THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Noise and climate impacts of an unconstrained commercial supersonic network

Authors: Dan Rutherford, Ph.D.; Brandon Graver, Ph.D.; Chen Chen

Date: 30 January 2019

Keywords: supersonic, aviation, noise, CO_2

SUMMARY

Three U.S.-based startups, strongly supported by the current U.S. administration, are working to develop new commercial supersonic transport (SST) aircraft. This paper estimates the environmental impacts of reintroducing commercial SSTs at scale into the global aviation fleet. Using an open source emissions model developed at Stanford University, we model the landing and takeoff (LTO) noise, sonic boom, and carbon dioxide (CO_2) emissions from a new, unconstrained SST network of 2,000 aircraft linking 500 city-city pairs in 2035.

Reintroducing SSTs at this scale would have substantial noise and climate impacts. This fleet would support approximately 5,000 flights per day at 160 airports located predominately in Europe, North America, the Middle East, Asia, and Oceana. Of these flights, 87% are expected to be international, with one-third (33%) being transoceanic. The two busiest airports, Dubai and London Heathrow, could each see more than 300 operations per day. Other airports that could see 100 or more daily SST LTOs include Los Angeles, Singapore, San Francisco, New York-JFK, Frankfurt, and Bangkok. The aircraft could double the area around airports exposed to substantial noise pollution compared to existing subsonic aircraft of the same size.

Substantial parts of the world would experience disruptive sonic booms from the new SST aircraft. Canada, Germany, Iraq, Ireland, Israel, Romania, Turkey, and parts of the United States would experience frequent sonic booms; the most heavily impacted regions could be exposed to between 150 and 200 incidents per day, or up to one boom every five minutes over a hypothetical 16-hour flight day. The SST fleet would emit an estimated 96 (88 to 114) million metric tons (MMT) of CO_2 per year, roughly the combined emissions of American, Delta, and Southwest Airlines in 2017, and an additional 1.6 to 2.4 gigatonnes of CO_2 over their 25-year lifetime. That would consume about one-fifth of the entire carbon budget afforded international aviation under a 1.5°C climate trajectory, assuming that aviation maintains its current share of emissions.

The findings highlight the need for robust standards to manage the noise and climate impacts of commercial SSTs. Aspiring manufacturers could boost the public acceptability of their designs by committing to meet existing environmental standards for subsonic aircraft and by supporting new en route noise standards that would mandate low-boom technology.

INTRODUCTION

In this paper, we analyze the LTO noise, sonic boom, and CO_2 implications of manufacturer goals to sell 2,000 new commercial SST aircraft serving 500 city-city pairs in 2035. We start by introducing recent efforts to revive supersonic flight along with the existing noise and climate impacts of commercial aviation. Next, we describe the methodology we used to identify future commercial SST routes, map the associated sonic booms, and model the fuel burn and CO_2 of that network. Then, we identify the markets, airports, and countries that would be most affected by noise pollution from these aircraft and their annual and lifetime CO_2 emissions. Finally, we close with some policy implications and areas of future research.

Acknowledgements: We thank Anastasia Kharina and Tim MacDonald for help with sonic boom mapping and fuel burn modeling for this paper. Tim Johnson, Vera Pardee, Clare Lakewood, Ben Rubin, Dale Hall, Andrew Murphy, Darren Rhodes, Bryan Comer, Amy Smorodin, and Joe Schultz provided constructive input and feedback on an initial draft. Airline Data Inc kindly provided the dataset used to identify future SST routes. The research was generously funded through the support of the ClimateWorks Foundation.

BACKGROUND

Greenhouse gas emissions and air pollution from commercial aircraft are rapidly increasing. If the global aviation sector was treated as a country, it would have been the sixth largest source of CO_2 from energy use in 2015, emitting more than Germany (Air Transport Action Group, 2017; Olivier, Janssens-Maenhout, Muntean & Peters, 2016). If current trends hold, CO_2 emissions from international aviation are expected to approximately triple by 2050 (International Civil Aviation Organization [ICAO], 2013), potentially accounting for 18% of global anthropogenic emissions if the rest of the world decarbonizes consistent with a 1.5°C emissions trajectory (International Coalition for Sustainable Aviation, 2019).

Low fuel prices have accelerated increases in air travel. CO_2 emissions from U.S. domestic aviation increased 7% from 2014 to 2016 in response to low fuel prices and increased demand (Olmer & Rutherford, 2017), and hit an all-time peak of 162 MMT in 2017 (Graver & Rutherford, 2018). Similar increases are observed globally, with CO_2 emissions increasing to 859 MMT in 2017, up 10% from 2015 levels (Air Transport Action Group, 2017; International Air Transport Association, 2018).

Aircraft noise—which is mainly associated with LTO today but will include sonic booms over most of the flight path if SSTs are reintroduced—poses a serious risk to public health. Exposure to aircraft noise has been linked to sleep disturbance, learning delay in children, mental health problems, heart disease, and annoyance (World Health Organization, 2018; Aviation Environment Federation, 2016). Evidence suggest that the public is increasingly sensitive to airport noise (UK Civil Aviation Authority, 2017). For example, Washington, D.C., metro area airport noise complaints more than doubled from 2016 to 2017, in part due to greater noise exposure linked to changes in flight paths under the FAA's NextGen program (Aratani, 2018).

Three U.S.-based startups are working to develop new SST aircraft. One aspiring manufacturer, Boom Supersonic, is working to bring a 55-seat commercial jet dubbed "Overture" into service by 2025.[1] Boom aims to sell up to 2,000 jets serving a network of 500 city-city pairs (Morris, 2018; Bellamy, 2018). If successful, Boom's aircraft would be the first commercial supersonic jet since the Concorde and the Tu-144, developed by Aerospatiale/BAC and Tupolev, respectively. Only Concorde reached commercial service; it flew its first scheduled supersonic passenger service in 1976 and was retired in 2003.

Concorde was powered by turbojet engines with afterburners, which led to high fuel burn and takeoff noise. Concorde failed commercially due to its high operational costs and operating restrictions linked to its explosive sonic boom, which could reach up to 109 perceived level decibels (PLdB).[2] Sonic boom, which propagates for tens of miles on either side of a supersonic flight path, is an explosive, double-tap shock wave that follows an aircraft whenever it flies faster than the speed of sound. Sonic boom was linked to significant community disturbance in testing over Oklahoma City in 1964 (Borsky, 1965), along with a successful class action lawsuit against the U.S. government over the testing. This led many countries, including the United States in 1973, to ban commercial aircraft from operating at supersonic speeds over land.

The development efforts of emerging SST manufacturers are strongly supported by the Trump administration, which is advocating for permissive international environmental standards for SSTs (Lampert & Freed, 2018). Since 2016, advocates of supersonic flight have pushed to lift existing bans on overland flight in the United States (Weigel, 2016; Hammond, 2017b; Snead, 2018). These advocates won a partial victory in October 2018 when Trump signed the 2018 FAA Reauthorization Act into law. The act includes several provisions related to U.S. domestic standard setting, including a periodic review of whether the overland flight ban can be lifted, but it did not clarify the exact environmental standards that new SSTs would need to meet (Rutherford, 2018b). By 2025, the International Civil Aviation Organization (ICAO), the specialized United Nations agency that regulates international aviation, could develop a full set of environmental standards for SSTs, including for en route noise (sonic boom) and cruise CO_2.

Because emerging SSTs are still under development, relatively little is known about their likely environmental performance. Kharina, McDonnell, and Rutherford (2018) assessed the aircraft-level environmental performance of emerging SSTs using Boom's design as a reference point. That work concluded that emerging commercial SSTs could emit 5 to 7 times as much CO_2 per passenger as comparable subsonic aircraft on equivalent routes, while failing all applicable environmental standards for new subsonic jets. Subsequent analysis concluded that new SSTs are unlikely to achieve fuel burn parity compared with current subsonic business class (Rutherford, 2018a). The sonic boom characteristics of emerging SSTs have not yet been assessed.

1 See boomsupersonic.com. Two other manufacturers—Aerion (https://www.aerionsupersonic.com) and Spike (www.spikeaerospace.com)—are aiming to produce supersonic business jets. These are expected to be less noisy, have fewer deliveries, and be operated fewer hours than commercial SSTs, and so are beyond the scope of this analysis.

2 See Nickol (2018). Another way of expressing sonic boom intensities is via the metric of atmospheric overpressure measured in pounds per square foot (psf). Relative to a baseline atmospheric pressure of 14.7 psf, Concorde recorded an overpressure of 1.94 psf. See National Aeronautics and Space Administration (2017).

METHODOLOGY

In this paper, we model the noise and CO_2 impacts of an unconstrained network of 2,000 new commercial SST aircraft operating over 500 city-city pairs in 2035. As advocated by one manufacturer (Dourado, 2017) and other proponents of supersonic flight (Hammond, 2017a), we assume that overland flight bans are lifted and replaced by en route noise standards that allow the operation of near-term SST designs throughout the globe. Similarly, we assume sufficient capacity for designated airports for these flights, either by increasing throughput or by replacing subsonic flights with SSTs.

Because no commercial SSTs are currently in service, future supersonic routes are identified using existing subsonic operations after taking into consideration factors such as seating class (premium vs. economy), flight distance (stage length), required runway (takeoff field) length, and refueling stops needed for supersonic aircraft to serve long-haul routes. Routes suitable for a 500 city-city pair network were identified using a global set of subsonic operations data for November 2018 provided by Airline Data Inc (2018). That data set, which included information on airport of departure and arrival, carrier name, number of departures, number of seats by cabin class, aircraft type, and flight distance, covered 782,000 flights over 24,000 city-city and aircraft combination pairs.

The top 596 city-city pairs by premium seat count were used to identify 500 potential SST routes after accounting for refueling stops needed for transoceanic service.[3] Several steps were taken to identify premium traffic most suitable for commercial SSTs. First, flights with a distance of less than 1,500 nm (2,800 km) were filtered out because supersonic flights would provide only modest (less than 1 hour) time savings. Second, 12 city-city pairs with flights over 8,100 nautical miles (15,000 km), including Hong Kong to Los Angeles and Singapore to San Francisco, were removed because they would require multiple refueling stops. Third, regional jets and small, single-aisle aircraft (Airbus A320 and smaller) flights were removed to focus on flat-bed premium seating and to exclude airports with runways too short for supersonic service.[4] These filters left in place a dataset of flights with a total of 4.8 million premium seats flown over 2,967 city-city pairs for further analysis.

The second step was to identify 500 city-city pairs using this traffic. Those pairs were sorted by total number of seats offered, ranking from the busiest (London Heathrow to New York-JFK) to the least busy (Delhi to Jeddah) routes. One-way flights between the two city-city pairs were combined to provide a round-trip total. Direct flights under 4,050 nautical miles (7,500 km) were modeled without modification—flights over this length were analyzed further to identify airports for refueling. This is necessary because our reference aircraft has a substantially shorter design range than existing long-haul subsonic aircraft and would require refueling stops for longer transoceanic flights.

To integrate the effect of winds, we assumed that refueling stops would be needed at 90% of the design range of the aircraft, corresponding to 4,050 nautical miles (7,500 km).[5] This principle identified 236 routes requiring refueling stops. Refueling airports were identified using Great Circle Mapper (2019) with the goal of minimizing diversion from great-circle distance and, therefore, dilution of time savings.[6]

LTO noise, sonic boom mapping, and CO_2 emissions of these flights were estimated using the reference SST aircraft developed in Kharina et al. (2018) and modeled using SUAVE, an open source aircraft performance software developed at Stanford University (Stanford Aerospace Design Lab, 2017). That reference aircraft was developed from publicly available data on Boom's "Overture," summarized in Table 1. Full details of the reference aircraft specification, including the best case, most likely, and worse case engine and airframe configurations, can be found in Kharina et al. (2018). The SST aircraft were assumed to be delivered at a rate of 200 per year starting in 2025, and operated an average of 2,777 hours per year, equivalent to a typical subsonic single-aisle aircraft internationally (Rutherford, Singh, & Zeinali, 2011).

We consider two types of noise pollution from supersonics: LTO noise at airports, and en route noise from sonic boom. Communities claim noise impacts from aircraft operating up to 7,000 feet (2,134 meters), although this study examines the impact on the

3 Approximately 600 original subsonic routes were required to identify a network of 500 distinct city-city pairs after accounting for refueling stops. These additional routes were needed because the addition of refueling stops creates duplicate city-city pairs in the analysis.

4 Our reference aircraft has a balanced takeoff field length of 10,000 ft (Kharina et al., 2018). This is comparable to a twin-aisle aircraft but considerably longer than that of small single-aisle aircraft (e.g., Airbus A320 at 6,900 ft) and regional jets (e.g., Embraer E175 at 4,100 ft) See Globalair.com (2018) and Embraer (n.d.).

5 The effect of winds may be that refueling stops are needed in one direction (e.g., westbound flights from California to Japan) between 90% and 100% of design range but not on the return (in this case, eastbound back from Japan). A detailed treatment of this effect is beyond the scope of this study. The overall noise and CO_2 impacts of a new SST network should not be sensitive to this assumption.

6 Great-circle distance is the shortest distance linking two points on the surface of a sphere. Aircraft will typically fly as close as possible to great-circle distance between airports in order to minimize travel time and fuel use.

Table 1. Airframe parameters for the reference SST (Kharina et al., 2018)

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] (m²)	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.

LTO phase of operations up to 3,000 feet (915 meters). International LTO noise standards for aircraft are set by ICAO. Subsonic aircraft are certified in accordance with the latest noise standards issued periodically by ICAO, but there are currently no applicable standards for supersonic aircraft.

One way to understand the noise intensity of emerging SSTs is to consider existing subsonic aircraft standards. Existing noise standards for commercial jets are contained in Annex 16 to the Convention on International Civil Aviation, also known as the Chicago Convention.

Standards denoted as Chapter 3, Chapter 4, and Chapter 14 apply to larger subsonic aircraft certified after December 31 in the years 1977, 2006, and 2017, respectively (European Aviation Safety Agency, the European Environment Agency, & EUROCONTROL [EASA, EEA, and EUROCONTROL], 2016).[7] These standards are set based on "effective perceived noise in decibels," or EPNdB, calculated as the simple sum of noise at three points: fly-over, sideline, and approach.[8]

7 These standards are referred to as Stage 3, 4, and 5 in the United States respectively.

8 Fly-over, measured under the takeoff flight path 6.5 km from the takeoff point, and sideline, the noisiest point recorded within 450 meters from the runway axis, are both meant to characterize takeoff noise. Approach, measured 2 km from the runway under the approach flight path, is meant to approximate noise at landing. See Dickson (2013).

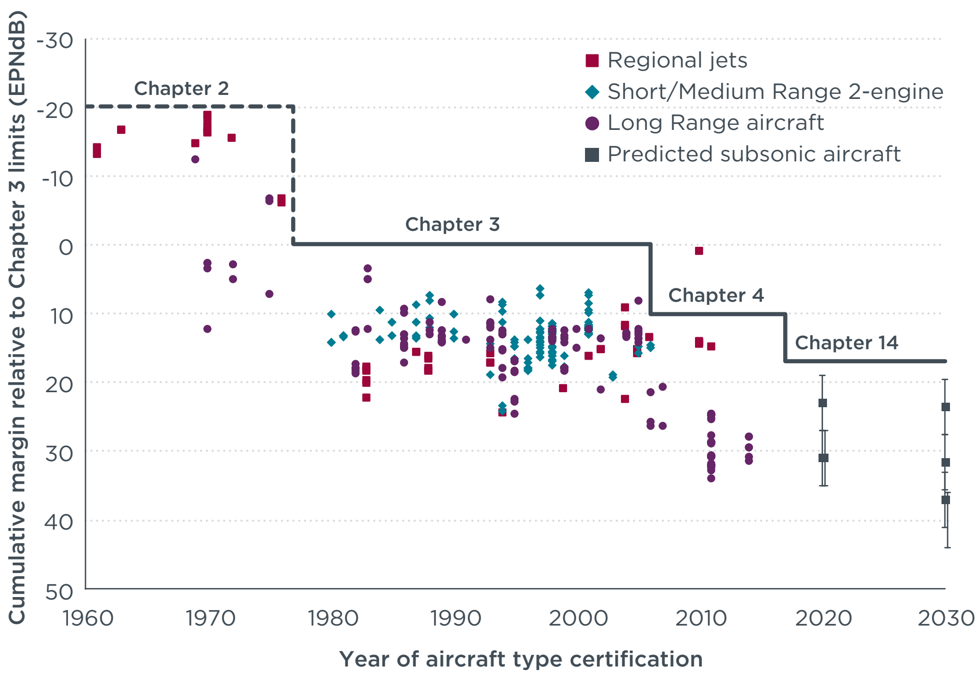

Figure 1. Subsonic aircraft noise performance vs. year of type certification (adapted from EASA, EEA, and EUROCONTROL, 2016)

Figure 1 introduces the relative stringency levels of each of these noise limits versus existing and predicted subsonic jets. Each aircraft type's LTO noise performance is shown as a margin to Chapter 3 limits, which vary by aircraft size but range between 280 and 314 EPNdB. Note the trend in over-compliance: Many subsonic aircraft certified as early as 1980 could already meet or exceed Chapter 4 noise limits, while larger aircraft certified after 2010 were quiet enough to comply with Chapter 14 noise requirements.

The exact LTO noise footprint of emerging commercial SSTs will vary by design and cannot be estimated precisely given that the designs are still in the early development stages. Still, some general observations can be made. Early design studies (Welge et al., 2010) and recent aircraft-level modeling (Kharina et al., 2018) suggest that emerging commercial SSTs would need to adopt special measures, namely modified LTO procedures and engine derating strategies, to meet Chapter 4 noise limits. Those aircraft are unlikely to meet the current Chapter 14 noise standard for subsonics because doing so would require new, more expensive clean sheet engines rather than the derivative engines that are currently under consideration (Norris, 2018).[9] Recent U.S. SST policy assessments (Dourado & Hammond, 2016) and public statements from one manufacturer (Dourado, 2017) indicate a preference that Chapter 3 noise limits be applied to emerging commercial SSTs; we assume in this unconstrained analysis that our representative SSTs meets those limits.[10]

Sonic boom corridors were modeled for the 500 routes using ArcGIS (ESRI, 2019). Great-circle distance routes were identified using GPS Visualizer in GPX format for analysis (Schneider, 2019). We assumed boom corridors of 100 km in width (50 km on either side of the SST aircraft), or roughly one mile for every 1,000 feet in cruise altitude, consistent with National Aeronautics and Space Administration (NASA, 2017), starting at 970 km from the origin airport and ending 570 km from the destination airport. This approximates Concorde's operational profile and somewhat underestimates areas experiencing sonic boom since some of the aircraft's climb and descent would also be operated at supersonic speeds. Sonic booms for the 500 city-city pairs were aggregated into a heat map based upon the Robinson projection.

The precise intensity of the sonic boom from the reference aircraft cannot be predicted without detailed acoustical modeling. Based upon manufacturer claims[11] and preliminary design work completed by Boeing on an aircraft with similar capabilities,[12] a sonic boom intensity on the order of 95 PLdB and 1 pound per square foot (psf) overpressure might be expected. This would be experienced as two explosive, low-frequency impulsive sounds akin to artillery fire or an explosion.[13] NASA research to develop a low-boom demonstrator aircraft with sonic booms as quiet as 75 PLdB, equivalent to the volume of a car door slamming, is ongoing (NASA, 2018) but will not be deployed for near-term SST designs.[14]

For a detailed introduction of the reference aircraft and operational assumptions used for fuel burn modeling, see Kharina et al. (2018). Most likely, best, and worst case configurations corresponding to a derivative turbofan, a clean sheet turbofan, and a derivative turbojet, respectively, were used to estimate fuel burn on 500 routes. Improvements in the lift-to-drag ratio (L/D) were assumed to be +10%, +20%, and no change relative to the Concorde for the most likely, best, and worst configurations, respectively. Takeoff weights were estimated assuming that 60% of available seats were filled with no belly freight carriage.[15] To streamline modeling, existing SUAVE models were parameterized into an Excel format by curve fitting 10 coefficients around three parameters: stage length, payload, and percentage of time in supersonic flight. The Excel model was found to have minimal (~1%) deviations from the initial representative SUAVE model and therefore determined to be fit for the purposes of this calculation.

To compare the estimated SST CO_2 inventory with existing or future

9 This finding may only be appropriate for aircraft aiming for higher supersonic cruise speeds (e.g., above Mach Number 2.0), which will require very high thrust, low bypass ratio engines, making them disproportionately noisy in landing and takeoff. Aerion and Spike, which are developing business SSTs with lower supercruise speeds (MN 1.4 to 1.6), have committed to meeting Chapter 14 noise limits. See Trautvetter (2018) and Phelps (2018).

10 Most recently, Boom has stated that its Overture aircraft "will be as quiet as the subsonic aircraft flying similar routes today" (Boom Supersonic, 2019). This statement references the noise performance of in-service, rather than new, subsonic aircraft. In-service aircraft are currently subject to Chapter 3 noise limits in the United States, Europe, and Japan, making this statement consistent with the assumption that future commercial SSTs will meet Chapter 3 noise limits.

11 Boom claims that its aircraft will produce a sonic boom "at least 30 times quieter than Concorde's" (Boom, n.d.). Assuming this refers to sound intensity, which doubles with every 3 dB increase, that suggests a sonic boom intensity about 15 dB below that of Concorde, which peaked at 109 PLdB.

12 Boeing estimated the sonic boom of a modeled smaller configuration (765-076E), which would carry 30 passengers at MN 1.6 to 1.8, to be between 91 and 100 PLdB with overpressures of about 1 psf. Boeing also estimated that the 765-076E should be able to provide ~91 PLdB through non-linear CFD-based boom optimization. See Welge et al. (2010).

13 Indoors, the boom could lead to a noticeable rattle of windows and doors due to effective outdoor to indoor transmission (Rhodes, 2018).

14 Lockheed-Martin is developing a Quiet Supersonic Transport (QueSST) for NASA to begin collecting data on community response to sonic boom starting in 2023. Separately, preliminary design work completed for NASA by Boeing suggests a fuel burn penalty on the order of 10% for a 5db reduction in perceived boom (Welge et al., 2010). This indicates a tradeoff between en route noise and fuel burn that may limit the uptake of low-boom technologies unless mandated.

15 Historical load factor data for supersonics is limited. 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%. SST fuselage design and high fuel burn will strictly limit belly freight carriage.

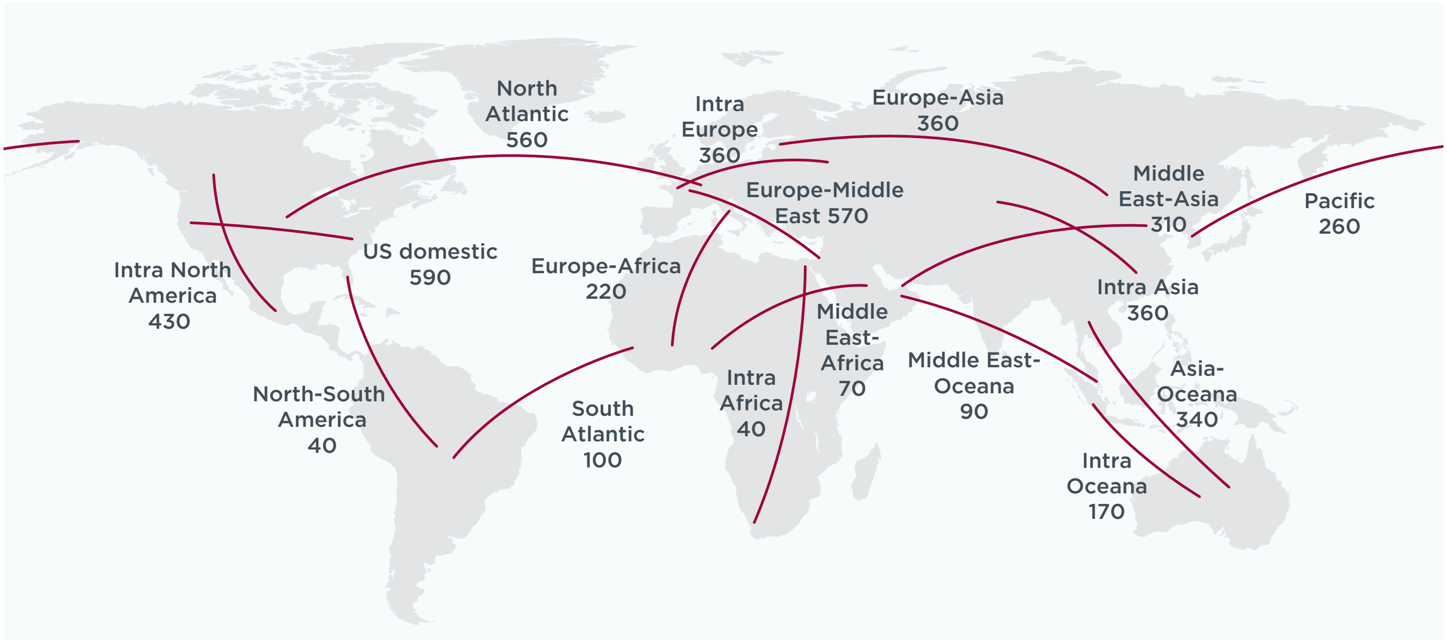

Figure 2. Daily commercial supersonic flights by market

emissions from the subsonic fleet, assumptions needed to be made regarding whether the modeled SST flights represented completely new (induced) flights, if the passengers are diverted completely from subsonic business class, or some combination of the two. Two scenarios are considered here: a "lower impact" scenario where new supersonic trips replace equivalent subsonic trips on a one-to-one basis, and a "higher impact" scenario where all SST flights are assumed to be additional to existing subsonic business class demand. Previous work (Kharina et al., 2018) found that emerging commercial SSTs could be three times as fuel intensive per passenger as comparable subsonic aircraft in a best case scenario. Thus, under the "lower impact" scenario, two-thirds of SST CO_2 is estimated to be additional to the subsonic inventory; for the "higher impact" scenario assuming all induced demand, 100% of the inventory is assumed to be additional.

RESULTS

This section summarizes the key results of this study. We start with an overview of the routes and markets identified, identify key airports where SST aircraft could be operated, present sonic boom intensity maps from those operations, and close with an estimation of annual and lifetime CO_2 emissions from the network identified.

MARKETS AND COUNTRIES SERVED

Two thousand new SSTs serving a network of 500 city-city pairs are expected to generate about 5,000 flights per day. Figure 2 summarizes 17 markets representing about 98% of all projected SST movements. Traffic flows shown by the red lines are region-level and do not represent operations between two specific airports.

Figure 2 highlights the highly international nature of expected SST operations, which would link 160 airports located predominately in Europe, North America, the Middle East, Asia, and Oceana. About 650 (13%) of the daily flights would be domestic flights departing and landing at airports in the same country. The overwhelming majority of these domestic flights (12% of total SST flights) would be in the United States. Of the remaining 4,300 (87%) international flights, roughly one-third are expected to be intracontinental (e.g., intra-Europe), with the remaining two-thirds being intercontinental or transoceanic. Overall, one-third (33%) of projected flights would operate predominately over an ocean.

Three routes—U.S. domestic, Europe to the Middle East, and North Atlantic,—would each account for about 12% of total SST flights, with intra-North America, intra-Europe, intra-Asia, and Asian to Oceana routes also being major markets. Smaller markets, including Intra-Africa, North to South America, Middle East to Africa, Middle East to Oceana, South Atlantic, Intra-Oceana, and Europe to Africa, are each expected to account for between 1% and 4% of the predicted traffic.

Table 2 summarizes the annual SST movements by country of departure, both for individual countries and cumulative share. The top five countries—the United States, United Kingdom, United Arab Emirates, China, and Russia[16]—would represent about one-half of all movements. More than a quarter of all SST flights would depart from U.S. airports. Other major countries include Japan (about 4% of movements), India (also 4%), and Germany, Singapore, and France, each with about 3% of all flights.

Table 2. Commercial supersonic transport movements by departure country in 2035

Rank	Country	Movements/day	Share of Movements	Cumulative share of Movements
1	**United States**	1317	27%	27%
2	**United Kingdom**	351	7%	34%
3	**United Arab Emirates**	322	7%	40%
4	**China**	237	5%	45%
5	**Russia**	215	4%	49%
6	**Japan**	183	4%	53%
7	**India**	183	4%	57%
8	**Germany**	158	3%	60%
9	**Singapore**	140	3%	63%
10	**France**	132	3%	65%
11	**Thailand**	121	2%	68%
12	**Canada**	119	2%	70%
13	**Australia**	118	2%	73%
14	**Qatar**	92	2%	74%
15	**South Korea**	86	2%	76%
16	**Turkey**	85	2%	78%
17	**Netherlands**	74	1%	79%
18	**Malaysia**	66	1%	81%
19	**Indonesia**	62	1%	82%
20	**Switzerland**	50	1%	83%
	Other	844	17%	100%
	Total	**4,954**	**100%**	

AIRPORTS AND LTO NOISE

Table 3 summarizes the 25 busiest airports by flights in this network. Daily movements (landings and takeoffs) by airport, along with the cumulative share, are shown. "Transit" airports, defined as airports where more than 75% of available seats would come from refueling stops, are not broken out given the uncertainty about exactly where those refueling operations would occur.[17]

Dubai and London Heathrow are expected to be the two busiest airports, accounting for 7% and 6%, respectively, of daily SST movements. Following those would be Los Angeles, with about 180 daily movements, or about 4% of the global total. The next busiest airports—Singapore, San Francisco, New York-JFK, Frankfurt, and Bangkok—are each expected to field less than half as many flights as those two major hubs. In total, the 25 busiest airports shown in Table 3 would account for more than half of all supersonic operations. Five of the top 25 busiest airports, and 12 of the top 50, would be in the United States.

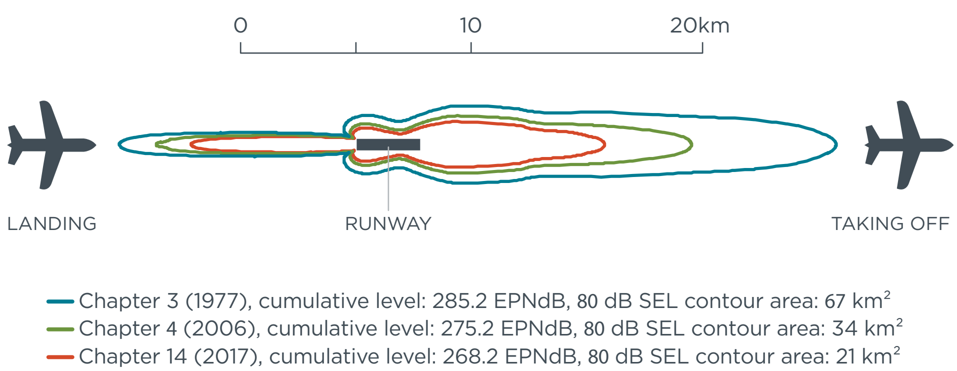

Figure 3. 80 dB Sound exposure level contours for 75-tonne aircraft just meeting the various ICAO chapter limits (adapted from EASA, EEA, and EUROCONTROL, 2016).

These movements, combined with the large noise footprint of emerging SSTs, could substantially increase perceived noise at high-volume airports. Figure 3 provides an illustrative example of how the noise footprint, in terms of area exposed to 80 dB sound exposure levels (SEL), of a typical 75-tonne maximum takeoff mass (MTOM) Chapter 3-compliant aircraft (blue) compares with an aircraft complying with Chapter 4 (green), and Chapter 14 (red) noise limits. The area exposed to this level of aircraft noise by a typical Chapter 3 aircraft is twice that of a Chapter 4 aircraft, and more than three

16 Russian flights would be attributable in large part to its airports becoming key supersonic refueling stops between Europe and Asia.

17 Examples include Ted Stevens Anchorage International Airport in Alaska; Moscow's Sheremetyevo International Airport; and Minneapolis-Saint Paul International Airport in Minnesota. Refueling stops would account for 100%, 90%, and 94% of available seats for those airports, respectively.

times as much area as a Chapter 14 compliant aircraft.

The relative magnitude of this increased noise exposure on local communities will vary by airport. As an example, in 2017, our second busiest potential SST airport, London Heathrow, had a total of 1,273 subsonic movements per day (UK Civil Aviation Authority, 2018). Of those, 730 (57%) were single-aisle variants of the A320 family comparable in size to our reference SST (60 to 97 tonnes MTOM). The large majority (87%) of those certified variants are Chapter 4 aircraft (European Aviation Safety Administration, n.d.). In 2015, Chapter 3 compliant aircraft represented about 1% of total operations in Heathrow (GreenAir Communications, 2017), and the airport has the goal of making all operations Chapter 4 noise compliant by 2020 (Heathrow Airport Limited, 2016). The addition, or substitution, of more than 300 Chapter 3 compliant SST operations per day at Heathrow would clearly conflict with this goal.

SONIC BOOM

The 500 city-city pairs were used to identify sonic boom corridors assuming a 100 km wide boom carpet (50 km on either side of the SST aircraft), assuming that existing overland SST flight bans are lifted. The resulting global map is shown in Figure 4. Airports served in the network are depicted as red dots, with the number of sonic booms experienced per day indicated by the colors in the heat map. The 25 busiest airports by SST movements summarized in Table 3 are labeled by their airport codes.

Table 3. Commercial supersonic transport movements by airport in 2035

Rank	Airport	Movements/ day	Share of Movements	Cumulative share of movements
1	**Dubai International (DXB)**	322	7%	7%
2	**London Heathrow (LHR)**	314	6%	13%
3	**Los Angeles (LAX)**	181	4%	16%
4	**Singapore Changi (SIN)**	140	3%	19%
5	**San Francisco (SFO)**	140	3%	22%
6	**New York (JFK)**	126	3%	25%
7	**Frankfurt (FRA)**	125	3%	27%
8	**Bangkok International (BKK)**	113	2%	29%
9	**Paris Charles de Gaulle (CDG)**	97	2%	31%
10	**Hamad International (DOH)**	92	2%	33%
11	**Indira Gandhi International (DEL)**	91	2%	35%
12	**Hong Kong (HKG)**	89	2%	37%
13	**Istanbul Atatürk (IST)**	85	2%	39%
14	**Tokyo Narita (NRT)**	84	2%	40%
15	**Seoul Incheon (ICN)**	84	2%	42%
16	**Amsterdam Schiphol (AMS)**	74	1%	44%
17	**Beijing Capital (PEK)**	73	1%	45%
18	**Kuala Lumpur (KUL)**	66	1%	46%
19	**Sydney (SYD)**	63	1%	48%
20	**Shanghai Pudong (PVG)**	62	1%	49%
21	**Mumbai (BOM)**	62	1%	50%
22	**Tokyo Haneda (HND)**	58	1%	51%
23	**Chicago O'Hare (ORD)**	56	1%	52%
24	**Newark International (EWR)**	52	1%	53%
25	**Toronto Pearson (YYZ)**	50	1%	55%
Other[1]		2255	45%	100%
	Total	**4,954**		

[1]: Other includes "transit" airports, defined as 75% or more of available seats being from refueling stops.

Several clarifications are in order. Blank areas in the map surrounding some of airports served are due to the distances needed to accelerate to and decelerate from supersonic speeds. Furthermore, the map represents an approximation of actual operations because some flights are likely to deviate from great-circle distance tracks due to weather and airspace constraints and also because aircraft might be operated at subsonic speeds to avoid sonic boom over certain areas. The latter would reduce the absolute incidence of sonic boom while diluting SST time savings and commercial advantages; the former effect would reduce the frequency of booms experienced along direct flight paths but expand the total area affected.

Figure 4 highlights that significant areas of the world would be impacted by en route noise pollution. Countries most impacted by sonic boom could include Canada, Germany, Iraq, Ireland, Israel, Romania, Turkey, and the United States. The most heavily impacted regions could be exposed to between 150 and 200 distinct booms per day, or up to one boom every five minutes over a hypothetical 16-hour flight day. This equals about 20 times the number of booms that Oklahoma City residents experienced each day during the 1964 supersonics testing campaign (Borsky, 1965).

Figures 5 and 6 provide regional maps of sonic boom incidence for Europe and North America, respectively. Airports served are indicated by their airplane symbol; those falling within the top 25 in terms of SST movements are labelled with their airport code.

As shown in Figure 5, Europe would be heavily impacted by sonic boom if 2,000 new SSTs are brought into service. Operations departing or landing in London Heathrow, particularly to and from Dubai, would expose parts of Ireland, Germany, Austria, Hungary, Romania, and Turkey to between 150 and 200 sonic booms per day after combining with other cross-European traffic. Average frequency would be about one boom every 5 minutes over a typical day. More moderate but still substantial impacts, on the order of at least one boom every 20 minutes, would be experienced throughout most of Germany and Eastern Europe. Scandinavian and southern European countries, including Spain, Portugal, and Italy, would be less affected.

Significant sonic boom exposure would also be felt in North America (Figure 6). Newfoundland and Nova Scotia in Canada, and coastal Maine in the United States, would experience the largest impacts. In the Mountain West and Great Plains, parts of Arizona, Colorado, Nebraska, and Utah plus Western Alaska would experience sonic booms about every six to 10 minutes (100 to 150 times daily), while much of the Midwest, Oregon, and western Alaska would experience a sonic boom at roughly 20-minute intervals (50 times per day). Other states, including California, Florida, and Hawaii, would experience little or no sonic boom, although exposure to LTO noise at their airports could be significant (see Table 3).

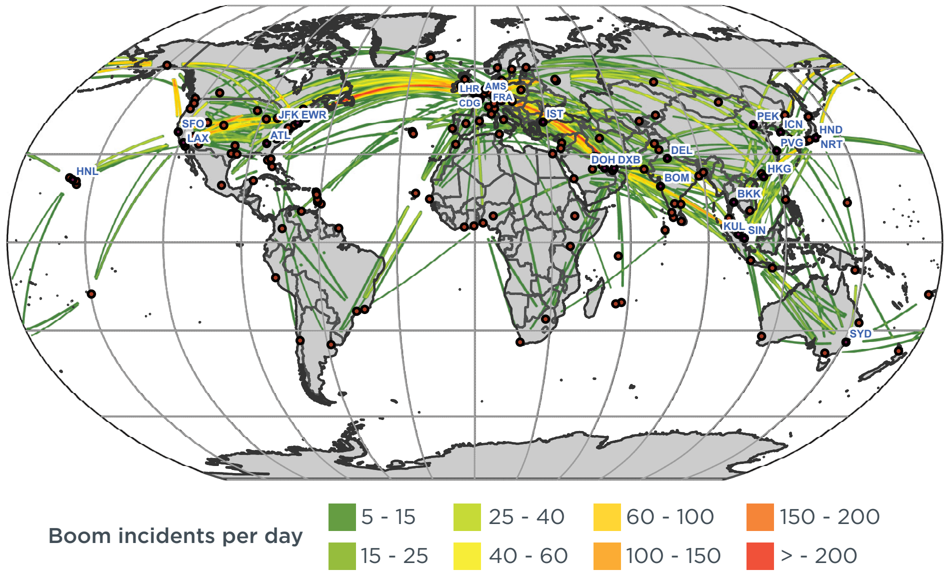

Figure 4: Global sonic boom incidence

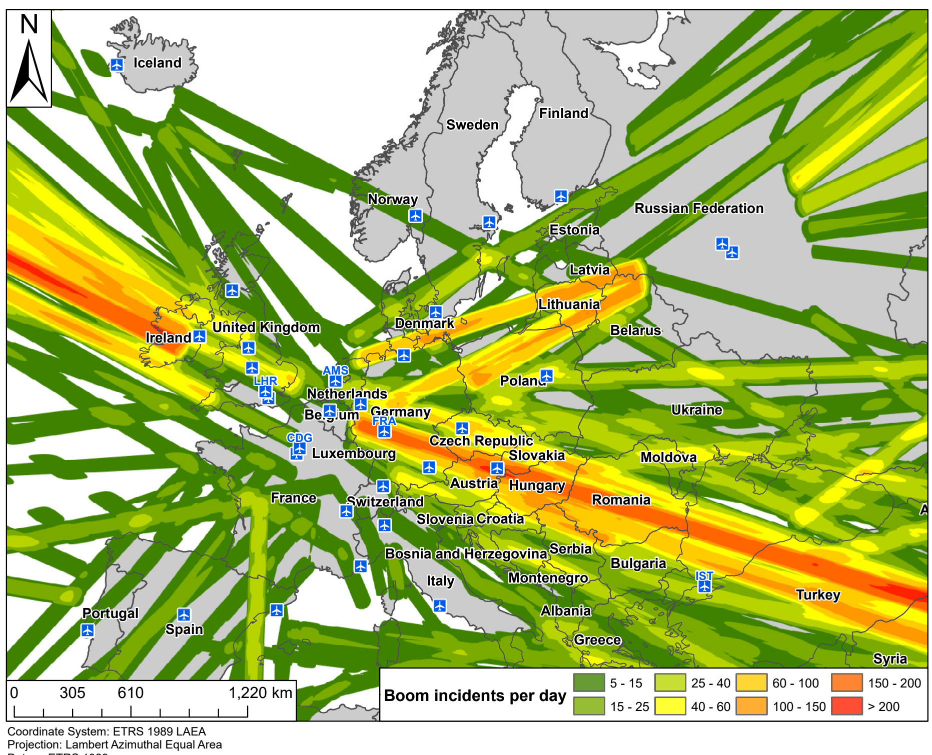

Figure 5: Sonic boom incidence in Europe

FLEETWIDE CO_2

Two thousand commercial SSTs would emit an estimated 96 MMT of CO_2 per year in 2035 (88 MMT CO_2 to 114 MMT CO_2 for best and worst configurations, respectively). Compare that with the 162 MMT CO_2 emitted by U.S. airlines in 2017 (Graver & Rutherford, 2018). Under the "higher impact" induced demand scenario, all of these emissions would be in addition to the emissions from the existing subsonic fleet; under the "lower impact" scenario, which assumes complete substitution from subsonic business class, SSTs would add 64 MMT CO_2 (59 to 76 MMT CO_2) to the existing subsonic inventory.

To put this into perspective, 64 MMT roughly equals the combined CO_2 emissions of American and Southwest Airlines in 2017 (red planes, Figure 7); adding Delta (pink planes) approximates the 96 MMT projected under the "higher impact" scenario. As another point of reference, Lufthansa Group—Europe's largest combination of carriers representing Lufthansa, Lufthansa Cargo, SWISS, Austrian, Eurowings, Brussels Airlines, and their subsidiaries—emitted about 30 MMT CO_2 in 2017 (Lufthansa, 2018).

Table 4 shows the breakdown of CO_2 emitted by country of departure, taking into account those airports that the aircraft will be operated from.

As shown in the table, one-quarter (24%) of SST CO_2 emissions would be attributable to flights departing from U.S. airports. Other major CO_2 emitters by country of departure would include the United Kingdom, United Arab Emirates, China, and Russia; collectively, those five countries would be responsible for about half of all supersonic CO_2 emitted. Other countries, including India, Japan, Singapore, France, Germany, and Australia, would each be responsible for about 3% of supersonic CO_2 emitted. The top 20 countries, rounded out by Indonesia and Brazil, would account for more than 80% of total supersonic CO_2 produced.

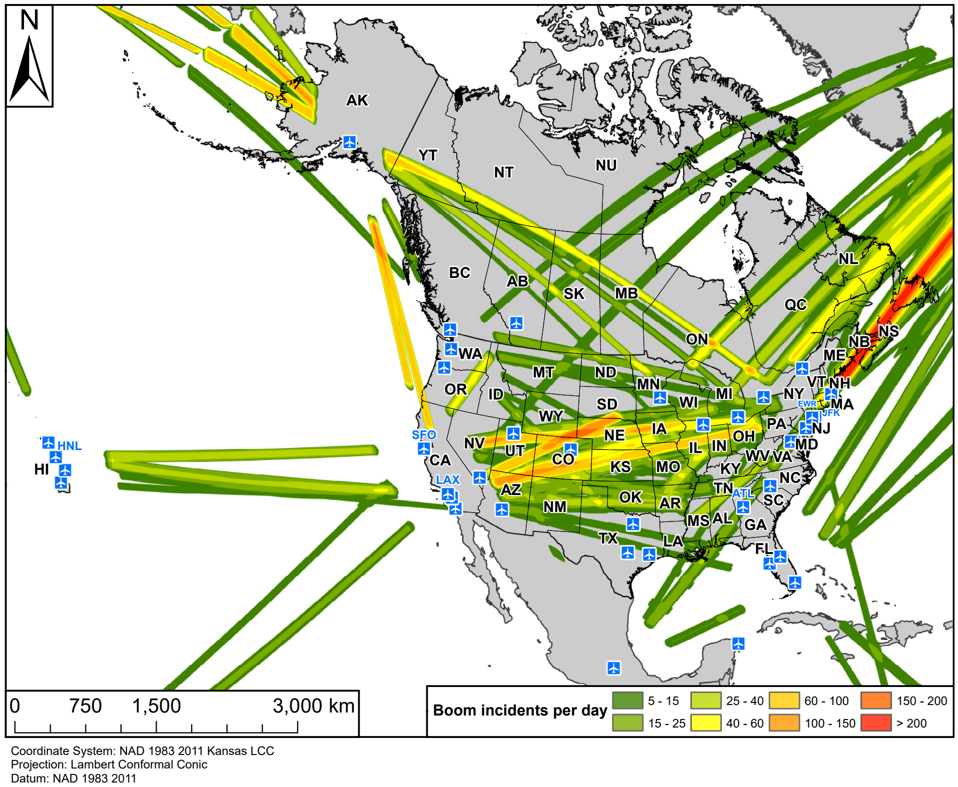

Figure 6: Sonic boom incidence in North America

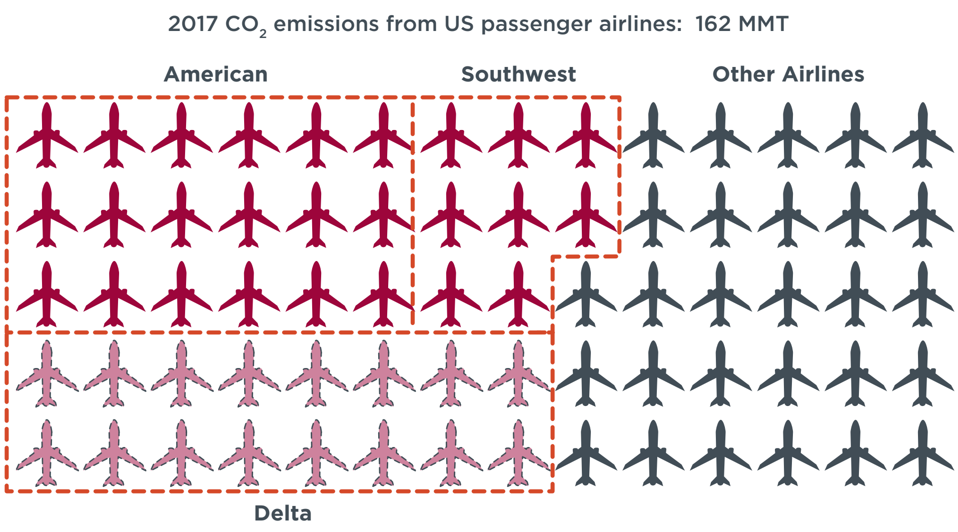

Figure 7. 2035 commercial supersonic transport aircraft vs. 2017 U.S. aviation CO_2 emissions

These increased emissions would be significant. A new fleet of emerging SST could emit an estimated 1.6 to 2.4 gigatonnes of CO_2 over their 25-year lifetime, depending on assumptions about induced versus substituted demand. This would make even more challenging industry's goal of halving net CO_2 emissions from aviation from 2005 levels by 2050 (International Air Transport Association, 2018), let alone meeting the wider societal challenge of getting global emissions to net zero of the second half of the century (Intergovernmental Panel on Climate Change [IPCC], 2018). This range of emissions represents about one-fifth of a proportional carbon budget afforded international aviation under a 1.5°C carbon budget consistent with the Paris climate accord.[18]

Table 4. Commercial supersonic transport aircraft CO_2 by country of departure, 2035

Rank	Country	CO_2 (MMT)	Share of CO_2	Cumulative share of CO_2
1	United States	23.4	24%	24%
2	United Kingdom	7.6	8%	32%
3	United Arab Emirates	6.9	7%	40%
4	China	5.1	5%	45%
5	Russia	3.8	4%	49%
6	India	3.6	4%	53%
7	Japan	3.5	4%	56%
8	Singapore	2.9	3%	59%
9	France	2.8	3%	62%
10	Germany	2.7	3%	65%
11	Australia	2.6	3%	68%
12	Thailand	2.2	2%	70%
13	Canada	2.1	2%	72%
14	Qatar	1.9	2%	74%
15	South Korea	1.9	2%	76%
16	Netherlands	1.6	2%	78%
17	Turkey	1.4	1%	79%
18	Malaysia	1.4	1%	81%
19	Indonesia	1.3	1%	82%
20	Brazil	1.0	1%	83%
		16.1	17%	100%
	Total	**96**	**100%**	

CONCLUSIONS AND NEXT STEPS

This analysis highlights the need for robust environmental standards to manage the expected noise and CO_2 impacts of reintroducing commercial SSTs. The estimated 5,000 SST flights per day in 2035 could lead to more than 100 Chapter 3 noise flights being introduced at each of eight airports globally. Large regions of the globe could be exposed to sonic booms at a frequency of more than once per hour. Increasing CO_2 emissions from these aircraft could make it even more challenging for industry to achieve its climate goals. International standards will be needed given that 87% of projected flights would depart one country and land in another.

ICAO is initiating work on SST standards for LTO noise, air pollution, sonic boom, and cruise CO_2. A full set of standards may be finalized by 2025 and take effect before 2030. Regulators are faced with two choices: either to develop new SST standards that would allow those aircraft to produce more noise, air pollution, and climate pollution than new subsonic designs, or to apply existing subsonic standards to SSTs. Aspiring SST manufacturers could boost public acceptance for their designs by committing to meet existing LTO noise and cruise CO_2 standards for subsonic aircraft and by supporting new en route noise standards that would mandate low-boom technology. Lacking these commitments, manufacturers may find it difficult to access additional capital to finalize their aircraft designs: to date, Boom has raised about $141 million (Bogaisky, 2019), or about 2% of the $6 billion it estimates will be needed to fully develop its aircraft (Adams, 2018).

Additional research is needed to improve our understanding of the environmental implications of reintroducing supersonic flight. This analysis represents an initial, unconstrained modeling approach assuming no overland flight bans or local airport restrictions. If those restrictions instead remain in place, some fraction of the actual noise and pollution impacts of new SST designs will be mitigated, for several reasons. First, as noted above, noise-constrained airports may be unable to absorb the indicated flights. Second, overland flight bans would limit

18 According to Olivier et al. (2016), international aviation emitted 503 MMT of CO_2 in 2015, or 1.42% of the global energy-related total. IPCC's recommended carbon budget to allow a 66% chance of meeting a 1.5 degree climate target after 2015 is about 620 gigatonnes (IPCC, 2018; simple average of the AR5 and GMST global temperature approaches). A simple multiplication of these factors equals international aviation's proportional share of 8.8 gigatonnes.

the viability of some routes, leading to lower overall market share. Related, the need to refuel longer flights, for example between East Asia and North America, may reduce time savings enough to make those routes unviable commercially. Further work to test these assumptions for robustness, and also to refine assumptions about induced versus substituted demand, is needed.

Other work is also needed to fill in our understanding of these aircraft. This includes economic analysis to determine expenses, fares, and yields on representative routes. High-fidelity noise and emissions modeling at key airports is recommended, both at the commercial hubs highlighted in this paper but also general aviation airports (e.g., Teterboro) that may host supersonic business jets. Likewise, a comprehensive analysis of the climate impacts of these aircraft is recommended. Non-CO_2 climate forcers, including water vapor, nitrogen oxides, black carbon, and aviation-induced cloudiness are expected to be significant given the high cruise altitude of SSTs (IPCC, 1999).

REFERENCES

Adams, E. (2018, November 15). The Baby Boom charts a return to supersonic flight. *Wired*. Retrieved from https://www.wired.com/story/boom-aerospace-baby-boom-demonstrator-supersonic/

Air Transport Action Group (2017). Facts and figures. Retrieved from https://www.atag.org/facts-figures.html

Airline Data Inc. (2018). *The Hub* [Flight schedules data.] Accessible at http://www.airlinedata.com

Aratani, L. (2018, November 23). Complaints about noise from Washington-area airports skyrocket. *The Washington Post*. Retrieved from https://www.washingtonpost.com/local/trafficandcommuting/complaints-about-noise-from-washington-area-airports-skyrocket/2018/11/23/d578951c-ece7-11e8-96d4-0d23f2aaad09_story.html

Aviation Environment Federation. (2016). Aircraft noise and public health: The evidence is loud and clear. Retrieved from https://www.aef.org.uk/uploads/Aircraft-Noise-and-Public-Health-the-evidence-is-loud-and-clear-final-reportONLINE.pdf

Bellamy, W. (2018, November 13). Aerion, Boom taking different paths to supersonic economics. *Avionics International*. Retrieved from https://www.aviationtoday.com/2018/11/13/aerion-boom-taking-different-paths-supersonic-economics/

Bogaisky, J. (2019, January 4). Boom raises $100M to develop a supersonic airliner. It's going to need a whole lot more. *Forbes*. Retrieved from https://www.forbes.com/sites/jeremybogaisky/2019/01/04/boom-raises-100m-to-develop-supersonic-jet-its-going-to-need-a-lot-more/#583e563877e*3*

Boom Supersonic. (2019). *Boom Supersonic closes $100 million Series B to develop Overture, its revolutionary Mach-2.2 airliner* [Press release]. Retrieved from https://s3-us-west-2.amazonaws.com/boom-press-assets/Series+B+Announcement+-+Press+Release+-+English.pdf

Boom Supersonic. (n.d.) Frequently asked questions: Environment. Retrieved from *https://boomsupersonic.com/contact#faq-section*.

Borsky, P. (1965). Community reactions to sonic booms in the Oklahoma City area. *National Opinion Research Center New York*. Retrieved from https://apps.dtic.mil/docs/citations/AD0613620

Dickson, N. (2013, May). *ICAO noise standards*. Presentation at the ICAO Symposium on Aviation and Climate Change, "Destination Green." Retrieved from https://www.icao.int/Meetings/Green/Documents/day%201pdf/session%202/2-Dickson.pdf

Dourado, E., & Hammond, S. (2016). Make america boom again: How to bring back supersonic transport.Retrieved from the Mercatus Research website: https://www.mercatus.org/system/files/mercatus-dourado-supersonic-transport-v1.pdf

Dourado, E. (2017, June 27). *Lee-Gardner Amendment would reduce supersonic fuel burn by 20 percent or more* [Blog post].Retrieved from https://blog.boomsupersonic.com/lee-gardner-amendment-would-reduce-supersonic-fuel-burn-by-20-percent-or-more-34a189465af4

Embraer. (n.d.). E175 specifications. Retrieved from https://www.embraercommercialaviation.com/wp-content/uploads/2017/02/Embraer_spec_175_web.pdf

ESRI. (2019). *ArcGIS* [Software]. Accessible at https://www.arcgis.com

European Aviation Safety Administration. (n.d.) EASA certification noise levels. Retrieved from https://www.easa.europa.eu/easa-and-you/environment/easa-certification-noise-levels

European Aviation Safety Agency, the European Environment Agency, & EUROCONTROL. (2016). European aviation environmental report 2016. (ISBN 978-92-9210-197-8). Retrieved from https://ec.europa.eu/transport/sites/transport/files/modes/air/aviation-strategy/documents/european-aviation-environmental-report-2016-72dpi.pdf

FAA Reauthorization Act of 2018, H.R. 302, 115th Cong. (2018) Retrieved from: https://www.congress.gov/bill/115th-congress/house-bill/302/text

Global Aviation Navigator. (2018). Airbus A320 technical specifications. Retrieved from *https://www.globalair.com/aircraft-for-sale/Specifications?specid=639*

Graver, B., & Rutherford, D. (2018). U.S. passenger jets under ICAO's CO_2 standard, 2018-2038 [Working paper]. Retrieved from the The International Council on Clean Transportation website: *https://www.theicct.org/publications/us-passenger-jets-icao-CO2-standard*.

Great Circle Mapper. (2019). *Great Circle Mapper* [Website]. Accessible at http://www.gcmap.com

GreenAir Communications. (2015, January 15). Heathrow sets out blueprint for tackling aircraft noise as Qatar's all-new Airbus A350 XWB makes its London debut. *GreenAir Online*. Retrieved from http://www.greenaironline.com/news.php?viewStory=2029

Hammond, S. (2017a, February 28). The business case for supersonic overland. Retrieved from the Niskanen Center website: https://niskanencenter.org/blog/supersonic-overland/

Hammond, S. (2017b, June 28). In support of the Lee-Gardner Amendment to overturn the ban on supersonic overland. Retrieved from the Niskanen Center website: https://niskanencenter.org/blog/support-lee-gardner-amendment-overturn-ban-supersonic-overland/

Heathrow Airport Limited. (2016). Environmental noise directive noise action plan 2013-2018. Retrieved from https://www.heathrow.com/file_source/HeathrowNoise/Static/Noise_Action_Plan_Oct_2016.pdf

Intergovernmental Panel on Climate Change. (1999). Aviation and the global atmosphere. Retrieved from https://www.ipcc.ch/report/aviation-and-the-global-atmosphere-2/

Intergovernmental Panel on Climate Change. (2018). Global warming of 1.5°C. [Special report]. Retrieved from http://ipcc.ch/report/sr15/

International Air Transport Association. (2018). Fact sheet: Climate change & CORSIA. Retrieved from https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-climate-change.pdf

International Civil Aviation Organization. (2013). Present and future trends in aircraft noise and emissions [Working paper]. (A38-WP/26). Retrieved from https://www.icao.int/Meetings/a38/Documents/WP/wp026_en.pdf.

International Coalition for Sustainable Aviation. (2019). Assessing the need for a long-term climate goal for international aviation. Submission to the 11th meeting of ICAO's Committee for Aviation Environmental Protection. CAEP/11-IP/25.

Kharina, A., McDonnell, T., &Rutherford, D. (2018). *Environmental performance of emerging supersonic transport aircraft* [Working paper]. Retrieved from the International Council on Clean Transportation website: https://www.theicct.org/publications/environmental-performance-emerging-commercial-supersonic-aircraft.

Kingsley-Jones, M. (2002, February 12). BA cautious on Concorde plans. Retrieved from the Flight Global website: www.flightglobal.com/news/articles/ba-cautious-on-concorde-plans-143024/.

Lampert, A., & Freed, J. (2018, July 12). Exclusive: U.S. and Europe clash over global supersonic jet noise standards. *Reuters*. Retrieved from https://www.reuters.com/article/us-airplane-supersonic-usa-exclusive/exclusive-u-s-and-europe-clash-over-global-supersonic-jet-noise-standards-idUSKBN1K21YQ

Lufthansa Group. (2018). Balance: Sustainability report (Issue 2018). Retrieved from https://www.lufthansagroup.com/fileadmin/downloads/en/responsibility/LH-sustainability-report-2018.pdf

Morris, H. (2018, July 27). 2000 supersonic jets to link hundreds of cities with more affordable tickets. *Australian Financial Review*. Retrieved from https://www.afr.com/business/transport/aviation/2000-supersonic-jets-to-link-hundreds-of-cities-with-more-affordable-tickets-20180727-h137ay

National Aeronautics and Space Administration. (2017). *NASA Armstrong fact sheet: Sonic booms*. Retrieved from https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-016-DFRC.html

National Aeronautics and Space Administration. (2018, November 19). *NASA's quiet supersonic technology project passes major milestone* [Press release]. Retrieved from https://www.nasa.gov/press-release/nasa-s-quiet-supersonic-technology-project-passes-major-milestone/

Nickol, C. (2018, February 27). NASA Low Boom Flight Demonstration (LBFD) Project Overview. Presentation at Aviation Noise & Emissions Symposium in Long Beach, California. Retrieved from https://aqrc.ucdavis.edu/sites/g/files/dgvnsk1671/files/inline-files/Craig_Nickol%20LBFD%20Overview%20for%20NE%20Symp%202%2027%2018%20rev4.pdf

Norris, G. (2018, July 10). Boom focuses on derivative engines for supersonic airliner plan. *Aviation Week & Space Technology*. Retrieved from http://aviationweek.com/propulsion/boom-focuses-derivative-engines-supersonic-airliner-plan

Olivier J.G.J., Janssens-Maenhout, G., Muntean, M., and Peters, J.A.H.W. (2016). *Trends in global CO_2 and total greenhouse gas emissions: 2016 report*. PBL Netherlands Environmental Assessment Agency, The Hague. (PBL publication number: 2315). European Commission, Joint Research Centre (JRC Science for Policy Report: 1034). Retrieved from http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf

Olmer, N., & Rutherford, D. (2017). *U.S. domestic airline fuel efficiency ranking, 2015-2016* [White paper]. Retrieved from the International Council on Clean Transportation website: http://www.theicct.org/publications/us-domestic-airline-fuel-efficiency-ranking-2015-16

Phelps, M. (2018, October 15). Aerion unveils Stage 5 GE Affinity engine for supersonic AS2. *AIN Online*. Retrieved from https://www.ainonline.com/aviation-news/business-aviation/2018-10-15/aerion-unveils-stage-5-ge-affinity-engine-supersonic-as2

Rhodes, D. (2018, December 19). Personal communication (email).

Rutherford, D. (2018a, September 28). *New supersonic transport aircraft: Fuel burn parity, or environmental parody?* [Blog post] Retrieved from the International Council on Clean Transportation website: https://www.theicct.org/blog/staff/new-supersonic-transport-aircraft-fuel-burn-parity-or-environmental-parody

Rutherford, D. (2018b, October 10). *Death, taxes, and supersonic aircraft? Considering what's certain, and what isn't, under the FAA Reauthorization Act* [Blog post]. Retrieved from the International Council on Clean Transportation website: https://www.theicct.org/blog/staff/death-taxes-and-supersonic-aircraft

Rutherford, D., Singh, N., & Zeinali, M. (2011). Projection of aviation energy use and related characteristics—methodology and final report. [Consultant report to Argonne National Laboratory]. International Council on Clean Transportation. Washington, D.C.

Schneider, A. (2019). *GPS Visualizer* [Website]. Accessible at www.gpsvisualizer.com/calculators

Snead, J. (2018, June 6). *It's time to let supersonic flight soar again* [Commentary]. Retrieved from The Heritage Foundation website: https://www.heritage.org/transportation/commentary/its-time-let-supersonic-flight-soar-again

Stanford Aerospace Design Lab. (2017). *SUAVE* [Software]. Accessible at http://suave.stanford.edu

UK Civil Aviation Authority. (2017). *Survey of noise attitudes 2014: Aircraft*. Retrieved from https://publicapps.caa.co.uk/docs/33/CAP%201506%20FEB17.pdf

UK Civil Aviation Authority. (2018). *Heathrow Airport 2017 summer noise contours and noise action plan contours*. (ERCD Report No. 1801). Retrieved from https://www.heathrow.com/file_source/HeathrowNoise/Static/Heathrow_Airport_2017_Summer_Noise_Contours_and_Noise_Action_Plan_Contours.pdf

Trautvetter, C. (2018, September 4). Spike aims for Stage 5-compliant supersonic bizjet. *AIN Online*. Retrieved from https://www.ainonline.com/aviation-news/business-aviation/2018-09-04/spike-aims-stage-5-compliant-supersonic-bizjet

Weigel. D. (2016, December 15). House conservatives want Trump to undo regulations on climate, FDA, Uber. *The Washington Post*. Retrieved from https://www.washingtonpost.com/news/post-politics/wp/2016/12/15/house-conservatives-want-trump-to-undo-regulations-on-fda-climate-uber/?utm_term=.c962495d3226

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). Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100030607.pdf

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

World Health Organization. (2018). *Environmental noise guidelines for the European region*. (ISBN 978 92 890 5356 3(. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0008/383921/noise-guidelines-eng.pdf?ua=1