AIAA SciTech Forum
January 3-7, 2022, San Diego, CA & Virtual
AIAA SCITECH 2022 Forum

10.2514/6.2022-0366

Emerging Federal Regulatory Framework for Future Supersonic Transport Aircraft

Benjamin D. Webb, [1] *and* Timothy T. Takahashi[2]
Arizona State University, Tempe, AZ, USA

This paper examines the most recent FAA notice-for-proposed rulemaking (NPRM) regarding future supersonic transport aircraft certification. We place this in context with: 1) the history of the Federal Regulation framework for Transport Category Airport, 2) issues surrounding the certification of Concorde, 3) the technical results from NASA N+2 Supersonic Transport studies, and 4) the commercial model for planned future Supersonic Transport Aircraft. We show that the NPRM has considerable emphasis on community noise for takeoff and landing as well as for oversight, but lacks specificity in other regulatory reforms that might enable quieter operations.

I. Introduction

IT HAS BEEN NEARLY TWENTY YEARS since Concorde operated its last commercial supersonic flight. Except for extremely limited flights of the TU-144 in Soviet-era Russia, [1] Concorde has been civilization's only operational supersonic transport. [2] The absence of Concorde left a gap in the aviation market that many dreamed of filling but thought would never be economically viable.

With ever-increasing concerns of environmental impacts, supersonic aircraft became a pariah in the eyes of many. They burn significantly more fuel than a comparable subsonic airliner, are extremely noisy during takeoff and landing, and create strong sonic booms along their flight path. Many feel that it would not be possible to replace Concorde until technology had evolved enough to make an economically profitable and environmentally friendly SST. While there is certainly truth to that viewpoint, significant advancements in aerodynamics and propulsion have been made in the 60 years since engineers developed Concorde. While more advancements will arise, current aircraft regulations are in place that prevent an SST from being in full operational use; these regulations may be outdated or even conflict with one another.

In 2019 and again in 2020, the United States Federal Aviation Administration (FAA) published Notice(s) of Proposal for Rule Making (NPRM) to establish new regulations to facilitate the development and certification of a new generation of Supersonic Commercial Aircraft. [3][4] While these proposals only address smaller aircraft, that is, aircraft with a maximum takeoff weight (MTOW) not to exceed 150,000-lbm and a top speed not greater than Mach 1.8, it indicates a willingness for the Government to contemplate fundamental changes to the regulatory structure that will enable successful product development.

This paper seeks to provide some history into man's pursuit of ever-faster travel, discusses the aspects of the Concorde that ultimately led to its economic failure, and provides some commentary on both the current proposed rule changes as well as other items of regulatory reform that can enable the successful development and operation of future commercial supersonic transports.

---

[1] M.S. Candidate, Aerospace and Mechanical Engineering, School for Engineering of Matter, Transport & Energy, P.O. Box 876106, Tempe, AZ, 85281, Student Member AIAA

[2] Professor of Practice, Aerospace and Mechanical Engineering, School for Engineering of Matter, Transport & Energy, P.O. Box 876106, Tempe, AZ, 85281, Associate Fellow AIAA

II. Aviation History Before the Jet Age

Human beings have always been fascinated by the thought of flight. We can see examples of such fascinations in history as far back as Greek mythology with the stories of Daedalus and Icarus. This fascination continued through the ages to Leonardo da Vinci who designed several unsuccessful gliders (see FIGURE 1) and even one of the earliest designs of a helicopter-like machine.

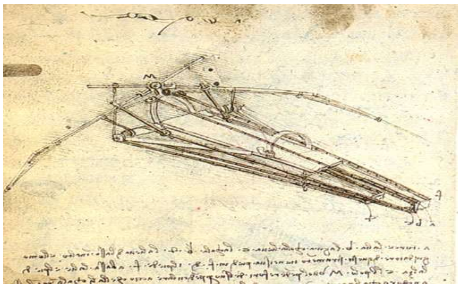


FIGURE 1 - Leonardo Da Vinci's sketch of a flying machine

FIGURE 2 – First powered flight of the Wright Flyer

Despite this fascination, it would take a long time for humans to take to the skies successfully. It was not until 1783 in Paris, France, when two men successfully traveled five miles in a hot air balloon designed by the Montgolfier Brothers. [5] Over the next century, many more people would take to the sky in hot air balloons, powered lighter-than-air dirigibles, and gliders. All of these advancements paved the way to perhaps one of the most famous events in aviation history, the first powered, heavier-than-air flight by the Wright Brothers on December 17, 1903, in Kitty Hawk, NC; see FIGURE 2. This event and World War I were the catalysts that got aviation on the fast track of advancements up to the current day.

The events of World War I would begin a path that would lead to many significant advancements in aviation. While these early planes were used in air-to-air combat, they were initially seen as a reconnaissance tool. [5] Perhaps the most famous of the World War I aircraft is the Sopwith Camel which had a maximum speed of just over 90 knots [6], a far cry from the speeds achieved by modern aircraft.

With the war ending in 1919, society entered a new age where returning military aviators sought to bring flight services to the general public. In the United States, the modern world of commercial aviation began in 1925 when Congress passed the Airmail Act, which allowed private companies to provide express airmail service. [7] It boosted commercial aviation in the United States in that it offered economic incentives to fly but made no mention regarding safety standards in its text. In fact, before 1925, there were no federal-level laws regarding civil aviation policy.

Later that year, President Coolidge formed the Morrow Board to provide guidance to the emerging industry. [8] The board heard testimony from experts in the fields of aviation and commerce, including Herbert Hoover, the Secretary of Commerce in the Coolidge administration. Hoover testified that:

> "The government was obliged to lend its support to commercial aviation, as it had always done in the maritime industry. …the government had for a century… provided education and competency standards for ships officers, required federal inspections of ships…" [8]

The board emphasized that if commercial aviation in the United States were to be realized, the safety and reliability standards of the industry would have to be regulated by the Federal Government.

Congress responded to the suggestions of the Morrow Board by passing the Air Commerce Act of 1926 [9][10]. The Act directs the Federal Government (executive branch) through the Department of Commerce (initially the Aeronautics Branch and later the Bureau of Air Commerce) to 1) create and maintain a national system of navigational aids, and 2) adopt rules and regulations to promote the safety of flight. [35] More specifically, the Federal government has a responsibility to 1) promulgate and enforce safety regulations, 2) to license and register aircraft, 3) to produce aeronautical charts, 4) to supply meteorological advice and reports, 5) to investigate accidents, and 6) to certify and medically examine pilots. [9]

Safety improved slowly through the 1930's, but the industry continued to be plagued with high profile disasters, including the 1931 crash of a TWA aircraft that killed the famous football coach Knute Rockne [11] and a 1935 crash of another TWA aircraft that killed Senator Bronson Cutting [R-NM] [8].

The Civil Aeronautics Act of 1938, later amended to its final form in 1940, revamped the regulatory framework for commercial air travel. It created two new agencies, the Civil Aeronautics Board (CAB) and the Civil Aeronautics Administration (CAA). [8][12] The CAB was responsible for control over air carrier economic regulations and investigating aircraft accidents. The CAA was responsible for air traffic control, safety programs, and airway development. The creation of these agencies also led to much more stringent civil law for aviation; these rules may be found in the first edition of the Federal Code of Regulations.

The CFR is a byproduct of the Roosevelt administration's Federal Register Act. [13] It provides detailed regulations pertaining to the design, construction, maintenance, and operation of private and commercial aircraft in a single document.

In 1946, the CAA amended the Code of Federal Regulations and separates 14 CFR § 4 (design standards for aircraft) into two sections: 14 CFR § 4a [14] and 14 CFR § 4b (1946) [15]. All future "transport category aircraft" were to be certified under the more stringent safety standards of Part 4b.

We also see a rise in collisions between aircraft during the immediate postwar era, particularly between military and commercial aircraft. In response, the Eisenhower administration passed the Federal Aviation Act of 1958 [8][16], which dissolved the CAA and replaced it with the Federal Aviation Agency, which was answerable only to congress.

III. The rise of the jet airliner and the possibility of a supersonic transport


FIGURE 3- Boeing 707-100

FIGURE 4 – Douglas DC-8-12

By the late 1950's, serious design work began on turbine-powered airliners. The Boeing 707 and the Douglas DC-8 pushed the envelope in terms of range and speed. Both aircraft had top speeds of a little over 500 knots and ranges that exceeded 3,000-NM. [6] These two aircraft entered into commercial service in 1958 and 1959, respectively.

The Federal Aviation Agency did not choose to certify these aircraft purely under existing 14 C.F.R. § 4b rules. Instead, they issued a series of special regulations, beginning with SR-422, [17] which partially superseded a variety of existing Federal Regulations, including 14 CFR § 4b.110 through § 4b.125 and § 4b.743. Both the Boeing 707 and Douglas DC-8 were certified under this regulatory structure; see FIGURE 3 and FIGURE 4. [18][19] Compared to the earlier 14 CFR § 4b rules, these revised regulations stipulated different allowable levels of minimum performance during takeoff to provide some safety margin in the event of an engine failure. The revised landing rules disallow credit for any sort of thrust reverse device (reverse thrust developed by propellers was an allowable procedure). [20] Moreover, the revised "en route limitations" regulations required increased margin of safety with an engine inoperative to ensure no possibility of controlled flight into terrain, stipulating that "no airplane shall be taken off at a weight in excess of that which, according to the one-engine-inoperative en route net flight path data shown in the Airplane Flight Manual, will permit compliance with. … [regulations] at all points along the route." [21] Including sufficient reserve engine-inoperative climb capability must exist to have positive net climb capability "at an altitude of at least 1,000 feet above all terrain and obstructions along the route within **5** miles on either side of the intended track." [22]

Despite the arrival of the Boeing 707 and the Douglas DC-8, plans for a commercial SST were already in the works before either aircraft entered into service. The origins of the first SST, the B.A.C./Aerospatiale Concorde, can be traced back to aerodynamic work conducted at the Aerodynamics Department of the Royal Aircraft Establishment in the early to mid-1950s. [23] This early work concluded that a Mach 2 SST, capable of flying from London to New York, was a possibility. It was not long after this initial work that in 1956, the British Government's Ministry of Supply created the Supersonic Transport Aircraft Committee or S.T.A.C. This committee brought together researchers and engineers to make this possibility of a supersonic SST a reality. While this committee did bring researchers and engineers together, including an eventual collaboration with the French aircraft maker Aerospatiale, it would be 13 years until the Concorde's first flight and 20 years before entering commercial service.

IV.The Relative Failure of the Concorde

The B.A.C./Aerospatiale Concorde would offer regular commercial service from 1976 until it was retired in 2003. When announced, Concorde quickly accumulated orders from 16 major airlines, including major US operators Pan Am, United, American, TWA, Braniff, and Continental, as well as national flag carriers like Lufthansa, Japan Air Lines, Sabena, and Air Canada. [24] These airlines all canceled their orders long before Concorde achieved airworthiness certification, leaving British Airways (ex. BOAC) and Air France as the sole operators of this type. [24] During that period, the only time it did not operate was from July 25, 2000, to November 7, 2001 – when all Concordes were grounded after Air France Flight 4590 crashed on takeoff. This accident killed all 109 people on board, yet it was the only fatal accident with a Concorde, making Concorde one of the safest airliners. [25]

Despite its statistically safe history, the Concorde was an aircraft that was ahead of its time and suffered from poor takeoff and landing performance in addition to the sonic boom. [26] These characteristics, along with high operating costs, would lead to the cancellation of the Boeing 2707 SST and Lockheed L-2000 SST projects. The only other SST to see commercial service was the USSR's Tupolev Tu-144, but it would only last in commercial service for three years due to reliability and safety issues.

A. Payload / Range Capability

Concorde, in production form, as delivered to British Airways and Air France seated 100 passengers in a 2x2 configuration; see FIGURE 5. [24] Concorde's limited range, with acceptable fuel reserves along with its sonic boom, limited its supersonic capability to overwater flights and required frequent stopovers.

British Airways primarily operated Concorde on the London (Heathrow) to New York (JFK) corridor; 2999-NM great circle distance. BA001 typically left London in the late morning, arriving in New York around 9:30 am. BA002 typically left London in the evening, arriving in New York around 6 pm. Return flights departed New York in the morning and noontime, arriving in London at 5:15 pm and 8 pm, respectively. British Airways intermittently flew London (Heathrow) to Washington (Dulles) (3195-NM), London (Heathrow) to Toronto (Pearson) (3090-NM), and London to Bahrain (2754-NM). Range limitations permitted BA to offer continuing service after refueling from Washington to Miami (MIA) and Dallas (DFW), the latter being a short-lived code-share with Braniff. British also operated continuing service from Bahrain to Singapore (3425-NM). [24]

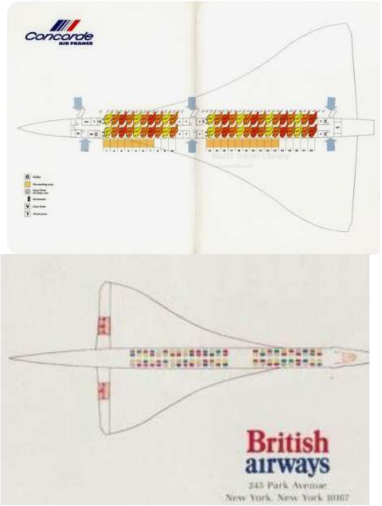


FIGURE 5 - Concorde Interior Layout [24]

Air France scheduled services from Paris (CDG) included New York (JFK) (3158-NM great circle distance) and Washington (Dulles) (3355-NM). Air France briefly offered limited continuing service to Mexico City. Air France also initiated service from Paris (CDG) to Caracas with a refueling stop at Santa Maria Island in the Azores and Paris to Rio Di Janiero with a refueling stop at Dakar; see FIGURE 6a. [24]

We can see the technical limitations of Concorde in bold relief in FIGURE 6b. While the Air France 1:00 pm departure from IAD enables subsonic connections from the eastern United States to Paris, it has an arrival into Paris so late to preclude further connections within Western Europe. The same situation applied to the British Airways noontime departure from JFK, while the morning departure left too early to permit connections at JFK.

FIGURE 6 - Air France Concorde Route Structure [24]

B. Poor Takeoff and Landing Performance

Most would argue that the primary goal or performance metric that one would want to meet when designing an SST is efficient cruising at the design cruise Mach number. During Concorde's development, it became evident that using a slender delta-style wing would be the most advantageous for an efficient supersonic cruise. [23] While slender delta-style wings lead to efficient supersonic cruise characteristics, they suffer from low maximum lift coefficients. Conventional subsonic commercial transport aircraft have an additional advantage of using high-lift devices, such as leading-edge slats and trailing-edge flaps; conversely, Concorde's delta-like wing did not allow for leading-edge slats. Furthermore, the wing's trailing edge is occupied by the engines and "elevons," combined ailerons and elevators, leaving no room for flaps. [26]

We should start by looking at the required field length for takeoff and landing. The critical field length required for takeoff is regulated by 14 C.F.R. §25.113:

> (a) Takeoff distance on a dry runway is the greater of—
> (1) The horizontal distance along the takeoff path from the start of the takeoff to the point at which the airplane is 35 feet above the takeoff surface, as determined under §25.111 for a dry runway; or
> (2) 115 percent of the horizontal distance along the takeoff path, with all engines operating, from the start of the takeoff to the point at which the airplane is 35 feet above the takeoff surface, as determined by a procedure consistent with §25.111. [27]

The point at which an aircraft is 35 feet above the ground corresponds to what is known as second-segment climb speed V_2. This is the speed required for the aircraft to maintain the required climb gradient in one-engine-inoperative situations. The second-segment climb speed, V_2, is determined to be the greater of V_{2MIN} defined in 14 C.F.R. §25.107(b), V_R the rotation speed described in 14 C.F.R. §25.107(e), and V_{MC} the minimum control airspeed defined in 14 C.F.R. §25.149(b).

The rotation speed, V_R, as defined in 14 C.F.R. §25.107(e), says:

> (e) V_R, in terms of calibrated airspeed, must be selected in accordance with the conditions of paragraphs (e)(1) through (4) of this section:
> (1) V_R may not be less than—
> (i) V_1;
> (ii) 105 percent of V_{MC};
> (iii) The speed (determined in accordance with §25.111(c)(2)) that allows reaching V_2 before reaching a height of 35 feet above the takeoff surface; or
> (iv) A speed that, if the airplane is rotated at its maximum practicable rate, will result in a V_{LOF} of not less than—
> (A) 110 percent of V_{MU} in the all-engines-operating condition, and 105 percent of V_{MU} determined at the thrust-to-weight ratio corresponding to the one-engine-inoperative condition; or
> (B) If the V_{MU} attitude is limited by the geometry of the airplane (i.e., tail contact with the runway), 108 percent of V_{MU} in the all-engines-operating condition, and 104 percent of V_{MU} determined at the thrust-

> to-weight ratio corresponding to the one-engine-inoperative condition. [28]

Where V_1 is the takeoff decision speed, defined in 14 C.F.R. §25.107(a), and is the airspeed "selected by the applicant as the 'go-no-go' speed for takeoff." [29] As Takahashi points out, this is the speed that the pilot is committed to takeoff when exceeded, even in situations where an engine becomes inoperative. When below V_1, the pilot can choose to do an aborted takeoff. V_{MU} is the calibrated airspeed where the aircraft can produce enough lift to lift off the ground safely.

This emphasis in reviewing some of the takeoff speed requirements is that they significantly impact the noise level during takeoff. As one might expect, they are also a contributing factor behind the takeoff field length requirements. As mentioned in work by Maltby [23] and Hirschberg & Leyman [26], the Concorde's slender delta-style wing and tailless vertical tail design provided significant advantages in supersonic cruise efficiency but at the cost of low-speed performance and handling.

A review of the requirements shown above shows that V_2 and V_R are predominantly functions of the aircraft's ability to generate lift and maintain control. Unfortunately, Concorde's wing does not have a high lift coefficient, nor does it have separate alerion and elevator control surfaces. Thus it required significantly higher takeoff speeds when compared to conventional subsonic jet airliners. The required takeoff field length for Concorde is shown in Table 1. As a comparison to subsonic airliners, the takeoff field length requirements for the Embraer E190-E2 and McDonnel Douglas DC-10-10 are also provided. The Embraer E190-E2 was chosen because it carries approximately the same number of passengers as the Concorde. In contrast, the McDonnell Douglas DC-10-10 was selected because it has a similar maximum takeoff weight (MTOW) as the Concorde. Due to the poor low-speed performance of the Concorde, it has a much higher takeoff speed and takeoff field length than subsonic airliners with similar passenger capacities and takeoff weight (see Table 1).

Table 1. Takeoff Field Length.

	Field Length (ft.)
Concorde[3]	11,250
E190-E2[4]	6,000
DC-10-10[5]	7,000

These characteristics only get worse as altitude or temperature increases. Thus, it becomes apparent that the available airports that Concorde can operate out of becomes limited. Furthermore, the increased speed leads to higher aerodynamic noise during takeoff. While the primary source of noise during takeoff comes from the engines, the margin for extra noise is slim; thus, any extra aerodynamic noise becomes a severe detriment to meeting noise regulations.

As with takeoff, the landing performance is significantly affected by the approach speed, V_{REF}. This speed is the minimum airspeed an aircraft can fly at while maintaining minimum stability and control requirements. Just as was the case with the takeoff performance, the poor low-speed performance of the Concorde's slender delta-style wing leads to a relatively high approach speed and landing field length. The approach speed V_{REF} is defined in 14 C.F.R. §25.125(b)(2) :

> (2) A stabilized approach, with a calibrated airspeed of not less than V_{REF}, must be maintained down to the 50-foot height.
> (i) In non-icing conditions, V_{REF} may not be less than:
> (A) 1.23 V_{SR0};
> (B) V_{MCL} established under §25.149(f); and
> (C) A speed that provides the maneuvering capability specified in §25.143(h). [33]

---

[3] TOW of 400,000 lb. @ SL ISA [30]

[4] TOW of 111,000 lb. @ SL ISA [31]

[5] TOW of 400,000 lb. @ SL ISA [32]

V_{SR0} is the landing configuration stall speed defined in 14 C.F.R. §25.103, and V_{MCL} is the minimum controllable airspeed when the plane is in its landing configuration.

Unfortunately, for the Concorde, the delta-style wing is not conducive to a low V_{SR0} or V_{MCL} due to its low lift coefficient and subpar lateral handling characteristics, respectively. [26] It is more challenging to get a specific value for the V_{REF} of an aircraft as the stall speed in landing configuration, V_{SR0}, is significantly impacted by the aircraft's weight at landing. Therefore, without running some takeoff and landing simulations, we cannot provide the approach speed of the Concorde or our two subsonic comparison aircraft. However, plenty of data is available to determine the landing distance required for each aircraft (see Table 2). To further complicate matters, additional rules regulate the required runway length for the landing of commercial aircraft.

As a factor of safety, 14 C.F.R. 121.195(b) states:

> (b) Except as provided in paragraph (c), (d), or (e) of this section, no person operating a turbine engine powered airplane may take off that airplane unless its weight on arrival, allowing for normal consumption of fuel and oil in flight (in accordance with the landing set forth in the Airplane Flight Manual for the elevation of the destination airport and the wind conditions anticipated there at the time of landing), would allow a full stop landing at the intended destination airport within 60 percent of the effective length of each runway described below from a point 50 feet above the intersection of the obstruction clearance plane and the runway. [34]

Table 2. Landing Field Length and 14 CFR §121.195 Required Length.

	Advisory Landing Distance (ft.)	Required Runway Length (ft.)
Concorde[6]	7,220	12,057
E190-E2[7]	4,022	6,703
DC-10-10[8]	4,300	7,167

Concorde's lack of low-speed lift and high-lift devices is evident by the fact that its landing field length is about 170% longer than the two subsonic airliners. This increased distance is indicative of a higher $V_{REF.}$ Things get worse when the requirements of 14 C.F.R. §121.195 are accounted for, as we see that the required landing runway length for the Concorde is a little over 12,000 feet. To put this into perspective, the longest runway at Phoenix Sky Harbor International Airport is 11,489 feet. Furthermore, as with takeoff performance, landing performance degrades as the altitude increases, temperature increases, or if the runway is wet. The values shown in Table 2 are for sea level and international standard atmosphere (ISA) on dry pavement. Phoenix Sky Harbor sits at a little over 1,100 feet above sea level and routinely has temperatures significantly above ISA conditions. Therefore, it would have to have a substantially longer runway to be able to accommodate the Concorde. As we saw with the takeoff performance, the Concorde's poor low-speed lift and handling characteristics severely restrict the available airports out of which it can operate. This limitation comes without accounting for the increased noise level associated with the Concorde during takeoff and landing.

C. Takeoff and Landing Noise

Takeoff and landing noise has become increasingly more regulated over the last 50 years as concerns have grown about the annoyance and long-term health effects. Before 1972, there were no standards regulating takeoff and landing noise, either in the United States or internationally. Then in 1972, the International Civil Aviation Organization (ICAO) implemented the first set of noise standards applicable to takeoff and landing conditions. [35] The FAA subsequently adopted these standards. The new requirements consist of the measurement of the noise levels at three different reference points. These three reference points are the lateral full-power reference point, flyover reference point, and approach reference point, and are defined in 14 C.F.R. §B36.3:

> (a) Lateral full-power reference noise measurement point:
> (1) For jet airplanes: The point on a line parallel to and 1,476 feet (450 m) from the runway centerline, or extended centerline, where the

---

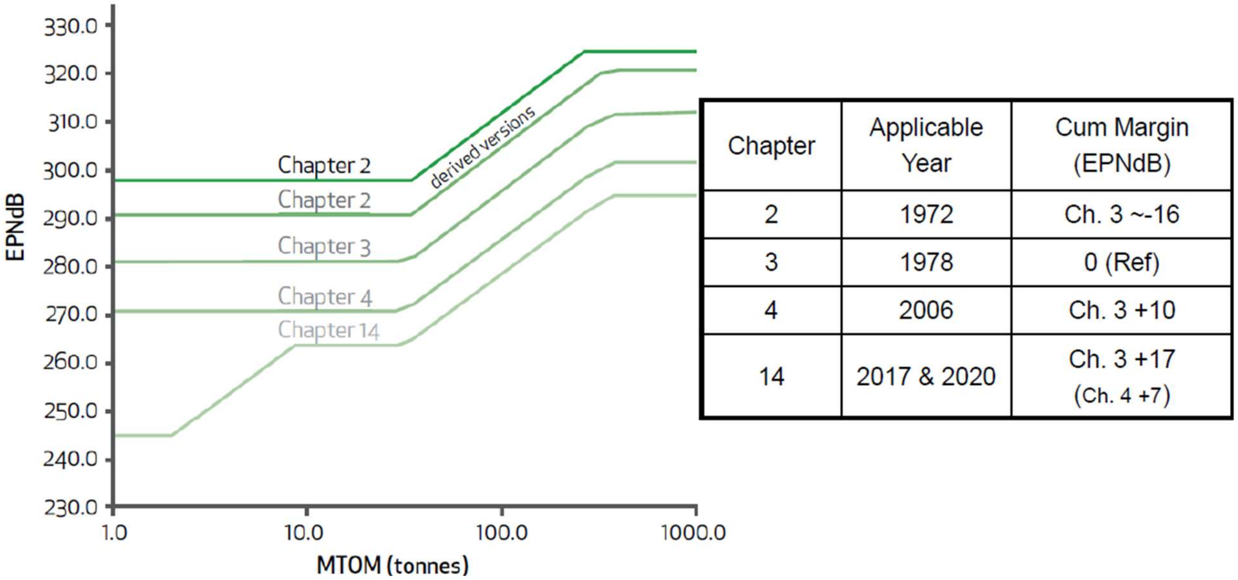
[6] MLW of 250,000 lb. @ SL ISA, no flaps [30]

[7] MLW of 108,000 lb. @ SL ISA, flaps full [31]

[8] LW of 250,000 lb. @ SL ISA, flaps 50° [32]

> noise level after lift-off is at a maximum during takeoff… For jet airplanes, when approved by the FAA, the maximum lateral noise at takeoff thrust may be assumed to occur at the point (or its equivalent) along the extended centerline runway where the airplane reaches 985 feet (300 meters) altitude above ground level.
> (b) Flyover reference noise measurement point: The point on the extended centerline of the runway that is 21,325 feet (6,500 m) from the start of the takeoff role;
> (c) Approach reference noise measurement point: The point on the extended centerline of the runway that 6,562 feet (2,000 m) from the runway threshold. [36]

An aircraft must meet a cumulative (all three noise levels combined) noise level requirement, as well as noise level requirements for each reference point. These requirements are found in 14 C.F.R. §B36.5 and shown in FIGURE 4. The stage that a subsonic transport aircraft falls in is set out in 14 C.F.R. §36.103. All aircraft certified before January 1, 1972, are considered Stage 1 aircraft (C.F.R. refers to stages that are analogous to ICAO chapters) and did not have to meet any noise requirements. Aircraft certified after August 1, 1972, fell into Stage 2 requirements. Stage 2 requirements show approximately 10 to 15 cumulative EPNdB decrease over Stage 1 requirements. Aircraft certified between November 5, 1975, and December 31, 2005, must meet Stage 3 requirements. Stage 4 was enforced on aircraft certified between January 1, 2006, and December 30, 2017, for aircraft with an MTOW greater than 121,253 lbs. If the aircraft has an MTOW of 121,253 lbs. or less than Stage 4, requirements were enforced until December 30, 2020. Currently, the strictest requirements are Stage 5 (chapter 14, ICAO), which apply for aircraft with an MTOW greater than 121,253 lbs. certified after December 30, 2017, or for aircraft with an MTOW less than 121,254 lbs. certified after December 30, 2020. [36]



Chapter	Applicable Year	Cum Margin (EPNdB)
2	1972	Ch. 3 ~-16
3	1978	0 (Ref)
4	2006	Ch. 3 +10
14	2017 & 2020	Ch. 3 +17 (Ch. 4 +7)

FIGURE 4. ICAO Annex 16 Noise Requirements [35].

Stage 4 requirements see a 10 EPNdB reduction over Stage 3 requirements, while Stage 5 requirements have a 7 EPNdB reduction over Stage 4 and a 17 EPNdB reduction over Stage 3. Further, the Concorde would have been certified under Stage 2 standards meaning that if it were to be certified today, it would be required to have a cumulative EPNdB value of approximately 33 EPNdB less than the Stage 2 requirements. In addition to meeting the cumulative requirement, each certified aircraft must also meet specific EPNdB values for each reference point. Unfortunately, these values are not easy to find, and they are of significant concern since the lateral noise measurement is the most challenging for supersonic aircraft. The FAA does allow some flexibility in these reference noise values. This flexibility is defined in 14 C.F.R. §B36.6, which states:

> Except when prohibited by sections 36.7(c)(1) and 36.7(d)(1)(ii), if the maximum noise levels are exceeded at any one or two measurement points, the following conditions must be met:
> (a) The sum of the exceedance(s) may not be greater than 3 EPNdB;

> (b) Any exceedance at any single point may not be greater than 2 EPNdb, and
> (c) Any exceedance(s) must be offset by a corresponding amount at another point or points. [37]

When in service, Concorde was given special certification highlighted in 14 C.F.R §36.301:

> (a) *General.* For the Concorde airplane, compliance with this subpart must be shown with noise levels measured… as prescribed in Subpart B… and demonstrated at the measuring points prescribed in appendix B…
> (b) *Noise limits.* It must be shown… that the noise levels of the airplane are reduced to the lowest levels that are economically reasonable, technologically practicable, and appropriate for the Concorde type design. [38]

This addition to the code of federal regulations essentially allowed Concorde to operate in the U.S., but it significantly limited the times and locations for takeoffs and landings. Furthermore, it is unlikely that we will see similar provisions for individual aircraft in the future. However, there are movements to regulate supersonic aircraft under different regulations. [3] These proposed regulations will be discussed later.

D. Sonic Boom

Concorde's second major acoustical issue is its best-known limitation; Concorde has a propensity to generate loud sonic booms. While an aircraft is traveling faster than the speed of sound, the aircraft is continuously shedding shockwaves which propagate in a cone-like shape trailing the aircraft. Eventually, these shockwaves will reach the ground. To make matters even worse, since the shockwave propagates out in a cone-like fashion, they spread laterally as well as vertically. Therefore, the sonic boom is not just heard directly beneath the aircraft's flight path but over a range of lateral distances away from the path. The area affected by the shockwave is commonly referred to as the sonic boom corridor, and it can be quite large. For this reason, supersonic flight overland was banned in the United States and many other countries. This ban is specified in 14 C.F.R. §91.817:

> (a) No person may operate a civil aircraft in the United States at a true flight Mach number greater than 1 except in compliance with conditions and limitations in an authorization to exceed Mach 1 issued to the operator in accordance with §91.818.
> (b) In addition, no person may operate a civil aircraft for which the maximum operating limit speed M_{MO} exceed a Mach number of 1, to or from an airport in the United States, unless—
> (1) Information available to the flight crew includes limitations that ensure flights entering or leaving the United States will not cause a sonic boom to reach the surface within the United States. [39]

Thus, it is not just supersonic flight over the land area of the United States, but anywhere outside the U.S. where a sonic boom could reach the surface of the land area that is banned. To help put things in perspective, recent research by NASA suggests that for supersonic booms to be considered safe and not an annoyance to the public, the maximum perceived decibel level (PLdB) of a sonic boom should be in the range of 65-70 PLdB. [65] The Concorde's sonic boom was typically around 105 PLdB. [65] This limitation most likely put the "nail in the coffin" for the Concorde in terms of it ever becoming economically viable. It was essentially limited to over-ocean flights and airports located along the coast. In theory, it could operate over land subsonically, but it would have been even more inefficient to do since the Concorde was designed for Mach 2 cruise conditions. The aerodynamic range in which an aircraft can efficiently operate is generally relatively small. Therefore, unlike other forms of transportation, aircraft are designed to work in very narrow ranges of flight speed and altitude.

V. Post Concorde Development

A. NASA HSCT Program

Beginning in 1990, and phased out at the end of FY 1999, NASA's High Speed Research effort funded internal and sponsored external academic and industrial contracts to enable a next generation of "High Speed Civil Transport" aircraft; see FIGURE 5. [40] Its goals were to fly 300 passengers above Mach 2 across either the Pacific or Atlantic. This was much more ambitious than Concorde in terms of payload and range. By 1995, the HSR program settled on a "Technology Concept Airplane" reference concept involving a 4-engined aircraft with a double-delta planform wing sized to fly the Pacific.

NASA funded technology focus areas included: aircraft sizing (Multi-Disciplinary-Optimization), aerodynamics, propulsion, and structures. NASA intended this research to provide technology to enable an aircraft "that does not harm the environment, has noise comparable to other future airliners and has high performance and durability to make the aircraft affordable to operate." [40] NASA also funded the development of "propulsion components including unique inlet, fan and nozzle designs … that would allow a future HSCT to operate without objectionably high noise levels. Tests on innovative combustor component designs demonstrated the ability to significantly reduce the nitrogen oxide emissions which are harmful to the environment. In addition, new engine materials were developed that would be able to withstand supersonic operations with temperatures near 3000 degrees Fahrenheit for most of the flight. Designers successfully incorporated all these technologies into a single propulsion system design for future supersonic transports." [40]

FIGURE 5 - NASA HSCT Rendering

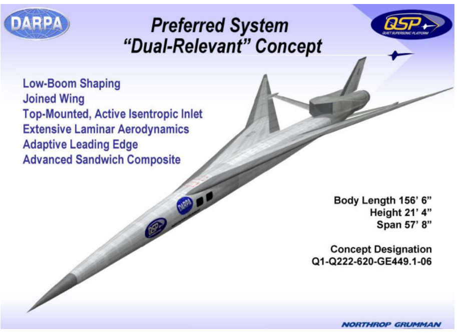


FIGURE 6 - Northrop Grumman QSP Rendering

B. DARPA QSP PROGRAM

In 2000, DARPA initiated a new effort, the Quiet Supersonic Platform (QSP) Program. [41] It sought to develop advanced technology and innovative configurations to dramatically reduce the required size and the environmental impact of a supersonic cruise aircraft. Its primary focus was to mitigate the sonic boom with an initial overpressure of <= 0.3 lbf/ft^2. This broad-based program funded work in industry (Lockheed Martin, Boeing, and Northrop Grumman) and academia; see FIGURE 6. It also led to the construction of a modified Northrop F-6, which generated a "shaped sonic boom" for reduced ground-level noise. [42]

C. NASA N+2 SUPERSONIC PROGRAM

NASA's more recent focus on supersonic research began in 2008 with funding to develop an "N+2 Supersonic Commercial Transport Aircraft." [43] In the first Phase, Boeing and Lockheed developed candidate geometries for notional low-sonic boom aircraft; see FIGURE 7. In the second Phase, NASA funded ground test activities focused on two distinct aspects of supersonic design—1) measurement of the sonic boom pressure signature at various distances around the aircraft and 2) measurements of engine inlet performance for top-mounted engines.

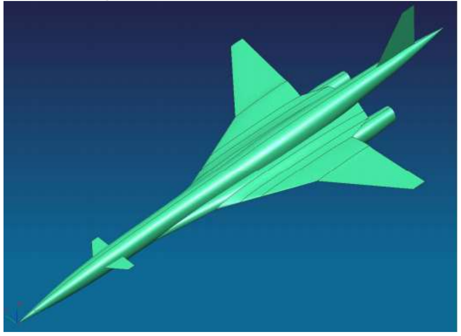


FIGURE 7 - Boeing N+2 HSCT Concept

During Phase I, Boeing designed a pair of airplanes – a 100 passenger (Model 765-072B) and a 30 passenger (Model 765-076E). Both offered ~4,000-NM Trans-Atlantic range and 10,000-ft "balanced field length" performance. [44]

Boeing performed its design studies using an in-house MDO code enabled by Phoenix Integration's ModelCenter trade study environment; see FIGURE 8. This MDO model included Overall Configuration, Aerodynamics, Stability & Control, Propulsion, Mass Properties, Acoustics, and Performance modules. The aerodynamic model employed a cocktail of Vortex Lattice and slender-body-theory linear wave-drag analysis methods along with proprietary empirical corrections. The propulsion module incorporated NASA's NPSS engine-cycle analysis code at its core.

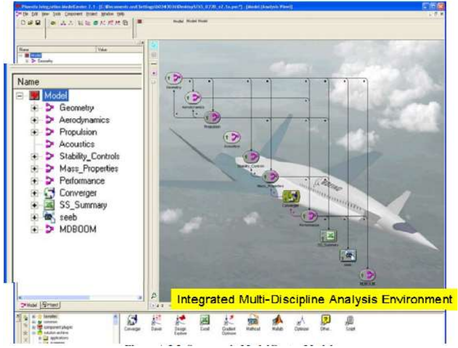


FIGURE 8 - Boeing MDO Environment Used to Support N+2 Trades

Mass Properties were estimated using a Boeing in-house "QWIKO" Supersonic Weights Estimation method. Takeoff Performance noise estimates were implemented in terms of limits to jet exit velocity. Sonic boom estimates were made using the MDBOOM (Boeing propagation code). [44]

Boeing began their study with a loft derived from their time in the NASA HSR/HSCT Program and iterated from there. Their trades were captured through a series of Design-of-Experiments. [44]

Engine cycle trades were all run using a 100-passenger concept with Mach 1.6 cruise and 4000 nm range. Boeing examined six engine cycles with varying jet exhaust velocity profiles. The Boeing team determined that proposed airport noise requirements (10-20 EPNdB below Stage 3) had a high probability of being met without a noise suppressor on the nozzle if the exhaust gas velocity could be kept at or below 1,100-ft/sec during takeoff and initial climbout. With engines sized for efficient transonic acceleration and super-cruise (i.e., cruise flight at supersonic speeds without the need for afterburners), they found a need for substantial de-rate to meet the imposed 1,100-ft/sec exhaust velocity goal to mitigate takeoff noise (derate to 79% full-power for some candidate engines, while others were unable to meet takeoff noise requirements at any thrust levels above idle). [44] In other words, their candidate airframe – with engines sized to overcome transonic drag – might be able to takeoff in 5,500-ft if it used full power (though it would be far too noisy to certify if operated in this manner) but could achieve takeoff in 10,000-ft if the engines were derated considerably. Boeing found that current air-worthiness regulations for engine-inoperative performance only "allows the thrust to be increased by 10%" over the reference thrust level limiting their design space. [44] [45] Boeing also recognized that a fully optimized de-rate schedule, "a programmed lapse rate" is a technology that should be employed in future design studies. [44]

D. RECENT COMMERCIAL DEVELOPMENTS

Over the last 20 years, there has been growing interest in the commercial aviation sector regarding the return to supersonic flight. Perhaps the two most ambitious of these companies are Boom Supersonic and Aerion. These two companies are taking different approaches to achieve acceptable supersonic travel.

Aerion has been developing its supersonic business jet since 2004. In addition to pursuing the business jet market, Aerion has taken the approach of creating a boomless aircraft. [46] The initial design was called the Aerion SBJ and was two-engine aircraft that Aerion claimed was capable of Mach 1.6 flight and Mach 1.1 boomless flight. [46][47] The Aerion SBJ never made it to production or flight test; in 2014, it was publicly rebranded as the three-engined AS2; see FIGURE 10a. [48] Over the next six years, the AS2 underwent two further public redesigns. The low-sweep laminar flow wing was a prominent feature of the original SBJ design and the first two AS2 designs (FIGURE 10a&b); the third redesign (FIGURE 10c) indicates a substantial change in strategy. Aerion returned to a classic low-mount, delta-planform wing with extensive fuselage area-ruling, a redesigned horizontal and vertical tail design, and engine inlet spikes. The final redesign of the AS2 recently completed high and low-speed wind tunnel tests. [47]


FIGURE 10 – a) 2014 AS2 Redesign, b) 2017 AS2 Redesign, c) 2020 AS2 Redesign

As of this writing, the AS2 is scheduled to begin initial production in 2023, with an anticipated first flight in 2025. [48] The AS2 promises a maximum cruise speed of Mach 1.4, with a boomless cruise speed of up to Mach 1.2. Furthermore, it promises efficient cruising speed and range in both supersonic flight and subsonic flight. The AS2 can fly 4,200 nm in supersonic cruise and 5,400 nm at subsonic cruise speeds of Mach 0.95. [47] Aerion also emphasizes its goal to make supersonic flight environmentally sustainable by using the first commercial aircraft engines capable of running on 100% synthetic fuel. [47] In March of 2021, Aerion released some limited information about their next aircraft called the AS3. The AS3 will be a 50-passenger airliner capable of a nearly hypersonic cruise speed of Mach 4 and an expected range of 7,000 nm. [48]

Unfortunately, shortly after completing the initial draft of this paper, Aerion announced that they would be shutting down all design and manufacturing. While information about the cause is not widely available, they likely lost funding and support for its work. This result is an unfortunate reality in today's aerospace industry, particularly regarding supersonic aircraft design. Research and design must be done to push the technological envelope needed to meet the strict requirements imposed on supersonic aircraft, yet the return on investment in these technologies is uncertain and long-term at best. This further emphasizes the need for updated requirements that best balance the operational safety of future supersonic aircraft and the financial burden undertaken for such endeavors.

Boom Supersonic is taking a different approach to the supersonic commercial market. Boom has decided to immediately target the business class airline market with their aircraft called Overture. The Overture, shown in FIGURE 11, is essentially a ¾ scale version of the Concorde. [50]


FIGURE 11 – Artist Rendering of Boom Overture [49]

Instead of the four afterburning turbofans used on Concorde, the Overture will use three non-afterburning turbofans. The use of non-afterburning turbofans will be the most significant hurdle that Boom will have to overcome; how will they develop an efficient and quiet low-bypass turbofan that can generate the high nozzle exhaust speeds required for efficient supersonic transport? The primary source of engine noise, particularly relevant during takeoff and landing, is driven by the speed of the exhaust jet leaving the engine nozzle. The higher the speed, the greater the noise. [50]

In July 2020, Boom announced that they had reached an agreement with Rolls-Royce to design the required engines with noise and environmental sustainability as essential design requirements. [51] Unlike Aerion, Boom is purposely going for business class passengers on long-distance trans-oceanic flights. They are not making use of any sonic boom reduction technologies. Instead, they are focusing on making the aircraft lighter with extensive use of composite materials and quieter, more efficient engines. If achieved, this would make the Overture much more acceptable to the public in terms of its much quieter takeoff and landing noise than that of the Concorde, which should open up more available routes. Furthermore, Boom predicts that the much more efficient engines will decrease the operating cost of the Overture by 75% compared to the Concorde. [50] On last report, Boom was planning for the first flight of its XB-1 demonstrator, a 1/3 scale model of the Overture, sometime in 2021; as of November 20, we have not seen press reports of a first flight. If successful, Boom plans to begin production of the Overture in 2022, with rollout and testing in 2025 and the first commercial delivery in 2029. [53]

In addition to these two better-known players in the supersonic commercial aviation industry, several startups and established companies are currently working on a commercial SST; see FIGURE 12. Based out of Boston, Spike Aerospace is presently developing a Mach 1.6 business jet comparable in size to the Aerion AS2. Unlike Aerion's "boom-less" approach, Spike takes the low-boom approach with a perceived loudness level of 75 PLdB compared to the Concorde's 105-110 PLdB. [54]

The Hermeus Corporation, a startup based in Atlanta, is currently developing a Mach 5 hypersonic airplane. In 2020, the United States Air Force selected Hermeus to further study Mach 5 flight and how it might be used to create a potential hypersonic Air Force One. [55] It was announced in March of 2021 that Hermeus had reached an agreement with NASA to collaborate on the research and development of supersonic and hypersonic aircraft. [55]

Exosonic, a startup based in California, is currently developing a low-boon Mach 1.8 70-seat airliner. They also were selected by the United States Air Force in 2020 to research and develop a potential supersonic aircraft for use by the Presidential and Executive Airlift Directorate. [56]

FIGURE 12 – a) Spike S-512 b) Hermeus c) Exosonic

VI. FAA Working Group and 2020 Notice for Proposed Rulemaking

Recently the FAA has been exploring and adopting changes in regulations regarding supersonic takeoff and landing noise and testing of commercial supersonic aircraft. In a 2019 notice of proposed rulemaking (NPRM), later adopted in 2021, the FAA updated and clarified the process required to obtain special clearance to conduct supersonic flight tests. [3] Before this rule change, the requirements to apply for this special authorization were located in Appendix B of 14 C.F.R. § 91. The language in Appendix B was adopted in 1973. As pointed out in the 2019 NPRM, "The appendix was intended to be used primarily to authorize supersonic flights needed to test the airworthiness of a new aircraft, determine the 'sonic boom characteristics' of an aircraft, or to show the conditions and limitations under which a supersonic flight did not allow a measurable sound pressure wave to reach the ground as a condition for other operation." [44] The FAA states a need to revise Appendix B because it was not well organized and led to many discrepancies in the interpretation of several key terms. Furthermore, this poor organization of the regulations did not provide a clear path for developers to submit applications for supersonic testing. In 2021, this proposed rule change was enacted, and Appendix B was revised. Further, instead of being placed in Appendix B, the revised regulations were put in a new section, 14 CFR § 91.818.

The FAA put forward another NPRM in 2020. [4] This NPRM proposed amending portions of parts 21 and 36 of Title 14 to include takeoff and landing noise certification of supersonic aircraft. Currently, the only certified supersonic commercial airliner is the retired Concorde. The Concorde noise certification requirements were first published in 1978 in § 36.301. [45] In 2018 the FAA's Office of the Chief Counsel released their interpretation of the applicability of 14 C.F.R. § 36 to new supersonic aircraft. They determined that § 36.301 only applied to the Concorde and not any future supersonic aircraft. In addition, they determined that the FAA would be obligated to create noise certification standards for future supersonic aircraft before they could issue a type certificate for a new supersonic aircraft. [4] In other words, noise certification standards need to be in place before any future aircraft can be certified. This interpretation of 14 C.F.R. § 36 led to the FAA issuing this NPRM on the takeoff and landing noise certification requirements of supersonic aircraft. While the FAA proposes implementing these new requirements, it emphasizes that this proposed change does not change the prohibition of supersonic flight over land in the U.S. and should not be interpreted as such.

Under this NPRM, [4] the FAA first proposes revising 14 C.F.R. § 21.93(b) to include supersonic aircraft as their own design type and include the Concorde as a separate type to distinguish the Concorde's certification requirements. Next, the FAA proposes to amend part 36 to include a new aircraft category called Supersonic Level 1 (SSL1). This initial category would be defined in § 36.1 and would consist of supersonic aircraft with a maximum MTOW of 150,000-lbm and a maximum cruise Mach number of 1.8. [46] The FAA worked with NASA and data provided by current SST developers and determined that most initial designs would fall into this category. Further, this initial category would provide a building block for future categories, including aircraft with higher MTOW's and cruise Mach numbers.

As part of this NPRM, the FAA proposes adding a Subpart E to 14 C.F.R. § 36 that would include the takeoff and landing noise limits of SSL1 category aircraft. [4] The FAA would also amend Appendix C to incorporate the noise levels and certification procedures for SSL1 aircraft. The three reference noise measurements used for subsonic aircraft, full-power lateral, flyover, and approach, would remain the same for SSL1. The only significant change in the noise certification procedures is that SSL1 category aircraft could use variable noise reduction systems (VNRS) to meet certification requirements. If an aircraft needed to use a VNRS to meet the certification requirements, it would be required to use the VNRS under normal operating procedures. A provision in the proposed changes would require that the flight crew check if the VNRS is operating correctly before takeoff. The proposed noise levels for SSL1 aircraft are 96.5 EPNdB for the lateral measurement of both two and three-engine aircraft. The approach limit is also the same for both two and three-engine aircraft and is limited to 100.2 EPNdB. The flyover limit is 91.0 EPNdB for two-engine aircraft and 94.0 EPNdB for three-engine aircraft.

Like subsonic aircraft, these proposed changes would have linearly decreased noise levels with the logarithm of the airplane weight. Also similar to subsonic aircraft, SSL1 aircraft would also need to meet a cumulative noise value, but unlike subsonic, they would not be allowed to use "credit" to make up for any of the three reference points. In other words, the three reference limits cannot be exceeded, even if the aircraft is significantly under the maximum level at another reference point. Looking at the cumulative noise values, these proposed limits would make SSL1 aircraft quieter than Stage 4 subsonic aircraft but louder than Stage 5 aircraft. Since Stage 5 levels were only adopted in the last few years, most of the U.S. commercial fleet is certified under Stage 4 levels. Thus, this proposed rule would require SSL1 aircraft to be quieter during takeoff and landing cycles than many subsonic aircraft.

As part of the NPRM, the FAA assessed the environmental impact of these proposed takeoff and landing noise level changes. Their analysis found that by 2034 subsonic aircraft will have cumulative noise levels of 267.0 ± 11.3 EPNdB. Meanwhile, they predict that two-engine SSL1 aircraft will have an average cumulative noise level of 269.3 EPNdB, while three-engine SSL1 aircraft will have an average cumulative noise level of 274.5 EPNdB. [45] This analysis shows that approximately 43% of two-engine and 26% of three-engine SSL1 aircraft will have lower cumulative takeoff and landing noise levels than subsonic aircraft. The FAA predicts that around 3% of the U.S. commercial fleet will be supersonic by 2034. Thus, even though they will be a little louder, the overall impact of supersonic aircraft on takeoff and landing noise will be minimal. [45]

VII. Further Considerations - How Do We Achieve an SST for the Future?

Designing an economically viable SST that meets today's more stringent regulations will require a lot of new technology, as well as advancements in current technology. The issues that stand in the way include increased fuel consumption, greenhouse gas emissions, takeoff and landing noise, and the sonic boom. Some of these issues involve elements that affect one another, often in a contradictory nature. For example, current subsonic aircraft engines are trending towards higher bypass-ratios (BPR) and lower thrust-specific fuel consumption (TSFC). These engines have led to significant decreases in fuel consumption, emissions and provide less noise during takeoff and landing. However, these engines come with a price. They produce more substantial amounts of drag, amounts that would make supersonic cruising not practical. Thus, a trade-off must be made. In this paper, we have limited our discussion to noise regulations. Therefore, we will focus only on the advancements and potential changes to regulations that pertain to these areas.

A. Advanced Takeoff Procedures

One of the proposed procedures is known as programmed thrust lapse. This is a method in which the flight control system automatically reduces the engines' thrust by up to 10% once the aircraft reaches V_2. Recall that the V_2 speed occurs when the aircraft reaches 35 feet above ground level. Further recall that 14 C.F.R. §B36.3(a)(1) requires the lateral noise reference point to occur when the aircraft reaches 985 feet above ground level. Thus, an automatic, smooth reduction in engine power could allow for quieter lateral noise values. This procedure is permitted under 14 C.F.R. §25.111(c)(4), which says:

> `(4) The airplane configuration may not be changed, except for gear retraction and automatic propeller feathering, and no change in power or thrust that requires action by the pilot may be made until the airplane is 400 feet above the takeoff surface. [57]`

The key here is that this thrust lapse must be done under the control of the engine computer, not the pilot. This is ideal because the computer will begin throttling down the engine quicker than the pilot. Studies suggest that a programmed thrust lapse could reduce the lateral noise level by 10 EPNdB. [58] The intention of 14 C.F.R. §25.904, which regulates automatic thrust control systems, appears to be safety-related, thus allowing the flight control system to increase the throttle level in the event of an engine failure or malfunction. [59] If this is the case, a modification or exception may be required to allow supersonic aircraft to use programmed thrust lapse to reduce takeoff noise.

Two more proposed procedures are De-Rated Thrust takeoffs and Reduced Thrust takeoffs, commonly used on many subsonic airliners today. [60] As explained in an FAA advisory circular (AC) 25-13, a de-rated thrust takeoff is when the thrust level used is less than the rated maximum takeoff thrust of the engine. [61] The thrust used in a de-rated thrust takeoff is a standard takeoff thrust value given in the airplane flight manual (AFM). When an aircraft is certified, it must meet various takeoff performance standards specified in 14 CFR § 25. As a safety precaution, the takeoff speeds and climb gradients set in 14 CFR § 25 require that aircraft demonstrate the specified speed and climb gradients with one-engine inoperative. [62] Thus, the designer must supply engines with enough thrust that if an engine failure occurs after the "go-no-go" speed, V1, the remaining engine(s) has enough power to continue accelerating the aircraft to its V_2 speed and maintain a specified climb gradient. Given that most new jet-powered airliners are two-engine aircraft, this requires that a single-engine should be able to power the aircraft at MTOW in a one-engine inoperative situation. Thus, a de-rated thrust takeoff takes advantage of this by not using the full-rated takeoff thrust of the engines. In 14 C.F.R. §I25.4(b), a de-rated thrust value of no less than 90% of the rated maximum thrust required for one-engine inoperative performance at the given takeoff weight and ambient conditions may be used. [45] Given that most airliners are two-engine aircraft and therefore have engines capable of producing enough thrust (from just one engine) for takeoff in one-engine inoperative conditions, a de-rated thrust value of 50% or less is not entirely unrealistic. This could be a potential change that not only allows for aircraft to take-off with less thrust (therefore less noise), but it also reduces fuel burn.

A reduced thrust takeoff is when the flight control system is given "false" ambient temperature information [63] that causes it to use less than normal rated takeoff thrust value. [29] This reduced thrust value must be no less than 75% of the rated takeoff thrust. AC 25-13 also stipulates that relevant speeds must still comply with all C.F.R. regulations for the given ambient conditions. [61] The reduced thrust takeoff was intended to save fuel and reduce noise when the ambient conditions and the aircraft's takeoff weight did not need the full-rated takeoff thrust of the engines. In addition to providing a reduction in fuel burn, the reduced thrust takeoff also provides noise reductions that should be at least equal if not greater than the reductions gained from the programmed thrust lapse procedure. The reduced thrust takeoff procedure, while technically legal, is often taken advantage of and has led to quite a few accidents due to not correctly "tricking" the flight control system. Perhaps one of the most serious accidents involved an Emirate A340-500 departing from Melbourne, AU:

> The 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 [reduced thrust] takeoff procedure based on an erroneous estimate of the aircraft flight weight. [64]

Thus, it would be recommended to change the regulations regarding reduced thrust takeoffs. Instead of allowing the pilot to enter the ambient information, allow the aircraft to make the required measurements to compute the required takeoff thrust. This change would essentially make a reduced thrust takeoff an extension of the de-rated thrust takeoff procedure but with higher levels of safety.

All three of these procedures mentioned show promise at reducing the takeoff noise associated with supersonic aircraft. While all three procedures are currently part of the C.F.R., there is some ambiguity in the situations they apply. This ambiguity is particularly the case with the programmed thrust lapse takeoff procedure.

The de-rated thrust takeoff procedure shows much promise, especially since most SST's powered for supersonic cruise without afterburners will likely have sufficient thrust to fly one-engine inoperative at low speed. As Boeing found in their Phase 1 work for NASA's N+2 program, current de-rated thrust takeoff requirements severely limited the ability to design a supersonic commercial airliner with the ability to meet current noise standards. [44][45] Boeing found that some of their proposed designs could achieve the desired performance and noise standards if a de-rated thrust take-off of 79% full-power thrust was used. [44] However, current standards only allow a de-rated takeoff with a maximum of a 10% reduction of the full-power thrust, less than half of the reduction needed to make the preliminary Boeing designs capable of meeting stringent proposed takeoff and landing noise levels. As was pointed out previously, this limitation of a maximum de-rate of 10% appears to be safety related. If an engine fails after the V1 speed, the remaining engines could be throttled up to the full-power to allow the aircraft to achieve the required V2 speed and one-engine inoperative climb gradient. In a four-engine aircraft, each engine would theoretically only be required to provide 25% of the required thrust. However, if one engine becomes inoperative, the remaining engines need to provide 100% of the required thrust. Thus, each engine would need to provide approximately 33% of the required thrust. This means that a four-engine aircraft would theoretically produce 132% of the required thrust with all four engines at full power. Therefore, an 8% de-rate could be used under all-engines operating procedures. Following the same line of reasoning, a three-engine aircraft could use an approximately 17% de-rate while a two-engine aircraft could use up to a 50% de-rated thrust level. Furthermore, this assumes that the normal performance of the airplane is right around the minimum one-engine inoperative performance. This is often not the case, with normal operating takeoff performance being better than the minimum required one-engine inoperative takeoff performance. Thus, a 21% de-rated thrust value could safely be used in a two-engine aircraft and likely a three and four-engine aircraft, with still enough thrust in the remaining engine(s) in a one-engine inoperative situation.

B. Separate Noise Requirements

At least in the short term, a suggested solution is to adopt different noise standards for supersonic aircraft. Proponents of this approach argue that it would invite more participants to design and manufacture supersonic aircraft. They argue that this increase in competition would spur innovation, eventually leading to improved designs that would not need different standards. Furthermore, proponents are only suggesting a minor relaxing of the standards. The FAA has recently been entertaining this idea quite seriously, as they issued a notice of proposed rulemaking (NPRM) in 2020 regarding noise certification of supersonic aircraft. [4] The changes proposed in this NPRM suggest that initial studies show that the supersonic commercial aircraft that will be ready in the next few years will be smaller than the Concorde, with MTOW's less than or equal to 150,000 lbs. They also show that these aircraft are likely to have a cruise speed of Mach 1.8, which is slightly less than the Concorde. The proposed rule calls for the amendment of 14 C.F.R. § 36, which regulates aircraft noise. [36][37] Among these amendments is the classification of noise limits named Supersonic Level 1 (SSL1) requirements. The FAA proposes that these SSL1 requirements would fall in between Stage 4 and Stage 5 requirements. Furthermore, they propose that these new requirements "would allow Variable Noise Reduction Systems (VNRS) to be used for noise certification testing, and if used for certification, would require the system to be activated during normal operations." [4] This proposed rule change is a promising step in the right direction, as there is currently a lot of interest in achieving commercial supersonic transport.

C. Sonic Boom and Other Technologies

There are many current research efforts aerodynamics that aim to reduce and possibly eliminate the intensity of the shockwaves created by supersonic aircraft. This reduction in the shockwave strength would lead to a reduction in the intensity of the sonic boom. NASA is currently working with the Lockheed Martin Skunk Works Program on the X-59 QueSST aircraft, which is being developed to test quiet supersonic technology. [65] The X-59 uses advanced geometry and flow control techniques to help reduce the intensity of the generated shockwaves. The initial flight is expected sometime in 2022 or 2023, and preliminary tests suggest that the X-59's sonic boom could have a PLdB of only 75 decibels. [65] This PLdB level would be a significant improvement over the sonic boom of the Concorde, which had an average PLdB of 105 decibels.

In addition to reducing the intensity of the sonic boom, a significant amount of work is being done to improve efficiency and lower the noise of supersonic aircraft engines. Some of the current engine technologies being studied that show promise are variable cycle engines (VCE) that can adjust their BPR to the flight conditions. [66] Another promising engine technology is inverted velocity profile (IVP) nozzles. [67] The idea behind IVP nozzles is to inject low-speed flow into the high-speed turbulent flow exiting the nozzle. This would allow for better mixing of the turbulent stream exiting the nozzle. The better mixing theoretically produces lower jet noise farther downstream of the nozzle.

These new technologies are exciting and show much promise. It will allow us to eventually achieve economically viable SST's and possibly hypersonic commercial transports. However, in the next few years, the initial SST's will need to use a combination of different noise standards and advanced takeoff and landing procedures. This will require amendments or clarifications to current C.F.R. regulations. These initial SST's will provide valuable data to progress the technology further, and I believe the proposals suggested in this paper can be used safely to make supersonic commercial aircraft once again a reality.

VIII. Conclusion

Based on the information discussed here, we see a continuing need for research to make commercial supersonic aircraft an economically feasible reality. However, changes will also need to be made to current aircraft design regulations to make this a reality. Current regulations simply do not allow aircraft manufacturers to take full advantage of the designs available to them. Current takeoff procedures severely limit designers in terms of the minimum required thrust at takeoff by placing an arbitrary maximum engine de-rate of 10%. Since engine thrust is the most prominent source of takeoff noise and supersonic aircraft will require engines with more than sufficient thrust at takeoff conditions, it would make sense to allow these aircraft to operate at as minimal thrust levels as safely possible. Not only would this lower takeoff noise, but it would also decrease fuel consumption and greenhouse gas emissions.

A recent FAA NPRM from 2020 shows promise at potential changes to include takeoff-and-landing noise level certification requirements for supersonic commercial aircraft. These potential noise level requirements will allow supersonic aircraft to have slightly higher takeoff-and-landing noise levels than current Stage 5 levels for subsonic aircraft. However, these levels will be less than the Stage 4 levels that many current subsonic commercial aircraft are certified. It is our opinion that this is a reasonable compromise. It still places reasonable noise restrictions on future supersonic aircraft while making it more economically viable to design and manufacture. This, in turn, would continue to spur innovation that would lead to more categories of supersonic aircraft and advancement in technology that would continue to lower noise levels and reduce emissions.

The COVID-19 pandemic has undoubtedly been felt in the aerospace industry. Most companies and airlines are focused on minimizing the loss due to decreased travel and are not as enthusiastic about investing in future aircraft designs. Particularly in uncertain and unproven supersonic aircraft. This makes it even more important to continue to fund this work and make technological improvements that will hopefully make supersonic travel a reality in the near future.

Acknowledgments

This paper derives from unsponsored work performed in conjunction with Mr. Webb's M.S. Thesis in Aerospace Engineering at Arizona State University.

References

1 Prisco, J. "Concordski: What ever happened to Soviets' spectacular rival to Concorde?" *CNN,* July 10, 2019. https://www.cnn.com/style/article/tupolev-tu-144-concordski/index.html
2 BBC News. "Concorde' back where she belongs'," *BBC News.* November 6, 2001.
3 Department of Transportation: Federal Aviation Administration, "NPRM: Special Flight Authorizations for Supersonic Aircraft," Federal Register, 2019. (call out page)
4 Department of Transportation: Federal Aviation Administration, "NPRM: Noise Certification of Supersonic Airplanes," Federal Register, 2020. (call out page)
5 Jarvis, Robert M, et al. Aviation Law: Cases and Materials. Durham: Carolina Academic Press, 2006.
6 Loftin, Jr., Laurence K. Quest for Performance: The Evolution of Modern Aircraft. Washington, D.C.: NASA Scientific and Technical Information Branch, 1985. Digital Book.
7 Air Mail Act of 1925 (Kelly Act), 43 Stat. 805, Feb 2, 1925.
8 Lawrence, Harry. Aviation and the Role of the Government. Kendall Hunt, 2014.
9 Air Commerce Act of 1926, 44 Stat. 568, May 20, 1926.
10 Legislative History of the Air Commerce Act of 1926, U.S. Government Printing Office, Washington, 1928.
11 "TWA Flight 599." Wikipedia. 2017. en.wikipedia.org/wiki/TWA_Flight_599. Accessed 2 May 2017.
12 Civil Aeronautics Act of 1938, 52 Stat. 977. 1938.
13 Federal Register Act. 49 Stat. 500. July 26, 1935. See: 44 U.S.C. 15 (2017)
14 14 CFR § 04a (1946)
15 14 CFR § 04b (1946)
16 Federal Aviation Act of 1956
17 14 CFR § 04b SR-422 (1960)
18 B707 type certificate
19 DC-8 type certificate
20 14 CFR § 04b SR-422 4T.122 (1960) "Landing Distance"
21 14 CFR § 04b SR-422 4T.121 (1960) "En-route Flight Paths"
22 14 CFR § 04b SR-422 4T.83 (1960) "En-route Limitations"
23 Maltby, R. L. "The Development of the Slender Delta Concept." Aircraft Engineering (1968): 12-17.
24 www.concordesst.com (accessed May 23, 2021)
25 The Boeing Company. "Statistical Summary of Commercial Jet Airplane Accidents: Worldwide Operations 1959-2019." 2020.
26 Hirschberg, Michael J. and Clives Leyman. Case Study by Aerospatiale and British Aerospace on the Concorde. American Institute of Aeronautics and Astronautics, 2000. Ebook. https://ebookcentral-proquest-com.ezproxy1.lib.asu.edu/lib/asulib-ebooks/detail.action?docID=3111622.
27 14 C.F.R. §25.113 (2021) "Takeoff distance and takeoff run."
28 14 C.F.R. §25.107 (2021) "Takeoff speeds."
29 Takahashi, Timothy. Aircraft Performance and Sizing, Volume II: Applied Aerodynamic Design. New York: Momentum Press, LLC, 2016.
30 British Airways Overseas Division, Concorde Flying Manual: Volume II (a), October 4, 1979.
31 Embraer S.A. "E190 Specifications." June 2017. https://www.embraercommercialaviation.com/wp-content/uploads/2017/06/Embraer_spec_E190_web-EN.pdf

32 McDonnell Douglas Corporation. "DC/MD-10: Airplane Characteristics for Airport Planning." January 1991. https://www.boeing.com/resources/boeingdotcom/commercial/airports/acaps/dc10.pdf

33 14 C.F.R. §25.125 (2021) "Landing."

34 14 C.F.R. §121.195 (2021) "Airplanes: Turbine engine powered: Landing limitations: Destination Airports."

35 ICAO. "Environmental Protection: Reduction of Noise at Source," [Online]. Available: https://www.icao.int/environmental-protection/Pages/Reduction-of-Noise-at-Source.aspx [Accessed 23 May 2021]

36 14 C.F.R. § 36 Appendix B (2021) "Reference Noise Measurement Points."

37 14 C.F.R. § 36 Appendix B (2021) "Trade-Offs."

38 14 C.F.R. § 36.301 (2021) "Noise limits: Concorde."

39 14 C.F.R. § 91.817 (2021) "Civil aircraft sonic boom."

40 NASA. "NASA's High Speed Research (HSR) Program - Developing Tomorrow's Supersonic Passenger Jet." 22 April 2008. [Online]. Available: https://www.nasa.gov/centers/langley/news/factsheets/HSR-Overview2.html#:~:text=As%20envisioned%2C%20the%20High%2DSpeed,possible%20within%2020%2D25%20years [Accessed 23 May 2021]

41 Graham, D., Dahlin, J.A., Meredith, K.B., Vadnais, J.L. "Aerodynamic Design of Shaped Sonic Boom Demonstration Aircraft," AIAA 2005-0005, 2005.

42 "Dual-Relevant Concept." [Online]. Available: https://www.globalsecurity.org/jhtml/jframe.html#https://www.globalsecurity.org/military/systems/aircraft/images/qsp-image01.jpg [Accessed 23 May 2021]

43 Anon., "Boeing/NASA N+2" https://www.globalsecurity.org/military/systems/aircraft/n2-ba.htm

44 Welge, H.R., et al. "N+2 Supersonic Concept Development and Systems Integration," NASA Contractor Report CR 2010-21684, August 2010.

45 14 C.F.R. § 25 Appendix I (2021)

46 Aerion Corporation, "Aerion SBJ: Specifications," 3 January 2014. [Online]. Available: https://web.archive.org/web/20140103223046/http://aerioncorp.com/jet. [Accessed 20 May 2021]

47 Aerion Corporation, "Aerion AS2 Supersonic Business Jet: Wind Tunnel Validation," 2 December 2020.

48 Aerion Corporation, "Aerion Corporation: AS2," 2021. [Online]. Available: https://aerionsupersonic.com/as2/. [Accessed 20 May 2021].

49 O'Hare, M. & Sillers,P., "Road to the Future: Supersonic airliner could fly LA to Tokyo in under three hours," *CNN,* 30 March 2021.

50 Boom Supersonic, "Boom Supersonic: Press Room," 2021. [Online]. Available: https://boomsupersonic.com/press. [Accessed 20 May 2021].

51 B. Fehrm, "Will Boom succeed where Concorde failed?," 17 November 2016. [Online]. Available: https://leehamnews.com/2016/11/17/will-boom-succeed-concorde-failed/. [Accessed 20 May 2021].

52 K. O'Connor, "Boom, Rolls-Royce Partner On Supersonic Overture," 30 July 2020. [Online]. Available: https://www.avweb.com/aviation-news/business-aviation-news/boom-rolls-royce-partner-on-supersonic-overture/. [Accessed 20 May 2021].

53 Boom Supersonic, "Boom Supersonic: Overture," 2021. [Online]. Available: https://boomsupersonic.com/overture. [Accessed 20 May 2021].

54 Spike Aerospace, "Spike Aerospace: The Spike S-512 Supersonic Business Jet," 2020. [Online]. Available: https://www.spikeaerospace.com/s-512-supersonic-jet/. [Accessed 20 May 2021].

55 Hermeus Corporation, "Hermeus Corporation: News," 6 August 2020. [Online]. Available: https://www.hermeus.com/news. [Accessed 20 May 2021].

56 M. O'Hare, "Exclusive look at designs for US supersonic presidential jet," *CNN,* 2 April 2021. [Online]. Available: https://www.cnn.com/travel/article/supersonic-air-force-one-exosonic-cabin-interior/index.html

57 14 C.F.R. § 25.111 (2021) "Takeoff path."

58 Berton, J. J., et al. "Noise predictions for a supersonic business jet using advanced takeoff procedures." The Aeronautical Journal 122.1250: 556-571. 2018.

59 14 C.F.R. § 25.904 (2021) "Automatic Takeoff Thrust Control System"

60 Takahashi, T.T. "The Impact of ATTCS on Reduced-Thrust Takeoff Field Performance." AIAA 2015-2698. 2015.

61 FAA Advisory Circular 25-13. "Reduced and Derated Thrust Takeoff Power," May 4, 1988.

62 14 C.F.R § 25.121 (2021) "Climb: One Engine Inoperative"

63 Fueri, M. "Flex Temperature, Choice of Takeoff Configuration," Airbus 14th Performance & Operations Conference, Bangkok, Thailand, April 4-8, 2006.

64 Anon., "Tailstrike and Runway Overrun. Melbourne Airport, Victoria, 20 March 2009," Australian Transport Safety Report ATSB A0-2009-012, 2009.
65 NASA. "Low-Boom Flight Demonstration." [Online]. Available: https://www.nasa.gov/mission_pages/lowboom/vehicle [Accessed 23 May 2021]
66 Huff, D.L., Henderson, B.S., Berton, J.J. & Seidel, J.A. "Perceived Noise Analysis for Offset Jets Applied to Commercial Supersonic Aircraft." AIAA 2016-1635, 2016.
67 Bridges, J., Brown, C.A. & Seidel, J.A. "NASA's Pursuit of Low-Noise Propulsion for Low-Boom Commercial Supersonic Vehicles." AIAA 2018-0264, 2018.