Make America Boom Again: How to Bring Back Supersonic Transport

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ABSTRACT

In 1973, the FAA banned civil supersonic flight over the United States. As a result, the supersonic aviation industry has not developed. It is now time to revisit the ban. Better technology—materials, engines, and simulation capabilities—means that it is now possible to produce a supersonic jet that is more economical and less noisy than those of the 1970s. In this paper, we examine the case for, the history of, and the legitimate issues created by supersonic flight. We conclude that it is past time to rescind the ban in favor of a modest and sensible noise standard.

JEL codes: L9, N7, R4, L5

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An aircraft flying roughly twice the speed of sound could take off in New York City and land in Los Angeles in just two hours. The technology to travel at this speed exists, but in 1973 the Federal Aviation Administration (FAA) issued a complete ban on civil supersonic aviation over all US land and territorial waters,[1] a ban that remains in effect to this day.

The issue is noise. As an airplane reaches the speed of sound (Mach 1 or 660 mph at high altitude[2]), air waves produced at the plane's nose are compressed, generating a shock wave that is known as a sonic boom because of the explosive noise it creates in the plane's wake.[3] The Concorde, the supersonic passenger jet developed in the 1960s by the United Kingdom and France, for example, produced a sonic boom as loud as 135 decibels when it reached land,[4] comparable to the noise level 100 feet from a jet engine.[5]

Many decades have passed since the Concorde's milestone transatlantic flight in 1969.[6] A new generation of supersonic plane designs takes advantage of 50 years of advances in materials science, aerospace engineering, and computer simulation techniques to substantially reduce the loudness of the sonic boom. In 2012, for example, a team of NASA-funded researchers reported results from wind tunnel tests in which scale model aircraft produced sonic booms perceived to be as quiet as 79 decibels, similar to the noise created by a car passing 10 feet away.[7] And in 2016, NASA's New Aviation Horizons Initiative awarded contracts

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[1] Civil Aircraft Sonic Boom, 14 C.F.R. § 91.817.

[2] "Speed of Sound at Different Altitudes," Fighter Planes and Military Aircraft, accessed July 18, 2016.

[3] Yvonne Gibbs, "NASA Armstrong Fact Sheet: Sonic Booms," NASA, February 28, 2014.

[4] This is the high end for the Concorde, which had a typical sonic boom of 105–110 decibels. Adrian Giordani, "The Challenges of Building a Hypersonic Airliner," BBC, September 15, 2015.

[5] "Decibel (Loudness) Comparison Chart," Galen Carol Audio, accessed July 18, 2016.

[6] "History of Concorde," ConcordePhotos.com, accessed July 18, 2016.

[7] Jim Banke, "Sonic Boom Heads for a Thump," NASA, May 8, 2012. The perceived decibel level (PLdB) is a subjective magnitude of loudness created in part to measure the loudness of impulse

to Lockheed Martin to begin production on the company's winning "quiet supersonic" plane design, which may be flown as soon as 2020.[8] At the same time, several ambitious start-ups have begun designing supersonic passenger planes of their own.

The FAA has stated publicly that a noise standard for supersonic transport is among its priorities. Nonetheless, the ban over land remains in place, limiting the potential market for commercial companies and creating regulatory uncertainty for companies not backed by federal contracts. After a more than 40-year moratorium on supersonic flight over land, a supersonic noise standard is long overdue. This paper explores what such a noise standard might look like.

"An affordable and commercially viable supersonic transport is unlikely to spring from the mind of a single engineer, much less a committee of bureaucrats."

WHY OVERLAND FLIGHT MATTERS FOR SUPERSONIC FLIGHT

The theory of industry learning curves is of such great importance to the aviation industry that this industry appears to be where the idea first originated.[9] An affordable and commercially viable supersonic transport is unlikely to spring from the mind of a single engineer, much less a committee of bureaucrats. Like the subsonic aviation industry that came before it, a supersonic aviation industry will require trial and error, competition, and a market discovery process to lead firms up the learning curve to commercial viability.[10]

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noises such as unmitigated sonic booms and of other complex waveforms that are not well characterized by a simple decibel measure (dB(A)). S. S. Stevens, "Perceived Level of Noise by Mark VII and Decibels (E)," *Journal of the Acoustical Society of America* 51, no. 2B (1972): 575. For a comparison of the noise levels of different events, see Gregg Vanderheiden, "About Decibels (dB)," accessed October 17, 2016, https://web.archive.org/web/20160804150658/http://trace.wisc.edu/docs/2004-About-dB/.

[8] J. D. Harrington and Kathy Barnstorff, "NASA Begins Work to Build a Quieter Supersonic Passenger Jet," NASA, February 29, 2016.

[9] K. Hartley, "The Learning Curve and Its Application to the Aircraft Industry," *Journal of Industrial Economics* 13, no. 2 (March 1965): 122–28.

[10] Don Lavoie, "The Market as a Procedure for Discovery and Conveyance of Inarticulate Knowledge," *Comparative Economic Studies* 28, no. 1 (1986): 1–19.

Instead, as we detail in later sections, developing supersonic transport has historically been approached as a massive government undertaking, motivated more often by geopolitical interests than by the drive to meet a specific market demand.[11] This has produced valuable basic research, to be sure, but it has also meant that even the most promising effort, the Concorde, was an inevitable commercial failure. Its high ticket price and maximum capacity of 125 passangers meant that the Concorde's profitability was extremely sensitive to changes in market demand. Yet with the advantages of minimal competition and the backing of two major governments, the Concorde was able to fly for 27 years without ever iterating its 1960s-era design.[12]

The question remains: If supersonic transport holds so much untapped potential, why haven't private-sector incumbents pushed harder for its return? The question itself may be flawed. Since the Concorde's retirement in 2003, major companies such as Boeing[13] and Airbus[14] have announced significant supersonic ambitions. Small venture-backed companies like Boom[15] and Aerion[16] have also revealed realistic plans for commercial supersonic jets within the decade. Nonetheless, the ban on overland supersonic transport has no doubt played a significant role in delaying these developments in two main ways. First, the ban greatly restricts potential market size. And second, it truncates the supersonic learning curve above the private sector's natural entry point, namely overland business jets.

The size of the forgone overland market is difficult to estimate precisely. At a first approximation, there are nearly seven domestic passenger flights within the United States for every international flight,[17] but how much of the US domestic market is accessible to supersonic flights depends on the scenario one considers. A larger passenger jet may only be practical for high-traffic coast-to-coast

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[11] Susan A. Edelman, "The American Supersonic Transport," in *The Technology Pork Barrel*, ed. Linda R. Cohen and Roger G. Noll (Washington, DC: Brookings Institution Press, 1991), 98–99.

[12] Erik M. Conway, *High-Speed Dreams: NASA and the Technopolitics of Supersonic Transportation, 1945–1999* (Baltimore: Johns Hopkins University Press, 2008), 36.

[13] Ben Woods, "Boeing Wants to Bring Back Supersonic Air Travel—and Take Us to Mars," *Wired*, July 20, 2016.

[14] Alan Tovey, "Concorde Mark 2: Airbus Files Plans for New Supersonic Jet," *Telegraph*, August 6, 2015.

[15] Rupert Neate, "Supersonic Jet Startup Vows 'Affordable' Travel—If You Have $5,000 to Spare," *Guardian*, March 23, 2016.

[16] Aerion Corporation, "Aerion Unveils Larger, Three-Engine Supersonic Business Jet Tailored to Emerging Global Demand," press release, May 19, 2014.

[17] Neate, "Supersonic Jet Startup Vows 'Affordable' Travel"; Bureau of Transportation Statistics, "Summary 2014 U.S.-Based Airline Traffic Data," Press Release No. BTS 15-15, March 26, 2016.

routes, for example, while small business jets are likely economical at much shorter distances as well as longer ones.

Elon Musk has argued that high-traffic city pairs that are more than about 1,500 km or 900 miles apart are best served by supersonic air travel, adding that "a quiet supersonic plane immediately solves every long-distance city pair without the need for a vast new worldwide infrastructure."[18] As it happens, 900 miles is roughly the average nonstop distance flown per departure on US airlines, suggesting that the forgone domestic market may be quite large indeed.[19]

This situation points to the second way that the overland prohibition has stalled the growth of commercial supersonic transport: by closing off the business jet category as the natural point for private actors to enter the supersonic learning curve. A smaller supersonic business jet doing more frequent trips would be able to meet a consumer demand without being vulnerable to the sort of losses experienced by the Concorde. Indeed, internal market analysis by Gulfstream has confirmed a large demand for quiet supersonic flights in a business jet category. However, Gulfstream's analysis argues that ending the prohibition on supersonic flight over land is "required" for the success of affordable supersonic transport, given that only 25 percent of small civil aircraft operations occur over water.[20]

The 2001 National Research Council's Committee on Commercial Supersonic Technology concurs, stating that "supersonic flight over land is essential for this class of vehicles [business jets], and the potential market is estimated to be at least 200 aircraft over a 10-year period."[21] This estimate is on the low end of the studies done to date, as summarized in table 1. Similarly, a survey of business jet operators found that most participants "guess the chance" of acquiring a supersonic business jet "in spite of an overland flight ban to be zero. In case the ban is lifted, the chance is seen as 50%."[22]

Lacking reasonable noise rules for supersonic flight over land, the United States shut down the market for smaller, low-boom business jets and thus sequestered the natural entry point for climbing the supersonic learning curve.

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[18] Elon Musk, "Hyperloop Alpha," *SpaceX*, August 12, 2013.

[19] Neate, "Supersonic Jet Startup Vows 'Affordable' Travel"; Bureau of Transportation Statistics, "Summary 2014 U.S.-Based Airline Traffic Data."

[20] Gulfstream Aerospace Corporation, "Supersonic Technology Development" (FAA Public Meeting: Supersonics, Washington, DC, July 14, 2011).

[21] Committee on Breakthrough Technology for Commercial Supersonic Aircraft et al., *Commercial Supersonic Technology: The Way Ahead* (Washington, DC: National Academies Press, 2001), 10.

[22] Bernd Liebhardt and Klaus Lütjens, "An Analysis of the Market Environment for Supersonic Business Jets" (paper presented at Deutscher Luft- und Raumfahrtkongress, 2011).

TABLE 1. MARKET STUDIES OF SUPERSONIC BUSINESS JETS

Market study	Demand for supersonic business jets
Gulfstream Aerospace study 1[(a)]	180 over 10 years
Gulfstream Aerospace study 2[(b)]	350 over 10 years
Meridian / Teal[(c)]	250–450 over 10 years
Teal Group 2007 study[(d)]	400 over 20 years
StrategyOne Consulting / Aerion[(e)]	220–260 over 10 years
Supersonic Aerospace International[(f)]	300+
Roland Vincent Associates / Aerion[(g)]	600 over 20 years

Sources: A partial version of this table was originally compiled by Gail M. Krutov, "Making the Small Supersonic Airliner a Reality: Obstacles and Solutions," NASA, 2009. Specifically: (a) Preston A. Henne, "The Case for Small Supersonic Civil Aircraft," *Journal of Aircraft* 42, no. 3 (2005): 765–74; (b) ibid.; (c) Meridian International Research, "SSBJ II Airline and Fractional Markets," 2000; Teal Group Corporation, "Small Supersonic Vehicle Definition and Market Outlook," 2002; (d) John Wiley, "The Super-Slow Emergence of Supersonic," *Business & Commercial Aviation*, September 1, 2007; (e) Aerion Corporation, "Proprietary Market Research Demonstrates Market Viability of Aerion Supersonic Jet," press release, November 2005; (f) Bill Sweetman, "Skunk Works Plans Worldwide Network of Thunderbirds-Style Supersonic Jets," *Jane's*, July 27, 2006; (g) Aerion Corporation, "Aerion Unveils Larger, Three-Engine Supersonic Business Jet Tailored to Emerging Global Demand," press release, May 19, 2014.

Indeed, early technological adoption among a luxury or business class of consumers is a recurrent phenomenon in the spread of innovation.[23] As Everett Rogers showed in his seminal work, *Diffusion of Innovation*, early adopters are often willing to pay a high initial price for a new product because of their greater resources and the pursuit of social status.[24] From there, firms reinvest profits in product design and use the benefits of volume and scale to introduce subsequent product versions with more and more mass market appeal. This is the strategy currently being employed by Tesla Motors in its attempt to mainstream electric vehicles.[25]

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[23] F. A. Hayek most clearly articulated this argument in *The Constitution of Liberty*: "At any stage of this process there will always be many things we already know how to produce but which are still too expensive to provide for more than a few. And at an early stage they can be made only through an outlay of resources equal to many times the share of total income that, with an approximately equal distribution, would go to the few who could benefit from them. At first, a new good is commonly 'the caprice of the chosen few before it becomes a public need and forms part of the necessities of life. For the luxuries of today are the necessities of tomorrow.' Furthermore, the new things will often become available to the greater part of the people only because for some time they have been the luxuries of the few." F. A. Hayek, *The Constitution of Liberty* (Abingdon, UK: Routledge, 2011).

[24] Everett M. Rogers, *Diffusion of Innovations*, 4th ed. (New York: Simon and Schuster, 2010), 252.

[25] In short, "Build sports car. Use that money to build an affordable car. Use that money to build an even more affordable [electric] car." Elon Musk, "The Secret Tesla Motors Master Plan (Just between You and Me)," Tesla, August 2, 2006.

As we discuss in later sections, public-sector-driven efforts like the Concorde, the Boeing 2707, or NASA's High Speed Civil Transport tended to ignore these path dependencies by attempting to go from a blank slate to passenger jets with capacities ranging from 100 to 300 passengers, typically out of laudable, if unrealistic, democratic aspirations. In contrast, a market in supersonic business jets would be able to iterate low-boom and cost-saving technologies while learning exactly what routes the market would bear. Only then would passenger capacities increase for the routes with the highest demand, eventually working up to full-size passenger jets that bring truly affordable supersonic transport to the masses while retaining the noise- and cost-minimizing insights gained from earlier iterations.

Skeptics of supersonic transport have suggested that the relative disinterest of the big incumbents proves that the market for supersonic transport is negligible. Yet the path dependencies inherent in aviation make this sector particularly vulnerable to the classic "innovator's dilemma." That is, on the margin, large incumbents will be more focused on investing in incremental improvements to existing passenger aircraft than on investing in truly disruptive but high-risk innovations.[26] Thus, without low barriers to entry for start-ups on the fringe, large incumbents are liable to leave genuine profit opportunities untapped.

In later sections we go into depth about why now, in particular, is an excellent time to reverse the ban on overland supersonic transport. Here it is sufficient to say that on multiple margins—from computer-assisted design to innovations in material science to the ease in raising the funds needed to overcome substantial upfront costs—recent decades have seen the barriers to entry for disruptive aviation technology fall dramatically. Thus, as is often the case, the last remaining barrier is regulatory.[27]

THE HISTORY AND CURRENT STATE OF SUPERSONIC FLIGHT

As early as 1919, researchers were aware that air flow dynamics approaching the speed of sound are markedly different from those well below that speed.[28] Transonic flow phenomena cause a decrease in lift and an increase in drag in

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[26] Clayton M. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Boston: Harvard Business School Press, 1997).

[27] Adam Thierer, *Permissionless Innovation: The Continuing Case for Comprehensive Technological Freedom*, rev. ed. (Arlington, VA: Mercatus Center at George Mason University, 2016).

[28] F. W. Caldwell and E. N. Fales, *Wind Tunnel Studies in Aerodynamic Phenomena at High Speed* (Report No. 83, National Advisory Committee for Aeronautics, 1920), 23.

airfoils beginning at their critical Mach number, which is the speed at which at least some air traveling around the wing moves at Mach 1. Through the early 1930s, aerodynamicists considered the speed of sound to be a practical limitation on the speed of flight. The term *sound barrier* gained currency as journalists and members of the public misunderstood this practical limitation to represent an insurmountable obstacle to supersonic aviation. Ground and flight research in the United States, United Kingdom, and Germany before and during World War II uncovered aircraft designs that greatly improved transonic performance.[29]

The first aircraft to fly faster than the speed of sound was the Bell X-1, built in 1945 by Bell Aircraft in cooperation with the US Air Force and the National Advisory Committee for Aeronautics (NACA). On October 14, 1947, Captain Charles "Chuck" Yeager was the first to fly the rocket-propelled X-1 faster than Mach 1 after drop-launching out of a B-29 bomber. The Air Force considered the flight so dangerous that officials contemplated giving Yeager the Medal of Honor. The next year, the plane reached 1,000 miles per hour; the Douglas D-558-2 Skyrocket, built for the Navy, reached Mach 2 in 1953; the X-1A, a derivative of the original X-1, reached 1,600 miles per hour in 1954.[30]

Then, in 1957, the launch of Sputnik 1 by the Soviet Union changed research priorities for the US government. Funding for supersonic programs went from 37 percent of NACA's research budget in 1955 to 18 percent in 1958; space programs went from 7 percent to 32 percent in the same period. Also in 1958, NACA was dissolved and incorporated into the new National Aeronautics and Space Administration (NASA).[31]

> "Through the early 1930s, aerodynamicists considered the speed of sound to be a practical limitation on the speed of flight."

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[29] Richard P. Hallion, "The NACA, NASA, and the Supersonic-Hypersonic Frontier," in *NASA'S First 50 Years: Historical Perspectives*, ed. Steven J. Dick (NASA 50th Anniversary Proceedings, 2009), 223–74.

[30] Ibid.

[31] Ibid.

In 1964, Lockheed Martin's Skunk Works division delivered the first of 32 SR-71 Blackbirds to the Air Force. The plane set an airspeed record of 2,193.2 mph in 1976;[32] this official record persists today, although there are accounts of the Blackbird reaching up to Mach 3.5 while in service in the 1980s.[33] That both the official and unofficial flight airspeed records for manned, air-breathing jet aircraft are held by an aircraft built in the 1960s—which is no longer in service—is one indication of the stagnation in supersonic aviation in the last 50 years.

The Tu-144 and the Concorde

Only two supersonic passenger planes have ever operated commercially—the Soviet-built Tupolev Tu-144 and the British and French Concorde.

The Tu-144 had its first flight in 1968, its first supersonic flight in 1969, and its first flight reaching Mach 2 in 1970. It entered into mail and freight service in 1975 and into commercial passenger service on November 1, 1977. After a crash during a test flight on May 23, 1978, that killed two crew members, the Tu-144 was removed from passenger service on June 1, 1978. The airplane had flown a total of 55 scheduled passenger flights over seven months. It continued to be used for research purposes even after the Tu-144 program was canceled in 1983. Sixteen Tu-144s were built over the lifetime of the program.

The Concorde had a much more successful track record. Following its maiden transatlantic flight in 1969, it entered service in 1976 and went on to accumulate over 240,000 flight hours across 81,000 flights before retiring in 2003. But to put these numbers into perspective, the world currently demands 100,000 commercial flights per day. The Concorde was therefore never widely accessed by mainstream consumers. With an average round-trip transatlantic ticket costing in excess of $15,000 in today's dollars, the Concorde's services were primarily used by wealthy and business travelers.

During its tenure, the Concorde came to represent different things to different people. For many, its iconic droop nose and slender delta wings are symbols of human technological achievement and a testament to the urgent pace of commercial aviation innovation of an earlier era. To others, the Concorde symbolizes all the reasons commercially viable supersonic transport is out of reach except to a small class of elites. This latter interpretation goes too far. The Concorde was never designed with commercial viability, let alone

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[32] FAI Record ID #8879, Fédération Aéronautique Internationale, accessed July 18, 2016, http://www.fai.org/fai-record-file/?recordId=8879.

[33] Brian Shul and Walter Watson, *The Untouchables* (Chico, CA: Mach 1, 1993), 173.

affordability, as its primary objective. Instead, it was literally a case of design by committee, namely the Supersonic Transport Advisory Committee (STAC), formed by the British government on November 5, 1956.[34] After three years of study, the committee released a report asserting the feasibility and desirability of either of two models: a 100-passenger Mach 1.2 plane or a 150-passenger Mach 1.8 plane. Through redesigns and negotiation with France, these recommendations would ultimately evolve into the Concorde's final 100-passenger and Mach 2 specification.

The primary motivation for the STAC report was political. Major public supersonic transport (SST) projects in both America and Western Europe foreshadowed the dynamics of the 1960s space race, as nations competed for aviation supremacy. A second motivation was diplomatic. Britain brought its STAC report to Paris and proposed working on an SST jointly in an effort to signal interest in joining the European Common Market and to reduce the project's cost to the British treasury.[35]

France and Britain signed the draft treaty on November 29, 1962, committing the two nations to collaboration, with heavy penalties if either backed out. The name itself, Concorde, was chosen as an allusion to the agreement represented by the joint project. But as might be expected with such an ambitious and politically motivated effort, the actual manufacturing and development of the Concorde was not always so harmonious.

The treaty called for production of the entire aircraft to be shared fifty-fifty between the two countries, with work shared among seven core companies on either side of the Channel, in addition to 800 subcontractors.[36] The British Aircraft Corporation (BAC) and French state-owned aircraft manufacturer, Sud-Aviation (later succeeded by Aérospatiale), had trouble agreeing on airframe designs and range requirements early on, and in 1963 they discovered that their joint design resulted in an aircraft range 500 miles shorter than the distance from Paris to New York.

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[34] It's interesting to note that this was only 11 days before Boeing began its own in-house SST study into what would later become the Concorde's American counterpart, the Boeing 2707. Conway, *High-Speed Dreams*, 36.

[35] As Peter Gillman notes, "The first minister of aviation to take up Concorde was Aubrey Jones, a young economist who at once foresaw the inevitable Treasury opposition to the project. He proposed to his officials that he seek a European partner for the venture as a way of sharing the costs and preempting Treasury objections. Jones was also one of the group of Conservatives who had been disappointed when Britain had not joined the European Common Market, formed in 1957. To him and others like him, a joint venture on so major a project offered some kind of 'surrogate' for entry." Peter Gillman, "Supersonic Bust," *Atlantic*, January 1977.

[36] Glen Segell, *The Defence Industrial Base and Foreign Policy* (N.p.: Glen Segell, 1998), 154.

Redesigns brought reappraisals of cost, with the estimate rising to £275 million from the £95 million maximum cost initially estimated for the STAC report. In 1964 the British Labour government threatened to pull out of the treaty but ultimately relented. By 1975, costs had ballooned to £1,096 million. Including interest charges and adjusting for Anglo-French exchange rates, by the time the Concorde entered service in 1976, true costs came closer to £4.26 billion—$27 billion in today's dollars.[37]

Production went ahead, and after several prominent test flights in 1972 and 1973, more than 70 orders had been placed by major airlines worldwide.[38] Then the 1973 oil crisis hit, and airlines canceled orders in droves. Only 20 Concordes were ever manufactured, of which just 14 saw passenger service.

The Concorde's Demise

In 1966 the environmental activist Richard Wiggs founded the Anti-Concorde Project, which was based on his belief that the Concorde represented a critical front line in the battle between technology and the environment. Wiggs, who died in 2001, made it his mission to prevent the development of supersonic transport. He took out full-page advertisements in the *New York Times*, testified at congressional hearings, and organized a coalition of academic advisors and residents' associations near major airports, all to oppose the Concorde. This mobilized public opposition created additional headwinds for the Concorde, which was already struggling from design flaws and a global oil shock.

Wiggs's campaign proved successful. In 1973, shortly after Boeing abandoned the 2707, its Mach 3, government-funded competitor to the British- and French-made Concorde, the Federal Aviation Administration issued the rule banning supersonic transport over the United States. The move came amid growing concerns about the impact of sonic booms over land, including fears that the shock waves would damage buildings, shatter windows, and create intolerable noise near airports.

The Concorde was banned from landing in the United States altogether until 1976, when the US secretary of transportation allowed the Concorde to land at JFK and Dulles airports for a 16-month trial period. Immediately, the New York Port Authority banned the Concorde from landing at JFK under its local authority for six more months in order to observe the experience at Dulles.

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[37] Gillman, "Supersonic Bust."

[38] "Concorde History: Airline Orders/Options," ConcordeSST, accessed August 1, 2016.

The furor surrounding the Concorde eventually died down as it became apparent that the Anti-Concorde Project's alarmist predictions were overblown. Yet the Concorde's problems were just beginning, as normalized commercial operations began to reveal the poor fit between product and market. The Concorde was certified to accommodate a maximum of 128 people, but on normal flights, it seated 100 passengers with British Airways and 92 with Air France.[39] This proved a difficult number of seats to fill. When demand declined even marginally, routes would lose money, and if demand didn't recover, the routes would have to be canceled. For example, in 1982 Air France suspended its round-trip Concorde flights between Paris and Washington, DC, and Paris and Mexico City because both biweekly routes were flying at 50 percent capacity. The cancellations contributed to losses of nearly $5 million a year.[40]

Yet demand for supersonic transport still existed. Even during Air France's cost-cutting in the 1980s, British Airways continued to fly the Concorde on "14 round trip flights a week between London and New York and three direct round trip flights a week between London and Washington D.C."[41] Frequent British Airways customers would occasionally be upgraded to the Concorde on transatlantic flights in an effort to create new demand through awareness and to fill the cabin.[42]

The issue was one of poor optimization. Commercial aircraft design faces a tradeoff in deciding how many passengers to accommodate: too few, and costs are insufficiently distributed; too many, and it becomes difficult to fill the plane on an average route. The Boeing 747, the original jumbo jet, is the best example of an affordability strategy based on economies of scale. By accommodating more than 500 passengers in its wide body and by focusing on high-demand, transcontinental routes, the 747 reduced costs per head dramatically and democratized long-distance air travel.

A high-capacity strategy does not necessarily make sense for supersonic transport, although that has not stopped government-directed efforts from acting on the same laudable democratic aspirations. When SST research was revived under NASA's High Speed Civil Transport project in the mid-1980s, for example, it was decided in advance that the final design would need to seat 300 passengers. This decision added enormous design challenges that contributed to the project's ultimate failure.[43]

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[39] "Concorde Technical Specs: Accomodation," ConcordeSST, accessed July 18, 2016.

[40] "Supersonic Jet Flights Suspended," *Daytona Beach Morning Journal*, September 28, 1982.

[41] Ibid.

[42] "What Was It Like to Fly on the Concorde?" Quora, July 7, 2015.

[43] Bill Sweetman, "Why We Don't Have an SST," *Air & Space Magazine*, August 2014.

Likewise, Britain's Supersonic Transport Aircraft Committee had not even considered mid-range designs for the Concorde. As discussed above, a smaller passenger jet flying more frequent trips would have likely met the demand without generating the same losses. Thus, while the supersonic ban over land has probably been fatal to the development of a private-sector alternative, it merely contributed to the Concorde's commercial failure.

> "A smaller passenger jet flying more frequent trips would have likely met the demand without generating the same losses."

The Concorde's ultimate demise was the result of two final, tragic setbacks. The first was the crash of Air France Flight 4590, the only fatal accident in the Concorde's 27-year history. Upon departure from Gonesse, France, on July 25, 2000, the aircraft's tire was punctured by a piece of debris, throwing a large chunk of the tire into the underside of the wing and causing the fuel tank to rupture and then ignite. With insufficient runway to safely abort, the pilot attempted to climb, but the aircraft lost speed and crashed into a nearby hotel, killing all 109 passengers and crew, as well as four hotel employees.[44]

The incident generated significant media attention, greatly damaging the Concorde's strong public reputation for safe operation.[45] An independent investigation later concluded that, while the aircraft had been slightly overloaded upon takeoff, Continental Airlines was criminally responsible for failing to carry out a scheduled runway inspection. Criminal charges were later overturned, leaving only a civil ruling that has resulted in excess of €100 million in compensation.[46]

The second setback came on September 11, 2001, when terrorists flew two planes into the World Trade

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[44] *Accident on 25 July 2000 at La Patte d'Oie in Gonesse (95) to the Concorde Registered F-BTSC Operated by Air France* (report translation, Ministère de l'Equipment des Transports et du Logement, Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile, n.d.).

[45] David Ruppe, "Concorde's Stellar Safety Record," *ABC News*, July 26, 2000. The Concorde had a strong safety record, in large part due to its high maintenance requirements, which created an additional level of scrutiny.

[46] "Concorde Crash: Continental Airlines Killings Verdict Quashed," *BBC News*, November 29, 2012.

Center. The subsequent drop in demand for air travel proved too much strain for the Concorde: the beleaguered airliner flew its final flight on November 26, 2003.[47]

The Boeing 2707 Boondoggle

As the French, British, and Soviet governments began work on SSTs in the late 1950s, many in the US government were afraid of falling behind. In 1960, Congress held the first hearings on a possible government-supported civilian SST. In March 1961, President Kennedy asked the FAA to create a report outlining "national aviation goals" for the next decade. When the report was released in September of that year, it strongly supported the development of an American SST. For the next two years, Congress appropriated money to the FAA for feasibility studies. On June 4, 1963, Pan Am announced that it had optioned six Concordes, much to the dismay of President Kennedy.[48] The following day, Kennedy announced that the US government would subsidize the development of an American SST.[49]

The American SST project differed from previous government supersonic transport efforts in at least two respects. First, unlike earlier supersonic programs, which were conducted under the auspices of NACA, the SST program was housed at the FAA (note that until 1967, the FAA was the Federal Aviation *Agency*). Second, unlike the earlier programs, which were focused on exploring the basic science around transonic and supersonic flight, the SST program was supposed to produce a profitable commercial project. From the inception of the program, Kennedy proposed that the selected manufacturers pay at least 25 percent of the cost of the project and that in no event would the government spend more than $750 million. These requirements were thought to ensure that the SST program would not become a giant boondoggle.

The requirements for the SST were ambitious. Not content to match the Concorde, the US government sought to build a plane that could carry up to 300 passengers (the Concorde carried a maximum of 128) and could cruise at Mach 3 (the Concorde flew at Mach 2). The latter requirement came straight from Presi-

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[47] "Concorde," accessed July 30, 2016, http://cs.mcgill.ca/~rwest/wikispeedia/wpcd/wp/c/Concorde.htm; Ruppe, "Concorde's Stellar Safety Record"; Paul Marston, "How Concorde Finally Fell Victim to the Bean-Counters," *Telegraph*, October 23, 2003.

[48] Audio of President Kennedy's phone calls addressing this issue are available on YouTube. "Phone Calls: JFK Is Mad at Pan Am's Juan Trippe (June 4, 1963)," YouTube, posted by David Von Pein's JFK Channel, November 5, 2013.

[49] Edelman, "American Supersonic Transport," 98–99.

dent Kennedy.[50] The speed differential was especially significant. Aluminum can withstand the heat generated by air friction at the Concorde's cruising altitude at Mach 2 but not at Mach 3. The program decided to pursue a titanium alloy for the SST's airframe, which ended up derailing the project for years as designers sought a fabrication method.[51]

In addition to the challenging specifications, the project was poorly managed by an agency that was more concerned with perceived success than with a rigorous evaluaton of the project's merits. The FAA papered over numerous warning signs that the program was doomed to fail. For example, in 1964 the FAA, enlisting the help of NASA and the Air Force, conducted sonic boom testing over Oklahoma City for a period of six months. These tests were known as Operation Bongo II. The city experienced up to eight booms a day, with peak overpressures of up to 2 pounds per square foot (psf), similar to what the SST was expected to produce. Over the course of the testing period, local opposition to the tests mounted, and after six months, the tests were put to a premature end by the furious local population. Yet an FAA report that summarized the test data stated that "the overwhelming majority felt they could learn to live with the numbers and kinds of booms experienced." It was clear that the SST would be too loud to operate over land, thus limiting its market, but the FAA did not want to admit that. The agency's position on the tolerability of massive sonic booms was in stark contrast to its total ban on civil booms of any kind less than a decade later.

On January 1, 1967, Boeing was announced as the winner of a lengthy, multi-stage SST design competition. Neither Boeing nor any of the other entrants matched the specifications set out at the beginning of the competition. None of the entrants proposed to pay more than 10 percent of the program's costs, far short of the 25 percent that Kennedy had initially proposed. Yet the program proceeded with the Boeing 2707 design. The next phase was to include developing a prototype.

In 1970, the FAA dramatically scaled back the ambitions for the prototype. It called the attempt to make the prototype match production objectives a "waste of time and money" and focused instead on using the prototype as a testing platform that would inform an eventual production model. Technical deficiencies mounted. The prototype's noise levels were about twice as high as the original specification. The weight of the production aircraft ballooned

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[50] David B. Frost, *John F. Kennedy in Quotations: A Topical Dictionary, with Sources* (Jefferson, NC: McFarland, 2013), 195.

[51] "Planes That Never Flew—The American SST—Boeing 2707 4/4," YouTube, posted by Sebastian Blaszczak, December 11, 2011.

to 750,000 pounds, and all attempts to make progress on the titanium airframe failed. In the face of so many challenges—technical problems, rapidly expanding costs, the public opposition induced by the 1964 Oklahoma City tests, and the burgeoning environmental movement—Congress killed the SST program in 1971.

The FAA's Current Stance toward Civil Supersonic Flight

In 1972, Congress passed Public Law 92-574, the Noise Control Act of 1972, which addressed noise regulation for everything from motor vehicles to household appliances. The bill required the FAA administrator, in consultation with the Environmental Protection Agency (EPA), to issue (1) standards for measuring aircraft noise and sonic booms and (2) regulations for their "control and abatement." The law did not require any particular sonic boom noise standard, much less total prohibition. Nonetheless, in 1973 the FAA issued the regulation that banned civil supersonic aviation over the United States. The regulation states straightforwardly that "no person may operate a civil aircraft in the United States at a true flight Mach number greater than 1." The exceptions are strictly limited to preauthorized flights in designated test areas for one of three main reasons:

- The flight is necessary to show compliance with airworthiness requirements.
- The flight is necessary to determine the sonic boom characteristics of the airplane or to establish means of reducing or eliminating the effects of sonic boom.
- The flight is necessary to demonstrate the conditions and limitations under which speeds greater than a true flight Mach number of 1 will not cause a measurable sonic boom overpressure to reach the surface.

In a 2008 policy statement, the FAA "anticipated" that it would consider issuing a noise standard on sonic booms (thereby lifting the current moratorium) only when "future supersonic airplane[s] produce no greater noise impact on a community than a subsonic airplane."[52] The FAA further stated that "noise standards for supersonic operation will be developed as the unique operational flight characteristics of supersonic designs become known and the noise impacts of supersonic flight are shown to be acceptable."[53]

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[52] Carl Burleson, Federal Aviation Administration, "Civil Supersonic Airplane Noise Type Certification Standards and Operating Rules," October 16, 2008.

[53] Ibid.

In 2011, there were preliminary signs that the FAA was considering a change in its supersonic policy. At a public meeting in Washington, DC, the agency gave a presentation that included a slide entitled “Why Now?” which argued, “Current research has demonstrated enough progress on reducing impact of sonic booms before they reach the ground for us to revisit this issue.”[54] This slide deck is available on the FAA’s website, but no additional public-facing work has been done by the agency on supersonic aviation since then.

ADDRESSING CONCERNS ABOUT SONIC BOOMS

When an aircraft flies, it constantly displaces air, which ripples through the atmosphere at the speed of sound. When the aircraft is flying below the speed at which the displacement propagates through the atmosphere, each new displacement occurs fully inside the expanding previous displacement. But when the aircraft itself is traveling faster than the displacement propagates, new points of displacement occur in front of the previously displaced air. As a result, the displacement of air from multiple points in time will reach an observer at the same time. It is this pileup of displaced air that produces the rapid change in air pressure that is experienced as a sonic boom.

The Mach cone, which represents the wavefront formed by overlapping spheres of sound waves (see figure 1), is not very different from the wake produced by a boat traveling faster than the speed at which displacement travels through water. The angle of the Mach cone (φ) is a function of the speed of the aircraft (v) relative to the speed of sound (v_s).

As a supersonic aircraft moves forward and collides with air at its front and along its wings, the air is pushed into local pockets of high pressure. Pockets of low pressure are created in the relatively evacuated space at the rear of the aircraft and behind the wings. This collection of pressure changes is called the pressure signature. Moving from the front to the back of the aircraft, the parts that have an increasing cross-sectional area generate overpressure and the parts that have a decreasing cross-sectional area generate underpressure.

Although this pressure signature can be quite complex close to the aircraft, as it propagates through the atmosphere, it tends to coalesce. Because sound moves more quickly through a denser (higher-pressure) medium, the areas of overpressure tend to cluster at the front of the signature, and the areas of underpressure tend to cluster at the end. By the time the wavefront reaches the ground,

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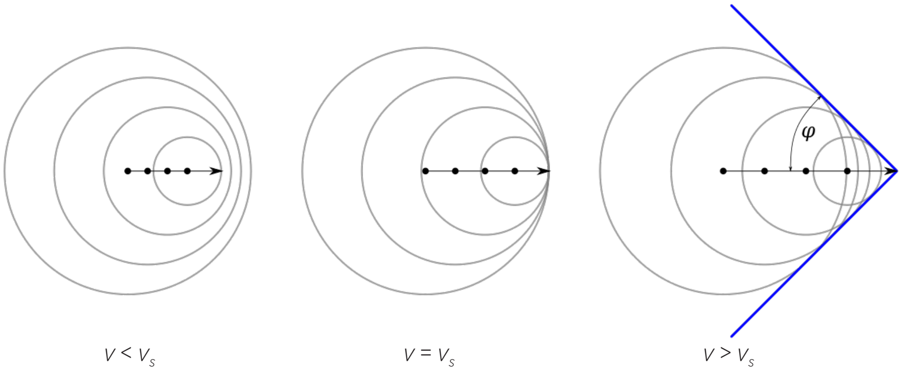
[54] Lourdes Maurice, “Civil Supersonic Aircraft Advance Noise Research,” FAA, July 14, 2011, 3.

FIGURE 1. THE MACH CONE



Note: v represents the speed of the aircraft, and v_s is the speed of sound. The blue lines represent the Mach cone.

Source: Courtesy Zykure (Wikimedia user), Creative Commons Attribution-ShareAlike 3.0 Unported license, March 2, 2009.

the pressure signature usually simplifies to an N-shaped wave, called an N-wave (see figure 2).

As the wavefront propagates, it also decays. Whereas normal acoustic decay occurs according to an inverse square law (at twice the distance, the sound is one-fourth as intense), the shock waves of a sonic boom decay more slowly.[55] As a result, simply flying a supersonic aircraft at a higher altitude is less effective at mitigating sonic booms than one might initially assume. Although many supersonic aircraft are designed to fly higher than subsonic aircraft in order to reduce drag, cruising altitude has a relatively moderate effect on the perceived boom on the ground. Nonetheless, the shock wave created by a plane flying supersonic up to a speed of Mach 1.2 and at 35,000 feet decays before it reaches the ground. This is often referred to as Mach cutoff.[56]

Because atmospheric density and temperature vary with altitude, sound propagates faster at lower altitudes. As a result, the Mach cone generated by an aircraft in the atmosphere refracts away from the surface of the Earth. This refraction limits the horizontal distance from which a sonic boom can be heard on the ground to the interval between the points on each side where the boom cone just grazes the ground. This space is called the boom carpet (see figure 3).

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[55] "In a uniform atmosphere, the magnitude of an N-wave sonic boom varies inversely as the ¾ power of the distance from the airplane to the ground." Domenic J. Maglieri et al., "Sonic Boom: Six Decades of Research," NASA, December 1, 2014, 208.

[56] "Concorde Crash," *BBC News*.

FIGURE 2. AN N-WAVE

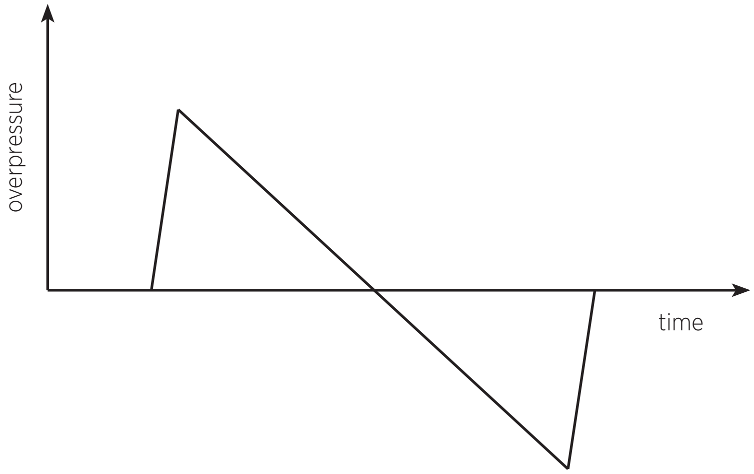
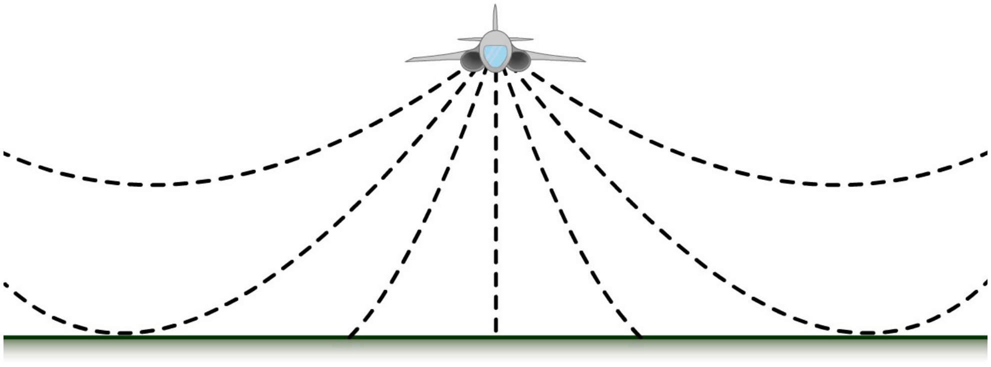


FIGURE 3. THE BOOM CARPET



Source: Based on C. H. E. Warren, “Sonic Boom Exposure Effects 1.2: The Sonic Boom—Generation and Propagation,” *Journal of Sound and Vibration* 20, no. 4 (1972).

The width of the boom carpet is approximately one mile for every 1,000 feet of altitude.[57] The intensity of the boom is strongest at the center of the boom carpet and diminishes with horizontal distance.

Aircraft design factors affect the intensity of a sonic boom. For example, a larger and boxier aircraft will displace more air and generate a larger boom. A heavier aircraft requires more extensive airfoils to generate more lift; larger

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[57] Gibbs, “NASA Armstrong Fact Sheet.”

wings displace more air. Consequently, a large and heavy aircraft generates a stronger sonic boom than a small, light aircraft. Aircraft mass is one of the most important determinants of sonic boom intensity, especially (but not only) holding materials constant.

Speed is a minor factor affecting sonic booms. Traveling much, much faster than Mach 1 only results in a marginal increase in boom intensity. As NASA reports, "Increasing speeds above Mach 1.3 results in only small changes in shock wave strength."[58]

All of the above is complicated by imperfections in the atmosphere, such as wind, air turbulence, temperature gradients, or other inhomogeneities—deviations from what is known in the aeronautics community as "nominal conditions." In non-nominal conditions, sonic booms may be moderately diminished or intensified. In addition, terrain other than flat ground can affect the perception of the boom on the ground. Reflection off of mountains or buildings can cause local pockets in which booms are intensified or diminished.

Sonic booms can also be affected by maneuvers other than straight-line, constant-speed flight. For example, when an aircraft is accelerating, the angle of the Mach cone gradually becomes more acute. The changing shape of the Mach cone as it moves forward results in some observation points experiencing a more intense, focused boom. The pressure signatures of these focused booms are U-shaped rather than N-shaped. Unlike steady-state booms that are experienced throughout a relatively large boom carpet, focused booms are only experienced at particular points relative to the flight path of the accelerating aircraft. Similar boom dynamics accompany other kinds of nonlinear, nonconstant movement such as diving and turning.

Focused booms primarily occur when changes in aircraft speed and direction are undertaken naïvely. A trained pilot can take measures to avoid focused booms. For example, lifting the nose of the aircraft slightly during acceleration counteracts the effect of acceleration on boom noise. Likewise, decelerating into a turn counteracts the turning focused boom. Using these counteraction measures, a supersonic aircraft can turn up to 30 degrees without focused booms.[59] Consequently, focused booms do not pose a serious problem for the legalization of overland supersonic flight.

Sonic booms, even focused booms, are not generally strong enough to damage living organisms or structures that are otherwise in good repair. In one

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[58] Ibid.

[59] Peter Coen, Project Manager, Commercial Supersonic Technology, NASA Langley Research Center, telephone interview by Samuel Hammond, July 14, 2016.

military experiment, an F-4 flew just above the speed of sound at an altitude of 100 feet, generating 144 psf of overpressure. The researchers who were exposed to this boom were unharmed.[60] It is rare for supersonic aircraft overpressure to exceed 2 psf, even without any mitigation efforts. Above this threshold, communities may experience occasional cracked windows but no structural damage to buildings. The most minimal mitigation techniques result in softer booms that produce no damage of any kind.

Reducing the Intensity of Sonic Booms

In the over 60 years of ongoing research into the physics of sonic booms, much has been learned that was not available to the designers of earlier projects like the Concorde or 2707. Expanded knowledge combined with innovations in materials science and aerospace engineering has produced strategies for dramatically reducing sonic boom intensity. The two most important breakthroughs have been the invention of strong but lightweight materials and the use of computer simulations for optimizing aircraft shape to affect the pressure signature.[61]

For aircraft flying up to and around Mach 2, carbon fiber is an excellent material that significantly outperforms aircraft-grade aluminum. It is strong and lightweight, yet highly shapable—certainly much easier to work with than the titanium alloy that the Boeing 2707 adopted. The lower weight of carbon fiber means that the airplane can generate less lift and therefore displace less air than an aluminum jet. Size matters for the same reason, suggesting that "a ten person business jet has a much better chance of producing an acceptable boom than a 300-passenger commercial transport."[62]

The second factor, modifying the shape of the aircraft and its airstream, has benefited greatly from advances in computer simulation. In the recent past, iterating aircraft designs was a time-consuming process that required the creation of scale models and the use of wind tunnels with imperfect instrumentation. Today, researchers use genetic shape algorithms to "evolve" low-boom designs through iterated simulations with computational fluid dynamics. These algorithms search for designs that optimize wing shape, volume and lift distribution,

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60. Andy S. Rogers, AOT Inc., "Analyzing Sonic Boom Footprints of Military Jets with GIS," 4, Yumpu, accessed July 29, 2016.

61. Robbie Cowart, "Developing Noise Standards for Future Supersonic Civil Aircraft," in *International Aviation Noise Standards* (Proceedings of Meetings on Acoustics, ICA, Acoustical Society of America, 2013), 2–6.

62. Maglieri et al., "Sonic Boom," 159.

the impact of thermal exhaust, and so on. Other methods of multi-objective optimization have also proven invaluable.[63]

Among the key shape-related factors is the fineness ratio, a measure of an aircraft's streamline defined by fuselage length divided by the fuselage's maximum diameter. A high fineness ratio is desirable for supersonic aircraft to reduce wave drag on the aircraft, which is why existing supersonic aircraft tend to have elongated bodies or long spikes at their nose. While past designs were constrained in their fineness ratio by practical size and length constraints, new shape and airstream alteration may allow for "phantom body" designs that elongate the aircraft's airstream as if the aircraft had a much higher fineness ratio than it actually does.

Many more exotic concepts, such as highly unconventional wing shapes or "thermal fins" that produce a heat field, may also prove effective at reducing or eliminating sonic booms, but they have not been as deeply researched.[64] A noise standard will help create the conditions to spur that research, promising continual improvements in sonic boom abatement.

Low-boom shapes blunt the peaks of the aircraft's N-wave pressure signature, creating a non–N shape, such as a flat top or ramp shape, and thus reducing the suddenness of the air pressure change responsible for perceived loudness. In the limit, a low-boom pressure signature resembles a sine wave, which, due to its gradual rise time, has been shown to be inaudible in experiments with observers both indoors and outdoors, holding amplitude and duration constant.[65] These "duller" pressure signatures are therefore well suited to measurement in A-weighted decibels, as we discuss below.[66]

> "It is possible that variable-geometry designs or changes to the airplane's shape in midflight can be used to reduce both cruise and climb booms. Tailored flight path operations that center the climb phase over less populated regions, or even the ocean, are other possibilities."

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[63] Mathias Wintzer and Kroo Ilan, "Optimization and Adjoint-Based CFD for the Conceptual Design of Low Sonic Boom Aircraft" (paper presented at the 50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Nashville, TN, January 2012).

[64] Maglieri et al., "Sonic Boom," 165.

[65] Burleson, "Civil Supersonic Airplane Noise Type Certification Standards and Operating Rules," 134.

[66] Sharper, N-shaped pressure waves are better measured in an alternative unit called PLdB (perceived decibel level) because it takes into account the sharpness of the pressure signature. Coen, interview.

Some challenges in using shape to reduce sonic boom remain. Most existing low-boom designs are optimized for the cruise phase of the flight, not the climb phase. In the short run, this may require a two-stage noise standard that relaxes noise stringency for climb-phase booms. In the long run, it is possible that variable-geometry designs or changes to the airplane's shape in midflight can be used to reduce both cruise and climb booms. Tailored flight path operations that center the climb phase over less populated regions, or even the ocean, are other possibilities.[67]

In general, exploring next-generation flight paths for civil supersonic transport will play an important role in reducing human exposure to sonic booms. For instance, before passing over a populated area a supersonic aircraft could perform a pull-up maneuver to traverse the area with a substantially reduced sonic boom due to a lower lift trajectory, before returning to its normal cruising altitude over less populated areas.[68] Nonetheless, it's important to emphasize that low-boom designs are not merely theoretical. Low-boom concepts have been validated in flight tests by the Defense Advanced Research Projects Agency (DARPA), NASA, Gulfstream Aerospace, and others.[69] Indeed, decades of experimentation, including some with FAA participation, have yielded substantial data that inform the details of a supersonic noise standard, including high-fidelity acoustic signatures of every facet of a sonic boom.[70] More data may be helpful, but it would come at the cost of continued delay. Slow and sequential government-funded studies are no substitute for the data that will be generated once a noise standard has been set and the commercial sector becomes more deeply involved.

Comparison to Noise Levels We Already Accept

Sonic booms are discussed in terms of peak force of overpressure and in A-weighted decibels (dB(A)). It is possible to convert between sound measurements and pressure measurements using the equation

$$dB = 20 \log_{10} \frac{\mathrm{P}}{0.00002},$$

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[67] Ibid.

[68] Maglieri et al., "Sonic Boom," 143.

[69] Lengyan and Qian Zhansen, "A CFD Based Sonic Boom Prediction Method and Investigation on the Parameters Affecting the Sonic Boom Signature," *Procedia Engineering* 99 (2015): 433–51.

[70] NASA's Shaped Sonic Boom Demonstrator and the NASA and Gulfstream Joint Quiet Spike project are the two best-known validations of using shape for boom abatement. For a high-level overview of the experiential data to date, see Maglieri et al., "Sonic Boom," chapter 4.

where *dB* is sound in (unweighted) decibels and *P* is pressure in Pascals (1 pound of force per square foot is equal to 47.8803 Pascals). However, sound pressure levels as measured in unweighted decibels are not the best indicator of a sound's effect on humans because the human ear is not equally sensitive to all sound frequencies. A-weighting discounts frequencies that are hard for humans to hear and emphasizes frequencies to which humans are particularly sensitive.

Most of the energy of a sonic boom is concentrated in the low (0.1–100 Hz) frequency range.[71] Consequently, sonic booms are experienced less intensely by humans (and other animals) than an unweighted decibel calculation would suggest. As a result, A-weighted decibels are a more appropriate measure.[72] In news reports and other sources that refer to sonic boom noise in decibels, the actual figures reported are usually A-weighted decibels. A-weighting is widely used for federal, state, and local noise regulation standards.

As discussed above, the sonic boom tests over Oklahoma City in 1964 reached peak overpressures of 2 psf, comparable to the overpressure generated by the Concorde (1.94 psf), which produced a nominal boom of 105 dB(A). This is quite loud, and it is therefore not surprising that the tests drew significant public opposition. A new noise standard for sonic booms would need to be set significantly lower than the level generated by the Concorde or the SST tests over Oklahoma City. A useful exercise for determining an acceptable sonic boom standard is to compare it with other noises that we already tolerate, as enshrined in existing noise regulation and as experienced in everyday life.

The Occupational Safety and Health Administration (OSHA) sets permissible noise exposures for workers, which, if not met, obligate the employer to provide protective equipment. OSHA allows up to one hour per day of exposure to 105 dB(A) noise without protective equipment, and up to eight hours per day of exposure to 90 dB(A).[73]

New York City publishes a list of common noise levels in dB(A):[74]

Whisper	30 dB(A)
Normal Conversation/Laughter	50–65 dB(A)

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[71] "Sonic Boom," USAF Fact Sheet 96-03, US Air Force, March 1996. For comparison, middle C on a piano is about 261 Hz, and humans are most sensitive to the range 2kHz–5kHz.

[72] To see how A-weighting affects sonic boom calculations, NASA cites the Concorde's overpressure as 1.94 psf. This works out to approximately 133 unweighted decibels of sound. However, when A-weighted, the sound of the Concorde's nominal boom was around 105 dB(A).

[73] See Occupational Health and Safety Administration, Guidelines for Noise Enforcement, 29 C.F.R. § 1910.95(b).

[74] New York City Department of Environmental Protection, *A Guide to New York City's Noise Code*, 2, accessed July 28, 2016.

Vacuum Cleaner at 10 feet	70 dB(A)
Washing Machine/Dishwasher	78 dB(A)
Midtown Manhattan Traffic Noise	70–85 dB(A)
Motorcycle	88 dB(A)
Lawnmower	85–90 dB(A)
Train	100 dB(A)
Jackhammer/Power Saw	110 dB(A)
Thunderclap	120 dB(A)
Stereo/Boom Box	110–120 dB(A)
Nearby Jet Takeoff	130 dB(A)

Another element of noise regulation to consider is the timing. Most cities in the United States have different regulations for noise during daytime hours and nighttime hours. Construction is often limited to daytime hours. We expect that any noise standard for sonic booms would similarly be more lenient during the day than at night when the majority of the population is sleeping.

A final element to consider in making noise comparisons is the duration of the sound. Although a thunderclap is 10 dB(A) louder than a jackhammer, many people may find the thunderclap more tolerable because it is over so quickly. Likewise, a sonic boom happens very quickly; for the Concorde, it was over in half a second. Consequently, any noise comparisons should factor in the fact that sonic booms have an inherently tolerable duration.

In our view, an initial sonic boom standard should be informed by noise levels that we already accept in society, accounting for time and duration of the sounds. Lawnmowers, motorcycles, and kitchen blenders all operate in the 85–90 dB(A) range and are widely accepted for sustained durations during daytime hours. Consequently, we believe this range would also be aceptable for the short durations of sonic booms. Because decibels are measured on a base-10 logarithmic scale, 85 dB(A) is 100 times quieter than the Concorde's nominal boom of around 105 dB(A). During nighttime hours, we would recommend a noise standard on the order of another 100-fold reduction. This would place the overnight noise standard at 65–70 dB(A), a noise level that would be further dampened by the fact that most people are indoors during these hours.

To be clear, these recommendations are for an initial standard only. As sonic boom mitigation technology improves, it may be desirable to ratchet down the noise standard over time. Nevertheless, because the aviation industry learns by doing, it is of overwhelming importance that the initial noise standard be not only acceptable to society but also immediately achievable. Getting civil supersonic aircraft back in the air is extremely important for ending four decades of aviation speed stagnation and regress. We anticipate that, with additional experience and research, it will eventually be possible to lower the daytime boom standard to 70–75 dB(A). But it would be a mistake to make the initial standard so stringent.

ADDRESSING CONCERNS ABOUT AIRPORT NOISE

In addition to sonic booms, supersonic aircraft also raise concerns about ordinary aircraft noise in the vicinity of the airport, particularly upon takeoff. The Concorde was quite loud at takeoff compared to the other aircraft of its era and certainly much louder than modern aircraft. It was heavy and fuel inefficient (and naturally these characteristics reinforced each other), requiring huge amounts of thrust on takeoff. The plane engaged its afterburners—a noisy and incredibly fuel-inefficient maneuver—immediately upon takeoff. Its engines were not modern turbofans, but rather pure turbojets, with a bypass ratio of 0.

A modern supersonic commercial jet would be quieter upon takeoff simply by virtue of being lighter and having better engines. Lighter materials and more efficient engines mean the jet would need to carry less fuel, which would make its taxiing weight lower. Lower weight means less thrust is necessary at takeoff. A modern supersonic commercial aircraft would not use afterburners and would use a turbofan, although perhaps one with a relatively low bypass ratio.

Even so, there are good reasons for a modern supersonic jet to be louder than a subsonic jet on takeoff. It is simply more fuel efficient for a jet aircraft to take off at maximum throttle, and that fuel efficiency counts for more when the fuel burn rate is higher, as it is with a supersonic aircraft. In addition, supersonic jets require a lower-bypass engine than subsonic jets because high-bypass engines are unable to propel air out the rear of the engine at the necessary speeds and because they generate more drag. As a result, supersonic engines will be somewhat louder than today's newest subsonic engines, and there will be large benefits in terms of fuel efficiency—and carbon emissions, and ultimately affordability—to allowing them to operate at full throttle at takeoff.

In order to legalize civil supersonic aviation, the FAA will need to issue airport noise standards for supersonic aircraft so that new aircraft can be type certified. Noise-related type certification regulations are located in 14 C.F.R. § 36. At present, subpart B deals with airport noise standards for subsonic jets, and subpart D, specifically § 36.301, sets airport noise standards for the Concorde. No noise certification requirements have been articulated for civil supersonic aircraft other than the Concorde, although 14 C.F.R. § 91.821 states that no one may *operate* a supersonic jet other than the Concorde that does not comply with what are known as Stage 2 noise standards.

Interestingly, § 36.301(b) reads in full, "It must be shown, in accordance with the provisions of this part in effect on October 13, 1977, 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." This passage, derived from a statute at 49 U.S.C. § 44715(b)4, creates a carve out for the Concorde from the type certification noise requirements that the FAA might have otherwise imposed.

As will be discussed at greater length in a later section, the FAA's airport noise standards are adopted from the International Civil Aviation Organization (ICAO), an agency of the United Nations, and referred to as various "stages." As already discussed, under current law, no standard exists for new supersonic jets to be type certified, and supersonic jets are required to operate at Stage 2 or better. Subsonic jets must operate at the more stringent Stage 3, and new subsonic jets must meet Stage 4 requirements in order to be certified. Beginning in 2018, subsonic jets must meet new Stage 5 requirements to be certified, although the operating requirements are not changing at that date.

Although current law allows Stage 2 supersonic aircraft to operate, it is unlikely that the FAA would certify new supersonic aircraft compliant with only Stage 2. In its latest policy statement on the matter, issued in 2008, the FAA stated, "We anticipate that any future Notice of Proposed Rulemaking issued by the FAA affecting the noise operating rules would propose that any future supersonic airplane produce *no greater noise impact on a community than a subsonic airplane*."[75] At the time, the newest noise standard was Stage 4, but as mentioned above, Stage 5 requirements will be implemented shortly.

"It would be a mistake to apply the same restrictive noise standards to supersonic as to subsonic aircraft. The tradeoff between noise and efficiency is very different for supersonic aviation."

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[75] Burleson, "Civil Supersonic Airplane Noise Type Certification Standards and Operating Rules." Emphasis added.

It would be a mistake to apply the same restrictive noise standards to supersonic as to subsonic aircraft. The tradeoff between noise and efficiency is very different for supersonic aviation, and consequently, benefit-cost analysis demands a laxer standard. One approach that may strike the right balance between the legitimate concerns of those living near airports and the need to advance supersonic aviation might be to use the existing Stage 3 operational limit for subsonic aircraft as the new certification standard for supersonic. This step would encourage the creation of new, affordable, and lower-emissions supersonic aircraft without any change in operational noise limits that affect communities near airports. These communities already tolerate Stage 3 noise, and new Stage 3 supersonic aircraft would not appreciably increase noise levels. After a sufficient number of supersonic aircraft were certified under Stage 3, the FAA could increase standards to Stage 4 to ensure that the industry moves over time to abate airport noise.

The problem with moving immediately to a Stage 4 (or Stage 5) standard, as the FAA has proposed, is that it would unduly burden a nascent industry as well as significantly increase carbon emissions and raise travel costs. The difference between Stage 3 and Stage 4 noise standards represents about a 20 percent change in fuel use for supersonic flight. The aviation industry is one that learns by doing; indeed, well-known learning-by-doing innovation models originated in aviation.[76] Consequently, starting at a reasonable-yet-permissive Stage 3 standard and then ratcheting up to stricter standards over time makes a good deal of sense.

ADDRESSING ENVIRONMENTAL CONCERNS

Emissions from supersonic transport have raised special concerns due to the high cruising altitude of civil SSTs. The Concorde, for example, flew at 60,000 feet, compared to subsonic passenger jets which typically fly below 40,000 feet. On the transatlantic routes in the mid-latitudes, the Concorde was flying in the lower layers of the stratosphere, roughly where the ozone layer begins.

Researchers in the 1970s[77] generated a polarized debate after it was posited that the nitrogen oxide emissions from a fleet of Concordes might cause reactions contributing to catastrophic ozone loss.[78] Several governments and academies of science set up committees that further investigated the claims, which were

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[76] Hartley, "Learning Curve and Its Application to the Aircraft Industry."

[77] Principally, H. S. Johnston, "Reduction of Stratospheric Ozone by Nitrogen Oxide Catalysts from Supersonic Transport Exhaust," *Science* 173, no. 3996 (1971): 517–22.

[78] Lawrence Badash, *A Nuclear Winter's Tale: Science and Politics in the 1980s* (Cambridge, MA: MIT Press, 2009).

ultimately rejected as unfounded, given the limited and uncertain data.[79] The view that SST emissions pose little threat to the ozone layer was cemented after subsequent researchers realized nuclear tests conducted by the United States and Soviet Union had injected large magnitudes of nitrogen oxide and other particulates into the atmosphere without causing significant ozone problems,[80] despite being comparable to, as one author put it, "the flying of 500 Concordes seven hours a day for some five years."[81] That did not stop anti-Concorde activists from propagating false and exaggerated claims of ozone risk. As supersonic researcher Preston Henne put it, "The difficulty in early programs was lack of credible understanding of atmospheric science. The absence of such knowledge left the door open for wild and exaggerated claims of atmospheric trauma based on speculation, misinformation, and political agendas."[82]

Atmospheric science has advanced significantly since the 1970s, and today it is widely accepted that emissions from supersonic aircraft in the lower stratosphere pose minimal risk to the ozone layer. While there remain gaps in our knowledge, instead of using those gaps to justify wild speculation, we can now conduct simulations of the global atmosphere to test a variety of SST emission scenarios.

One set of such simulations, conducted by the NASA Glenn Research Center, considered the effects of a fleet of supersonic business jets over a period of 10 years within the atmospheric conditions projected for 2020.[83] By varying the parameters of fuel burn, cruise altitude, and a nitrogen oxide emissions index, a total of 24 scenarios were evaluated. The most probable scenario considered a fleet of supersonic business jets burning 18 million pounds of fuel per day at a height of 15–17km, or roughly 50,000 to 56,000 feet. This scenario results in a maximum *local* ozone depletion of only 0.038 percent and a rate of *global* ozone depletion orders of magnitude smaller. For comparison, concern in the 1990s that pollution was creating a growing "hole" in the ozone layer stemmed from observations of ozone depletion on the order of 20–60 percent.[84]

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[79] Australian Academy of Science, *Atmospheric Effects of Supersonic Aircraft* (Report No. 15, 1972).

[80] P. Goldsmith et al., "Nitrogen Oxides, Nuclear Weapon Testing, Concorde and Stratospheric Ozone," *Nature* 244, no. 5418 (1973): 545–51.

[81] S. T. Butler, "Concorde and the Destruction of Ozone," accessed August 7, 2016.

[82] Preston A. Henne, "The Case for Small Supersonic Civil Aircraft" (paper presented at AIAA International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, OH, July 2003).

[83] Chowen Wey et al., *Parametric Analyses of Potential Effects on Stratospheric and Tropospheric Ozone Chemistry by a Fleet of Supersonic Business Jets Projected in a 2020 Atmosphere* (NASA technical report, NASA Glen Research Center, October 1, 2004).

[84] "Twenty Questions and Answers about the Ozone Layer: 2010 Update," in *Scientific Assessment of Ozone Depletion: 2010* (World Meteorological Organization, 2011).

In fact, emissions in the lower altitude range of 13–15km may actually create ozone on net—although at a similarly small rate—through a process related to the phenomenon of urban ozone. Supersonic business jets are thus essentially ozone neutral within their range of likely cruising altitudes because of the weak and ambiguous effects of nitrogen oxide. This gives a modest environmental advantage to smaller and slower supersonic aircraft since a lower mass and Mach number is conducive to a lower cruise altitude. Further study is warranted to assess the environmental impact of larger, high-altitude commercial passenger SSTs. Nonetheless, the evidence to date, including 27 years of Concorde operations, indicates that the ozone risk for passenger SSTs is also well within the realm of acceptability.

Importantly, as supersonic transport over land becomes less restricted it will fall under at least six distinct sources of environmental regulation, including local air quality certification standards and the Montreal Protocol on ozone pollution. In general, these regulations were not designed with SSTs in mind, meaning they may require updating with appropriate consultation from federal agencies like the EPA and international bodies like the ICAO. Clarifying the environmental status of overland SSTs under existing regulation is an essential step for creating the conditions of policy certainty the industry needs to thrive.[85]

TOWARD SUSTAINABLE AND AFFORDABLE SUPERSONIC FLIGHT

To maximize the benefits of supersonic technology, the US government should set supersonic policy with three principles in mind. First, supersonic aviation should be given the chance to succeed on its own merits, without prohibition but also without subsidies aside from (perhaps) research into basic science. Second, in inevitable tradeoffs between competing values, the government should err on the side of allowing supersonic technology to become available to the widest possible population, not just the wealthy. Third, the government should at least initially impose the absolute minimum level of prohibition necessary to address legitimate concerns about sonic booms and other supersonic-related problems. Over time, owing to incremental innovation generated by experience, it may be possible to impose stricter standards. In this section we discuss how policy challenges can be addressed with these principles in mind.

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[85] Committee on Breakthrough Technology for Commercial Supersonic Aircraft et al., *Commercial Supersonic Technology: The Way Ahead.*

Regulators Need to Provide Certainty

As noted above, the FAA's current position on legalizing supersonic aviation is that "noise standards for supersonic operation will be developed as the unique operational flight characteristics of supersonic designs become known and the noise impacts of supersonic flight are shown to be acceptable."[86] This position raises an obvious question: Acceptable according to what metric? The function of a noise standard is to publicly indicate what counts as acceptable. Instead, private entrepreneurs and firms that might want to design SSTs for overland flights must rely on nonbinding public statements to infer what the FAA privately regards as "acceptable" noise thresholds that would induce future rulemakings.

A noise standard must be created before the development and production of viable SSTs, not after. Insofar as the FAA is already offering guidance about what noise standards might be acceptable, there is no excuse for not simply issuing a standard. Doing so would merely turn the de facto rule contained in public statements into a de jure rule codified in law, creating valuable regulatory certainty for firms to raise capital and design supersonic aircraft to specification.

Rules Should Be Less Restrictive Than Subsonic Standards

In its 2008 policy statement discussed above, the FAA said that it "would propose that any future supersonic airplane produce no greater noise impact on a community than a subsonic airplane."[87] It is not clear why a supersonic noise standard should be as restrictive as the standards for subsonic aviation. Indeed, it is likely that, after a full accounting of benefits and costs, commercial supersonic transport may justify tolerating a somewhat higher noise standard than subsonic aircraft.[88]

As we have already discussed, the aviation industry is characterized by learning by doing. Because subsonic aviation has had decades to learn how to achieve noise abatement, subsonic noise standards have rightly gotten more severe over time. But supersonic aviation has not yet had a similar period to gen-

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[86] Burleson, "Civil Supersonic Airplane Noise Type Certification Standards and Operating Rules."

[87] Ibid.

[88] The most recent and rigorous benefit-cost analysis of airport noise standards calls into question the net benefit of stringent noise standards more generally. Land use policies that mitigate airport noise by financing noise insulation projects are much less expensive relative to the cost of phasing out fleets of noisier aircraft, and they achieve comparable benefits. By extension, we put forward that insulation projects are also cheaper than the implied cost of a forgone fleet of more environmentally friendly and fuel-efficient SSTs. Philip J. Wolfe et al., "Costs and Benefits of US Aviation Noise Land-Use Policies," *Transportation Research Part D: Transport and Environment* 44 (2016): 147–56.

erate the additional know-how to address the unique noise challenges it faces. Consequently, the noise standards for subsonic aircraft are likely too stringent to make overland SSTs viable and affordable, despite the nontrivial progress that has been made on supersonic noise abatement in the face of the ban.

Affordability Must Be a Priority

Since the 1960s, several technologies have developed that will make modern SSTs more affordable than the Concorde. While the Concorde was made out of aluminum and the attempt to use a titanium airframe for the Boeing 2707 foundered, modern supersonic jets can be made out of carbon fiber, which has in recent years become a commodity. In addition, modern commercial jet engine cores are powerful enough to reach supercruise speeds without afterburners, which waste fuel and are expensive to use. Consequently, new SSTs will be significantly cheaper to fly on than the Concorde was.

In addition to these technological improvements, policy can help to prioritize affordability in at least one way. There is a tradeoff between fuel economy and engine noise at takeoff. A supersonic aircraft will use far less fuel if it takes off and does its initial climb at full throttle instead of at some lower level of power. As a result, a stringent airport noise standard will significantly raise both the cost and the fuel emissions of supersonic aviation. If a valid principle of supersonic policy is to maximize affordability, it counsels in favor of a relatively liberal airport noise standard for supersonic aviation. That may mean allowing SSTs to abide by the Stage 3 airport noise standards that we currently tolerate, rather than the current Stage 4 or forthcoming Stage 5 standards for newly certified planes.

US Regulators Should Not Wait for an International Standard

US policy on civil supersonic aviation is affected by international policy. In particular, the UN's technical agency, the International Civil Aviation Organization, sets international aviation standards. Since 2004, the ICAO has operated a Supersonic Task Group (SSTG) out of its Committee on Aviation for Environmental Protection working group on noise. The FAA appears reticent to make any policy relating to civil supersonic aviation ahead of the creation of ICAO standards.

One problem with the SSTG's approach to fostering commercial supersonic flight is its apparently circular reasoning on issues related to acceptable noise levels. The ICAO's 2013 environmental report describes the challenges of supersonic commercialization as follows:

> First, and foremost, is to tailor a design that is environmentally acceptable, but designed to as yet undefined sonic boom requirements. Second, the aviation industry must define and successfully demonstrate the critical technologies. Third, the industry must prove, with a flight demonstrator, that sonic boom suppression technology is adequate. *The latter implies substantial research to define "acceptable" sonic boom*. Lastly, and equally important, the international community of aviation regulatory authorities must collaborate to define certification and operational standards for supersonic operations with acceptable low sonic boom.[89]

The ICAO's formulation of the challenge reflects the contradiction also present in the FAA's current stance on supersonic aviation, perhaps unsurprisingly since the United States has a leading role in the SSTG. On the one hand, it seems to recognize that the first step is to define an acceptable sonic boom standard. On the other, it has very little interest in defining a standard until the technology to comply with it is demonstrated. As of 2016, the SSTG has still not defined an acceptable boom standard.

Other things being equal, it is better to have international standards for aviation in general and for sonic booms in particular. An international standard would maximize the market size for underwriting the expensive aircraft development process. It would be a shame for a manufacturer to develop a new supersonic aircraft and then find that it can only operate in limited portions of the globe. But after a dozen years and no demonstrable progress on an acceptable boom standard, the FAA should not continue to wait for the ICAO to set such a standard. Article 38 of the Convention on International Civil Aviation explicitly allows ICAO member states to deviate from international standards.[90]

Even a stand-alone US standard would be an improvement on the status quo. Currently, civil supersonic aviation is legal over international waters and over land in parts of Siberia and Australia.[91] Adding the United States to that list would constitute a nontrivial increase in market size for any prospective new supersonic jet. And once new aircraft that are compatible with a US boom standard have been built, other countries that want domestic supersonic aviation will

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[89] International Civil Aviation Organization, *ICAO Environmental Report 2013: Aviation and Climate Change 2013*, 77. Emphasis added.

[90] International Civil Aviation Organization, "Convention on International Civil Aviation," 2006, 17–18.

[91] Australia allows supersonic flight as long as sonic booms do not reach the ground, which in practice, allows speeds up to Mach 1.15 or so. Henne, "Case for Small Supersonic Civil Aircraft."

have a strong incentive to simply adopt the standard that the United States has already articulated. Furthermore, at least initially, supersonic transport will continue to be expensive relative to subsonic transport. Consequently, the initial market for overland supersonic transport will be small, limited to countries like the United States that have a sufficiently large class of business travelers. Since the United States by itself represents a large fraction of this potential market, the argument that manufacturers must wait until there is an international standard makes little sense.

While it would be ideal to have comprehensive international standards for civil supersonic aviation, the United States should not wait for the ICAO. Indeed, given the US leadership within the SSTG, one may reasonably wonder whether the ICAO's slow movement on supersonic standards is a result of intentional FAA delay. Either way, unless the ICAO standards are immediately forthcoming, the benefits of simply waiting do not exceed the costs. The United States should take the opportunity to push the world forward in supersonic development adoption.

> "Currently, civil supersonic aviation is legal over international waters and over land in parts of Siberia and Australia. Adding the United States to that list would constitute a nontrivial increase in market size for any prospective new supersonic jet."

Policy Proposal

In this paper we have reviewed the history of supersonic aviation as well as the legitimate physical challenges that it poses. Combining these facts with our three policy principles (outlined at the beginning of this section) yields some recommendations, which we will now make concrete.

- First, the FAA should without delay issue a notice of proposed rulemaking rescinding the ban on overland supersonic aviation and creating certification and operating standards for supersonic aircraft.
- Second, operating standards for boom noise should, especially initially, be informed by noise levels—accounting for time and duration—that society already tolerates. As we have discussed, lawnmowers, motorcycles, and kitchen blenders all operate in the 85–90 dB(A) range, and therefore we believe that an

85–90 dB(A) range is appropriate for daytime operation. A lower standard can be adopted for nighttime operation.

- Third, an airport noise standard should be no more stringent than what we already tolerate with subsonic aircraft. While new subsonic aircraft cannot be certified below Stage 4, they continue to be allowed to operate at Stage 3. Given the relative lack of experience with supersonic aviation and the fuel economy tradeoffs associated with airport noise, new supersonic aircraft should be certified if they meet Stage 3 requirements.
- Finally, the government should not wait for the ICAO to issue supersonic noise standards that have been in the works without progress since 2004. Instead, it should take a clear global lead in supersonic aviation. The US overland market will be a major addition to the existing transoceanic market. Even if US rules are incompatible with those the ICAO eventually formulates, it is better to kick-start the market for supersonic transport earlier than to wait for compatibility.

CONCLUSION

The period since 1973 has been called the Great Stagnation.[92] Total factor productivity growth, the most important metric of economic growth, is significantly lower in the post-1973 period. Because aviation in general, and supersonic aviation in particular, represent and will continue to represent only a small part of the economy, they cannot account for a large portion of this broader economic decline. Yet it is striking that the change in total factor productivity growth occurred in the year of the supersonic ban.

The stagnation and regress in supersonic aviation over the past 40 years belies the rapid progress that was made beginning with the Wright brothers' first flight in 1903, which was estimated to achieve 6 mph. By 1953, we had reached Mach 2. By 1976, we had commercialized Mach 2 flight and reached Mach 3 with military jets.[93] Yet over the last several decades, something has gone horribly wrong. The Concorde is no longer in service and has no replacements. Our fastest commercial transports are subsonic.

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[92] Tyler Cowen, *The Great Stagnation: How America Ate All the Low-Hanging Fruit of Modern History, Got Sick, and Will (Eventually) Feel Better* (New York: Dutton 2011).

[93] Eli Dourado and Michael Kotrous, "Airplane Speeds Have Stagnated for 40 Years," Mercatus Center at George Mason University, July 20, 2016.

There are very good economic reasons for the failure of the Concorde. It was too heavy, its afterburners guzzled fuel, and it was only created in the first place because of French and UK government subsidies. But none of those economic limitations need apply to modern commercial supersonic transport. Despite our stagnation in speed, aircraft engineering has advanced significantly since the time of the Concorde. With lighter materials, more efficient engines, computer modeling, and simply more experience, it is certainly possible to create an aircraft that is faster and more affordable to fly on than the Concorde. Why hasn't it happened?

Our answer has been that the blanket prohibition of overland civil supersonic flight—in place in the United States, the biggest potential market, since 1973—has greatly reduced investment in supersonic technologies and research. Public-sector efforts have been no replacement, producing one boondoggle after another. Aviation is an industry that learns by doing, that advances through practice and incremental innovation. The complete ban on flight faster than Mach 1 over the United States has therefore eliminated a great deal of such incremental, bottom-up innovation. The ban must be rescinded.

To be sure, there are legitimate concerns surrounding supersonic flight, particularly concerns about sonic booms. But as we have shown, these concerns can be well addressed directly through noise standards and other more narrowly tailored regulations rather than the blanket prohibition we have today. An endemic, complacent regulatory attitude—like the view that subsonic aviation is good enough—may be a genuine link between our supersonic regress and our broader economic stagnation. If we want rapid economic growth, we must continually question the limitations we impose upon ourselves and press forward the boundary of what is possible.

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