# Environmental performance of emerging supersonic transport aircraft

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## SUMMARY

Three U.S.-based startup companies are working to develop new supersonic transport (SST) aircraft for planned entry into service in the mid-2020s. There are currently no international environmental standards for such aircraft, which last flew in 2003. Policymakers are considering whether to develop new specific SST standards or to apply existing standards for subsonic aircraft to the new designs.

This paper provides a preliminary assessment of the environmental performance of new commercial SSTs. Results suggest that these aircraft are unlikely to comply with existing standards for subsonic aircraft. The most likely configuration of a representative SST was estimated to exceed limits for nitrogen oxides and carbon dioxide ($CO_2$) by 40% and 70%, respectively. A noise assessment concludes that emerging SSTs are likely to fail current (2018) and perhaps historical (2006) landing and takeoff noise standards.

On average, the modeled SST was estimated to burn 5 to 7 times as much fuel per passenger as subsonic aircraft on representative routes. Results varied by seating class, configuration, and route. In the best-case scenario, the modeled SST burned 3 times as much fuel per business-class passenger relative to recently certificated subsonic aircraft; in the worst case, it burned 9 times as much fuel compared to an economy-class passenger on a subsonic flight.

These findings suggest two pathways for further development of commercial SSTs. First, manufacturers could maximize the likelihood of meeting existing environmental standards by developing new aircraft based upon advanced, clean sheet engines. Second, policymakers could establish new environmental standards specifically for SSTs based upon the performance of poorer performing derivative engines. Such standards would allow for increased air pollution, noise, and $CO_2$ relative to new commercial aircraft.

## INTRODUCTION

Aircraft produce about 3% of global carbon dioxide ($CO_2$) emissions and 11% of all $CO_2$ emissions from the transportation sector (EIA, 2018). The aviation sector is one of the fastest-growing sources of greenhouse gas emissions globally. Despite international agreements that call for reductions in $CO_2$, the International Civil Aviation Organization (ICAO) projects that $CO_2$ emissions from international aviation will triple from 2018 to 2050, given current trends (ICAO, 2013, 2016).

To mitigate this rise in $CO_2$ emissions, ICAO established two aspirational goals for international flights: fleet-wide fuel efficiency improvements of 2% annually through 2050, and zero net growth of aviation $CO_2$ emissions after 2020 (ICAO, 2010). In March 2017, ICAO formally adopted new global aircraft $CO_2$ emission standards for member states to implement starting in 2020. ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is expected to come into effect around the same time (ICCT, 2017).

Aircraft development is capital-intensive and risky; the vast majority of projects are undertaken by large airframe manufacturers, often with substantial government support. A more recent phenomenon is that of startups, often backed by major companies such as Boeing and Lockheed Martin, developing new aircraft

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designs. Examples include companies developing electric-powered aircraft, such as Zunum Aero and Joby Aviation, and three companies in the United States developing new supersonic transport (SST) aircraft: Boom Supersonic, Spike Aerospace, and Aerion Corporation. Boom is developing a commercial airliner, while Spike and Aerion are focusing on supersonic business jets.

The potential return of supersonic flights could have large environmental and noise pollution consequences. In 2015, aviation was responsible for about 800 million metric tons of $CO_2$ emissions, or about as much as the German economy. New supersonic aircraft could lead to further emission increases if they are less fuel-efficient than new subsonic aircraft.

The previous generation of civil supersonic aircraft, the Aérospatiale/BAC Concorde and Tupolev Tu-144, took their first flights five decades ago. Currently, there are no environmental standards applicable to new supersonic designs. ICAO's Committee on Aviation Environmental Protection (CAEP) is now developing noise and emission certification standards for supersonic aircraft (FAA, 2018a).

This paper presents a preliminary analysis of a new commercial SST's performance in terms of fuel burn, $CO_2$ and nitrogen oxide ($NO_X$) emissions, and landing and takeoff (LTO) noise. Other environmental factors, including sonic boom, particulate matter, and stratospheric water vapor have not been addressed. The analysis uses publicly available data, expert engineering judgment, and an open-source aircraft conceptual aircraft design tool (SUAVE). The analysis addresses a key data gap since manufacturers are currently releasing little information about the environmental performance of their designs. The work is meant to inform policymakers' thinking about future standards for new supersonic designs until such time that higher-fidelity data is made available.

**Table 1.** SST startup companies.

| Company | Aerion | Spike | Boom |
|---|---|---|---|
| **Aircraft type** | Business jet | Business jet | Airliner |
| **Aircraft name** | AS2 | S-512 Quiet Supersonic Jet | — |
| **Target entry into service** | 2025 | 2023 | 2023 |
| **Target speed** | Mach 1.4 | Mach 1.6 | Mach 2.2 |
| **Target maximum range** | 7,780 km | 11,500 km | 8,300 km |
| **Low-boom technology?** | No | "Quiet supersonic flight technology"[1] | No |
| **Corporate customers** | Flexjet | — | Virgin Group<br>Japan Airlines<br>CTrip |

[1] Spike Aerospace (2017b).

## BACKGROUND

### AIRCRAFT

There have been two commercial supersonic vehicles in the past: the Aérospatiale/BAC Concorde and the Tupolev Tu-144. Seventeen Tu-144s were manufactured, including 14 production aircraft that flew commercially 102 times before being decommissioned in 1978 (NASA, 2014). Concorde, while equally limited in production, had a more substantial service life. It flew its first scheduled supersonic passenger service in 1976 and the last in 2003. Both aircraft were powered by turbojet engines with afterburners, which led to high fuel burn and takeoff noise.

Three companies in the United States are currently developing new SSTs: Spike Aerospace, Aerion Corporation, and Boom Supersonic. Spike and Aerion are both focusing on business jet models, whereas Boom is developing a supersonic airliner.

Spike Aerospace (2017a), based in Boston, is collaborating with Siemens, MAYA Simulation, Greenpoint Technologies, BRPH, Aernnova, and Quartus Engineering Inc. Dubbed S-512, Spike's supersonic business jet is targeted to fly at Mach 1.6. Unlike Aerion and Boom, Spike's aircraft design would be powered by two engines, not three. It claims to use a "Quiet Supersonic Flight Technology" in designing its project airplane.

Aerion Corporation, Spike's competitor in delivering the first supersonic business jet, aims to perform the first flight of its AS2 aircraft in 2023 and to bring it into service in 2025. It is the only company to identify its engine manufacturer: General Electric. Aerion collaborated with Airbus in aircraft design and signed an agreement for co-development with Lockheed Martin, the developer of NASA's low-boom flight demonstrator experimental plane (or X-plane). This business jet is targeted to fly at Mach 1.4 using three engines.

Boom Supersonic is developing a 55-seat commercial jet capable of operating at Mach 2.2 with a design range of 4,500 nautical miles (8,300 km). Boom is not developing a specific technology or design to suppress sonic boom; instead, it is relying on the use of a newer engine and better aerodynamics than Concorde's to manage sonic boom. It is developing a one-third–scale supersonic airplane that will demonstrate Boom's technology prior to finalizing its airliner design. Boom claims that its aircraft "won't pollute any more than the subsonic business-class travel it replaces" (Dourado, 2018). Table 1 summarizes key elements of these three companies and their products.

Several government agencies are also involved in supersonic development. NASA has been a major player in SST technology development for decades, including building several supersonic X-planes. The agency's next supersonic X-plane, the Low Boom Flight Demonstrator, will be built by Lockheed Martin and delivered in 2021 (NASA, 2018). On the other side of the Atlantic, the European Union (EU) is funding the Regulation and Norm for Low Sonic Boom Levels, or RUMBLE. RUMBLE[1] aims to develop and assess sonic boom prediction tools, study the human response to sonic boom, and validate the findings using wind-tunnel experiments and flight tests. This is part of the effort by the EU to assess the "social acceptability" of new designs to support European regulatory development.

## POLICY

The development of new supersonic aircraft designs will be influenced by international aviation standards. Those are decided by ICAO, the specialized UN agency that sets recommended standards and practices for civil aviation worldwide. Currently, international standards to support the certification of new supersonic aircraft and engines are not in place.

1 https://rumble-project.eu/i/.

The ICAO noise standard does not include a regulatory limit for supersonic aircraft (ICAO, 2014a). In 2004, CAEP formed a supersonic task group under its Working Group 1, which focuses on noise pollution. This group has been monitoring the development of supersonic technologies in order to develop eventual en-route (sonic boom) and LTO noise standards.

Although the United States is an active participant in CAEP negotiations, it is moving forward independently to regulate supersonic aircraft noise. Citing concerns about sonic boom, the Federal Aviation Administration (FAA, 1973) banned civilian aircraft from flying faster than Mach 1 over U.S. soil. This contributed to effectively banning Concorde operations over the continental United States and limited its movement to transoceanic routes. Language currently incorporated into the 2018 FAA reauthorization bill would undo that restriction (U.S. Government Publishing Office, 2018).

Separately, the FAA (2018a) is initiating a process to develop U.S.-specific standards for civil supersonic aircraft noise, including a proposed rule for LTO noise certification of supersonic aircraft. This rulemaking process may or may not be in line with ICAO's standard setting. If the United States sets its own standards for SSTs, other countries may adopt operational restrictions on those aircraft. Thus, it is unlikely that the U.S. government will adopt a national standard instead of coordinating internationally through ICAO.

On the emissions side, ICAO has aircraft engine emission certification standards for engines capable of supersonic flight based on the Concorde (ICAO, 2017a). However, in 2007, CAEP agreed that these stringency limits are outdated and should not be applied to new supersonic designs (ICAO, 2014b).

The lack of supporting standards for both noise and engine emissions complicates the development of new supersonic aircraft. Without international standards providing regulatory certainty that their aircraft can be sold and operated worldwide, major manufacturers will be reluctant to invest in new designs. But developing an emission standard within ICAO typically requires primary flight and engine test data for a wide variety of aircraft types. Negotiations among ICAO member states can be slow. For example, the 2016 ICAO $CO_2$ standard (ICCT, 2016) took seven years, or more than two CAEP cycles of three years each, to develop. Typically, an additional four years of lead time is provided before new standards take effect.

Two general approaches are under consideration: either to develop specific, SST-only standards for new aircraft, or to require that new designs comply with existing LTO $NO_x$, noise, and $CO_2$ standards for new subsonic airplanes. Separately, both the economic viability and public acceptability of new supersonics will depend in part on their fuel efficiency. Four metrics—$NO_x$ emissions, noise, cruise $CO_2$ emissions, and mission fuel burn—are explored in this paper.

## METHODOLOGY

### SCOPE AND OVERALL APPROACH

According to the FAA (2018b), jet fuel consumption for commercial flights accounts for more than 90% of total U.S. jet fuel consumption for both domestic and international operations. Globally, general aviation is understood to be about 2% of total aviation fuel use (GAMA, 2009). Because business jets are a small contributor to overall emissions, we decided to focus on commercial supersonics in this analysis.

The first step in the analysis is to identify a representative commercial SST design. Boom Supersonic, the only company currently developing such an aircraft, provided that basis. Boom has received support from a variety of investors and customers. In March 2017, Boom (2017) announced that it had received $41 million in funding including from Y Combinator, Sam Altman, Seraph Group, Eight Partners, and others. Japan Airlines provided $10 million in addition to 20 aircraft preorders, while Virgin Atlantic holds an option on 10 aircraft. All in all, Boom has received 76 aircraft commitments across five airline customers (Etherington, 2017).

Boom is aiming for a 2023 entry into service for its aircraft. Before building its airliner, Boom is building a one-third–scale demonstrator aircraft dubbed XB-1 or "Baby Boom." Subsonic flight tests are planned near Boom's hangar at Centennial, Colorado, followed by supersonic flights at Edwards Air Force Base in Southern California for technology validation purposes.

At the start of this project, Boom was contacted for information about the design and performance characteristics of its aircraft. General confirmation of publicly available data was provided, but no detailed information regarding engine specification was offered.

The following public information was available to support this assessment. A three-view drawing on Boom's website was used to develop the geometric representation necessary for aerodynamic calculations (see below). Boom also provides estimated routes, travel times, ticket prices, and fuel costs on its website. Relative to present-day subsonic service, supersonic travel on Boom airliners is claimed to save more than half the time it takes to fly trans-Atlantic, and a little less than that for trans-Pacific, because the latter would require a refueling stop due to range limitations. Boom estimates one-way ticket prices for three routes: $3,200 between Tokyo and San Francisco, $3,500 between Los Angeles and Sydney, and $2,500 between New York and London. The company also claims a fuel efficiency similar to that of existing premium-class twin-aisle aircraft.

The following sections describe the tools and assumptions used to estimate $NO_x$ and $CO_2$ emissions, noise, and mission fuel burn of a reference commercial SST based on Boom's design. These values are compared against current ICAO subsonic emission standards and the fuel burn of equivalent commercial aircraft on representative missions.

## TOOL SUMMARY

To evaluate new supersonic aircraft, we chose SUAVE (Lukaczyk et al., 2015), an open-source conceptual aircraft design tool with development currently led by Stanford University. It was specifically designed to be able to evaluate the performance of unconventional aircraft, including supersonic configurations.

The aerodynamics model derived from SUAVE was used for both subsonic and supersonic conditions (Lukaczyk et al., 2015). These low-fidelity methods have been validated against Concorde performance numbers. Details are available in the initial SUAVE paper, with minor refinements made over time. Because the reference SST aircraft is largely the same shape as the Concorde, we expect that these methods will hold. However, we also recognize the availability of more advanced design and manufacturing methods, such as using the area rule to design a fuselage with reduced wave drag. As a result, the overall lift/drag ratio of the vehicle was improved by an average of 10% from the value initially calculated under the low-fidelity methods.

The engine model used in this work is a low-fidelity model built into SUAVE. High-level engine cycle parameters—namely bypass ratio, overall pressure ratio, and turbine inlet temperature—are used as inputs into the model. Efficiencies of the engine components are based on technology level estimates from Mattingly (2006). From these parameters, the thermodynamic equations are solved across the engine components to find the temperature and pressure at each combustion stage, along with the final exit jet velocity.

Piano 5 aircraft performance and design software (Lissys Ltd., 2017) was used to compare estimated supersonic aircraft fuel burn with comparable subsonic transport. Two subsonic aircraft were chosen as baseline: Airbus A321LR (long range) and Boeing B787-9. The narrow-body A321LR was chosen because of its similarity in overall weight and range capacity to the Boom aircraft, which makes it suitable for trans-Atlantic flights. The B787-9 was chosen to represent conventional transoceanic travels on a twin-aisle aircraft without a refueling stop. Both aircraft are state-of-the-art subsonic aircraft at the time of writing and will be representative of newer in-service aircraft when new commercial SSTs enter into service.

The mission profile used in modeling is based roughly on the profile flown by Concorde. We used the full mission profile to include the fuel burn used in the climb portion of the mission. In the

**Table 2.** Airframe parameters used for modeling.

| Parameter | Value | Source |
|---|---|---|
| **Maximum takeoff mass (kg)** | 77,000 | www.flightglobal.com/news/articles/dubai-boom-to-make-a-big-noise-at-show-about-shorte-442767 |
| **Design range (km)** | 8,300 | https://boomsupersonic.com/airliner |
| **Maximum passengers** | 55 | https://boomsupersonic.com/airliner |
| **Design speed (Mach number)** | 2.2 | https://boomsupersonic.com/airliner |
| **Length (ft)** | 170 | https://boomsupersonic.com/airliner |
| **Wingspan (ft)** | 60 | https://boomsupersonic.com/airliner |
| **Reference geometric factor[a] ($m^2$)** | 80 | Estimated |
| **Balanced field length (ft)** | 10,000 | https://boomsupersonic.com/airliner |
| **Cruise altitude (ft)[b]** | 60,000 | https://techcrunch.com/2017/01/12/boom-shows-off-its-xb-1-supersonic-demonstration-passenger-airliner |
| **Engine** | Medium-bypass-ratio turbofan, no afterburner | https://blog.boomsupersonic.com/why-we-dont-need-an-afterburner-a4e05943b101 |

[a] Reference geometric factor, which approximates an aircraft's pressurized floor area, is used to calculate the $CO_2$ standard metric value. The metric value is used to demonstrate compliance with ICAO's $CO_2$ standard (see below).
[b] We reduced the cruise altitude slightly in our analysis to meet a lower average altitude more consistent with a cruise-climb to 60,000 ft.

SUAVE framework, missions are constructed as a series of segments that are further split into control points. At each control point, conditions (altitude, speed, climb rate, etc.) are specified, and the equations of motion are solved to determine aircraft performance. This is done iteratively, segment by segment, to determine the full mission performance. See Lukaczyk et al. (2015) for further details of the mathematics involved.

## MODEL CONSTRUCTION

Parameters for the SST model were determined primarily using publicly available information on Boom's aircraft. In general, Boom's statements of its designed capability were taken as truth; we did not modify estimates for parameters such as maximum takeoff mass or engine bypass ratio based upon our own expert judgement. This may lead to overestimating the real-world performance of the reference SST aircraft. The high-level airframe parameters used in the model are shown in Table 2.

We used a three-view drawing available on Boom's website to develop the geometric representation necessary for aerodynamic calculations. The measurements were made with Digimizer, a digital measurement tool (MedCalc Software, 2018). We used the tool to estimate all airframe geometric parameters except for wing and vertical tail thickness. An OpenVSP (Fredericks, 2010) model based on these estimates is used to determine wetted areas. For the wing and tail thickness, we assumed that Boom would be able to create structures slightly thinner than Concorde, reducing the wing's maximum thickness from 3% to 2.25%. The vertical tail is assumed to be slightly thicker than the wing at 3.5% of the chord length. See Table A1 in the Appendix for the full list of geometric parameters.

Boom's exact engine configuration has yet to be announced. The company aims to develop an aircraft with a medium bypass–ratio turbofan using an existing core and no afterburners. A clean-sheet turbofan engine would provide lower noise, emissions, and fuel burn but with a higher development cost. Currently, no manufacturers are producing commercial turbofan engines that could operate at Mach 2.2. An alternative approach, described in Fehrm (2016), would be to develop a commercial SST using an engine derived from an in-production military turbojet aircraft.

We assume that the new supersonic aircraft will use a variable-geometry nozzle, as Concorde did, that will be capable of keeping the flow nearly perfectly expanded. The result is an idealized engine that provides accurate values when operated near its design point, which means that climb and cruise values are expected to be representative of a well-designed engine with the parameters specified in Table 3. Although doubts have been raised about the capability of constructing an efficient engine with the properties specified (Fehrm, 2016), we provide this analysis assuming that such an engine can be designed. We therefore expect that the calculated emissions will be optimistic.

Three engine models were developed to span the range of possible performance: most likely (derivative turbofan), best case (clean-sheet turbofan), and worst case (derivative turbojet). For the most likely case, we examined an engine expected to be usable on the Aerion AS2 based on the CFM56 (Fehrm, 2018). In its expected Mach 1.4 flight condition with refanning, the engine would have a lower-pressure compressor (LPC) pressure ratio of 2, a high-pressure compressor (HPC) pressure ratio of 10, and a turbine inlet temperature (T4) of 1650 K. To adapt this for Mach 2.2 flight, we assume that the pressure ratio is limited by the temperature at the compressor outlet as a result of material temperature limits in the compressor (Fehrm, 2016). This provides us with a HPC compression ratio of about 7.5. We also assume a bypass ratio of 3, consistent with Boom's stated engine plan. This may be optimistic given the resulting high ram drag on Mach 2.2 operations.

To represent the best-case scenario, we created an advanced engine aimed at meeting NASA's N+2 goals for supersonic aircraft (Welge et al., 2010). In this case, the assumption of a clean-sheet design allows us to vary T4 to find the maximum efficiency. We assume a compressor outlet temperature limit of 720°C for this design (Welge et al., 2010). This provides a somewhat more efficient engine. As a clean-sheet design, this engine would be more advanced, and therefore more complex and costly, than the derivative turbofan that near-term SST manufacturers are likely to deploy.

Our final engine is a turbojet based on an in-production military engine (EJ200) with constraints suggested in the series of articles on supersonic aircraft by Fehrm (2018). In this case, the compressor outlet temperature is limited to below 700°C. This engine provides a worst-case scenario estimate on engine performance, although it is unlikely to be used for commercial aircraft because of excessive noise. An aircraft based on this existing military engine could be brought to market more easily and more cheaply than one using a turbofan.

**Table 3. Engine parameters used for modeling.**

| Parameter | Configuration | | |
|---|---|---|---|
| | **Best** | **Most likely** | **Worst** |
| **Engine type** | Clean-sheet turbofan | Derivative turbofan | Derivative turbojet |
| **Bypass ratio** | 3.0 | 3.0 | — |
| **Overall pressure ratio** | 15 | 15 | 13.8 |
| **Turbine inlet temperature (K)** | 1850 | 1650 | 1800 |
| **Landing and takeoff thrust available (lbf)** | 40,000 | 50,000 | 30,000 |
| **Top of climb thrust available (lbf)** | 7,600 | 8,200 | 9,200 |

We checked that these engines are capable of producing the required takeoff and cruise thrust. Boom claims a takeoff thrust in the range of 15,000 to 20,000 lbf per engine (Trimble, 2017). We estimate the need for about 7,000 to 8,000 lbf per engine in cruise and somewhat more than that for climb. Our analysis indicates that this performance is possible for all three engines with resizing.[2] All engine models use the same component efficiencies. Table 3 summarizes the engine parameters used in the modeling.

Uncertainty in the aerodynamic performance of the representative SST was captured by varying the level of assumed aerodynamic improvement over the Concorde. Improvements of 20%, 10%, and 0% (no improvement) in the lift-to-drag ratio were assumed for the best-case, most likely, and worst-case configurations, respectively.

2 Note that LTO thrust exceeds what is needed because engines must be sized for top-of-climb thrust. Additional uncertainty is also present at takeoff because the design mass flow near zero speed is not available. It is expected that engines for new SSTs will be derated to bring them in line with LTO requirements.

## FUEL EFFICIENCY DETERMINATION

The fuel efficiency of the reference SST was compared to existing subsonic standards and aircraft using two metrics: the ICAO $CO_2$ metric value (CO2MV) (ICCT, 2016) and mission fuel burn.

The ICAO CO2MV is based on the maximum specific air range (SAR), which is a measure of cruise fuel efficiency. The MV is expressed as $1/(SAR \times RGF^{0.24})$, where RGF is the reference geometric factor determined by multiplying the pressurized fuselage length by the fuselage width. This approximates the amount of usable space in the aircraft. We estimate the pressurized length of the reference SST to be about 35 m and the width to be about 2.3 m.

Maximum SAR measures the distance (km) traveled per mass (kg) of fuel under optimal flight conditions. To calculate it, the aircraft is simulated at a variety of altitudes and cruise speeds to find the condition that gives the maximum value. In addition to finding the maximum cruise SAR, we also find the maximum SAR at Mach 2.2 and at subsonic conditions. Those values are important because SSTs will be required to fly over many countries subsonically and will likely not fly at maximum supersonic SAR if the associated speed is too low.

We next analyzed mission fuel burn. This is defined as gate-to-gate fuel burn minus fuel used to taxi the aircraft. To determine this, we use climb and descent segments similar to what Concorde performed, along with a cruise segment at constant altitude. Although we expect that the new supersonic aircraft will perform a cruise-climb to reduce fuel burn slightly, this would reduce mission fuel burn on the order of only 1 to 2%. Modeling an optimal trajectory is therefore not necessary to reach the level of accuracy targeted in this study.

Three different origin-to-destination missions were chosen for the analysis, corresponding to routes highlighted by Boom: San Francisco–Tokyo (SFO-NRT), Los Angeles–Sydney (LAX-SYD), and New York–London (JFK-LHR). Because of the SST's shorter design range, we assume that a refueling stop would be needed in Anchorage (ANC) and Tahiti (PPT) for the first two routes, respectively. These routes and distances are shown in Figure 1.

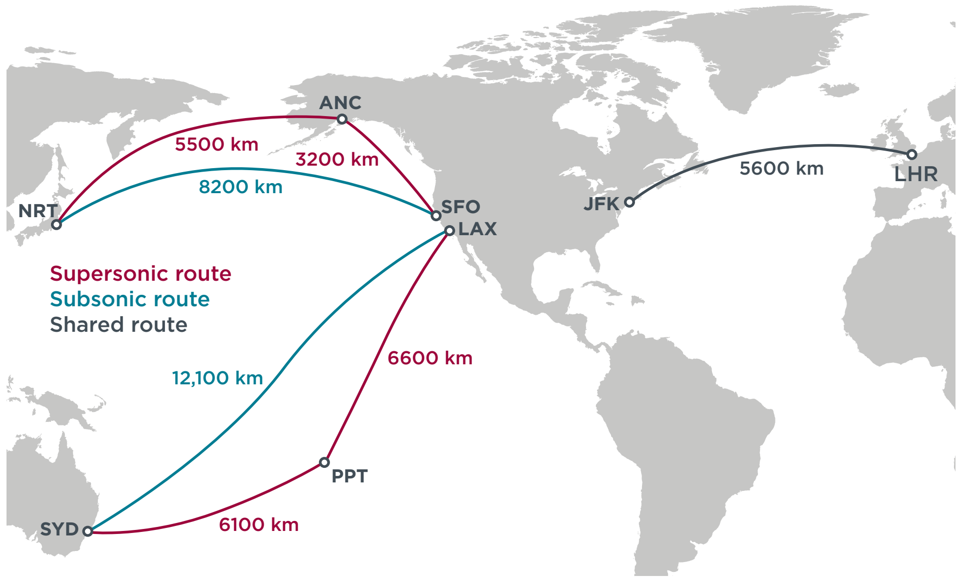


**Figure 1.** Routes investigated. (Source: GCmap.com)

Mission distances were assumed to be great-circle distances if there is not a substantial land mass under the route. Because the great-circle distance for the ANC-NRT route includes about 1,000 km traveling over Alaska, we estimated a subsonic flight over Alaska at a speed matching optimal subsonic SAR. This created a slightly slower (15 min) but more fuel-efficient flight path relative to a purely supersonic, longer-distance route that requires flying south out of ANC to clear Alaska's southern edge.

The analysis distinguishes between premium (both supersonic and subsonic) and economy (subsonic only) service. We assumed a load factor of 80% for economy and 60% for premium passengers based on Bofinger and Strand (2013).[3] To apportion fuel use between premium and economy seats on the subsonic aircraft, we assigned a weighting factor of 2 to 1 to account for the greater floor area of long-haul premium seats (ICAO, 2017b).[4] Freight was assumed to be negligible for narrow-body aircraft and the SST, whereas for wide-body aircraft it was assumed to be 16% of total payload for flights operating between North America and the Pacific or Southeast Asia/Oceania, and 34% of total payload for flights operating between North America and East Asia (ICAO, 2018).

To determine the aircraft takeoff weight for each SST mission, we first used the maximum takeoff weight in a generic full-range mission of 4,500 nautical miles. The landing weight was determined, corresponding to the sum of the payload, reserve fuel, and aircraft empty weight. This landing weight was then reduced to account for the 60% load factor assuming 100 kg per passenger. This provided the expected landing weight for each origin/destination-specific mission. The mission

3 Transparent load factor data for both premium subsonic and supersonic seating is limited. On subsonic operations, Delta reported an estimated first-class load factor of 57% in 2015 (Anderson, 2015). For supersonics, the Concorde's load factors were highest between London and New York and between Paris and New York for British Airways and Air France, respectively. BA's load factors between JFK and LHR were reported to be between 50 and 60% in 2002 (Kingsley-Jones, 2002) and as high as 73% in the first six months of operations in 1978 (Witkin, 1978). Air France achieved load factors above 60% on its Paris–New York and Paris–Rio de Janeiro routes (ibid.). Other routes, including Paris–Caracas and London–Bahrain, experienced load factors well below 60%.

4 Bofinger and Strand (2013) calculated a business-class to economy-class emissions multiplier of 1.86 to 2.71 for flights where the passenger weight share is 12.5% of the total aircraft weight, close to the simple average of subsonic flights in this analysis.

was then solved iteratively to determine what takeoff weight (and therefore fuel burn) would be needed to land at the specified weight.

In modeling the mission fuel burn of subsonic aircraft, default Piano 5 values for operational parameters such as engine thrust, drag, fuel flow, available flight levels, and speed were used.

Cruise speeds were set to allow 99% maximum specific air range. Flight times were estimated by including 20 min of taxi time (both in and out) for all flights, plus 30 min for refueling for routes longer than the range of the SST (Figure 1).

### EMISSIONS AND NOISE

$NO_x$ emissions were estimated for the most likely and best-case scenarios using emissions data for in-production engines in the ICAO engine emissions databank (ICAO, 2018).

An exponential curve of $NO_x$ emission indices versus overall pressure ratio (OPR) for current CFM56 (CFM56-5 and -7) engine data was used to adjust the emissions values.[5] These engines use rich-quench-lean (RQL) combustor technology. For the most likely (derivative turbofan) engine, no further adjustments were made. LTO emissions for the best-case engine (i.e., clean-sheet turbofan) were estimated by correcting for the lower emissions of the LEAP engine family relative to current CFM56 engines.

Building a sophisticated noise model was beyond the scope of this work, so we instead used exit jet velocities to investigate likely noise characteristics. The jet velocity is found by taking a mass-weighted average of the core and fan velocities from SUAVE's engine model. The accuracy of these jet velocities depends on the engine's capability to operate at an ideal nozzle area ratio, which assumes that the engine has a variable nozzle that can reach the necessary outlet area. Boeing has determined that a jet velocity of 1,100 ft/s will be sufficient to meet Chapter 3 minus 10 to 20 EPNdB[6] (Welge et al., 2010). Research suggests that the lateral noise limit is the key determinant of passing noise standards stricter than Chapter 3, so we focused specifically on that value.

## RESULTS

Table 4 summarizes the results for LTO $NO_x$ and cruise $CO_2$ (CO2MV) emissions of the reference SST aircraft relative to existing subsonic standards. Values for the most likely, best-case, and worst-case configurations are summarized, along with their regulatory values and the year each standard takes effect. Regulatory limits for $NO_x$ are set as a function of overall pressure ratio, whereas standards for $CO_2$ are set as a function of aircraft maximum takeoff mass. $NO_x$ emission estimates were not available for the worst-case configuration because emissions data is not available for military engines.

As Table 4 indicates, the reference SST is unlikely to meet existing commercial aircraft standards. It exceeded allowable LTO $NO_x$ limits by 38% in the most likely configuration, and CO2MV limits by 52% to 115%, with a most likely exceedance of 67%. The best-case, advanced clean-sheet engine was

**Table 4.** Modeled $NO_x$ and $CO_2$ performance of SST aircraft by configuration.

| Pollutant | Standard[a] | Year | Parameter | Configuration | | |
|---|---|---|---|---|---|---|
| | | | | Best | Most likely | Worst |
| $NO_x$ | CAEP/8 | 2014 | Overall pressure ratio | 15 | 15 | 13.8 |
| | | | SST (g/kN) | 18 | 40 | —[b] |
| | | | Standard (g/kN) | 29 | 29 | —[b] |
| | | | Exceedance | –37% | +38% | —[b] |
| $CO_2$ | CAEP/10 | 2020 | Maximum takeoff mass (kg) | 77,000 | | |
| | | | SST (kg/km) | 1.21 | 1.33 | 1.72 |
| | | | Standard (kg/km) | 0.80 | | |
| | | | Exceedance | +52% | +67% | +115% |

[a] ICAO's environmental standards are referenced to the meeting at which they were agreed. ICAO's current CAEP/8 ($NO_x$) and CAEP/10 ($CO_2$) standards were finalized in 2010 and 2016, respectively.
[b] $NO_x$ emission estimates were unavailable for this configuration.

5 This fit line is generally consistent with typical $NO_x$ correlation equations, such as the one found in the GasTurb manual, which is a widely used program for calculating engine cycle parameters (GasTurb, n.d.). This approach has the added benefit of providing $NO_x$ data for all of the required mode settings, whereas the SUAVE model cannot handle off-design conditions.

6 The ICAO Chapter 3 noise standard, applicable since 1978, is the current operational noise standard in many ICAO member states including the United States and Europe. This means that airplanes that do not comply with the Chapter 3 noise standard are not allowed to fly. The Chapter 4 noise standard, applicable from 2006 to 2017, is 10 EPNdB (cumulative) quieter than Chapter 3. The current applicable noise standard, Chapter 14, is 17 EPNdB (cumulative) more stringent than Chapter 3.

estimated to comply with the latest subsonic $NO_x$ standards. This finding is consistent with the view that staged lean-burn combustors can considerably reduce $NO_x$ emissions. Note that the CO2MV results are more certain than the $NO_x$ estimates.

A detailed assessment of noise certification levels is beyond the scope of this work. Some simple observations can be made, however. Relative to the jet exit velocity limit of 1,100 ft/s identified in Welge et al. (2010), SUAVE's engine model predicts a jet exit velocity of 1,350 ft/s in the most likely configuration, and 1,550 and 3,400 ft/s for the best- and worst-case configurations, respectively. This implies that the aircraft would not meet existing (Chapter 14/Stage 5) standards. Engine derating, combined with modified landing and takeoff procedures, is believed to be needed to bring new SST aircraft into compliance with the 2006 Chapter 4 noise standards (Welge et al., 2010). Certification to current subsonic noise standards is likely to require additional technological solutions—for example, a clean-sheet advanced variable-cycle engine—that are currently not being considered for near-term SSTs.

Figure 2 summarizes the expected mission fuel performance of the reference SST aircraft relative to new subsonic aircraft on comparable missions. The applicable routes, aircraft types, and fuel use (mass per passenger) are shown for average, premium, and economy passengers. Best- and worst-case SST scenarios are indicated as error bars on the blue SST bars.

As Figure 2 indicates, in its most likely configuration the modeled SST

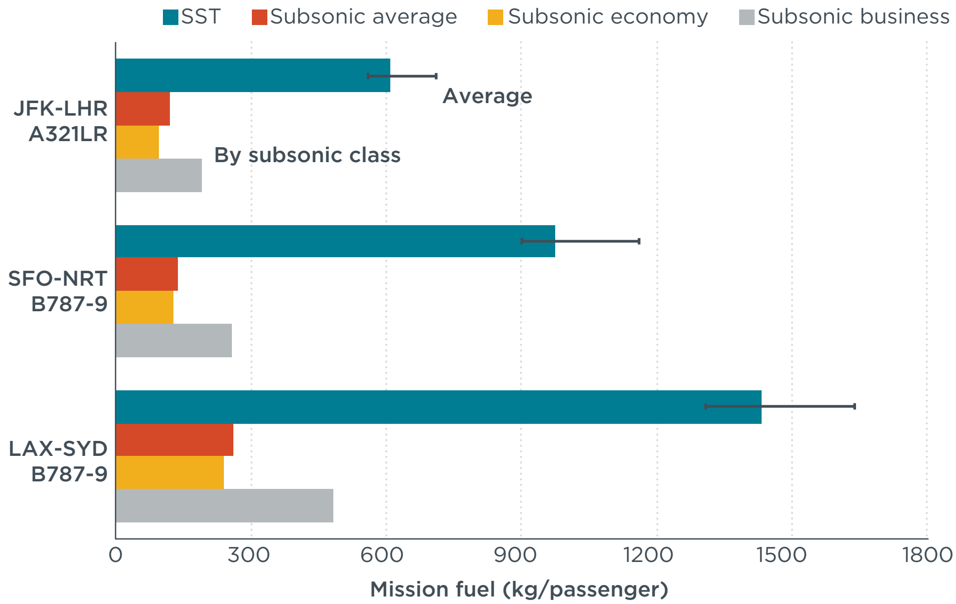


**Figure 2.** One-way mission fuel consumption per passenger by route and class.

consumed between 5 and 7 times as much fuel per passenger relative to comparable subsonic aircraft. Divided by class, the SST burned between 3 and 4 times as much fuel per passenger for premium (business) service, and between 6 and 8 times as much fuel per economy passenger.[7] The lower multiples were associated with the New York (JFK)–London (Heathrow) and Los Angeles–Sydney routes, which largely followed great-circle distances with relatively little belly freight carriage. The higher multiples were seen for the SFO-NRT route, which had a 6% excess flight distance to enable refueling and a high share of belly freight carriage.

These values are for the most likely SST configuration. Taking into account the full range of uncertainty, the per-passenger fuel intensity of the SST varied from 3 times (best configuration relative to subsonic business class, LAX-SYD) to 9 times (worst configuration relative to subsonic economy class, SFO-NRT) that of its subsonic equivalent. Estimated travel times were 30 to 50% shorter for the Mach 2.2 SST relative to the subsonic aircraft, which typically operate near Mach 0.85.

Aircraft fuel burn, LTO $NO_x$, and LTO noise are not the only environmental issues facing SSTs. Some of the issues not considered in this paper stem from the high cruise altitudes of SSTs, including cruise $NO_x$, stratospheric water vapor, and magnified non-$CO_2$ effects. Sonic boom or en-route noise impacts are also important but beyond the scope of this work.

7 High mission fuel burn is directly related to high $CO_2$ emissions during cruise. The gap between the SST's smaller (70%) exceedance to the $CO_2$ standard and its larger (5 to 7 times) overall fuel intensity is due to the way that the $CO_2$ standard assigns regulatory targets to individual aircraft. Supersonic aircraft, which are disproportionately heavy compared to subsonic aircraft carrying the same number of passengers, would receive less stringent targets if subject to the standard. See ICCT (2016) for further details.

## CONCLUSIONS AND NEXT STEPS

This working paper provides a preliminary assessment of the environmental performance of emerging commercial SST aircraft. Multiple scenarios representing most likely, best-case, and worst-case configurations were developed to bound the range of possible uncertainty. Where provided, manufacturer claims of airframe and engine design parameters were used as modeling inputs. Accordingly, our overall findings are likely optimistic; the actual performance of future supersonic aircraft may be worse.

This analysis suggests that near-term commercial SSTs are unlikely to comply with existing standards for commercial aircraft. The most likely configuration of a representative SST was estimated to exceed limits for $NO_x$ and $CO_2$ by 40% and 70%, respectively. A qualitative assessment of noise was consistent with the understanding that engine derating and modified LTO procedures would be needed to comply with older (2006) Chapter 4 noise standards. Advanced technologies, including variable-cycle engines and staged combustion, on a clean-sheet engine would likely be needed to meet current LTO noise and $NO_x$ standards.

These findings suggest two pathways for further development of commercial SSTs. First, manufacturers could refocus their development efforts on designs with advanced, clean sheet engines. Those are more likely to meet existing subsonic aircraft standards. Second, policymakers could establish new environmental standards for SSTs based upon designs using poorer performing derivative engines. Such standards would allow for increased pollution and nuisance relative to new commercial aircraft.

Independent of standards, the economic feasibility and social acceptability of new designs remain to be seen. The representative SST is expected to burn 5 to 7 times as much fuel per passenger as comparable subsonic aircraft. The results were sensitive to seating class, route, and the exact configuration of the aircraft. In its best possible configuration and route, the SST burned 3 times as much fuel per business-class passenger relative to subsonic aircraft; in the worst configuration with a refueling stop, the difference would be 9 times as much fuel for an economy-class passenger.

Fuel is typically an airline's single largest operating expense, accounting for 20 to 35% of overall airline operating costs. Current jet fuel prices of about $700 per metric tonne (IATA, 2018) mean that the fuel costs of transporting one passenger round-trip from San Francisco to Tokyo via SST would be around $1400, versus about $180 to $360 for subsonic economy class and business class, respectively. Profitable operation of these aircraft would require revenue and yields high enough to recover these extra fuel costs.

This increased fuel consumption would lead to proportional increases in $CO_2$ emissions. The share of $CO_2$ emissions attributable to international aviation is expected to increase from 1.4% today to between 7% and 14% of a Paris-compatible global carbon budget by 2075 (Rutherford, 2018). The introduction of new supersonic aircraft opens up the potential for even larger increases. The social acceptability of this increase, and therefore the public's support for supersonic travel, remains to be determined.

This working paper has provided an initial assessment of one aspect of SST operations, namely their emissions and noise characteristics. Substantial data gaps persist with respect to the characteristics of the engines that may be deployed as well as precise airframe parameters (e.g., maximum takeoff weight, empty weight, range, and payload). Further work is needed in particular to better characterize noise levels, both for LTO and supersonic en-route noise or sonic boom. LTO $NO_x$ emissions estimates could be refined further through the use of analytical models such as GasTurb. Furthermore, little is known about how LTO $NO_x$ relates to cruise $NO_x$ for these aircraft, and work will be needed to establish this relationship.

The viability of new commercial SSTs will depend on more than just pollution and nuisance. Additional work is needed to understand other aspects of commercial SSTs. A route-based analysis of how commercial SSTs may be integrated into current and future airline networks and air traffic management at airports is recommended. Similarly, an economic analysis of likely fares, operating costs, yield, profitability, etc., would help to clarify the business case for commercial supersonics.

## REFERENCES

Anderson, R. (2015). *Delta: A High Quality Company* [presentation]; https://s1.q4cdn.com/231238688/files/doc_presentations/2015/2015-Delta-Investor-Day-Presentation_F.pdf.

Bofinger, H., & Strand, J. (2013). *Calculating the Carbon Footprint from Different Classes of Air Travel.* World Bank Policy Research Working Paper 6471; https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-6471

Boom Supersonic (2017). "Boom has raised $33M in new funding to finish development and flight test of XB-1" [blog post]; https://blog.boomsupersonic.com/boom-has-raised-33m-in-new-funding-to-finish-development-and-flight-test-of-xb-1-c82e1f556c43

Dourado, E. (2018). Supersonic Planes Redux [Letter]. *The New York Times*. Retrieved from https://www.nytimes.com/2018/06/27/opinion/supersonic-planes-global-warming.html

Etherington, D. (2017). "Boom has orders for 76 of its future supersonic passenger jets." *TechCrunch*; https://techcrunch.com/2017/06/20/boom-has-orders-for-76-of-its-future-supersonic-passenger-jets/.

Federal Aviation Administration (FAA) (1973). Civil aircraft sonic boom, 14 C.F.R. § 91.817.

Federal Aviation Administration (FAA) (2018a). *Fact Sheet – Supersonic Flight*; www.faa.gov/news/fact_sheets/news_story.cfm?newsId=22754.

Federal Aviation Administration (FAA) (2018b). *FAA Aerospace Forecast, Fiscal Years 2018–2038*; www.faa.gov/data_research/aviation/aerospace_forecasts/media/FY2018-38_FAA_Aerospace_Forecast.pdf.

Fehrm, B. (2016). The Boom SST engine problem, Part 4. *Leeham News and Comment*; https://leehamnews.com/2016/12/15/boom-sst-engine-problem-part-4/.

Fehrm, B. (2018). Aerion's supersonic engine presented. *Leeham News and Comment*; https://leehamnews.com/2018/02/26/aerions-supersonic-engine-presented/.

Fredericks, W. (2010). *Aircraft Conceptual Design Using Vehicle Sketch Pad.* 48th AIAA Aerospace Sciences Meeting, Orlando, FL.

GasTurb (n.d.). *GasTurb 13 Manual*; www.gasturb.de/manual.html.

General Aviation Manufacturers Association (GAMA) (2009). *Business Aviation Commitment on Climate Change*; https://gama.aero/wp-content/uploads/GAMA-IBAC-Joint-Position-on-Business-Aviation-Tackling-Climate-Change-1.pdf.

International Air Transport Association (IATA) (2018). Jet Fuel Price Monitor; www.iata.org/publications/economics/fuel-monitor/Pages/index.aspx.

International Civil Aviation Organization (ICAO) (2010). Assembly Resolutions in Force (as of 8 October 2010). Doc 9958, ISBN 98-92-9231-773-7.

International Civil Aviation Organization (ICAO) (2013). *ICAO Environmental Report, 2013*; www.icao.int/environmental-protection/Pages/EnvReport13.aspx.

International Civil Aviation Organization (ICAO) (2014a). *International Standards and Recommended Practices: Annex 16 to the Convention on International Civil Aviation: Volume 1, Aircraft Noise.*

International Civil Aviation Organization (ICAO) (2014b). *Doc 9501, Environmental Technical Manual Volume II, Procedures for the Emissions Certification of Aircraft Engines.* ISBN 978-92-9249-534-3; www.icao.int/environmental-protection/Documents/SGAR_2016_ETM_Vol2.pdf.

International Civil Aviation Organization (ICAO) (2016). *ICAO Environmental Report 2016*; www.icao.int/environmental-protection/Pages/env2016.aspx.

International Civil Aviation Organization (ICAO) (2017a). *International Standards and Recommended Practices: Annex 16 to the Convention on International Civil Aviation: Volume 2, Aircraft Engine Emissions*.

International Civil Aviation Organization (ICAO) (2017b). *ICAO Carbon Emissions Calculator Methodology Version 10*; www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v10-2017.pdf.

International Civil Aviation Organization (ICAO) (2018). *ICAO Aircraft Engine Emissions Databank v24* [database]; www.easa.europa.eu/easa-and-you/environment/icao-aircraft-engine-emissions-databank.

International Council on Clean Transportation (2016). *International Civil Aviation Organization $CO_2$ Standard for New Aircraft*; www.theicct.org/publications/international-civil-aviation-organization-co2-standard-new-aircraft.

International Council on Clean Transportation (2017). International Civil Aviation Organization's Carbon Offset and Reduction Scheme for International Aviation (CORSIA); www.theicct.org/sites/default/files/publications/ICAO%20MBM_Policy-Update_13022017_vF.pdf.

Kingsley-Jones, M. (2002). "BA cautious on Concorde plans." *Flight International*; www.flightglobal.com/news/articles/ba-cautious-on-concorde-plans-143024/.

Lissys Ltd. (2017). Piano 5 for Windows [aircraft modeling software]; www.lissys.demon.co.uk/Piano5.html.

Lukaczyk, T., Wendorff, A., Botero, E., MacDonald, T., Momose, T., Variyar, A., Vegh, J. M., Colonno, M., Economon, T. D., Alonso, J., Orra, T. H., & da Silva, C. I. (2015, June). *SUAVE: An Open-Source Environment for Multi-Fidelity Conceptual Vehicle Design*. 16th AIAA Multidisciplinary Analysis and Optimization Conference, Dallas, TX; http://adl.stanford.edu/papers/suave-open-source.pdf.

Mattingly, J. D. (2006). *Elements of Propulsion: Gas Turbines And Rockets*. Reston, VA: American Institute of Aeronautics and Astronautics.

MedCalc Software. (2018). *Digimizer*. https://www.digimizer.com/.

National Aeronautics and Space Administration (NASA) (2014). *NASA Armstrong Fact Sheet: Tu-144LL Supersonic Flying Laboratory*; www.nasa.gov/centers/armstrong/news/FactSheets/FS-062-DFRC.html.

National Aeronautics and Space Administration (NASA) (2018). "NASA awards contract to build quieter supersonic aircraft" [press release]; www.nasa.gov/press-release/nasa-awards-contract-to-build-quieter-supersonic-aircraft.

Rutherford, D. (2018, June 4). "ICAO, why can't you be a bit more like your sister?" ICCT staff blog; www.theicct.org/blog/staff/icao-why-cant-you-be-bit-more-your-sister.

Spike Aerospace (2017a). "Spike Aerospace to fly the first SX-1 demonstrator"; www.spikeaerospace.com/spike-aerospace-to-fly-the-first-sx-1-demonstrator.

Spike Aerospace (2017b). "Spike Aerospace Expands Quiet Supersonic Aircraft Development Efforts"; www.spikeaerospace.com/spike-aerospace-expands-quiet-supersonic-aircraft-development-effort/.

Trimble, S. (2017). "Analysis: JAL invests heavily in supersonic Boom." *FlightGlobal*; www.flightglobal.com/news/articles/analysis-jal-invests-heavily-in-supersonic-boom-443857.

U.S. Energy Information Administration (EIA) (2018). *Annual Energy Outlook 2018 with Projections to 2050*; www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf.

U.S. Government Publishing Office (2018). *Federal Aviation Administration Reauthorization Act of 2017. Report of the Committee on Commerce, Science, and Transportation*; www.congress.gov/115/crpt/srpt243/CRPT-115srpt243.pdf.

Welge, H., Bonet, J., Magee, T., Chen, D., Hollowell, S., Kutzmann, A., Mortlock, A.,

Stengle, J., Nelson, C., Adamson, E., Baughcum, S., Britt, R., Miller, G., & Tai, J. (2010). *N+2 Supersonic Concept Development and Systems Integration*. NASA/CR-2010-216842.

Witkin, R. (1978, June 10). "Repeat Passengers (one has flown 63 times) encourage Concorde's operators despite current losses." *New York Times*; www.nytimes.com/1978/06/10/archives/new-jersey-pages-repeat-passengers-one-has-flown-63-times-encourage.html.

## Appendix

**Table A1.** Detailed geometric parameters.

| Parameter | Value | Source |
|---|---|---|
| **Main wing aspect ratio (span$^2$/reference area)** | 1.39 | Calculated |
| **Main wing thickness/chord ratio** | 0.0225 | Engineering Judgement |
| **Main wing quarter chord sweep (degrees)** | 55.9 | Measured using Digimizer (MedCald Software, 2018). |
| **Main wing span (m)** | 18.3 | Boom website |
| **Main wing root chord (m)** | 20.8 | Measured using Digimizer. |
| **Main wing tip chord (m)** | 2.8 | Measured using Digimizer. |
| **Main wing mean aerodynamic chord (m)** | 12.0 | Calculated |
| **Main wing total length (m)** | 21.7 | Measured using Digimizer. |
| **Main wing reference area (m$^2$)** | 241 | Measured using Digimizer. |
| **Main wing wetted area (m$^2$)** | 344 | Calculated with OpenVSP Model |
| **Tail aspect ratio** | 0.65 | Calculated |
| **Tail thickness/chord ratio** | 0.035 | Engineering Judgment |
| **Tail quarter chord sweep (degrees)** | 60 | Measured using Digimizer. |
| **Tail span (m)** | 4 | Measured using Digimizer. |
| **Tail root chord (m)** | 11.9 | Measured using Digimizer. |
| **Tail tip chord (m)** | 2.1 | Measured using Digimizer. |
| **Tail mean aerodynamic chord (m)** | 9.4 | Measured using Digimizer. |
| **Tail total length (m)** | 12 | Measured using Digimizer. |
| **Tail reference area (m$^2$)** | 24.6 | Measured using Digimizer. |
| **Tail wetted area (m$^2$)** | 60.4 | Calculated with OpenVSP Model |
| **Fuselage length (m)** | 51.8 | Boom website |
| **Fuselage maximum height (m)** | 2.7 | Measured using Digimizer. |
| **Fuselage width (m)** | 2.4 | Measured using Digimizer. |
| **Fuselage wetted area (m$^2$)** | 332 | Calculated with OpenVSP Model |
| **Fuselage front projected area (m$^2$)** | 5.3 | Measured using Digimizer. |
| **Fuselage effective diameter (m)** | 2.55 | Estimated |
| **Propulsor length (m)** | 10.6 (underwing)<br>12.6 (fuselage) | Measured using Digimizer. |
| **Propulsor nacelle diameter** | 1.4 | Measured (approximate due to square shape) |
| **Propulsor inlet diameter** | 1.2 | Estimated |
| **Propulsor total wetted area (m$^2$)** | 45 | Estimated (ignored in-fuselage propulsor) |