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Improved Field Performance through Regulatory Changes to Enable Speed Scheduled Reverse Thrust

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This paper presents arguments supporting proposed changes to the certification requirements contained in 14 CFR §25.109, §25.125, and §25.933. We find that current certification requirements are overly prescriptive in that they define both procedure and capability in such a manner that they discourage innovations in safety and environmental impact. Thus, they impede the very policy objectives they are intended to advance. The current language of 14 CFR §25.109 requires that the applicant assumes a critical engine failure during take-off, without considering the likelihood of such a failure or the significance of its impact on the available propulsive power. Direct compliance would favor aircraft with a larger number of engines, opposite current industry trends. 14 CFR §25.109 and 14 CFR §25.125 effectively preclude the applicant from taking credit for reverse thrust capability in determining accelerate-stop and landing distances. These regulations arise from a belief that thrust reversing systems are not sufficiently safe and reliable. Finally, 14 CFR §25.933 requires the applicant to demonstrate that the thrust reversing system, even a system intended only for ground use, can be safely deployed and re-stowed in-flight. Compliance with this regulation is onerous enough that aircraft designers limit the capability and benefit of the reversing system. This paper proposes changes to these regulations that would enable the applicant to use statistical means to show that the aircraft design achieves a level of safety equivalent to or better than the current requirement language. Compliance would be demonstrated thru a hazard assessment and safety analysis, similar to the proven approach used to demonstrate compliance with the requirements of 14 CFR §25.1309. Lastly, this paper includes a quantitative trade study illustrating the advantages of such a regulatory approach, improving aircraft safety and performance, and decreasing the environmental impact of aviation.

Nomenclature

b = reference span of the wing in feet
Cn = coefficient of rudder effectiveness (dimensionless)
$\frac{dCn}{drud}$ = yawing moment coefficient per degree of rudder deflection (per degree)
δrud = maximum rudder deflection in degrees
ft = feet, a measure of distance
P = Probability (dimensionless)
q = dynamic pressure in pounds per square foot
sec = seconds, a measure of time
$Sref$ = reference area of the wing in square feet
T = asymmetric thrust in pounds force
V_1 = decision speed in knots
V_2 = obstacle clearance speed in knots
V_{EF} = speed at which critical engine failure is assumed to occur in knots

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V_{MCG} = minimum controllable ground speed in knots
V_{MCL} = minimum controllable air speed in the landing configuration in knots
V_R = rotation speed in knots
V_{REF} = refusal speed in knots
y_e = butt-line distance from the aircraft centerline to the operating unsymmetric engine

I. Introduction

ON May 26th, 1991 a Lauda Air Boeing 767-300ER departed Bangkok Airport headed for Vienna, Austria as flight number NG 004[1]. Approximately five minutes into the flight the crew observed an alert system message related to the thrust reverser isolation valve. Approximately 10 minutes later the aircraft disappeared from air traffic radar. The aircraft crashed into mountainous jungle terrain about 94 nautical miles northwest of Bangkok. The flight crew and all 213 passengers were killed in what was later determined to be an unrecoverable in-flight thrust reverser deployment. During investigation of the wreckage the left hand thrust reverser was confirmed to be in the deployed position. Simulations performed by Boeing eventually demonstrated that at the prevalent flight conditions, such an in-flight deployment would likely result in an unrecoverable loss of aircraft control, even for an experienced flight crew. As a result of events similar to flight NG 004, the federal aviation administration enacted significant changes to the relevant aircraft certification standards contained in 14 CFR §25.933 (1977).[2] In 1990, 14 CFR §25.933 was amended to require that aircraft demonstrate in-flight thrust reverser deployment and restow capability, even for thrust reverser systems designed for ground use only. [3, 4]

It would be inaccurate to suggest that the changes in 14 CFR §25.933[4] were a direct result of the Lauda Air incident, as the planned regulatory changes were made shortly before the crash. The Lauda Air event is an example of the type of event that motivates significant changes in aircraft certification standards. It is ironic that the regulatory changes in 14 CFR §25.933 were unable to prevent the Lauda Air event as such changes only apply to new designs, not to existing designs.[5] Morever, it appears that that Boeing did not demonstrate direct compliance with all aspects of 14 CFR §25.933 (1977).[3] The investigation report[1] suggests that Boeing may have only demonstrated compliance over a portion of the flight envelope.

Following the Lauda Air event, the Federal Aviation Administration (FAA) issued several airworthiness directives, and adopted a set of expectations for thrust reverser design that are not actually reflected in section §25.933.[6,7] In particular, later thrust reverser designs intended only for ground use incorporate redundant locking mechanisms that prevent inadvertent deployment. The FAA tasked the Powerplant Installation Harmonization Working Group (PPIHWG) to develop recommendations concerning new or revised requirements and guidance material for thrust reverser systems. In 1999, the PPIHWG proposed draft Advisory Circular (AC) No. 25.933X[8], which outlined two methods of demonstrating compliance in the spirit of 14 CFR §25.933[4]: a controllability method and a reliability method. Although the draft AC 25.933X has never been promulgated as a formal regulation, the methods described within it have been used to achieve aircraft certification through an equivalent level of safety (ELOS) finding.

The Lauda Air event illustrates the motivation behind this work, which is to address the frequently ineffective nature of regulations produced in reaction to such events. The requirements of today's 14 CFR §25.109 (2015)[9], §25.125 (2015)[10], and §25.933[4] undoubtedly evolved from incidents and tragedies following which investigators determined that a particular failure mode or scenario significantly reduced the safety of the aircraft. It is logical that the identification of these failure modes and scenarios lead to regulations intended to prevent future events. Unfortunately, these regulations may remedy the errors of the past in a manner that is relevant only to specific designs or practices prevalent at the time. Such events may produce regulations that are overly prescriptive, defining not only *what* must be demonstrated, but also *how* it must be demonstrated. Such regulations hinder progress as technologies in the industry advance. This paper proposes improvements to 14 CFR §25.109[9], §25.125[10], and §25.933[4] which are intended to allow innovations that can enhance both the safety and efficiency of aircraft designs.

This work extends an effort begun by Takahashi & Creighton in 2014,[11] and continued by Takahashi in 2015[12] to employ numerical simulation of generic transport-category aircraft to study potential areas for regulatory reform that would enable future commercial aircraft designs to operate more safely from a wider variety of metropolitan airports. Moreover, these papers document the widespread use of piloting procedures that functionally ignore the certification procedures required by 14 CFR § 25 (such as "certified factored" landing distances). Aircraft have 'two-sets-of-books' for field performance – one containing distances and procedures that strictly follow FAA certified 14 CFR § 25 processes, and another comprising 'advisory' data that does not follow the procedures mandated by the FAA but that are actually used by pilots on a regular basis.

II. Analysis of Current Regulations

This section reviews the current certification requirements of 14 CFR §25.109 (2015)[9], §25.125 (2015)[10], and §25.933 (2015)[13]. We include a review of 14 CFR §25.107 (2015)[14] to facilitate understanding the derivations of various takeoff "cue speeds." In order to better understand the intent and impact of these regulations, an aircraft system dynamic model is used to simulate accelerate-stop distance and landing distance calculations under a variety of scenarios. Note that accelerate-stop distance and landing distance simulations generated using this aircraft system dynamic model are presented herein without any "safety factors" or other multipliers applied.

A. Description of Aircraft System Dynamic Model

The aircraft system dynamic model reflects the following general methods and assumptions. We utilize the 1976 standard atmosphere for all analyses, and may vary runway altitude. We can also adjust the runway coefficient of friction and the braking system efficiency (as described in §25.109) to represent operations on dry and wet runways.. Our trade studies allow us to vary the wing reference area, the wing span, and wing aspect ratio, as well as the weight distribution between nose wheels and the main landing gear. We can vary the number of engines, the take-off thrust per engine, thrust reverser effectiveness (maximum reverse thrust divided by maximum takeoff thrust), as well as the thrust reverser deployment time (delay between deploy command and start of engine acceleration). We specify the moment arm from centerline of aircraft to centerline of the critical engine, the yawing moment coefficient of the rudder per degree deflection, and the maximum rudder deflection. We can vary the thrust reverser cut-off speed (minimum speed at which thrust reverse usage is recommended), as well as the engine acceleration time from idle to maximum reverse thrust.

Aircraft dynamics are simulated by taking account of the combined effects of drag, braking force, forward thrust and reverse thrust. Acceleration rates are calculated based on net force and aircraft weight. Aircraft speed and distance are calculated using numerical integration. Drag force is calculated based on the prescribed drag coefficient, dynamic pressure, and wing reference area. Braking force is calculated using the prescribed weight distribution, coefficient of friction for the runway surface, and braking system efficiency. The coefficient of friction can be input as a constant value, or one of the polynomial curves from 14 CFR §25.109(c) can be used. Engine thrust during takeoff uses the prescribed constant value. Engine thrust at idle is assumed to be 4% of take-off thrust. Maximum reverse thrust is calculated from take-off thrust using the prescribed thrust reverser effectiveness.

For accelerate-stop distance simulation, user inputs include: coefficient of drag in takeoff configuration, takeoff weight, decision speed V_1, engine failure recognition and response time, time delay after V_1 before the throttle is reduced to idle, and engine deceleration time to idle. An iterative method is used to find the critical engine failure speed V_{EF} that provides the prescribed decision speed V_1 after the prescribed delay.

With all engines initially operating, the aircraft accelerates from rest to V_{EF}. If the scenario prescribes a critical engine failure, then the thrust of the affected engine is set to zero. The aircraft then accelerates from V_{EF} to V_1. At V_1, the first pilot action is simulated as application of the brakes. It is assumed that it takes about 1 second for the braking system pressure to ramp up from zero to full braking force. This is intended to reflect delays in pilot and aircraft system response. It is assumed that the pilot's second action is to move the throttle lever(s) to the idle position. The engine(s) decelerate(s) from take-off power to idle power over a prescribed duration. If the scenario to be simulated prescribes the use of reverse thrust, then an appropriate delay for thrust reverser deployment is simulated. After thrust reverser deployment, acceleration of the engine(s) from idle to maximum reverse power is simulated. As the aircraft decelerates, if the scenario to be simulated calls for the thrust reverser to be stowed by a prescribed cut-off speed, then the reverse thrust power setting is reduced to zero below this speed. The aircraft continues its deceleration to a full stop. The distance associated with two seconds at V_1 is added so as to reflect the requirements of §25.109.

For landing distance simulation, user inputs include: 1) V_{REF}, 2) the coefficient of drag in landing configuration, 3) the landing weight, 4) the approach slope, 5) the total duration of air phase, 6) the time delay to get the nose wheel down, the spoilers deployed, and the brakes on, and 7) the time delay from touch-down to thrust reverser deploy command.

The landing simulation begins at V_{REF} with the aircraft at the prescribed 50-ft reference height above the landing surface. The aircraft descends at V_{REF} and a prescribed approach slope (3^{o} used throughout) until the height above the surface is zero. During flare and touchdown, we assume that all engines are at flight idle, unless the prescribed scenario assumes that a previous engine failure has occurred, in which case the affected engine is assumed to produce no thrust. Additional flare time is added to achieve a total air phase of a prescribed duration. During this flare time, the aircraft decelerates based on drag effects alone. Touch-down occurs at the end of the flare. If the scenario to be simulated prescribes the use of reverse thrust, thrust reverser deployment begins at a prescribed duration after touch-down. Thrust reverser deployment is assumed to be complete after a prescribed duration. Concurrently with thrust reverser deployment, it is assumed that the pilot will de-rotate the nose wheel onto the runway, deploy the spoilers, and apply the wheel brakes. If the scenario prescribes the use of reverse thrust, we assumed that the engine begins accelerating at this time, and reaches maximum reverse thrust within a prescribed duration. If the scenario to be simulated calls for the thrust reverser to be stowed by a prescribed cut-off speed, then the reverse thrust power setting is reduced to zero below this speed. The aircraft continues its deceleration to a full stop.

For the purpose of this study, we simulate dry runway conditions with a coefficient of friction of 0.38 and a braking system efficiency of 1.0 We simulate wet or contaminated runway conditions with a coefficient of friction of 0.20 and a braking system efficiency of 0.8. Other parameters and assumptions used in the aircraft system dynamic model are summarized in Table 1 and Table 2. Note that the parameters associated with a small twin engine passenger jet are used for the majority of simulations in this report, unless otherwise specified.

No attempt has been made to carefully calibrate or validate the accuracy of the aircraft system dynamic model relative to an existing aircraft type design. Doing so would require access to numerous aircraft system design and performance parameters that are likely considered proprietary. Instead, we broadly tune our simulation so that our model offers sufficient accuracy to illustrate the general trends and effects of the proposed regulatory changes.

Table 1. Scenario Assumptions Used in Aircraft System Dynamic Model

Scenario Assumptions			Used for Accel-Stop Simulation	Used for Landing Simulation
Altitude of runway	ft	0	X	X
Engine failure recognition and response time	sec	2	X	
Time after V1 before throttle reduction	sec	2	X	
Engine deceleration time	sec	2	X	
Engine acceleration time to reverse thrust	sec	3	X	X
Obstacle clearance height	ft	50		X
Approach slope	degrees	3		X
Total duration of air phase, including flare	sec	6		X
Delay time to get nose down, spoilers deployed, and brakes on	sec	3		X
Time delay while pilot ramps up braking pressure	sec	1	X	X
Time delay from touch-down to deploy command	sec	0		X

B. 14 CFR §25.107 – Takeoff Speeds

Although no changes to 14 CFR §25.107 (2015)[14] are proposed herein, it is helpful to understand some aspects of this section as they impact the accelerate-stop distance determination required by 14 CFR §25.109. 14 CFR § 25.107 defines and constrains a number of aircraft speeds that drive the accelerate-stop and accelerate-go distances. First, V_{EF} is defined as the critical engine failure speed, or the speed at which a critical engine failure is assumed to occur. By definition V_{EF} may not be less than the minimum controllable ground speed V_{MCG}. Next, V_1 is a speed selected by the applicant, and is sometimes referred to as the decision speed. This terminology implies that for significant failures occurring before V_1 the pilot will generally reject the takeoff because adequate stopping distance is available. For significant failures occurring after V_1, the pilot is generally obligated to continue the takeoff as adequate stopping distance may not be available. By definition V_1 must not be less than V_{EF} plus the speed gained after critical engine failure before the first pilot action. So by definition, $V_{MCG} < V_{EF} < V_1$. The actual selection of V_1 speed will depend on other values selected for rotation speed V_R and obstacle clearance speed V_2. V_2 must be selected to provide adequate stall margin, control margin, and gradient of climb. V_R must be selected so as to achieve V_2 speed and an obstacle clearance height of 35-ft within the available takeoff distance (so-called accelerate-go distance). So by definition, $V_1 < V_R < V_2$. The selection of V_R and V_2 speeds is largely a function of aircraft climb performance, an aspect not represented within the aircraft dynamic system model used in this study. Consequently, we will utilized published or assumed representative values for V_1 speed throughout this study.

C. 14 CFR §25.109 – Accelerate-Stop Distance

14 CFR § 25.109 (2015) defines the methods and assumptions that should be used to demonstrate the accelerate-stop distance associated with a rejected takeoff scenario. The resulting accelerate-stop distance data is used to validate aircraft design parameters, and to define operational procedures and limitations that will ultimately be reflected in the aircraft flight manual and related documents. The requirements of 14 CFR §25.109 indicate that accelerate-stop distance should be determined for both dry runway and wet runway conditions. The accelerate-stop distance for dry runway conditions is selected in accordance with 14 CFR §25.109(a) as the greater of the distances determined for each of two scenarios. In the first scenario, per 14 CFR §25.109(a)(1), the accelerate-stop distance includes the following distances:

1) The distance necessary to accelerate the aircraft from standing start with all engines operating to a speed of V_{EF} at which point a critical engine failure is assumed to occur.
2) The distance necessary to accelerate the aircraft from V_{EF} to the highest speed reached during the rejected takeoff assuming that the pilot takes the first action to reject the takeoff at speed V_1.
3) The distance necessary to decelerate the aircraft to a full stop.
4) A distance equivalent to two seconds at a speed of V_1.

In the second scenario, per §25.109(a)(2), the same distances are included except that no engine failure is assumed to occur.

As explained in reference 15, V_1 is not necessarily the highest speed achieved during the rejected takeoff. The aircraft may continue accelerating past V_1 due to delays in pilot and aircraft response. For example, one such delay is the engine spool down period, which causes the engines to continue producing thrust for a short period after the throttle lever is pulled back to idle. During this delay, the aircraft may continue to accelerate, despite deliberate pilot action to reject the takeoff.

It's interesting to note the selection of V_1 speed for the assumed two-second delay included in the accelerate-stop distance calculation. It is unlikely that an aircraft accelerating past V_1, and later decelerating past V_1, would spend significant time at V_1 speed. It is clear that the two-second window is intended to provide a margin of safety for delays in pilot and aircraft response. Note that the accelerate-stop distance calculation already assumes a delay after engine failure before the first pilot action.

We compute the relationship between the accelerate-stop distance and the V_1 speed by assuming that the critical engine failure occurs immediately before V_1 is achieved. In effect, this implies that the critical engine failure speed can be selected just as decision speed V_1 can be selected. In practice, the speed at which an actual engine failure might occur cannot be predicted. The assumption that engine failure occurs just before V_1 (at the so called V_{EF} speed) represents a worst case assumption for the resulting distance estimates. If an actual engine failure occurs before V_{EF}, the pilot can be assured that the aircraft can be safely brought to a stop within the available runway distance. If the critical engine failure occurs after V_{EF}, the pilot may not be able to safely bring the aircraft to a stop. But the pilot can be assured of sufficient climb performance to clear a 35-ft obstacle at the end of the runway.

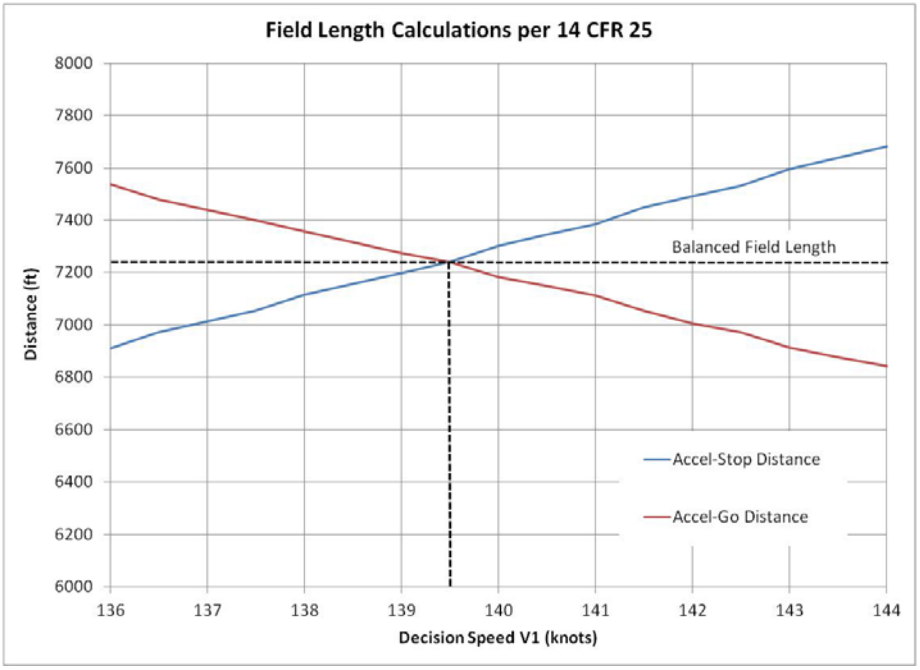

Figure 1. Balanced Field Length Calculation.
Accelerate-stop distance trends up with increasing V_1 *speed. Accelerate-go distance trends down with increasing* V_1 *speed.*

Increasing V_1 (and V_{EF}) tends to increase the accelerate-stop distance; the aircraft needs more space to accelerate past V_1, and then decelerate to full stop. Conversely, increasing V_1 (and V_{EF}) tends to decrease the accelerate-go distance; the aircraft is likely to achieve better climb performance after lift-off. These trends are depicted in Figure 1 for a hypothetical aircraft. The point where the accelerate-stop and accelerate-go curves intersect is known as the "balanced field length," and represents the minimum field length required to safely execute a takeoff. The V_1 speed that provides this balanced field length demarks a critical decision point for the pilot. If the pilot elects to abort the take-off after exceeding V_1, the accelerate-stop distance may exceed the balanced field length. If a critical engine failure occurs before V_1 and the pilot elects not to abort the take-off, the accelerate-go distance may exceed the balanced field length. If the accelerate-stop distance could be reduced, for example thru the use of reverse thrust, then the balance field length would be reduced and the V_1 speed would increase. This would reduce runway length requirements, and improve aircraft climb performance.

The accelerate-stop distance for wet runway conditions is selected in accordance with 14 CFR § 25.109(b) as the greater of the distance determined per the dry runway requirements in § 25.109(a), or the distance determined in accordance with 14 CFR § 25.109(a), except that wet runway values for V_{EF}, V_1, and brake system stopping force are used. Sub-sections 25.109(c) and (d) provide coefficient of friction and braking system efficiency values for various wet runway scenarios.

The aircraft system dynamic model is useful for illustrating the implications of these rules. Figure 2 and Figure 3 provide illustrations of the accelerate-stop distance according to 14 CFR § 25.109(a) and (b). The distance according to 14 CFR § 25.109(a)(1) is labeled "One Engine Inoperative after V_{EF}", and the distance according to 14 CFR § 25.109(a)(2) is labeled "All Engines Operating". These illustrations assume a hypothetical twin engine narrow-body airliner with characteristics broadly similar to the Airbus A320-200. Figure 2 uses relatively high values for braking system effectiveness (coefficient of friction and braking efficiency). Figure 3 uses relatively low values for braking system effectiveness. These figures illustrate that the accelerate-stop distance for the one engine inoperative scenario may or may not exceed the accelerate-stop distance for the all engines operating scenario. The difference between these distances depends on the brake system effectiveness in relation to engine thrust. Figure 4 provides a similar illustration using relatively high values for braking system effectiveness, but this time with relatively large delays in pilot and aircraft system response. This figure illustrates that large delays tend to increase the all engines operating distance relative to the one engine operating distance. The inclusion of both criteria within the 25.109(a) requirement provides assurance that the worst case scenario will be considered. It's significant to note that wet or contaminated runway conditions, and delays in pilot or aircraft system response, increase the likelihood that the all engines operating scenario will have a greater accelerate-stop distance than the one engine inoperative scenario.

14 CFR § 25.109(e) and (f) prescribes that "means other than wheel brakes" may be used to determine accelerate-stop distance if that means is safe, reliable, provides consistent results, and does not require exceptional skill to operate. However, the use of engine reverse thrust to determine accelerate-stop distance on a dry runway is specifically disallowed.

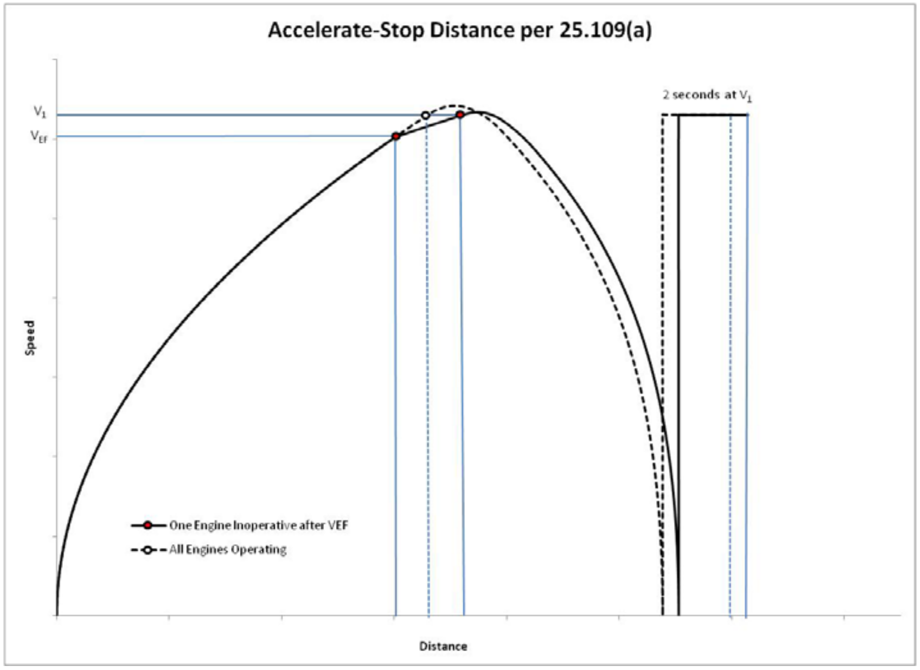

Figure 2. Accelerate-Stop Distance with High Braking System Effectiveness.

Reference 15 provides insight into the reason why the FAA disallows credit for reverse thrust on a dry runway.[15] The FAA believes that the additional safety provided by not accounting for reverse thrust in calculating the accelerate-stop distance on a dry runway is necessary to offset other hazards that can significantly affect the dry runway accelerate-stop performance. Some of these hazards include: runway surfaces that provide poorer friction characteristics than the runway used during flight tests to determine stopping performance, dragging brakes, and brakes whose stopping capability is reduced because of heat retained from previous braking efforts. This rationale hinges upon a belief that neglecting the quantifiable benefit of reverse thrust offsets other un-quantified hazards. Until these other hazards are delineated and better understood, it seems optimistic to assume that neglecting the benefit of engine reverse thrust provides an equivalent level of safety. Further, prohibiting credit for reverse thrust discourages

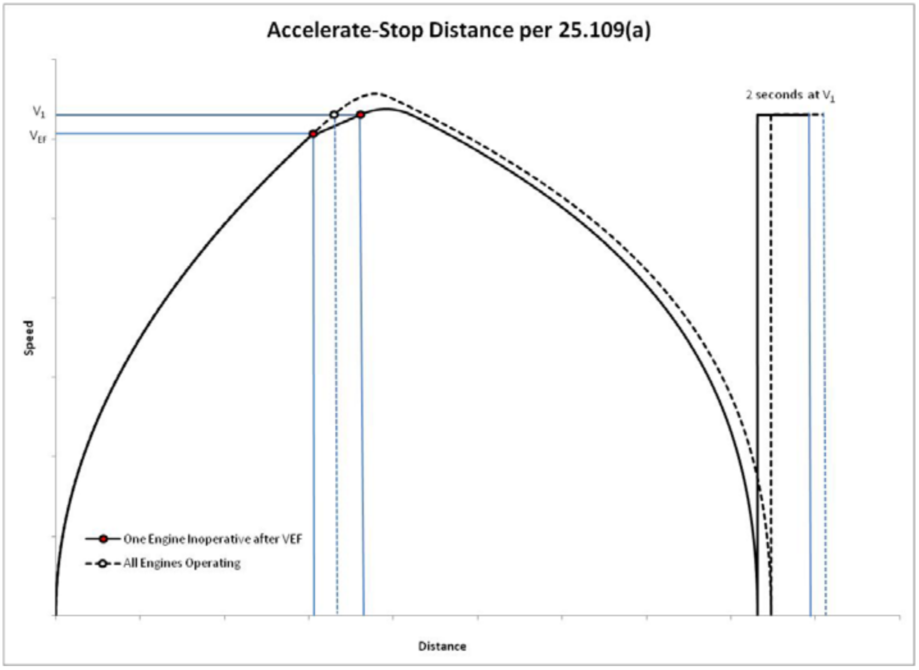

Figure 3. Accelerate-Stop Distance with Low Braking System Effectiveness.

aircraft designers and applicants from incorporating more advanced thrust reverser systems. If the FAA desires a margin of safety for un-quantified hazards, this could be accomplished in other ways that don't discount the benefits of a thrust reversing system. By specifically prohibiting credit for reverse thrust, regulators effectively stifle performance and safety innovations that could be provided in a next-generation thrust reversing systems.

In the "unapproved" section of the flight manual, the FAA allows the manufacturer to take credit for a reliable reverse thrust system on wet runways. Reference 15 suggests that thrust reverser reliability should be such that the probability of failure is no more than 1 failure in 1000 attempts. This approximately aligns with the "minor failure condition severity classification" defined in Aerospace Recommended Practice (ARP) 4761[16]. In effect, one could infer that a thrust reverser system would be considered to be "reliable" if the probability of failures resulting in loss of reverse thrust capability were on the order of 1 in 1000. This level or reliability is readily achieved by modern thrust reverser systems.

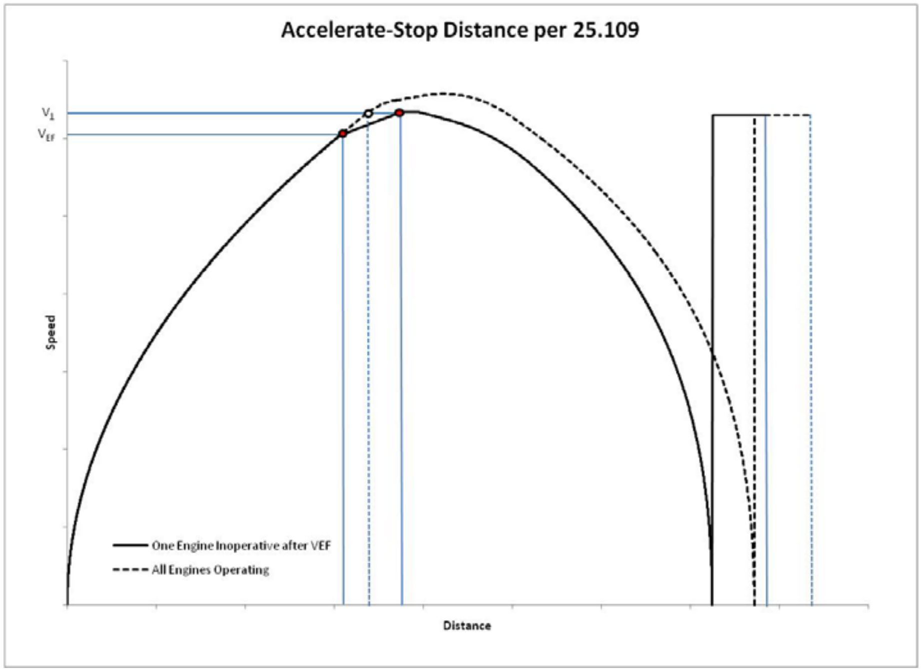

Figure 4. Accelerate-Stop Distance with Large Delays.

Guidance material for demonstrating compliance with 14 CFR § 25.109 is provided in Advisory Circular AC 25-7B.[17] For demonstrating accelerate-stop distance on a wet runway with reverse thrust, AC 25-7B disallows the use of modulated brakes or thrust reversers for directional control. In effect, directional control can only be maintained by use of the rudder. As aircraft speed is reduced, the effectiveness of the rudder is reduced, and thus the ability to maintain directional control is reduced. One can infer that modulating the brakes is not desirable because maximum braking force is needed. However, a similar argument does not apply to reverse thrust. During certain failure scenarios, such as after an engine failure or if a thrust reverse fails to deploy, the available thrust reverse(s) would produce an asymmetric reverse thrust that could cause or contribute to loss of directional control. Although maximum reverse thrust may be desired, it may not be achievable without causing loss of control. In this case, if reverse thrust cannot be modulated, then in effect credit for reverse thrust is not permitted. One can infer that the restriction in AC 25-7B, prohibiting modulated reverse thrust, is based on a perception that modulating reverse thrust would require exceptional pilot skill or alertness. This is an example of overly prescriptive regulation, which stifles innovation that could enhance the safety and efficiency of future aircraft.

D. 14 CFR §25.125 – Landing Distance

14 CFR § 25.125 defines the methods and assumptions that should be used to demonstrate landing distance. The resulting landing distance data is used to validate aircraft design parameters, and to define operational procedures and limitations that will ultimately be reflected in the aircraft flight manual and related documents. As described in this regulation, the total landing distance starts from a point 50-ft above the runway at speed not less than V_{REF}. V_{REF} is a function of aircraft stall speed and minimum controllable air speed in the landing condition, V_{MCL}. In this study, we use published or assumed values for V_{REF}. This regulation also requires that the scheduled landing procedure may not "require exceptional skill or alertness," and that "means other than wheel brakes may be used if that means

is safe and reliable." 14 CFR § 25.125(g) prescribes that if any device that is used depends on the operation of the engines, then landing distance should be determined with that engine inoperative.

For a multi-engine aircraft with multiple thrust reversers, subpart (g) does not clearly state whether credit for reverse thrust is always disallowed for certified landing distance computation. Anecdotally, manufacturers only publish certified landing distances without reverse thrust. We believe that a broader interpretation, consistent with the spirit of 14 CFR § 25.109, is that only one critical engines should be assumed inoperative. The remaining engine(s), and any thrust reversers that depend on them, remain available and could potentially be used to decelerate the aircraft during landing.

Guidance material related to 14 CFR § 25.125 is provided within AC 25-7B. For demonstrating landing distance, AC 25-7B allows that the brakes may be modulated to maintain directional control. However, one can infer that modulating the brakes is not desirable when maximum braking force is needed, such as during an emergency landing condition. Without an express statement regarding modulation of reverse thrust, one can argue that reverse thrust is permitted only if it does not require exceptional pilot skill or alertness. The ability to maintain directional control using aerodynamic surfaces declines as the aircraft speed is reduced because the effectiveness of the rudder is proportional to the square of the indicated airspeed. During certain failure scenarios, such as after an engine failure or if a thrust reverser fails to deploy, excess asymmetric thrust could overpower the rudder and lead to a loss of directional control. In this case, modulation of reverse thrust would be necessary to ensure that directional control can be maintained. Pilot input suggests that modulation of reverse thrust is somewhat routine, and does not generally require exceptional skill or alertness.[18] We believe that an automated system that modulates reverse thrust could reduce pilot workload, shorten certified landing distances and improve safety.

E. 14 CFR §25.933 – Reversing Systems

14 CFR § 25.933 (2015)[13] defines a number of requirements related to thrust reversing systems, their design and installation. The modern regulation has evolved as a result of accidents and tragedies that have occurred throughout aviation history. This inference is supported by the very specific and prescriptive nature of the requirements contained within this section. 14 CFR § 25.933(a)(1) prescribes that thrust reversers intended for ground use only must be designed to produce no more than idle thrust if deployed in flight. This is common practice in the industry today, and is typically achieved via a "throttle snatch" feature which prevents throttle advancement and/or engine acceleration above idle if the reverser is not in the stowed and locked position. However, it's unclear why this functionality would be required if the applicant could demonstrate that the aircraft is capable of continued safe flight at higher power settings.

14 CFR § 25.933(a)(1)(i) requires the applicant to demonstrate that the thrust reverser can be restored to the forward thrust position. It is unclear why this capability would be required if the applicant could demonstrate that the aircraft is capable of continued safe flight with the thrust reverser deployed. Also, if a thrust reverser intended for ground use only had experienced some failure condition that permitted it to deploy in-flight, then it is likely that the very same failure condition would prevent it from being restored to the forward thrust position.

14 CFR § 25.933(a)(1)(ii) requires the applicant to demonstrate that the airplane is capable of continued safe flight and landing after deployment. It's unclear why this capability would be necessary if the applicant could demonstrate that an in-flight deployment was unlikely to ever occur. Conversely, intentional in-flight use of reverse thrust has been certified for operational use. For example, DC-8s, certified under 14 CFR § 4b (1953) permit the use of in-flight reverse thrust at idle settings to facilitate rapid descent.[19]

For thrust reversing systems intended only for ground use, it is often impractical to demonstrate compliance with these provisions. 14 CFR § 25.933 is another example of overly prescriptive regulation that, if complied with directly, would prevent valuable innovations in thrust reverser safety and reliability.

III. Impact of Current Regulations

This section discusses the impacts that the current certification requirements of 14 CFR §25.109, §25.125, and §25.933 have on aircraft design, certification, and operation.

A. 14 CFR §25.109 – Accelerate-Stop Distance

14 CFR § 25.109 specifically disallows credit for reverse thrust when determining accelerate-stop distance on a dry runway. This section also places limitations on the use of reverse thrust when determining accelerate-stop distance on a wet runway.

Figure 5 provides a comparison of accelerate-stop distances for a hypothetical A320-200 sized aircraft simulated for two scenarios where one engine is assumed inoperative (OEI) after V_{EF}, one with credit for reverse thrust and one without. For this simulation, relatively high values for braking effectiveness are used to simulate dry runway conditions. It is assumed that the thrust reverser on the operating engine has an effectiveness of 50%, neglecting for a moment how this asymmetric thrust would affect the controllability of the aircraft. This simulation assumes that a thrust reverser cut-off speed is not observed, thus permitting the use of reverse thrust until a full stop is achieved. This assumption is intended to represent an emergency condition, where stopping the aircraft is the highest priority. From Figure 5 one can infer that the benefit of reverse thrust on a dry runway is relatively small (~4% reduction in accelerate-stop distances).

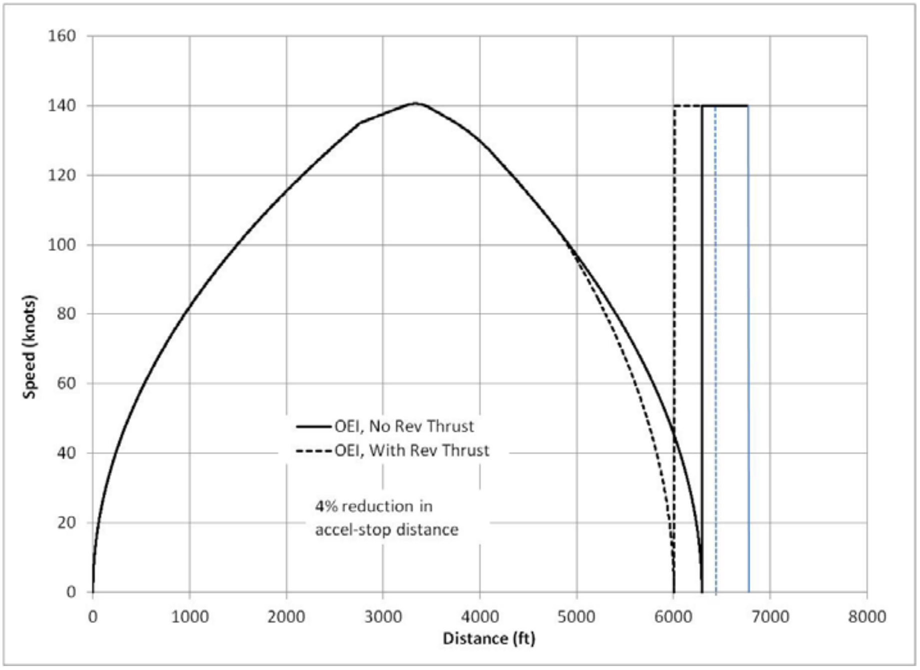

Figure 5. Accelerate-Stop Distance with One Engine Inoperative on Dry Runway.

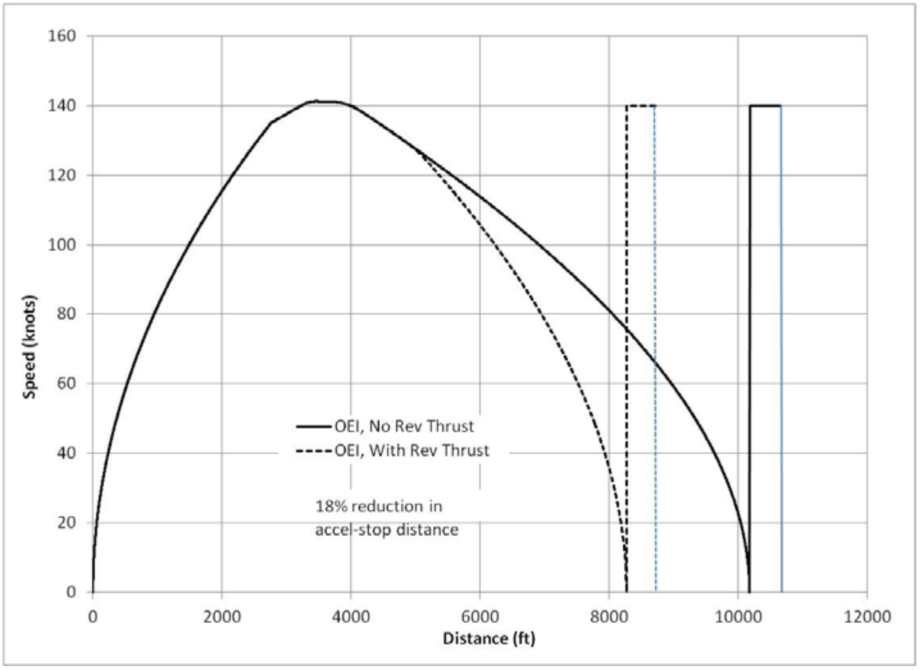

Figure 6. Accelerate-Stop Distance with One Engine Inoperative on Wet Runway.

Figure 6 provides a

similar comparison, but this time using relatively low values for braking effectiveness to simulate wet or contaminated runway conditions. From Figure 6 one can infer that the benefit of reverse thrust on a wet or contaminated runway could be substantial (we see a ~18% reduction in accelerate-stop distance), if a means for ensuring the controllability of the aircraft can be derived.

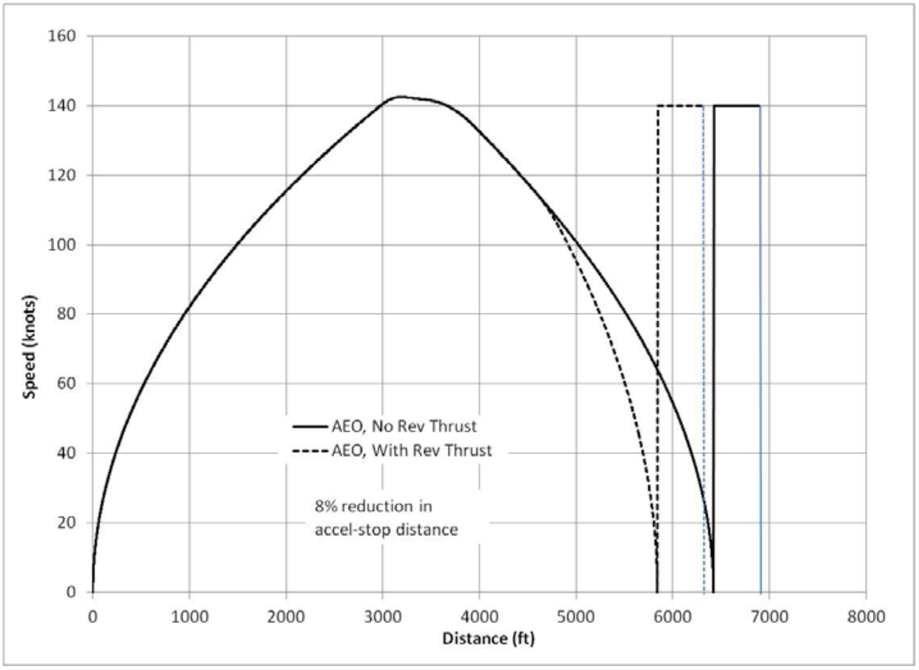

Figure 7. Accelerate-Stop Distance with All Engines Operating on Dry Runway.

Figure 7 provides a comparison of accelerate-stop distance for the same hypothetical aircraft simulated for two rejected take-off scenarios where all engines are operating (AEO), one with credit for reverse thrust and one without. For this simulation, relatively high values for braking effectiveness are used to simulate dry runway conditions. It is assumed that each thrust reverser has an effectiveness of 50%, and since the thrust is symmetric no detrimental effect on aircraft controllability is expected. From Figure 7 one can infer that the benefit of reverse thrust on a dry runway is relatively small, though perhaps still beneficial. Figure 8 provides another comparison, this time with all engines operating on a wet or contaminated runway. From Figure 8 one can infer that the benefit of using both thrust reversers on a wet or contaminated runway is substantial (a ~29% reduction) However, these results provide a “best case” assessment of the benefits of reverse thrust during a rejected takeoff. The actual benefits will likely be somewhat less when cut-off speed and other operational aspects are considered.

14 CFR § 25.109 requires the assumption that a critical engine failure will occur during takeoff, regardless of the probability or impact of such a failure. Therefore, the engine-inoperative accelerate-stop distance is more likely to control the certified take-off distance than the all-engines-operating rejected takeoff scenario.

In 2014, Takahashi &Creighton concluded that a four engine aircraft configuration, taking credit for two engines of reverse thrust, could

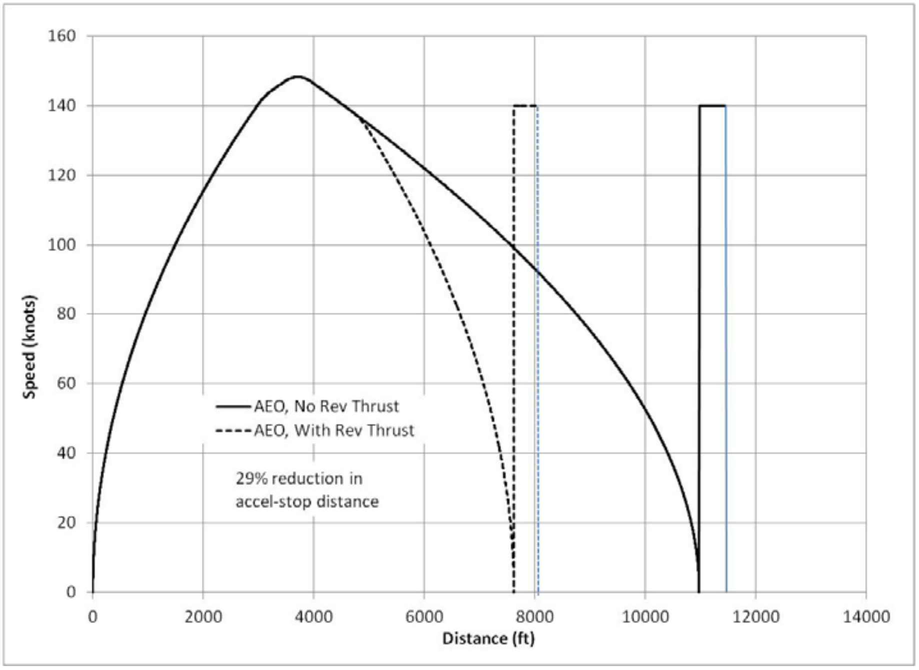

Figure 8. Accelerate-Stop Distance with All Engines Operating on Wet Runway.

demonstrate superior field performance than a similarly sized two engine aircraft.[11] This conclusion is based on the assumption that reverse thrust could only be used if it were produced symmetrically. In other words, if the critical engine failure left the aircraft without two symmetrical engines, both capable of producing reverse thrust, then credit for reverse thrust would not be practical.

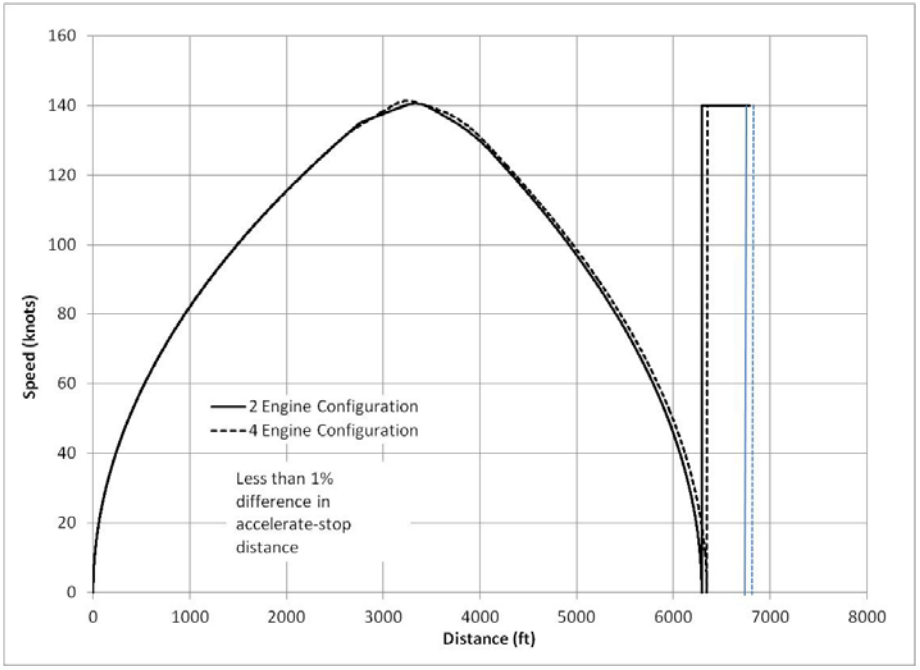

Figure 9. Accelerate-Stop Distance for 2 Engine and 4 Engine Configurations on Dry Runway Without Reverse Thrust.

Figure 9 illustrates the accelerate-stop distance for a hypothetical A320-200 sized aircraft, on a dry runway, equipped in each of two configurations. The first configuration represents a twin engine aircraft, with each engine producing about 26,000 lbf of thrust. The second configuration represents a four engine aircraft, where each engine produces about 13,000 lbf of thrust, to achieve the same total thrust as the twin engine configuration. For the simulation illustrated in Figure 9, reverse thrust is not used to decelerate the aircraft in either configuration. For the 4 engine configuration, the critical engine failure at V_{EF} represents about 25% loss of propulsive thrust, as compared to 50% for the twin engine configuration. Figure 9 suggests that, without any credit for reverse thrust, the accelerate-stop distance for these two configurations is quite similar.

Figure 10 illustrates the accelerate-stop distance for the same two aircraft configurations on a dry runway, with credit for reverse thrust but with a restriction that only symmetric reverse thrust can be used. In effect, this prohibits the use of reverse thrust on the twin engine configuration (only one thrust reverser is available), but allows two engines of reverse thrust on the four engine configuration. Figure 10 suggests that there is a benefit in using symmetric reverse thrust on the four engine configuration, but the benefit is relatively small.

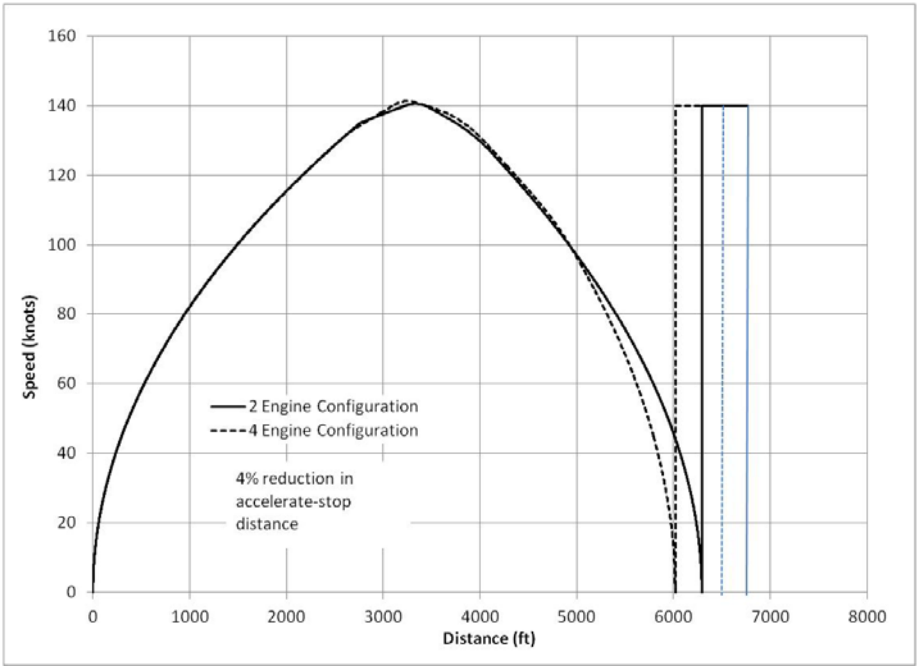

Figure 10. Accelerate-Stop Distance for 2 Engine and 4 Engine Configurations on Dry Runway With Symmetric Reverse Thrust.

Figure 11 illustrates the accelerate-stop distance for the same two aircraft configurations on a wet runway, with credit for reverse thrust but with the same restriction allowing only symmetric reverse thrust. Figure 11 suggests that there is a significant benefit in using symmetric reverse thrust with the 4 engine configuration on a wet runway.

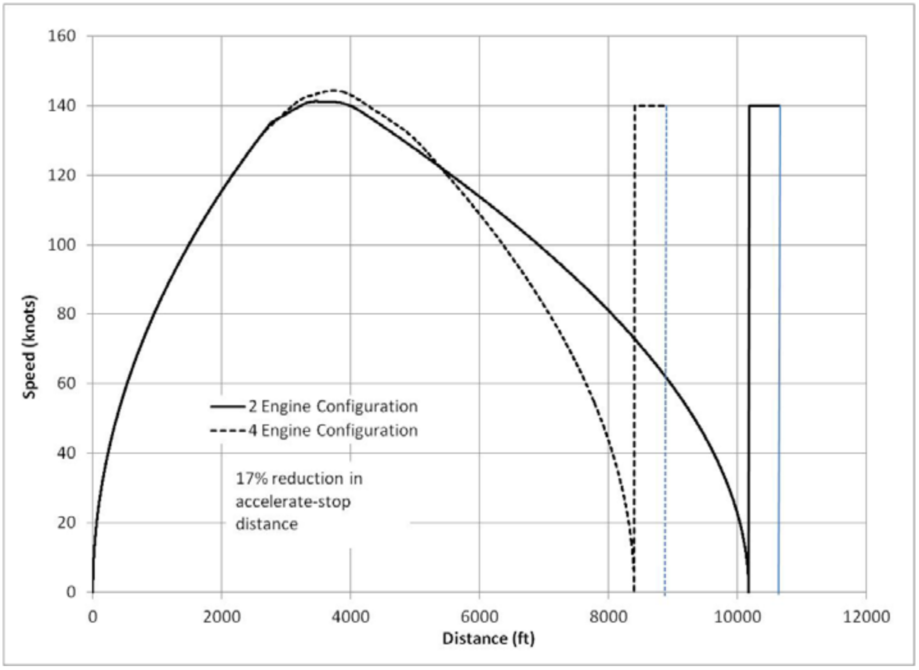

Figure 11. Accelerate-Stop Distance for 2 Engine and 4 Engine Configurations on Wet Runway With Symmetric Reverse Thrust.

Increasing the number of engines has little direct effect on the accelerate-stop distance without credit for reverse thrust. The only difference that arises is the amount of forward thrust that is present for the short duration after critical engine failure and before the pilot pulls the throttles back to idle. However, increasing the number of engines significantly reduces the accelerate-go distance. This is because the critical engine failure results in a much smaller reduction in available thrust, leaving the aircraft with superior accelerate and climb performance after the engine failure. Hypothetically, this should allow a reduction in balanced field length, as rotation can commence at a lower speed. This would also result in a lower V_1 decision speed, resulting indirectly in a reduced accelerate-stop distance.

Increasing the number of engines reduces the relative effect of the critical engine failure. This is a classical approach for increasing the safety of aircraft through redundancy. However, increased redundancy does not always result in a net benefit. There are a number of negative side effects from increased redundancy. For example, redundancy increases the total number of aircraft components, and thereby increases the probability of component failure. Increasing the number of engines on the aircraft will increase the number of potential failures that could result in engine failure during the takeoff run. In fact, if all other aspects of the design remain similar, then increasing the number of engines from two to four effectively doubles the probability of engine failure during takeoff. Redundancy also increases the complexity of the aircraft system design. This can lead to an increased potential for errors such as design errors, pilot errors, or maintenance errors. Even if increasing the number of engines helped to reduce the accelerate-stop distance demonstrated per 14 CFR §25.109, it's not clear that this would improve the overall safety of the aircraft.

It's equally important to recognize that a typical twin engine aircraft could not be easily replaced by or re-designed as a four engine aircraft with similar cost, weight, and performance characteristics. Doing so would require that the engines be designed and produced so as to deliver half the thrust of the original engine, at about half the original weight and half the original cost. In general, industry experience suggests that engine cost, weight, and performance do not scale well with thrust. There are a number of reasons for this, as described in reference 20:

1. Boundary layer effects do not scale down with engine size. Consequently, boundary layer effects become an increasingly important contributor to compressor and turbine inefficiencies in smaller engines.
2. Smaller engines require tighter clearances in order to control leakage as a percentage of total flow. If such clearances become impractical, increased leakage must be tolerated, with impacts on cycle efficiency.

3. Smaller engines require tighter manufacturing tolerances, as the available margin for tolerance stack-up is reduced. Tighter tolerances drive increased manufacturing costs.
4. As combustor size is reduced, the amount of its surface area that needs to be cooled increases relative to the engine airflow. This increases the demand for cooling airflow, reducing cycle efficiency.
5. Good fuel atomization requires a relatively large number of fuel nozzles. As engine size is reduced, fuel flow through each nozzle is reduced. This requires smaller fuel nozzles, which are increasingly prone to plugging. Often, the designer must make compromises between nozzle size and quantity with effects on combustor performance.
6. Large engines employ relatively complex turbine cooling schemes that are often impractical to employ on smaller engines due to the reduced component sizes and manufacturing limitations. Consequently, smaller engines are often limited to lower combustor exit temperatures, reducing thermal efficiency.
7. Many engine components function as pressure vessels. The operating pressures of small engines are similar to large engines, so similar wall thicknesses are required. These wall thicknesses become increasingly significant on smaller engines, disproportionately driving weight and creating space constraints.
8. In general, smaller engines must run at higher rotational speeds than larger engines in order to achieve adequate performance. Increased rotational speeds induce higher loads, which in turn drives the selection of heavier materials or thicker cross sections, with corresponding effects on cost and weight.

In summary, the provisions of 14 CFR § 25.109 require the applicant to assume a critical engine failure, regardless of the probability or impacts of such a failure. This creates a preference for aircraft with a larger number of engines. It also stifles innovations that would otherwise reduce the probability or impact of such a failure, because no credit is allowed for such innovations.

B. 14 CFR §25.125 – Landing Distance

Section 25.125 contains provisions that, depending on interpretation, would either limit or prohibit the use of reverse thrust when determining landing distance. Ambiguity in the certification requirements often force aircraft designers to make conservative assumptions in order to minimize program risk. Consequently, the provisions of §25.125 will discourage the use thrust reversal in determining landing distance. The following paragraphs are intended to illustrate the impacts of §25.125, by demonstrating the potential impacts of thrust reversal on landing distance.

Figure 12 provides a comparison of landing distances for a hypothetical A320-200 sized aircraft simulated for two scenarios where one engine is assumed inoperative, one with credit for reverse thrust and one without. For this simulation, relatively high values for braking effectiveness are used to simulate dry runway conditions. It is assumed that the thrust reverser on the operating engine has an effectiveness of 50%, neglecting for a moment how this asymmetric thrust would affect the controllability of the aircraft. This simulation

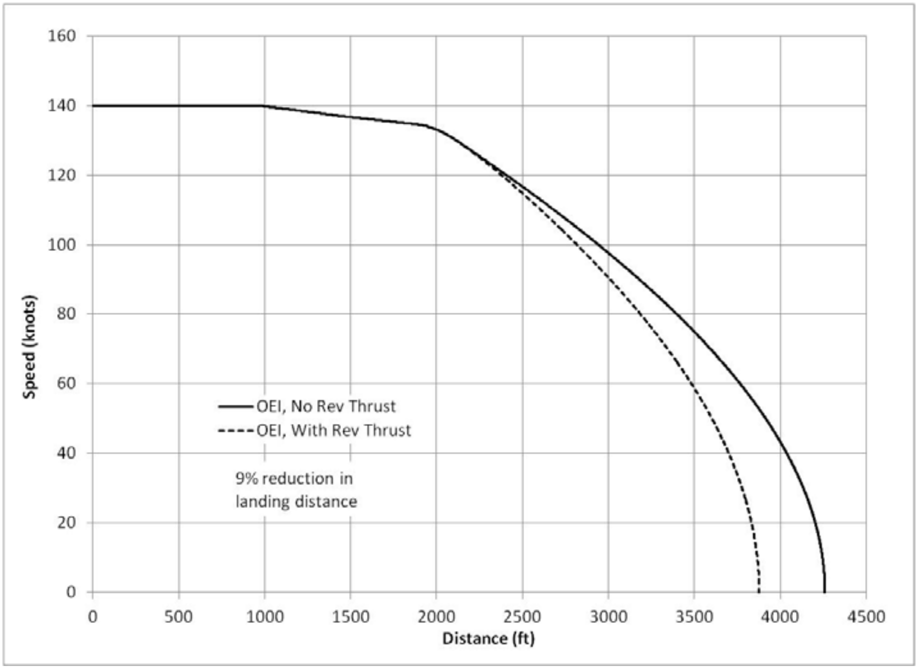

Figure 12. Landing Distance with One Engine Inoperative on Dry Runway.

assumes that a thrust reverser cut-off speed is not observed, thus permitting the use of reverse thrust until a full stop is achieved. This assumption is intended to represent an emergency condition, where stopping the aircraft is the highest priority. From Figure 12 one can infer that the benefit of reverse thrust on a dry runway is relatively small (~9%).

Figure 13 provides a similar comparison, but this time using relatively low values for braking effectiveness to simulate wet or contaminated runway conditions. From Figure 13 one can infer that the benefit of reverse thrust on a wet or contaminated runway could be substantial, if a means for ensuring the controllability of the aircraft can be derived. In the particular simulation shown here, reverse thrust enables a 23% reduction in landing distance.

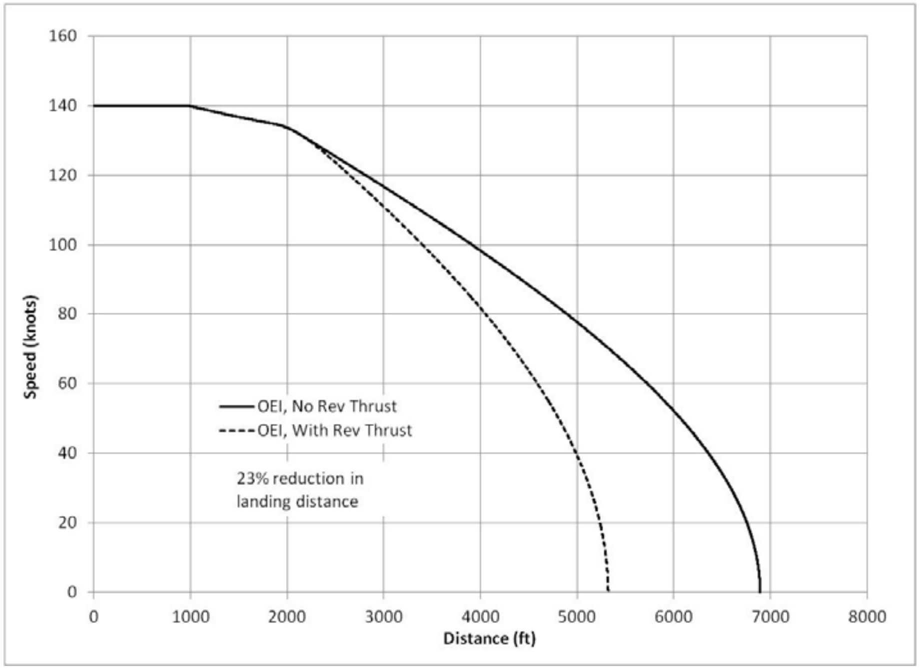

Figure 13. Landing Distance with One Engine Inoperative on Wet Runway.

Figure 14 provides a comparison of landing distance for the same hypothetical aircraft simulated for two scenarios where all engines are operating, one with credit for reverse thrust and one without. For this simulation, relatively high values for braking effectiveness are used to simulate dry runway conditions. It is assumed that each thrust reverser has an effectiveness of 50%, and since the thrust is symmetric no detrimental effect on aircraft controllability is expected. From Figure 14 one can infer that the effect of reverse thrust on a dry runway is relatively small, though perhaps still beneficial. Figure 15 provides another comparison with all engines operating, this time on a wet or contaminated runway. From Figure 15 one can infer that the benefit of using both thrust reversers on a wet or contaminated runway is substantial (~35% reduction). However, these results provide a "best case" assessment of the benefits of reverse thrust during landing. The actual

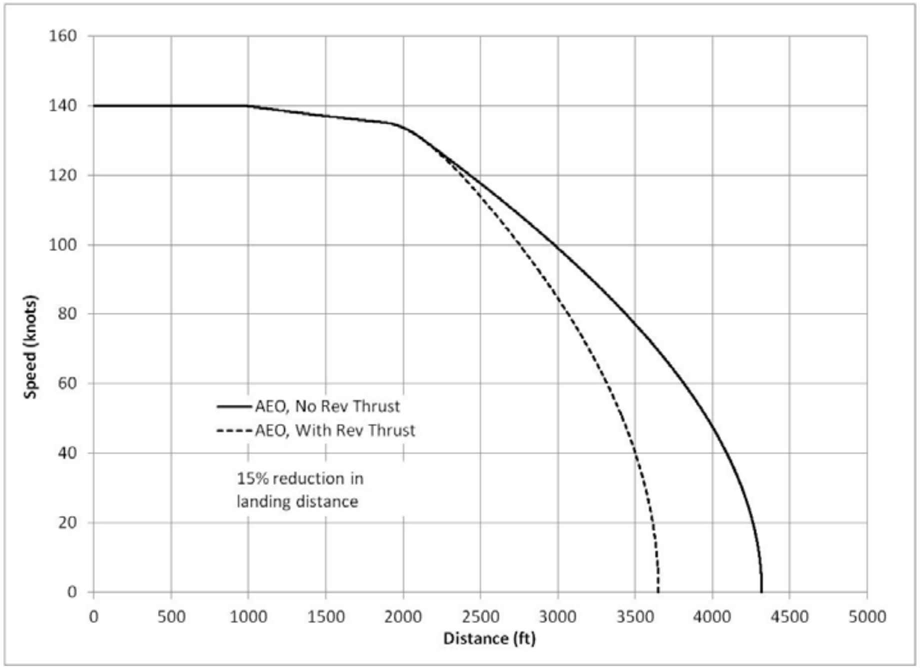

Figure 14. Landing Distance with All Engines Operating on Dry Runway.

benefits will likely be somewhat less when cut-off speed and directional control aspects are considered.

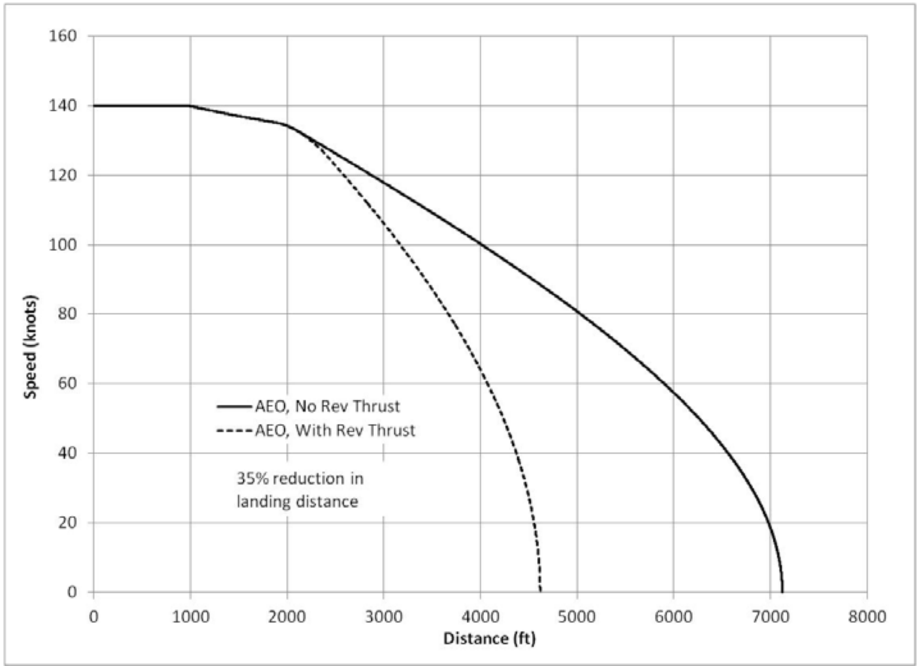

Figure 15. Landing Distance with All Engines Operating on Wet Runway.

In summary, the requirements of 14 §25.125 serve to discourage (at best) or prohibit (at worst) the use of thrust reversal when determining landing distance. As the previous paragraphs illustrate, the use of thrust reversers can be beneficial in reducing landing distance, particularly on wet or contaminated runways. When one considers the number of runway excursion events that have occurred throughout aviation history, and that continue to occur despite the current requirements, it is clear that the current regulations are not having the desired effect.

C. 14 CFR §25.933 – Reversing Systems

As previously discussed, 14 CFR §25.933 contains a number of certification requirements that often make it impractical to demonstrate direct compliance. These impractical requirements effectively discourage the use of thrust reversal, despite the obvious benefits. These requirements also force aircraft integrators to make design decisions and compromises that potentially reduce the effectiveness of the thrust reversing system, without a clear safety benefit.

Consider first the requirement of 14 CFR §25.933(a)(1), which specifies that a thrust reverser system intended only for ground use must be designed so that, following an in-flight deployment, the engine will produce no more than idle thrust. This is a logical requirement if one assumes that any engine power setting greater than idle will inevitably result in loss of aircraft controllability. However, the requirement discourages an applicant from pursuing innovations that would enable aircraft control after an inadvertent deployment. Such an innovation would be of significant benefit, not only by enhancing the safety of the aircraft in flight, but also by enabling enhancements in the reliability and effectiveness of the thrust reverser system. Furthermore, the requirements of 14 CFR §25.933(a)(1) have an undesirable side effect. If the aircraft system is designed so that the engine is forced to idle when the thrust reverser malfunctions, then a minor failure in the thrust reverse position indication system could cause a significant loss of power from the affected engine, even if the thrust reverser is safely stowed and locked. In effect, this overly prescriptive requirement attempts to mitigate a perceived hazard, but in the process increases the potential for another significant hazard.

Consider next the requirement of 14 CFR §25.933(a)(1)(i), which specifies that the applicant must demonstrate the ability to re-stow the thrust reverser after an in-flight deployment. Notionally, this would be a desirable capability if it were practical and introduced no additional hazard. However, industry experience suggests that it is both impractical and, in some cases, undesirable to have this capability.

For thrust reversing systems intended only for ground use, the actuation system is often sized so that it is only capable of deploying or stowing the thrust reverser with the engine or the aircraft at low speed. This is a deliberate design feature that reduces system weight, and provides protection against unintended deployment. Thrust reversers are often designed so that, at high engine or air speeds, the aerodynamic forces tend to keep the thrust reverser stowed even if the actuation system inadvertently attempted to deploy. This is sometimes achieved by incorporating so called "over-stow" functionality, wherein the thrust reverser must move past the normally stowed position to the over-stow position before the locks can be released. Often, actuation systems are sized so that they are unable to achieve the over-stow position except at low engine or air speeds. This increases aircraft safety by providing an additional line of defense against inadvertent deployment. The forces that the actuation system must overcome to re-stow a thrust reverser after inadvertent deployment are typically much greater than the forces required for over-stow. Clearly, if this design philosophy is embodied, the actuation system would be incapable of restoring the thrust reverser to the forward thrust position at some flight conditions. Regardless, an actuation system that is capable of deploying and stowing the thrust reverser at high engine or air speed would have to be sized for significantly higher loads than an actuation system designed for ground use only. This would have significant cost and weight impacts.

Finally, consider the requirement of 14 CFR §25.933(a)(1)(ii), which specifies that the aircraft must be capable of continued safe flight and landing under any possible position of the thrust reverser. Direct compliance with this provision would likely force the aircraft designer to reduce the effectiveness of the thrust reverser system, so as to ensure that the effect of an in-flight deployment is manageable. Alternatively, direct compliance would require that the thrust reverser and aircraft have such performance and strength margin as to render them impractical.

The aerodynamic loads exerted on the structure of a deployed thrust reverser are often significantly higher in flight than they are during ground use. For example, many thrust reversers incorporate so called "pivot doors" or "blocker doors" to deflect engine airflow and redirect it to produce reverse thrust. The aerodynamic loads exerted on these blocker doors increase with engine speed and with aircraft speed. So, direct compliance with these requirements would necessitate the use of heavier and more costly structural components associated with the thrust reverser. Also, the forces generated by the thrust reverser are typically transmitted through the engine structure and/or the pylon structure back to the airframe. So the engine, pylon, and airframe structures must all be enhanced to accommodate an in-flight deployment, even if the thrust reverser is only intended for ground use.

Due to the difficultly in producing a light weight, cost effective thrust reverser system that complies with the requirements of 14 CFR § 25.933, it is common for applicants to utilize an equivalent level of safety (ELOS) approach. Typically, the ELOS approach is to demonstrate that inadvertent deployment is extremely improbable using reliability analysis. A methodology for demonstrating ELOS using reliability methods was presented by the Powerplant Installation Harmonization Working Group (PPIHWG) in draft AC 25.933X[8] associated with a Notice of Proposed Rule Making (NPRM) dated 16 December 1999.[21] The draft AC 25.933X lays out an ELOS approach consisting of a system safety assessment prepared in a manner similar to that used to demonstrate compliance with §25.1309. The safety assessment must demonstrate that the probability of catastrophic in-flight thrust reversal is extremely improbable, and cannot result from any single failure or malfunction. Historically, the FAA approved ELOS approaches similar to that described in draft AC 25.933X. In some cases, the FAA has required the applicant to satisfy additional provisions such as:

- In addition to a traditional failure modes and effects analysis (FMEA, or so called "bottom up analysis"), the applicant must also perform a rigorous top down analysis to ensure that any and all obscure single failure modes are identified.[22]
- The applicant must perform a specific risk analysis to demonstrate that the aircraft will continue to meet the "no single failure" criteria at the beginning of each and every flight, wherein any and all failure modes that could exist and remain undetected for more than one flight cycle are assumed to be present. [22]
- The applicant must verify that any influences which could render the safety assessment invalid have been identified. The applicant must define and implement an acceptable means for managing these influences throughout the life of the fleet. [22]
- The applicant must implement an acceptable means to monitor and report in-service experience and respond effectively to any conditions which would invalidate the safety assessment. [22]

In summary, the requirements of 14 CFR §25.933 are onerous enough to discourage the use of reverse thrust in "certified" landing distance computations. For this reason, we believe there is significant opportunity to improve the safety, performance, and efficiency of future aircraft by incorporating thrust reversing systems that maximize both the safety and the performance of the aircraft. However, this is likely only practical if the FAA adopts some minor changes to present certification requirements.

IV. Proposed Changes to the Regulations

The regulatory environment created by 14 CFR §25.109, §25.125, and §25.933 discourages the use of thrust reversal as a supplemental means of deceleration for "certified distances." These regulations strictly prohibit credit for reverse thrust in some circumstances, and severely limit credit for thrust reversal in others. These field performance requirements do not appear to actually prevent accidental in-flight deployment or runway excursions. Consequently, we propose changes to these sections so as to permit innovations that could serve to enhance both the safety and the performance of future aircraft.

A. 14 CFR §25.109 – Accelerate-Stop Distance

14 CFR s§25.109 requires the applicant to determine the accelerate-stop distance in a manner that considers all possible failures, delays in pilot and aircraft system response, as well as adverse runway conditions. Because an accidental runway excursion can lead to injury or loss of life, regulations are needed to ensure that all reasonable precautions have been taken. 14 CFR §25.109 emphasizes one particular failure condition: critical engine failure. Engine failure can represent a significant hazard to the safety and performance of the aircraft. Engine failure can result in a significant loss of propulsive thrust, affecting the aircraft's acceleration and climb performance. Despite advances in engine technology, engine failure can result from a number of failures such as rotor burst, bearing seizure, loss of lubrication, loss of fuel supply, etc. Consequently, it is reasonable to expect an applicant to have considered this failure condition in determining accelerate-stop distance.

For field performance computations, a "critical engine failure" is a condition that leads to both a loss of thrust and the aircraft developing an "out of trim" condition in either pitch and or yaw. AC 25-7B refers to "idle cuts" and "fuel cuts" as means for simulating critical engine failure. This would seem to imply that critical engine failure could be simulated by pulling the throttle of the affected engine to idle, or by depriving the affected engine of fuel.

Although critical engine failure is certainly a failure scenario that should be considered in determining accelerate-stop distance, it is perhaps not the only failure that should be considered. A rejected take-off scenario may be prompted by an out-of-trim tailplane, wheel, tire, or landing gear failures as well as inadvertent deployment of the thrust reverser, spoilers, or speed brakes.

Another key aspect of 14 CFR §25.109 is the relationship between the decision speed V_1 and the engine failure speed V_{EF}. As previously discussed, the selection of V_1 speed will be based, at least in part, on critical field length considerations. This is necessary to ensure that, in the event of a significant failure such as engine failure, the pilot is aware of the most appropriate course of action to ensure the safety of the aircraft. For failures occurring beneath V_1, the appropriate action is to reject the takeoff. For failures occurring above V_1, the pilot must proceed with the takeoff because adequate stopping distance may not be available. The assumption that the critical engine failure occurs immediately before achieving V_1 speed represents a worst case assumption. This is an aspect of the current regulation that should certainly be retained.

Because a runway excursion may result in serious injury or loss of life, the designers should demonstrate that these hazards are extremely improbable. 14 CFR §25.1309 and related guidance material already provides a suitable framework for assessing such hazards. JAR 25.1309[23] contains similar requirements, but also contains a unique provision which requires that catastrophic failure conditions should not result from any single failure or malfunction, regardless of probability.

Consistent with the foregoing, the authors propose that the requirements of 14 CFR §25.109 should be amended to be more general and less prescriptive; changes to several aspects would be beneficial. First, we think that the phrase "critical engine failure" should be replaced with "critical failure," any functional hazard resulting in significant loss or reduction in aircraft performance that would necessitate a rejected takeoff. Incidentally, the definition of V_{EF} in 14 CFR §25.107 would also require a similar amendment. Compliance with §25.109 could be demonstrated by performing a quantitative safety assessment to show that the probability of catastrophic runway excursion is "extremely improbable" as defined in ARP 4761.[16] This includes a broader failure modes and effects analysis (FMEA) and fault tree analysis (FTA) to identify any and all failure conditions, or combinations of failure conditions, that could significantly increase critical field length or prevent safe flight. These analysis methods are well defined in advisory circular AC 25.1309-1A[24]. Single failure conditions that result directly in increased accelerate-stop distance should be considered, regardless of probability. Combinations of failures should also be considered, unless it is demonstrated that the combination of such failures is extremely improbable ($P < 1E-9$). The most critical failure condition or combination should be identified, and the accelerate-stop distance should be determined by assuming that this most critical failure condition occurs at V_{EF}.

According to these proposed changes, engine failure must be considered in determining accelerate-stop distance unless it can be shown that engine failure is extremely improbable ($P < 1E-9$) and does not result from any single failure or malfunction (multiple failures required). Given the state of current engine technology, it is likely that engine failure will continue to be a critical failure. However, these proposed changes open a certification pathway for aircraft with innovative propulsion systems (such as distributed propulsion).

The second proposed change to 14 CFR §25.109 is to amend subpart (f) so as to permit credit for reverse thrust on wet or dry runways, subject to the restrictions in subpart (e). As previously discussed, subpart (f) currently prohibits credit because the FAA desires that the regulation reflect some margin of safety to protect against hazards not accounted for in the accelerate-stop distance determination. This could be achieved in a variety of ways that do not discount the benefits of thrust reversal. For example, the assumed duration at V_1 speed could be increased from two seconds to perhaps three seconds or more. Alternatively, the dry runway accelerate-stop distance could be factored to account for variations in runway friction. Hypothetically, the applicant could determine the effective coefficient of friction of the runway used, and calculate a correction factor dividing by a reference value or minimum expected value of friction. A variety of methods could be devised for ensuring that the dry runway accelerate-stop distance is conservative, without creating a regulatory environment that effectively discriminates against the use of thrust reversal.

If an amendment to subpart (f) were achieved as described above, then finding a means for ensuring compliance with subpart (e) would be essential to enable credit for reverse thrust. Subpart (e) effectively requires that thrust reversal be safe and reliable, provides consistent results, and does not require exceptional pilot skill. As previously discussed, reference 15 suggests that thrust reversal would be considered reliable if the probability of thrust reverser failure is no more than 1 failures in 1000 deployment attempts. This approximately aligns with the "minor failure condition severity classification" defined in ARP4761[16]. It is proposed that an applicant could demonstrate compliance with this aspect by performing a safety assessment, including FMEA and FTA, to demonstrate that the probability of a thrust reverser failing to deploy when commanded is less than 1E-3. Based on industry experience, the authors believe that achieving such thrust reverser reliability would not pose a significant cost or weight burden on aircraft designers and integrators. In fact, it is likely that many thrust reverser systems in-service today could satisfy this criteria without modification. Regardless, any decision by the applicant to take credit for reverse thrust would have to be the result of a trade study assessing the costs and benefits of doing so.

In order to address the "consistent results" provision of the requirement, first consider that the decelerating effects of thrust reversal are fundamentally consistent. The effects of reverse thrust, more so than other systems such as wheel brakes, are governed by laws of physics that are easily predictable, and subject to little variation. The only factors that would likely prevent consistent results are: failure of the thrust reverser to deploy, which has already been addressed, and failure of the engine to achieve the commanded thrust setting. The latter corresponds directly with the "loss of thrust control" criteria that an applicant will likely satisfy in order to demonstrate compliance with 14 CFR §33.28[25] according to AC33.28-1[26]. Typically, propulsion houses demonstrate compliance with 14 CFR §33.28 by a quantitative safety assessment intended to predict the probability of engine failures that would prevent the pilot from achieving the desired level of engine thrust. This could be extended to include both the forward and reverse thrust modes of operation, if both are not already addressed. In effect, demonstrating compliance with the "consistent results" aspect of 14 CFR § 25.109 will likely impose little or no extra burden on the applicant.

Finally, in order to take credit for thrust reversal, an applicant must also demonstrate that the use of thrust reversal does not require exceptional pilot skill. Fundamentally, compliance with this aspect would require that the aircraft flight manual or related publications provide a thrust reversal **procedure** that requires no exceptional skill. It should not foreclose clever automation strategies that promote pilot safety. Any asymmetric reverse thrust would have to be limited so as not to exceed the directional control capability of the aircraft. As described in AC 25-7B, the use of modulated braking effort or nose wheel steering as means of maintaining directional control is not desirable. Consequently, any asymmetric reverse thrust would have to be limited so as not to exceed the yaw capability of the rudder, while considering any other destabilizing influences such as wind.

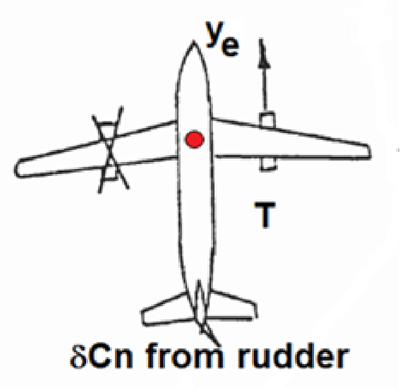

Figure 16. Force Balance for Simplified Minimum Controllable Speed Computation. *Force balance necessary to achieve directional stability during an asymmetric thrust condition. The rudder must induce a moment of magnitude greater than that induced by the asymmetric reverse thrust.*

The yaw capability of the rudder is primarily a function of aircraft speed. Consequently, a simplified quasi-static moment balance approach can be used to estimate the minimum aircraft speed necessary for directional control during asymmetric reverse thrust. As shown in Figure 16, the sum of the moments developed by the thrust of the remaining engines must be opposed by the yawing moment developed by the rudder. Accordingly, the net moment on the aircraft can be expressed as:

$$\boldsymbol{Cn = 0 \approx \frac{dCn}{drud} \cdot \delta rud - \frac{T \cdot y_e}{q \cdot Sref \cdot b}} \tag{1}$$

Where *dCn/drud* is a measure of the rudder effectiveness (the yawing moment coefficient per degree of rudder deflection); δrud is the maximum rudder deflection in degrees, *T* is the asymmetric thrust in pounds, y_e is the butt-line distance from the aircraft centerline to the operating asymmetric engine in feet, *q* is the dynamic pressure in pounds per square foot, *Sref* is the reference area of the wing in square feet, and *b* is the reference span of the wing in feet. Using the relationship between indicated airspeed and dynamic pressure, one can solve Eq. 1 in terms of indicated airspeed giving the following result:

$$\boldsymbol{V_{MCG} \approx \sqrt{\frac{T \cdot y_e}{1481 \cdot Sref \cdot b \cdot (\frac{dCn}{drud}) \cdot \delta rud}} \cdot 660.8} \tag{2}$$

Where V_{MCG} is the minimum speed, in knots, necessary to maintain directional control over the asymmetric engine thrust. Further, Eq. 2 can be rearranged to express the maximum permissible asymmetric thrust as a function of aircraft speed:

$$\boldsymbol{T \approx \left(\frac{V_{MCG}}{660.8}\right)^2 \cdot \left(\frac{1481 \cdot Sref \cdot b \cdot (\frac{dCn}{drud}) \cdot \delta rud}{y_e}\right)} \tag{3}$$

Note that a margin of safety can be applied to V_{MCG} so as to ensure that thrust *T* remains safely below the controllable limit, even with destabilizing influences such as wind present. Also note that thrust *T* as defined in Eq. 3 represents the asymmetric portion of reverse thrust. For aircraft with more than two engines, there could also be a symmetric component of reverse thrust not included in *T*.

The aircraft system dynamic model includes necessary computations to determine and simulate this maximum permissible asymmetric thrust. For the purpose of this study, a margin of 5 knots has been applied to V_{MCG}, so that the calculated maximum allowable asymmetric thrust *T* corresponds to an aircraft speed 5 knots slower than aircraft speed.

Figure 17 provides an illustration of accelerate-stop distance for a hypothetical A320-200 sized aircraft simulated for a scenario where the critical engine is assumed inoperative (CEI) after V_{EF}. For this simulation,

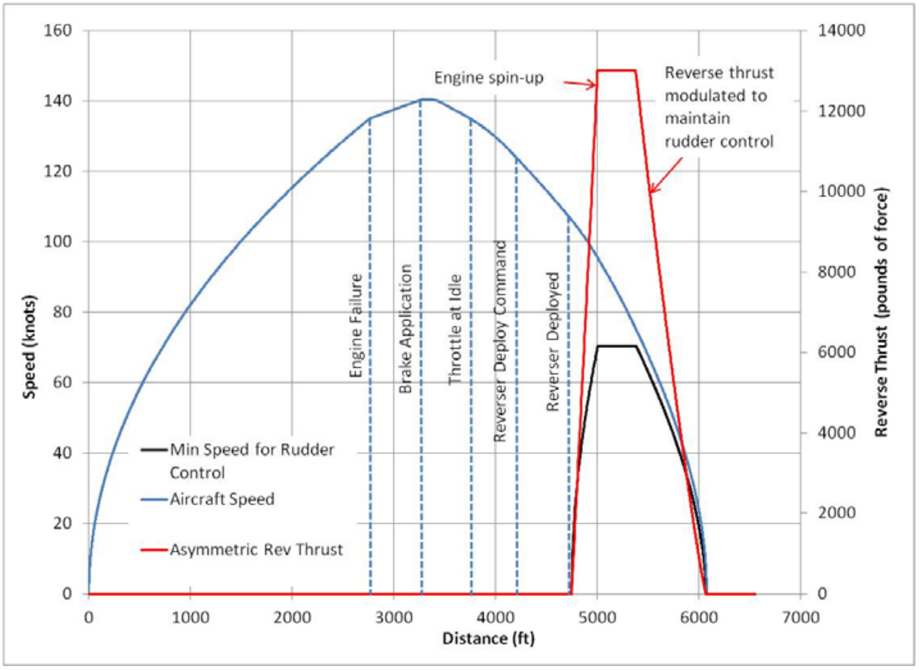

Figure 17. CEI Accelerate-Stop Distance with Asymmetric Reverse Thrust on Dry Runway.

relatively high values for braking effectiveness are used to simulate dry runway conditions. It is assumed that the thrust reverser on the operating engine has a maximum effectiveness of 50%, but reverse thrust is varied during deceleration so as to maintain directional control using the rudder. This simulation assumes that a thrust reverser cut-off speed is not observed, thus permitting the use of reverse thrust until a full stop is achieved. This assumption is intended to represent an emergency condition, where stopping the aircraft is the highest priority. Figure 17 illustrates that during a rejected takeoff on a dry runway, maximum reverse thrust can only be achieved for a short duration, limiting the benefit of thrust reversal. Figure 18 provides a comparison of accelerate-stop for the same scenario, with and without the use of reverse thrust. Figure 18 suggests that the benefit of asymmetric reverse thrust on a dry runway is relatively small. However, if the regulations permitted credit for asymmetric reverse thrust during rejected takeoff, there are a variety of aircraft design changes and innovations that might increase the benefit. For example, mounting the engines closer to the aircraft centerline would decrease the moment arm of the asymmetric thrust, thus reducing the net moment on the aircraft. This would allow higher levels of reverse thrust during deceleration. Regional and business jet aircraft often have engines mounted to the empennage rather than the wing, and may get more benefit from credit for asymmetric reverse thrust.

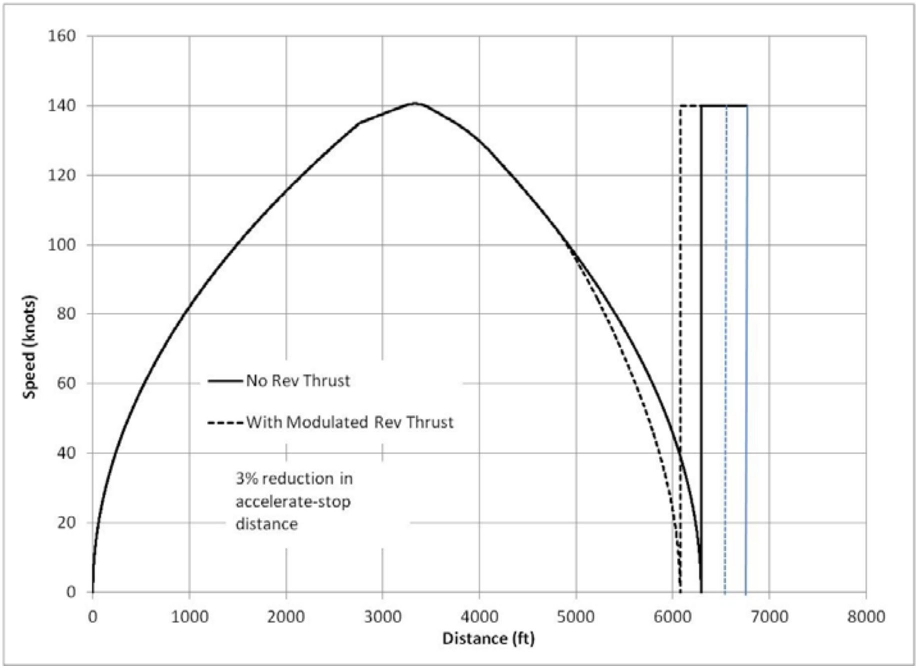

Figure 18. CEI Accelerate-Stop Distance with Asymmetric Reverse Thrust on Dry Runway.

Figure 19 provides an illustration of accelerate-stop distance for the same hypothetical aircraft using similar assumptions as above, except this time using relatively low values for braking effectiveness to simulate wet runway conditions. Figure 19 illustrates that during a rejected takeoff on a wet or contaminated runway, maximum reverse thrust can be sustained for a relatively long duration, increasing the benefit of thrust reversal. Figure 20 provides a comparison of accelerate-stop for the same aircraft and assumptions, for scenarios with and without the use of reverse thrust. Figure 20 suggests that the benefit of asymmetric reverse thrust on a wet runway is significant, even when the reverse thrust is modulated to maintain rudder control.

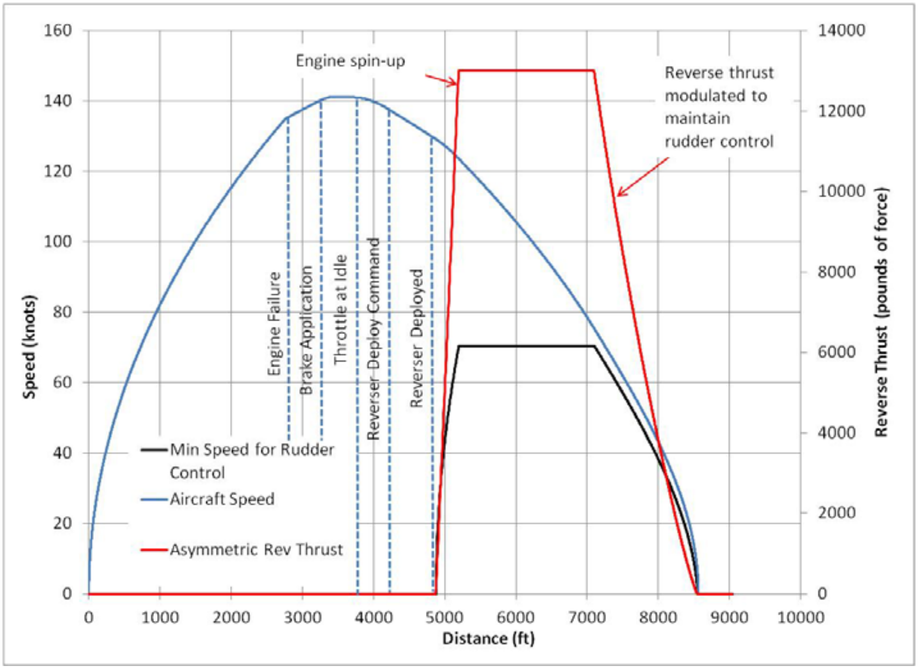

Figure 19. CEI Accelerate-Stop Distance with Asymmetric Reverse Thrust on Wet Runway.

The use of asymmetric reverse thrust requires that the thrust be modulated so as not to exceed the capability of the rudder. AC 25-7B prescribes that the thrust reversers may not be modulated in order to maintain directional control. It's unclear if this provision is intended to prohibit modulating engine speed during reverse thrust operation, or just to prohibit varying the thrust reverser position so as to modulate reverse thrust. Clearly, it is not desirable that the pilot be distracted by directly modulating reverse thrust. Nonetheless, pilot interviews reveal that this is a common practice.[18]

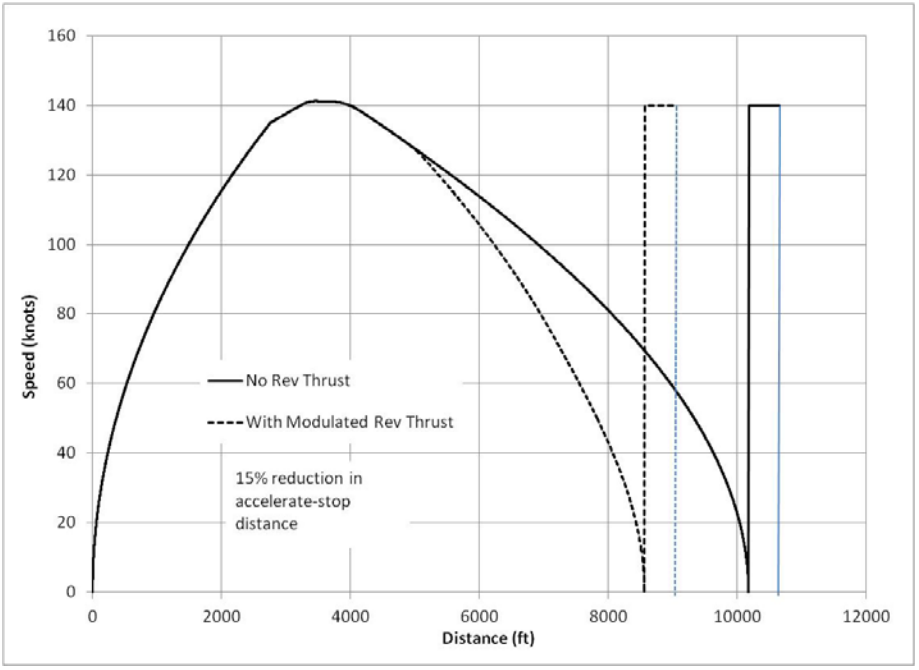

Figure 20. CEI Accelerate-Stop Distance with Asymmetric Reverse Thrust on Wet Runway.

A full-authority-digital-electronic-control (FADEC) can be employed to modulate engine speed during reverse thrust operations. As the aircraft decelerates, the rudder force available to counter asymmetric reverse thrust is diminished. Therefore, the reverse thrust power setting must follow the available rudder power to ensure positive control. This speed-scheduled automation is common place in modern FADEC systems. In fact, many such systems already modulate engine speed during reverse thrust in order to prevent exhaust gas re-ingestion and foreign object damage (FOD). Similarly, these systems commonly adjust the engine power setting in response to detected failures. Some examples include so called "automatic power reserve" or "automatic take-off thrust control systems" which automatically adjust engine power setting in response to certain detected failure conditions.

Modern FADEC systems make such automation predictable and reliable, enhancing both the safety and efficiency of the aircraft. Conceptually, modulation of reverse thrust could be automated so that, after detection of certain failures, reverse thrust is limited to a maximum value that allows directional control to be maintained. As the aircraft decelerates, the effectiveness of the rudder decreases and thus the available reverse thrust would also decrease automatically. Such a system, if easily certified, will enhance performance and safety.

B. 14 CFR §25.125 – Landing Distance

It is clear that the intent of 14 CFR §25.125 is to ensure that the scheduled landing distance is determined with enough inherent pessimism as to prevent runway over-runs on aircraft flown by mediocre people lacking "exceptional pilot skill or alertness."[10] Subsection (g) of this regulation requires that the effects of engine failure must be considered if a deceleration means relies on the engine. While dead-stick landings have and will occur, scheduled landing distances found in aircraft flight manuals presume only the failure of a single engine during touchdown and roll out. Because engineers design aircraft to prevent or minimize common mode failures, a multiple engine failure during landing is the end product of a series of multiple failures or malfunctions. If the probability of multiple engine failures is sufficiently remote, we should be allowed to schedule landing distances to allow for reverse thrust provided that we consider the sudden malfunction of a single engine.

We propose that the 14 CFR §25.125 be amended to allow for a broader basis of compliance that includes a more general functional hazard assessment to identify all sources that significantly increase landing distances. Compliance should be based on a FMEA that identifies any and all component failures, single or in combination, which result in this functional hazard. It should include a fault tree analysis to demonstrate that the probability of runway over-run is sufficiently remote; engineers should concern themselves with a potential problem only when the probability of failure of a single system or combination of systems exceeds P >1E-9. The most critical of these failures should be assumed present when determining the "certified landing distance" in accordance with §25.125.

Based on this approach, if an applicant wishes to take credit for thrust reversal when determining landing distance, he must consider the effects of unexpected engine failure. To attain certification, the applicant must demonstrate that the use of asymmetric reverse thrust during landing does not require exceptional pilot skill or alertness. The guidance material in AC 25-7B suggests that brake modulation may be permissible as a means of directional control during landing demonstration. However, for the purpose of this study the authors have assumed that brake system modulation is not

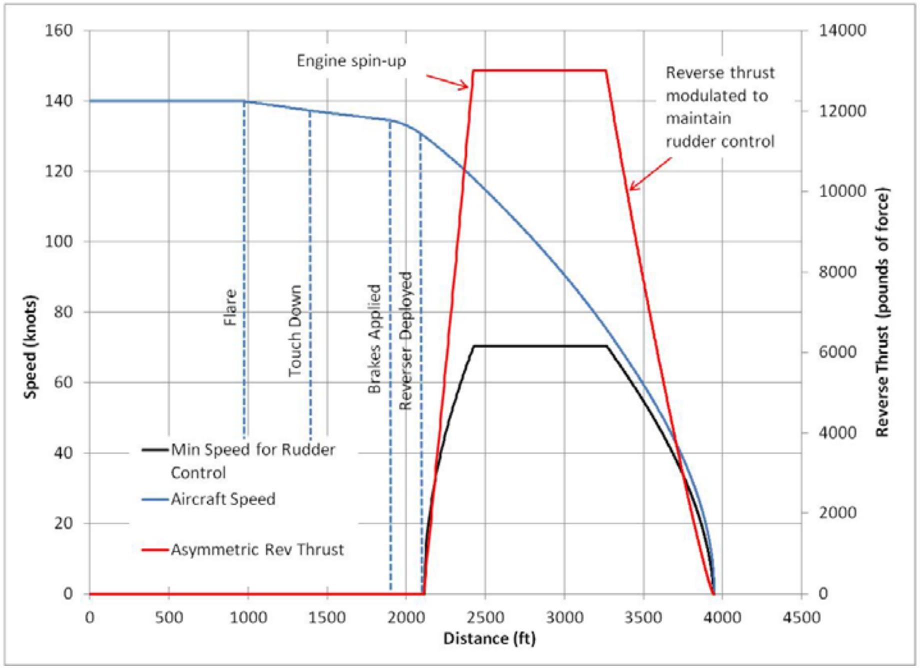

Figure 21. Landing Distance with Asymmetric Reverse Thrust on Dry Runway.

desirable. Consequently, the rudder is the only available means for maintaining directional control under an asymmetric thrust condition. However, the asymmetric thrust generated by the thrust reverser(s) could be modulated so as to remain within the limits of rudder control. This could be accomplished by reducing the engine power level as the aircraft decelerates. The authors believe that a FADEC scheduled reverse thrust system would be safe and effective; it would not require exceptional pilot skill or alertness.

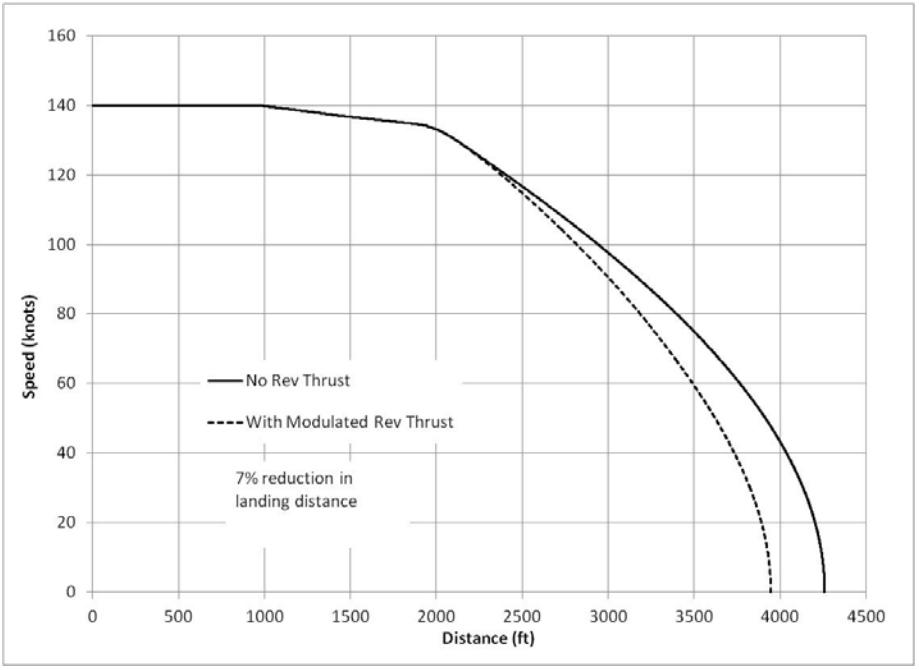

Figure 22. Landing Distance with Asymmetric Reverse Thrust on Dry Runway.

The modulation of reverse thrust during landing would have the effect of reducing the overall benefit of thrust reversal. In order to understand the net benefit of asymmetric reverse thrust, the aircraft dynamic system model is used to simulate the landing distance determination. For the purpose of this study, a margin of 5 knots has been applied to V_{MCG}, so that the calculated maximum allowable asymmetric thrust *T* corresponds to an aircraft speed 5 knots slower than the actual aircraft speed. Figure 21 provides an illustration of landing distance for a hypothetical A320-200 sized aircraft simulated for a scenario where one engine is assumed inoperative prior to landing. For this simulation, relatively high values for braking effectiveness are used to simulate dry runway conditions. It is assumed that the thrust reverser on the operating engine has a maximum effectiveness of 50%, but reverse thrust is varied during deceleration so as to maintain directional control using the rudder. This simulation assumes that a thrust reverser cut-off speed is not observed, thus permitting the use of reverse thrust until a full stop is achieved. This assumption is intended to represent an emergency condition, where stopping the aircraft is the highest priority. Figure 21 illustrates that during landing on a dry runway,

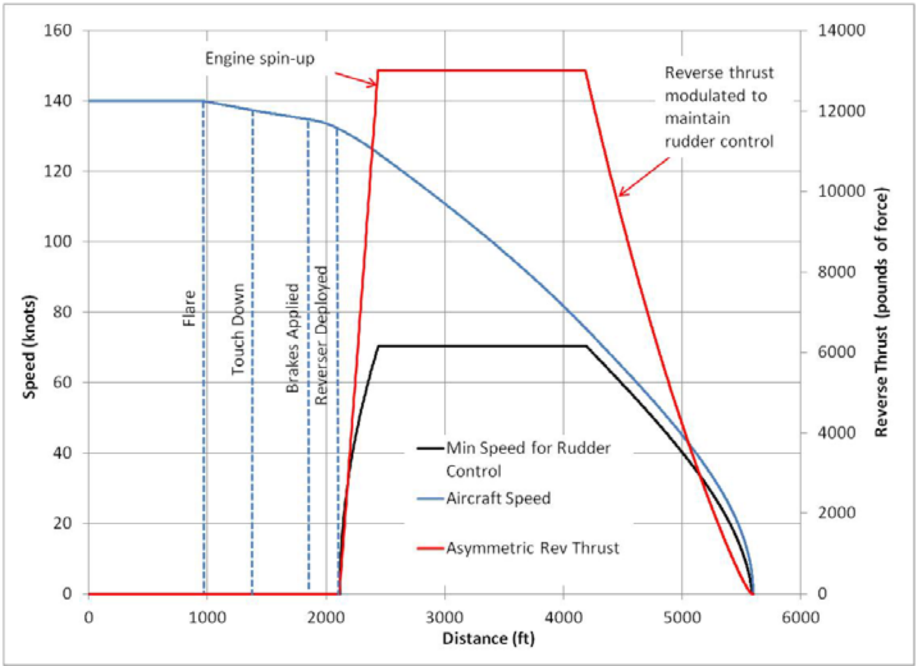

Figure 23. Landing Distance with Asymmetric Reverse Thrust on Wet Runway.

maximum reverse thrust can only be achieved for a short duration, limiting the benefit of thrust reversal.

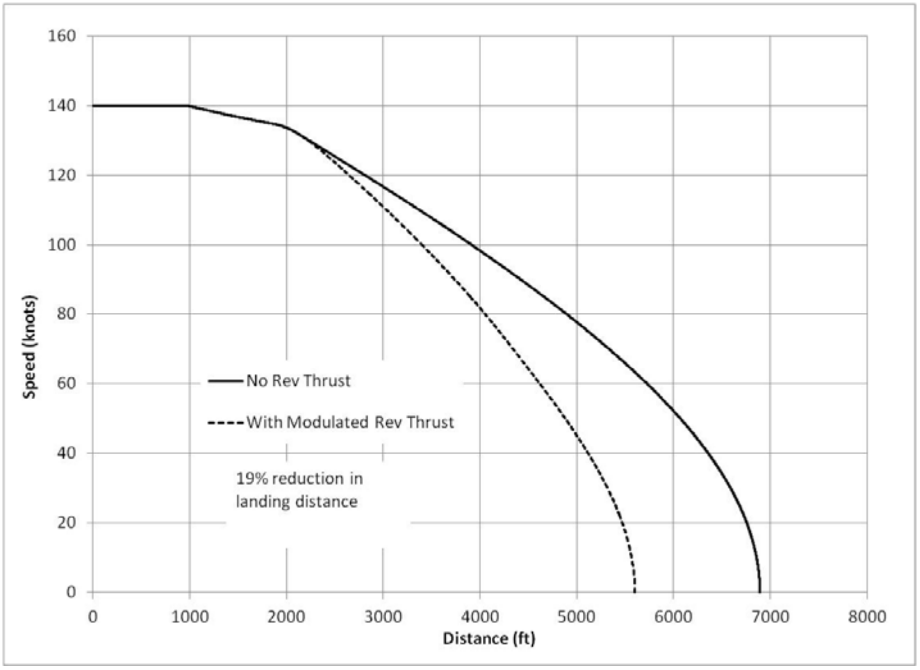

Figure 24. Landing Distance with Asymmetric Reverse Thrust on Wet Runway.

Figure 22 provides a comparison of landing distances for the same scenario, with and without the use of reverse thrust. Figure 22 suggests that the effect of asymmetric reverse thrust on a dry runway is relatively small, though likely still beneficial. As previously discussed, there are aspects of the aircraft configuration that could increase the benefit. For example, mounting the engines closer to the aircraft centerline would decrease the moment arm of the asymmetric thrust, thus reducing the net moment on the aircraft. This would allow higher levels of reverse thrust during deceleration. Regional and business jet aircraft often have engines mounted to the empennage rather than the wing, and may get more benefit from credit for asymmetric reverse thrust.

Figure 23 provides an illustration of landing distance for the same hypothetical aircraft using similar assumptions as above, except this time using relatively low values for braking effectiveness to simulate wet or contaminated runway conditions. Figure 23 illustrates that during landing on a wet or contaminated runway, maximum reverse thrust can be sustained for a relatively long duration, increasing the benefit of thrust reversal. Figure 24 provides a comparison of landing distance for the same aircraft and assumptions, for scenarios with and without the use of asymmetric reverse thrust. Figure 24 suggests that the benefit of asymmetric reverse thrust on a wet runway is significant, even when the reverse thrust is modulated to maintain rudder control.

C. 14 CFR §25.933 – Reversing Systems

We believe that the requirements of 14 CFR §25.933 (2015) are overly prescriptive, to the point that certification is usually performed using an equivalent-level-of-safety (ELOS) approach. Because ELOS certification is inherently subjective, it tends to discourage the use of novel technology. Moreover, this approach can lead to disparity in the industry, if ELOS findings are not provided in a uniform and consistent manner.

The Powerplant Installation Harmonization Working Group (PPIHWG) proposed an alternate method of compliance in NPRM 16 December 1999. This proposal included draft advisory circular AC 25.933X which outlined two methods of demonstrating compliance: one method demonstrates safety through controllability, the other demonstrates safety through reliability. The provisions of the controllability method align reasonably well with the current requirements of §25.933, essentially demonstrating direct compliance. However, the provisions of the reliability method bear no direct relation to the current requirements in 14 CFR §25.933 (2015). In effect, the reliability method described in draft AC 25.933X represents a formalization of the ELOS approach that is often employed. Therefore, it would seem beneficial to amend the requirements of §25.933 so as to permit the reliability approach, and eliminate any ambiguity with regard to its acceptability. This could be accomplished by a few relatively minor amendments in §25.933. First, this section should be amended to clarify that, for thrust reversers intended only for ground use, the requirements of subparts (a)(1) apply unless it can be demonstrated that inadvertent in-flight deployment is extremely improbable and does not result from any single failure or malfunction. In effect, if it can be demonstrated that inadvertent deployment is unlikely to ever occur throughout the entire life of the aircraft fleet, then it should be unnecessary to demonstrate that:

1. The engine will produce no more than idle thrust following an inadvertent in-flight deployment.
2. An operable thrust reverser can be restored to the forward thrust position.
3. The aircraft is capable of continued safe flight and landing under any possible position of the thrust reverser.

Similarly, subpart (a)(3) should be amended to clarify that this provision is not required if it can be demonstrated that inadvertent deployment is extremely improbable and does not result from any single failure or malfunction. This would relieve system designers of the obligation to force engine speed to idle in the event of relatively minor failures such as indication system failures. In turn, this would reduce the potential for erroneous indications to could cause loss of thrust control events.

V. Quantitative Trade Studies

The purpose of this section is to present some comparative studies that demonstrate the effects of the regulatory changes proposed herein. The studies are performed using the aircraft system dynamic model to simulate accelerate-stop and landing distances for several hypothetical aircraft configurations similar to types currently in-service. The configurations studied are as follows:

- A small twin engine passenger aircraft with characteristics similar to the Airbus A320-200
- A twin engine business jet aircraft with characteristics similar to the Gulfstream G550
- A large twin engine passenger aircraft with characteristics similar to the Boeing 777-300ER
- A large four engine passenger aircraft with characteristics similar to the Boeing 747-400

The key parameters used to simulate each of these aircraft configurations are presented in Table 2, and are derived from openly published data, as well as our own engineering estimates. We believe that this model is sufficiently accurate to represent the general trends and characteristics. For all of these simulations, a thrust reverser cut-off speed of 50 knots has been used. It is assumed that a critical engine failure occurs at V_{EF} during takeoff, or is present prior to landing, consistent with the proposed regulatory changes in consideration of current engine technology. Note that for the four engine aircraft configuration, it is assumed that the critical engine is an outboard engine (rather than an inboard engine), as a failure of an outboard engine generates a more asymmetric condition.

Table 2. Aircraft Configuration Data Used in Aircraft System Dynamic Model

Aircraft Configuration		Small Twin Engine Passenger Jet	Twin Engine Business Jet	Large Twin Engine Passenger Jet	Large Four Engine Passenger Jet
Number of engines	each	2*	2*	2*	4*
Takeoff thrust per engine	lbf	26000*	15385*	115000*	62000*
Thrust reverser effectiveness	none	0.5	0.5	0.5	0.5
Reference area of wing	ft^2	1320	1300	4605	5650
Wing span	ft	112*	93.5*	212*	211.5*
Aspect ratio	none	9.1	6.5	9	7.9
Fraction of weight on main gear	none	0.85	0.85	0.85	0.85
Thrust reverser deploy time	sec	3	3	3	3
Coefficient of drag in takeoff configuration	none	0.044	0.044	0.044	0.044
Takeoff weight	lbm	172000*	91000*	660000*	550000*
Decision speed V_1	knots	140	141*	160	160
Landing speed V_{REF}	knots	140	136*	154	154
Coefficient of drag in landing configuration	none	0.158	0.158	0.158	0.158
Landing weight	lbm	146000*	75000*	524000*	550000*
Moment arm from aircraft centerline to centerline of critical engine	ft	12	8	31.5	60
Coefficient of rudder effectiveness	1/degrees	0.0025	0.001	0.0027	0.0023
Maximum rudder deflection	degrees	25	25	25	25

*Entries indicated are derived from Ref. 27, 28, 29, 30, 31, 32, or 33. All other entries are assumed or estimated.

Figure 25 through Figure 28 illustrate the impact of the proposed changes on accelerate-stop and landing distance performance for a hypothetical twin engine business jet with characteristics similar to the Gulfstream G550. These results suggest that the benefit of thrust reversal on a dry runway is relatively small, but the benefit on a wet or contaminated runway is significant.

Similarly, Figure 29 through Figure 32 illustrate the impact for a hypothetical small twin engine passenger jet with characteristics similar to the Airbus A320-200. It is significant to note that these results, in comparison with the results illustrated in Figure 17 through Figure 24, suggest that the effect of the 50 knot thrust reverser cut-back limitation on stopping distance is extremely small. This is due, in part, to the fact that the rudder control limitation requires that the asymmetric reverse thrust level be relatively low, even before the 50 knots speed is achieved

Figure 33 through Figure 36 illustrate the impact of the proposed changes on accelerate-stop and landing distance for a hypothetical large twin engine passenger jet with characteristics similar to the Boeing B777-300ER. Again, these results suggest that the benefit on a dry runway is relatively small, but the benefit on a wet or contaminated runway is significant. These results also suggest that the benefit for a large aircraft may be greater than for a small aircraft.

Finally, Figure 37 through Figure 40 illustrate the impact for a hypothetical large four engine passenger jet with characteristics similar to the Boeing B747-400. These results suggest that the benefit for a four engine aircraft is somewhat greater than for a twin engine aircraft. This is primarily due to the symmetric reverse thrust component that is available from 2 engines, despite the critical engine failure.

When considering the relatively small benefit of thrust reversal on a dry runway, it should be noted that the regulatory changes proposed herein may allow innovations in aircraft and thrust reverser design that could result in increased reverse thrust performance.

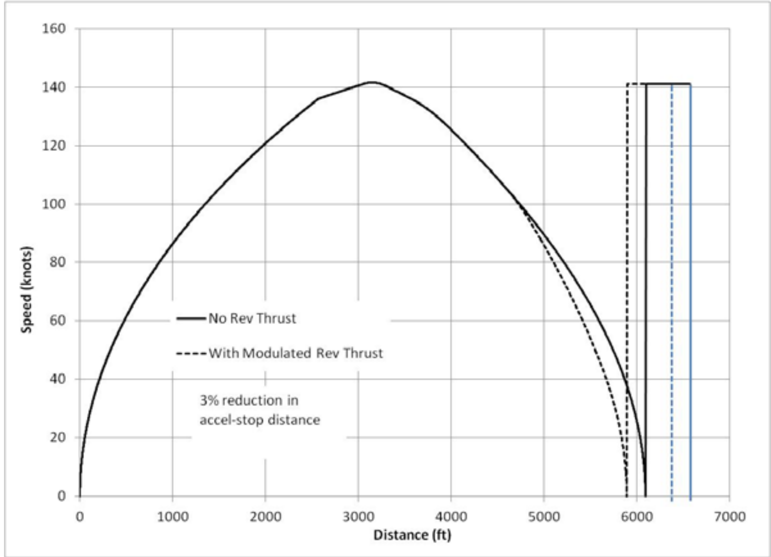

Figure 25. Business Jet Accelerate-Stop Distance with Asymmetric Reverse Thrust on Dry Runway.

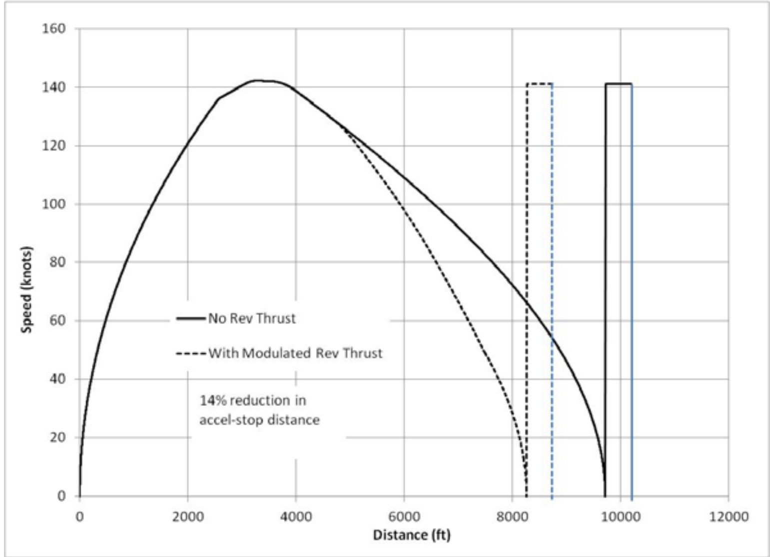

Figure 26. Business Jet Accelerate-Stop Distance with Asymmetric Reverse Thrust on Wet Runway.

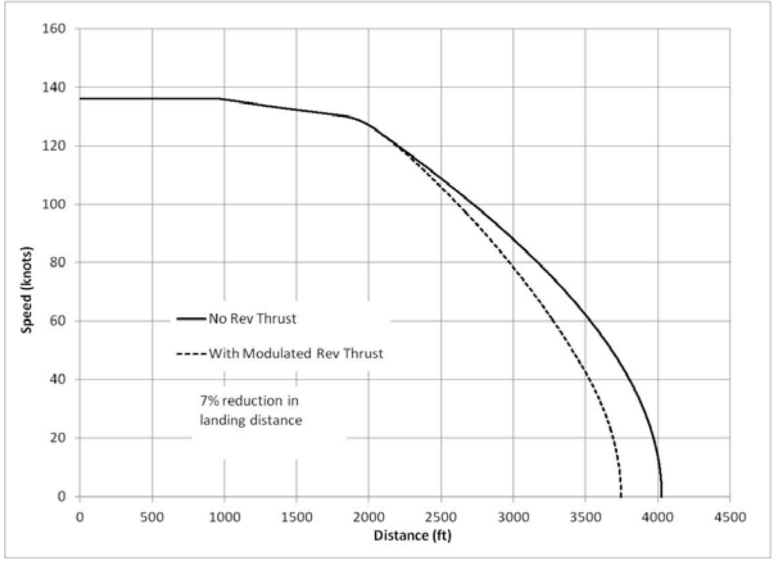

Figure 27. Business Jet Landing Distance with Asymmetric Reverse Thrust on Dry Runway.

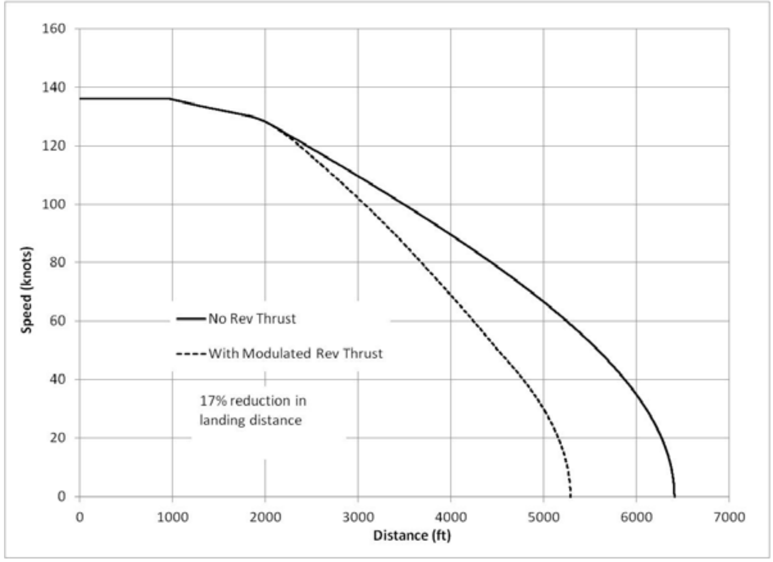

Figure 28. Business Jet Landing Distance with Asymmetric Reverse Thrust on Wet Runway.

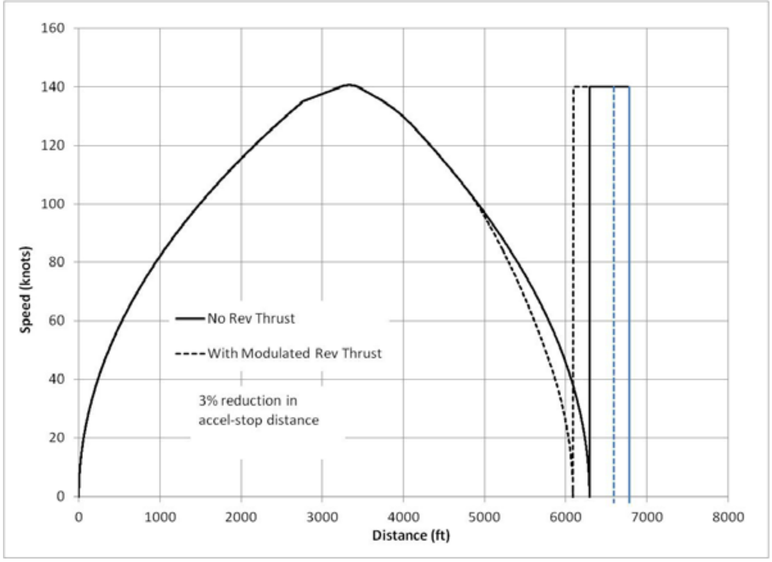

Figure 29. Small Twin Jet Accelerate-Stop Distance with Asymmetric Reverse Thrust on Dry Runway.

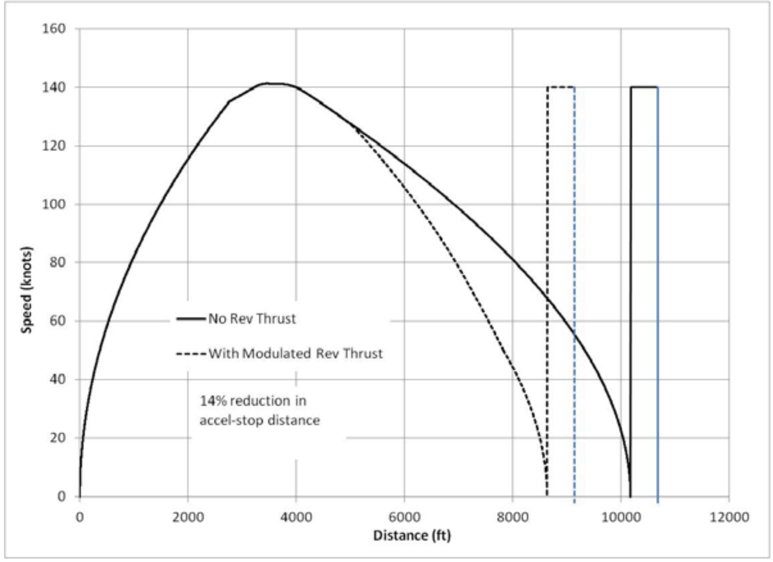

Figure 30. Small Twin Jet Accelerate-Stop Distance with Asymmetric Reverse Thrust on Wet Runway.

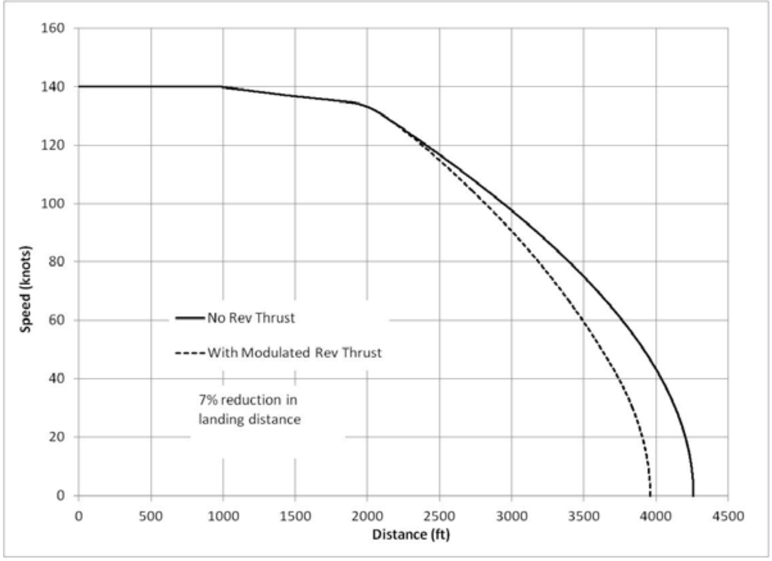

Figure 31. Small Twin Jet Landing Distance with Asymmetric Reverse Thrust on Dry Runway

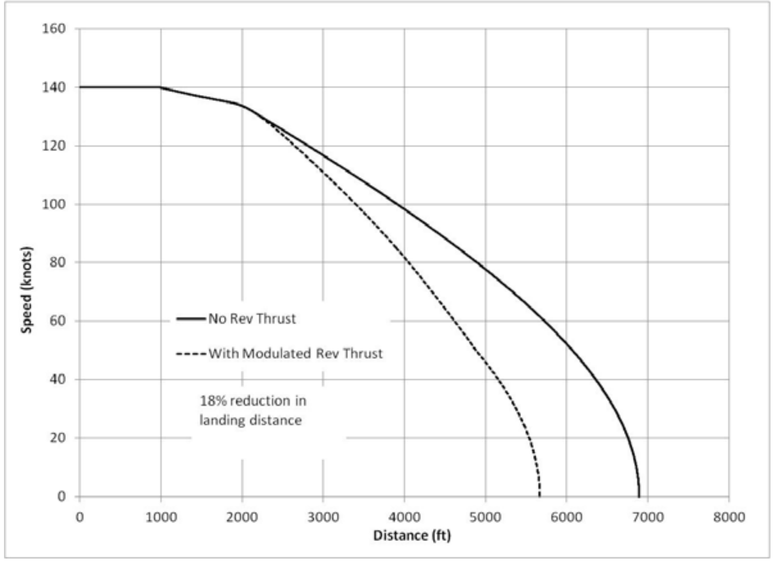

Figure 32. Small Twin Jet Landing Distance with Asymmetric Reverse Thrust on Wet Runway.

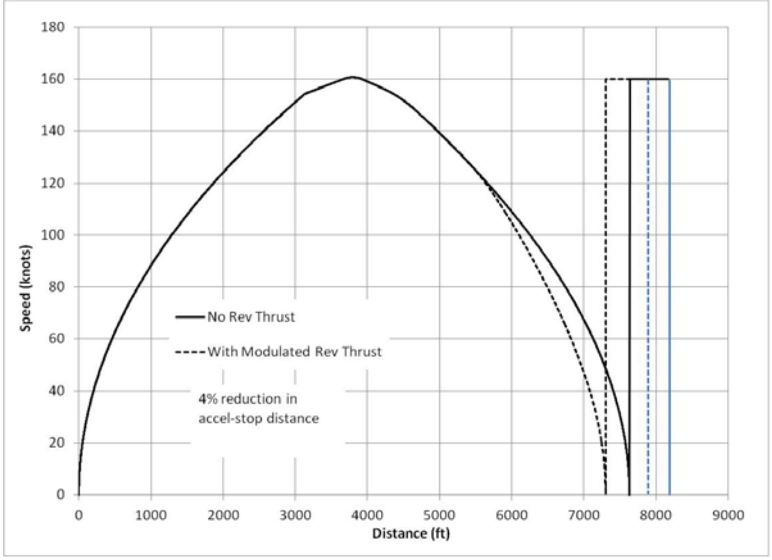

Figure 33. Large Twin Jet Accelerate-Stop Distance with Asymmetric Reverse Thrust on Dry Runway.

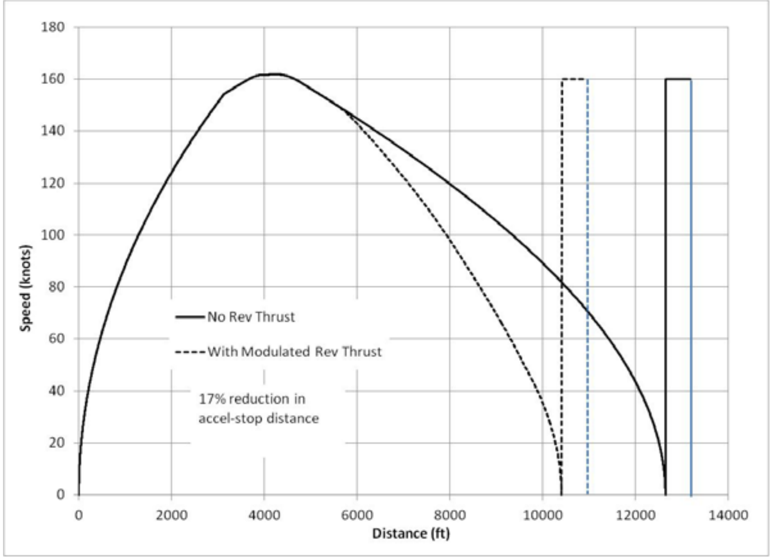

Figure 34. Large Twin Jet Accelerate-Stop Distance with Asymmetric Reverse Thrust on Wet Runway.

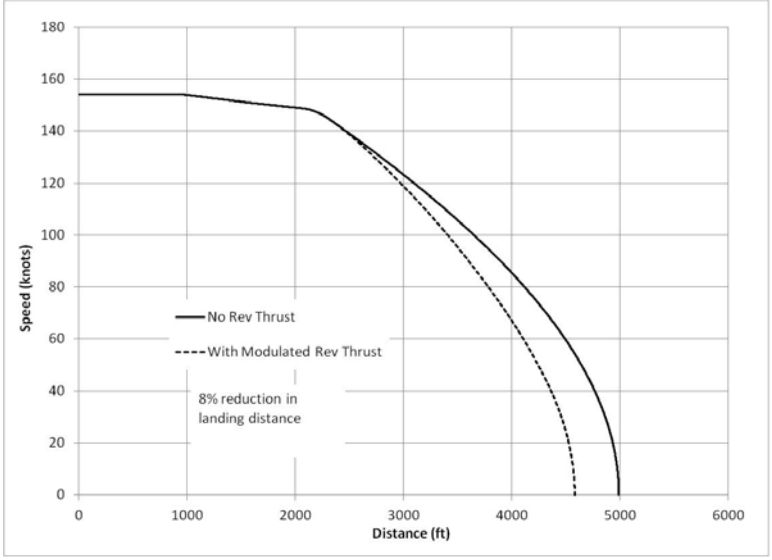

Figure 35. Large Twin Jet Landing Distance with Asymmetric Reverse Thrust on Dry Runway.

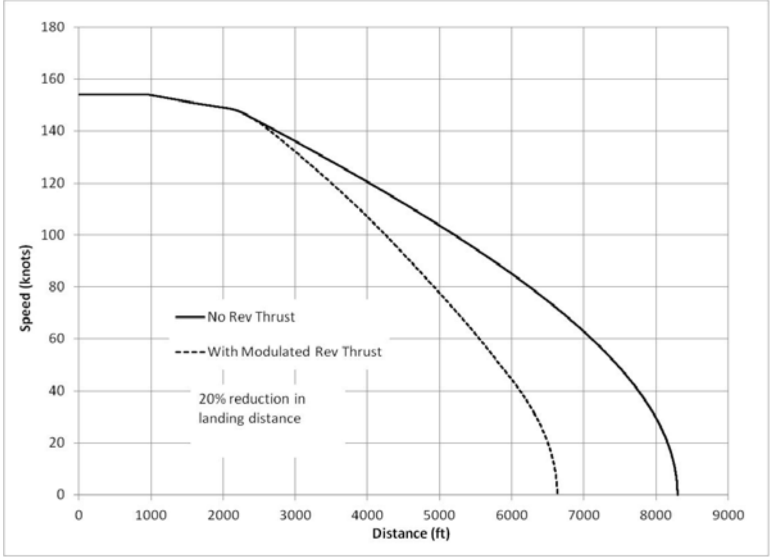

Figure 36. Large Twin Jet Landing Distance with Asymmetric Reverse Thrust on Wet Runway.

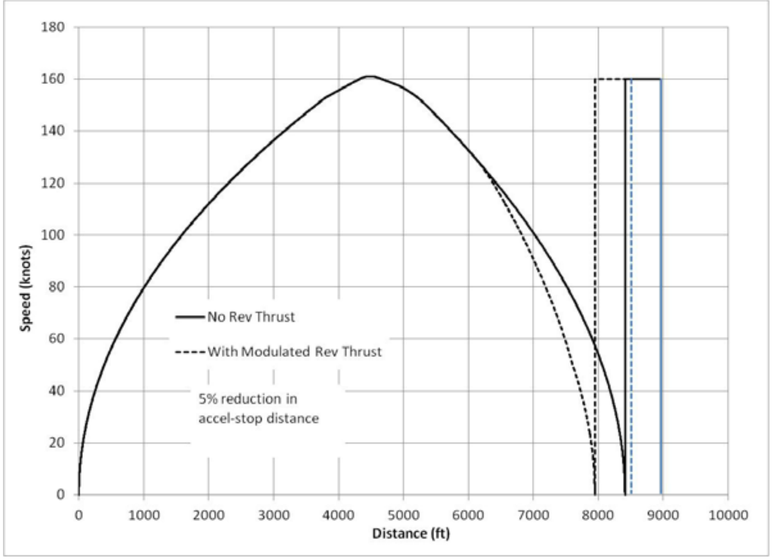

Figure 37. Large Four Engine Accelerate-Stop Distance with Asymmetric Reverse Thrust on Dry Runway.

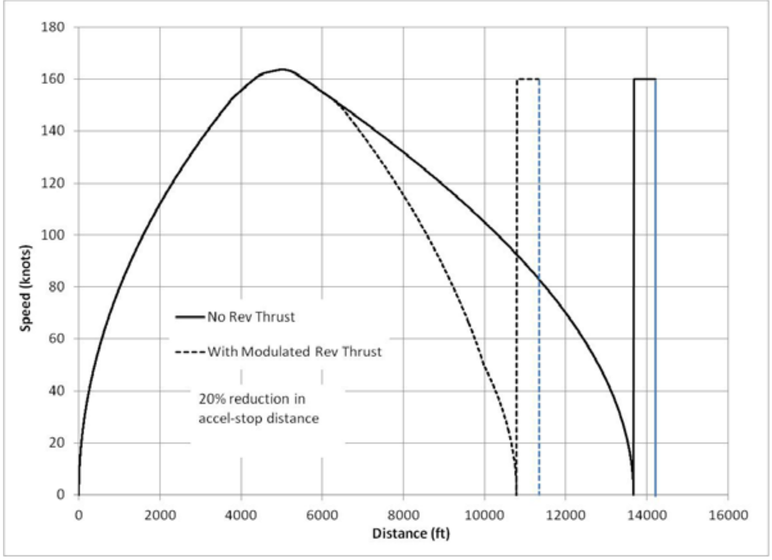

Figure 38. Large Four Engine Accelerate-Stop Distance with Asymmetric Reverse Thrust on Wet Runway.

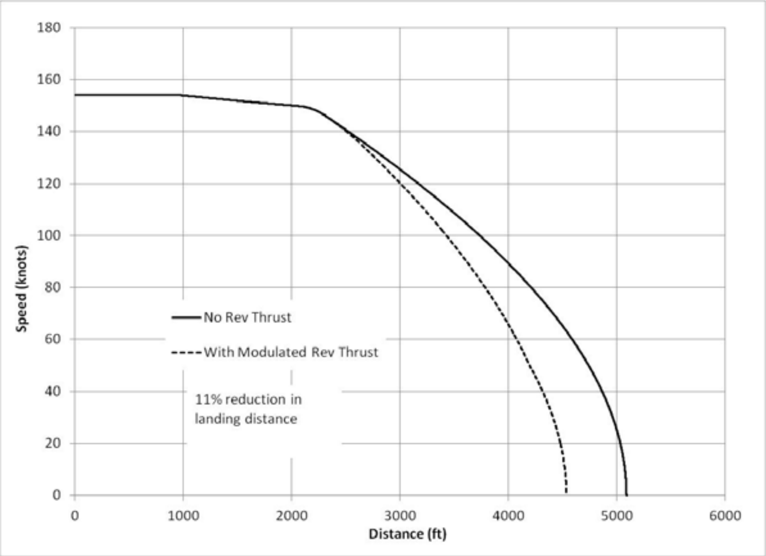

Figure 39. Large Four Engine Landing Distance with Asymmetric Reverse Thrust on Dry Runway.

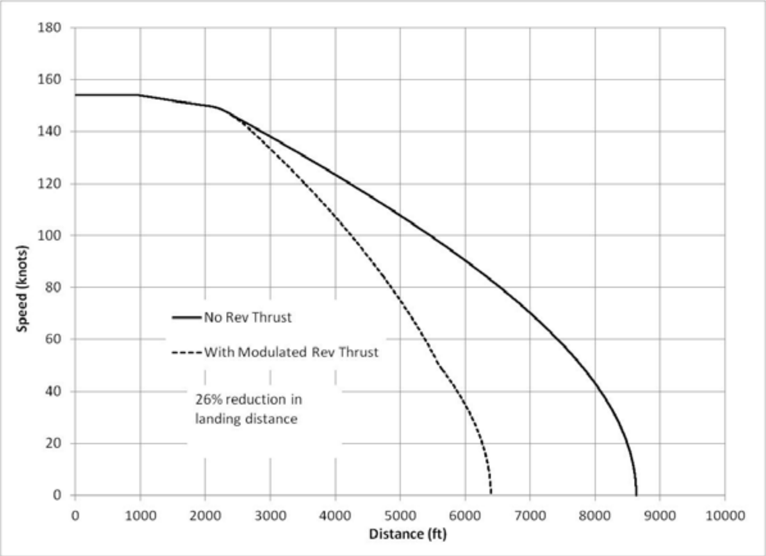

Figure 40. Large Four Engine Landing Distance with Asymmetric Reverse Thrust on Wet Runway

VI. Conclusion

The regulatory environment created by the current 14 CFR §25 requirements serves to discourage the usage of thrust reversing systems for certified procedures. Although many aircraft are fitted with reverse thrust systems, they are not integrated into the flight system as well as technology would otherwise permit. This situation is a byproduct of several regulations which are ripe for revision: 14 CFR §25.109 functionally prohibits the use of thrust reversers to determine certified take-off critical field length. 14 CFR §25.125 imposes similar limitations on certified landing distances. Presently, many operators in the United States fly aircraft using "uncertified" procedures, a practice that defeats the purposes of having certification in the first place.

We believe that regulatory changes are essential if the industry hopes to achieve advancement in the safety and performance of FADEC controlled thrust reversing systems. We propose that, in relation to the current regulatory environment, increased dependence on and credit for the use of thrust reversal could benefit the safety, reliability, performance, and efficiency of future aircraft. To enable this transition, we suggest changes in §25.109, §25.125, and §25.933 that would permit full credit for thrust reversal, but only after it is demonstrated that the thrust reversing system is sufficiently safe and reliable. This would allow operators to fly using FAA certified distances and procedures as opposed to relying on advisory performance data developed using procedures where pilot workload is increased due to an intentional lack of automation.

Our performance simulations suggest that the use of highly integrated thrust reverser systems can be of significant benefit, particularly under wet or contaminated runway conditions. These benefits are most pronounced on larger aircraft, and on aircraft with a larger number of engines. These benefits are significant even though thrust reversal must be limited by aspects such as rudder control and cut-back procedures. We believe that a regulatory environment that embraces the use of reverse thrust is one that will enhance both aviation safety and increase aircraft performance with a minimum of detrimental side effects.

Acknowledgements

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