

# (Un)controlled Flight into Terrain: A History of Obstacle Clearance Regulations

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Because aviation is comprehensively regulated, commercial flying is safer than it ever was before. This was not the case during the early years of aviation. Back in the early 1930's, only limited regulations governed takeoff distance (land based aircraft were expected to takeoff in less under 1000-ft) and all-engines-operating climb (the “Rule of Eight,” which required aircraft to have an all engines operative climb rate (in ft/min) of eight times its stall speed (in knots)). In this paper, we make a historical inquiry into the evolution of regulations governing the takeoff obstacle clearance problem. We show that the FAA, and its predecessor agencies, typically establish and amend Federal Aviation Regulations on a reactionary—not proactive—basis after high profile crashes. We trace amendments to key regulations governing the obstacle clearance problem to specific air accidents where insufficient climb performance was deemed as the probable cause of death.

## Nomenclature

$AGL$	=	altitude above ground level (ft)
$ALT$	=	altitude (above sea level) (ft)
$V_{FTO}$	=	en-route climb speed (final – flaps up) (nM/hr)
$V_{MCA}$	=	engine-inoperative minimum control speed in the air (nM/hr)
$V_{MCG}$	=	engine-inoperative minimum control speed on the ground (nM/hr)
$V_{SR}$	=	reference stall speed (nM/hr) (depends on flap setting, or could be for the en-route wing configuration)
$V_1$	=	takeoff go/no-go decision speed (nM/hr)
$V_2$	=	takeoff engine-inoperative second segment (takeoff flaps deployed) climb speed (nM/hr)
$W$	=	aircraft weight (lbm)

## I. Introduction

AN old adage says “there are old pilots and there are bold pilots;” yet even “bold pilots” do not intentionally crash their aircraft. When aviation was young, aircraft crashes were a frequent occurrence. At the turn of the twentieth century, when the rigid Zeppelin airship was the foremost long range aircraft, 34 airships of the first 88 built were directly lost to “accidents” and “bad weather.”<sup>1</sup> While it is difficult to determine the loss rate of fixed wing aircraft built during the First World War, due to so many being lost in combat, the loss rate during the “barnstorming” era subsequent to the cessation of hostilities was worrisome. The United States government,

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recognizing a clear need to regulate this activity to ensure that all who take to the skies do so in a manner that is safe for everybody, acted by passing the Air Commerce Act of 1926.<sup>2</sup>

During this period, before Roosevelt and the “New Deal,” lawyers questioned the permissibility of the Federal Government to regulate aviation. A committee formed by the American Bar Association wrote an opinion that suggested that “the Supreme Court has gone so far in allowing the regulation of intrastate commerce by a Federal agency that there is no doubt that this court would support a Federal Statute giving the Federal Government exclusive power to register aircraft, license pilots and establish rules for aerial navigation.”<sup>3</sup>

Thus, in 1926 Congress and President Coolidge acted upon this recommendation and signed into law an Act that gave the Secretary of Commerce executive power to foster the development of “air commerce.” That is “transportation in whole or in part by aircraft of persons or property for hire, navigation of aircraft in the furtherance of a business, or navigation of aircraft ... in the conduct of a business.”<sup>4</sup> The powers bestowed upon the Executive include the ability to (1) license pilots, (2) establish air traffic rules and (3) issue airworthiness certificates for aircraft and major aircraft components.<sup>3</sup> Since 1926, the Federal Government has promulgated regulations in place limiting who could fly and what could fly as well as rules that dictate *how* a pilot should operate aircraft with respect to its performance.

Despite the government’s best intentions, this first step to ensure safety in the air was unsurprisingly not enough. Several aviation accidents placed the Department of Commerce under considerable scrutiny, with many questioning its effectiveness. Realizing the need to strengthen its stance on aviation safety, the Roosevelt administration encouraged the Civil Aeronautics Act of 1938, which established the independent Civil Aeronautics Authority and inherited all aviation responsibilities of the Secretary of Commerce. Sometime later, this entity split into two agencies: (1) The Civil Aeronautics Administration, who was responsible for the certification of aircraft and pilots, and (2) the Civil Aeronautics Board, tasked with the establishment of safety regulations.<sup>4</sup>

Passage of additional legislation in 1958 gave rise to the Federal Aviation Agency, which inherited the responsibilities of the Civil Aeronautics Administration. In 1967, the Federal Aviation Agency downsized to the Federal Aviation Administration (FAA), which operated within the newly-established Department of Transportation (DOT). The FAA retains many of its responsibilities from when it was an agency, except for the power of air accident investigation, which principally resides with the DOT. Of the many retained powers, the FAA has the authority to establish Federal Aviation Regulations (FARs). Title 14 (Aeronautics & Space) of the Code of Federal Regulations (CFR) is the repository for these rules.<sup>5</sup> Additionally, the FAA has the power to investigate suspected violations of these FARs, as well as initiate administrative action against those who violate them.<sup>6</sup>

Despite the change of hands over time, the power to issue airworthiness certification currently resides with the FAA. Just as how a pilot may not operate an aircraft without the appropriate airman certificate, aircraft cannot legally fly without a valid airworthiness certificate. To procure airworthiness certification, aircraft designers must prove that their aircraft abides by the Federal Regulations that govern both structural design and performance. To demonstrate compliance with federally-regulated performance minimums, a flight test that demonstrates an aircraft’s capabilities under a variety of operating conditions suffices. A test to destruction is evidence enough to support claims of compliance to structural design regulations. Due to the FAA’s strict criteria on who can fly, what can fly, and how aircraft should fly, taking to the skies in present-day is safer than ever before.

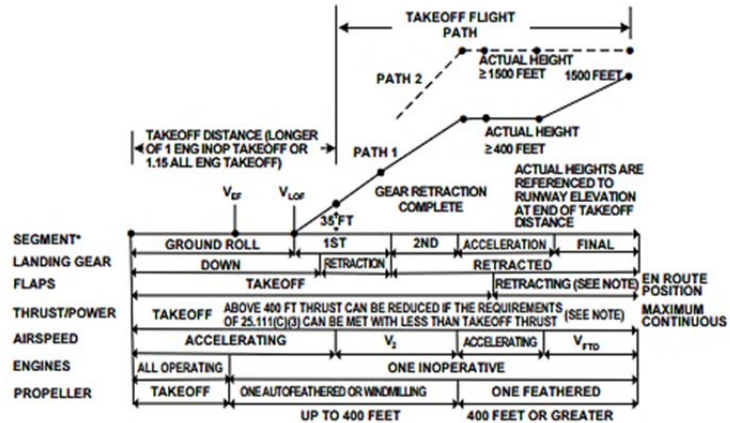
As things presently stand, “bold pilots” ignore aircraft operating procedure made according to Federal Regulations while “old pilots” carefully follow such procedure. These procedures, as documented in a FAA approved Aircraft Flight Manual, limit speeds and weights to ensure that pilots always fly with ample reserve aircraft performance – this includes a substantial buffer with respect to accidental stall, sufficient stability and control to handle atmospheric turbulence and other forms of bad weather, and reserve climb performance to ensure that an aircraft never will accidentally fly into terrain due to a failed engine.

## II. Federal Regulations Pertinent to the Present-Day Obstacle Clearance Problem

To support this claim of flight being “safer than before”, it is necessary to paint a picture of the dispatch problem as it stands today. A collection of Federal Regulations fills this picture. In terms of basic aircraft performance independent of terrain, modern day 14 CFR § 25.111<sup>7</sup> implies a standard four-segment takeoff procedure (see Figure 1). Regulations 14 CFR § 25.113<sup>8</sup>, 14 CFR § 25.115<sup>9</sup> and 14 CFR § 25.117<sup>10</sup> provide supporting documentation and additional clarification. Regulation 14 CFR § 25.121<sup>11</sup> requires aircraft to demonstrate minimum climb capability at altitudes less than 1,500-ft AGL with an engine-inoperative before being allowed to takeoff. Regulation 14 CFR § 25.123<sup>12</sup> proscribes minimum climb capability when flying in the “en-route” configuration. Several other regulations such as 14 CFR § 25.101<sup>13</sup>, 14 CFR § 25.103<sup>14</sup>, 14 CFR § 25.107<sup>15</sup>, 14 CFR § 25.143<sup>16</sup> and 14 CFR 25.149<sup>17</sup> govern the minimum permissible airspeed for flight.

### A. Takeoff Flight Path

Regulation 14 CFR § 25.111<sup>11</sup> holds that the total takeoff path “[extends] from a standing start to a point in the takeoff at which the airplane is 1,500 feet above the takeoff surface, or at which the transition from the takeoff to the en-route configuration is completed and  $V_{FTO}$  is reached, whichever is higher.” In other words, the takeoff flight path is defined as the segment of flight that begins from rest on the runway to when the aircraft attains *either* (1) an altitude of 1,500 feet above ground level *or* (2) completion of the transition into en-route configuration *and* flies at the final takeoff speed,  $V_{FTO}$ , whichever is higher in altitude. This definition of the takeoff flight path is important because other regulations refer to it; we will discuss this later.

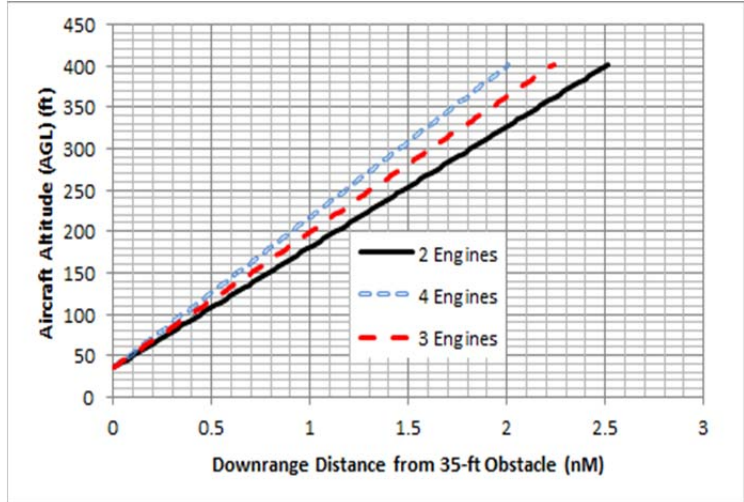


**Figure 1. Typical takeoff profile.** Upon end of the second segment climb, that being at 400-ft AGL or higher, the aircraft levels off and picks up speed for the fourth (final) segment climb. Note that takeoff procedures are planned with the critical engine-inoperative case in mind, as evidenced by this figure.

The FAA requires operating limitations to ensure that aircraft demonstrate performance capabilities that meet or exceed the minimums imposed by Federal Regulation. The expectation of the FAA is that all aircraft, for example, are safely operable in all expected operating conditions – including when one engine is inoperative. Federal Regulation 14 CFR § 25.121<sup>11</sup> establishes required minimums on gross climb gradient performance expected of an aircraft when operating with one engine-inoperative. For a two-engine aircraft taking off with flaps out, gear down, and one engine-inoperative, the vehicle must produce a steady positive gross climb gradient for first segment climb at the liftoff speed,  $V_{LOF}$ . Three- and four-engine aircraft must produce a steady gross climb gradient of 0.3% or 0.5%, respectively. After completion of gear retraction, subpart (b) requires that the engine-inoperative aircraft must produce a steady gross climb gradient of either 2.4%, 2.7%, or 3.0%, depending on if there are either two, three, or four-engines equipped, respectively, flying at the second-segment climb speed  $V_2$ . Subpart (c) regulates the “final” takeoff climb, which is typically characterized by the aircraft flying in the en-route configuration (takeoff flaps and gear stowed). In this segment, the engine-inoperative aircraft must produce a steady gross climb gradient of 1.2% for two-engine vehicles, 1.5% for three-engine vehicles, and 1.7% for four-engine vehicles at  $V_{FTO}$ .

These minimum prescribed climb gradients do not promote rapid climb.

Consider the first segment flight path inferred by 14 CFR § 25.121<sup>11</sup>. If a two-engine aircraft develops 0.1% gross climb gradient upon lift off, it would traverse 35,000-ft before it could climb to 35-ft altitude. Given that the longest military runway in the United States (Runway 6 at Edwards Air Force Base) is 18,150-ft long, no practical runway exists that could possibly service an aircraft with such poor initial climb. The 0.3% and 0.5% minimum first segment gradient requirement for three and four-engine aircraft are little better. A 0.3% gradient implies an 11,677-ft air phase distance between wheels up and 35-ft AGL; a 0.5% gradient implies a 7,000-ft air phase distance between wheels up and 35-ft AGL. Therefore, in practice, the first segment gradient requirement (whose air phase distance is buried into the runway critical field length distance computation) does not govern any realistic departure.



**Figure 2. FAA Minimum Second Segment Climb profile.** Upon end of the second segment climb (400-ft AGL or higher), the aircraft will need to level off.

Consider the second segment flight path inferred by 14 CFR § 25.121<sup>11</sup>; see Fig. 2. If a two-engine aircraft develops 2.4% gross climb gradient upon lift off, it would traverse 15,300-ft (~2.5 nM) downrange before it could climb to the 400-ft minimum flap retraction altitude. The 2.7% and 3.0% minimum second segment gradient requirement for three and four-engine aircraft are somewhat better: a three-engine aircraft will traverse 2.23-nM; a four-engine aircraft need traverse 2.0-nM to attain 400-ft altitude. While real world operations may encounter close-in terrain or other obstacles along such a shallow flight path, these minimum climb gradients seem reasonable as a hard limit to ensure safe departures.

In order to compute the climb gradient, the engineer must know the weight, the thrust developed by the engines and the aerodynamic drag:

$$\% \text{ Gradient} = \frac{T - D}{W} \quad (1)$$

Commercial aircraft engines utilize thermodynamic cycles that render thrust as a strong function of pressure altitude (ALT), flight speed (indicated airspeed) and airfield temperature (OAT).

Aircraft drag is a function of aircraft geometry, attitude and flight speed that prescribe a reference wing area ( $S_{ref}$ ) and a strongly lift coefficient dependent drag coefficient ( $C_D$ ) that is also a function of flight speed (Mach #) and pressure altitude (ALT):

$$D = C_D(C_L, M, ALT) q S_{ref} \quad (2)$$

The dynamic pressure in lbf/ft<sup>2</sup> is a function of equivalent (indicated airspeed):

$$q \cong 1481 \left( \frac{\text{KIAS}}{660.8} \right)^2 \quad (3)$$

Thus, the climb performance of an aircraft is a strong function of the inherent aircraft geometry **and** the flight speed at which the pilot attempts to climb. It should be no surprise that the  $V$  speeds which pilot fly their aircraft during takeoff climb out are governed by Federal Regulation.

Regulation 14 CFR § 25.107(c)<sup>15</sup> details how the aircraft designer should establish the engine-inoperative second segment climb cue speed,  $V_2$ . This speed ensures that the aircraft can attain the steady gross climb gradient in the previously-discussed 14 CFR § 25.121(b) (second segment climb gradient) with adequate margins for stall and controllability. This speed may be no slower than (1)  $V_{2MIN}$ , (2)  $V_R$ , the rotation speed, or (3) the speed which provides the maneuvering capability specified in 14 CFR § 25.143(h)<sup>16</sup>, whichever is greater.

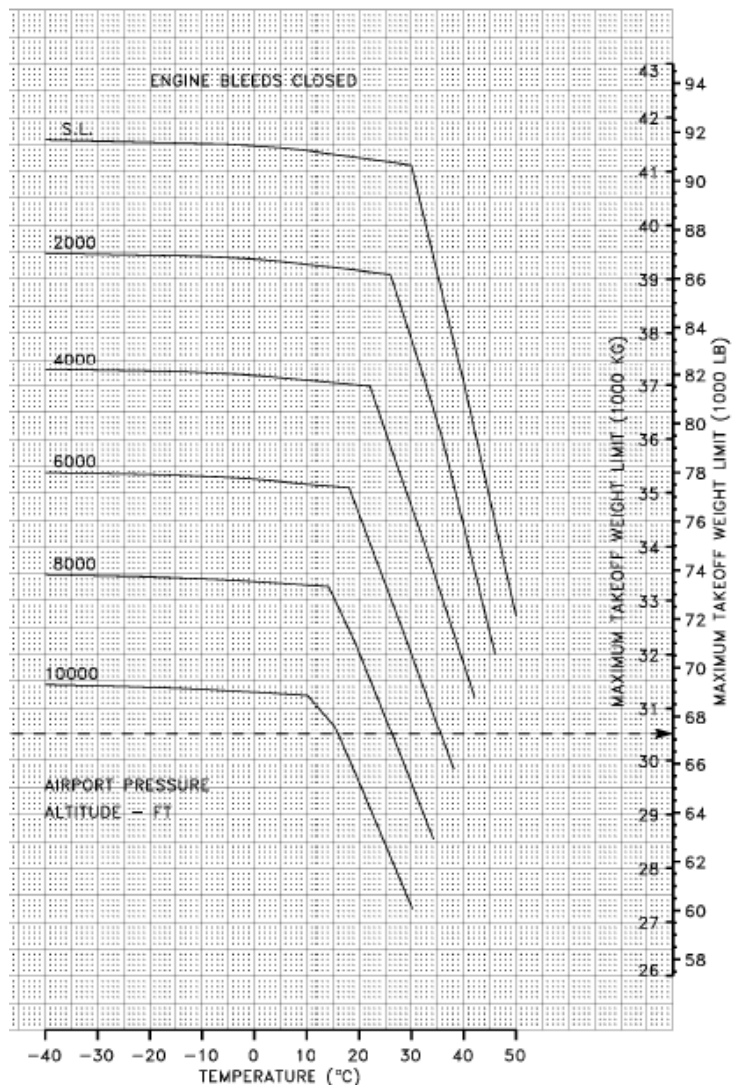
Regulation 14 CFR § 25.107(g)<sup>15</sup> controls the final takeoff speed,  $V_{FTO}$ . Compliance with this law ensures that the aircraft climb at the minimum gross climb gradient prescribed by 14 CFR § 25.121(c) (final takeoff climb gradient), as well as be no slower than (1) 1.18 times the reference stall speed  $V_{SR}$ , or (2) the speed which gives the aircraft the maneuvering capability outlined in 14 CFR § 25.143(h)<sup>16</sup>.

### B. Dispatch

Prior to takeoff, either a pilot or his agent must file an approved flight plan with the FAA. Among the necessities of a flight plan is a carefully-planned takeoff procedure. To ensure continued safety for all involved persons, the FAA encourages the use of an evidenced-based FAA approved aircraft flight manual (AFM).

The AFM is useful for both pilots and dispatch personnel alike, for it contains the important cue speeds to which the pilot must fly to. It additionally includes maximum dispatch weight guidance charts, WAT (weight-altitude-temperature) limit charts, which identifies the maximum-allowable takeoff weight with respect to airfield altitude and ambient temperature so that the aircraft will always perform as well as or better than the federal minimums. So long as the pilot flies the aircraft at the prescribed cue speeds, climb gradient performance in the event of an engine failure should meet basic federal standards.

To ensure that dispatch personnel do not forego the use of these WAT limit charts, 14 CFR § 121.189(a) dictates that “no person operating a turbine engine powered airplane may take off ... at a weight greater than that listed in the Airplane Flight Manual for the elevation of the airport and for the ambient temperature existing at takeoff”.<sup>18</sup> In layman’s terms, this regulation makes it illegal to take flight in an aircraft at a weight which is



**Figure 3. Example Modern WAT limit chart.** For a given airport altitude and temperature, this chart gives a maximum allowable takeoff weight. Dispatch underneath this weight guarantees compliance with minimum climb gradient requirements. Reproduced from CRJ-700 AFM

greater than that suggested by the WAT limit charts. This effectively guarantees that all aircraft will dispatch with enough climb gradient performance to abide by the federal minimums in the event of an engine failure – again, so long as the pilot operates the aircraft at the prescribed cue speeds.

To add an additional “margin of error” for takeoff planning, dispatch personnel are required to consider an aircraft’s *net* climb gradient performance, as opposed to its *gross*, or actual, climb gradient performance when planning departure in the presence of terrain or other obstacles. To safely dispatch, the aircraft must be able to climb over (or avoid by turning) all obstacles along the intended flight path. Flight planning documents, such as Standard Instrument Departure (SID) charts will give dispatch and pilots a recommended ground track to overfly as well as a minimum climb gradient (often given in terms of feet of altitude gain per nautical mile flown).

Regulations found in 14 CFR § 121 make numerous references to the aircraft’s *net* climb gradient performance.<sup>19</sup> The calculation of an aircraft’s net flight path from knowing the gross is through a simple “derate” applied to the latter. As per 14 CFR § 25.115(b), “the net takeoff path flight data must be determined so that they represent the actual [gross] takeoff flight paths ... reduced at each point 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.”<sup>9</sup>

The en-route *net* flight path, interestingly, requires a different “derate” from that of the takeoff *net* flight path. Quoting regulation 14 CFR § 25.123(b), “the one-engine-inoperative net flight path data must represent the actual [gross] climb performance diminished by a gradient of climb of 1.1 percent for two-engine airplanes, 1.4 percent for three-engine airplanes, and 1.6 percent for four-engine airplanes.<sup>12</sup> Per 14 CFR § 25.123 (a), this derate applies strictly to when the aircraft is *both* in the en-route configuration—flaps and gear stowed—and at a speed no less than  $V_{FTO}$ .<sup>12</sup>

Applications of these derates creates a “margin of error” which can account for variations in pilot attention (climb speeds being slightly “off” the cue speed), atmospheric conditions (temperature and winds), and engine performance degradation due to wear.

By law, the dispatcher must take a pessimistic stance on the aircraft’s expected performance; the actual aircraft performance should always exceed that used in the flight plan.

### **III. Regulatory History of the Obstacle Clearance Problem**

The existence of these interlocking regulations aids the FAA’s pursuit of ensuring continued flight safety for all. A perusal of early regulations indicates that today’s regulations are the result of 90 years of additions and amendments.

To understand just how much Federal Regulations have matured over the years, we will present the history of obstacle clearance regulation.

Because Federal Regulation of aviation predates Roosevelt’s “New Deal” and its major reform to Federal Administrative Law, Federal Aviation Regulations predate today’s Code of Federal Regulations. The Federal Register system of publication was created on July 26, 1935, when President Roosevelt signed the Federal Register Act. [20] This law originally provided for a complete compilation of all existing regulations promulgated prior to the first publication of the Federal Register; this is what led to the 1938 publication of the first Code of Federal Regulations. Since 1938, Federal Aeronautics regulations have been found in Title 14.<sup>21</sup>

#### **A. Early Regulations**

Predating the CFR, we managed to unearth a copy of the 1929 edition of AERONAUTICS BULLETIN No. 7 – AIR COMMERCE REGULATIONS.<sup>22</sup> In this document, we found licensing requirements of aircraft and pilots, among other miscellaneous topics such as operation and air traffic rules. Upon close review, we found little guidance relating to aircraft performance with exception of “exclusive of taking off from or landing on an established ... airport ... aircraft shall not be flown ... at a height less than 500-feet.”<sup>22</sup>

We have also found the 1933 edition of AERONAUTICS BULLETIN No.7A - AIRWORTHINESS REQUIREMENTS FOR AIRCRAFT § 76 providing minimum performance guidelines.<sup>23</sup> Here, we learned that to be federally certified as airworthy, all passenger carrying airplanes must: “(1) Land at a speed not exceeding 65 miles per hour ... (where) Landing speed (is) the stalling speed at sea level. (2) Take-off within 1,000 feet at sea level.”<sup>23</sup> Aircraft must also demonstrate minimum climb performance where the climb rate in ft/min in “the first minute after taking off shall [exceed] eight times the theoretical stalling speed in miles per hour, but shall be not less than 300 feet [per minute].”<sup>23</sup>

The “rule of eight” for climb performance is graphically depicted in Figure 4. As the stall speed increases, so must the climb capability. Because these early regulations do not specify any relationship between the scheduled climb speed and stall it is impossible to define a precise equivalent climb gradient. However, the “rule of eight” effectively specifies a minimum 6.6% climb gradient if the aircraft is scheduled to fly at  $1.2 V_s$  (see Figure 5).

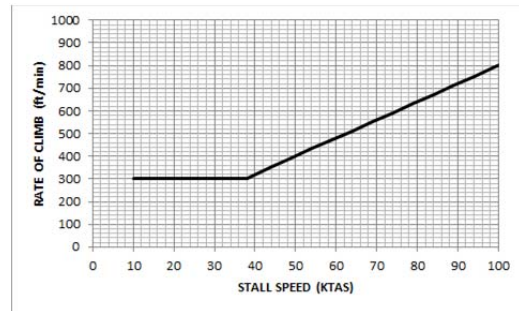
In its original form, airworthiness regulations were located within Title 14 of the CFR § 4.<sup>24</sup> Regulation 14 CFR § 04.7010 (1938) requires that “landplanes shall take-off within 1,000 feet in standard calm air at sea level”.<sup>24</sup> This is the same as found in the older Aeronautics Bulletin. This regulation comes off as quite odd, for intuition tells us that the available runway length limits an aircraft’s takeoff roll, not some arbitrary value.

Nestled under the “Flight loads” section, we find regulation 14 CFR § 04.211 (1938) which controls structural design limit speeds of the aircraft.<sup>25</sup> We also find 14 CFR § 04.702 (1938) “Climb”. This regulation requires that “landplanes shall climb, in feet the first minute after leaving the ground, at least eight times the measured ... stalling speed (with flaps retracted) in miles per hour, but not less than 300 feet.”<sup>26</sup> In other words, an all engines operative aircraft must follow the “rule of eight” for initial takeoff climb. Since no mention is made regarding engine-inoperative performance, we must assume that the “rule of eight” (6.6% climb gradient) is a federal minimum for all engines operating flight.

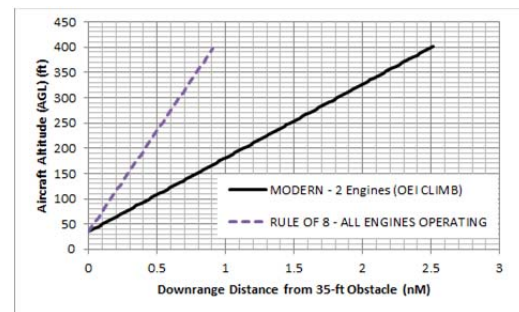
Unlike the most current revision of the CFR, where cue speeds are regulated precisely, older versions tend to be very vague when discussing flight speed. For multi-engine aircraft, exceptions to 14 CFR § 04.211 (1938) “Design Airspeeds”<sup>25</sup> can be found under 14 CFR § 04.2220 (1938) “Maneuvering”<sup>27</sup> and 14 CFR § 04.2223 (1938) “Tab effects (vertical surfaces)”<sup>28</sup> —both of which are in the Vertical tail surfaces section—as well as 14 CFR § 04.2230 (1938) “Maneuvering”<sup>29</sup> in the “Ailerons” section. These speeds effectively control the design aerodynamic loads for the various control surfaces. Such regulations do not recommend a speed for flight, climb or descent.

Beyond the “rule of eight,” the few performance requirements we found are nestled under 14 CFR § 04.71 (1938) “Modified performance requirements for airline carriers.”<sup>30</sup> This regulation extends the takeoff distance limitation to 1,500 feet for landplanes.

To make things even more confusing, there also exists 14 CFR § 04.73 (1938) “Performance characteristics of airline carriers,”<sup>31</sup> as if § 04.71 was insufficient in of itself. Under this section is contained two regulations of interest to us: § 04.731 (1938) “Climb”<sup>32</sup> and § 04.732 (1938) “Take-off”<sup>33</sup> These regulations are not necessarily restrictive in nature – rather, they detail what performance data should be submitted and how it should be computed.



**Figure 4. “Rule of Eight” Minimum Take-Off Climb Performance.** From early Air Commerce Regulations



**Figure 5. “Rule of Eight” Minimum Take-Off Climb Gradient** From early Air Commerce Regulations.

These regulations require aircraft designers to submit a package of computed data for takeoff, climb, and other flight segments, for consideration during airworthiness certification.

Curiously, 14 CFR § 04.731 “Climb” (1938) has a provision for the engine-inoperative case; it requires the aircraft designer to show the best steady climb with the throttle of the critical engine closed, with the ignition switch on or off, whichever produces the lower climb rate, operating at “not to exceed take-off power.”<sup>32</sup> Regulation 14 CFR § 04.732 “Take-off,” (1938) on the other hand, requires the aircraft designer to submit data computed with “all engines functioning normally.”<sup>33</sup> Synthesizing these regulations, we believe that the 1938 rules demonstrate some awareness of the need for sufficient engine-inoperative climb performance. We also believe that they completely neglect the engine-inoperative penalty associated with runway distance or obstacle clearance. These rules also give tremendous discretion to the manufacturer to deem what engine-inoperative climb performance was “enough.” Not knowing the criteria for “enough” engine-inoperative climb performance, it can only be speculated that this judgement call is subjective in nature.

Unlike present day, revisions to the Code of Federal Regulations from 1938 to 1947 were provided as a “supplemental” text, published annually. These supplements can be thought of as “changelogs”; they do not necessarily reproduce the entire Code but rather call out what changes were made.

For example, 1938’s year-end supplement to the CFR is only one page long. It applies nine changes to 14 § 04. There were two modifications to Federal Regulations which are of interest in this discussion: § 04.71 “Modified performance requirements for airline carriers”,<sup>34</sup> and § 04.73 “Performance characteristics of airline carriers”.<sup>35</sup> Both regulations were amended by replacing “airline carriers” in the title with “air carrier airplanes”, likely done out of the need for clarity. Otherwise, there are no substantial changes in material to note here.

The 1939 supplement to the 14 CFR § 04 is slightly longer in length, with five pages worth of amendments. Beginning with this supplement, we see how regulations are added, amended, or revoked. For example, the government amended 14 CFR § 04.73 (1939) “Performance characteristics of air carrier aircraft” with additional language; it now forbids the operation of an aircraft by an air carrier in scheduled air transportation unless performance data was submitted to and approved by the Civil Aeronautics Authority.<sup>36</sup> This change comes in response to the revocation of § 04.730 – 04.734, which is superseded by 14 CFR § 04.73 (1939).<sup>37</sup> This would come off as a most curious change, as § 04.730 was the only provision which had regulatory language which demanded the aircraft designer submitted engine-inoperative climb performance for review by the Authority – revoking it without appending that language elsewhere comes off as a move that could preclude flight safety in the event of engine failure. Fortunately, an amendment to 14 CFR § 04.70 (1939) “Performance requirements” requires that, in addition to the aircraft’s compliance with performance requirements in standard atmosphere and at all weights up to the “standard weight,” flight tests must demonstrate that the aircraft is safely operable within a range of intermediate center of gravity positions with one engine-inoperative. We infer that “safely operable” means “capable of steady level flight.”<sup>38</sup>

The 1939 supplement also amends the definitions to airspeeds such as design level speed, design gliding speed, and design flap speed. With respect to the obstacle clearance problem, the 1939 supplement of the Code provides no substantial changes, if at all, to it; all that can be observed in this iteration is the incorporation of stricter, precise regulatory language. We see no mention of cue speeds for takeoff, climb, approach or landing.

For 1939 we see that 14 CFR § 04.743 “Air speed limitations” was amended with regulatory language which expressly forbids the operation of an aircraft at an airspeed greater than those specified on the aircraft certificate.<sup>39</sup> With this language absent from the 1937 and 1938 supplement iterations of 14 CFR § 04, one could only imagine what caused the need to change that regulation. We speculate that the 1938 crash of Northwest Airlines Flight 2 (a Lockheed Super Electra - NC17388) prompted this change. Civil Aeronautics Authority investigators determined that both vertical fins and both rudders were missing at the crash site.<sup>40</sup> They believed that the tail surfaces failed due to flutter. Further investigation discovered that the machine used by Lockheed (and authorized by the Department of Commerce) to measure the aircraft’s structural vibration modes was inaccurate; this gave Lockheed engineers misleading results. Subsequently, all Super Electras were grounded then modified to eliminate the possibility that flutter would cause in-flight structural failure.<sup>40</sup>

## B. 1940 Revisions After Pan AM Sikorsky S-43 Crash

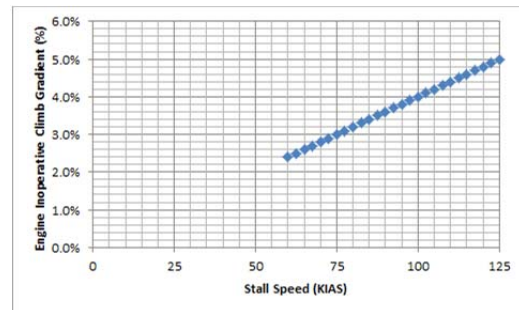
Changes incorporated into the 1940 supplemental version of 14 CFR § 04<sup>41</sup> materially provide some important changes to takeoff and obstacle clearance performance. We speculate that the 1939 crash of a Pan Am Sikorsky S-43 (NC16933) prompted this change.<sup>42</sup> This aircraft crashed after engine failure encountered during a landing approach at Rio De Janiero. Engine failure left the pilot in command of an aircraft in an unrecoverable a descending left yaw turn. Under these circumstances, the pilot could neither climb nor maintain heading; 14 of the 16 people on board died.

Unlike prior revisions to the Code, changes made during 1940 establish a greater level of safety thanks to additional provisions on engine-inoperative climb performance.

As a welcome bonus, a new regulation 14 CFR § 04.753 (1940)<sup>43</sup> requires each aircraft to be equipped with a pilot operational handbook (POH) containing relevant performance data.

Regulation 14 CFR § 04.723 (1940),<sup>44</sup> retitled “One-engine-inoperative performance”, now requires the submission of engine-inoperative climb performance data to the Administrator. What sets this regulation apart from 1938’s version of § 04.731 “Climb” is the additional requirement of keeping the Administrator-approved climb data in the airplane at all times, in a place conveniently accessible to the pilot. 14 CFR § 04.702 (1940) “Climb” was revised for additional specifics on top of the nominal 300 feet in the first minute climb; this regulation required an “average rate of climb for the first minute after the airplane leaves the take-off surface ... eight times the ... stalling speed in miles per hour with the flaps and landing gear retracted, or 300 feet per minute, whichever is greater.”<sup>45</sup> Because deployed flaps and landing gear negatively impact climb performance, this modification to the “rule-of-eight” implicitly requires the manufacture to provide additional all-engines-operating climb performance to counteract the degradation during initial climb-out with gear extended.

These changes also impact 14 CFR § 04.75 (1940)<sup>46</sup> “Alternative requirements for certification of airplanes in the ‘Transport Category’”, which overrides 14 CFR § 04.701 “Take-off”, among other regulations.<sup>47</sup> 14 CFR § 04.75 (1940) requires that the en-route climb with the critical engine-inoperative is no less than  $0.02 V_s$ , at a speed not less than  $110\% V_s$ , where  $V_s$  is the stall speed of the aircraft. Additionally, this regulation requires that the sea level climb performance with the critical engine-inoperative is no less than  $0.04 V_s$ . Note that this is the first time that: (1) the words “transport category” were used in 14 CFR § 04, and (2) a hardline was established for satisfactory engine-inoperative climb performance, as opposed to being at the subjective discretion of the Administrator. Figure 6 plots this function; for aircraft of the day with 75-KIAS stall speeds this regulation would require demonstration of a 3% engine-inoperative climb gradient (the current modern standard for four-engine aircraft). For aircraft with faster stall speeds, the required reserve climb performance would be stronger than the current two, three or four-engine standard.



**Figure 6. Minimum Engine-inoperative Climb Gradient @ Sea-Level** Note that this performance must be demonstrated in the en-route (flaps up) as opposed to takeoff (flaps deployed) configuration.

A new regulation, 14 CFR § 04.7500 (1940) “Take-off”,<sup>48</sup> details takeoff expectations of “transport category aircraft.” It establishes that the official takeoff distance must be the greater of: (1) the sum of the distance from a standing start to the indicated airspeed which ensures full control with the critical engine-inoperative and the distance required to bring the aircraft to a full stop, or (2) the sum of the distance from a standing start to the indicated airspeed which ensures full control with the critical engine-inoperative, as well as the distance required to attain an altitude of at least 50 feet above the takeoff surface at a speed no less than  $110\%$  the power-off stall speed at a steady climb rate specified in § 04.75(a). The verbiage “full control with the critical engine-inoperative” is a harbinger of the modern minimum control ground speed ( $V_{MCG}$ ) and minimum control air speeds ( $V_{MCA}$ ) requirements for safe takeoff.

### C. War Time Changes – Codification of Cue Speeds

While supplemental versions of the Code of Federal Regulations were published on an annual basis, this does not imply that Title 14 received updates each year.

Our research finds the next substantive revision to 14 CFR § 04 being delayed until 1943. This publication<sup>49</sup> enforces amendments to structural certification regulations, such as producing evidence of compliance for wing strength, vibration tests, etc. It also incorporates changes in required equipment. After thorough inspection, we find that the 1943 supplement provides no amendments, additions, or revocation, of Federal Regulations which govern the obstacle clearance problem.

The 1944 supplement to the Code of Federal Regulations begat a single change to 14 CFR § 04.<sup>50</sup> This amended regulation governed the equipment of aircraft with position lights which makes the vehicle easily locatable in a night sky.<sup>51</sup> The 1944 supplement to the Code provides no changes to the takeoff obstacle clearance problem.

While there were no major civilian aviation catastrophes during the Second World War, operational experience with multi-engine military transports and bombers clearly influenced the Civil Aeronautics Agency thinking on engine-inoperative climb.

The 1945 supplement to the Code of Federal Regulations<sup>52</sup> bought along some terminology with which we are familiar today. Regulation 14 CFR § 04.01 (1945) “Airplane categories”<sup>53</sup> explicitly defines the types of aircraft which are certified under Part 4: (1) transport, and (2) restricted. The first category, transport, has existed since the inception of Part 4, but the second category, restricted, is new in this revision. Curious readers should know that aircraft certified under the restricted category are expected to be used for purposes other than transport; although, as far as certification goes, compliance with applicable regulations under the transport category is still expected, in addition to operating restrictions which provides an equivalent level of safety to that provided by the transport category regulations as “deemed appropriate by the Administrator.”<sup>53</sup> Since the takeoff obstacle clearance problem is one that can potentially preclude continued flight safety in the event of an emergency, one could hypothesize that the restricted aircraft must abide by applicable regulations such as engine-inoperative climb performance. As another bonus spotted in this section, 14 CFR § 04.071 (1945) “Weights”<sup>54</sup> incorporates some terminology which is like those used in present day, such as empty weight, design takeoff weight, and design landing weight.

One of the more important changes found 1945 supplement is a restructuring of the performance section. What was previously found under 14 CFR § 04.7 has been recast as section 14 CFR § 04.12.<sup>55</sup> Regulation 14 CFR § 04.1220 (1945) “Speeds”<sup>56</sup> calls out cue speeds such as  $V_1$  and  $V_2$ . It also gives guidance for aircraft designers on how to correctly pick the values of each. For  $V_2$ , the obstacle clearance speed must provide the climb rate required by 14 CFR § 04.1231 (1945) “Climb – One-engine-inoperative – Flaps in take-off position”;<sup>57</sup> it must not be less than (1)  $1.20 V_{s_1}$  for two-engine aircraft, or  $1.15 V_{s_1}$  for multi-engine aircraft, and (2)  $1.10 V_{mc}$ , the minimum critical engine-inoperative control speed. Thus the engine-inoperative takeoff safety speed ( $V_2$ ) must be set fast enough to provide considerable reserve climb capability, freedom from incipient stall ( $V_{s_1}$  is the stall speed of the aircraft with flaps in the takeoff position) and adequate margin for lateral/directional controllability ( $V_{mc}$ ).

A new regulation 14 CFR § 04.1222 (1945) “Take-off path”<sup>58</sup> bears the likeness of a “climb-only” procedure, albeit worded somewhat awkwardly by using the phrase “horizontal distance traversed and the height attained” to signify climb. This iteration of the Code uses specific language for a windmilling critical engine-inoperative when performing first and second segment climb. To succinctly summarize this nascent regulation, the total takeoff path is the summation of (1) the runway distance required to accelerate to  $V_2$  with an engine failure at  $V_1$ , (2) the climb with windmilling engine and gear retracting at  $V_2$ , (3) the climb with windmilling engine until it has stopped at  $V_2$  (note that the process of stopping the windmilling propeller can occur no earlier than 50 feet above the takeoff surface), and (4) the climb until the limit on takeoff power is reached at  $V_2$ .

The 1945 CFR contains both all engines operating and one-engine-inoperative limits for minimum climb performance.

Regulation 14 CFR § 04.1230 (1945)<sup>59</sup> requires that the steady climb rate at 5,000 ft must be no less than  $8 V_{s_0}$ , the landing stall speed, with the gear out and flaps in the most favorable position, at, curiously, maximum takeoff weight; the regulation also requires that climb rates must be determined for a variety of altitudes and operational weights, albeit this latter provision was mentioned in a previous CFR revision. With respect to emergency performance, 14 CFR § 04.1231(a) “One-engine-inoperative: Flaps in the take-off position” requires a steady climb rate of at least  $0.035 V_{s_1}$  at takeoff with a speed of  $V_2$  and windmilling propeller, but no less than 50 ft.<sup>60</sup>

Regulation 14 CFR § 04.1231 (1945)<sup>60</sup> “One-engine-inoperative: Flaps in en-route position” mandates that, at a standard altitude of 5,000 feet and at the maximum takeoff weight with stopped propeller, the steady climb rate must be at least either  $0.02 V_{s_0}^2$  for aircraft whose maximum takeoff weight is 40,000-lbm or less, or  $0.04 V_{s_0}^2$  for aircraft whose maximum takeoff weight is 60,000-lbm or more, with a linear variation of the aforesaid equations between 40,000-lbm and 60,000-lbm. Curiously, this regulation does not explicitly call out a hard minimum on expected climb performance.

Compared to the earlier climb rate minimums, we note that the expectations for engine-inoperative takeoff performance have changed markedly. The required minimum steady rate of climb for takeoff has changed from  $0.04 V_s$  (gradient) to  $0.035 V_{s_1}^2$  (ft/min) with an absolute minimum of 50 ft/min. Similarly, expectations for en-route climb have changed from a steady climb rate of  $0.02 V_s$  (gradient) to anything in the range of  $0.02 V_{s_0}^2$  to  $0.04 V_{s_0}^2$  for a takeoff weight ranging from <40,000-lbm to >60,000-lbm.

In Figure 7, we plot the implied gradients as a function of stall speed. The 1945 all engines operating landing climb works out to a need to demonstrate 6.58% gradient independent of stall speed when flown at  $1.2 V_s$ . Conversely, the engine-inoperative gradients are a sliding function of aircraft stall speed. For a large (>60,000-lbm certified maximum takeoff weight) aircraft with a 75-KIAS stall speed, the aircraft must sustain at least a 2.6% gradient in the takeoff configuration and 2.5% gradient in the en-route (flaps up) configuration when flown at  $1.2 V_s$ . This is actually a more stringent requirement than a modern 14 CFR § 25 certified twin engine aircraft would have to demonstrate (>2.6% vs. >2.4%, >2.5% vs. >1.2%).

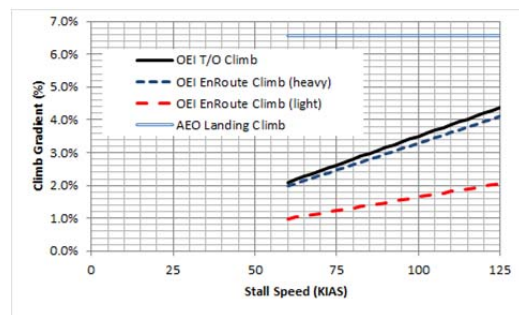


Figure 7. Minimum Climb Gradient @ Sea-Level 1945 Rules.

Interestingly, the 1945 revision to the Code also introduces 14 CFR § 04.1232 (1945)<sup>61</sup> “Two-engines inoperative” for aircraft with four or more engines, however this regulation merely requires that the aircraft designer specify the climb rates for this condition at a variety of weights and altitudes (which was already expected for the cases regulated by § 04.1230 and § 04.1231, as well as in past revisions of the CFR); this regulation imposes no expectations on two-engines inoperative climb performance.

With the new expectations on climb performance for both all engines operating and engine-inoperative conditions, one can speculate that, perhaps, the level of safety implied by these regulations either remained the same or improved; a conclusion regarding that speculation is hard to produce given that climb rate, expressed in ft/min, is not directly comparable with a minimum climb gradient which would be expressed as a percent gradient or feet gained per nM flown.

To determine if an aircraft’s climb rate is strong enough to overcome expected obstacles assuming the obstacle heights are known, one would need to know the time required for the aircraft to reach the obstacle; however, since this is a function of ground speed and flight path angle, calculating this by hand is no easy task for the problem becomes unnecessarily complicated. In other words, the establishment of a minimum climb rate is nice in that it guarantees some climb performance with a failed engine, but it does not guarantee that this performance is necessarily enough to overcome obstacles in the aircraft’s predicted takeoff path.

## D. Bifurcation of Regulatory Basis – General Aviation Separates From Transport Category Design; New Dispatch Rules Arise

While the 1946 supplement to the Code of Federal Regulations brings no landmark changes to regulations governing aircraft takeoff performance like in the previous year, this revision is still quite important. This revision of the Code redesignates and separates 14 CFR § 4 into 14 CFR § 4a and 14 CFR § 4b (1946).<sup>62</sup> All “transport category aircraft” were to be certified under Part 4b.

1946 revisions also include renumbering and modifying the 14 CFR 61 dispatch rules. En-route limitations are now found at 14 CFR § 61.219 (1946)<sup>63</sup> “All airplanes; all engines operating” and 14 CFR § 61.220 (1946) “All airplanes; one engine inoperative.”<sup>64</sup> Under these revised regulations:

“Airplanes shall be dispatched only at such take-off weights that, .... the rate of climb with all engines operating (as set forth in the airplane operating manual), shall be, in feet per minute,  $6 V_{so}$  at an altitude at least 1,000 feet above the elevation of the highest ground or obstruction within 10 miles of either side of the intended track” and that “the rate of climb with one engine inoperative (as set forth in the Airplane Flight Manual) shall be, in feet per minute  $\left(0.06 - \frac{0.08}{N}\right) V_{s0}^2$ , where  $N$  is the number of engines installed and  $V_{s0}$  is expressed in miles per hour, at an altitude at least 1,000 feet above the elevation of the highest ground or obstruction within 10 miles of either side of the intended track.”<sup>63</sup>

Thus, aircraft are now expected to dispatch along a flight path where the aircraft will have ample reserve climb gradient to overfly all terrain even with one engine inoperative.

This is the first time the number of installed engines is a consideration with respect to engine-inoperative climb performance; by the form of the equation, the expectation is that aircraft with more installed engines are expected to produce stronger engine-inoperative climb performance.

In Figure 8, we plot these new implied en-route gradients as a function of stall speed. The 1946 engine-inoperative climb gradient for a two-engine aircraft roughly corresponds to the lightweight aircraft from the 1940 rules; the four-engine formula roughly corresponds to the heavyweight aircraft from the 1940 rules. For a four-engine large (>60,000-lbm certified maximum takeoff weight) aircraft with a 75-KIAS stall speed, the aircraft must still sustain at least a 2.6% gradient in the takeoff configuration and 2.5% gradient in the en-route (flaps up) configuration when flown at  $1.2 V_s$ . This continues to be more stringent than a modern 14 CFR § 25 certified twin engine aircraft would have to demonstrate (>2.6% vs. >2.4%, >2.5% vs. >1.2%).

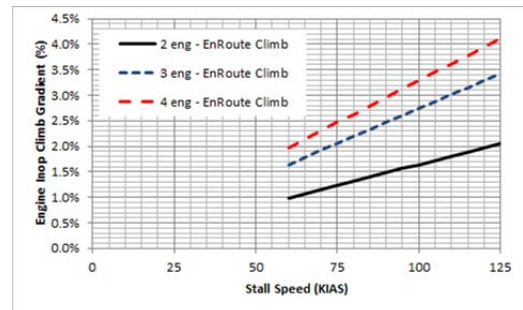


Figure 8. Minimum Climb Gradient @ Sea-Level 1952 Rules.

In the 1949 edition the Code of Federal Regulations, performance regulations for transport category aircraft were consolidated under 14 CFR § 4b.91 (1949) “Performance”.<sup>65</sup> For example, 14 CFR § 4b.95 (1949) is “Speeds”, which details selection criteria for  $V_1$  and  $V_2$ .<sup>66</sup> Since last observed in the 1945 supplement, we see no substantial change to the regulatory language to changes the interpretation of the regulation. Similarly, 14 CFR § 4b.97 (1949)<sup>67</sup> is now “Take-off path”, which unsurprisingly reads very similarly to when it was last seen in 1945. Regulations 14 CFR § 4b.102 (1949)<sup>68</sup> and 14 CFR § 4b.103 (1949),<sup>69</sup> “Climb: All engines operating” and “Climb: One engine inoperative,” also read the same as their 1945 counterparts.

It seems that the 1949 Code of Federal Regulations, with respect to Title 14, Part 4b, brings no changes in regulatory language that affects the obstacle clearance problem.

## **E. 1952 Amendments – High Lift Systems Become Ubiquitous For Takeoff and Landing**

Amendments to 14 CFR § 4b next appear in 1952. Regulation 14 CFR § 4b.114 (1952) “Take-off speeds”,<sup>70</sup> provides guidelines for  $V_1$  and  $V_2$  choice; this is essentially unchanged. Regulation 14 CFR § 4b .119 (1952) “Climb;”<sup>71</sup> all engines operating” is also materially similar as before, except a clarification in the regulatory language was attempted via the insertion of the phrase “cruising configuration”, likely due to the potential ambiguity of “wing flaps in the most favorable position” clause.

With respect to palpable changes in the 1952 edition of 14 CFR, the agency refined the regulatory language within 14 CFR § 4b.116 (1952) “Take-off path” to consider the drag of a stopped propeller during first segment climb (before the landing gear has retracted).<sup>72</sup> In the 1949 iteration of this regulation, during the gear retract, the failed engine’s propeller would be in the process of windmilling down. In the new revision, the greater drag of a stopped propeller must be considered.

Regulation 14 CFR § 4b.120 (1952) “One-engine-inoperative climb” was revised for clarity;<sup>73</sup> for example, subsection (a), “Flaps in take-off position; landing gear extended”, requires only a steady rate of climb of no less than 50 ft/min with a windmilling inoperative engine; the astute reader will realize that this restriction is new, for the 1949 iteration of the Code only governed engine-inoperative climb performance for (1) flaps in the takeoff position with gear retracted and (2) flaps in the en-route position and with gear retracted.

We speculate that this regulation came into being as a consequence of the 1951 Miami Airlines C-46 crash.<sup>74</sup> Just after takeoff, air traffic controllers saw a trail of white smoke coming from the right side of the aircraft (N1678M). The aircraft continued ahead in the direction it took off in for a distance of about four miles, slowly gaining an altitude of approximately 800 to 1,000 feet. The tower, concerned about the danger of there being a fire, pressed the airport crash alarm button. A Miami Airlines employee observing the takeoff from the ground also saw the smoke, which he believed was due to an overheated right brake. The control tower instructed the captain to lower the landing gear and return for an emergency landing. Shortly after the landing gear was lowered, a large burst of flames erupted from underneath the right nacelle, the aircraft gradually lost altitude from here. All 52 passengers and 4 crew aboard died in the crash.

## **F. Dawn of the Jet Age – 1956 Amendments and Special Regulations SR-422**

It seems no substantial changes that affect our understanding of the takeoff obstacle clearance problem were presented in the 1956 version of the Code of Federal Regulations.<sup>75</sup>

We find minor revisions in the language of 14 CFR § 4b.114 (1956) “Take-off speeds”.<sup>76</sup> For example, now  $V_2$  choice is governed by the greater of (1)  $1.2 V_{S_1}$  for two-engine aircraft and for aircraft without propellers that have no provisions for obtaining a significant reduction in stall speed with one-engine-inoperative, or  $1.15 V_{S_1}$  for propeller-driven multi-engine aircraft and for aircraft without propellers which have provisions for obtaining a significant reduction in stall speed with one engine-inoperative, and (2)  $1.10 V_{mc}$ . This regulation brings nothing new to the obstacle clearance problem; however, the language behind this suggests the coming of jet engine transports.

Similarly, regulation 14 CFR § 4b.119 (1956) “Climb; all engines operating”<sup>77</sup> brings nothing new to the table, other than the addition of provision (7) under subpart (a), which indicates that a minimum climb rate of  $8 V_{S_0}$  must be achieved at a speed no greater than  $1.4 V_{S_0}$ ; this amendment presumably prevents pilots from “overspeeding” the aircraft past the intended design speeds to achieve the minimum climb rate, which might somehow damage the airframe and preclude flight safety. It seems no substantial changes that affect our understanding of the takeoff obstacle clearance problem were presented in the 1956 version of the Code of Federal Regulations.

The additional regulatory language contained within the 1956 version of “Take-off path”, that being the phrasing “aircraft without propellers”, foreshadows what comes in the 1960 version of the Code.<sup>78</sup>

By this point in time, aircraft equipped with much stronger turbine engines have become commonplace, and the Civil Aeronautics Authority (which became the Federal Aviation Agency in this short time span) recognized the need to impose alternative certification requirements for this class of transport category aircraft. The establishment of alternative regulations first began with the issuance of SR-422,<sup>79</sup> which details that for aircraft certified after August 27, 1957, instead of abiding by Federal Regulations 14 CFR § 4b.110 through § 4b.125 and § 4b.743, an alternative set of regulations applies. Following this special regulation comes SR-422A,<sup>80</sup> which allows aircraft certified after August 27, 1957 the option for compliance with either the regulations promulgated under SR-422 or SR-422A, with aircraft certified after September 30, 1958 obligated to comply with regulations under SR-422A. The last of relevant special regulations provided in the 1960 Code of Federal Regulations, SR-422B<sup>81</sup> requires that aircraft certified after August 29, 1959 must comply with an alternative set of regulations in lieu of § 4b.110 through § 4b.125, § 4b.133, and § 4b.743.

We can find no specific air crashes that prompt these changes. The limited government transparency of the era leads us to speculate that the revised rules were developed by government regulators working closely with the engineering teams at Boeing (the 707), Douglas (the DC-8) and Convair (the CV880) who developed the first generation of jet propelled transports.

Beginning with the special regulations under SR-422 within 14 CFR § 4b SR-422 4T.114 (1960) “Take-off speeds”<sup>82</sup> reads essentially identical to previous iterations, giving guidelines which governs the aircraft designer’s choice of  $V_1$  and  $V_2$  speeds, except now that  $V_2$  choice must satisfy climb gradient expectations as detailed in 14 CFR § 4b SR-422 4T.120(a) and (b), as opposed to climb rate expectations.

On the other hand, special regulation 14 CFR § 4b SR-422 4T.116 (1960) “Take-off path”<sup>83</sup> is markedly different that found previously. Its regulatory language defines the total takeoff path as starting from a static point on the runway to when the aircraft attains *either* a height of 1,000 ft above the takeoff surface, or when the transition to the en-route configuration at a speed which complies with 14 CFR § 4b SR-422 4T.120(c) (1960)<sup>84</sup> (which regulates en-route climb gradient) is completed, whichever altitude is higher. This formulation of total takeoff path is quite like present day, albeit the term  $V_{FTO}$  is absent and 1,500 ft substitutes 1,000 ft in the present formulation. Like in earlier regulations, subparts of this regulation require the pilot hold  $V_2$  and induce no configuration changes to the aircraft; however, unlike previous regulations, this restriction is lifted once the aircraft has attained an altitude of 400 feet above the takeoff surface. Additionally, subpart (g) of this regulation requires that when the aircraft attains 400 feet above the takeoff surface, the steady gross climb gradient must be at least 1.4% for two-engine aircraft and 1.8% for four-engine aircraft. This is unsurprising as subpart (c) of 4T.120 “One-engine-inoperative climb: Final take-off” requires a steady gross climb gradient of 1.4% and 1.8% for two- and four-engine aircraft when flying in the en-route configuration. With respect to second segment climb, subpart (b) of this regulation requires 2.5% and 3.0% for two- and four-engine aircraft, respectively. Additionally, for first segment climb (where the flaps and gear are out), subpart (a) requires the aircraft produces at least a steady positive gross climb gradient, irrespective of equipped engine count.

For distant obstacle clearance, we now find a formalized process to “derate” the gross flight path to procure the net flight path. Regulation 14 CFR § 4b SR-422 4T.121 (1960) “En-route flight paths”<sup>85</sup> has provisions on that subject in two subparts. Subpart (a) mandates that for the one engine-inoperative condition, the aircraft’s net flight path is determined from the gross engine-inoperative performance minus 1.4% for two-engine aircraft, or minus 1.8% for four-engine aircraft. By subpart (b), four-engine aircraft which are unfortunate enough to have two inoperative engines must have their net flight path determined by taking the gross performance minus 0.6%. A new regulation 14 CFR SR-422 4T.82 (1960) “Takeoff obstacle clearance limitations”,<sup>86</sup> which falls under the special Part 40T “Operating Rules” as promulgated by SR-422 in § 4b, details that “no airplane shall be taken off at a weight in excess of that shown in the Airplane Flight Manual to correspond with a net takeoff flight path which clears all obstacles ... by at least a height of 35 feet vertically.” This regulation serves as the first establishment of an absolute minimum vertical margin of safety that must be maintained between an obstacle and the aircraft where the engine-inoperative-case is planned.

The regulations promulgated under SR-422A are unsurprisingly like the previous SR-422, but with a few notable additions and amendments. For example, 14 CFR § 4b SR-422A 4T.114 (1960) “Take-off speeds”<sup>87</sup> under SR-

422A now includes guidance for how aircraft designers should choose the rotation speed  $V_R$ . Regulation 14 CFR § 4b SR-422A 4T.116 “Take-off path” now defines the total takeoff flight path as starting from a static point on the runway to when the aircraft attains an altitude of 1,500 feet above the takeoff surface or when the aircraft completes the transition into the en-route configuration at a speed which complies with 4T.120(c), whichever is higher; additionally, now there is an expectation that the aircraft must reach  $V_2$  by 35 feet above the takeoff surface and hold this speed until 400 feet above said surface. Regulation 14 CFR § 4b SR-422A 4T.120 (1960) “One-engine-inoperative climb”<sup>88</sup> was amended by now requiring: (1) for first segment climb, either a steady positive gross climb gradient for two-engine aircraft or a steady gross climb gradient of no less than 0.5% for four-engine aircraft, and (2) for final climb in the en-route configuration, a steady gross climb gradient of 1.2% for two-engine and 1.7% for four-engine aircraft is expected. With respect to calculation of the net flight path, newly-established 14 CFR § 4b SR-422A 4T.117a “Take-off flight path” requires a 1.0% detriment to the aircraft’s gross takeoff flight path, which is defined as starting at a height of 35 feet above the takeoff surface, irrespective of the number of installed engines. For the en-route portion of flight, 14 CFR § 4b SR-422A 4T.121 “En-route flight paths”<sup>89</sup> mandates that the net flight path is calculated by a 1.1% derate for two-engine aircraft and 1.6% derate for four-engine aircraft of the gross flight path; for a four-engine aircraft with two inoperative engines, a 0.5% diminishment of climb gradient performance is taken to calculate the net flight path. Evidently, some of the climb gradient requirements and net flight path calculations promulgated under SR-422 are relaxed under SR-422A.

SR-422B brings a bit more substantial changes to SR-422A yet which carry over into the present day understanding of the takeoff obstacle clearance problem. For example, the revised 14 CFR § 4b SR-422B 4T.114 (1960) “Takeoff speeds”<sup>90</sup> introduced the minimum second segment safety speed,  $V_{2min}$ , which inherited the guidelines originally set forth for choice of  $V_2$  speed; under the amended regulation,  $V_2$  choice is now governed by the highest of either (1)  $V_{2min}$ , or (2)  $V_R$  plus the speed attained prior to reaching a height of 35 feet above the takeoff surface, so long as the chosen speed complies with the climb gradient expectations of 14 CFR § 4b SR-422B 4T.120 (1960);<sup>91</sup> additionally, this iteration introduces guidelines for how the minimum unstick speed,  $V_{MU}$ , is determined and revises guidelines for  $V_R$  determination. With respect to 14 CFR § SR-422B 4T.117 (1960) “Takeoff flight path”,<sup>92</sup> this regulation was amended so that a 0.8% climb gradient decrement should be taken for two-engine aircraft, and a 1.0% climb gradient decrement for four-engine aircraft. Regulation 14 CFR § 4b SR-422B 4T.120 (1960) “One-engine-inoperative climb” was amended so that the engine-inoperative second segment climb gradient expectations are now 2.4% and 3.0% for two- and four-engine aircraft, respectively.<sup>91</sup> Unsurprisingly, the formulation of the obstacle clearance problem implied by the regulations promulgated under SR-422B is quite like that of the present day (see Figure 9).

From 1960 to 1964, the regulations established under SR-422B was present in each annual publication of 14 CFR § 4b, existing as a separate set of certification requirements exclusively for turbine-powered aircraft. Within this short time span, very few amendments to the previously-discussed regulations occurred. Again, because of the limited government transparency of the era we can only speculate that the revised rules were the result of issues found during certification of first generation jet transport aircraft.

RULES	4 ENG	3 ENG	2 ENG
14 CFR 25 (modern)	3.00%	2.70%	2.40%
SR 422 / SR 422A	3.00%		2.50%
SR 422B	3.00%		2.40%

**Figure 9. Takeoff Second Segment Climb Gradient Rules.** Comparing SR 422, 422A, 422B and modern 14 CFR 25 rules.

We can find no substantiating document to explain the reasoning behind the magnitude of the “gross-to-net” climb gradient performance decrement and why both the climb performance and the required safety margin is greater for four-engine aircraft as it would be for two-engine aircraft. The only obvious answer is that the decrements chosen would roughly half the “net” gradient over the “gross” gradient when the aircraft is flown at its extreme weight limit (where the gross climb performance just barely meets the regulatory minimums). Due to a lack of regulatory transparency, this reasoning will remain a mystery.

In 1962, the only revision to regulations pertinent to this conversation is to 14 CFR § 4b SR-422B 4T.114 (1962) “Takeoff speeds”,<sup>93</sup> which amended the guidelines on how  $V_R$  is established by adding a clause that it must be high

enough such that aircraft's liftoff speed  $V_{LOF}$  is no less than either  $1.10 V_{MU}$  in the all engines operative case or  $1.05 V_{MU}$  in the engine-inoperative condition.

In 1963, considerations for upcoming three-engine aircraft (i.e. Boeing 727) were incorporated into the regulations 14 CFR § 4b SR-422 4T.120 (1963),<sup>94</sup> 14 CFR § 4b SR-422 4T.121 (1963) and 14 CFR § 4b SR-422 4T.117 (1963). A three-engine aircraft must demonstrate the following engine-inoperative performance: steady gross climb gradient of 0.3% in first segment, a steady gross climb gradient of 2.7% in second segment, a steady gross climb gradient of 1.5% in en-route configuration. With respect to the takeoff net flight path calculation, a 0.9% decrement to gross climb gradient for three-engine aircraft is required as per 14 CFR § 4b SR-422 4T.117a (1963) "Takeoff flight path".<sup>95</sup> Similarly, to calculate the net en-route flight path for a three-engine aircraft, a 1.4% decrement to climb gradient must be taken as per 14 CFR § 4b SR-422 4T.121(a), or a 0.3% decrement in the event of two-engines inoperative as per 4T.121(b).<sup>96</sup>

## G. Modern Era – Part 4b Becomes Today's Part 25

As part of an ongoing government project to streamline and clarify regulatory language and remove obsolete or redundant provisions, Part 4b within Title 14 of the Code of Federal Regulations was reorganized as Part 25 on December 24, 1964.<sup>97</sup> Because the goal of this project was to clarify existing regulations, no substantive technical amendments were introduced at this time. Thus, relevant regulations governing the takeoff obstacle clearance problem contained within SR-422B were rolled over to the new 14 CFR § 25.<sup>98</sup> This gave rise to the regulatory numbering with which we are familiar today: 14 CFR § 25.107 (1965) "Takeoff speeds",<sup>99</sup> 14 CFR § 25.111 (1965) "Takeoff path",<sup>100</sup> 14 CFR § 25.121 (1965) "Climb: One-engine-inoperative",<sup>101</sup> 14 CFR § 25.115 (1965) "Takeoff flight path",<sup>102</sup> and 14 CFR § 25.123 (1965) "En-route flight paths".<sup>103</sup>

From this point forward, amendments to regulations became much easier to track as changes were consistently noted below with a reference to the Federal Register entry and effective date; a year-to-year analysis of revisions to the Code is no longer necessary.

During 1965, 14 CFR § 25.111 "Takeoff path" was revised by Amendment 25-6,<sup>104</sup> succinctly titled as "Limited Weight Credit for Airplanes Equipped With Standby Power." In the context of this revision, "airplanes equipped with standby power" refers to commercial transport aircraft that are equipped with standby rockets that can be used in cases of emergency. Since the use of standby rockets immensely bolsters climb performance, the FAA realized the need of an alternative formulation of the takeoff path for those aircraft. As such, subpart (e), which allows for said alternative formulation of the takeoff path for aircraft equipped with standby rocket engines, was created.

Passage of Amendment 25-38 in 1976 led to another revision of 14 CFR § 25.107 "Takeoff speeds".<sup>105</sup> However, this amendment is not significant insofar that it changes the material understanding of the problem itself. Rather, this amendment merely established guidelines regarding  $V_{2min}$  choice for aircraft equipped with reciprocating engines, which happen to be identical to the guidelines for aircraft equipped with turbopropeller engines.

Shortly thereafter, revisions to 14 CFR § 25.107 "Takeoff speeds" and 14 CFR § 25.111 "Takeoff path" occurred under Amendment 25-42 in 1978.<sup>106</sup> With respect to the first regulation, changes include amended guidelines on  $V_1$  choice, which must now be at least the assumed engine failure speed  $V_{EF}$  plus the speed gained in the interval which the pilot reacts to the failed engine and completes his first action in halting the aircraft. This formulation is markedly safer from the previous, which merely called for a  $V_1$  choice at which the aircraft is safely controllable with no exceptional piloting skill if the engine were to suddenly fail, is the current accounts for speed gained due to pilot reaction time. Guidelines regarding  $V_{MU}$  choice were amended so that the set of speeds must be selected throughout a range of thrust-to-weight ratios; for the all engines operative condition, the resulting  $V_{LOF}$  must be  $1.10 V_{MU}$ , or under engine-inoperative conditions,  $1.05 V_{MU}$ . With respect to the second regulation, the formulation of the takeoff flight path was amended such that an engine failure is assumed to occur at  $V_{EF}$  as opposed to  $V_1$ . This change enhances flight safety because accelerating to  $V_2$  from  $V_{EF}$  requires a longer runway distance than if the aircraft accelerated to  $V_2$  from  $V_1$ ; this means that if the pilot erroneously attempts to continue the takeoff at a speed less than  $V_1$  but greater than  $V_{EF}$ , the runway should still be long enough for liftoff.

14 CFR § 25.111 “Takeoff path” was later amended in 1980 by Amendment 25-54 to cover up a “loophole” (45 FR 60172, 1980).<sup>107</sup> In the previous formulation, changes in the aircraft configuration in second segment climb was expressly prohibited until the aircraft attains 400 feet above the takeoff surface, however, no provisions prohibiting changes in power or thrust by pilot action existed (Takeoff path, 1978). This means that the pilot could increase thrust after lifting off to hold  $V_2$  for a high climb slope. Implementation of this amendment means that the pilot can no longer adjust the throttle setting to hold the  $V_2$  speed, which prevents the pilot from flying the aircraft at too high of an angle of attack which would quickly lead to a stall in the event of an engine failure.

This regulation was later “modified” in 1990 by Amendment 25-72,<sup>108</sup> which aimed at updating regulations for improved clarity and accuracy. For 14 CFR § 25.111, paragraph (a)(1) was amended to fix an editorial error. Instead of basing the takeoff path on the ideal thrust and drag found at ambient atmospheric conditions, the takeoff path must be formulated under the operational procedures established by the aircraft manufacturer.

## H. 1995 and Subsequent Revisions – Harmonization with European Rules

Engine-inoperative climb performance was amended in 1995 under Amendment 25-84,<sup>109</sup> titled as “Revision of Certain Flight Airworthiness Standards To Harmonize With European Airworthiness Standards for Transport Category Airplanes”. The purpose of this amendment is to align certain flight requirements with the JAR-25, or European Joint Aviation Requirements 25. With respect to 14 CFR § 25.121(1996) “Climb: One-engine-inoperative”, subpart (d)(1), which deals with approach performance, was amended so that the aircraft is expected to produce the minimum required balked landing climb gradient specifically at the go-around power setting.<sup>110</sup>

Multiple changes to regulations pertinent to the takeoff obstacle clearance problem occur in 1998. Amendment 25-92,<sup>111</sup> “Improved Standards for Determining Rejected Takeoff and Landing Performance”, revised regulations 14 CFR § 25.107 (1999) “Takeoff speeds”<sup>112</sup> and 14 CFR § 25.115 (1999) “Takeoff flight path”.<sup>113</sup> This amendment, in combination with others, improved safety by requiring determination of takeoff performance on wet runways, and requiring rejected takeoff and landing stopping distance calculations to be based on worn brakes. With respect to 14 CFR § 25.107 “Takeoff speeds”, subsection (a)(2) was amended with alternative wording, but materially is the same as previously. The amendment to 14 CFR § 25.115 (1999) “Takeoff flight path”<sup>113</sup> allows for an alternative formulation of the takeoff distance required if the runway is wet.

Amendment 25-94,<sup>114</sup> which was also passed in 1998 to correct minor errors, amended regulations 14 CFR § 25.107 (1999) “Takeoff speeds”<sup>112</sup> and 14 CFR § 25.111 (1999) “Takeoff path”.<sup>115</sup> The first was amended by correcting typographical errors (i.e. replace  $VR$  with  $V_R$ ) and the second was amended by correcting a reference to a nonexistent regulation.

Passage of Amendment 25-108 in 2002 led to the revision of 14 CFR § 25.107 “Takeoff speeds”,<sup>116</sup> 14 CFR § 25.111 (2003) “Takeoff path”,<sup>117</sup> and 14 CFR § 25.121 (2003) “Climb: One-engine-inoperative”.<sup>118</sup> With respect to the first regulation, selection criteria for  $V_{2min}$  was revised so that it may not be less than either (1) 1.13  $V_{SR}$  (down from 1.2  $V_{SR}$ ) for two- and three-engine turboprop and reciprocating engine aircraft, as well as for turbojet aircraft without provisions for a significant reduction for the engine-inoperative stall speed, or (2) 1.08  $V_{SR}$  (down from 1.15  $V_{SR}$ ) for turboprop and reciprocating engine aircraft with more than three-engines, as well as for turbojet aircraft with provisions for a significant reduction of the engine-inoperative stall speed; additionally, now  $V_2$  must be selected high enough so that it provides the aircraft with maneuvering performance required by § 25.143(g). 14 CFR § 25.111 “Takeoff path” received a clerical revision which replaced “a speed is reached at which compliance with § 25.121(c) is shown” with “ $V_{FTO}$ ”. Additionally, § 25.121 “Climb: One-engine-inoperative” now gives the final takeoff climb gradients—which are materially the same as before—at a speed of  $V_{FTO}$ .

Passage of Amendment 25-115 in 2004<sup>119</sup> revised 14 CFR § 25.111 (2005) “Takeoff path”,<sup>120</sup> as well as other regulations, to the more stringent standards of JAR-25. Materially speaking, this regulation is relatively unchanged after the amendment, except the insertion of “automatic” into subpart (c)(4)’s phrase “except for gear retraction and

propeller feathering” between the “and” and “propeller.” A novel interpretation of the revised 14 CFR § 25.111(c)(4) means that the pilot can no longer play with the propeller feathering during second segment climb.

In 2007, passage of Amendment 25-121 “Airplane Performance and Handling Qualities in Icing Conditions”,<sup>121</sup> led to the revision of four regulations which govern the takeoff obstacle clearance problem. This amendment was created to address the safety risk of icing conditions, which was found to contribute to nine accidents since 1983. For 14 CFR § 25.107 (2008) “Takeoff speeds”,<sup>122</sup> the calculation of  $V_1$ ,  $V_R$ , and  $V_2$  for flight in icing conditions can use the non-icing values of  $V_{MCG}$ ,  $V_{MC}$ , and  $V_{MU}$ . Regulation 14 CFR § 25.111 (2008) “Takeoff path”,<sup>123</sup> sees clerical revisions to subparts (c)(3)(iii) and (c)(4), with the addition of (c)(5) which allows for an alternative flight path calculation under icing conditions. Revised regulation 14 CFR § 25.121 (2008) “Climb: One-engine-inoperative”,<sup>124</sup> now requires that the climb gradient minimums are met under icing conditions (i.e. taking into account thrust degradations as well as reference stall speed elevation found during flight with the anti-ice system engaged). Additionally, 14 CFR § 25.123 (2008) “En-route flight paths”,<sup>125</sup> has been modified so that the flight path must be calculated at a speed not less than  $V_{FTO}$  (as opposed to the previous “determined at any selected speed”), which must also account for climb degradation during icing.

In 2011, passage of Amendment 25-135<sup>126</sup> resulted in the further revision to 14 CFR § 25.107 “Takeoff speeds”. This Amendment aimed at harmonizing requirements such as takeoff speeds with the certification standards of the European Aviation Safety Agency (EASA). 14 CFR § 25.107 (2012)<sup>127</sup> now has reduced speed margin between  $V_{MU}$  and  $V_{LOF}$  for geometry-limited aircraft, which allows for reduction in  $V_R$ . In turn, this reduces required takeoff distance, at the risk of incipient tail strike. In other words, as opposed to the criteria where  $V_{LOF}$  is the higher of 1.10  $V_{MU}$  for all engines operating or 1.05  $V_{MU}$  for one engine-inoperative, geometry-limited aircraft which protect against early or over-rotation beyond the safe liftoff pitch attitude can use a  $V_{LOF}$  which is the greater of 1.08  $V_{MU}$  for all engines operating or 1.04  $V_{MU}$  for one engine-inoperative.

The last revision to regulations governing the takeoff obstacle clearance problem occurs in 2014 under Amendment 25-140,<sup>128</sup> which further deals with aircraft and engine certification requirements under various icing conditions. Regulations 14 CFR § 25.111 (2015) “Takeoff path”,<sup>129</sup> 14 CFR § 25.121 (2015) “Climb: One-engine-inoperative”,<sup>130</sup> and 14 CFR § 25.123 (2015) “En-route flight paths”,<sup>131</sup> now include revised language which focuses on the “most critical of ice accretion(s).” In other words, aircraft designers must now focus on the worst-case scenario icing conditions.

#### IV. Summary and Conclusions

From this historical inquiry, we see that obstacle clearance rules have significantly matured over time.

The earliest Aeronautics Bulletin No. 7, “Air Commerce Regulations” primarily controlled structural design and pilot responsibilities with only cursory expectations for aircraft performance. By 1938, we see rudimentary but serious efforts being made to establish an acceptable level of safety in terms of the aircraft (minimum structural strength as well as minimum performance specifications) as well as airmen (the pilots and the mechanics).

We believe that the Pan Am Sikorsky S-43 crash prompted a serious change in certification strategy. After 1940, all certified aircraft must be safely controllable under engine-inoperative conditions. It is also in this year where we note an acknowledgement in takeoff distance penalty due to a failed engine.

The 1945 revisions brought many changes which are still present in the current regulatory framework. At this time guidance on selection criteria for  $V_1$  (takeoff decision speed) and  $V_2$  (takeoff obstacle clearance speed) were established. Dispatch limitations now apply to pilots; there is an FAA certified “absolute minimum” engine-inoperative climb performance standard which must be met on all departures.

From 1957–1960, three special regulations (SR-422, SR-422A and SR-422B) for airworthiness of jet propelled aircraft were issued. Douglas DC-8’s designed to these rules continue to fly today. These “nearly modern” rules now express takeoff climb capability in terms of climb gradient, not climb rate. These rules, with minor changes, were later formalized as Part 25 in Title 14 of the Code of Federal Regulations. Amendments made over the subsequent

53 years do not reconceptualize the problem; they merely adjust guidelines for takeoff speed choice, critical field length for “contaminated” runways, and climb performance expectations in adverse weather conditions.

The modern requirements for more stringent engine-inoperative climb capability for four-engine aircraft appear to be an artifact held over from the earliest days; climb performance was expected to be stronger for heavier aircraft with higher stall speeds. Smaller and lighter aircraft were allowed reduced safety margins. Along the way, regulators conflated four-engine configurations with high stall speed / high gross weight airframes.

We can find no stated basis behind the differences in the magnitude of the “gross-to-net” climb gradient degradation required for obstacle clearance computations. Beginning in the 14 CFR 4b (1960) were regulations that placed less stringent requirements on two-engine (presumably smaller) airframes. This artifact from history remains in place today.

Although aircraft routinely operate out of challenging runways nestled in valleys, we have not come across a high-profile aircraft accident where a lack of climb performance due to an inoperative engine has led to (un)controlled flight into terrain. When and if such an accident occurs, it will prompt the FAA into further revisiting the engine-inoperative climb regulations.

We see that the FAA clearly takes great care in ensuring the present’s federal aviation regulations establish a level of safety that is no less than that of the previous year. With the recent provisions accounting for pessimistic weather conditions such as “contaminated” runways and heavy icing conditions, taking flight in the present day is safer than ever before.

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