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

10.2514/6.2017-3276

# Experimental Investigation of Typical Aircraft Field Performance versus Predicted Performance Targets

Donald L. Wood,[1]
Timothy T. Takahashi,[2]
*Arizona State University, Tempe, AZ*

*and*

Lance V. Bays[3]
*Dragonfly Aeronautics LLC, Alpharetta, GA*

**Field performance is primarily a function of forces acting on an aircraft and its ability to achieve flight speed. It is also subject to variability from the introduction of human factors. While physical effects are easily calculated, pilot techniques used during the transition to flight or during an aborted take-off must be modelled using stochastic principles. Regulations set forth by the FAA help engineers design aircraft and determine certified field performance. Other FAA regulations lay out how commercial air carriers must handle airfield operations; however much is left open to interpretation. In order to shed some light on commonly used procedures, we polled commercial pilots on techniques they actually use. We also observed advanced student pilots flying a CRJ-200 simulator during normal and emergency situations. The results were quite diverse; and illuminate many inconsistencies in procedure that results in a wide variation in performance.**

## I. Introduction

Pilot technique inexorably influences aircraft field performance. Take-off begins with the aircraft at a standing start. It accelerates through a ground run. Upon achieving sufficient airspeed, the pilot rotates the aircraft on its main wheels to establish a positive angle of attack on the wing. Once the wings generate sufficient lift to overcome weight, the aircraft achieves flight and climbs away.

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

The Federal Aviation Administration (FAA) provides standardization in the form of federal regulations. These require manufacturers and operators to guarantee compliance with minimum performance targets that ensure safe flight. Standards provided in 14 CFR § 23 and 14 CFR § 25 give manufacturers minimum performance targets that aircraft must achieve by design. After aircraft leave the production floor, 14 CFR § 91, 121, and 135 specify operational standards that flight crews must follow in day-to-day operations.

---

[1] Aviation Management and Human Factors M.S. Candidate, Ira A. Fulton Schools of Engineering, 7001 E. Williams Field Rd, Mesa, AZ 85212. Member AIAA.

[2] Professor of Practice, Aerospace and Mechanical Engineering, School for Engineering of Matter, Transport & Energy, P.O. Box 876106, Tempe, AZ, 85287. Associate Fellow AIAA.

[3] Director of Fleet Engineering, DragonFly Aeronautics, LLC, 12600 Deerfield Pkwy, Alpharetta, GA 30004. Senior Member. AIAA.

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. Take-off 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 take-off for verification purposes.

Numerical simulations calibrated to flight test results provide the basis for field performance estimates presented in an FAA approved Aircraft Flight Manual (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 take-off regime.

In theory, the ground roll portion of the take-off should be consistently predictable; the only factors acting on the aircraft are the acceleration and drag forces. The human element begins to enter the equation at a point where pilot intervention is required. Pilots may introduce this element when performing take-off at "hand-set" reduced power settings; something we find common in modern commercial operations.

We also found significant human response in a standard take-off, with all-engines-operating. Upon achieving rotation speed (*VR*), the pilot commands the aircraft to pitch nose-up in order to achieve flight. The pilot directly controls the pitch angle and pitch rate during rotation. The rate at which the pilots raise the aircraft nose to achieve initial flight attitudes varies widely. This influences both the ground roll and the air-phase distance, prior to the aircraft attaining stabilized climb-out at an altitude 35-ft above the runway. Variation in procedure can lengthen take-off distance.

We also found significant human response in a rejected take-off scenario. Here an emergency occurs at a relatively low speed; the pilot elects to abort the take-off 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 (*V1*) 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. Variation in procedure can add significant length to the accelerate-stop distance.

As with the standard take-off, the human element in an engine-inoperative continued take-off introduces variability into the actual field length. If pilots behave differently during a ground emergency as opposed to ordinary departures, the engine inoperative take-off distance will vary widely. Unless engineers account for such variability, accurate numerical prediction of real-world field length utilization becomes elusive.

This paper seeks to determine how pilots typically operate aircraft in commercial operations during the take-off. We present two studies: 1) a survey of active pilots regarding the procedures they use, and 2) field observations of procedures used by flight crews in the cockpit during training. From these studies, we develop some statistical insight into actual flight operations. Ultimately, we may better correlate actual runway performance with the nominal, pro-forma distances found in an AFM. With such data, we can see why, where and when actual operations deviate from AFM predictions.

## II. The Regulations

The reason why this work is important is that existing Federal regulations are vague. A student who first encounters the regulations in 14 CFR § 23 & 25 gets the impression that these published standards explicitly govern piloting procedures. An engineer responsible for coding a physics-based simulation for TOLD or reducing flight test data discovers many ambiguities. Supporting documentation published by the FAA, such as advisory circular AC-25-7C offers some clarification; however, many decisions remain left open to interpretation. [1]

Regulations found in 14 CFR § 23 and 14 CFR § 25 provide manufacturers with minimum performance standards that aircraft must achieved by design. These standards dictate the physical properties, such as weight limits, minimum climb gradients, V-speeds, etc. For specific parameters, these regulations define and govern the calculation of take-off distances and associated weight limitations. The distances covered by the regulations in the take-off 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 35-ft above the runway. Thus, the entire certified take-off distance comprises of more than just the ground roll, but also the initial flight phase for near runway obstacle clearance. Having a well-defined take-off distance, the Maximum Take-off Weight (*MTOW*) and related V-speeds can be determined and used to create operational field length requirements.

### a. Take-off Regulations - Engineering

The portions of 14 CFR § 23 & 25 that govern take-off performance for commercial transport and commuter aircraft are noticeably similar in language. Both regulatory sections hold very similar standards for take-off requirements and definitions. For the purpose of this paper, we will refer to 14 CFR § 25 as these regulations give slightly more detailed requirements and standards compared to those in 14 CFR § 23.

A series of intertwined requirements control engineering and operational details needed to schedule take-off: 14 CFR § 25.101 [2], 14 CFR § 25.107 [3], 14 CFR § 25.109 [4], 14 CFR § 25.111 [5] and 14 CFR § 25.113 [6]. Below are edited copies of current (2017) take-off regulations:

**14 CFR § 25.101 – General**

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

**14 CFR § 25.107 – Take-off speeds.**

(a) *V1* 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 take-off surface; and
  (3) A speed that provides the maneuvering capability specified in § 25.143(h).

…

(e) *VR*, in terms of calibrated airspeed, must be selected in accordance with the conditions of paragraphs (e)(1) through (4) of this section:
  (1) *VR* may not be less than—
    (i) *V1*;
    (ii) 105 percent of $V_{MC}$;
    (iii) The speed (determined in accordance with §25.111(c)(2)) that allows reaching *V2* before reaching a height of 35 feet above the take-off 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 $V_{MU}$ in the all-engines-operating condition, and 105 percent of $V_{MU}$ determined at the thrust-to-weight ratio corresponding to the one-engine-inoperative condition; or

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

…

(3) It must be shown that the one-engine-inoperative take-off 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 take-off distance using the established *VR*. The take-off distances must be determined in accordance with §25.113(a)(1).

(4) Reasonably expected variations in service from the established take-off 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 take-off distances established in accordance with §25.113(a).

**14 CFR 14 § 25.109 Accelerate-stop distance.**

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

(1) The sum of the distances necessary to—

b. Accelerate the airplane from a standing start with all-engines-operating to *VEF* for take-off from a dry runway;

c. Allow the airplane to accelerate from *VEF* to the highest speed reached during the rejected take-off, assuming the critical engine fails at *VEF* and the pilot takes the first action to reject the take-off at the *V1* for take-off 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 take-off 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 take-off, assuming the pilot takes the first action to reject the take-off at the *V1* for take-off 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 take-off 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.

…

**14 CFR § 25.111 Take-off path.**

(a) The take-off path extends from a standing start to a point in the take-off at which the airplane is 1,500 feet above the take-off surface …

(2) 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 take-off; and

(3) 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. …

**14 CFR § 25.113 Dry runway take-off distance and take-off run.**

(a) Take-off distance on a dry runway is the greater of-

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

2) 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 at which the airplane is 35 feet above the take-off surface, as determined by a procedure consistent with §25.111.

…

(c) If the take-off distance does not include a clearway, the take-off run is equal to the take-off distance. If the take-off distance includes a clearway-

(1) The take-off run on a dry runway is the greater of—

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

(ii) 115 percent of the horizontal distance along the take-off path, with all-engines-operating, from the start of the take-off to a point equidistant between the point at which $V_{LOF}$ is reached and the point at which the airplane is 35 feet above the take-off surface, determined by a procedure consistent with §25.111.

The standards published in these regulations form the design targets engineers use to draft aircraft geometries and systems, which then define the operational parameters and procedures published in the AFM. The reader should always keep in mind that flight manuals provide reference performance data, based upon models that assume that pilots operate aircraft in a precise manner.

These regulations give a clear definition for calculating critical field length. We explain the construction of our numerical analysis field performance code in AIAA 2017-0007 [7] and in Takahashi's text [8][9]. These sources delve into more detail on the intricacies of calculating balanced or critical field length.

Despite the details covered in the regulations, many ambiguities exist; these require some form of clarification. For example, in 2012, the FAA published AC-25-7C, the latest revision helping to clarify "Certified Take-off and Landing Procedures."[1] These circulars clarify the agencies position on ambiguous or vague statements made elsewhere in the regulations.

Detailed examination of the pertinent sections of AC-25-7C and their application to take-off procedures can be found in our first paper, AIAA 2017-0007. [7] To summarize, the reader should understand that 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 take-off simulations. Understand that these simulations are calibrated to match individual results attained by test pilots who do not necessarily fly the aircraft with "average skill". In the real world, a substandard pilot will invite disaster in the event of an aircraft operating at or near the field length limits exhibits mechanical trouble.

These regulations have been around for many years and have gone through many rounds of revisions throughout the years in an effort to keep pace with the advancing technology used in aircraft.

Interestingly, from an AFM perspective, the reader should understand that 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 *V2min* speed computation in 14 CFR § 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 from one carrier to another depending on the type of airframes in use.

Conversely, commercial operators flying in the Contiguous U.S. must adhere to the standards published in the operations regulations, 14 CFR § 91, 121 and 135, and change their practices to reflect any updates to these regulations.

### b. Take-off Regulations - Operations

Regulations found in 14 CFR § 91, 121 and 135 provide air carriers and pilots with additional standards that aircraft must abide by during operation. These CFR'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.

While, the standards published in 14 CFR § 91 form basic operational requirements for pilots of all aircraft. Requirements published 14 CFR § 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 be divided into two categories; (1) aircraft operating in a commuter or "on-demand" operation and (2) as regularly scheduled or "flag" operation. Aircraft flown under commuter category operations are regulated by 14 CFR § 135, whereas larger aircraft are regulated by 14 CFR § 121 rules. Commuter aircraft can be quite varied in size and performance, with aircraft certified under both 14 CFR § 23 and 25. Part 121 operators typically fly aircraft that are certified under 14 CFR § 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 take-off regulations for civil transport flag operations in the contiguous United States can be found in 14 CFR § 121.1 [10] and 121.189. [11] Below are edited copies of current take-off regulations:

**14 CFR §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

**14 CFR §121.189 Airplanes: Turbine engine powered: Take-off 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 take-off 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 take-off run must not be greater than the length of the runway.

…

Several factors play into the field lengths aircraft need in order to achieve flight, or perform a rejected take-off, 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 take-off procedures and rotation rates for continued take-off 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. These omissions introduce significant error into the predicted field length outputs. We examine this variability in a companion paper [12] that presents the effects on field length requirements from deviations in piloting techniques. We show that slight deviations in procedures (e.g. pitch rate, engine failure reaction times, etc.) can result in a significant (i.e. 1,000+ ft) increase in actual field length. If unaccounted for, they assure a runway overrun when an engine fails. More importantly, no federal regulation enforces standardized training procedures in these critical flight regimes.

Examination of several flight manuals, as discussed in AIAA-2017-0007 [7], showed little or no accounting for the variability in piloting techniques and offered few procedural standards during the take-off phase. This illuminates the inconsistency in manufacturer evaluation or publication of effects on field performance due to varying pilot techniques, however, not all AFM's reflect this; although some manufacturers do provide highly detailed take-off procedures. These procedural inconsistencies in the published AFM's lead to inconsistent aircrew training; pilots should be trained to respect 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.

## III. Overview of Field Work

In order to evaluate commercial aircraft operations in real world settings, we will explore multiple avenues to obtain relevant data.

One source of information pertaining to procedures is to query the line pilots flying aircraft in the field. This gives us 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 take-off. The data collected through recounts from pilots is subject to personal interpretation of procedures and can be erroneous from the techniques that are actually used.

A second source for understanding actual performance is to observe aircraft in real-world operations. By observing the take-off runs and associated timings at a major commercial airport, we could sample how actual performance aligns with predicted values.

The third source, offering the potentially highest resolution data regarding procedural impact, may be found through in-cockpit observations. We may observe actual procedures used during take-off run and correlate them against predicted performance. This is limiting in that the observable take-off 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, our in-cockpit observations of emergency procedures will be restricted to observations of student pilots operating a FAA certified flight simulator.

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

Thus our final observational strategy will comprise a three-part process; (1) a survey is conducted to gauge standard procedures used among commercial pilots, (2) a sampling of commercial aircraft actual field usage during take-off is gathered and run through a statistical analysis, (3) in cockpit observations are conducted in a FAA certified simulator with commercial student pilots. This paper will cover our initial foray into elements 1 and 3.

### A. Survey

We carried out an initial examination of the issues surrounding piloting techniques through an anonymous survey among qualified pilots that are current or former aircrew for commercial air carriers. 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 and currently working as line pilots. We asked screening questions to determine if the responding pilots were engaged in relevant operations. This filtered out a few respondents, as they were not qualified 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.

We took special precautions 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 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 take-off. Initial evaluation questions were asked to ensure that the respondents were, in fact, certified to operate commercial aircraft and regularly flew for commercial operators. We asked these pilots to identify the aircraft they were currently certified to fly in order to ensure the aircraft are multi-engine turbine airliners that this paper and its companion papers are addressing. Finally, we asked the aircrews 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; see Fig. 1. 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 paper, 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 2,000 total flight hours.

Examining Fig. 2, which illustrates common practices for obtaining aircraft weight information and V-speeds for the take-off 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 take-off speeds are given as an output. While this shows a majority of commercial operators

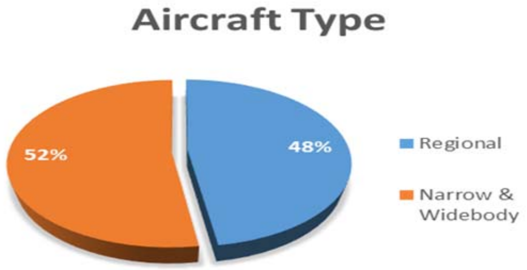

Figure 1. Aircraft type flown by survey respondents.

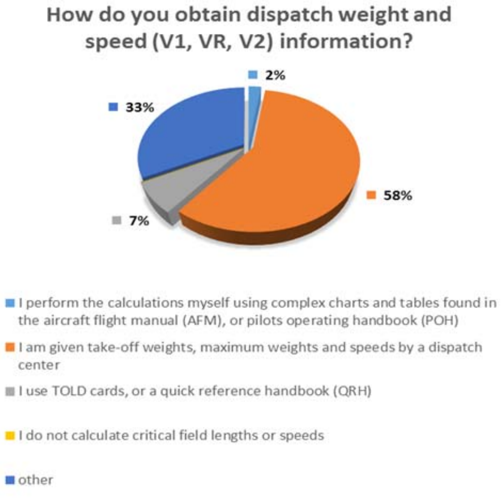

Figure 2. Common practice for obtaining Dispatch weight and V-speeds.

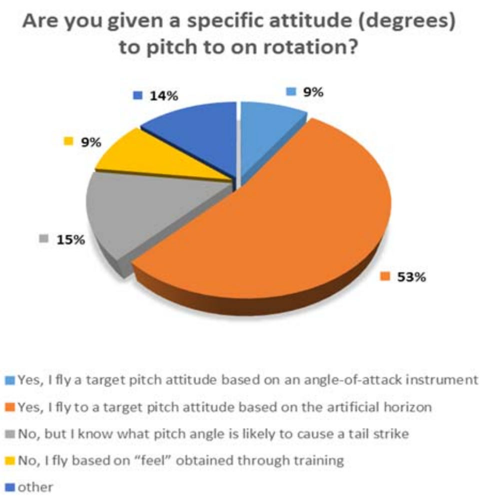

Figure 3. Common practice for pitch attitude during take-off.

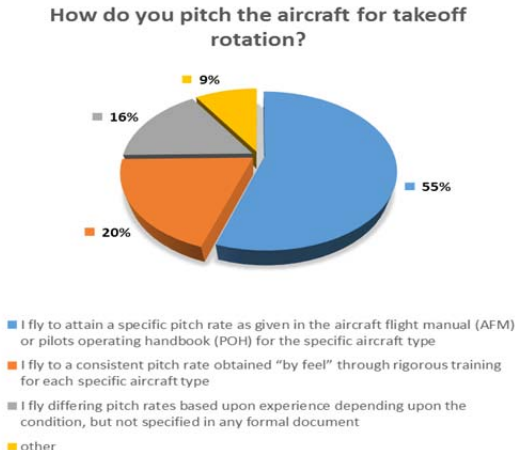

Figure 4. Common practice for AEO pitch rates during take-off.

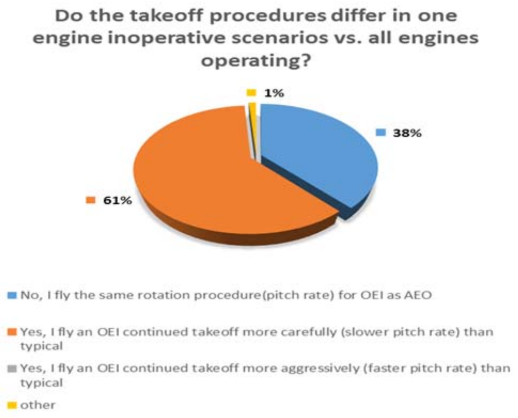

Figure 5. Common practices for OEI pitch attitude and pitch rate during take-off.

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.

Fig. 3 shows common practices for pitch attitude targets during the take-off 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 take-off 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.

Fig. 4 shows common practices for pitching rates during rotation on take-off. 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.

What strikes us about these responses is the large percentage of reporting pilots not following 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 reveals a disclaimer: "`Do not follow flight director commands until after liftoff`," [13] and "The flight director pitch command is not used for rotation." 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. In our previous conference paper, we found pitch rate to be one of the strongest contributors to overall take-off distance. [7]

Fig. 5 shows common practices for pitch rate procedures for one-engine-inoperative (OEI) take-off scenarios. Interestingly the majority of reporting pilots state that they actually use a slower pitch rate in the event of an engine failure during take-off 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 take-off 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.

This certainly begs the question, are a majority of pilots ignoring OEI take-off procedures, or is there no standardized procedure in place to train pilots to and they are left to guess the appropriate actions?

Figs. 6 and 7 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 surveyed 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. We find this feedback concerning in that if the aircraft were pushed to the limit of its capabilities during the take-off run, it would surely overrun the runway, despite the predicted field length requirements falling within the runaway being used.

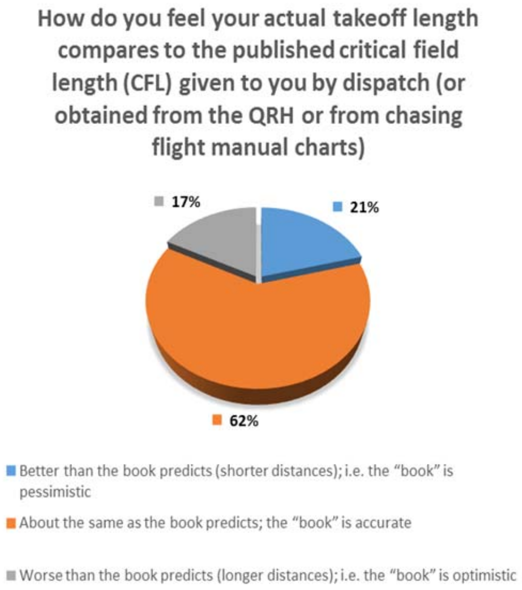

Figure 6. Perception on runway usage compared to predicted filed length requirements.

Evaluation of the survey results reveals clear procedural differences among commercial aircraft operators during the take-off 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.

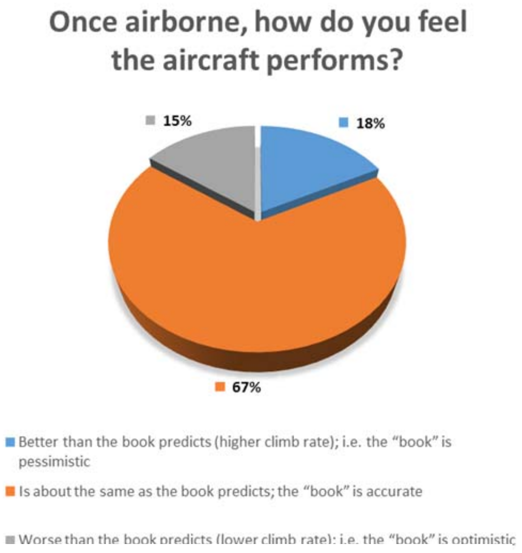

Figure 7. Perception of initial climb out to predicted climb performance

These operational inconsistencies brought to light from this survey directly align with the previous research we have conducted on procedural effects on filed length requirements. Some comments volunteered by responding pilots seem to show an awareness for the procedural inconsistencies and ambiguity in calculating filed 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.**"

Coming from a military aircraft background, where manufacturers scheduled take-off performance found in the AFM contains all sorts of useful information: predicted take-off ground roll, all-engines-operating; liftoff as well as rotation speed, we find commercial manuals alarmingly vague.

One 2000+ hour CRJ pilot tells us that "**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.**" We concur. Our CRJ-200 quick-reference-handbook, [14] gives cue-speeds (*V1*, *VR*, *V2*) in table form for various weights, airfield altitudes and temperatures. Nowhere, does it give a predicted runway length.

We also found one pilot response intriguing, in light of our 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.**" He went on to tell us that we "**fail to understand performance calculations in a [Part] 121 environment.**" And that "**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.**"

We disagree with this pilot; is regulatory compliance all that matters, even if you end up flying into the side of a mountain?

We concur that dispatch and pilots alike may remain blissfully unaware of scheduled aircraft performance.

We found the more detailed CRJ-200 aircraft flight manual [15] to be set up entirely in a manner for dispatch to determine the maximum permissible dispatch weight for a given airport runway. There was no direct or in-direct method to "chase the charts" to determine what the predicted take-off distance (all-engines-operating) should be for any given dispatch scenario.

## B. Student Pilot Observations

The survey also uncovered 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 instructional material deficiencies. These deficiencies lead to utilization of improper piloting techniques that could adversely affect field performance.

### 1. Observation Site

The CRJ-200 flight simulator is located at Arizona State University Polytechnic campus. This is a 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.

We conducted observations on the CRJ-200 training class, which is part of the professional flight program at ASU (AMT 490). A total of twenty students were enrolled in this course for 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).

### 2. Observation Protocol

Observations were conducted using a four camera security recording station for video acquisition. We did not record student names. Our observations are anonymized post-facto; we are looking for overall trends – not pilot specific trends.

We synchronize video capture of the broad cockpit, with close-up views of the PFD and overall forward view. (see Figure 8).

The flight simulator computers were able to produce a data log file, with outputs for selected data streams (e.g. airspeed, altitude, position on runway, angle-of-attack, power-lever settings, etc.)

Cockpit, primary flight displays (PFD), and external views were primarily used for capturing pilot timings and procedures. The data logger was the main source for numerical data acquisition.

Figure 8 – CRJ-200 Crew Observation Recording Log – PFD, Sim Datalog, Cockpit and external forward view. Spring 2017 – ASU

### 3. All-Engines-Operating Data Set

Over the Spring 2017 semester, we captured 50 total all-engines-operating take-off attempts. Following the “Rule of 30,” we recorded enough data 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 35-ft. 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. We captured pilot timings in rotation, speeds, and lift off pitch angles as well as the runway distance covered in ground, transition and air phases.

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 7,169-ft runway. High altitude airports were also used; 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 give us 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. Under an “assumed temperature” procedure, pilots can limit take-off thrust to a lower value by “telling the engines” (through the input of a fictitious temperature into the flight management computer (FMC)), that the outside air temperature (OAT) is much higher than it actually is. This can “fool” the electronic engine control software into thinking that the temperature is much higher, making it limit take-off thrust to that produced with a lower *N1* than it would otherwise be governed to. On a CRJ-200, the pilots will then manually advance throttles to establish the target *N1* rpm for take-off.

If the pilots press the “TOGA” button on the throttles, the PFD will display a fixed pitch attitude value and disengage presentation of heading cues. In the event of an engine failure, pilots are manually responsible retard to idle or to advance the throttles further to obtain true “full thrust.”

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*, *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, for 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.

In Fig. 9, we can see the wide range of observed distances for the total take-off distance (to 35-ft), the *TODR*. The average *TODR* observed was 4,801-ft, with a standard deviation of 838-ft. 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 7,576-ft, 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 *TORA=TODA=9,000-ft.*, this was a safe, legal take-off.

We did not observe any rolling starts.

Basic physics implies a strong correlation between aircraft weight and take-off distance, when we turn to Fig. 10, we see essentially no correlation in our experimental dataset ($R^2$*~0.36* in an attempted linear fit). Thus, our 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.

Looking deeper into the problem, let us look at the various factors in order.

To begin, do the pilots actually begin take-off rotation at the handbook prescribed *VR* speed?

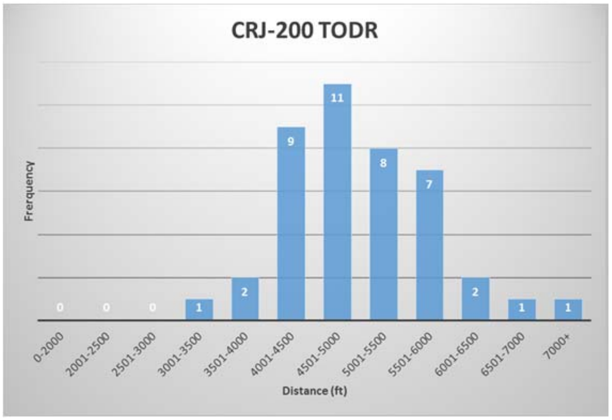

Figure 9 – CRJ-200 All-engines-operating – Take-off-distance to 35-ft (TODR). Spring 2017 – ASU

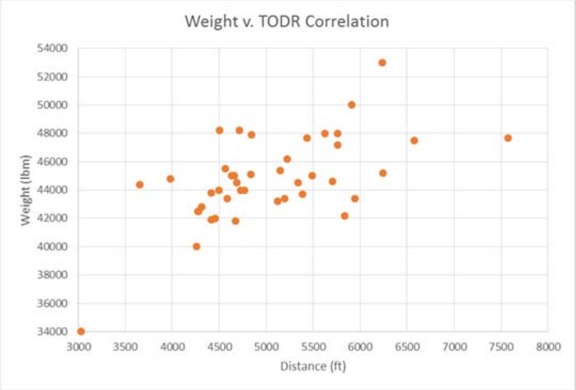

Figure 10 – CRJ-200 All-engines-operating – Take-off-distance to 35-ft (TODR) vs dispatch weight. Spring 2017 – ASU

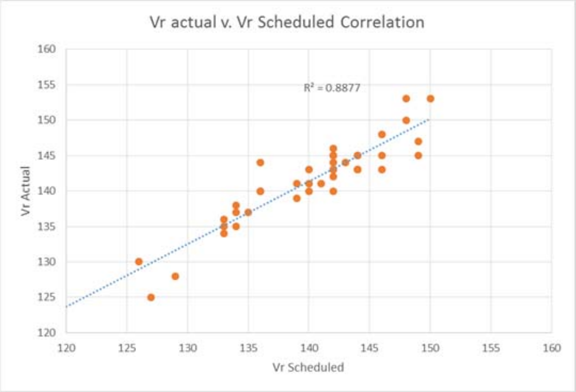

Figure 11 – CRJ-200 All-engines-operating – Rotation speed observed vs scheduled (VR) speed correlation. Spring 2017 – ASU

In Fig. 11 (prior page) and 12, we see that pilots do not particularly closely adhere to the flight manual provided rotation speed. We plot the deviation of airspeed from the rotation speed (*VR*) provided by dispatch as entered into the flight management computer (rounded to 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. We found 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). We see some skew in the data set towards delayed rotation. Sometimes pilots rotated 5 or more knots late. We can see that 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.

In Fig.13, we look at the actual pitch rate (degrees of attitude per second) achieved by pilots during initial take-off rotation. We see no identifiable distribution from this dataset; although the median pitch rate observed was 2.6°/deg. We see a large number of low pitch rates arising from a situation where the nosewheel begins to lift prior to a serious, pilot initiated rotation maneuver. This is due to trim setttings on the horizontal stabilizer. Because of the nature of the landing gear incidence of the CRJ-200, the aircraft develops considerable lift on the ground with Flaps 8. At *VR*, aircraft is already generating ~80% of its weight in aerodynamic lift.

We found that some dispatch cases required more effort to rotate than others. We speculate 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.

We note that the actual aircraft attitude necessary for lift-off is fairly low. The median lift-of attitude was $\alpha=5^{o}$; with a standard deviation of +/- 0.5°.

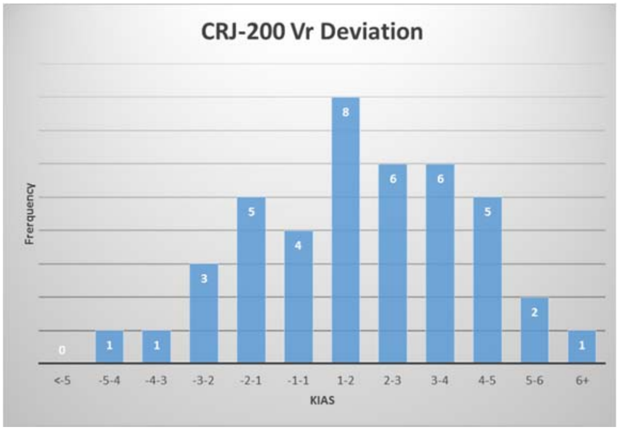

Figure 12 – CRJ-200 All-engines-operating – Rotation speed deviation. Spring 2017 – ASU

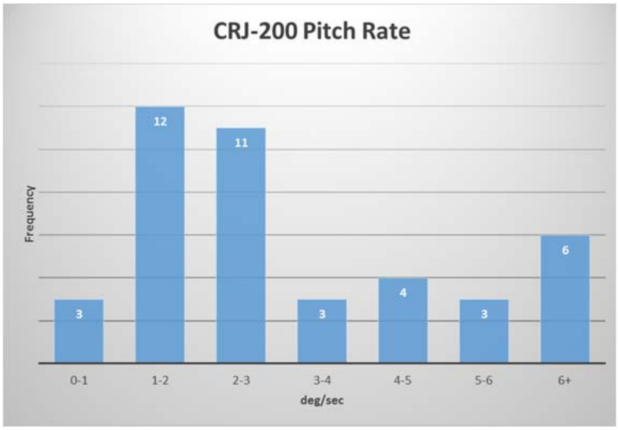

Figure 13 – CRJ-200 All-engines-operating – Pitch Rate. Spring 2017 – ASU

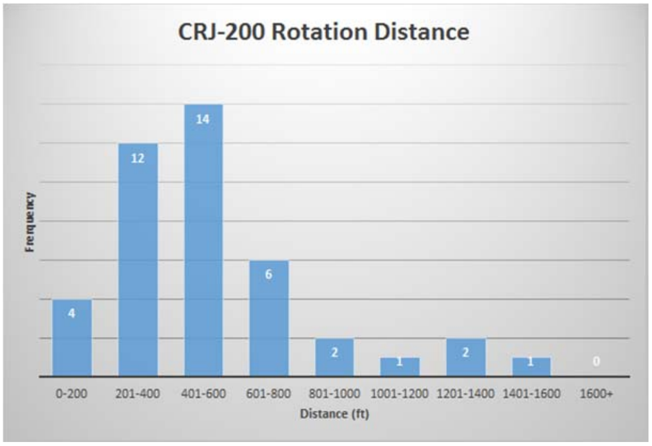

Figure 14– CRJ-200 All-engines-operating – Rotation Ground Roll Distance. Spring 2017 – ASU

The rotation pitch rate also influences the air-phase distance as well as the speed that the aircraft attains at the screen height, 35-ft above the runway. While engineers select a *VR* speed so that an aircraft with one-engine-inoperative will just attain the *V2* speed at the 35-ft point, aircraft with all-engines-operating will typically accelerate past *V2*.

In Fig. 14 (prior page), we see the wide range of ground roll consumed during take-off rotation. The median ground-roll during rotation was 480-ft, but we see one outlier where rotation consumed 1,443-ft of runway. The lack of anything resembling a normal distribution reflects upon the haphazard nature behind pilot rotation.

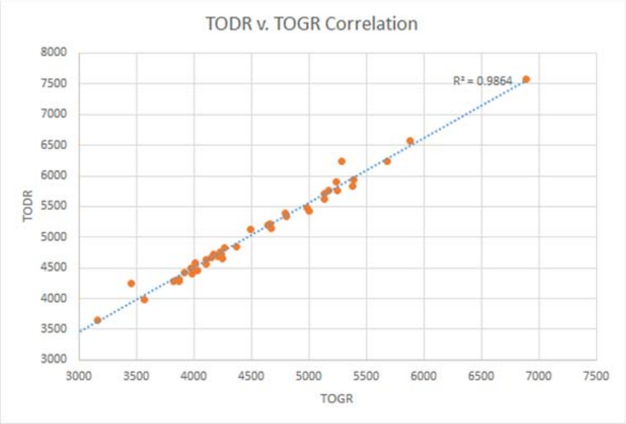

Figure 15– CRJ-200 All-engines-operating – TODR/TOGR Correlation. Spring 2017 – ASU

Thus, when it comes to air phase we see some scatter. Turning to Fig. 15, which plots observed take-off ground roll (*TOGR*) against the take-off distance to 35-ft (*TODR*) we see how total take-off distances reflect variance in both ground and air-phase procedure. The large observed variation in rotation rates exacerbates the "scatter." On average, we see a 535-ft air phase distance, with a standard deviation of 100-ft and a worst-case outlier with a 954-ft air phase.

We also note 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*, we wonder whether a successful a rejected-take-off (RTO) could be executed near the decision speed.

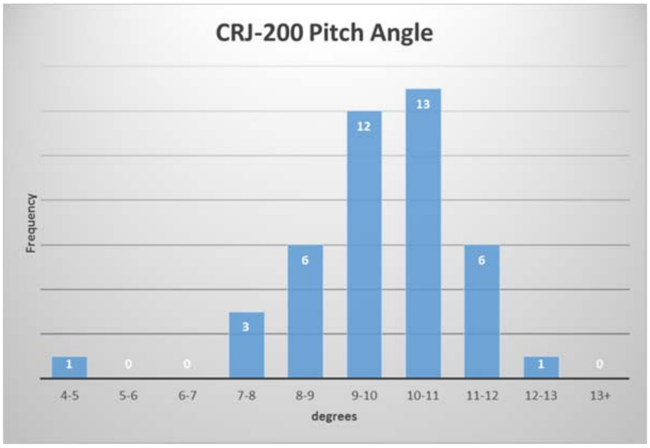

Figure 16- CRJ-200 All-engines-operating – Pitch Angle at 35-ft Spring 2017 – ASU

In Fig. 16, we see that pitch angle (horizon attitude) attained as the aircraft achieves 35-ft above-ground-level. Here, we see something resembling a normal distribution. The median pitch angle (which includes the flight path angle) is 10°; with a standard deviation of +/- 1.4°.

This wide variation in pitch angle results in take-off with widely varying load factor. Pulling 1.5-gees during initial climbout markedly increases induced drag, and reduces the available thrust for acceleration. We see this in terms of the second-segment climb speed that is attained at the screen height.

As expected, with all-engines-operating, pilots routinely overshoot the engine-inoperative *V2* speed. In Fig. 17, we see the wide variance in overspeed. While the handbook indicates a desired all-engines-operating second-segment climb speed of *V2+10* knots, we see tremendous scatter; a forced linear fit results

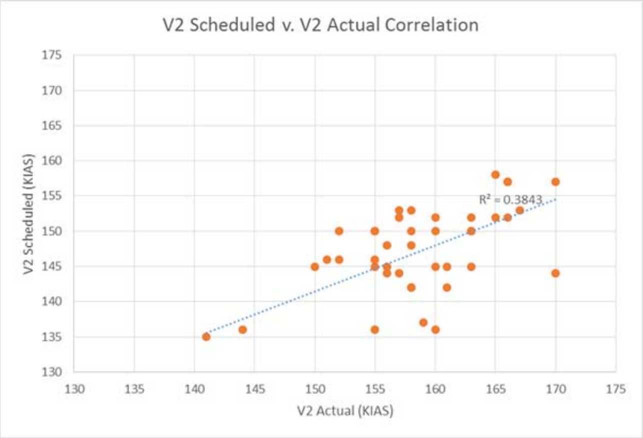

Figure 17- CRJ-200 All-engines-operating – airspeed at 35-ft vs V2 scheduled. Spring 2017 – ASU

in $R^2 \sim 0.38$. Fortunately, we see no cases where second segment climb, all-engine-operating, stabilizes beneath the scheduled *V2* speed. However, the variance in overspeed (see Fig. 18) is quite wide. Our mean observed overspeed for *V2* is 11-knots with a standard deviation of +/- 5.7-knots.

### 4. Accelerate-Stop Data Set

We analyzed 23 rejected take-off (RTO) cases with accelerate-stop maneuver. Because most rejected take-offs involve a decision to abort that is made considerably below the formal decision speed, *V1*, distance information is not meaningful.

Referring to Fig. 19, we can see that the majority of pilots have quick reaction times, but as usual there were outliers. Because we observed training flights, we are aware that pilots were often cued by the instructor before dispatch that an emergency might arise.

Recall standard cockpit procedure. The pilot monitoring (PM) operates throttles during 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 a CRJ-200, the lift-dump deploys the spoilers automatically upon throttle retard (no pilot intervention to deploy). For almost all of our observed cases, we saw pilots using reverse thrust, even in the case of an engine failure. On average, our observed 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! We saw a standard deviation of 2.2-sections in our, admittedly, small sample size data set.

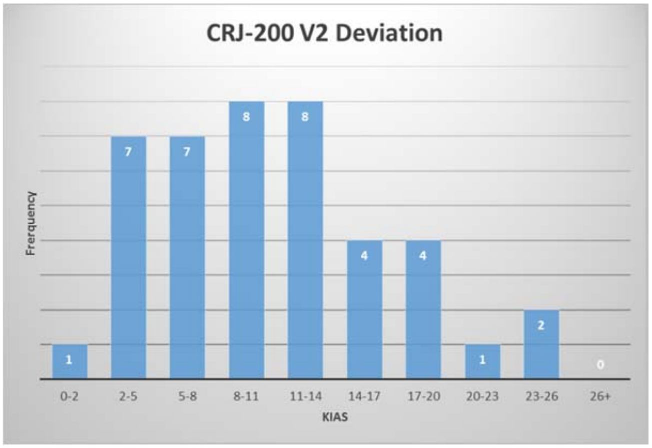

Figure 18- CRJ-200 All-engines-operating – airspeed deviation from V2 at 35-ft Spring 2017 – ASU

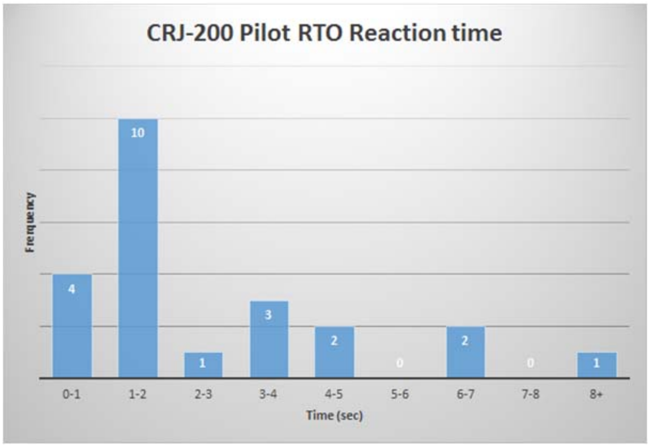

Figure 19- CRJ-200 Rejected Take Off Reaction Time Spring 2017 – ASU

Recall that 14 CFR § 25.109 [4] requires engineers to include a distance safety margin "`equivalent to 2 seconds at the V1 [speed] for take-off from a dry runway`." 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 have 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.

### 5. OEI Accelerate-Go Data Set

We analyzed five engine failures at or above *V1*. These cases resulted in pilots flying an engine inoperative accelerate-go procedure. Because of our small sample size, we cannot draw definitive statistics, but we can share several anecdotes that cause us 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 35-ft AGL.

In one case, the aircraft was unable to reach *V2*. This flight was departing KRIC (Richmond International Airport) on Runway 2, with 6,600-ft 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*=~62%. The aircraft reached *V1* at 4,400-ft 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 35-ft AGL at 147 KIAS. The aircrew continued to pitch the aircraft to 13° nose up; this caused airspeed to bleed off. By approximately 300-ft 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 600-ft 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.

Similar to this aircrew, we have noticed a similar trend across the other OEI observations we were able to obtain. While other aircrews were able to obtain *V2* at the 35-ft screen height, 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 400-ft AGL, but the resulting airspeed fell significantly below *V2*; often below *VR*! We only observed one case where the flight crew was able to maintain a stabilized *V2* throughout OEI second-segment-climb.

We suspect 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 us a better idea as to how pilots react to emergencies and how mishandling the stricken aircraft affects field performance.

# IV. SUMMARY & CONCLUSIONS

This paper sought to determine the impact pilot procedure has on aircraft field performance. Through a survey of line pilots and observing advanced student pilots in the cockpit, we have been able to draw preliminary conclusions as to what is happening in the cockpit in a commercially operated aircraft on a daily basis.

Line pilots that routinely fly commercial aircraft are blissfully unaware of the distances they require for take-off. In our survey, many respondents indicated that the calculation of critical field length was not something they routinely performed. Dispatch gives pilots the V-speeds required for take-off.; they proceed to fly without further question.

We witnessed large variations in pilot timings during rotation under normal AEO conditions. The lack of standardization in take-off procedure allows pilots to fly the aircraft as they choose. Lift-off pitch-attitude targets are displayed on the PFD, however, this offers neither tail strike protection nor V-speed compliance. Many flight manuals call this fact out; yet pilots admit to reliance on this using the flight director as a rotation pitch target (or using even more ad-hoc procedures). With such large variability in rotation timings, rates and pitch targets, a deterministic prediction of field performance seems to offer a false sense of security.

Reaction times for initiation of RTO demonstrate considerable 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. Despite this, many pilots 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.

Pilots have difficulty adhering to climb speeds during an OEI take-off. 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 certainly flirt 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. Our observations have shown that pilot timings significantly vary. The deviation in these timings often results in much more runway usage than dispatch would expect. 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.

## Acknowledgements

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

## References

[1] Federal Aviation Administration, Flight Test Guide for Certification of Transport Category Airplanes, Advisory Circular AC-25-7C, U.S. Department of Transportation, Washington, D.C., Oct 16, 2012.
[2] 14 CFR § 25.101 “Performance: General” (2017).
[3] 14 C.F.R. § 25.107 “Take-off Speeds” (2017).
[4] 14 C.F.R. § 25.109 “Accelerate-Stop Distance” (2017).
[5] 14 C.F.R. § 25.111 “Take-off Path” (2017).
[6] 14 C.F.R. § 25.113 “Take-off Distance and Take-off Run” (2017).
[7] Takahashi, T.T., Wood, D.L. and Bays, L.V., “An Introduction to the Impact of Pilot Techniques Upon “Certified” Field Performance,” AIAA 2017-0007, (2017).
[8] Takahashi, T.T., *Aircraft Performance and Sizing Vol. I*, Momentum Press, New York, 2016.
[9] Takahashi, T.T., *Aircraft Performance and Sizing Vol. II*, Momentum Press, New York, 2016.
[10] 14 C.F.R. § 121.1 “Applicability” (2017).
[11] 14 C.F.R. § 25.113 “Take-off Distance and Take-off Run” (2017).
[12] Wood D.L, Takahashi, TT. and Bays, L.V. “The Effect of Piloting Practices Upon Actual as Opposed to Scheduled Take-off Field Performance,” AIAA 2017-3422, (2017).
[13] Boeing 737-500 Flight Crew Training Manual
[14] CRJ-200 QRH
[15] CRJ-200 Airplane Flight Manual