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The Impact of ATTCS on Reduced-Thrust Takeoff Field Performance

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This paper explores the interplay between the five regulations (14 CFR § 25.105, 14 CFR § 25.107, 14 CFR § 25.109, 14 CFR § 25.113, and 14 CFR § 25.121) and their interactions with two other regulations: 14 CFR § 25.149 and 14 CFR § 25.904. Together, these laws control the means by which the takeoff runway requirements of transport category aircraft are computed. Inspection of airline pilot manuals indicate the popularity of "reduced thrust" or "flex-temp" takeoff procedures that are not discussed in popular aircraft design texts. This paper documents the design and certification implementation strategies that the designer should take when including de-rated thrust takeoff procedures and alternative decision speed strategies into the aircraft conceptual design process.

Nomenclature

CFR = *Code of Federal Regulations*
DOT = *Department of Transportation*
FAA = *Federal Aviation Administration*
FADEC = *Full Authority Digital Engine Controller*
TOLD = *Take-Off and Landing*

ASD and ASDA = *Accelerate-Stop-Distance / Accelerate-Stop-Distance-Available*
TOD and TODA = *Takeoff Distance (beginning of roll to 35-ft obstacle at end of runway) / Takeoff Distance Available*

KIAS = *Knots Indicated Airspeed*
Vs = *Stall Speed (as called out in various parts of the CFR)*
V1 = *Takeoff Go/No-Go Decision Speed (one-engine inoperative)*
V2 = *Takeoff Obstacle Clearance Speed (one-engine inoperative)*
VR =*Takeoff Rotation Speed*
V_{MCA} = *Minimum Controllable Airspeed (Takeoff flap setting) (one-engine inoperative)*
V_{MCG} = *Minimum Controllable Groundspeed (Takeoff flap setting) (one-engine inoperative)*

I. Introduction

THE "laws-of-men" plays a very important function within the aviation community. One cannot deny the fact that governing rules have an impact on engineering design. Similarly, the "laws-of-physics" play an equally important role in engineering design. For a hypothetical aircraft to fly in steady level flight, lift must balance against weight, thrust must oppose drag. For a commercial aircraft to be allowed to fly, it must also operate within the bounds of relevant Federal Regulation. In a famous court case, Supreme Court Justice Jackson once said:

> "**Planes do not wander about in the sky like vagrant clouds. They move only by federal permission, subject to federal inspection, in the hands of federally certified personnel and under an intricate system of federal commands."**[1]

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Because a minor commercial aviation incident can jeopardize the safety of hundreds of passengers, aviation is a pervasively regulated business. Aircraft operate in a global marketplace that rewards safe, fuel efficient, low-noise and low-emissions designs. To anybody deeply involved in aircraft operations, it is obvious that these metrics are as much a function of how an aircraft is operated ("how you use it") as it is a function of how it is designed ("how you configure it"). To the designer, things are less obvious. I sincerely doubt that the engineers who configured the Boeing 727-100 conceptualized the possibility of the Raisbeck "Stage 3 Systems Hush Kit."[2] Here, minor changes to the flap rigging and a procedural change applied to the operating manual greatly reduced the takeoff noise footprint of this older airliner. This allowed the 727-100 to be compliant with "Stage 3" airport noise regulations that were enacted many years after the aircraft were built.

Since 1926, the FAA and its predecessor agencies have promulgated many rules and regulations to manage the industry of commercial aerospace. Many of these regulations are known by the engineers who design the planes as well as the pilots who fly them. Yet even though regulations exist (and are easily accessible on-line), problems arise. Most engineers consider the regulatory framework as immutable as the equations of motion. This is understandable because classical aircraft performance texts[3,4,5,6] do not discuss how the regulatory environment to which aircraft are designed and operated has changed over time. In this paper, I will explore the realm of potential impact of a rule promulgated in 1987: **14 CFR § 25.904**[7] that has not seen much scholarly attention. A *scholar.google.com* search reveals a single patent US Patent 6,880,784 and no AIAA papers or journal articles that expressly refer to rule 14 CFR § 25.904.

Today, the policy objectives of the Department of Transportation include both climate change[8] and flight safety of civil aircraft in air commerce.[9] Thus evolved regulations should promote both a greener and safer future. If improved rules could enable the design of more efficient, safer, more community friendly aircraft, existing laws should be amended and new laws promulgated.

Recent government efforts, such as the NASA Environmentally Responsible Aircraft program, produce conceptual and preliminary-design level proposals of all-new highly efficient airframes that synergistically exploit advances in propulsion, aerodynamics and materials technology.[10] These aircraft sizing studies are quantitative technical assessments.[11] They do not concern themselves with trading the regulatory environment as independent design variables.

Because many classical aircraft performance texts[3,5,6] do not teach a strict physics and regulatory based approach to computing TOLD distances, most aircraft design studies are based upon methods which are at best obsolete, and at worst misleading. The differences between a "textbook" and a physics-based and regulation compliant simulation are large. Generally speaking, higher obstacle clearance speeds (*V2*) lead to longer takeoff runs. However, lowering the obstacle clearance speed may result in an aircraft with inferior engine-inoperative second segment climb capability. Thus, the aircraft designer must balance the need for excess thrust against a desire for a high maximum lift coefficient in order to attain satisfactory field performance. This sort of design nuance evades those with only a theoretical, academic perspective.

From an optimal design perspective, regulatory changes and nuance have wide ranging potential impacts upon vehicle sizing. This author believes that improved aircraft designs demand both **technological and regulatory** advancement. This is the second paper in a series, exploring the impact of regulatory changes on aircraft safety, operating economy, as well as local community and global environmental impact.

II. Regulatory Background

Changes in regulation can significantly impact aircraft design. For example, classical aircraft performance texts[3,5,6] teach the engineer that aircraft land at a reference, or "refusal" speed, *Vref*, of 1.3 times the landing stall speed. This was true under an older regulation, but has not been true since the relevant regulation was amended in 2007! Although older aircraft operated to the older stall speed ratio, newly certified aircraft land with *Vref* equal to 1.23 times the landing stall speed. For an aircraft with a 150 KIAS stall speed, the difference in approach speed is 10.5 KIAS. To achieve such a change in performance through aerodynamic, rather than regulatory changes, would require, at minimum, different flap rigging. More likely, the aircraft would require larger, heavier, more mechanically complex landing flaps. The savvy aircraft designer must understand the mechanics of flight and the mechanics of the modern regulatory state.

Early in the aircraft design process, the design teams files an application for a type certificate. For a clean-sheet aircraft, a new type certificate will be issued. The designer establishes a permanent regulatory framework for certification; this comprises the regulations that are "in place" at the time of type certificate application. For many derivative aircraft, an 'amended type certificate' is issued. For an amended type certificate, the basic regulatory framework of certification remains unchanged for the undisturbed systems common to the original and 'new' design.[12] In some circumstances, an existing design can voluntarily be brought up to the new standard; for example the "next generation" B737 is certified using the more aggressive TOLD stall speed regulations.[12] Thus, an amendment to design and operation regulations can have wide ranging impacts upon future clean-sheet and derivative designs.

Because TOLD runway requirements are so vital to aircraft design and operations, these regulations should be carefully scrutinized. Five intertwined regulations (14 CFR § 25.105, 14 CFR § 25.107, 14 CFR § 25.109, 14 CFR § 25.111, 14 CFR § 25.113, and 14 CFR § 25.121) govern the takeoff runway requirements of transport category aircraft.

- 14 CFR § 25.105[13] describes the overall procedure for takeoff (ensuring that the runway length is adequate for an all-engines-operating takeoff, a rejected-takeoff due to engine failure, as well as continued takeoff where the engine fails above the "decision speed").
- 14 CFR § 25.107[14] describes the basis for selecting the "decision speed," *V1*, where an engine-failure will lead to either a rejected or continued takeoff, the "rotation speed," *VR*, where the pilot lifts the nose wheel off of the ground to begin flight, and the "takeoff safety speed," *V2*, that the aircraft should attain or exceed at the point it is 35-feet above the runway.
- 14 CFR § 25.109[15] describes the accelerate-stop procedure for a rejected takeoff.
- 14 CFR § 25.111[16] describes the accelerate-go procedure for a flight with all engines operating and a flight with a critical engine failure above the decision speed. It specifies a minimum initial climb capability for the aircraft with an inoperative engine.
- 14 CFR § 25.113[17] describes the means to compute the total takeoff distance.
- 14 CFR § 25.121[18] provides a minimum climb capability for the aircraft with a critical engine inoperative and landing gear retracted; this is the "second segment climb gradient" constraint.

Three other regulations play in counterpoint to the six major takeoff procedural regulations.

- 14 CFR§ 121.189[19] describes the need for a pilot to comply with all runway length requirements (AEO as well as OEI) **and** the second segment climb gradient constraint before attempting a takeoff. There are many situations where the aircraft has sufficient runway to takeoff OEI, but insufficient reserve climb capability to avoid obstacles. These conditions are known as "WAT Limited."
- 14 CFR § 25.149[20] describes the means to determine the "minimum control speed" both on the runway and in the air when the aircraft operates with a critical engine inoperative.
- 14 CFR § 25.904[7] and associated requirements in 14 CFR § 25 Appendix I[21] describe the ability of an aircraft to feature electronically or electromechanically governed engines whose thrust levels are keyed to the operational health of other engines and to other flight conditions.

Remember that aircraft are operated according to a blend of historical and modern rules. The 'certified performance manual' is developed according to the airworthiness rules in place at the time the FAA is petitioned to issue a type-certificate. Current aircraft in operation may be certified to either 14 CFR **§** 4b (some elderly jets such as B727s) or various version of the 14 CFR **§** 25 rule set. Recall, when the FAA changes a performance rule, manufacturers need not update their flight manuals. Conversely, operators must follow current 14 CFR § 91 **and** 14 CFR **§** 121 rules.

III. Operational Background

Why are any of these regulations important? Why is this technology interesting?

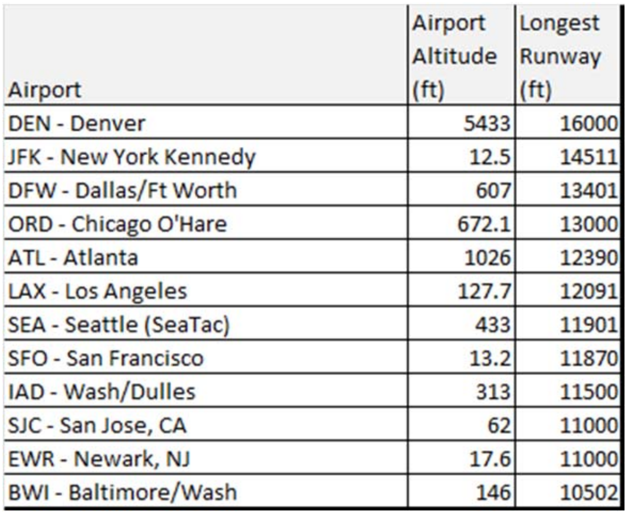
It is because aircraft are engineered to achieve a level of measured performance on a particularly stressing runway. For most of their operational life, they will fly into and out of airports that have runways much longer than those required by law. This margin of safety is good. However, a de-rated thrust takeoff may allow an aircraft to achieve other policy objectives (community noise, ground level emissions) without compromising safety.

Aircraft must be able to operate into and out of practical airports. In the twenty first century, major metropolitan areas have at least one airport with a very long runway suitable to take a heavily loaded, underpowered aircraft. Figure 1 documents the airport elevation and longest runway of 12 major United States domestic hub airports. With the exception of Denver International Airport, which is located at 5,433-ft elevation, the other airports are located at very modest elevations. All of these airports have runways at least 10,000-ft long; with the long runway at Denver (runway 16R/34L) spanning 16,000-ft (more than three statute miles).

The United States also has many alternative runways (see Figure 2). Some of these are older runways found in major metropolitan areas (such as Dallas' Love Field, Houston's Hobby Airport or San Diego's Lindbergh Field). Other operational alternatives comprise shorter "crosswind landing" runways at major domestic hub airports.

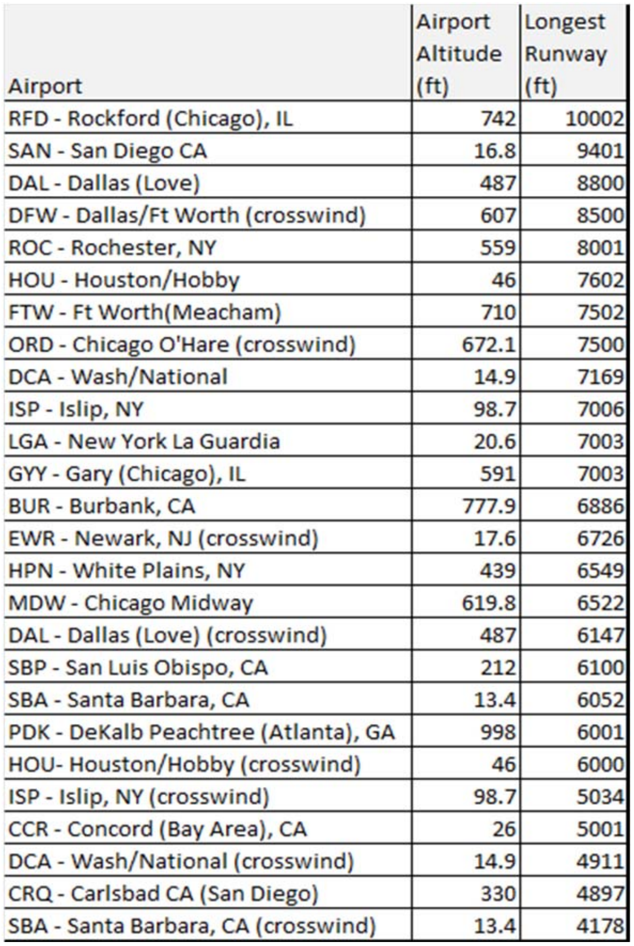
The five most significant "metroplex" airports with shorter runways (<7,200-ft long) that see scheduled airline traffic comprise Southern California's Burbank Airport (BUR), Chicagoland's Midway Airport (MDW), New York's LaGuardia (LGA) and Westchester County (HPN) airports as well as the capitol region's Ronald Reagan Washington National Airport (DCA).

Many "metroplex" airports (such as Concord, CA and DeKalb/Peachtree Airport near Atlanta, GA) do not presently support scheduled commercial flights; they have rather short runways. Other airports, such as Fort Worth TX's Meacham Field (FTW) or Rockford, IL (RFD) have relatively long runways. All of these airports are ripe for future growth in domestic, scheduled passenger traffic.



Airport	Airport Altitude (ft)	Longest Runway (ft)
DEN - Denver	5433	16000
JFK - New York Kennedy	12.5	14511
DFW - Dallas/Ft Worth	607	13401
ORD - Chicago O'Hare	672.1	13000
ATL - Atlanta	1026	12390
LAX - Los Angeles	127.7	12091
SEA - Seattle (SeaTac)	433	11901
SFO - San Francisco	13.2	11870
IAD - Wash/Dulles	313	11500
SJC - San Jose, CA	62	11000
EWR - Newark, NJ	17.6	11000
BWI - Baltimore/Wash	146	10502

Figure 1 – Primary Runways at Major US Hub Airports



Airport	Airport Altitude (ft)	Longest Runway (ft)
RFD - Rockford (Chicago), IL	742	10002
SAN - San Diego CA	16.8	9401
DAL - Dallas (Love)	487	8800
DFW - Dallas/Ft Worth (crosswind)	607	8500
ROC - Rochester, NY	559	8001
HOU - Houston/Hobby	46	7602
FTW - Ft Worth(Meacham)	710	7502
ORD - Chicago O'Hare (crosswind)	672.1	7500
DCA - Wash/National	14.9	7169
ISP - Islip, NY	98.7	7006
LGA - New York La Guardia	20.6	7003
GYY - Gary (Chicago), IL	591	7003
BUR - Burbank, CA	777.9	6886
EWR - Newark, NJ (crosswind)	17.6	6726
HPN - White Plains, NY	439	6549
MDW - Chicago Midway	619.8	6522
DAL - Dallas (Love) (crosswind)	487	6147
SBP - San Luis Obispo, CA	212	6100
SBA - Santa Barbara, CA	13.4	6052
PDK - DeKalb Peachtree (Atlanta), GA	998	6001
HOU- Houston/Hobby (crosswind)	46	6000
ISP - Islip, NY (crosswind)	98.7	5034
CCR - Concord (Bay Area), CA	26	5001
DCA - Wash/National (crosswind)	14.9	4911
CRQ - Carlsbad CA (San Diego)	330	4897
SBA - Santa Barbara, CA (crosswind)	13.4	4178

Figure 2 – Secondary Runways at Major US Hub Airports and Metroplex (regional) Airport Runways

Figure 3 lists a worldwide collection of airports with famously challenging runways. The runway at Juneau, AK is, essentially, at sea-level. It has a reasonable length runway but is nestled in a mountainous coastal region. Dutch Harbor, AK is at sea-level, but is a treacherously short strip. Vail/Eagle, Aspen, CO and Gunnison, CO all see significant wintertime snowfall. They are located high in the Rocky Mountains. Even more extreme is the airport at La Paz, Bolivia; it is located high in the Andes at altitude more than 13,000-ft above sea-level.

Figure 4 lists both primary and secondary airports for many first world metropolitan areas.

The London megalopolis is serviced by no less than five airports: Heathrow, Gatwick, Luton, Stansted and London City. Of these, only London City(LCY) has a short runway (4,948-ft). For noise abatement reasons, LCY operations demand a steep approach path.

Most scheduled service into Toronto, Canada arrives at Pearson airport at Malton, ON. Toronto also has a small "Island Airport" with a 3,988-ft runway that is a convenient short ferry ride from the Bay Street Train Station located in the financial district.

Tokyo and Paris have multiple airports; all with long runways.

The major German cities of Munich and Frankfurt have single, large airports with long runways.

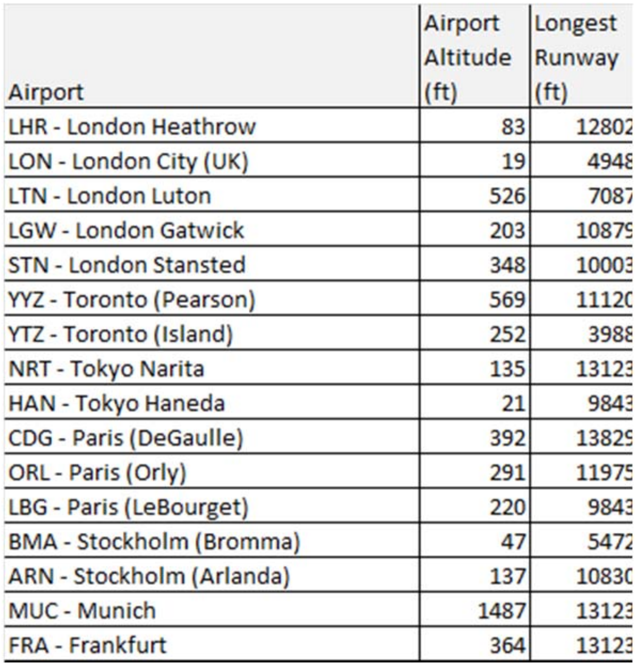
Berlin used to operate Templehof airport with a shorter 6,870-ft runway; this airport has now closed. Berlin air commerce is expected to consolidate at the new Berlin-Brandenburg Airport.

Only Stockholm, Sweden has a short "metroplex" airport convenient to the city center: Stockholm Bromma with a 5,472-ft runway.

Turning now to Figure 5, the reader can see that a real airliner has the ability to trade takeoff gross weight for runway length. Generally speaking, the heavier you load an aircraft the more runway length you need for safe TOLD. For the example of the MD-81, this aircraft takeoff at its 140,000-lbm maximum weight from any airport with a 7,000-ft or longer runway provided that the airport is located near sea-level and the weather represents dry,

Airport	Airport Altitude (ft)	Longest Runway (ft)
ASE - Aspen, CO	7838	8006
GUC - Gunnison, CO	7680	9400
FLG - Flagstaff, AZ	7014	8800
GCN - Grand Canyon, AZ	6609	8899
JNU - Juneau, AK	25	8857
PADU - Unalaska (Dutch Harbor), AK	22	4100
LPB - La Paz, Bolivia	13325	13123
EGE - Vail / Eagle, CO	6547	9000

Figure 3 – Challenging Airports (due to elevation and/or short runways)



Airport	Airport Altitude (ft)	Longest Runway (ft)
LHR - London Heathrow	83	12802
LON - London City (UK)	19	4948
LTN - London Luton	526	7087
LGW - London Gatwick	203	10879
STN - London Stansted	348	10003
YYZ - Toronto (Pearson)	569	11120
YTZ - Toronto (Island)	252	3988
NRT - Tokyo Narita	135	13123
HAN - Tokyo Haneda	21	9843
CDG - Paris (DeGaulle)	392	13829
ORL - Paris (Orly)	291	11975
LBG - Paris (LeBourget)	220	9843
BMA - Stockholm (Bromma)	47	5472
ARN - Stockholm (Arlanda)	137	10830
MUC - Munich	1487	13123
FRA - Frankfurt	364	13123

Figure 4 – World Metropolitan Airports

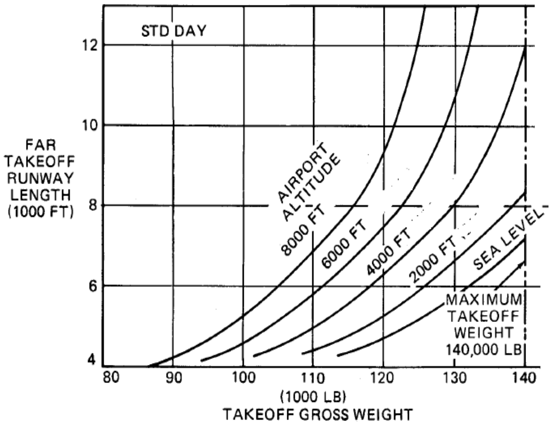


Figure 5 – Takeoff Runway Requirement for MD-81

"standard day" conditions. For an airport like Stockholm-Bromma, this aircraft would be restricted to operations below ~125,000-lbm. As an aside, an MD-81 when restricted to 125,000-lbm takeoff weight can safely fly a ~750-nM stage with a full load of 137 passengers and baggage. Thus, an aircraft like an MD-81 that is "sized" for longer distance flights at higher takeoff weights from longer runways is commercially usable for short, regional flights into and out of airports like Stockholm-Bromma or Carlsbad, CA.

Looking at this collection of airports in the context of airplane performance, there is little compelling reason to design modern commercial aircraft to operate at maximum Takeoff weight from runways significantly shorter than 5,000-ft. Nonetheless designers should pay attention to ensure that their aircraft can operate out of shorter (< 7,000-ft) runways in bad weather (wet or snow covered runways) as well as on sunny, but hot, summer days. When operating on long runways, designers can consider alternative flight procedures including de-rated thrust takeoff.

IV. Concept of Operations for De-Rated Thrust Takeoff

Simpler de-rated thrust takeoff procedures are already in place among aircraft produced by Boeing[22] and Airbus[23]. Prior to flight, dispatch is required to ensure that the departure runway is equal to or longer than that required by the aircraft. When aircraft weight, and runway conditions indicate that the aircraft has excess performance using full power, dispatch may advise use of a lower-power engine setting.

One common technique is to "fool" the FADEC by having pilots input a fictitious temperature into the flight management system (FMS) computer. The Boeing 737 Classic Flight Crew Training manual describes the Assumed Temperature Method de-rate as one where "reduced takeoff thrust is achieved by selecting an assumed temperature higher than the actual ambient temperature."[24] Because jet engines produce less thrust as the ambient air temperature increases, this trick effectively tells the computer to limit the turbine-inlet-temperature (TIT) and rpm (N1) of the engine. Under this procedure, pilot cue speeds (*V1*, *V2*, *VR*) and minimum control speeds (V_{MCA} and V_{MCG}) are set by the full power takeoff thrust levels of the engine because "at any time during takeoff, thrust levers may be advanced to the full rated takeoff thrust" setting.[24] With a reduced power takeoff, the aircraft will accelerate more slowly, utilize more runway and have a shallower initial climb-out than it would absent the de-rate. However, the aircraft will be quieter during its initial takeoff roll than it would be otherwise.

A number of aircraft incidents and accidents have occurred when the flex temp was incorrectly calculated. The most serious accident occurred to an Emirates Airlines A340-500[25]. This aircraft first over rotated, and then struck several structures at the end of the Melbourne, AU runway. The excess takeoff roll was due to pilots utilizing a de-rated thrust takeoff procedure based on an erroneous estimate of aircraft flight weight.

In addition, an aircraft may offer a "fixed de-rate" thrust setting on its FADEC (Full Authority Digital Engine Controller). The Boeing 737 Classic Flight Crew Training manual describes the Fixed De-Rate procedure as one where reduced takeoff thrust is "obtained by selection of a fixed takeoff de-rate in the FMC."[24] Under this procedure, pilot cue speeds (*V1*, *V2*, *VR)* and minimum control speeds (V_{MCA} and V_{MCG}) are set by the de-rated takeoff thrust levels of the engine. The Boeing manual specifically advised that "thrust levels should not be advanced beyond the fixed de-rate limit unless conditions are encountered during takeoff where additional thrust is needed on both engines, such as a wind shear condition."[24] When conducting either a fixed de-rate or an "Assumed Temperature Method" takeoff, the Boeing manual states that pilots may override the nominal takeoff power setting by advancing the throttles manually beyond the "THR HLD" mode stop. In a fixed de-rate takeoff, the pilot must take two steps: first pressing the throttle mounted "TO/GA" (TakeOff/Go Around) override switch to unlock the full capability of the engines while manually advancing the throttles beyond the "THR HLD" setting. The Boeing training manual contains express warnings concerning this procedure: in the event an engine fails, "any thrust increase beyond the fixed de-rate limit **could result in loss of directional control**."[24]

If an aircraft is conceptualized around a FADEC equipped power plant, software programming nuances can radically alter the piloting experience under normal and abnormal (critical engine inoperative) conditions. Considerable FMS integration with weight-on-wheels sensors and airport navigation aids can eliminate the need to pilots to "trick" the FADEC into producing reduced thrust. With a keyed power-lever controller in the cockpit, engineers could program the system to enable a variety of different thrust de-rate schedules.

A FADEC could easily be programmed to apply a progressive airspeed-dependent or even airspeed-and-altitude de-rate schedule that would optimize flight operations for a reduced community noise nuisance. For example, it could have a reduced thrust profile on the ground at static conditions, and gradually increase thrust as the aircraft accelerates down the runway and gains distance from the community. This implementation would provide a net benefit to airline safety because current aircraft can be flown under circumstances where the cue-speeds (*V1, V2, VR*) do not correspond to minimum safety levels required for the actual thrust levels that the pilot has at his command.

In the event of engine failure, the safety of the passengers trumps community noise standards. The thrust of the remaining engines after an engine failure may prove either beneficial or hazardous to the crippled airframe.

Uncommanded yawing moments due to engine failure are directly proportional to the thrust asymmetry. Because aircraft engine thrust levels tend to lapse with increasing airspeed and aerodynamic forces scale proportionally with the square of the airspeed, there is a critical indicated airspeed where the aerodynamic control power of a fully deflected rudder can just balance the asymmetric thrust of a failed engine. This speed is known as the “minimum control ground speed,” V_{MCG}. For the aircraft to successfully fly, it must also not bank so sharply that it drags a wing-tip into the ground. Thus, there is a critical indicated airspeed where the aerodynamic control power of a fully deflected rudder and proportionally opposing ailerons can balance the asymmetric thrust of a failed engine and allow flight with less than 5^o of bank angle. This speed is known as the “minimum control airspeed,” V_{MCA}.

The takeoff decision speed must be faster than V_{MCG}, or the aircraft will uncontrollably veer off of the runway in the event of unrecognized engine failure.

The rotation speed of the aircraft must be faster than both V_{MCG} and V_{MCA}, or the aircraft will “capsize” upon attempted takeoff – digging wingtips into the runway and/or veering off course.

If the engine fails while the aircraft is still on the runway, thrust asymmetry tends to produce a yawing moment that would steer the airplane off of the runway centerline. Moreover, if engine failure occurs before the aircraft passes V_{MCG}, the thrust of the remaining engine would also continue to accelerate the airframe towards impending doom. Thus, it would be a safety benefit for an aggressive FADEC to immediately reduce the thrust (a “throttle pull”) on the remaining engine(s) in the event of engine failure far below the decision speed or V_{MCG}.

Above the decision speed, the rudder has enough aerodynamic capability to counter the thrust asymmetry of the remaining engines. The aircraft is expected to complete its takeoff. Takeoff safety improves with reduced pilot workloads. However two opposing actions come into play: if the FADEC increases the thrust (a “throttle push”) on the remaining engines, the aircraft will accelerate and climb more strongly (which is helpful for obstacle clearance) but the pilot will need to input increasing amounts of rudder to counter the stronger thrust asymmetry.

The Lockheed C-130J (which attained an FAA type certificate) is equipped with a complex ATTCS full-authority digital electronic control (FADEC).[26] The automatic thrust control system optimizes the balance of power on the engines, allowing lower values of minimum control speeds and superior short-airfield performance.[27] The C-130J FADECs are interconnected and can sense not only the failure of another engine, but identify which engine fails. On the C-130J FADEC implementation, the FADEC can “pull back” as well as “push” the throttles of the remaining engines. It is programmed to “pull back” the thrust from the opposing outboard engine in the event of an outboard engine failure at low indicated airspeeds. It ensures that the aircraft always operates above the V_{MCG} or V_{MCA} as established and allows the full performance of the uprated engines to be utilized once the aircraft reaches higher flight speeds.

More complex indicated-airspeed, altitude, weather, weight and configuration dependent de-rated thrust procedures have the potential to further impact new and retrofit-design airframes in many positive ways. The software engineering potential available to the performance engineer who controls the FADEC algorithm seems almost unlimited until the engineer reads 14 CFR § 25.904[7] and associated requirements in 14 CFR § 25 Appendix I closely.[20]

`14 C.F.R. § 25.904 Automatic takeoff thrust control system (ATTCS). (2014)`

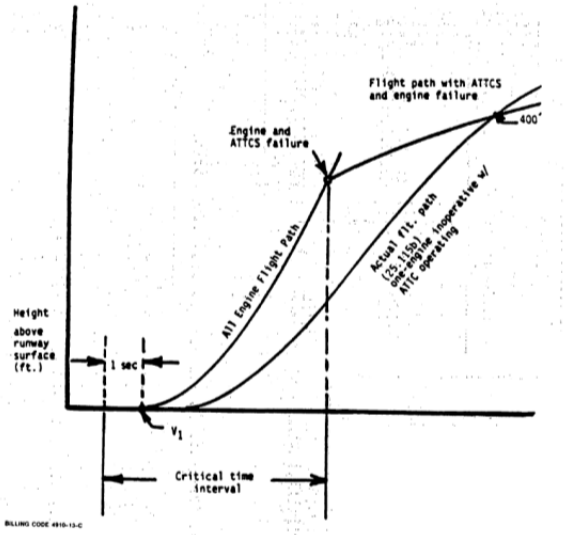
Each applicant seeking approval for installation of an engine power control system that automatically resets the power or thrust on the operating engine(s) when any engine fails during the takeoff must comply with the requirements of appendix I of this part.
[Amdt. 25-62, 52 FR 43156, Nov. 9, 1987]

The regulation is remarkably cryptic: it refers the engineer to read and follow Appendix I (see below).

14 C.F.R. 25.APPENDIX I (2014)

I25.1 General.
(a) This appendix specifies additional requirements for installation of an engine power control system that automatically resets thrust or power on operating engine(s) in the event of any one engine failure during takeoff.
(b) With the ATTCS and associated systems functioning normally as designed, all applicable requirements of Part 25, except as provided in this appendix, must be met without requiring any action by the crew to increase thrust or power.

I25.2 Definitions.
(a) **Automatic Takeoff Thrust Control System** (ATTCS). An ATTCS is defined as the entire automatic system used on takeoff, including all devices, both mechanical and electrical, that sense engine failure, transmit signals, actuate fuel controls or power levers or increase engine power by other means on operating engines to achieve scheduled thrust or power increases, and furnish cockpit information on system operation.
(b) **Critical Time Interval**. When conducting an ATTCS takeoff, the critical time interval is between V1 minus 1 second and a point on the minimum performance, all-engine flight path where, assuming a simultaneous occurrence of an engine and ATTCS failure, the resulting minimum flight path thereafter intersects the Part 25 required actual flight path at no less than 400 feet above the takeoff surface. This time interval is shown in the following illustration:



I25.3 Performance and System Reliability Requirements.

The applicant must comply with the performance and ATTCS reliability requirements as follows:
(a) An ATTCS failure or a combination of failures in the ATTCS during the critical time interval:
(1) Shall not prevent the insertion of the maximum approved takeoff thrust or power, or must be shown to be an improbable event.
(2) Shall not result in a significant loss or reduction in thrust or power, or must be shown to be an extremely improbable event.
(b) The concurrent existence of an ATTCS failure and an engine failure during the critical time interval must be shown to be extremely improbable.
(c) All applicable performance requirements of Part 25 must be met with an engine failure occurring at the most critical point during takeoff with the ATTCS system functioning.

I25.4 Thrust Setting.

The initial takeoff thrust or power setting on each engine at the beginning of the takeoff roll may not be less than any of the following:
(a) Ninety (90) percent of the thrust or power set by the ATTCS (the maximum takeoff thrust or power approved for the airplane under existing ambient conditions);
(b) That required to permit normal operation of all safety-related systems and equipment dependent upon engine thrust or power lever position; or
(c) That shown to be free of hazardous engine response characteristics when thrust or power is advanced from the initial takeoff thrust or power to the maximum approved takeoff thrust or power.

I25.5Powerplant Controls.

(a) In addition to the requirements of § 25.1141, no single failure or malfunction, or probable combination thereof, of the ATTCS, including associated systems, may cause the failure of any power plant function necessary for safety.
(b) The ATTCS must be designed to:
(1) Apply thrust or power on the operating engine(s), following any one engine failure during takeoff, to achieve the maximum approved takeoff thrust or power without exceeding engine operating limits;
(2) Permit manual decrease or increase in thrust or power up to the maximum takeoff thrust or power approved for the airplane under existing conditions through the use of the power lever. For airplanes equipped with limiters that automatically prevent engine operating limits from being exceeded under existing ambient conditions, other means may be used to increase the thrust or power in the event of an ATTCS failure provided the means is located on or forward of the power levers; is easily identified and operated under all operating conditions by a single action of either pilot with the hand that is normally used to actuate the power levers; and meets the requirements of § 25.777 (a), (b), and (c);
(3) Provide a means to verify to the flightcrew before takeoff that the ATTCS is in a condition to operate; and
(4) Provide a means for the flightcrew to deactivate the automatic function. This means must be designed to prevent inadvertent deactivation.

I25.6 Powerplant Instruments.

In addition to the requirements of § 25.1305:
(a) A means must be provided to indicate when the ATTCS is in the armed or ready condition; and
(b) If the inherent flight characteristics of the airplane do not provide adequate warning that an engine has failed, a warning system that is independent of the ATTCS must be provided to give the pilot a clear warning of any engine failure during takeoff.

[Amdt. 25-62, 52 FR 43156, Nov. 9, 1987]

The schematic seen in 14 CFR § 25 Appendix I.2b refers to the “net” flight path computation required by 14 CFR § 25.115b[28] and used to address obstacle clearance concerns. 14 CFR § 25.115b calls for the net takeoff flight path to be derived from the actual takeoff flight paths and then de-rated by a “gradient of climb equal to— (1) 0.8 percent for two-engine airplanes; (2) 0.9 percent for three-engine airplanes; and (3) 1.0 percent for four-engine airplanes.”

Compliance with 14 CFR § 25.I3[20] requires significant redundancy in the ATTCS and associated FADEC system. In other words, a complex ATTCS requires a system comprising multiple radar altimeters, GPS receivers and air-data systems and proven arbitration logic that ensures safe flight in the event one or more systems fail during flight.

Strict compliance with 14 CFR § 25.I4a[20] is more tricky. This regulation limits the ATTCS to a 10% thrust “push” in the event of an engine failure. This is not a major problem if the aircraft adopts a “flex temp” approach to de-rate, but otherwise potentially compromises the implementation of a more complex system. These regulations seem to be a codification of “Special Conditions” that were negotiated between FAA and Boeing in the development of a B737-200 engine control upgrade back in 1979. According to the docket, the 10% thrust “push” allowed by the ATTCS for performance credit cannot be applied for operations with reduced thrust. The FAA expressly states that “the initial thrust set at the beginning of takeoff may not be less than 90 percent of the maximum takeoff thrust approved for the airplane under existing conditions.”

According to FAA Advisory Circular AC 25-13, de-rated thrust procedures are limited to 75% of the thrust available to pilot under "existing ambient conditions."[29] Moreover, the minimum control speeds (V_{MCG} and V_{MCA}) used to plan a reduced thrust takeoff may not be "less than those which will comply with the required airworthiness controllability criteria when using the takeoff thrust … for the ambient conditions, including the effects of an Automatic Takeoff Thrust Control System (ATTCS)." These restrictions seem appropriate for simple ATTCS and de-rated thrust takeoff procedures but are overly restrictive to the development of a future system. This policy document insists that operations "utilizing reduced takeoff thrust settings … are not authorized on runways contaminated with standing water, snow, slush, or ice, and are not authorized on wet runways unless suitable performance accountability is made for the increased stopping distance on the wet surface."

Real-world aircraft have incorporated ATTCS, and may potentially be flown under "reduced thrust" or "flex temp" departure procedures. This section summarizes the FAA's position on ATTCS for popular aircraft.

1. The Lockheed C-130J civilian type certificate (TCDS A1SO[15]) does not contain any form of express call out or special condition for its speed dependent "throttle pull" ATTCS system.

2. The Airbus A318/319/320/321 family (certified under TCDS A28NM[30])) complies with 14 CFR § 25 rules in place through amendment 25-56. This means that it predates the promulgation of rule 14 CFR § 25.904, and need not expressly comply with these regulations. Instead, its electronic engine controls are certified under a special conditions exception.[31] Here, the FAA certified a FADEC that interfaces with different computer systems and enables an "autothrust mode" which commands engine thrust without the pilot changing the power lever position. On an A320 family aircraft, the flight management system can command the engines to produce full thrust (regardless of lever position) if the computer senses a need for high angle-of-attack stall protection. The autothrust mode is defeated if the pilot pushing a button on the power lever or if they move the power lever to the "takeoff/go-around" (TOGA) or flight idle (IDLE) setting.

3. The Airbus A330 family (certified under TCDS A46NM[32])), A340 family (certified under TCDS A43NM[33])) and Airbus A380 (certified under TCDS A58NM[34])) all postdate the promulgation of 14 CFR § 25.904. There are no waivers, special conditions or "equivalent levels of safety" called out in these type certificates regarding compliance with 14 CFR § 25.904. These aircraft all feature FADEC equipped engines.

4. The Boeing 777 family (certified under TCDS T00001SE[35])) and Boeing 787 (certified under TCDS T00021SE[36])) both postdate the promulgation of 14 CFR § 25.904. There are no waivers, special conditions or "equivalent levels of safety" called out in these type certificates regarding compliance with 14 CFR § 25.904. These aircraft all feature FADEC equipped engines.

5. The Embraer 170/190 family (certified under TCDS A56NM[37])) is certified under a special condition exception.[38] The Embraer ERJ-170 series incorporates ATTCS in its engine's FADEC system architecture. Its ATTCS automatically increases thrust to the maximum go-around thrust available under the ambient conditions: 1) if an engine failure occurs during an all-engines-operating go-around, or 2) if an engine has failed or been shut down earlier in the flight. Current regulations preclude credit for higher thrust during a missed-approach climb because of crew workload concerns. Since the ATTCS incorporated on the ERJ-170 series airplanes allows the pilot to use the same power setting procedure during a go-around, regardless of whether or not an engine fails, the FAA found that this design "adequately addresses the concerns about pilot workload which were discussed in the preamble to Amendment 25-62." While an ERJ-170 pilot may disable the ATTCS for takeoff; the system automatically re-engages when the pilot moves the power lever to a setting below TOGA, the aircraft attains > 700 feet AGL or a speed >140 KIAS).

Thus, the docket reveals the possibility for the FAA to certify an aircraft featuring a complex indicated-airspeed, altitude, weather, weight and configuration dependent de-rated thrust system provided that the manufacturer applies for a "Special Conditions" exception to a strict interpretation of existing rules. Numerical simulations can be used to identify what is the "art of the possible" in terms of the noise, performance and safety consequences of a complex ATTCS.

V. Numerical Simulations

A point mass simulation of aircraft TOLD procedures enables quantitative trade studies for policy-making decisions. Unlike the simple TOLD formulae found in common text books,[3,5,6] this simulation permits both balanced and un-balanced field length operations, abides by minimum controllable ground speed and airspeed regulations, allows for de-rated thrust takeoffs, and permits research into heuristic based schedules for proposed ATTCS.

The aerodynamics of the aircraft on the runway and in flight are represented by a simple, quadratic expression for drag:

$$CD = CD_0 + CL^2 / (\pi AR\, e) \tag{1}$$

and a slightly more complex equation for lift

$$CL = CL_0 + dCL/d\alpha\ \alpha \tag{2}$$

where:

$$dCL/d\alpha = 0.1177 * AR / (AR+3) \tag{3}$$

Where AR used in both the lift and drag equations is the "effective aspect ratio" of the planform, and e is so called "Oswald" efficiency factor of the wing. Values of e may approach 1.0 in flight. For this simulation, e, was presumed to be 0.85 for takeoff configuration flaps, 0.80 for initial approach configuration flaps and 0.70 for the aircraft with final approach configuration (fully extended and deflected) flaps. A simple ground effects model, relates the "effective aspect ratio" of the planform to its true geometric aspect ratio, by following this relationship:

```
If $HAG$< 100-ft                                                          (4)
  $AR = (b^2/ Sref) / ( -0.158 * \log_e(1 / ( 2*HAG+15)/100))) + 0.7868)$
else
  $AR = (b^2/ Sref)$
```

where HAG is the height above ground.

The propulsion model used in these simulations was prepared using the NPSS engine modeling program developed by NASA.[39] This process builds a series of databases of "five column" performance data (thrust and thrust-specific-fuel-consumption as a function of Mach number, altitude and power code) representing different types of high bypass-ratio turbofan engines. The model used here has a reference Bypass Ratio of 4.7:1. This engine is roughly equivalent in technology to the CFM 56 engine featured on the B737 or A320. It has an overall operating pressure ratio of 33:1; A maximum turbine inlet temperature, of 2300^{o}F, and a Fan Pressure Ratio of 1.6:1. In order to utilize this data, interpolation was repeatedly utilized to determine propulsion data at desired points. Thrust values are dynamic and lapse with speed and altitude.

A simple, time stepping algorithm applies thrust, drag and lift forces in appropriate balance to simulate all phases of takeoff. The simulation considers the following cases: 1) Normal Takeoff, with all engines operating, beginning with the aircraft at rest and rotation occurring at VR. 2) Rejected Takeoff, where a critical engine fails during the ground roll, and the pilot brings the aircraft to a stop on the runway. 3) Takeoff with Engine Failure, where a critical engine fails during the ground roll, and the pilot continues flight, rotating at a speed VR, necessary to ensure that the aircraft just clears a hypothetical 35-ft obstacle placed at the end of the runway while flying at the regulation imposed "obstacle clearance speed," $V2$. These procedures consider the regulatory influence of the minimum controllable ground speed, V_{MCG}, as well as the minimum controllable airspeed, V_{MCA}. The program estimates the second segment climb gradient based upon the specific excess power, $Ps = (T-D)/W$, at 400-ft above the airfield altitude while flying at the prescribed $V2$ speed. In addition to the lost thrust, under engine inoperative situations, the aircraft drag model includes the windmill drag of the disabled engine.

The trade studies shown herein consider an aircraft of approximate size, weight and configuration to a B737 or A320. These values were chosen to be representative of a future, high-technology but otherwise conventionally configured narrow-body wing-body-tail airliner. TOLD performance estimates were made over a broad range of flight weights, *W*, from 100,000-lbm through 170,000-lbm. The aircraft has a wing with *Sref*= 1250-ft^2; and span, *b*=110-ft; this implies a geometric aspect ratio of 9.1. The clean configuration zero lift drag coefficient, CD_0 = 0.0210; Takeoff configuration CD_0 = 0.0240; approach configuration CD_0 = 0.0290; and landing configuration CD_0 = 0.0510. The drag increments due to a stopped engine and associated control surface deflections is ΔCD_0 = 0.0180. The Takeoff configuration *CLmax* is 2.05; approach flaps *CLmax* is 2.45; the landing flaps *CLmax* is 2.8. The lift-coefficient at $\alpha=0^o$ with the Takeoff flaps deployed is 0.7; the maximum ground angle-of-attack, α_{max} is 14^o.

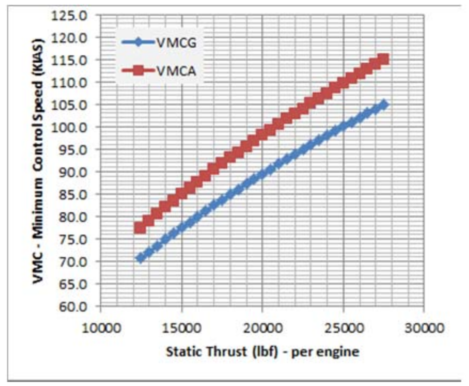


Figure 6 - Minimum Control Speeds (V_{MCA} and V_{MCG}) as a function of Engine Thrust

Minimum control speeds are assumed to be based upon aerodynamic forces (which scale with the square of the indicated airspeed) opposing yawing moments induced by the maximum thrust. For this particular airframe of interest, the following schedule (see Figure 6) represents V_{MCA} and V_{MCG} speeds under de-rated-thrust conditions.

$$VMCA \approx 47.8\,KIAS + 0.0025\,(StaticThrust) \qquad (5)$$

$$VMCG \approx 43.7\,KIAS + 0.0023\,(StaticThrust) \qquad (6)$$

Given these specifications, the simulation was exercised to perform several trade studies. All simulations presume flight near sea-level at stadndard-day conditions, but with a variety of possible weights and thrust derating schemes.

The baseline scenario models an aircraft with two 27,500-lbf static thrust engines, V_{MCG}=105 KIAS and V_{MCA}=115 KIAS, and no ATTCS "thrust push" in the event of a failed engine.

Figure 7 plots the "Critical Field Length" for this aircraft as a function of weight. Per 14 CFR§ 121.189[19], the pilot may not plan a to takeoff "at a weight greater than that listed in the Airplane Flight Manual at which compliance with the following may be shown: (1) The [one engine inoperative] accelerate-stop distance must not exceed the length of the runway plus the length of any stopway. (2) The [one engine inoperative] takeoff distance must not exceed the length of the runway plus the length of any clearway … (3) The [all engines operating] takeoff run must not be greater than the length of the runway … [and] that allows a net takeoff flight path that clears all obstacles." 14 CFR § 25.113 states the reported all-engines-operating takeoff run must be 115% of the actual takeoff distance from standstill to the point where the aircraft attains a flying altitude of 35-ft.[17]

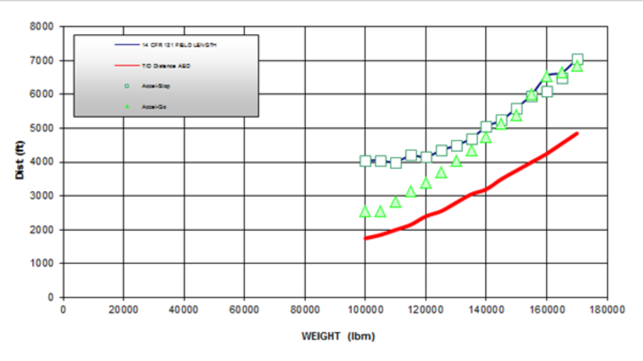


Figure 7 - T/O simulation for the reference airframe (BASELINE case) as a function of weight. Flight from a sea-level airport under standard-day (+15^{o}C) conditions. 14 CFR § 121 Critical Field Length, AEO takeoff, OEI Accel-Stop and OEI Accel-Go distances in ft.

In these simulations, we estimate the critical field length for an aircraft operating at the lowest possible decision speed that can develop balanced field conditions. As *V1* increases from *V1min* to *VR*, the accelerate-go distance remains unchanged while the accelerate-stop distance lengthens. The rotation speed is governed by 14 CFR § 25.107(e)[14]; it states that *VR* may not be less than either *V1*, 105% of V_{MCA}, and should be sufficient so that the aircraft naturally accelerates to reach *V2* before reaching an altitude of 35-ft. above the t/o service, does not lift off at an airspeed of less than either 110% of *Vmu* for AEO or 105% of *Vmu* OEI. 14 CFR § 25.107(a)[14] gives the manufacturer considerable discretion in the choice of the decision speed; "*V1* … is selected by the applicant" and is limited by the rotation speed (on the fast side) and the speed of a recognized but unplanned engine failure (on the slow side).

At 170,000-lbm flight weight, the reference configuration requires a minimum runway of 7,050-ft. This distance is controlled by both the one-engine-inoperative accelerate-go and accelerate-stop conditions. Turning now to Figure 8, we can see that the rotation speed, *VR*, is scheduled just a few knots below the obstacle clearance speed, *V2*. Neither *VR* nor *V2* are governed by minimum unstick speed (*Vmu*), or the minimum control speeds (V_{MCA} and V_{MCG}). The decision speed, *V1*, is chosen to balance the accelerate-go and accelerate-stop distances so that a one-engine-inoperative rotation at the scheduled rotation speed, *VR*, will allow the aircraft to leave the runway and attain the required *V2* speed at the 35-foot "obstacle height." However, when operating out of a long runway (say a 10,000-ft sea level runway) the aircraft will operate under wildly "unbalanced" field conditions. Based upon the scheduled rotation speed, **neither the accelerate-go nor the accelerate-stop distance nor the engine-inoperative climb gradient** applies. Under any foreseeable scenario, either all engines operating or with a critical engine failure just above the decision speed, the aircraft will rotate and leave the runway with ample distance remaining.

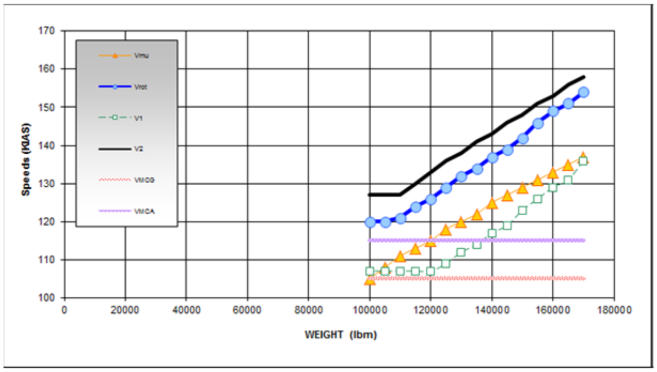


Figure 8 - T/O simulation for the reference airframe (BASELINE case) as a function of weight. Operation from a sea-level airport under standard-day (OAT=+15°C) conditions. Cue speeds: Minimum Unstick (*Vmu*), Rotation (*VR*), Decision (*V1*), Obstacle Clearance Speed (*V2*), V_{MCA} and V_{MCG}. and OEI Accel-Go distances

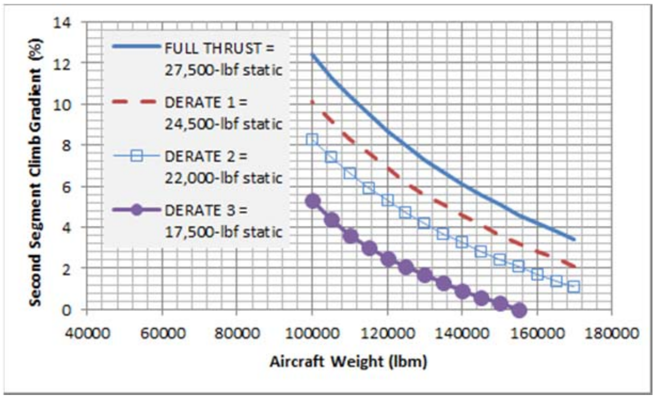


Figure 9 – Climb Gradient @ V2 and Airfield Altitude + 400-ft as a function of Aircraft Weight. Full thrust and for various de-rated "throttle pull" thrust levels.

If the pilot plans for takeoff at lighter weights, the critical field length will shorten; but in a non-linear manner. In general, a lighter weight will permit a lower scheduled rotation speed and a lower scheduled decision speed. Below a ~140,000-lbm takeoff weight, it is no longer practicable to have the limiting scenario result in a "balanced" field condition; the aircraft's critical field length is limited solely by the accelerate-stop scenario. Below ~120,000-lbm takeoff weight, the decision speed, *V1*, is limited by V_{MCG}; thus continued reductions in aircraft weight can no longer shorten the accelerate-stop distance. Below ~110,000-lbm, the aircraft rotation speed becomes V_{MCA} limited; this will "flatten" the trend towards shorter accelerate-go distances as a function of reduced takeoff weight.

Figure 9 plots the one-engine inoperative climb gradient attained during second-segment climb at V2, 400 feet above the airfield altitude. With the "full" 27,500-lbf static thrust engine (following the NPSS derived thrust lapse with speed and altitude), the aircraft easily exceeds its 14 CFR § 25.121 required 2.4% minimum climb gradient at all possible takeoff weights. Our baseline aircraft (reminiscent of the A320 or B737) has been engineered to have enough residual climb capability to be fully usable at maximum takeoff weight even on hot days, or on flights from airports located noticeably above sea-level.

If the engines are de-rated for a noise-abatement takeoff on a long runway, the role of the ATTCS comes into play. Returning to Figure 9, we can see the impact of reduced thrust on the one-engine inoperative second segment climb gradient. With a 24,500-lbf static thrust engine de-rate (following the NPSS derived thrust lapse with speed and altitude), the aircraft meets the 2.4% minimum climb gradient at weights less than 165,000-lbm. With a 22,000-lbf static thrust engine de-rate, the aircraft meets the 2.4% minimum climb gradient at weights less than 150,000-lbm. With a 17,500-lbf static thrust engine de-rate, the aircraft meets the 2.4% minimum climb gradient at weights less than 120,000-lbm. Thus a broad engine de-rate for all-engines-operating takeoff will significantly limit the aircraft's usable maximum takeoff weight due to operations becoming governed by the second-segment-climb gradient (14 CFR § 25.121) and obstacle clearance (14 CFR § 121.189[19]) regulations.

To better document the pro and con of various thrust de-rate schedules, we will now examine aircraft performance under eight alternative scenarios.

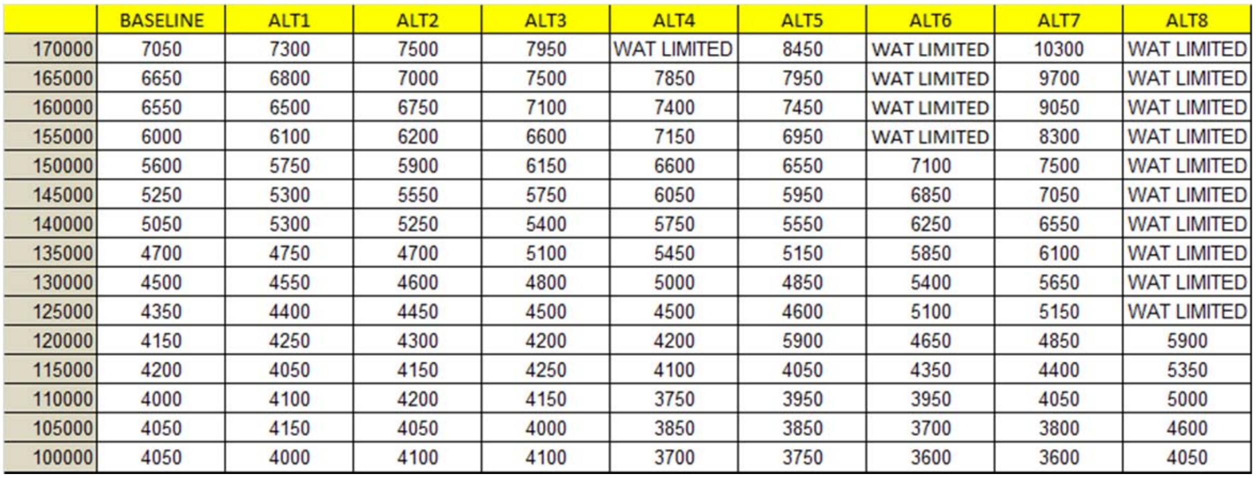
Alternative one models an aircraft with two 26,000-lbf static thrust engines, V_{MCG}=105 KIAS and V_{MCA}=115 KIAS, and an immediate ATTCS "thrust-push" to a 27,500-lbf static thrust rating in the event of a failed engine.

Alternative two models an aircraft with two de-rated 24,750-lbf static thrust engines, V_{MCG}=105 KIAS and V_{MCA}=115 KIAS, and an immediate ATTCS "thrust-push" to a 27,500-lbf static thrust rating in the event of a failed engine. This is the limit of ATTCS "thrust-push" allowable under the "90% rule."

Alternative three models an aircraft with two de-rated 22,000-lbf static thrust engines, V_{MCG}=105 KIAS and V_{MCA}=115 KIAS, and an immediate ATTCS "thrust-push" to a 27,500-lbf static thrust rating in the event of a failed engine. This has ATTCS "thrust-push" in excess of FAA policy.

Alternative four models an aircraft with two de-rated 22,000-lbf static thrust engines, V_{MCG}=99 KIAS and V_{MCA}=108 KIAS, and an immediate ATTCS "thrust-push" to a 24,500-lbf static thrust rating in the event of a failed engine. This has ATTCS "thrust-push" within FAA policy guidelines; but sacrifices overall thrust for accelerate-go and second segment climb performance.

Table 1 – Critical Field Length as a Function of Weight. Baseline and alternative ATTCS strategies.



	BASELINE	ALT1	ALT2	ALT3	ALT4	ALT5	ALT6	ALT7	ALT8
170000	7050	7300	7500	7950	WAT LIMITED	8450	WAT LIMITED	10300	WAT LIMITED
165000	6650	6800	7000	7500	7850	7950	WAT LIMITED	9700	WAT LIMITED
160000	6550	6500	6750	7100	7400	7450	WAT LIMITED	9050	WAT LIMITED
155000	6000	6100	6200	6600	7150	6950	WAT LIMITED	8300	WAT LIMITED
150000	5600	5750	5900	6150	6600	6550	7100	7500	WAT LIMITED
145000	5250	5300	5550	5750	6050	5950	6850	7050	WAT LIMITED
140000	5050	5300	5250	5400	5750	5550	6250	6550	WAT LIMITED
135000	4700	4750	4700	5100	5450	5150	5850	6100	WAT LIMITED
130000	4500	4550	4600	4800	5000	4850	5400	5650	WAT LIMITED
125000	4350	4400	4450	4500	4500	4600	5100	5150	WAT LIMITED
120000	4150	4250	4300	4200	4200	5900	4650	4850	5900
115000	4200	4050	4150	4250	4100	4050	4350	4400	5350
110000	4000	4100	4200	4150	3750	3950	3950	4050	5000
105000	4050	4150	4050	4000	3850	3850	3700	3800	4600
100000	4050	4000	4100	4100	3700	3750	3600	3600	4050

Alternative five models an aircraft with two de-rated 20,000-lbf static thrust engines, nominal V_{MCG}=90 KIAS and V_{MCA}=115 KIAS. ATTCS is implemented using a "thrust-push" up to the original 27,500-lbf static thrust rating in the event of a failed engine. Thrust levels are keyed to airspeed ensuring that the thrust push does not cause the aircraft to lose directional control.

Alternative six models an aircraft with two de-rated 20,000-lbf static thrust engines, V_{MCG}=94 KIAS and V_{MCA}=103 KIAS, and an immediate ATTCS "thrust-push" to a 22,000-lbf static thrust rating in the event of a failed engine. This has ATTCS "thrust-push" within FAA policy guidelines; but sacrifices overall thrust for accelerate-go and second segment climb performance.

Alternative seven models an aircraft with two de-rated 16,000-lbf static thrust engines, nominal V_{MCG}=75 KIAS and V_{MCA}=115 KIAS. ATTCS is implemented using a "thrust-push" up to the original 27,500-lbf static thrust rating in the event of a failed engine. Thrust levels are keyed to airspeed ensuring that the thrust push does not cause the aircraft to lose directional control.

Alternative eight models an aircraft with two de-rated 16,000-lbf static thrust engines, V_{MCG}=84 KIAS and V_{MCA}=92 KIAS, and an immediate ATTCS "thrust-push" to a 17,500-lbf static thrust rating in the event of a failed engine. This has ATTCS "thrust-push" within FAA policy guidelines; but sacrifices overall thrust for accelerate-go and second segment climb performance.

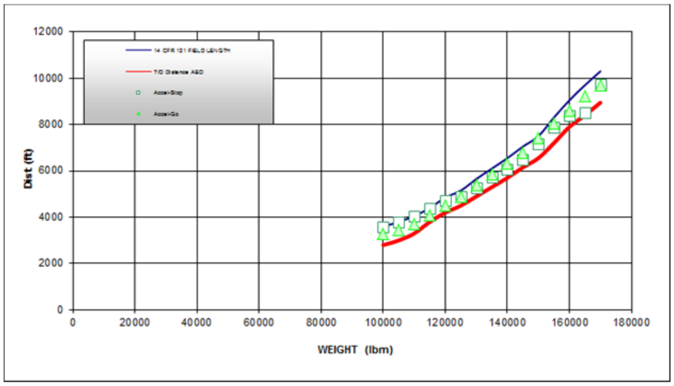


Figure 10 –T/O simulation for Alternative 7 as a function of weight. Flight from a sea-level airport under standard-day (+15^{o}C) conditions. 14 CFR § 121 Critical Field Length, AEO takeoff, OEI Accel-Stop and OEI Accel-Go distances in ft.

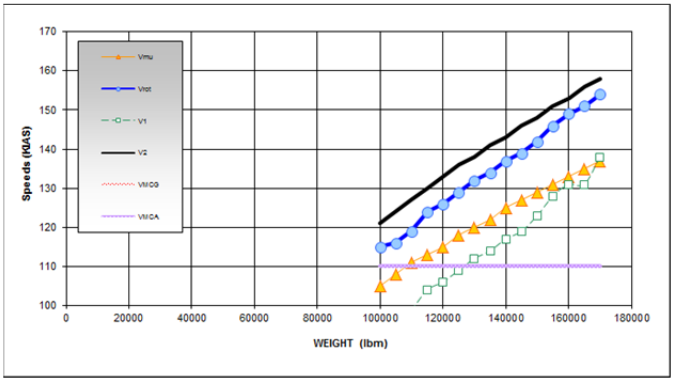


Figure 11 –T/O simulation for Alternative 7. Operation from a sea-level airport under standard-day (OAT=+15^{o}C) conditions. Cue speeds: Minimum Unstick (*Vmu*), Rotation (*VR*), Decision (*V1*), Obstacle Clearance Speed (*V2*), V_{MCA} and V_{MCG}. and OEI Accel-Go distances

For otherwise identical aerodynamics and basic propulsion characteristics (holding static thrust loading equal), the differences in distances shown in Table 1 are dramatic. For operation on a long, sea-level runway, like those found at Boston, JFK or LAX, a very aggressive thrust-derating scheme can be employed (Alternative 7). This ATTCS implementation utilizes a 40% de-rate to 16,000-lbf static thrust with both engines operating. This allows ample runway margin at all foreseeable takeoff weights with a significant reduction in community noise. In order to maintain statutory minimum critical engine inoperative climb gradients, this schema must allow the remaining engine to produce its full power upon sensed engine failure – not limit itself to the 14 CFR § 25.I2(b) imposed limit of a 10% throttle push. If limited to a 10% throttle push (Alternative 8), this level of de-rate will be "WAT Limited;" the aircraft will have insufficient excess thrust to climb at weights in excess of 115,000-lbm.

Figures 10 and 11 (above) demonstrate how the indicated airspeed keyed "throttle push" from a significant de-rate to full power to achieve safe operation. Due to the low initial thrust, V_{MCG} is set to only 75 KIAS; this results in an extremely slow decision speed, *V1*, at the lightest weights. A byproduct of the low decision speed is a reduction in the accelerate-stop distance. Unlike the baseline model, the trend in accelerate-stop distance with weight no longer "flattens out." Because full power is eventually achieved in a one-engine-inoperative scenario (through aggressive ATTCS intervention), despite the significant de-rate at the beginning of the takeoff roll this aircraft has the full second-segment climb capability (along with the full V_{MCA}) of the baseline aircraft. Interestingly, the critical field length is governed by the 14 CFR 25.113 imposed 115% of the all-engines-operating distances! [17]

While the required runway lengths are longer, this substantial de-rate continues to allow safe flight from most airports.

The reduced value of V_{MCG} is a byproduct of the de-rated thrust takeoff. It enables slower decision speeds, *V1*. Lower V_{MCG} values imply greater control authority and a reduction in pilot workload in the event an engine fails above V_{MCG}. However, reductions in decision speed force a pilot to commit to an engine-out takeoff in the event an engine fails above an unnecessarily low *V1* speed. Is this good public policy?

Most pilots would prefer to reject rather than continue a takeoff in the event of engine failure. It is straightforward to produce certified data for takeoff planning where the decision speed is increased far above statutory minimums. This leads to longer accelerate-stop distances; but these distances may well be within the available runway length. Thus a flight plan incorporating an elevated decision speed may well prove safer in the event of engine failure.

Alternative nine models the baseline aircraft with two 27,500-lbf static thrust engines, V_{MCG}=105 KIAS and V_{MCA}=115 KIAS, but with *V1*=*VR*. Figure 12 plots the “Critical Field Length” for this aircraft as a function of weight. With the elevated decision speed, at 170,000-lbm flight weight, the aircraft now requires a minimum runway of 8,100-ft limited by one-engine-inoperative accelerate-stop conditions with the engine failure occurring right at rotation. Turning now to Figure 13, we can see that the decision speed, *V1*, matches the rotation speed, *VR*. Both are scheduled just a few knots below the obstacle clearance speed, *V2*. As weight declines, the decision speed continues to track *VR*, and the required runway length diminishes while still governed by the accelerate-stop-distance. Under any foreseeable scenario on a dry 10,000-ft runway, the aircraft can either rotate and leave the runway or stop with ample distance remaining.

Alternative ten models an aircraft with two de-rated 16,000-lbf static thrust engines, V_{MCG}=75 KIAS and V_{MCA}=115 KIAS, and an immediate ATTCS “thrust-push” to a 27,500-lbf static thrust rating in the event of a failed engine. ATTCS is implemented using a “thrust-push” up to the original 27,500-lbf static thrust rating in the event of a failed engine. Thrust levels are keyed to airspeed ensuring that the thrust push does not cause the aircraft to lose directional control. As with alternative 9, we have elevated the decision speed to rotation speed, *V1*=*VR*, at all weights.

The combination of elevated decision speed and severe (40%) thrust de-rate gives the longest runway distances in this study. Referring now to

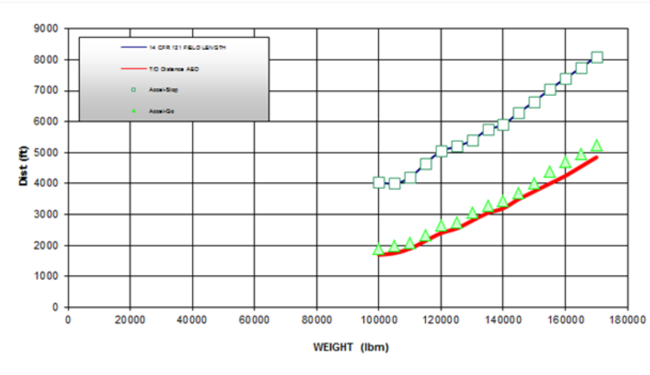


Figure 12 –T/O simulation for Alternative 9 (baseline configuration but with an elevated decision speed). *V1*=*VR*. Flight from a sea-level airport under standard-day (+15°C) conditions. 14 CFR § 121 Critical Field Length, AEO takeoff, OEI Accel-Stop and OEI Accel-Go distances in ft.

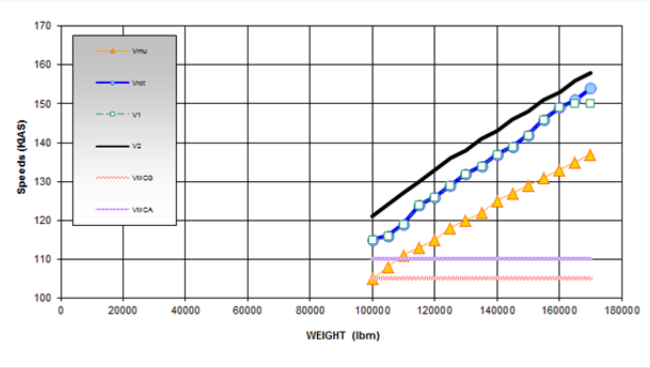


Figure 13 - T/O simulation for Alternative 9 (Baseline Configuration with *V1*=*VR*). Operation from a sea-level airport under standard-day (OAT=+15°C) conditions. Cue speeds: Minimum Unstick (*Vmu*), Rotation (*VR*), Decision (*V1*), Obstacle Clearance Speed (*V2*), V_{MCA} and V_{MCG}.

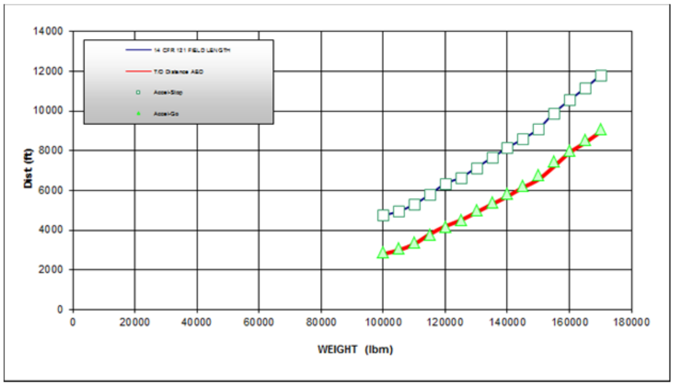


Figure 14 –T/O simulation for Alternative 10 (severely de-rated thrust with aggressive ATTCS and *V1* =*VR*). Flight from a sea-level airport under standard-day (+15°C) conditions. 14 CFR § 121 Critical Field Length, AEO takeoff, OEI Accel-Stop and OEI Accel-Go distances in ft.

Figure 14, the reader can see that the aircraft now requires nearly 12,000-ft runway for operations at high gross weights. This distance permits this aircraft to operate from JFK in the winter at any possible takeoff weight.

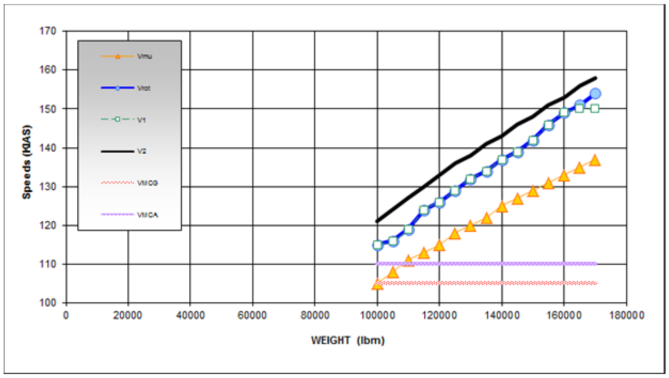


Figure 15 - T/O simulation for Alternative 10 (severely de-rated thrust with aggressive ATTCS and *V1*=*VR*) Operation from a sea-level airport under standard-day (OAT=+15^{o}C) conditions. Cue speeds: Minimum Unstick (*Vmu*), Rotation (*VR*), Decision (*V1*), Obstacle Clearance Speed (*V2*), V_{MCA} and V_{MCG}. and OEI Accel-Go distances

Limiting the aircraft to operations at 140,000-lbm, a realistic departure weight for a short haul flight on an A320 or B737 class airframe, unlocks the true potential of an aggressive ATTCS system in conjunction with elevated decision speeds. With a 137 knot decision speed at 140,000-lbm (see Figure 15), the accelerate-go distances with one-engine inoperative (and the remaining engine employing full ATTCS "throttle push") are essentially similar to the all-engines-operating (at a severe de-rate) takeoff distances. In all cases, the critical field length is governed by the accelerate-stop distance which is ~8,000-ft. So long as the aircraft is scheduled to operate out of a runway longer than this (a reasonable assumption), there is no runway overrun hazard.

From a pilot's standpoint, in the event that the decision speed is the rotation speed it would nearly eliminate the situation where the aircraft would continue departure after an engine failure on takeoff roll. If an engine were to fail after rotation (for example due to FOD ingestion), the ATTCS "throttle push" ensures a positive rate of climb using the remaining engine. Because 1) the decision speed is set equal to the rotation speed, and 2) the rotation speed is above V_{MCA}, full power can be immediately applied to the remaining engine. Aircraft utility can be enhanced with software selectable intermediate de-rate and elevated decision speed options. This will permit the operator to better tailor aircraft operations to the weather at hand on a particular runway of interest.

VI. Conclusions and Policy Recommendations

This paper also demonstrates the potential of generic studies of transport aircraft performance to inform public policy makers of the limitations found in the current regulatory system. Improved aircraft designs demand both **technological and regulatory** advancement.

The physics-based simulation employed herein is considerably more complex than that described in popular aircraft performance texts. At the same time, this simulation does not rely upon any manufacturer proprietary data. High quality lift, drag and thrust estimates may be inferred from public documents.

The author finds that existing ATTCS regulations are simultaneously too vague and too restrictive to easily certify an aircraft with a complex automatic thrust control system. Analysis of the Special Conditions and basic certification docket for the Boeing 737, Lockheed C-130J, Embraer 170 and Airbus A320 family aircraft reveals that even older designs successfully incorporate complex speed, attitude and altitude dependent FADEC auto throttle control systems. The docket does not indicate any major safety hazard stemming from this level of cockpit automation. The docket also demonstrates that the currently popular "flex temp" de-rating schema has an increased potential for pilot error; one that could be reduced through a more widespread adoption of a Boeing-style "de-rated thrust" system but applied to an Airbus-style power-level control schema (with multiple de-rate stops). Enhanced safety on long runways can be attained with an ability to schedule elevated decision speeds, *V1*, potentially as fast as the rotation speed, *VR*, in conjunction with a de-rated thrust takeoff. If flight manuals and mission computers were programmed to offer a variety of decision speed strategies, pilots would have the ultimate in flexibility in operations: when conditions permit they could select a noise-friendly takeoff on a long runway with an elevated decision speed; they could also select a high-thrust, short-field friend schedule with a reduced decision speed. Presently, aircraft training manuals indicate that pilots attempt these procedures manually; through the use of "assumed temperature methods" and manual triggering of full engine power through judicious use of the TO/GA override switch.

If the dynamic range of available thrust de-rates and ATTCS "throttle push" authority is expanded, aircraft equipped with such systems could greatly reduce their community noise footprint with an increase to passenger safety. Aggressive "throttle push" under de-rated thrust conditions could be automated in a method transparent to the pilot; rather than relying on a pilot to press a TO/GA button, advance the throttles and "beware" of the fact that the aircraft may possibly now operating outside of its minimum control airspeed and groundspeed.

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