

Experimental Investigation of Typical Aircraft Field Performance
Versus Predicted Performance Targets

by

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ABSTRACT

This thesis explores the human factors effects pilots have when controlling the aircraft during the takeoff phase of flight. These variables come into play in the transitory phase from ground roll to flight, and in the initiation of procedures to abort a takeoff during the ground run. The FAA provides regulations for manufacturers and operators to follow, ensuring safe manufacture of aircraft and pilots that fly without endangering the passengers; however, details regarding accounting of piloting variability are lacking. Creation of a numerical simulation allowed for the controlled variation of isolated piloting procedures in order to evaluate effects on field performance. Reduced rotation rates and delayed reaction times were found to cause significant increases in field length requirements over values published in the AFM. A pilot survey was conducted to evaluate common practices for line pilots in the field, which revealed minimum regulatory compliance is exercised with little to no feedback on runway length requirements. Finally, observation of pilots training in a CRJ-200 FTD gathered extensive information on typical piloting timings in the cockpit. AEO and OEI takeoffs were observed, as well as RTOs. Pilots showed large variability in procedures and timings resulting in significant inconsistency in runway distances used as well as V-speed compliance. The observed effects from pilot timing latency correlated with the numerical simulation increased field length outputs. Variability in piloting procedures results in erratic field performance that deviates from AFM published values that invite disaster in an aircraft operating near its field performance limitations.

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NOMENCLATURE

AEO	=All Engines Operating
AGL	=Above Ground Level
ASDA	=Accel-Stop Distance Available
C.F.R.	= Code of Federal Regulations
FTD	=Flight Training Device
KIAS	=Knots Indicated Airspeed
OEI	=One Engine Inoperative
PF	=Pilot Flying
PFD	=Primary Flight Display
PM	=Pilot Monitoring
QRH	=Quick Reference Handbook
RTO	=Rejected Takeoff
TODA	=Takeoff Distance Available (beginning of roll to 35ft obstacle at end of runway)
TODR	=Takeoff Distance Run
TOGA	=Takeoff / Go Around
TOGR	=Takeoff Ground Roll
TORA	=Takeoff Run Available
VEF	=Speed at which the critical engine is assumed to fail
V _s , V _{s0} , V _{s1} , V _{sr}	=Stall Speed (as called out in various parts of the C.F.R.)
V1	= Takeoff Go/No-Go Decision Speed (one-engine inoperative)
V2	= Takeoff Obstacle Clearance Speed (one-engine inoperative)

V2MIN	=Minimum Climb Out Speed (113% Vs)
VEF	=Engine Failure Airspeed
VLOF	=Liftoff Airspeed
VMCA	=Minimum Controllable Airspeed (takeoff flap setting) (one-engine inoperative)
VMCG	=Minimum Controllable Airspeed (on the ground, during the takeoff run)
VMU	=Minimum Unstick Airspeed
VR	=Rotation Speed

I. Introduction

Within commercial aviation, aircraft field performance is inexorably linked to the requirements in the C.F.R. The Federal Aviation Administration (FAA), operating under the U.S. Department of Transportation, regulates commercial aviation in the United States. Air carriers and aircraft that conduct operations in the commercial aviation industry are bound to these regulations; they have the same effect as law. Operators or manufacturers not in regulatory compliance are subject to significant fines and punishments.

The regulations published by the FAA require manufacturers and operators to guarantee compliance with minimum performance targets to ensure safe flight. Standards provided in 14 C.F.R. § 23 and 14 C.F.R. § 25 give manufacturers minimum performance targets that their aircraft must achieve by design. After aircraft leave the production floor, 14 C.F.R. § 91, 121, and 135 offer operational standards for flight crews to follow in day-to-day operations these ensure safety through procedural compliance.

FAA regulations act to ensure that aircraft remain within their aerodynamic and structural limits; compliance with these rules ensure that operators do not place undue risk on their equipment, crew, passengers and cargo. More essential to the topic discussed in this thesis, FAA takeoff requirements mandate that aircraft must not operate off a runway that is shorter than the Airplane Flight Manual (AFM) would predict for the conditions at the time of departure. This forces aircrews and/or operations to calculate the field length requirements prior to attempting takeoff.

One of the challenges when determining aircraft field performance and requirements is understanding the pilot-aircraft interface. Pilot technique during takeoff

is a vital component in aircraft field performance. Takeoff begins with the aircraft at a standing start. It accelerates through a ground run. Once sufficient airspeed is achieved, the pilot pitches the aircraft on its main wheels to establish a positive angle of attack on the wing. As the pitch angle increases, the wings generate sufficient lift to overcome weight, the aircraft achieves flight and climbs away.

Evaluation of the takeoff ground run, flight transition and flight phase is required in order to predict how an airframe will perform in these regimes. Ultimately, the pilot is in direct control of the aircraft and initiates all maneuvers. Therefore, depending on the pilot's ability to fly the aircraft in the manner consistent with the predictive model, the real world performance figures can significantly deviate from numerical predictions.

Numerical simulations calibrated to flight test results provide the basis for field performance estimates presented in an FAA approved AFM. Typical field performance estimation tools assume consistent and accurate pilot techniques in order to achieve the predicted field performance. This brings into question the effects on field performance from human factors in the takeoff regime.

The ground roll portion of the takeoff is consistently predictable in that the dominant factors acting on the aircraft are the acceleration and drag forces. Wind is also a factor that influences the takeoff distances, however, the scope of this research follows the FAA takeoff regulations that are founded in still air conditions.

The human element begins to enter the equation at a point where pilot intervention is required. This can be in a rejected takeoff scenario where an emergency occurs at a relatively low speed and the pilot elects to abort the takeoff by bringing the aircraft to a stop on the runway. The pilot's reaction to alarm signals and determination

of whether or not the aircraft has surpassed the decision speed (V_1) can add significant time intervals between recognition and action of application of braking, all while the aircraft is still traveling down the runway at speed.

Application of human factors in a continued takeoff scenario can also lead to unforeseen variability in the field length requirements. Upon achieving flight speed, the pilot commands the aircraft to rotate nose-up in order to achieve flight. The pilot directly controls the pitch angle and pitch rate during rotation. Variation in procedure can add significant length to takeoff distances. Without accounting for the variability introduced by piloting techniques, an accurate prediction of real-world field length utilization becomes elusive.

This research seeks to determine how pilots typically operate aircraft in commercial operations during the takeoff through observations in a high fidelity, commercial aircraft simulator.

From these studies, a statistical model of reaction times can be used to correlate actual runway performance from the nominal pro-forma distances found in an AFM. This gives an objective view of where runway usage deviates from predictions and what the probable causes may be.

II. Regulatory Background

The early days of commercial aviation saw little regulation or attention to safety. Manufacturers were not required to build aircraft to meet any performance or safety standards. Operators were not required to perform any rigorous flight planning. Federal Air Traffic Control (ATC) did not exist until 1936, more than 20 years after the first commercial flight took off ([IATA], 2017). Through the years, government regulation

began to impose rules and standards on the industry that raised the bar for safety and reliability.

In 1914, Percival Fansler, along with other investors, commissioned two flying boats to cross the bay from Tampa to St. Petersburg, FL, which was to become the first commercial air service ([IATA], 2017). The carrier only operated for a few months before a mishap resulted in waning interest that resulted in the business folding. This was a common turn of events in the early days of commercial aviation.

Lack of any safety standardization and performance requirements often resulted in planes that were awkward or hazardous to fly that put the passengers on board in serious risk. This was usually discovered only after an incident or mishap that often resulted in casualties.

Interestingly, the U.S. government entered commercial aviation not as a regulatory body, but as a financial backer. In 1918, the U.S. Post Office, with the support of the Federal government, began a venture of using aircraft as a means for transporting mail (Lawrence, 2014). Initially, this service was very haphazard and resulted in mail and many pilots being lost.

In 1925, Congress passed the Air Mail Act, which allowed the Post Office to deal with private contractors in the carriage of mail (Air Mail Act, 1925). This boosted commercial aviation, however, the Air Mail Act had no regulatory language in it that required or enforced any safety standardization or compliance.

Just one year later, in 1926, the Air Commerce Act was passed (Air Commerce Act, 1926). This act marked a turning point between aviation and the Federal government, as it was charged with the creation and adoption of rules and regulations that

promoted safety in the manufacture and operation of aircraft. From this point on, the Federal government actively participated in regulating aviation. The rules and regulations that were created through the Air Commerce Act were rudimentary and a first step in aviation regulation.

In 1938, the Civil Aeronautics Act was passed, which offered a more comprehensive and complete set of rules and regulations (Civil Commerce Act, 1938). The passage of this Act along with the Federal Register Act was what created the C.F.R. that exists today (Federal Register Act, 1935). Title 14 of the C.F.R. is the aeronautics portion of the code, where all of the manufacturing, performance and operational regulations are under.

This early C.F.R. contained several requirements that would be recognizable today in the modern regulations such as, pilot certificate requirements, aircraft inspection and maintenance, air traffic rules and aircraft airworthiness (Code of Federal Regulations, 1938).

Most notably, are the regulations contained in 14 C.F.R. § 61, which contained the Civil Airline Rules. These rules go beyond the general aviation rules in keeping with a heightened duty of care to the passengers that ride on commercially operated aircraft.

Some of the detailed requirements are as follows:

- Limitations on the pilot duty hours and mandates for an appropriate rest period (Flight Time Limitations, 1938)
- If an engine fails on a multi engine aircraft, the aircraft must be able to maintain an altitude of at least 1000ft until it can make it to an appropriate airport to land (Day Operation Over Water (Multi-engine), 1938)

- Weather Bureau reports must be used for flight planning (Weather, 1938)
- Dispatch must not release an aircraft if weather at the intended destination falls below minimums (Weather Minimums, 1938)
- Dispatch must estimate aircraft takeoff weights using a prescribed “load manifest form” (Clearance and Load Manifest Forms, 1938)
- Reserve fuel requirements for both visual and instrument flight rules flight plans (Adequate Fuel Supply, 1938)

The 1938 C.F.R. resembles the modern day C.F.R. that governs flight operations, however, holes still exist. No runway requirements or One Engine Inoperative (OEI) climb performance exists.

In 1940, the C.F.R. was amended into what more resembles its modern form. These regulations addressed, in more detail, takeoff performance requirements for aircraft, as well as OEI climb performance. Detailed requirements are found below:

- Takeoff at Sea Level must be performed within 1000ft (Takeoff, 1940)
- Eight times the measured clean stalling speed, or 300ft/min, whichever is greater (Climb, 1940)
- Aircraft must show climb performance with an engine out at appropriate flight weights as necessary, as deemed appropriate by the administrator (One Engine Inoperative, 1940)

In these early versions of the C.F.R., general aviation aircraft and commercial transport aircraft were all regulated under the same C.F.R. sections. Unless explicitly identified, any requirements that general aviation operators followed were the same for commercial operators.

In the 1940 supplemental C.F.R., “Transport Category” aircraft did receive a more stringent takeoff requirement. This requirement stated the takeoff distance required would be the greater of:

(1) the sum of the distance from a standing start to the indicated airspeed which ensures full control with the critical engine-inoperative and the distance required to bring the aircraft to a full stop, or (2) the sum of the distance from a standing start to the indicated airspeed which ensures full control with the critical engine-inoperative, as well as the distance required to attain an altitude of at least 50 feet above the takeoff surface at a speed no less than 110% the power-off stall speed at a steady climb rate specified in § 04.75(a). (Takeoff, 1940)

In this regulation, the ancestral definition of minimum control airspeed on the ground (VMCG) and minimum control airspeed while airborne (VMCA) can clearly be seen. The more modern “V-speeds” were introduced in the 1945 C.F.R. supplement (Performance, 1945).

The requirement to demonstrate take-off runway performance in both normal and emergency conditions (either an accelerate-stop rejected takeoff or an accelerate-go with failed engine) is essentially modern in concept. The 50% reduction in headwind credit for takeoff climb is a form of increased safety margin, as mentioned in 14 C.F.R § 04.760 (Operating Limitations, 1940). The fact that these regulations only apply to “transport category” aircraft destined for airline service indicates that this is an attempt to define through regulation, a “heightened duty of care.”

The C.F.R. was amended through the years following implementation until the late 1950s, with the advent of the first generation of jet airliners. These aircraft had very differing performance than the propeller driven aircraft that preceded them. As such, SR-422 was issued in 1957 as the basis for certification of the first turbojet powered aircraft (Federal Aviation Regulations, 2017). This special order brought about the field length requirements that are used today. 14 C.F.R. § 4b SR-422 4T.117 redefined the takeoff distance as, “horizontal distance along the take-off path from the start of the take-off to the point where the airplane attains a height of 35 feet above the take-off surface (Takeoff Distance, 1960).” It also includes an all-engines operating safety margin, where the official takeoff distance can be no shorter than “115 percent of the horizontal distance along the take-off path, with all engines operating, from the start of the take-off to the point where the airplane attains a height of 35 feet above the take-off surface (Takeoff Distance, 1960).”

This change is significant in that the obstacle clearance height was lowered from 50ft to 35ft in order to accommodate the new jet airliners climb performance. The turbojet aircraft could reach appropriate climb rates, but had much higher airspeeds. This resulted in a lower overall climb gradient. Interestingly, instead of holding the aircraft manufacturers to the emplaced requirements, the obstacle clearance height, and the climb gradient, was lowered.

In 1965, the modern C.F.R. came into being. The FAA completely reformed and reorganized the aeronautical portion of the regulations. Most of Part 4b was incorporated into 14 C.F.R. § 25, while SR-422 and Parts 40 and 41 were combined into 14 C.F.R. §

121 (Aeronautics and Space, 1965). Since then this, C.F.R. has remain largely unchanged with the only occasional addition of small amendments.

III. Modern Commercial Regulations

The reason why this work is important is that existing Federal regulations are vague. A fledgling pilot who first encounters the regulations in 14 C.F.R. § 23 & 25 gets the impression that these published standards explicitly govern piloting procedures. An engineer responsible for coding a physics-based simulation for takeoff and landing or reducing flight test data discovers many ambiguities. Supporting documentation published by the FAA, such as advisory circular AC-25-7 (in various versions published throughout the years) offers some clarifications, however, many decision points are left open to interpretation.

Regulations found in 14 C.F.R. § 23 and 14 C.F.R. § 25 provide manufacturers with minimum performance standards that aircraft must achieve by design. These standards dictate the physical properties, such as weight limits, minimum climb gradients, V-speeds, etc. For takeoff specific parameters, these regulations are used in the calculation of takeoff distances and weight limitations as well as the definitions of takeoff distances. The distances covered by the regulations in the takeoff regime are; 1) the ground roll phase, defined as the horizontal distance covered while the aircraft is accelerated until flight speed is achieved, and 2) the airborne phase, which is the horizontal distance covered after the main wheels leave the runway until 35ft above the runway (Dry Runway Takeoff Distance and Takeoff Run, 1998). Thus, the entire certified takeoff distance comprises of more than just the ground roll, but also the initial flight phase for near runway obstacle clearance. The relevant C.F.R.s will be examined

in further detail to expand on the intricacies of determining Critical Field Length (CFL) requirements.

A. Takeoff Regulations - Engineering

The portions of 14 C.F.R. § 23 & 25 that govern takeoff performance for commercial transport and commuter aircraft are noticeably similar in language. Both regulatory sections hold very similar standards for takeoff requirements and definitions. For the purpose of this paper, observations will only be referenced to 14 C.F.R. § 25 as this regulation gives slightly more detailed requirements and standards over those found in 14 C.F.R. § 23. Any compliance or deviation from 14 C.F.R. § 25 is highly likely to have similar effects in 14 C.F.R. § 23.

Below are edited copies of current takeoff regulations pertinent to determining CFL in commercial operations:

- 14 C.F.R. § 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.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-38, 41 FR 55466, Dec. 20, 1976; Amdt. 25-92, 63 FR 8318, Feb. 18, 1998] (General, 1998)

- 14 C.F.R. § 25.107 - Takeoff speeds.

(a) V_1 must be established in relation to VEF as follows:

(1) VEF is the calibrated airspeed at which the critical engine is assumed to fail.

VEF 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 VEF 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 VMC;
- (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] (Takeoff Speeds, 2011)

- 14 C.F.R. 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] (Accelerate-Stop Distance, 1998)

- 14 C.F.R. § 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] (Takeoff Path, 2007)

- 14 C.F.R. § 25.113 Dry runway 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.

...

(b) If the takeoff distance does not include a clearway, the takeoff run is equal to the takeoff distance. If the takeoff distance includes a clearway-

(1) The takeoff run on a dry runway is the greater of—

- (i) The horizontal distance along the takeoff path from the start of the takeoff to a point equidistant between the point at which VLOF is reached and the point at which the airplane is 35 feet above the takeoff surface, as determined under §25.111 for a dry runway; or

- (ii) 115 percent of the horizontal distance along the takeoff path, with all engines operating, from the start of the takeoff to a point equidistant between the point at which VLOF is reached and the point at which the airplane is 35 feet above the takeoff surface, 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] (Dry Runway Takeoff Distance and Takeoff Run, 1998)

Despite the details covered in the regulations, many ambiguities exist that require some form of clarification. For example, in 2012, the FAA published AC-25-7C, the latest revision helping to clarify “Certified Takeoff and Landing Procedures” (Flight Test Guide for Certification of Transport Category Airplanes, 2012). These circulars are not legally binding; however, clarification is given on the agency’s standing with regard to any ambiguous or vague statements.

The standards published in these regulations form the design targets engineers use to draft aircraft geometries and systems, which provide a starting point for operational parameters and procedures published in AFMs. Once the aircraft is built, the flight envelope and other flight characteristics are determined through flight test since the FAA holds, “flight test demonstrations are the preferred method to show compliance” (Flight Test Guide for Certification of Transport Category Airplanes, 2012). Once the FAA approves the AFM and certifies the aircraft as “airworthy,” the aircraft should fly “by the

book.” These flight manuals provide reference performance data, based upon models that assume that pilots operate aircraft in a specific manner.

The FAA concedes that, “simulation(s) may be an acceptable alternative to flight demonstrations in certain situations” (Flight Test Guide for Certification of Transport Category Airplanes, 2012). Thus, in practice the data found in an aircraft flight manual derive from numerical simulations that are calibrated against flight test demonstrations. Therefore, the fidelity of any simulations is dependent upon the quality of aerodynamic and propulsive data.

The spirit of the FAA one-engine-inoperative rules is to assume a catastrophic failure of an engine. In most cases, the manufacturer will flight test one-engine-inoperative performance data using a “throttle chop” procedure, where the critical engine is reduced to idle thrust as a safety measure. The idle engine can quickly be brought back to any thrust setting if so needed. However, the FAA requires the manufacturer to substantiate one-engine-inoperative takeoff and landing performance with “at least a limited number of fuel cuts” that render the engine truly inoperable.

Takeoff procedures used to develop demonstration data should be attainable “in service by crews of average skill, using methods or devices that are safe and reliable, and include allowances for any time delays in the execution of the procedures that may reasonably be expected in service” (Flight Test Guide for Certification of Transport Category Airplanes, 2012). The FAA discourages “exceptional piloting techniques ... from being used to generate unrealistic takeoff distances” (Flight Test Guide for Certification of Transport Category Airplanes, 2012). These guidelines ensure that an

aircraft flight manual contains performance values that are “representative of that which can reasonably be expected to be achieved in operational service” (Flight Test Guide for Certification of Transport Category Airplanes, 2012).

To summarize, the FAA allows manufacturers to predict AFM field performance using numerical simulations calibrated to some flight test data in lieu of a comprehensive table of actual test flight outcomes. These numerical simulations assume consistent and precise pilot procedures and techniques in the operation of the aircraft. In reality, there exists variability in the adherence to procedure and execution timings. The worst-case scenarios of deviation stand to add significant distances to the field length requirements that may not be considered by the numerical takeoff simulations. These simulations are calibrated to match individual results attained by test pilots who are instructed not to fly the aircraft with “average skill.” In reality, the combination of a substandard pilot and a “worn-out” aircraft operating at the limits of the AFM stated performance limits may incite disaster.

Interestingly, from an AFM perspective, aircraft are only required to adhere to the design regulations that were in place at the time of their certification. The aircraft is then exempt from any changes that take effect within the regulations (for example a change to the minimum V_{2min} speed computation in 14 C.F.R. § 25.107 that went into effect in 1998). With many aircraft, still in service today, that originally saw certification 20, 30, 40 years ago or more, many procedures exist throughout commercial fleets that can vary wildly depending on the type of airframes in use. This procedural variability may exist between carriers, or in the case of carriers with large fleets, variation may exist within a single carrier.

Conversely, commercial operators flying in the Contiguous U.S. must adhere to the standards published in the operations regulations, 14 C.F.R. § 91 (Applicability, 2016), 121 (Applicability, 2007) and 135 (Applicability, 2014), and change their practices to reflect any updates to these regulations.

B. Takeoff Regulations - Operations

Regulations found in 14 C.F.R. § 91, 121 and 135 provide air carriers and pilots with additional standards that aircraft must abide by during operation. These C.F.R.'s offer less clarity on the specifics of performance targets with the only clearly defined requirement being that the aircraft must not operate at an airfield with runway of insufficient length. It would seem that this is a bit redundant, in that no qualified pilot would operate an aircraft off a runway that was sure to run out of tarmac before achieving flight speed, however, determining field length requirements is far from intuitive.

The standards published in 14 C.F.R. § 91 form operational requirements for aircrews to follow. These regulations are simplistic. The only requirement is that the aircraft must operate off a runway with enough length to accommodate a rejected takeoff or a continued takeoff. This leaves any procedures required to accomplish this wide open for any operator to interpret. With these regulations, the FAA is essentially telling operators that they are indifferent in the methods or procedures used, so long as the aircraft operates off runways with sufficient length. These requirements only apply to the transport category aircraft not operating commercially or in any other “for hire” capacity.

Conversely, the requirements published 14 C.F.R. § 121 and 135 form the operational regulations for air carriers that operate in a commercial or a “for hire” capacity.

Commercial aviation in the U.S. can generally be divided into two categories; (1) aircraft operating in a commuter or “on-demand” operation and (2) as a scheduled or “flag” operation. The aircraft flown under commuter category operations are regulated by 14 C.F.R. § 135, whereas the aircraft operated under scheduled category operations are regulated by 14 C.F.R. § 121 rules. Commuter aircraft can be quite varied in size and performance, with aircraft certified under both 14 C.F.R. § 23 and 25. Scheduled air carriers typically operate regional size turbofan aircraft, or larger, that are certified under 14 C.F.R. § 25. Detailed examination of specific regulations will be limited to part 121, due to the similarities in the specific regulations between part 121 and 135. Any compliance or deviation from part 121 is highly likely to have similar effects in part 135.

The operational takeoff regulations for civil transport flag operations in the contiguous United States can be found in 14 C.F.R. § 121.1 and 121.189. Below are edited copies of current takeoff regulations:

- 14 C.F.R. §121.1 Applicability

This part prescribes rules governing—

- (a) The domestic, flag, and supplemental operations of each person who holds or is required to hold an Air Carrier Certificate or Operating Certificate

[Doc. No. 28154, 60 FR 65925, Dec. 20, 1995, as amended by Amdt. 121-328, 72 FR 6912, Feb. 13, 2007; Amdt. 121-336, 72 FR 63411, Nov. 8, 2007] (Applicability, 2007)

- 14 C.F.R. §121.189 Airplanes: Turbine engine powered: Takeoff limitations.

...

(c) No person operating a turbine engine powered airplane certificated after August 29, 1959 (SR422B), may take off that airplane at a weight greater than that listed in the Airplane Flight Manual at which compliance with the following may be shown:

(1) The accelerate-stop distance must not exceed the length of the runway plus the length of any stopway.

(2) The takeoff distance must not exceed the length of the runway plus the length of any clearway except that the length of any clearway included must not be greater than one-half the length of the runway.

(3) The takeoff run must not be greater than the length of the runway.

...

[Doc. No. 6258, 29 FR 19198, Dec. 31, 1964, as amended by Amdt. 121-268, 63 FR 8321, Feb. 18, 1998] (Airplanes: Turbine Powered: Takeoff, 1998)

Several factors play into the field lengths aircraft need in order to achieve flight, or perform a rejected takeoff, with an appropriate factor of safety. These can include mechanical variables, such as variations in weight, thrust, or braking effectiveness, but piloting techniques can also have a significant effect on field length requirements. Factors such as reaction timing for activating rejected takeoff procedures and rotation rates for continued takeoff procedures are all human factors that can introduce substantial growth to field length requirements.

Problems begin to arise in the calculation of critical field length requirements if one or more variables cannot be accounted for, which introduces significant error into the

predicted field length outputs. More importantly, no federal standardization exists to enforce standardization of procedure in these critical flight regimes.

A survey of AFMs from 14 C.F.R. §25 certified aircraft, or similar, across a variety of manufacturers finds considerable ambiguity in takeoff rotation procedure. The Lockheed C-130J AFM (military spec) specifically states, “Takeoff performance data assumes a rotation rate of approximately 3 degrees per second” (Martin, 2011).

Alternatively the Lockheed C-5A AFM (military spec) states that, “takeoff performance charts are based on rotation time, which varies from 3 seconds at light gross weights to 5 seconds at heavy weights” (Martin, 2012). The Beechjet 400A AFM recommends a rotation target pitch of, “13° to 15° desired” attitude; where performance charts specifically call out distances computed following a procedure where the “airplane was rotated to an attitude of approximately 14° nose up” (Beechcraft). No pitch speeds are given. The Hawker 800XP pilot training manual is even more ambiguous, providing neither a target pitch attitude, nor target pitch rate for takeoff rotation (Hawker). The DC-10 AFM does not provide a target pitch attitude, but calls out that the manual bases distances upon a “rotation time of four seconds” (Douglas). Alternatively a B737 Classic flight crew training manual (FCTM) provides a target pitch attitude (15° nose up) and a target pitch rate of 2° to 3° per second (Flight Crew Training Manual: 737 Classic). The B737-800 FCOM provides a target pitch attitude (15° nose up) but does not suggest a pitch rate (Flight Crew Training Manual: 737-800). Similarly, the DGAC Approved Airbus narrow body (A318/319/320/321) flight manual trains pilots to “achieve a normal and continuous rotation rate to a pitch attitude of 12.5°” (Airbus).

Examination of these flight manuals show little or no accounting for the variability in piloting techniques and offered few procedural standards during the takeoff phase. This illuminates the inconsistency in manufacturer evaluation or publication of effects on field performance due to varying pilot techniques. However, this is not reflected in all AFM's as some manufacturers do provide highly detailed takeoff procedures. These procedural inconsistencies in the published AFM's lead to inconsistent aircrew training, as pilots are generally trained with respect to the procedures laid out in the AFM. Highly detailed AFM's lead to increased pilot training and flight crews capable of consistently operating the aircraft very close to predicted field length requirements, whereas poorly detailed AFM's lead to flight crews that have to operate with procedures open to interpretation and are full of ambiguity, leading to significant deviations in actual runway usage. While these AFMs provide insight into piloting techniques that manufacturers may, or may not, account for to determine field length requirements, the standard operating procedures used by airlines were not evaluated.

IV. Certified Takeoff Procedure

Airplane operating procedures that are appropriate for determining takeoff distance are commonly found in the performance section of the AFM, as required by the FAA. This is where the V speeds are presented along with associated distances required to achieve the various speeds. The FAA requires all commercial aircraft manufacturers to determine these speeds through flight-testing or simulation, and the aircraft must adhere to these speeds through inherent performance and piloting procedures.

The minimum control ground speed (VMCG) is the lowest indicated airspeed during the takeoff run where the aircraft can maintain directional control with the loss of

the critical engine on the runway (Minimum Control Speed, 2015). Directional control must be maintained with the use of rudder alone; no credit for nose wheel steering is given. Interestingly, mil-spec rules that govern military aircraft similar to the way the C.F.R.s govern civilian aircraft allow for the use of nose wheel steering in the calculation of VMCG, resulting in a lower airspeed ([DOD], 1997).

The minimum control air speed (VMCA) is the lowest indicated airspeed that the aircraft can maintain directional stability with the critical engine failed while airborne (Minimum Control Speed, 2015). This is to be accomplished with just the use of rudder and no more than 5° of bank angle.

The engine failure speed (VEF) is the airspeed at which the critical engine failure occurs (Minimum Control Speed, 2015). This does not take into account sagging thrust from engine spool-down. The designer must choose the VEF speed, which can be anywhere from VMCG to VMCA.

The takeoff decision speed (V1) is the indicated airspeed at which a “go-no-go” decision for takeoff continuation is essentially made for the pilot (Takeoff Speeds, 2015). During the takeoff run, if the critical engine fails below V1, the takeoff is aborted. If the critical engine fails above V1 the takeoff is continued OEI. V1 may be selected as low as the VEF speed, plus any gains in airspeed attained through two seconds of residual acceleration with one engine still functioning at takeoff thrust. During the Rejected Takeoff (RTO), the pilot deploys aerodynamic drag/lift-dump devices and uses the wheel brakes to bring the aircraft to a stop. Reverse thrust credit is not permitted in calculating the stop distance after RTO has been initiated. Within the regulations, the FAA requires the accounting of pilot reaction times stating:

V1 is determined by adding to VEF (the speed at which the critical engine is assumed to fail) the speed gained with the critical engine inoperative during the time interval between the instant at which the critical engine is failed and the instant at which the test pilot recognizes and reacts to the engine failure, as indicated by the pilot's application of the first retarding means during accelerate-stop tests (Takeoff Speeds, 2011).

The determination of V1 includes the time it takes for the pilot to initiate the first steps to bring the aircraft to a stop. The FAA requires a minimum reaction time of one second; however, if greater reaction times are shown during test runs or by pilot experience, the designer should adjust the reaction times accordingly.

While the regulations give a defined reaction time, AC-25-7C delves into more detail as to what reaction times are reasonable during RTO. The advisory circular suggests a one-second delay for each step a pilot must take to transition from takeoff acceleration to all-stop deceleration (Flight Test Guide for Certification of Transport Category Airplanes, 2012). Most commercial transport aircraft require three steps for full braking configuration, such as aerodynamic braking/lift-dump deployment, throttle retard and wheel braking. This implies that a reasonable reaction timing would be approximately three seconds.

Under the RTO regulations, the designer must also include the distance covered in an additional two-second period at V1 in calculating the accelerate-stop distance during a RTO (Accelerate-Stop Distance, 1998). While the FAA acknowledges and mandates accounting for human delays, the delays are not accounting for pilot indecision or confusion that arises from an emergency. The time delays are merely reaction times for

emergency recognition and the time required to configure the aircraft for maximum effort braking. Expanding further on this, AC-25-7C states:

The two-second time period is only provided as a method to calculate the required distance increment, and is not considered to be a part of the accelerate-stop braking transition sequence ... no credit for pilot actions, or engine and systems transient responses (e.g., engine spin-down) ... during this two-second time period (Flight Test Guide for Certification of Transport Category Airplanes, 2012).

Any benefit of automated systems for braking or other retarding devices that decrease the number of pilot actions are not to be reflected in the two second time.

For the FAA certified RTO procedure, the three reaction timings are: (1) One second of acceleration under OEI prior to V1, (2) a two to three second delay at V1 for initiating braking action (without using any braking credit), and (3) two seconds at V1 to account for the decision making process required to determine if the aircraft is in fact experiencing an emergency that requires aborting the takeoff.

The minimum unstick speed (VMU) is the lowest possible speed an aircraft can safely achieve flight (Takeoff Speeds, 2011). This is usually determined during testing by rotating the aircraft onto its tail and accelerating under part power until the wheels just leave the ground.

The rotation speed (VR) is the indicated airspeed that the pilot rotates the aircraft on its main wheels to a positive pitch angle (Takeoff Speeds, 2011). At this airspeed the aircraft will achieve flight with enough residual performance to accelerate to V2 just as the wheel reach 35ft AGL under OEI. Under normal AEO operations, the aircraft is

expected to overshoot V_2 . The FAA gives no regulatory requirement for the rate the aircraft is rotated, however, AC-25-7C expands on the expectation, stating: the airplane is rotated at its maximum practicable rate” (Flight Test Guide for Certification of Transport Category Airplanes, 2012). The FAA requires that V_R be no less than V_1 , or 105% of V_{MCG} , or 105% of V_{MU} (Takeoff Speeds, 2011).

The lift off speed (V_{LOF}) is the indicated airspeed where the aircraft first becomes airborne. Since the aircraft is still accelerating under takeoff power, in either AEO or OEI, it is expected to continue to gain airspeed after V_R is achieved and the aircraft begins rotation. This results in V_{LOF} occurring at a higher airspeed than V_R .

The second segment climb speed (V_2) is the indicated airspeed the aircraft must achieve at 35ft AGL in order to meet the minimum climb gradients. V_2 must be achieved in either OEI or AEO cases with takeoff flaps set and the landing gear in the down position. The FAA mandates that V_2 may not be lower than 113% of the stall speed with the flaps in the takeoff position or 110% of V_{MCA} , whichever is lower (Takeoff Speeds, 2015).

V. Numerical Simulation

In an effort to understand the relationship between aircraft field performance and piloting timings and techniques are related, a numerical simulation was created that calculates takeoff distances based on differing procedural timings. This work was previously carried out in AIAA-2017-0007, which evaluated piloting and physical effects on aircraft field performance (Takahashi, Wood, & Bays, 2016). This thesis will only cover the pertinent portions of the paper that analyze the takeoff flight regime.

A. Takeoff Simulation Description

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” (the accelerate-stop-distance-available (ASDA)), and
- “Takeoff distance must not exceed the length of the runway plus the length of any clearway” (the takeoff distance available (TODA))
- “Takeoff (ground) run must not be greater than the length of the runway.” (Takeoff Ground Run (TOGR)) (Airplanes: Turbin Engine Powered: Takeoff Limitations, 1998)

Compliance with these requirements will determine a successful takeoff or RTO but are not the regulatory requirements for dispatch determination of field length requirements. Critical Field length (CFL) computation will follow the regulatory requirements in 14 C.F.R. § 25.113, which states that the takeoff distance is to be greater than:

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 (Dry Runway Takeoff Distance and Takeoff Run, 1998)

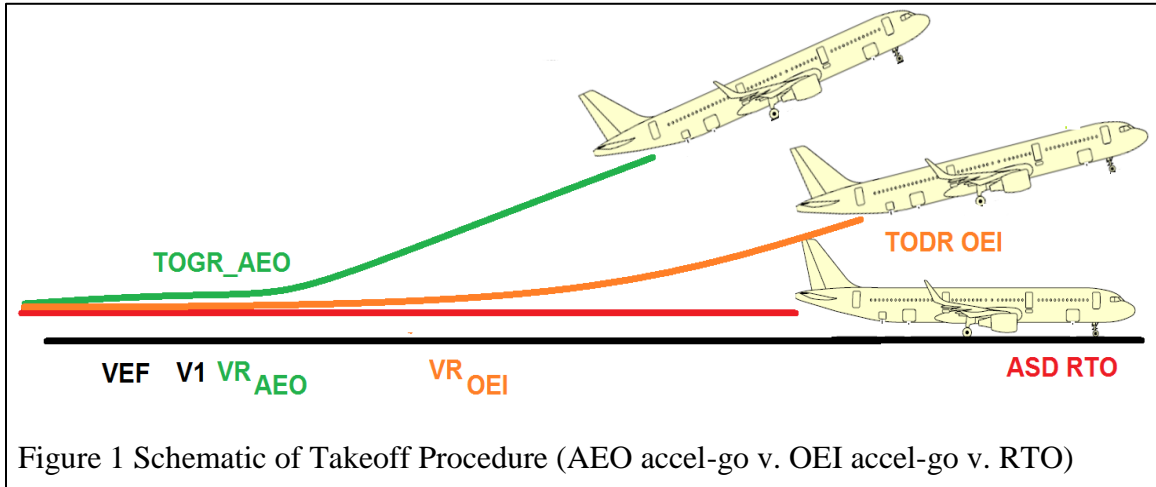


Figure 1 Schematic of Takeoff Procedure (AEO accel-go v. OEI accel-go v. RTO)

Thus, three inequalities govern field length:

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

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

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

For a conventional runway, where the entire runway is paved (no distinct clearway or stopway), critical field length may be defined as:

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

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.

i. Accelerate-Stop Simulation

The accelerate-stop, or RTO, case is governed by the requirements in 14 C.F.R § 25.109. The simulation numerically integrates the 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 V1), the pilot initiates the RTO procedures, and
- When the pilot decides to abort the takeoff for any reason just as the aircraft reaches V1, and initiates RTO with all engines operating

In scenario 1: following the C.F.R. requirements, the total distance covered by the aircraft when it accelerates is calculated:

- “from a standing start with all engines operating to VEF,”
- “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”
- travel “a distance equivalent to 2 seconds at the V1” speed, and
- “come to a full stop” (Accelerate-Stop Distance, 1998)

In scenario 2: following the C.F.R. requirements, total distance covered by the aircraft when it accelerates is calculated:

- “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,”
 - travel “a distance equivalent to 2 seconds at the V1 ” speed
 - “with all engines still operating, come to a full stop on dry runway”
- (Accelerate-Stop Distance, 1998)

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(s) at idle also contribute to the stopping distance. Presently, the use of thrust reversers is forbidden by regulation when calculating the accelerate-stop distance. In an actual rejected takeoff situation, if reverse thrust is available, pilots will use it to help stop the aircraft quickly.

ii. Failed Engine Accelerate-Go Simulation

The OEI accelerate-go case is governed by the requirements in 14 C.F.R § 25.109. The simulation numerically integrates the aircraft time and position history to simulate:

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

- With one engine failed, allow the aircraft to climb until it reaches a height of 35ft above the runway surface; VR must be selected so that the aircraft has enough residual performance to accelerate to the scheduled V2 speed at this point. (Takeoff Path, 2007)

iii. All Engines Operating Takeoff Simulation

The AEO accelerate-go case is governed by the requirements in 14 C.F.R § 25.113, which reflects normal operating conditions. The simulation numerically integrates the aircraft time and position history to simulate:

- Accelerating from a standing start with all engines operating to the VR rotation speed,
- Command a nose-up attitude until the aircraft leaves the runway (where $Lift > Weight$),
- Allow the aircraft to climb until it reaches a height of 35ft above the runway surface; the aircraft is allowed to considerably exceed the scheduled V2 speed. (Dry Runway Takeoff Distance and Takeoff Run, 1998)

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

The purpose of determining the field length requirements for accel-go and accel-stop cases are so that the dispatcher can determine what field length requirement goes with a particular decision speed. Since the dispatcher can select the V1, the field lengths can be tailored, so the accel-go and accel-stop distances are identical. This is known as the balanced field case, which represents the shortest runway distance that the aircraft can

operate off. A balanced field case will have an equidistant OEI continued acceleration and initial climb out from V_1 , and an accel-stop distance.

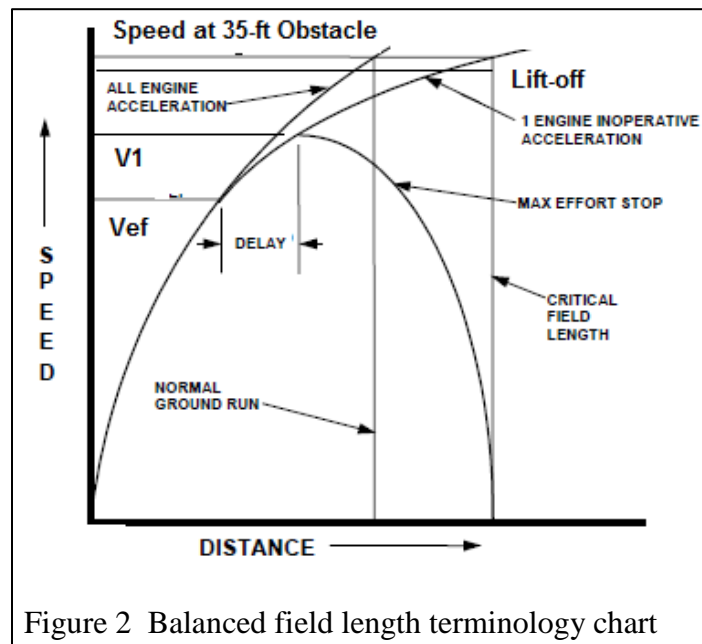


Figure 2 Balanced field length terminology chart

Depending on the runway condition and the aircraft loading, a scenario exists where it may be impossible to obtain a balanced field case. In lightweight or low traction runways, the field performance may be accel-stop limited since the aircraft will have difficulty stopping. Since V_{EF} , which controls V_1 , cannot be lowered past $VMCG$, the accel-stop distance will hit a lower floor that could result in the accel-stop distance remaining longer than the OEI or AEO accel-go case. Conversely, at heavy aircraft weights and short runways, the case may arise where the aircraft is accel-go limited. The limiting factor in this case is often the OEI accel-go case, as the aircraft's ability to accelerate is significantly hampered. This demonstrates the interaction between balanced field determination and the coupling with the decision speed.

In the modern world with exceedingly long runways, a special scenario exists where, although a balanced field case can be reached, the dispatcher may elect to raise

V1 to an airspeed where it equals VR. If it can be concluded that the aircraft has enough runway to perform a successful RTO at nearly VR, the dispatcher has a unique option to make the pilot's lives a little easier. In a balanced field scenario, several knots separate V1 and VR. In the case of an engine failure, the pilot is expected to maintain aircraft control and continue to accelerate until rotation speed with markedly reduced acceleration. Compound this with a cockpit awash with warning lights and aural announcements, and the atmosphere is ripe for an error or mishap to occur. The startled pilot could understandably choose to react instinctively, instead of relying on training and acting rationally. Setting the decision speed to the same airspeed as VR, given enough runway length, the decision process is effectively removed and a more straightforward process emerges. If a warning arises below flight speed, the aircraft is brought to a stop; if the warning alerts above VR, the aircraft is already flying and the aircrew continues the climb out OEI.

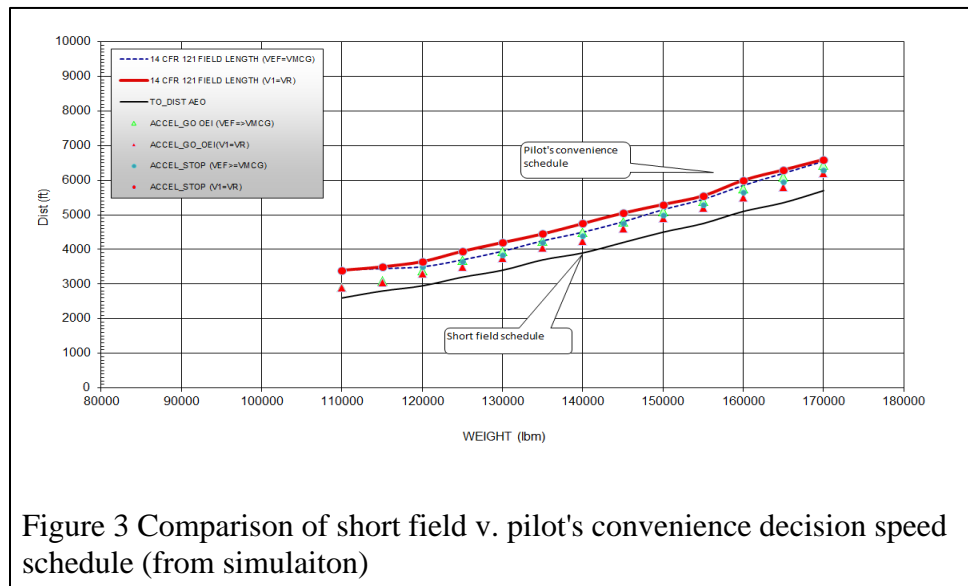
VI. Trade Studies

The numerical simulation used to evaluate aircraft field performance used a common narrow body airframe, similar to an A320. Various timings in the takeoff regime were evaluated.

OEI accel-go or accel-stop scenarios commonly drive field length requirements. The ability of an aircraft to accelerate and come to a stop can greatly affect runway usage. Acceleration during the ground run is easily predicted, and assumed to be well correlated with the weight and configuration of the aircraft. Ambiguity begins to arise when the pilots begin to interact with the aircraft in an RTO scenario, or the continuation with the takeoff. In the RTO case, the pilot's reaction to engine failure, or other

indications that warrant an aborted takeoff, can have strong effects on field requirements. The reaction times are varied to examine how much horizontal distance is covered at differing timings. The accel-go field requirements are vulnerable to rotation rates once VR is achieved. The rotation rates for AEO and OEI are varied to examine how much horizontal distance is covered at differing rates.

The simulation was calibrated against performance figures given in the A320 manual. This was accomplished by making small adjustments in the zero lift drag and braking traction coefficients. Once the simulation aircraft matched the performance targets, evaluation of field length requirements was carried out. Refer to AIAA 2017-0007 for detailed description on the calibration process.



In Figure 3, the effects of decision speed on balanced field lengths are examined with respect to weight. Following 14 C.F.R. § 121, for permissible dispatch, the runway must be no longer than the greatest distance as controlled by 14 C.F.R. § 25.113. In all cases studied, the field length increases with higher weights. By setting the decision speed (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 $V1=VR$. This is to be expected as the balanced field length decision speed, $V1$, is always slower than the rotation speed.

Table 1 Effect of Variant Condition on Certified Takeoff

Wt (lbm)	14 CFR 121.189		14 CFR 121.189		V1 (short	
	TAKEOFF		TAKEOFF		field)	
	CFL(FT)	SHORT FIELD	CFL(FT)	V1=VR	(KIAS)	VR (KIAS) V2 (KIAS)
170000		6550	6600	141	147	154
165000		6200	6300	138	145	152
160000		5850	6000	136	143	149
155000		5450	5550	133	140	147
150000		5150	5300	130	138	145
145000		4800	5050	128	136	142
140000		4500	4750	124	133	140
135000		4250	4450	122	131	137
130000		3950	4200	118	128	135
125000		3700	3950	115	126	132
120000		3500	3650	114	123	129
115000		3450	3500	114	121	127
110000		3400	3400	114	120	124

Table 1 demonstrates the calculated field length requirements for takeoff across varying weights. At the lightest weight VR is limited to the no less than $1.05 \cdot VMCG$. At all weights above, VR is a function of the aircraft's ability to achieve $V2$ under OEI conditions. In this case the $V1$ speeds are limited at the lighter weights by the $VMCG$ floor limit. At the heavier weights the accel-stop and accel-go constraints factor into calculation of $V1$. Interestingly, the field length requirements for balanced field $V1$ and pilot's convenience $V1=VR$, at the heavy and light weights converge. This would indicate that the accel-go performance is the dominant factor in the $V1$ calculation, since the aircraft is able to stop in nearly the same distances at $V1$ and VR . At the mid-weight ranges the required field lengths diverge, indicating that the accel-stop performance is the

driving factor in performance predictions, since the aircraft need markedly more runway to stop at the higher speed of VR.

Table 2 Effect of Long Rotation Times on Certified Takeoff

Wt (lbm)	T.O Short Field distance penalty (ft)	T.O. Pilot's Convenience distance penalty (ft)
170000	750	700
165000	1000	900
160000	1200	1050
155000	1350	1250
150000	1350	1200
145000	1300	1050
140000	1350	1100
135000	1250	1050
130000	1250	1000
125000	1150	950
120000	1050	950
115000	750	850
110000	450	550

Table 2 illustrates the effects of a reduced rotation rate on field performance. The lagging rotation time causes the VR speed to increase significantly. The slow rotation would result in the aircraft achieving very sluggish climb performance as the pitch attitude is very slow to reach the ideal angle for best climb rate. This causes the aircraft to accelerate well past V2 (under OEI thrust), however much more field length is used due to the shallow climb gradient (recall, horizontal distance is still factored until the aircraft is over 35ft AGL). Interestingly, due to all of the increased V speeds across the board, the balanced field V1 and VR speeds are in very close proximity, as are the field

length requirements. The elevated V2 speeds have dragged the decision and rotation speeds up significantly resulting in greater field length requirements.

Table 3 Effect of Slow Acting Pilot on RTO Initiation on Certified Takeoff

Wt (lbm)	T.O Short Field distance penalty (ft)	T.O. Pilot's Convenience distance penalty (ft)
170000	150	600
165000	150	500
160000	200	500
155000	250	600
150000	250	500
145000	350	500
140000	300	550
135000	250	550
130000	350	550
125000	550	500
120000	650	600
115000	700	550
110000	700	700

Table 3 demonstrates the effects of slow pilot reaction times to an engine failure. Recall, that these are the times added to the field length distances and V speeds as annotated in 14 C.F.R. § 25.10944 and AC 25-7C. 11 The light weight cases show the V1 and VR speeds in very close proximity. This is to be expected, since the delayed reaction times allow the aircraft to accelerate for a longer time period. By the time the pilot reacts to the engine failure, the aircraft has already accelerated to VR. The field length requirements are much higher over baseline at the reduced weights as well, due to the pilots delay in applying the braking action in an RTO situation. However, at the heavier weights the balanced field V1 and VR speeds and distances diverge. This is

likely due to the increased distance covered at the higher VR speed before braking is applied, over the balanced field V1 speed. Interestingly, the balanced field length requirements and the V1 speed do not diverge much from the baseline performance, indicating at higher weights, lagging pilot's reactions aren't highly detrimental to the field performance.

VII. Overview of Field Work

In order to evaluate commercial aircraft operations in real world settings, multiple avenues are explored to obtain relevant data. This work was previously carried out in AIAA-2017-3276, which was presented at the Aviation Technology, Integration and Operations conference (ATIO), as a predecessor to this thesis (Wood, Takahashi, & Bays, 2017).

One source of information pertaining to procedures is to query the line pilots flying aircraft in the field. This gives insight into what is actually happening in the cockpit across a sizable cross section of the piloting community and can illuminate the procedures, or deviation from, commonly used during takeoff. The data collected and statements from pilots are subject to personal interpretation of procedures and can be erroneous from the techniques that are actually used.

Another source, and potentially highest resolution data regarding procedural impact, may be found through in-cockpit observations. Observations of actual procedures used during the takeoff run illuminate the day-to-day operations of commercial aircraft. This is limiting in that the observable takeoff runs are restricted to the operators that would agree to allow observers into the cockpit and how many flights an observer could physically sit in throughout an acquisition period. Because engine

failure is a rare occurrence, the in-cockpit observations of emergency procedures will be restricted to observations of student pilots operating a flight simulator.

The data gathered in these observations have enough overlap to build an informative picture into the actual state of field performance in the commercial industry today.

Execution of the observations was done through a two-part process; a survey was conducted to gauge standard procedures used among commercial pilots and in cockpit observations conducted in a FAA certified level 6 simulator with commercial student pilots.

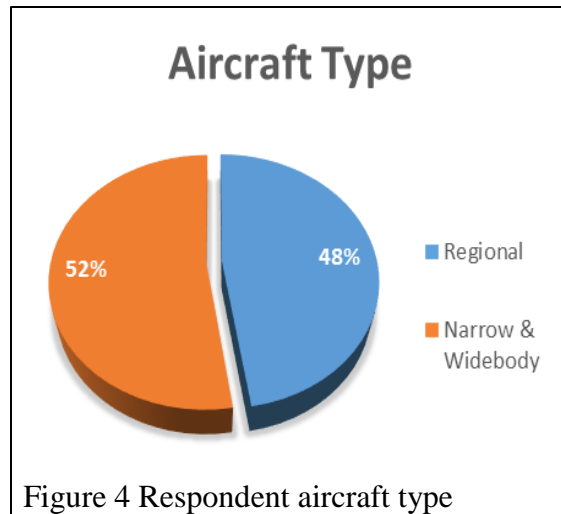
A. Survey

An initial examination of the issues surrounding piloting techniques through an anonymous survey was carried out. The survey was posted on airliners.net and airlinepilotforums.com on October 6, 2016 and remained open to responses for seven days. Ninety-three pilots responded, with the vast majority being ATP or commercially certified aviators and are currently working as line pilots. Screening questions were asked to determine if the responding pilots were engaged in relevant operations. This filtered out a few respondents, as they flew aircraft outside the scope of this research or did not operate aircraft as a commercial operator.

The survey was not restricted to aircrew in the United States and was available to foreign carriers, however, the survey was conducted in English and is considered applicable to this topic as commercial operations, and the government regulations that they operate under, in other first world, English speaking, countries are predominantly similar in scope to that of the U.S.

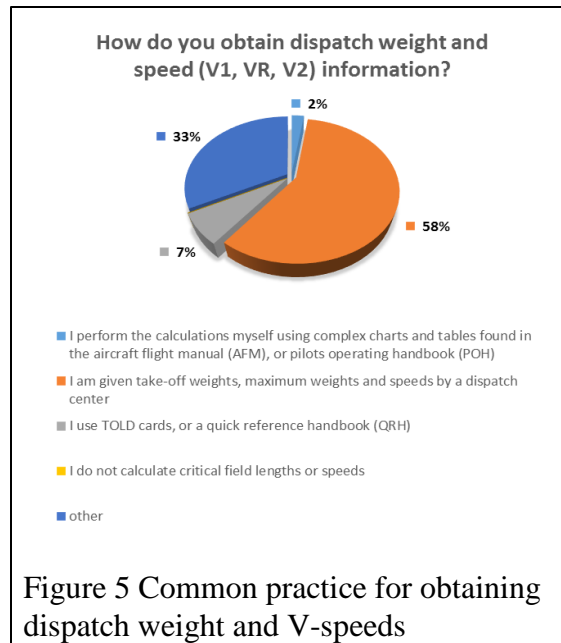
Special precautions were taken to ensure anonymity of the responding pilots. No names or other identifying characteristics, of persons or organizations were captured. This was to promote honest and casual responses by participating aircrew without fear of retaliation or repercussions. Respondents were advised that their identity would be protected and that participation in the survey was consent to use data for analysis purposes. The survey and recruitment materials were cleared through the Arizona State University Industrial Review Board to ensure all federal privacy regulations were adhered to.

The survey consisted of a short multiple-choice questionnaire for aircrew to respond with the techniques and procedure they use during takeoff. Initial evaluation questions were asked to ensure responding aircrew was in fact certified in the operation of commercial aircraft and flew in regular commercial operations. These pilots were asked to identify the aircraft they were currently certified to fly in order to ensure the aircraft are multi-engine turbine transport category. Finally, the aircrews were asked to identify the procedures they commonly used for calculating field length requirements and V-speeds, as well as their opinion on how well the aircraft met the predicted values.



Very high percentages of aircrew responding to the survey were commercially rated pilots or above, and most flew for commercial “for hire” air carriers. All responding aircrew routinely flew commercial aircraft from small regional operators up to large intercontinental turbofan airliners. All of these aircraft fall within the scope of this thesis, therefore the survey is considered relevant and the information gained to be usable.

The respondents covered an almost equal cross section of the regional and standard carrier aircraft with 92% of pilots holding Airline Transport Pilot certifications or higher, with a large percentage of these aircrews having over 2000 total flight hours.



Examining Figure 5, which illustrates common practices for obtaining aircraft weight information and V-speeds for the takeoff run, the majority of pilots are given the information by dispatch. However, a significant cross section of the operators obtain this critical information in cockpit through the use of hardcopy reference material (TOLD cards, QRH, etc.) or through the use of third party software on a laptop or other “electronic flight bag solutions”. With this method, weights are entered into the software and takeoff speeds are given as an output. While this shows a majority of commercial operators use methods consistent to their respective dispatch centers, nearly half of the other aircrews use differing methods, with 33% of the respondents using third party performance software.

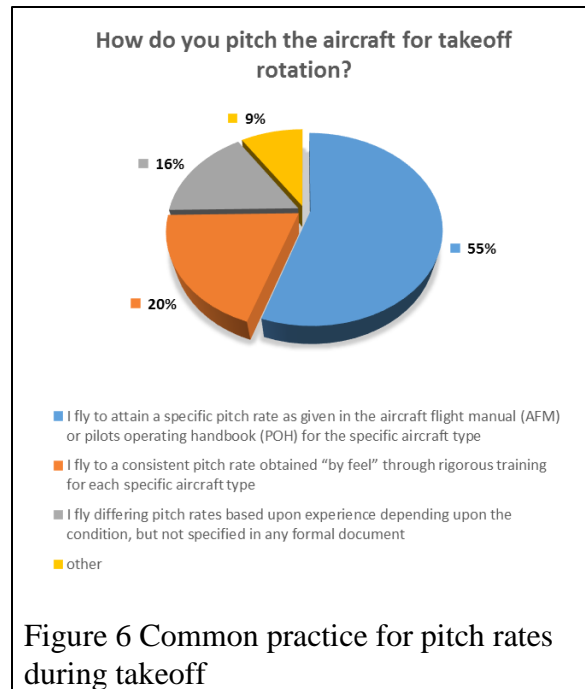


Figure 6 shows common practices for pitching rates during rotation on takeoff. Slightly more than half of reporting aircrews use a defined pitch rate as set forth by the AFM, whereas the remainder chooses pitch rate procedures completely arbitrarily. Some of these pilots are following prompts from a flight director; however, this generally does not give pitching rates, just a target attitude. Strikingly, a large percentage of reporting pilots do not follow any defined pitch rate standard, which can lead to detectable variability in the pitch rate timing. More alarmingly was the use of flight director for rotation rate cues. Examination of a Boeing 737-3/4/500 training manual states, "Do not follow flight director commands until after liftoff," and "The flight director pitch command is not used for rotation" (Boeing, Flight Crew Training Manual: 737 Classic). While following flight director cues is common, the explicit documentation directing aircrews to ignore the flight director, in this example, leads to concern that the aircrews are not familiar with the procedures published in the AFM. Rotation rate was one of the

strongest contributors to increased takeoff distance in the numerical simulation previously discussed.

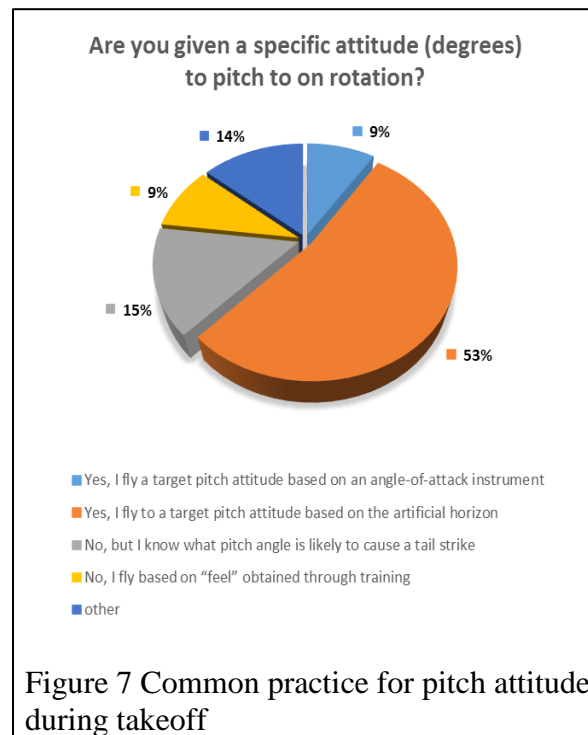


Figure 7 shows common practices for pitch attitude targets during the takeoff run. The majority of pilots use a target pitch angle with reference to the artificial horizon, while about a quarter of the respondents use an angle of attack indicator or flight director for pitch angle information. This is likely due to the large number of less sophisticated aircraft in operation that are lacking high fidelity feedback on critical flight information. More interesting is that nearly a quarter of the respondents initiate takeoff without any pitch target for rotation. This begins to illustrate that there exists a significant population of currently operating aircrews out there that use procedures lacking in standardization.

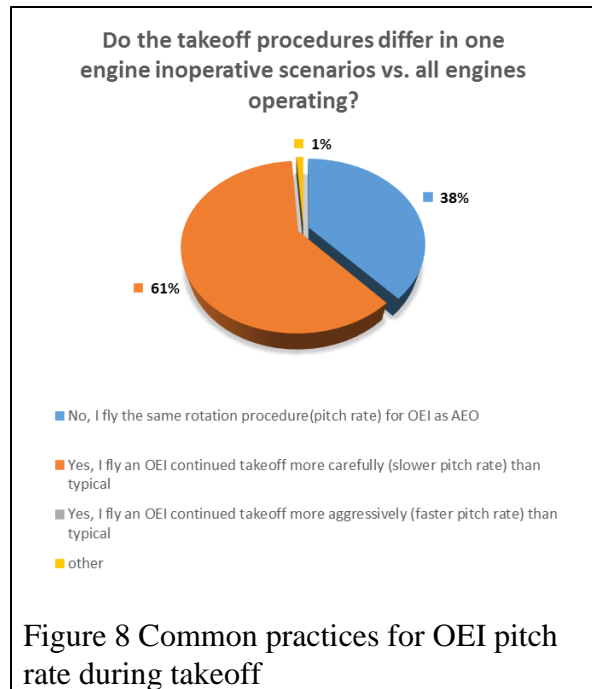


Figure 8 shows common practices for pitch rate procedures for One Engine Inoperative takeoff scenarios. Interestingly the majority of reporting pilots state that they actually use a slower pitch rate in the event of an engine failure during takeoff past decision speed. This is significant in that not only is the aircraft's acceleration reduced, requiring more runway to accelerate to rotation speed, but the reduced pitch rate also increases takeoff distances. It is safe to assume manufactures and operations account for the reduced acceleration effects, however, the variability in pitch rates leads to significant divergence in the actual runway used in comparison to the predicted distances. These certainly beg the question, "are a majority of pilots ignoring OEI takeoff procedures, or are there no standardized procedure in place to train pilots to and they are left to guess the appropriate actions?"

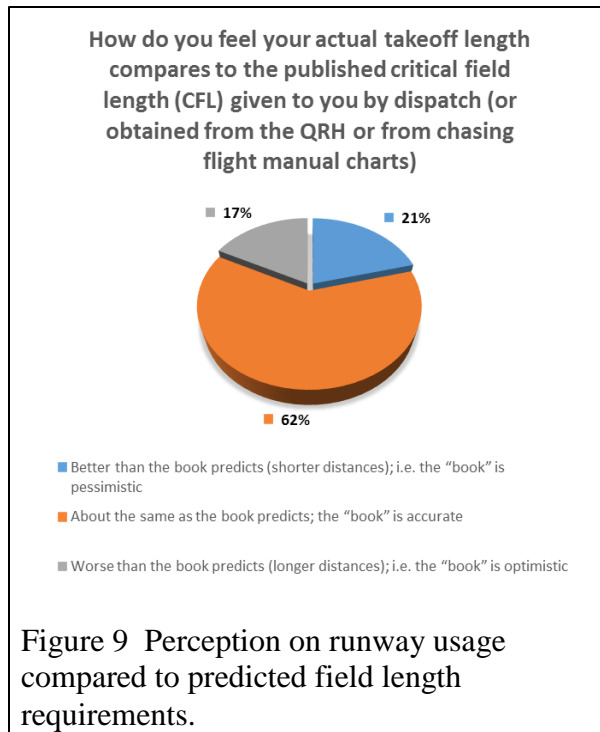
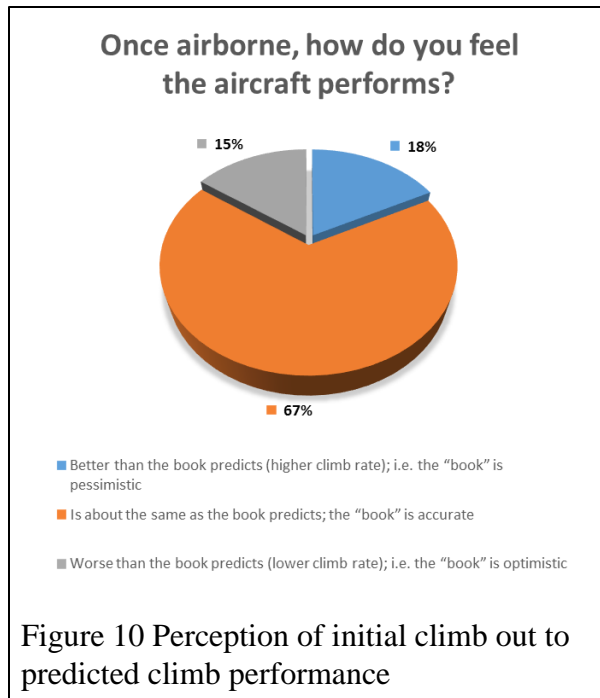


Figure 9 and 10 show the perception among the commercial piloting community on how well aircraft performance aligns with the predictions set forth in the AFM's and by dispatch. The common perception is that aircraft commonly meet the field performance targets in runway length and climb out after liftoff. A significant fraction of pilots state that the aircraft diverges from the officially supplied performance estimate (given through the AFM, or by other dispatch or performance software). While some report better performance than predicted, a noticeable portion of reporting pilots (17%) state the aircraft perform worse than expected. This feedback is concerning in that if the aircraft were pushed to the limit of its capabilities during the takeoff run, it would surely overrun the runway, despite the predicted field length requirements falling within the runway being used.



Evaluation of the survey results reveals clear procedural differences among commercial aircraft operators during the takeoff regime. Without procedural standardization across the entire industry, this is to be expected. Non-standard procedures from one air carrier to another can result in a particular airframe having two different field requirement predictions. While some operators seem to show more sophisticated field performance prediction capability, a significant cross section of the industry operates with rudimentary or non-existent take off procedures.

Of further interest is the reported deviation in aircraft performance to the predicted values. Surely no one would complain about an aircraft that performs better than expected, however, this raises concern that an aircrew wouldn't be able to take full advantage of an airframe's full field performance potential which restricts operations to a field that is longer than the aircraft would need. Conversely, the non-insignificant

reporting of aircraft that actually perform worse than the prediction bears consequences even more dire.

These operational inconsistencies brought to light from this survey directly align with previous research conducted on procedural effects on field length requirements. Some comments volunteered by responding pilots seem to show an awareness for the procedural inconsistencies and ambiguity in calculating field length requirements. One respondent illuminated this with a very succinct and direct statement by saying, “Measure with a micrometer, Mark with a grease pencil, Cut with an axe. That about sums up the way aircraft performance works.”

One 2000+ hour CRJ pilot is quoted saying, “our performance data really doesn't inform us of items such as CFL or expected rates of climb. It is designed to meet the regulatory requirements for runway performance and obstacle clearance, but beyond that we don't get any more useful information.” In agreement, the CRJ-200 quick-reference-handbook, gives cue-speeds (V1, VR, V2) in table form for various weights, airfield altitudes and temperatures ([CRJ], Quick Reference Handbook, 2012). Nowhere, does it give a predicted runway length.

Another interesting pilot response, in light of the student pilot observations; A 2000+ hour CRJ and B737 pilot wrote, “Company dispatch software governs aircraft performance. If it provides numbers for a given runway and aircraft configuration, it is legal.” The pilot continues, stating that the survey, “fail[s] to understand performance calculations in a [Part] 121 environment.” In addition, “all I worry about is flying the airplane according to company profile and rotating at the proper point in time.” He insists, “As long as I safely meet Part 25 climb requirements that is all that matters.”

While this pilot appears very firm in his opinion, it begs the question, is regulatory compliance all that matters, even if you end up flying into the side of a mountain?

This survey reveals that dispatch and pilots alike may remain blissfully unaware of scheduled aircraft performance.

The more detailed CRJ-200 aircraft flight manual appears to be set up entirely for dispatch to determine the maximum permissible dispatch weight for a given airport runway ([CRJ], 2012). There was no direct or in-direct method to “chase the charts” to determine what the predicted take-off AEO distance should be for any given dispatch scenario.

B. Student Pilot Observations

The survey reported inconsistencies in the procedures used by pilots in normal take-off and during emergencies. Operational procedures do vary between airframes; however, procedures can vary between operators flying similar aircraft. Being able to determine the training protocols used during initial and recurring pilot training, may help uncover pilot training material deficiencies. These deficiencies lead to utilization of improper piloting techniques that could adversely affect field performance. In order to remove the subjective interpretations of line pilots, in cockpit observations were conducted to determine commonly used procedures and piloting techniques.

i. Observation Site

The CRJ-200 flight simulator is located at Arizona State University Polytechnic campus. This is a FAA certified Level 6 Flight Training Device (FTD) with high-resolution projectors for external views and an exact replica of the CRJ-200 cockpit.

Flight control yokes have force feedback capability with stick pusher. The instructor station has full control over all aircraft systems and the weather environment.

Observations were conducted on the CRJ-200 training class, which is part of the professional flight program at ASU (AMT 490). Twenty students were enrolled in the spring 2017 semester. Student pilots taking part in this class have already attained commercial certification. Several students actively work as Certified Flight Instructors (CFI's).

ii. Observation Protocol

Observations were conducted using a four-camera security recording station for video acquisition. Student names or other identifying information was not recorded; no cockpit audio was captured either. Observations are anonymized post-facto; overall trends were sought out – not pilot specific trends.

Video capture of the broad cockpit was synchronized, with close-up views of the Primary Flight Display (PFD), the datalogger screen and external forward view. The recorded data stream in the flight simulator computers was able to produce a datalog file, with outputs for selected data streams in continuously updating text format (e.g. airspeed, altitude, position on runway, angle-of-attack, power-lever settings, etc.).



Figure 11 CRJ-200 observation video recording demonstrating the cockpit, PFD, datalogger and external views

Cockpit, PFD, and external view were primarily used for capturing pilot timings and procedures. The datalogger was the main source for numerical data acquisition.

iii. All-Engines-Operating Data Set

Over the spring 2017 semester, 50 total all-engines-operating take-off attempts were captured. Following the “Rule of 30,” enough data was recorded to provide a meaningful correlation of a normal distribution when using simple statistical metrics such as the mean and the standard deviation.

All-engines-operating (AEO) take-off observations captured data from the beginning of the take-off roll, through rotation and up to 35ft. Forty-two normal AEO take-offs resulted in usable data. This provided adequate sampling power for a statistical analysis on pilot timings and other trends. Pilot timings in rotation, speeds, and lift off pitch angles as well as the runway distance covered in ground, transition and air phases were captured.

Most AEO take-offs were performed from large "hub" airports with long runways. The majority of flight operations took place out of KPHX (Sky Harbor International Airport), KCLE (Cleveland-Hopkins International Airport), and KIAD (Washington Dulles International Airport). A few departures used KDCA (Ronald Reagan Washington/National Airport), with its shorter 7,169ft runway to emulate short field operations. Flights were conducted at high altitude airports; in this case, operations were flown out of KSLC (Salt Lake City International Airport). Smaller spoke airports were also used, such as KSBA (Santa Barbara Municipal Airport) and KPWM (Portland International Airport).

These observations provided direct insight into the dynamics within the cockpit, as well as the relationship between pilots and dispatch.

All observed take-off procedures were "legal," in the sense that they were performed at a dispatch weight below AFM limits for a given runway.

Many take-offs were made using an "assumed temperature" (FLEX) derate procedure; this is a common procedure for dispatch to authorize when aircraft fly out of long runways. Normal operation requires that the aircrew set the engines to a predetermined maximum thrust "N1" RPM. This limits the amount of fuel going to the engine resulting in a temperature within the "hot section" of the engine that can be withstood indefinitely, while producing less thrust than the engine is rated for. The N1 limit is tied to the external temperature, which results in a lower limit if the aircraft is in a hot environment. If the engines are placed in a true full throttle condition, maximum possible thrust will be generated, however, the hot section will begin to overheat and

cause damage to the internals. The maximum thrust setting is usually reserved for emergencies.

Under an “assumed temperature” procedure, pilots can limit take-off thrust to a lower value by utilizing a given temperature that is actually much hotter than the actual OAT. The assumed temperature limits the N1 to a much lower RPM than it would be. This has the effect of lowering the engine noise, often for noise abatement, and reducing wear and tear on the engine. The cost is the reduced thrust causes the aircraft to require significantly more runway; hence, the assumed temperature is only performed on exceptionally long runways.

If the pilots press the “TOGA” button on the throttles, the flight director will display a fixed pitch attitude target of 15° nose up and disengage presentation of heading cues. In the event of an engine failure, pilots are manually responsible for advancing the throttle further to obtain true maximum thrust on the remaining good engine.

When given an approved assumed temperature dispatch; pilots will then punch in the dispatch-provided temperature into the FMC, and set the cue-speeds for the flight director (V1, VR, and V2) following the quick-reference-handbook values for actual dispatch weight, actual airfield pressure altitude and the dispatch-provided assumed temperature for the airfield.

In this data set, pilots followed assumed temperature derate procedures for many runways. Yet the assumed temperature was in no way particularly customized to the specifics of a given dispatch. For example, the training flights departing Washington/National (KDCA) Runway 1, dispatch would provide an assumed

temperature of 41°C. For a CRJ-200, this allows for safe dispatch up to 53,000-lbm; actual dispatch weights were typically within a thousand pounds of 47,500-lbm.

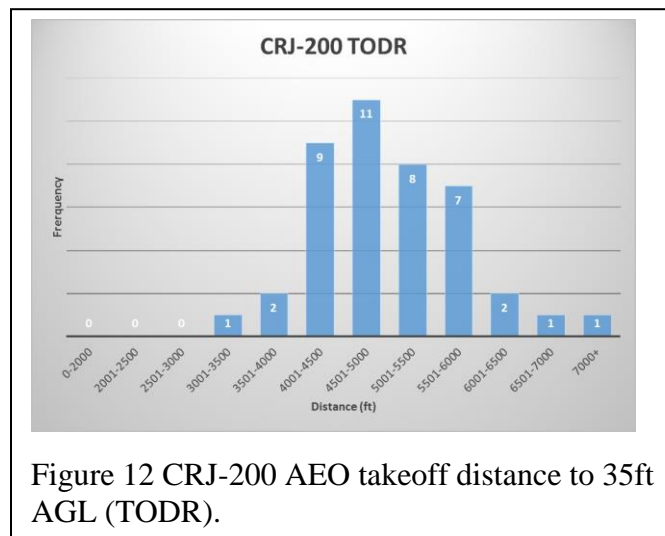


Figure 12 displays the wide range of observed distances for the total Takeoff Distance Required (to 35ft), the TODR. The average TODR observed was 4,801ft, with a standard deviation of 838ft. While typical dispatch weights varied only slightly (the lightest dispatch was at 34,000-lbm, the heaviest at 53,000-lbm). The longest observed take-off distance was 7,576ft, for a flex-thrust departure from Cleveland/Hopkins (KCLE) Runway 24R at 47,700-lbm flying into a 20-knot headwind. Because Runway 24R has a declared distance TOGR=TODA=9,000ft., this was a safe, legal take-off. No rolling starts were observed.

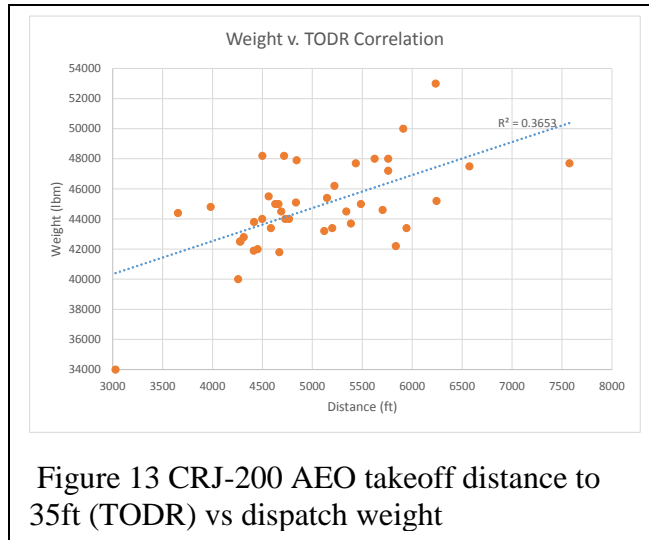


Figure 13 CRJ-200 AEO takeoff distance to 35ft (TODR) vs dispatch weight

Basic physics implies a strong correlation between aircraft weight and take-off distance, examining figure 13, no correlation is evident in the experimental dataset ($R^2 \sim 0.36$ in an attempted linear fit). Thus, these observations confirm that pilot practice including variations in engine thrust arising from the assumed temperature derate procedure, pitch-rate and adherence to the provided cue speeds have completely overwhelmed the inherent mechanics of the problem.

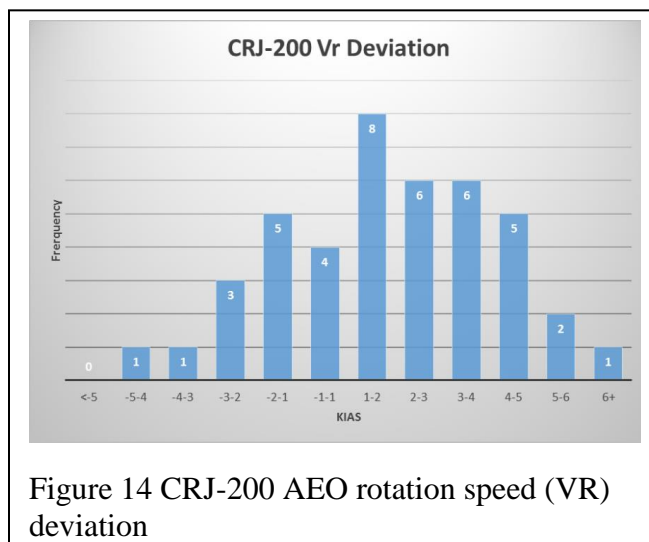
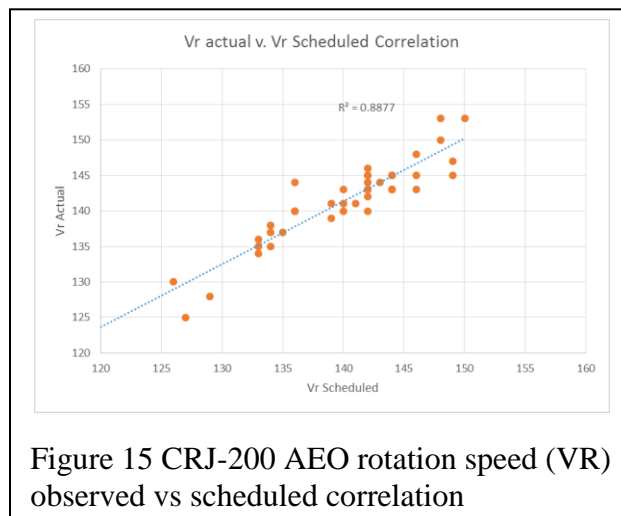


Figure 14 CRJ-200 AEO rotation speed (VR) deviation

As evidenced in figure 14 (prior page) and figure 15, pilots do not particularly closely adhere to the flight manual provided rotation speed. The plot includes deviation of airspeed from the rotation speed (VR), provided by dispatch, as entered into the flight management computer (selectable in 2 knot increments as limited by CRJ-200 software) against the observed airspeed at initiation of rotation. These observations call out the indicated airspeed displayed on the PFD at the actual moment of rotation. The actual rotation airspeed includes some time lag associated with latencies in the air data system, thus the true indicated airspeed may be several knots faster. It was discovered that the majority of pilots initiated within a few knots of VR (68% of pilots rotate within 2.4 knots of the official speed; the median pilot rotated 1 knot above VR). Some skew is present in the data set towards delayed rotation with some pilots rotating five or more knots late. Pilot latency is further increased because standard cockpit procedure has the pilot-monitoring (PM) calling out the VR, while the pilot flying (PF) actually controls the aircraft.



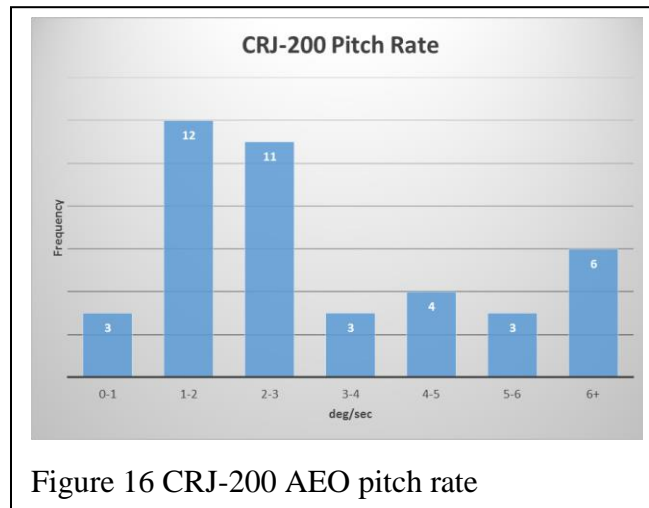


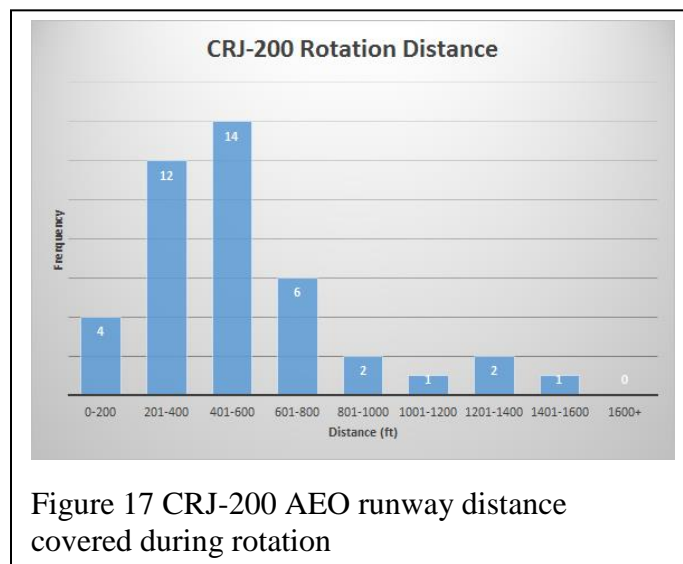
Figure 16 shows the actual pitch rate (degrees of attitude per second) achieved by pilots during initial take-off rotation. No identifiable distribution is evident in this dataset; although the median pitch rate observed was 2.6°/deg. A large number of low pitch rates arose from a situation where the nosewheel begins to lift prior to a serious, pilot initiated rotation maneuver. It is suspected that significant horizontal stabilizer trim inputs have the effect of “pre-rotating” the aircraft as it accelerates down the runway. A large trim input would begin to pitch the aircraft without any input from the pilot. Coupled with the typical flap eight-takeoff setting and ground incidence from the landing gear, the aircraft is already generating ~80% of its weight in aerodynamic lift. This contributes to a remarkable small amount of pitch input required from the pilot resulting in considerably short rotation times.

It was discovered some dispatch cases required more effort to rotate than others. It is speculated that a combination of CG and stabilizer trim setting being the root cause for this dispersion.

The peculiar, non-normal distribution also implied a lack of uniformity in pitch rate procedures. Rotation execution appears to be haphazard with no standardization in training.

Interestingly, the actual aircraft attitude necessary for lift-off is fairly low. The median lift-off attitude was 5° with a standard deviation of $\pm 0.5^\circ$.

The rotation pitch rate also influences the air-phase distance as well as the speed that the aircraft attains at 35ft AGL. While engineers select a VR speed so that an aircraft with one-engine-inoperative will just attain the V_2 speed at the 35ft point, aircraft with all engines operating will typically accelerate past V_2 .



In Figure 17, the wide range of ground roll consumed during take-off rotation is evident. The median ground-roll during rotation was 480ft, but outliers exist up to 1,443ft of runway consumed. The lack of anything resembling a normal distribution reflects upon the haphazard nature behind pilot rotation.

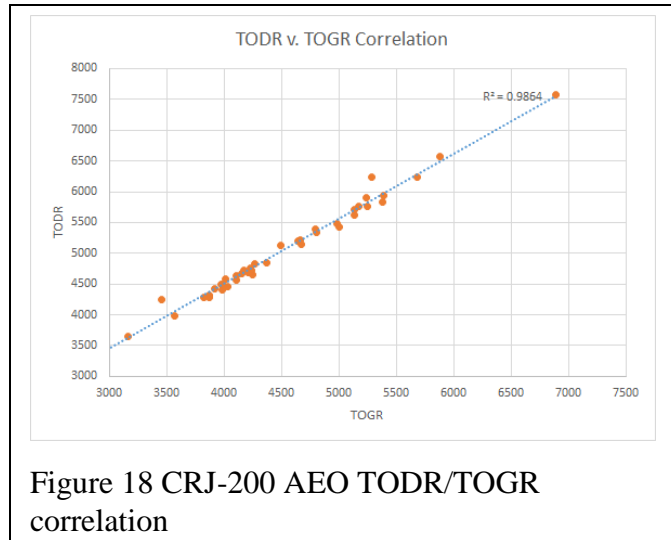
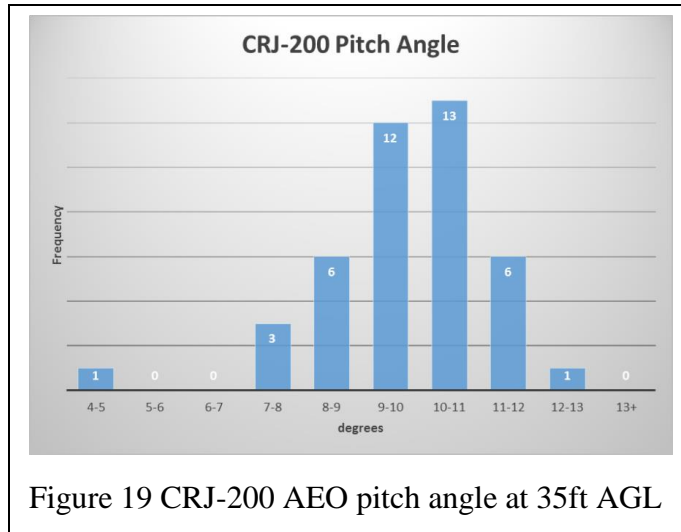


Figure 18 CRJ-200 AEO TODR/TOGR correlation

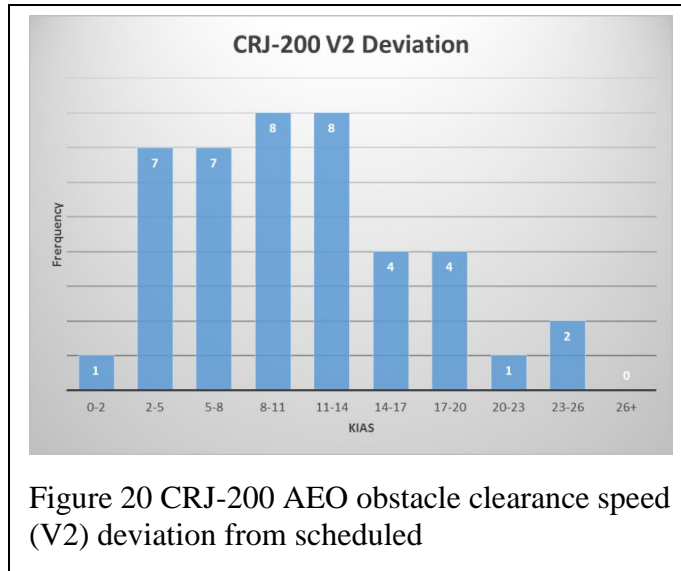
Turning to Figure 18, which plots observed take-off ground roll TOGR against TODR, considerable scatter is shown in the total take-off distances, reflecting variance in both ground and air-phase procedure. The large observed variation in rotation rates exacerbates the scatter. The average air-phase distance was 535ft, but with a standard deviation of 100ft and a worst-case outlier with a 954ft air phase.

Worthy of note is the number of cases where aircraft used almost the entire runway (9,000+ft) under AEO conditions. Given that dispatch schedules V1 close to VR, it casts doubt on whether a successful a rejected-take-off (RTO) could be executed near the decision speed.

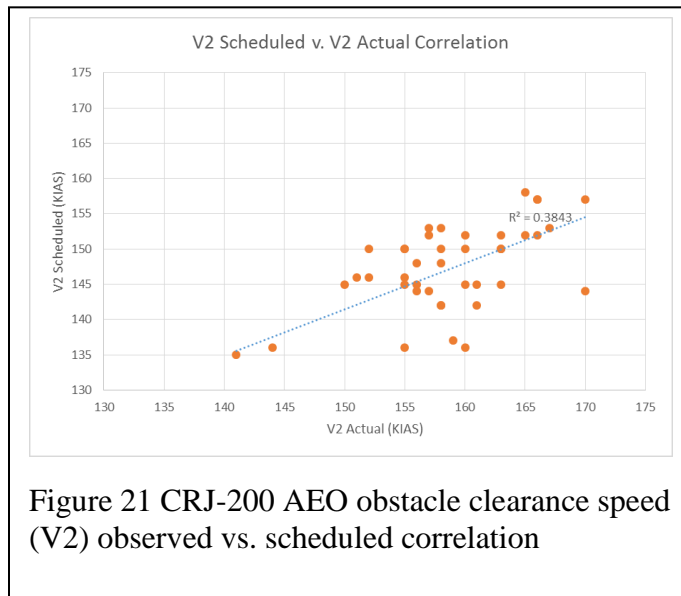


In figure 19, the pitch angle attained as the aircraft achieves 35ft above-ground-level is shown. In contrast, this data set presents much closer to a normal distribution than the previously examined data. The median pitch angle is 10° with a standard deviation of $\pm 1.4^{\circ}$.

This wide variation in pitch angle results in take-off with widely varying load factor. Pulling 1.5-gees during initial climb out markedly increases induced drag, reducing the available thrust for acceleration. This is reflected in the second-segment climb speed that is attained at the screen height.



In AEO scenarios, pilots routinely overshoot the OEI V2 speed as expected. While no aircrews fell short of V2, the variance in over speed is quite wide as evidenced by figure 20. The mean observed over speed for V2 is 11-knots with a standard deviation of +/- 5.7-knots. Examining figure 21, a wide variance in V2 is shown. While the handbook indicates a desired all-engines-operating second-segment climb speed of V2+10 knots, tremendous scatter is evident; a forced linear fit results in $R^2 \sim 0.38$.



iv. Accelerate-Stop Data Set

Observations also included 23 rejected take-off (RTO) cases with an accelerate-stop maneuver. Because most rejected take-offs involve a decision to abort that is made considerably below the formal decision speed, V1, analysis of distance information is not useful.

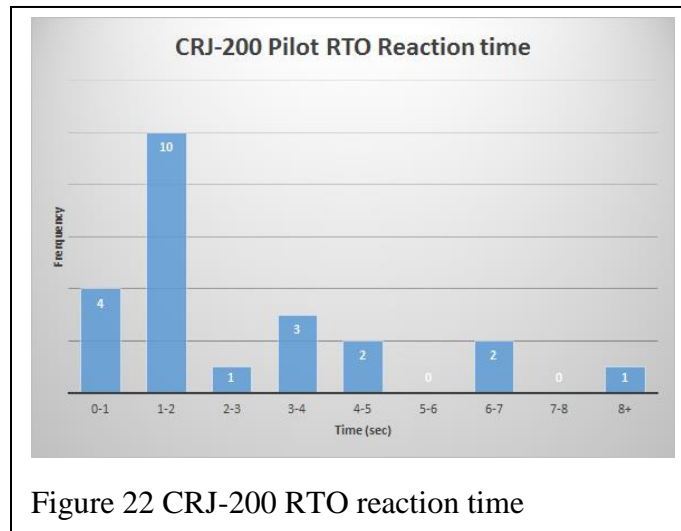


Figure 22 CRJ-200 RTO reaction time

As evidenced by figure 22, the majority of pilots have quick reaction times, but as usual, there were outliers. Recalling that the observations are on training flights, pilots were often cued by the instructor before dispatch that an emergency might arise.

Standard procedure during takeoff has the pilot monitoring (PM) operating throttles during the take-off run, while the pilot flying (PF) controls the aircraft. If either pilot says, “Abort!” the PM retards throttles and PF operates brakes. On the CRJ-200, lift-dump/aerodynamic braking is deployed automatically upon throttle retard (no pilot intervention to deploy). For almost all observed cases, pilots also employed reverse thrust to help with RTO deceleration, even in the case of an engine failure. The average

reaction time was 2.7-seconds, with a median reaction time of 1.9-seconds, a low of 0.2 seconds and a high of 8.6-seconds with a standard deviation of 2.2-seconds.

Recall that 14 C.F.R. § 25.109 requires engineers to include a distance safety margin “equivalent to 2 seconds at the V1 [speed] for take-off from a dry runway” (Accelerate-Stop Distance, 1998). While the median reaction time was ~2 seconds, a considerable number of pilots exhibited sufficient inattention. This regulation might not really reflect the reaction time for pilots with “average skill.”

Accelerate-stop distances displayed lots of variability due to differing abort initiation speeds, thrust reverser deploy strategies and braking effort. In practice, a RTO from high speed to a full stop was uncommon. Most crews simply slowed their aircraft down, and left the runway using a high-speed turnoff making determining runway use difficult.

v. OEI Accelerate-Go Data Set

Continued takeoffs with engine failures rarely occurred during observations, as such only five engine failures at or above V1 were captured. Due to the small sample size, drawing definitive statistics is not possible, but several anecdotes can be shared that cause concern.

In all observed OEI cases, the aircrews were able to rotate at VR with adequate runway to spare. Interestingly, the speeds entered into the FMS from the speed cards place V1 within 2-3 knots of VR. As previously discussed, an engine failure below V1 initiates a rejected-take-off procedure, whereas failure above V1 commits the aircraft to flight. With the close proximity of V1 and VR in the CRJ-200 dispatch solutions, the decision speed is essentially the rotation speed (V1=VR). Since the instructor can only

fail the engine at or after V1, to ensure the aircrew continues the take-off, achieving VR is assured.

In most cases, the crew was able to pitch the aircraft to achieve V2 at 35ft AGL.

In one case, the aircraft was unable to reach V2. This flight was departing KRIC (Richmond International Airport) on Runway 2, with 6,600ft usable. The aircraft dispatched at a 48,000-lbm take-off weight with V1 set at 140 KIAS, VR set at 144 and V2 set at 150-KIAS. The crew used an assumed temperature (FLEX) throttle setting for take-off PLA= \sim 62%. The aircraft reached V1 at 4,400ft downwind at which an engine failure occurred. The aircraft immediately reached VR and rotated through 9° pitch attitude; VLOF occurred at 145 KIAS. The aircraft reached 35ft AGL at 147 KIAS. The aircrew continued to pitch the aircraft to 13° nose up; this caused airspeed to bleed off. By approximately 300ft AGL, the airspeed had sagged down to 140 KIAS, 4 KIAS below VR and 10 KIAS below the scheduled V2 speed. The airspeed drifted up a few knots as the aircraft climbed through 600ft AGL, although still under VR, at which point the autopilot was activated. The automated flight controls leveled the aircraft off and accelerated it back to V2 before resuming second-segment climb to flap retraction altitude.

Comparable to this aircrew, similar trends across the other OEI observations were observed. Other aircrews were able to obtain V2 at the 35ft screen height, although they too pitched the aircraft to a point where the airspeed began to drop off. These pitch angles are appropriate in an AEO case, but too steep in an OEI scenario. In each case, the aircraft was able to climb to 400ft AGL, but the resulting airspeed fell significantly below V2; often below VR! Only one case was observed where the flight crew was able

to maintain a stabilized V2 throughout OEI second-segment-climb. Recall that the aircraft is required to maintain V2 until at least an altitude of 400ft (Takeoff Path, 2007).

It is suspected that lack of strict procedural adherence to the V-speeds in an OEI scenario stems from confusion in the cockpit, compounded by lack of strong understanding of climb performance and airspeed interaction. Pilots become so engrossed with engaging the autopilot and systems operation that they lose basic airmanship; they forget to fly the aircraft. Future observations will give a better idea as to how pilots react to emergencies and how mishandling the stricken aircraft affects field performance.

VIII. Summary & Conclusion

This thesis sought to determine the impact piloting procedure has on aircraft field performance. The government attempts to regulate the industry as best it can in an effort to uphold air carriers to the highest standards of safety. The regulatory framework has evolved throughout the years in response to disasters and tragedies to promote hyper-safe air travel. Unfortunately, these standards are not entirely comprehensive in regards to field performance.

Major takeoff and landing components are regulated; however, small details are over looked that can have profound effects on field performance. Some aircraft manufacturers recognize the impacts from human factors in piloting, which is evidenced in these high-resolution flight manuals. Conversely, AFMs from other manufacturers are severely lacking in any procedural information. In order to predict critical field length with any accuracy, all factors must be evaluated for impact on performance. Omitting certain variables, will produce erroneous field length requirement outcomes.

By employing a numerical simulation, individual piloting techniques and the associated effects on field performance were evaluated in detail. Even small deviations in variables, such as rotation rate and reaction times, created significant growth in the runway required for takeoff. Small delays in action can really add up distance when the aircraft is traveling 100+ knots down the runway. This was brought to light in Table 2 where leisurely rotation rates resulted in field length increases of over 1000ft in most cases.

Further examination in piloting techniques through a survey of line pilots and observing advanced student pilots in the cockpit, preliminary conclusions as to what is happening in the cockpit in a commercially operated aircraft on a daily basis can be inferred.

It appears that line pilots who routinely fly commercial aircraft are woefully unaware of the distances required for take-off. The survey revealed many respondents did not routinely perform calculation of critical field length. Many pilots are simply given the V-speeds required for take-off. They proceed to fly without further question to the source or validity of the data.

Large variations in pilot timings during rotation under normal AEO conditions were observed. The lack of standardization in take-off procedure allows pilots to fly the aircraft as they choose. Presentation of rotation targets on the PFD offer neither tail strike protection nor V-speed compliance without proper configuration. Many flight manuals call this fact out; yet pilots admit to reliance on this target (or using even more ad-hoc procedures). With such large variability in rotation timings, rates and pitch

targets, a non-stochastic prediction of field performance seems to offer a false sense of security.

These “real-world” observations on piloting procedures reinforce the trends observed in the numerical simulation on piloting effects. Data from the FTD observations shows a clear increase in runway usage from slow rotation during takeoff. This correlates with the outputs produced from the numerical simulation, where sluggish rotation rates caused massive increases in field length requirements. Accounting for pilot timings in the transitory period between ground roll and flight phases is vital to accurately predicting critical field lengths; however, without clear and consistent piloting techniques, predicted field length requirements will be useless.

Reaction times for initiation of RTO have large amounts of variance between pilots. While many pilots were able to initiate RTO in a timely fashion, the fact that they fly in a simulator with clearly defined lesson objectives begs the question, of how many students knew the emergency was coming? This foresight would certainly skew results to favor quick reaction times, yet many pilots still had lengthy reaction times. It remains unclear if the pilots did not know whether to abort or not, or if the warning signals just take a long time to register. Any direct assessment of accel-stop runway usage proves impossibly difficult with such a large variability in pilot reaction.

Similar to rotation rates on the AEO takeoffs, the observed reaction times to warning signals calling for RTO initiation aligned with delayed reactions in the numerical simulation. Postponed reactions in the CRJ-200 FTD that lead to delayed RTO commencement resulted in markedly longer stopping distances. This increased runway usage was also shown in the numerical simulation output with delayed reaction times.

The numerical simulation only detailed RTO initiation at V1 resulting in much higher sensitivity to delays in braking commencement. The observed pilots performed RTOs at various speeds; however, in the case of a high-speed abort in reality, the distances would grow considerably for unhurried reactions. In any case, the reaction times observed in the FTD had significant variance that results in erratic stopping distances, making prediction problematic.

Pilots also demonstrated difficulty adhering to climb speeds during an OEI take-off during observations. Whether due to the distraction of engine failure warnings or the frantic efforts to operate the aircraft systems, most student pilots had great difficulty in achieving a stabilized V2. Some cases had the aircraft fly second segment beneath the VR speed; they are certainly flirting with stall. While engine failures are uncommon in the field, the fact remains that they do happen and pilots should be able to adhere to V-speeds to the benefit of everyone on board.

Pilot timings can cause a significant increase in runway usage during take-off. These observations have shown that pilot timings vary significantly. The deviation in these timings often results in much more runway usage than dispatch would expect or pilots are aware of. Airports with extraordinarily long runways may be the redeemer for many of these pilots.

Aircraft can only perform as well as the pilots that fly them.

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APPENDIX A
PILOT SURVEY

Piloting Techniques Survey

I, Donald Wood, am a graduate student under the direction of Dr. Timothy Takahashi in the Ira A. Fulton College of Engineering at Arizona State University.

I am inviting multi-turbine certified airmen that actively fly Part 23 and 25 certified aircraft in commercial transport operations to participate in a survey on common practices for calculating critical field length and procedures used during takeoff. You have the right to not answer any question, and may stop participation at any time.

Your participation in this survey is voluntary, and restricted to persons 18 and over. If you choose not to participate or to withdraw from the survey at any time, there will be no penalty. No compensation is offered for participation in this survey.

Responses will be used to gauge attitude and common practices among the commercial piloting community for determining aircraft field performance. The data will also be used as justification in conducting research into providing the commercial flight operations community with a more rigorous and thorough critical field length prediction tool. It is our goal to increase safety while improving aircraft performance through updated approved flight manuals and pilot training. There are no foreseeable risks or discomforts to your participation.

All responses are kept anonymous and any identifying data (deductive or otherwise) that is discovered will be destroyed. There is no personal information asked or required, and IP addresses are not tracked. The results of this study may be used in reports, presentations, or publications but your name will not be used. Any data used for reporting purposes will be in aggregate form. If you have questions, concerns, or complaints, talk to the research team at dlwood1@asu.edu or Timothy.Takahashi@asu.edu

This research has been reviewed and approved by the Social Behavioral IRB. You may talk to them at (480) 965-6788 or by email at research.integrity@asu.edu if:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You have questions about your rights as a research participant.
- You want to get information or provide input about this research.

This survey should take no more than 5-10 minutes of your time to complete.

1. Please select your current pilot licensing.
 - a. Private Pilot License (PPL)
 - b. Commercial Pilot's License
 - c. Certified Flight Instructor (CFI)
 - d. Airline Transport Pilot (ATP)
2. Are you currently an actively flying pilot?
 - a. Yes
 - b. No
3. Do you fly for a part 121 commercial transport airline?
 - a. Yes
 - b. No
4. Please select the total number of flight hours you have accumulated
 - a. 0-100hrs
 - b. 101-500hrs
 - c. 501-1000hrs
 - d. 1001-2000hrs
 - e. 2000hrs+
5. When did you complete your last initial pilot training?
 - a. 0-2yrs
 - b. 3-6yrs
 - c. 7-10yrs
 - d. 11-15yrs
 - e. 15+yrs
6. When did you complete your last recurring pilot training?
 - a. 0-2yrs
 - b. 3-6yrs
 - c. 7-10yrs
 - d. 11-15yrs
 - e. 15+yrs

The following questions all refer to the multi-engine turbine aircraft you typically fly (not to a Cessna 152 or other “private pilot” aircraft you might fly on weekends)

7. How do you obtain dispatch weight and speed (V1, VR, V2) information?
 - a. I perform the calculations myself using complex charts and tables found in the aircraft flight manual (AFM), or pilots operating handbook (POH)
 - b. I am given take-off weights, maximum weights and speeds by a dispatch center
 - c. I use TOLD cards, or a quick reference handbook (QRH)
 - d. I do not calculate critical field lengths or takeoff speeds
8. Are you given a specific attitude (degrees) to pitch to on rotation?
 - a. Yes, I fly to a target pitch attitude based on an angle-of-attack instrument
 - b. Yes, I fly to a target pitch attitude based on the artificial horizon
 - c. No, but I know what pitch angle is likely to cause a tail strike
 - d. No, I fly based on “feel” obtained through training
9. How do you pitch the aircraft for takeoff rotation?
 - a. I fly to attain a specific pitch rate as given in the aircraft flight manual (AFM) or pilots operating handbook (POH) for the specific aircraft type
 - b. I fly to a consistent pitch rate obtained “by feel” through rigorous training for each specific aircraft type
 - c. I fly differing pitch rates based upon experience depending upon the condition, but not specified in any formal document
10. Do the takeoff procedures differ in one engine inoperative scenarios vs. all engines operating?
 - a. No, I fly the same rotation procedure(pitch rate) for OEI as AEO
 - b. Yes, I fly an OEI continued takeoff more carefully (slower pitch rate) than typical
 - c. Yes, I fly an OEI continued takeoff more aggressively (faster pitch rate) than typical
11. How do you feel your actual takeoff length compares to the published critical field length (CFL) given to you by dispatch (or obtained from the QRH or from chasing flight manual charts):
 - a. Better than the book predicts (shorter distances); i.e. the “book” is pessimistic
 - b. About the same as the book predicts; the “book” is accurate
 - c. Worse than the book predicts (longer distances); i.e. the “book” is optimistic

12. Once airborne, how do you feel the aircraft performs?
- a. Better than the book predicts (higher climb rate); i.e. the “book” is pessimistic
 - b. Is about the same as the book predicts; the “book” is accurate
 - c. Worse than the book predicts (lower climb rate); i.e. the “book” is optimistic
13. If you have any additional comments on aircraft field performance calculation procedures or piloting techniques for maximized field performance, please enter them below;