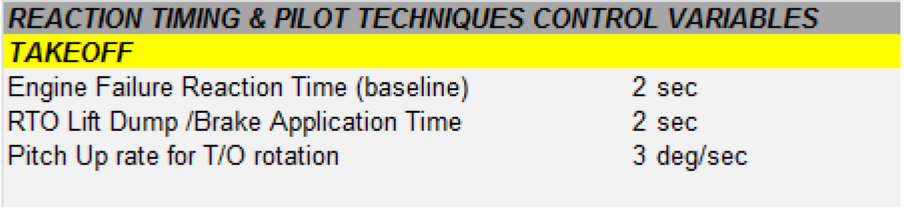
The nominal aircraft configuration employed here is reminiscent of an Airbus A320. Our best estimate at reverse engineering published field performance values for an A320 with IAE V2527-A5 engines is shown below.

We find excellent agreement between certified performance and our analytical model based upon the following assumptions. It features an aspect ratio 8.5 wing of Sref=1319 ft^2. Gear up zero-lift drag for takeoff (and approach flaps) is CD0=0.0350. Extended landing gear adds an additional ΔCD0=0.0100. Lift dump spoilers add an additional ΔCD0=0.0250 and reduce lift ΔCL=-0.3 for takeoff, ΔCL=-0.4 for landing. Windmill drag of an inoperative engine adds ΔCD0=0.0150. Setting takeoff flaps produces CLmax=2.10 with zero incidence CL0=0.3. The notional ground incidence is α=-1^{o}. Maximum ground incidence at tail strike (for *VMU* computations) is α_{max}=18^{o}. Cue speeds, controlled by lateral-directional control power, are limited by: *VMCG*=115 KIAS; *VMCA*=110 KIAS; *VMCL*=110 KIAS. Thrust = 27,000-lbf static with speed dependent thrust lapse commensurate with a BPR=6 engine; there is no thrust push upon sensed engine failure.

Table 1 – Baseline Aerodynamic Parameters

Baseline Aerodynamics	
CLmax	2.1
CL0	0.30
CD0	0.0350
AR	8.5
Ground Incidence	-1^{o}
dCD gear	+0.0100
dCD inop engine	+0.0050
dCL spoilers	-0.30
dCD spoilers	+0.0250

Table 2 - Baseline Timing



REACTION TIMING & PILOT TECHNIQUES CONTROL VARIABLES	
TAKEOFF	
Engine Failure Reaction Time (baseline)	2 sec
RTO Lift Dump /Brake Application Time	2 sec
Pitch Up rate for T/O rotation	3 deg/sec

Table 3- Baseline Field Performance Estimates (reverse engineered A320) Performance computed using μ=0.50 braking traction

Wt (lbm)	Alt(ft)	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOF F CFL(FT) V1=VR	TODR AEO (ft) VEF>= VMCG	TOGR AEO (ft) VEF>= VMCG	TODR OEI (ft) VEF>= VMCG	TOGR OEI (ft) VEF>= VMCG	ASDA OEI (ft) VEF>= VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMU (ktas)	VMU (kias)	VMCG (ktas)	VMCG (kias)	VMCA (ktas)	VMCA (kias)	VR (kias)	V2 (kias)	AEO CLimb (ktas)	AEO Climb (kias)	VEF (OEI) V1=VR (kias)	ROC_ 2SEG (ft/min)	GRAD 2SEG (%)
170000	0	6800	7350	5450	5050	6800	6100	6650	6050	5350	7350	134	134	115	115	110	110	147	152	160	160	145	560	3.6
165000	0	6450	7000	5150	4800	6450	5800	6400	5850	5200	7000	132	132	115	115	110	110	145	150	158	158	142	620	4
160000	0	6100	6700	4900	4550	6100	5500	6050	5500	4900	6700	130	130	115	115	110	110	143	148	156	156	140	680	4.5
155000	0	5750	6350	4600	4250	5750	5200	5650	5100	4550	6350	128	128	115	115	110	110	140	145	153	153	137	740	5
150000	0	5450	6100	4300	4000	5450	4950	5400	4800	4300	6100	126	126	115	115	110	110	138	143	151	151	135	800	5.5
145000	0	5200	5850	4100	3750	5200	4750	5100	4550	4100	5850	124	124	115	115	110	110	136	140	148	148	133	860	6
140000	0	4850	5500	3800	3500	4850	4400	4800	4300	3850	5500	122	122	115	115	110	110	133	138	146	146	129	930	6.6
135000	0	4600	5250	3600	3300	4600	4200	4550	4050	3650	5250	119	119	115	115	110	110	131	135	143	143	127	1000	7.3
130000	0	4350	5000	3350	3050	4250	3850	4350	3750	3400	5000	117	117	115	115	110	110	128	133	141	141	124	1070	8
125000	0	4300	4750	3150	2900	3900	3550	4300	3550	3200	4750	115	115	115	115	110	110	126	130	138	138	121	1150	8.7
120000	0	4250	4550	2900	2650	3450	3150	4250	3300	3000	4550	113	113	115	115	110	110	123	128	136	136	118	1230	9.5
115000	0	4200	4350	2700	2500	3200	2900	4200	3100	2800	4350	110	110	115	115	110	110	121	125	133	133	116	1320	10.4
110000	0	4200	4150	2550	2350	2900	2600	4200	2950	2650	4150	108	108	115	115	110	110	119	122	130	130	113	1410	11.4

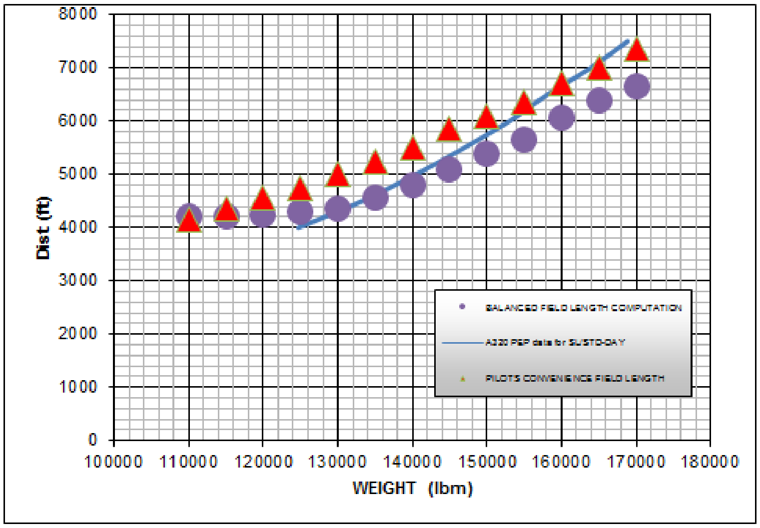


Figure 3 - Baseline Field Performance Results (comparison with A320 flight manual)

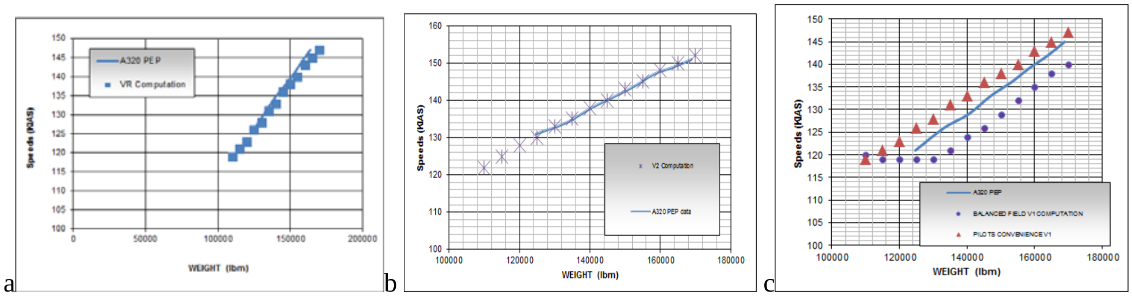


Figure 4 - Baseline Cue Speeds (comparison with A320 flight manual)

Following our best guess at the baseline reaction times for takeoff and landing (see Table 3), we attempted to calibrate our simulation against published field performance data. To reasonably match published distances (refer to Figure 3), we had to employ (for the baseline model) aggressive dry braking coefficients.

For takeoff, we match *VR* and *V2* speeds exactly (refer to Figure 4a and 4b respectively). Official Airbus procedure schedules (refer to Figure 4c) the decision speed *V1*, as *VR-5KIAS*, which is neither a *V1=VR* "pilots convenience" schedule nor a speed which supports a short-runway balanced field condition. length speed. Returning to Figure 3, you can see how our simulation splits the difference in speeds and distances regarding the "official" procedure.

This simulation supports a trend of sagging field performance proportional to takeoff weight increase. Takeoff and landing distances grow with increased weights, which is to be expected. Elevated *V* speeds are also evident within the trends. Higher airspeeds needed for takeoff result in higher decision speeds. This causes the balanced field lengths to grow, as the distance required to stop has increased with the higher velocity and weight.

In Figure 5, we examine the effects of weight on decision speed for true balanced field length operation. Following 14 CFR § 121.189,[12] for permissible dispatch, the runway must be no longer than the greatest distance as controlled by 14 CFR § 25.113.[6] In all cases studied, the field length increases with higher weights. By setting *V1* between *VMCG* and *VR*, we can usually obtain a balanced field condition (where accel-stop equals accel-go). In all cases, the required field length is noticeably shorter than that found when *V1*=*VR*. Remember, that as the decision speed (*V1*) increases so does the accelerate-stop distance. At the same time, a higher engine failure speed results in quicker overall acceleration to flight conditions hence shorter engine-inoperative accel-go distances. This is to be expected as the balanced field length decision speed (*V1*) is always slower than the rotation speed (*VR*).

In Figure 6, the effects on the *V* speeds are evaluated with increasing weights. As expected, increasing weight drives up the V speeds. At lighter weights, however, *V1* "flat-lines" in order to stay above *VMCG*. This is to prevent an OEI takeoff continuation below the minimum control ground speed.

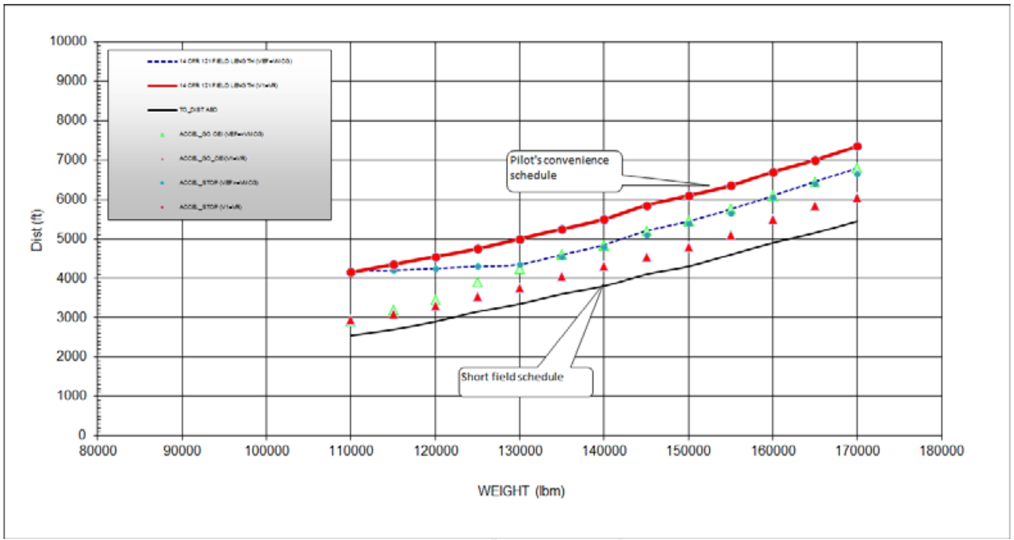


Figure 5 – Comparison of short field vs pilots convenience decision speed schedule (from simulation)

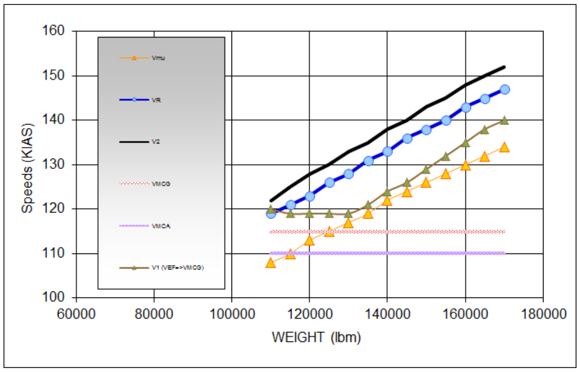


Figure 6 –Takeoff cue speeds from simulation, short field vs. pilots convenience speed schedule

B. Effect of Variant Configuration – Certification

In this section, we present tabular and graphical data that show the effects of perturbing the aircraft configuration from the baseline.

In a companion paper, AIAA-2017-####, we will discuss the effect of changes in aircraft configuration and piloting procedure on actual distances seeking to identify cases where the "book" distances are either highly optimistic (which is a potential safety hazard) or pessimistic (which unnecessarily restricts dispatch).[12]

In this paper we look at the effects of specification changes upon what would be considered "book" values – that is the performance of the aircraft when flown to uniform procedures appropriate for certification. We concentrate here on the changes in "book" performance that arise from seemingly minor changes in aircraft specification such as: overall engine thrust level, minimum control airspeed limits, tire rolling resistance, extra zero-lift-drag, reduced lift induced drag (winglets), tail strike and free flight stick pusher limits, lift dump effectiveness and tire traction.

The reader should remember that our numerical simulation time step integrates in 0.1 second intervals. To better simulate "real world" pilots, we trigger events only when the aircraft exceeds cue speeds. These speeds are always rounded to the nearest whole knot. Our simulation also rounds also reported speeds to the nearest knot; all distances to the nearest 50-ft and all gradients to the nearest tenth of a percent.

Tables 4 and 5 (overleaf) reports the performance of the baseline aircraft modified with an across-the-board reduction in engine thrust of 500-lbf per engine. In other words, the effects of a pair of 26,500-lbf engines (with the expected velocity and altitude lapse) in lieu of the baseline pair of 27,000-lbf engines. Here, we see an overall degradation of the engine inoperative second segment climb performance (ROC_2SEG and GRAD_2SEG) of approximately -0.3%. We also see longer take-off distances across the board; the increased distances do not exceed 150-ft.

Table 4 - Field Performance Estimates – 500-lbf thrust per engine degradation / no-change in idle thrust (reverse engineered A320, ESDU braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	26500	6850	7450	5600	5150	6850	6100	6800	6200	5450	7450	115	110	141	163	147	152	520	3.4
165000	0	26500	6550	7150	5250	4900	6550	5900	6450	5850	5150	7150	115	110	138	161	145	150	570	3.8
160000	0	26500	6250	6800	5000	4600	6250	5650	6100	5550	4950	6800	115	110	135	160	143	148	630	4.2
155000	0	26500	5850	6400	4650	4300	5850	5300	5750	5250	4700	6400	115	110	132	158	140	145	690	4.7
150000	0	26500	5600	6150	4450	4100	5600	5050	5450	4950	4400	6150	115	110	129	156	138	143	750	5.2
145000	0	26500	5300	5900	4150	3850	5300	4800	5150	4650	4150	5900	115	110	127	155	136	140	820	5.7
140000	0	26500	4950	5550	3900	3600	4950	4500	4850	4400	3900	5550	115	110	123	153	133	138	880	6.3
135000	0	26500	4650	5300	3650	3350	4650	4250	4650	4100	3700	5300	115	110	122	151	131	135	950	6.9
130000	0	26500	4400	5000	3400	3100	4350	3950	4400	3850	3450	5000	115	110	119	148	128	133	1030	7.6
125000	0	26500	4350	4850	3200	2900	3950	3600	4350	3600	3250	4850	115	110	119	147	126	130	1100	8.3
120000	0	26500	4300	4550	2950	2700	3550	3200	4300	3400	3050	4550	115	110	119	145	123	128	1180	9.1
115000	0	26500	4250	4400	2750	2500	3250	2900	4250	3150	2800	4400	115	110	120	143	121	125	1270	10
110000	0	26500	4200	4150	2550	2350	2950	2650	4200	3000	2700	4150	115	110	120	142	119	122	1360	11

Table 5 - Aircraft Performance Penalty– 500-lbf thrust per engine degradation / no-change in idle thrust

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)
170000	50	100	-0.2
165000	100	150	-0.2
160000	150	100	-0.3
155000	100	50	-0.3
150000	150	50	-0.3
145000	100	50	-0.3
140000	100	50	-0.3
135000	50	50	-0.4
130000	50	0	-0.4
125000	50	100	-0.4
120000	50	0	-0.4
115000	50	50	-0.4
110000	0	0	-0.4

Tables 6 & 7 (overleaf) report the performance increasing both *VMCA* and *VMCG* by 5-KIAS into the certified takeoff distances for the purposes of developing 'book' data. When these constraints are active, they impact the choice of decision speed for short-field operation. Because *VMCA* and *VMCG* limits only impact the baseline aircraft at very light weights, the impact of this change is only evident at flight weights less than 130,000-lbm. Interestingly, while an increase in minimum control speed requires a longer runway, the higher rotation and *V2* speeds lead to a slight increase in engine inoperative climb performance.

Tables 8 and 9 (overleaf) report the performance change resulting from elevating *VMCG* by 5-KIAS. When the *VMCG* constraint on decision speed (*V1*) is active, it elevates *V1*. Because *VMCG* limits only impact the baseline aircraft at very light weights, the impact of this change is only evident at flight weights less than 130,000-lbm. For this aircraft, the elevated *VMCG* speed does not impact rotation or *V2* speeds; hence there is no change in engine inoperative climb performance.

Table 6 - Field Performance Estimates – 5 KIAS increase in *VMCA* and *VMCG* (reverse engineered A320, μ=0.5 braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6800	7350	5450	5050	6800	6100	6650	6050	5350	7350	120	115	140	163	147	152	560	3.6
165000	0	27000	6450	7000	5150	4800	6450	5800	6400	5850	5200	7000	120	115	138	162	145	150	620	4
160000	0	27000	6100	6700	4900	4550	6100	5500	6050	5500	4900	6700	120	115	135	160	143	148	680	4.5
155000	0	27000	5750	6350	4600	4250	5750	5200	5650	5100	4550	6350	120	115	132	158	140	145	740	5
150000	0	27000	5450	6100	4300	4000	5450	4950	5400	4800	4300	6100	120	115	129	156	138	143	800	5.5
145000	0	27000	5200	5850	4100	3750	5200	4750	5100	4550	4100	5850	120	115	126	155	136	140	860	6
140000	0	27000	4850	5500	3800	3500	4850	4400	4800	4300	3850	5500	120	115	124	153	133	138	930	6.6
135000	0	27000	4750	5250	3600	3300	4500	4050	4750	4050	3650	5250	120	115	123	151	131	135	1000	7.3
130000	0	27000	4700	5000	3350	3050	4000	3600	4700	3750	3400	5000	120	115	124	149	128	133	1070	8
125000	0	27000	4600	4750	3150	2900	3700	3350	4600	3550	3200	4750	120	115	124	148	126	130	1150	8.7
120000	0	27000	4550	4550	2900	2650	3250	2950	4550	3300	3000	4550	120	115	124	145	123	128	1230	9.5
115000	0	27000	4550	4550	2800	2550	3200	2900	4550	3200	2900	4550	120	115	124	146	124	127	1340	10.5
110000	0	27000	4500	4400	2650	2450	3000	2750	4500	3050	2800	4400	120	115	125	146	124	127	1480	11.6

Table 7 - Aircraft Performance Penalty– 5 KIAS increased *VMCA* and *VMCG*

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)	V2 Bump
170000	0	0	0	0
165000	0	0	0	0
160000	0	0	0.3	0
155000	0	0	0	0
150000	0	0	0	0
145000	0	0	0	0
140000	0	0	0	0
135000	150	0	0	0
130000	350	0	0	0
125000	300	0	0	0
120000	300	0	0	0
115000	350	200	0.1	2
110000	300	250	0.2	5

Table 8 - Field Performance Estimates – 5 KIAS increase in *VMCG* only (reverse engineered A320, μ=0.5 braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6800	7350	5450	5050	6800	6100	6650	6050	5350	7350	120	110	140	163	147	152	560	3.6
165000	0	27000	6450	7000	5150	4800	6450	5800	6400	5850	5200	7000	120	110	138	162	145	150	620	4
160000	0	27000	6100	6700	4900	4550	6100	5500	6050	5500	4900	6700	120	110	135	160	143	148	680	4.5
155000	0	27000	5750	6350	4600	4250	5750	5200	5650	5100	4550	6350	120	110	132	158	140	145	740	5
150000	0	27000	5450	6100	4300	4000	5450	4950	5400	4800	4300	6100	120	110	129	156	138	143	800	5.5
145000	0	27000	5200	5850	4100	3750	5200	4750	5100	4550	4100	5850	120	110	126	155	136	140	860	6
140000	0	27000	4850	5500	3800	3500	4850	4400	4800	4300	3850	5500	120	110	124	153	133	138	930	6.6
135000	0	27000	4750	5250	3600	3300	4500	4050	4750	4050	3650	5250	120	110	123	151	131	135	1000	7.3
130000	0	27000	4700	5000	3350	3050	4000	3600	4700	3750	3400	5000	120	110	124	149	128	133	1070	8
125000	0	27000	4600	4750	3150	2900	3700	3350	4600	3550	3200	4750	120	110	124	148	126	130	1150	8.7
120000	0	27000	4550	4550	2900	2650	3250	2950	4550	3300	3000	4550	120	110	124	145	123	128	1230	9.5
115000	0	27000	4550	4550	2800	2550	3200	2900	4550	3200	2900	4550	120	110	124	146	124	125	1320	10.4
110000	0	27000	4500	4400	2650	2450	3000	2750	4500	3050	2800	4400	120	110	125	146	124	122	1410	11.4

Table 9 - Aircraft Performance Penalty– 5 KIAS increase in *VMCG* only

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)
170000	0	0	0
165000	0	0	0
160000	0	0	0
155000	0	0	0
150000	0	0	0
145000	0	0	0
140000	0	0	0
135000	150	0	0
130000	350	0	0
125000	300	0	0
120000	300	0	0
115000	350	200	0
110000	300	250	0

T

Table 10 - Field Performance Estimates – 5 KIAS increase in *VMCA* (reverse engineered A320, μ=0.5 braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6800	7350	5450	5050	6800	6100	6650	6050	5350	7350	115	115	140	163	147	152	560	3.6
165000	0	27000	6450	7000	5150	4800	6450	5800	6400	5850	5200	7000	115	115	138	162	145	150	620	4
160000	0	27000	6100	6700	4900	4550	6100	5500	6050	5500	4900	6700	115	115	135	160	143	148	680	4.5
155000	0	27000	5750	6350	4600	4250	5750	5200	5650	5100	4550	6350	115	115	132	158	140	145	740	5
150000	0	27000	5450	6100	4300	4000	5450	4950	5400	4800	4300	6100	115	115	129	156	138	143	800	5.5
145000	0	27000	5200	5850	4100	3750	5200	4750	5100	4550	4100	5850	115	115	126	155	136	140	860	6
140000	0	27000	4850	5500	3800	3500	4850	4400	4800	4300	3850	5500	115	115	124	153	133	138	930	6.6
135000	0	27000	4600	5250	3600	3300	4600	4200	4550	4050	3650	5250	115	115	121	151	131	135	1000	7.3
130000	0	27000	4350	5000	3350	3050	4250	3850	4350	3750	3400	5000	115	115	119	149	128	133	1070	8
125000	0	27000	4300	4750	3150	2900	3900	3550	4300	3550	3200	4750	115	115	119	148	126	130	1150	8.7
120000	0	27000	4250	4550	2900	2650	3450	3150	4250	3300	3000	4550	115	115	119	145	123	128	1230	9.5
115000	0	27000	4200	4350	2700	2500	3200	2900	4200	3100	2800	4350	115	115	119	144	121	127	1340	10.5
110000	0	27000	4200	4200	2550	2350	2950	2650	4200	2950	2650	4200	115	115	120	143	120	127	1480	11.6

Table 11 - Aircraft Performance Penalty– 5 KIAS increase in *VMCA*

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)	V2 Bump
170000	0	0	0	0
165000	0	0	0	0
160000	0	0	0	0
155000	0	0	0	0
150000	0	0	0	0
145000	0	0	0	0
140000	0	0	0	0
135000	0	0	0	0
130000	0	0	0	0
125000	0	0	0	0
120000	0	0	0	0
115000	0	0	0.1	2
110000	0	50	0.2	5

Table 13 - Aircraft Performance Penalty– Double Rolling Resistance

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)
170000	0	0	0
165000	0	0	0
160000	0	0	0
155000	0	0	0
150000	0	0	0
145000	0	0	0
140000	0	0	0
135000	0	0	0
130000	0	0	0
125000	0	0	0
120000	0	0	0
115000	0	0	0
110000	0	0	0

Table 12 - Field Performance Estimates – Double rolling resistance (reverse engineered A320, μ=0.5 braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6800	7350	5450	5050	6800	6100	6650	6050	5350	7350	115	110	140	163	147	152	560	3.6
165000	0	27000	6450	7000	5150	4800	6450	5800	6400	5850	5200	7000	115	110	138	162	145	150	620	4
160000	0	27000	6100	6700	4900	4550	6100	5500	6050	5500	4900	6700	115	110	135	160	143	148	680	4.5
155000	0	27000	5750	6350	4600	4250	5750	5200	5650	5100	4550	6350	115	110	132	158	140	145	740	5
150000	0	27000	5450	6100	4300	4000	5450	4950	5400	4800	4300	6100	115	110	129	156	138	143	800	5.5
145000	0	27000	5200	5850	4100	3750	5200	4750	5100	4550	4100	5850	115	110	126	155	136	140	860	6
140000	0	27000	4850	5500	3800	3500	4850	4400	4800	4300	3850	5500	115	110	124	153	133	138	930	6.6
135000	0	27000	4600	5250	3600	3300	4600	4200	4550	4050	3650	5250	115	110	121	151	131	135	1000	7.3
130000	0	27000	4350	5000	3350	3050	4250	3850	4350	3750	3400	5000	115	110	119	149	128	133	1070	8
125000	0	27000	4300	4750	3150	2900	3900	3550	4300	3550	3200	4750	115	110	119	148	126	130	1150	8.7
120000	0	27000	4250	4550	2900	2650	3450	3150	4250	3300	3000	4550	115	110	119	145	123	128	1230	9.5
115000	0	27000	4200	4350	2700	2500	3200	2900	4200	3100	2800	4350	115	110	119	144	121	125	1320	10.4
110000	0	27000	4200	4150	2550	2350	2900	2600	4200	2950	2650	4150	115	110	120	143	119	122	1410	11.4

Tables 10 and 11 (above) report the performance impact stemming from elevating *VMCA* by 5-KIAS. For this aircraft, we see that the higher *VMCA* does not directly impact ground decision speeds; instead, it elevates *V2* speeds at light flight weights. Here we see an increase in *V2* speed over baseline, only impacting flight at the lightest of weights (110,000-lbm). When the *VMCA* constraint is active, on decision speed (*V1*) is active, it elevates *V1*. Because *VMCG* limits only impact the baseline aircraft at very light weights, the impact of this change is only evident at flight weights less than 130,000-lbm. For this aircraft, the elevated *VMCA* speed does improve engine inoperative climb performance slightly (12.0% vs 11.9% gradient at 110,000-lbm).

Tables 12 and 13 (above) report the performance degradation found by increasing the rolling resistance of the unbraked wheels by a factor of two. That is documenting the increased ground roll resulting from a change in rolling resistance from a baseline value of μ=0.0025 to μ=0.0050. Here we see that the performance degradation from this change is lost within the rounding error of the simulation. There is no effective change in estimated critical field length distances.

Tables 14 and 15 (below) report the performance impact found by increasing the zero lift aerodynamic drag coefficient 25 counts from 0.0350 to 0.0375 (an 7% increase in zero-lift drag) into the certified takeoff distances. Here we see a small across-the-board penalty in engine inoperative second segment climb gradient but only marginal changes (beyond rounding error) in field performance. The dominant factor in determining the takeoff ground roll is the thrust acting in opposition to the aircraft mass, not the zero-lift drag.

Table 14 - Field Performance Estimates - 25 counts extra CD0 (reverse engineered A320, μ=0.5 braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6750	7400	5500	5100	6750	6050	6750	6050	5350	7400	115	110	141	163	147	152	540	3.5
165000	0	27000	6450	7050	5200	4800	6450	5800	6400	5750	5100	7050	115	110	138	162	145	150	590	3.9
160000	0	27000	6150	6700	4900	4550	6150	5550	6050	5500	4900	6700	115	110	135	160	143	148	650	4.3
155000	0	27000	5750	6350	4600	4250	5750	5200	5700	5150	4600	6350	115	110	132	158	140	145	710	4.8
150000	0	27000	5450	6100	4300	4000	5450	4950	5450	4850	4350	6100	115	110	130	156	138	143	780	5.3
145000	0	27000	5200	5900	4100	3800	5200	4700	5150	4550	4050	5900	115	110	127	155	136	140	840	5.9
140000	0	27000	4850	5450	3850	3500	4850	4400	4800	4300	3900	5450	115	110	123	153	133	138	910	6.5
135000	0	27000	4650	5300	3600	3300	4650	4250	4550	4050	3650	5300	115	110	120	151	131	135	980	7.1
130000	0	27000	4400	5000	3350	3050	4250	3850	4400	3750	3400	5000	115	110	119	149	128	133	1050	7.8
125000	0	27000	4350	4750	3150	2900	3900	3550	4350	3600	3250	4750	115	110	119	147	126	130	1130	8.6
120000	0	27000	4300	4500	2900	2700	3500	3150	4300	3350	3000	4500	115	110	119	146	123	128	1210	9.4
115000	0	27000	4250	4350	2750	2500	3200	2850	4250	3100	2800	4350	115	110	120	144	121	125	1300	10.3
110000	0	27000	4200	4100	2550	2350	2900	2600	4200	2950	2650	4100	115	110	120	143	119	122	1390	11.2

Table 15 - Aircraft Performance Penalty– 25 counts extra CD0

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)
170000	-50	50	-0.1
165000	0	50	-0.1
160000	50	0	-0.2
155000	0	0	-0.2
150000	0	0	-0.2
145000	0	50	-0.1
140000	0	-50	-0.1
135000	50	50	-0.2
130000	50	0	-0.2
125000	50	0	-0.1
120000	50	-50	-0.1
115000	50	0	-0.1
110000	0	-50	-0.2

Tables 16 and 17 (below) report the performance impacts found by increasing the effective aspect ratio from 8.5 to 9.0 (a 5.8% increase in AR). This effectively reduces induced drag by 5.8%. Here we see a small across-the-board improvement in engine inoperative second segment climb gradient (approximately 0.3% improvement). We see marginal improvements (less than 100-ft) in in field performance. The dominant factor in determining the takeoff ground roll is the thrust acting in opposition to the aircraft mass, not the induced drag in ground effect.

Tables 18 and 19 (overleaf) report the performance change where the maximum ground angle of attack for tailstrike has been reduced from 18 to 17 degrees angle of attack. This will alter the minimum unstick speed of the aircraft, and potentially alter the lift-off speeds. This sort of configuration change can arise when designers implement a fuselage stretch to the baseline design. This sort of configuration change can also arise operationally when an aircraft is found to be easy to over-rotate by line pilots. Here we see a significant degradation in field performance; the reduced ground rotation would increase certified distances by up to 350-ft (more than 5%). This effect is present in all takeoff cases except those where takeoff speeds are elevated because *V2* is limited by *VMCA* concerns.

Table 16 - Field Performance Estimates – Increased Effective AR (reverse engineered A320, μ=0.5 braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6700	7300	5350	5000	6700	6050	6550	5950	5300	7300	115	110	139	162	146	152	620	4
165000	0	27000	6300	6900	5100	4750	6300	5700	6300	5750	5100	6900	115	110	137	161	144	150	670	4.4
160000	0	27000	6050	6600	4850	4450	6050	5500	5950	5400	4850	6600	115	110	134	159	142	148	730	4.9
155000	0	27000	5750	6350	4550	4200	5750	5200	5650	5100	4550	6350	115	110	132	158	140	145	790	5.4
150000	0	27000	5450	6100	4300	4000	5450	4950	5400	4800	4300	6100	115	110	130	156	138	143	850	5.9
145000	0	27000	5100	5800	4000	3700	5100	4650	5100	4500	4050	5800	115	110	126	154	135	140	920	6.4
140000	0	27000	4850	5500	3800	3500	4850	4400	4800	4300	3850	5500	115	110	123	153	133	138	980	7
135000	0	27000	4550	5200	3550	3250	4550	4150	4500	4000	3600	5200	115	110	120	150	130	135	1050	7.7
130000	0	27000	4350	5000	3350	3050	4250	3850	4350	3750	3400	5000	115	110	119	149	128	133	1130	8.3
125000	0	27000	4300	4750	3100	2850	3900	3550	4300	3550	3200	4750	115	110	119	147	126	130	1200	9.1
120000	0	27000	4250	4550	2900	2650	3450	3150	4250	3300	3000	4550	115	110	119	145	123	128	1280	9.9
115000	0	27000	4200	4300	2700	2450	3100	2800	4200	3050	2750	4300	115	110	119	143	120	125	1370	10.8
110000	0	27000	4200	4150	2550	2300	2850	2600	4200	2900	2650	4150	115	110	120	143	119	122	1460	11.8

Table 17 - Aircraft Performance Penalty– Increased Effective AR

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)
170000	-100	-50	0.4
165000	-150	-100	0.4
160000	-50	-100	0.6
155000	0	0	0.4
150000	0	0	0.4
145000	-100	-50	0.4
140000	0	0	0.4
135000	-50	-50	0.4
130000	0	0	0.3
125000	0	0	0.4
120000	0	0	0.4
115000	0	-50	0.4
110000	0	0	0.4

Table 18 - Field Performance Estimates – Tail Strike – 1-degree reduction in Maximum Ground Angle of Attack with associated increase in *VMU* (reverse engineered A320, ESDU braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	7100	7750	5700	5300	7100	6400	7000	6300	5600	7750	115	110	144	167	151	152	560	3.6
165000	0	27000	6650	7350	5300	4950	6650	6050	6550	5850	5200	7350	115	110	140	164	148	150	620	4
160000	0	27000	6300	6950	5050	4700	6300	5750	6300	5650	5050	6950	115	110	138	163	146	148	680	4.5
155000	0	27000	6000	6650	4800	4400	6000	5450	5950	5300	4800	6650	115	110	135	161	144	145	740	5
150000	0	27000	5700	6350	4450	4100	5700	5150	5550	4950	4450	6350	115	110	131	159	141	143	800	5.5
145000	0	27000	5350	6100	4200	3900	5350	4850	5350	4700	4200	6100	115	110	130	157	139	140	860	6
140000	0	27000	5100	5800	3950	3650	5100	4650	5000	4450	4000	5800	115	110	126	155	137	138	930	6.6
135000	0	27000	4750	5500	3700	3400	4750	4350	4750	4150	3750	5500	115	110	123	153	134	135	1000	7.3
130000	0	27000	4550	5250	3500	3200	4550	4150	4450	3900	3550	5250	115	110	120	152	132	133	1070	8
125000	0	27000	4300	4950	3200	2950	4150	3800	4300	3650	3300	4950	115	110	119	150	129	130	1150	8.7
120000	0	27000	4250	4700	3000	2750	3700	3400	4250	3400	3100	4700	115	110	119	147	126	128	1230	9.5
115000	0	27000	4200	4550	2800	2550	3400	3100	4200	3200	2900	4550	115	110	119	146	124	125	1320	10.4
110000	0	27000	4200	4250	2600	2350	3000	2700	4200	3000	2700	4250	115	110	120	144	121	122	1410	11.4

Table 20 - Field Performance Estimates - Stick pusher setting (reduction in CLmax from 2.1 to 2.00) (reverse engineered A320, ESDU braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6900	7550	5550	5200	6900	6200	6850	6150	5450	7550	115	110	142	165	149	156	600	3.8
165000	0	27000	6500	7100	5250	4850	6500	5850	6450	5850	5200	7100	115	110	139	163	146	153	660	4.2
160000	0	27000	6150	6800	4900	4550	6150	5600	6150	5500	4950	6800	115	110	136	161	144	151	720	4.7
155000	0	27000	5750	6350	4600	4250	5750	5200	5650	5100	4550	6350	115	110	132	158	140	149	780	5.1
150000	0	27000	5450	6100	4300	4000	5450	4950	5400	4800	4300	6100	115	110	129	156	138	146	840	5.6
145000	0	27000	5200	5850	4100	3750	5200	4750	5100	4550	4100	5850	115	110	126	155	136	144	910	6.2
140000	0	27000	4850	5500	3800	3500	4850	4400	4800	4300	3850	5500	115	110	124	153	133	141	970	6.8
135000	0	27000	4600	5250	3600	3300	4600	4200	4550	4050	3650	5250	115	110	121	151	131	139	1050	7.4
130000	0	27000	4350	5000	3350	3050	4250	3850	4350	3750	3400	5000	115	110	119	149	128	136	1120	8.1
125000	0	27000	4300	4750	3150	2900	3900	3550	4300	3550	3200	4750	115	110	119	148	126	134	1200	8.9
120000	0	27000	4250	4550	2900	2650	3450	3150	4250	3300	3000	4550	115	110	119	145	123	131	1280	9.7
115000	0	27000	4200	4350	2700	2500	3200	2900	4200	3100	2800	4350	115	110	119	144	121	128	1370	10.5
110000	0	27000	4200	4150	2550	2350	2900	2600	4200	2950	2650	4150	115	110	120	143	119	125	1460	11.5

Table 19 - Aircraft Performance Penalty– – Tail Strike – 1-degree reduction in Maximum Ground Angle of Attack with associated increase in *VMU*

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)
170000	300	400	0
165000	200	350	0
160000	200	250	-0.4
155000	250	300	0
150000	250	250	0
145000	150	250	0
140000	250	300	0
135000	150	250	0
130000	200	250	0
125000	0	200	0
120000	0	150	0
115000	0	200	0
110000	0	100	0

Table 21 - Aircraft Performance Penalty– Stick pusher setting (reduction in CLmax from 2.05 to 2.00)

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)	V2 Bump
170000	100	200	0.2	4
165000	50	100	0.2	3
160000	50	100	0.2	3
155000	0	0	0.1	4
150000	0	0	0.1	3
145000	0	0	0.2	4
140000	0	0	0.2	3
135000	0	0	0.1	4
130000	0	0	0.1	3
125000	0	0	0.2	4
120000	0	0	0.2	3
115000	0	0	0.1	3
110000	0	0	0.1	3

Table 22 - Field Performance Estimates – Ineffective lift dump (reverse engineered A320, μ =0.5 braking traction)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	6900	7600	5450	5050	6900	6200	6750	6050	5350	7600	115	110	139	163	147	152	560	3.6
165000	0	27000	6550	7200	5150	4800	6550	5900	6450	5850	5200	7200	115	110	136	162	145	150	620	4
160000	0	27000	6200	6950	4900	4550	6200	5600	6150	5500	4900	6950	115	110	134	160	143	148	680	4.5
155000	0	27000	5850	6600	4600	4250	5850	5250	5750	5100	4550	6600	115	110	131	158	140	145	740	5
150000	0	27000	5550	6350	4300	4000	5550	5050	5450	4800	4300	6350	115	110	128	156	138	143	800	5.5
145000	0	27000	5250	6100	4100	3750	5250	4800	5200	4550	4100	6100	115	110	125	155	136	140	860	6
140000	0	27000	4950	5700	3800	3500	4950	4550	4850	4300	3850	5700	115	110	121	153	133	138	930	6.6
135000	0	27000	4650	5500	3600	3300	4650	4250	4650	4050	3650	5500	115	110	120	151	131	135	1000	7.3
130000	0	27000	4550	5200	3350	3050	4250	3850	4550	3750	3400	5200	115	110	119	149	128	133	1070	8
125000	0	27000	4500	5000	3150	2900	3900	3550	4500	3550	3200	5000	115	110	119	148	126	130	1150	8.7
120000	0	27000	4450	4750	2900	2650	3450	3150	4450	3300	3000	4750	115	110	119	145	123	128	1230	9.5
115000	0	27000	4400	4550	2700	2500	3200	2900	4400	3100	2800	4550	115	110	119	144	121	125	1320	10.4
110000	0	27000	4450	4350	2550	2350	2900	2600	4450	2950	2650	4350	115	110	120	143	119	122	1410	11.4

Table 24 - Field Performance Estimates – Reduced braking μ (reverse engineered A320)

Wt (lbm)	Alt(ft)	T/O THRUST (PER ENGINE STATIC) (lbf) incl DERATE	14 CFR 121.189 TAKEOFF CFL(FT) VEF>=VMCG	14 CFR 121.189 TAKEOFF CFL(FT) V1=VR	TODR AEO (ft) VEF>=VMCG	TOGR AEO (ft) VEF>=VMCG	TODR OEI (ft) VEF>=VMCG	TOGR OEI (ft) VEF>=VMCG	ASDA OEI (ft) VEF>=VMCG	TODR OEI (ft) V1=VR	TOGR OEI (ft) V1=VR	ASDA OEI (ft) V1=VR	VMCG (kias)	VMCA (kias)	V1 (OEI) VEF>=VMCG (kias)	VLOF (AEO) (kias)	VR (kias)	V2 (kias)	ROC_2SEG (ft/min)	GRAD_2SEG (%)
170000	0	27000	7050	8000	5450	5050	7050	6350	7000	6050	5350	8000	115	110	137	163	147	152	560	3.6
165000	0	27000	6750	7600	5150	4800	6750	6100	6600	5850	5200	7600	115	110	134	162	145	150	620	4
160000	0	27000	6400	7300	4900	4550	6400	5800	6250	5500	4900	7300	115	110	131	160	143	148	680	4.5
155000	0	27000	6000	6950	4600	4250	6000	5450	5950	5100	4550	6950	115	110	128	158	140	145	740	5
150000	0	27000	5700	6700	4300	4000	5700	5200	5600	4800	4300	6700	115	110	126	156	138	143	800	5.5
145000	0	27000	5400	6450	4100	3750	5400	4900	5350	4550	4100	6450	115	110	123	155	136	140	860	6
140000	0	27000	5050	6050	3800	3500	5050	4600	5000	4300	3850	6050	115	110	119	153	133	138	930	6.6
135000	0	27000	4900	5800	3600	3300	4700	4300	4900	4050	3650	5800	115	110	118	151	131	135	1000	7.3
130000	0	27000	4850	5500	3350	3050	4250	3850	4850	3750	3400	5500	115	110	119	149	128	133	1070	8
125000	0	27000	4800	5300	3150	2900	3900	3550	4800	3550	3200	5300	115	110	119	148	126	130	1150	8.7
120000	0	27000	4750	5050	2900	2650	3450	3150	4750	3300	3000	5050	115	110	119	145	123	128	1230	9.5
115000	0	27000	4700	4800	2700	2500	3200	2900	4700	3100	2800	4800	115	110	119	144	121	125	1320	10.4
110000	0	27000	4700	4600	2550	2350	2900	2600	4700	2950	2650	4600	115	110	120	143	119	122	1410	11.4

Table 25 - Aircraft Performance Penalty– Reduced braking μ (ESDU → μ=0.39)

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)
170000	250	650
165000	300	600
160000	300	600
155000	250	600
150000	250	600
145000	200	600
140000	200	550
135000	300	550
130000	500	500
125000	500	550
120000	500	500
115000	500	450
110000	500	450

Table 23 - Aircraft Performance Penalty– Ineffective lift dump

Wt (lbm)	T.O. Short Field Penalty (ft)	T.O. Pilot's Convenience Penalty (ft)	Second Segment Climb Penalty (%)
170000	100	250	0
165000	100	200	0
160000	100	250	-0.2
155000	100	250	0
150000	100	250	0
145000	50	250	0
140000	100	200	0
135000	50	250	0
130000	200	200	0
125000	200	250	0
120000	200	200	0
115000	200	200	0
110000	250	200	0

Tables 20 and 21 (above) report the performance change where the maximum airborne lift coefficient (CLmax) has been has been reduced from 2.1 to 2.00. This is ~5% reduction, which results in a ~2.5% increase in stall speed and hence a few knots increase in the *V2* speeds. The changes in obstacle clearance speeds cross couple and impact the selection of rotation speeds. These changes also impact the choice of decision speed for short field takeoff. The increase in *V2* speed improves second segment gradient; the aircraft climbs more strongly when flown at higher airspeeds. Since the faster *V2* speed demands higher rotation speed, it drives up runway requirements slightly. Because the A320 has powerful brakes, many flight conditions are limited by all-engine operating performance rather than by critical-engine inoperative performance (recall Equation(5)).

Tables 22 and 23 (above) report the performance change where the ground spoilers have ineffective lift dump capability (increasing the zero-incidence ground lift coefficient from CL ~ 0 to CL ~ +0.3). The changes in lift dump impact the effective “weight-on-wheels” during maximum braking on a rejected takeoff. This change has no impact on either the all-engines-operating accel-go or the critical-engine-inoperative accel-go performance; it only hurts stopping distances. Consequently, the effect is only noticeable under circumstances where the aircraft is accel-stop limited (such as during pilots convenience *V1=VR* takeoff or during *VMCG* limited takeoff at light weight). For this aircraft, we note a distance penalty of ~100 to 150-ft.

Tables 24 and 25 (above) report the performance change where the where the braking traction has been reduced from the higher values implied in our calibration (μ~0.5) to μ ~0.39. These changes impact the deceleration capability of the airframe during rejected takeoff braking events and thus fundamentally change the decision speed required for balanced field length operations. With reduced traction leading to longer braking distances, we need to reduce the decision speed (*V1*) in order to “rebalance” accel-go against accel-stop. There is a substantial distance penalty arising from this change even under short-field operating procedures. Field length requirements grow by 400-ft at higher gross weights. When the aircraft is accel-stop limited, such as for short field departures at very light weights, or when operating under a pilots convenience *V1=VR* schedule, the increased accel-stop distances manifest themselves in terms of a ~1000 to 1300-ft distance penalty.

These studies clearly show that the available braking traction is the most important factor when designing (or improving upon an existing) airframe. The braking system needs to have high thermal capacity, so as to reject a takeoff at typical rotation speeds and high gross weights. In addition, the braking system needs to be able to modulate and prevent wheel lockup to actually achieve levels of traction where braking $\mu >> 0.4$.

V. Conclusions

This paper sought to examine the effects on field performance from changes in aircraft configuration. In order to best evaluate these differences, it is important to know the baseline in order to establish deviations. For our study, we chose an Airbus A320 as the baseline. This aircraft has unusually powerful, high-thermal capacity carbon brake linings (many aircraft have “brake energy limited” decision speeds). The Airbus A320 seems to have exceptionally well balanced detail design features – where the tail strike angle, the maximum lift coefficient, the lift dump system and the brake system produce a nearly ideal set of circumstances to optimize takeoff.

For more ordinary aircraft, those with “brake energy limits” or with certified distances that seem in line with lower braking traction levels, we believe that a braking system upgrade may provide unforeseen performance benefits. Recall the trend illuminated here: that a higher *V2* speed may prove beneficial for obstacle clearance (greater second segment gradient). If an aircraft, once limited by brake energy or moderate traction, could be unburdened, decision (*V1*), rotation (*VR*) and obstacle clearance speeds (*V2*) may be tuned for reduced pilot workload (*V1=VR*) and improved climb out. As the braking traction increases, holding a constant decision speed we see accelerate-stop distances shorten. Balancing accel-stop against accel-go would permit a considerably higher decision speed; a performance improvement that most line pilots would welcome.

Acknowledgements

This paper derives from work funded by Dragonfly Aeronautics LLC under Contract No. FP00006911. Mr. Wood was a part time research assistant on this project. Professor Takahashi serves both as a consultant for DragonFly Aeronautics LLC and as the Research Investigator at Arizona State University. Professor Lenore Dai serves as Principal Investigator at Arizona State University.

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[2] *See generally:* 14 C.F.R. § 25

[3] 14 C.F.R. § 25.107 “Takeoff Speeds” (2015)

[4] 14 C.F.R. § 25.109 “Accelerate Stop Distance” (2015)

[5] 14 C.F.R. § 25.111 “Takeoff Path” (2015)

[6] 14 C.F.R. § 25.113 “Takeoff Distance and Takeoff Run” (2015)

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