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Environmental limits on supersonic aircraft in 2035

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Summary

There is renewed interest in reviving supersonic aircraft travel, with startups working to bring new designs to market as soon as 2029. In order to meet regulatory requirements and market expectations, those aircraft will need to operate within noise and climate constraints such as bans on supersonic flight over land in key markets. Moreover, government and industry commitments to net-zero aviation have led to pledges by supersonic manufacturers and their launch customers to operate supersonic aircraft on "e-kerosene" generated from renewable electricity.

This study investigates the market potential and atmospheric impacts of two potential supersonic transport (SST) aircraft: a small jet ("Small SST") seating 15 passengers and designed for 140% the speed of sound (MN 1.4), and a larger airliner ("Large SST") seating 75 and operating at MN 1.7. We model the potential market and climate impacts of both aircraft without environmental constraints, and then under noise and climate constraints. Using a modeling suite from the MIT Laboratory for Aviation and the Environment, we project the number of SSTs, potential operations, and overall fuel burn under four scenarios in 2035. We then employ the GEOS-Chem global chemistry transport model to derive the radiative forcing (RF) impact of ozone, water vapor, methane, and black carbon and sulfate aerosols from those operations. Finally, results are compared to the projected baseline for subsonic aircraft in 2035.

We find that environmental limits will sharply constrain the potential supersonic market. For the unconstrained case, we find a potential market for 130 (small) to 240 (large) supersonic aircraft under the base economic case in 2035, providing up to 0.6% of available seat kilometers that year. Under noise and climate constraints, the 2035 potential market falls by 95% to 100%; for all but the most optimistic economic case, we project that airlines will be unable to operate SSTs profitably with overland flight restrictions or using e-kerosene. The SSTs investigated are expected to burn 7 to 9 times

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more fuel per seat-km flown than the subsonic baseline; combined with the high price of e-kerosene, this results in a 25-fold increase in the cost of fuel relative to subsonic aircraft operated on conventional fossil jet fuel.

We then modeled the atmospheric impacts of a hypothetical case where e-fuels could be produced at cost parity with fossil jet fuel (Jet A). E-fuels can reduce lifecycle CO_2 emissions by about 90% compared to Jet A, but their use in supersonic aircraft would only modestly reduce (6 to 24%) CO_2 per seat kilometer compared to more fuel-efficient subsonic designs operating on Jet A. We find significant tradeoffs, however, in the use of e-fuels in supersonic aircraft owing to the high altitudes at which they fly. Operating the Large SST on e-kerosene could increase the medium-term RF of commercial aviation by two-thirds despite covering less than 1% of all traffic in available seat kilometers (ASK). E-fuels reduce ozone destruction per unit of fuel burn slightly (6 to 10%); still, even a small number of projected operations would cause around 0.16 and 0.76 Dobson Units (DU) of global ozone depletion, equivalent to up to 8% of the total impact of chlorofluorocarbon (CFC) emissions at their peak.

Overall, we conclude that environmental considerations are likely to tightly constrain supersonic markets for the foreseeable future. Both low-boom designs and ultralow cost sustainable aviation fuel (SAF) will be needed for a sizeable supersonic market to develop. In the near-term, any supersonic aircraft developed are likely to be operated on fossil fuels, not e-kerosene.

Introduction

Globally, commercial airlines emitted about 920 million tonnes of carbon dioxide (CO_2) in 2019 (Graver et al., 2020) or as about as much as the German and Dutch economies combined (Crippa et al., 2019). After accounting for the radiative forcing (RF) of short-lived climate pollutants, aircraft have accounted for about 4% of historic anthropogenic warming to date (Kloewer et al., 2021). While fuel burn and CO_2 have fallen in half as a result of the COVID-19 pandemic, without further action emissions are expected to at least double from 2019 levels by 2050 and could consume one-sixth of a Paris-compatible 1.5-degree Celcius carbon budget.

Recognizing the threat, countries are increasingly adopting net-zero targets and moving to regulate aviation emissions domestically. The UK has begun incorporating both domestic and international aviation emissions into legally binding carbon budgets, and along with the EU is investigating a mandate for airlines to use sustainable aviation fuel (SAF) (UK DfT, 2021; European Commission, 2021). In 2021, France halted the expansion of Charles de Gaulle Airport on climate grounds and has proposed banning domestic flights that compete with high-speed rail (Patel et al., 2021). In October, the United States released a net-zero aviation roadmap while Congress considers legislation that would subsidize SAF uptake (FAA, 2021). Most recently, a group of 23 governments committed to reducing aviation emissions consistent with a 1.5-degree Celsius pathway and will press an ambitious international climate goal at the International Civil Aviation Organization (ICAO) (UN Climate Change Conference, 2021).

Industry is also beginning to act. Net-zero goals are announced regularly worldwide, including in Europe (A4E), the UK (Sustainable Aviation UK), and the United States (A4E, 2021; Sustainable Aviation, 2020; A4A, 2021). The International Air Transport Association (IATA), which represents airlines globally, has committed to a net-zero emissions goal by 2050 that would require the use of up to 65% SAF (IATA, 2021). In the medium term, a growing number of airlines are announcing emission reduction targets under programs like the Science-Based Targets initiative (SBTi).

These policy targets have fueled interest in zero-emission planes, including hydrogen-fueled designs being developed by Airbus (n.d.) and ZeroAvia (n.d.), and electric aircraft from Eviation (n.d.) and Heart Aerospace (n.d.). There is also renewed optimism about reviving supersonic transport (SST) aircraft that can operate at faster than the speed of sound. Boom Supersonic, a startup based near Denver and supported by investments from Japan Airlines and United Airlines, is developing a commercial supersonic airliner called “Overture” for use over water (*Boom Supersonic*, 2021).[1] Virgin Galactic, previously a Boom partner, is now working independently with engine partner Rolls Royce to develop a supersonic aircraft capable of operating at three times the speed of sound (Mach Number 3.0; Virgin Galactic, n.d.) Another startup, Hermeus, is pursuing a hypersonic MN 5.0 design that it claims could enable 90-minute flights from New York to Paris (Hermeus, n.d.).

Several other companies, including the startup Exosonic (Exosonic, n.d.) and Lockheed Martin, have been or are working to develop low-boom designs. Prior to suspending operations due to a lack of capital in May 2021 (Bloomberg, 2021), Aerion Corporation was developing a 10-seat, Mach Number (MN) 1.4 business jet with the potential for “boomless cruise” to enable overland flight.[2] Lockheed has received funding from NASA to develop its X-59 Quiet Supersonic Technology (QueSST) to showcase a low-boom design and to underwrite research into community responses to sonic booms (*X-59 QueSST*, n.d.).

These efforts have been supported by governments, notably the United States, but also Japan. In 2019, Congress passed the FAA Reauthorization that directed the FAA to propose a domestic landing and takeoff (LTO) noise standard for supersonic aircraft (Rutherford, 2018). The FAA subsequently relaxed flight testing requirements for supersonic aircraft and in March 2020 released a draft rule that would establish “Chapter 4.5” LTO noise requirements for those aircraft (Rutherford, 2020). Meanwhile, the U.S. has pushed the United Nations International Civil Aviation Organization (ICAO) to develop international standards that would enable supersonic flights. That move has encountered stiff resistance from EU member states, airports, and civil society organizations (Rutherford, 2019) that are concerned about the environmental impact of reintroducing supersonic flight.

Supersonic aircraft will need to overcome environmental constraints before they can be widely reintroduced. In addition to air pollution and airport noise, supersonic aircraft generate a sonic boom continuously during supersonic cruise and also emit more greenhouse gases (GHGs) than comparable subsonic aircraft per kilometer traveled for the same passenger load. The former explains the efforts to develop boomless or low-boom aircraft by Aerion, Exosonic, and Lockheed Martin. To address concerns about climate change, Boom Supersonic intends to make Overture compatible with 100% sustainable aviation fuels (SAFs; Boom Supersonic, 2021), and United has voluntarily committed to using SAF in-service (Ostrower, 2021). Boom’s

1 Overture’s conceptual design has evolved during development. Boom originally aimed to produce a MN 2.2 commercial airliner that could seat 55 passengers (Kharina et al., 2018). In July 2021, in partnership with United Airlines, Boom announced a revised MN 1.7 design seating 65 to 88 passengers, with a 4,250 nm range and a 60,000 ft cruise altitude (*Boom Supersonic, 2021*).

2 Aerion Corporation suspended operations in summer 2021 due to inadequate access to capital for full project development. Some of those expenditures were linked to the cost of developing an engine; when Aerion ceased operations, GE immediately halted work on the “Affinity” engine for the AS2 (Lynch, 2021).

focus in particular is on e-kerosene generated from renewable electricity and captured carbon (Hardeman & Maurice, 2021). In principle, e-kerosene could dramatically reduce CO_2 emissions from SSTs, but its high cost could make it much more difficult for airlines to operate supersonic aircraft profitably.[3]

A number of academic studies over the past 50 years have investigated the environmental impacts of supersonic aviation. Many have focused on ozone impacts (Cunnold et al., 1977; Kawa et al., 1999), while climate impacts have been addressed in recent studies (e.g., Pitari et al., 2007; Zhang et al., 2021). These have consistently found that supersonic aircraft will affect stratospheric ozone, and also that the non-CO_2 climate impacts of supersonics differ from those resulting from subsonic aircraft emissions.

More recent work has aimed to model the environmental impacts of the new designs being developed today. Kharina et al. (2018) concluded that a MN 2.2 commercial supersonic aircraft could burn five to seven times more fuel per passenger than subsonic aircraft on comparable routes. Rutherford et al. (2019) projected that an unconstrained network of supersonic aircraft could emit up to 96 million tonnes (Mt) of CO_2 per year, or roughly the combined emissions of American, Delta, and Southwest Airlines in 2017. Those aircraft could expose parts of Western Europe and the United States to sonic booms as frequently as once every five minutes if declared 2035 sales targets are met. Neither study analyzed the profitability of supersonic aircraft, particularly under noise (overland flight) or climate constraints.

Speth et al. (2021) investigated both the economics and emissions of eight potential supersonic designs with different combinations of speed, payload, and range. A sizeable market of 440 to 470 aircraft was predicted for a 4500 nm, MN 1.6 design carrying 65 passengers, assuming no overland flight restrictions. But that market fell by 80 to 95% when overland flight restrictions were considered. That study also revealed that due to the high residence times of supersonic pollution emitted in the stratosphere, the medium-term radiative forcing (RF) per seat-kilometer traveled of a MN2.2 supersonic aircraft could be as much as 20x the subsonic baseline.[4] This included countervailing impacts from warming agents like nitrogen oxides (NO_x) and water vapor, and cooling species like aerosols.

This paper models the market size and potential emissions of an economically viable supersonic fleet in 2035 using the latest public design specifications. We model both an unconstrained network—no overland flight restrictions and baseline fossil jet fuel—and potential fleets under noise (overland flight ban) and climate (e-kerosene use) constraints.

3 Boom has an optimistic view of e-kerosene produced by its partner for flight testing, Prometheus Fuels. According to Boom's CEO, "Prometheus technology works like magic, it literally sucks carbon out of the atmosphere and converts it into liquid hydrocarbon." (*"Zero Carbon Footprint Supersonic Flight" – Boom Supersonic Makes Bold Claim after Fuel Partnership*, n.d.) In 2021, Prometheus announced that it would begin delivering e-kerosene at price parity to fossil jet fuel in California (Rob McGinnis, 2021). In October 2021, a small-scale demonstration project in Germany began producing e-kerosene, with a target production price of 5 euros/L in 2030, or about ten times the current cost of Jet A (Furtula & Jordans, 2021)

4 Radiative forcing, expressed in terms of milliwatts per square meter of heating or cooling, is a commonly used measure of climate impact. Pollutants from supersonic aircraft warm or cool the climate on different timescales. Long-term impacts, measured in decades to centuries, are dominated by CO_2. Medium-term impacts from emissions of NOx, water vapor, and aerosol particulates in the stratosphere, along with their corresponding impacts on atmospheric ozone, are felt over multiyear timescales. The short-term impacts, over timescales of several hours to several days, are dominated by contrail cirrus and low-altitude aerosols. For the purposes of this study, we refer to supersonic CO_2 RF as "long-term" and non-CO_2, non-contrail RF from supersonics as "medium-term". Short-term forcing from contrail cirrus is beyond the scope of this work, as explained in the methods section.

The balance of the paper is arranged as follows. The following section introduces the methods used to investigate this question, including the two reference SSTs modeled, the cases considered, and the economic and fuel assumptions applied. Following that, we present our key findings, including the SST market potential (number of aircraft, operations, and fuel burn) and atmospheric impacts. These include co-pollutants like NO_x and black carbon, the impact of those emissions on ozone concentrations, and the medium-term radiative forcing (RF) of those emissions. We close with some high-level policy recommendations and suggestions for future work.

Methods

Table 1 summarizes the five cases modeled under this project: a subsonic-only baseline (Case 0), an unconstrained supersonic with no noise or climate restrictions (1) followed by a noise-constrained case with existing overland flight bans (2). The two remaining cases (3a and 3b) investigate the implications of supersonic e-kerosene use. 3a was used to estimate the potential market; 3b was used to investigate the atmospheric impacts of e-kerosene use after 3a failed to generate a sufficient market for supersonic operations (see below).

Table 1. Scenarios investigated

Case	Scenario	Flight restrictions	Fuel type	Fuel cost (2011 $/kg)
0	Subsonic only	—	Jet A	$1.00
1	Unconstrained supersonic			
2	Noise-constrained supersonic	Overland flight ban		
3a	Climate-constrained supersonic	—	E-kerosene	$3.30
3b				$1.00

Two reference supersonic transport (SST) aircraft were developed for this study (Table 2). The Small SST, a 15-seat, MN 1.4 aircraft was developed from the basic specifications of Aerion's defunct AS2 business jet. The Large SST approximates the capability of the MN 1.7 "Overture" aircraft being developed by Boom. Both aircraft have four engines and a maximum takeoff mass (MTOM) ranging from 42 tonnes for the Small SST (equivalent to a medium-sized regional jet like Embraer's E-175) to 191 tonnes for the Large SST. This approximates the MTOM of a small widebody aircraft like Boeing's 767-300ER, although it would seat less than one-third as many passengers.

Table 2. Reference aircraft

Parameter	Small SST	Large SST
Cruise speed (MN)	1.4	1.7
Number of seats	15	75
Range (km)	7400	8300
Maximum takeoff mass (tonnes)	41.8	191
Fuel fraction	0.43	0.46
Wing area (m^2)	85.0	375
Cruise altitude (km)	16.2	14.9
Number of engines	4	4
Single-engine thrust (kN at design point [top of climb])	45.7	226

The economic and environmental impacts of these aircraft were investigated using two different fuels. Table 3 summarizes the characteristics of the model's conventional "Jet A" fossil jet fuel and a synthetic e-kerosene derived from renewable electricity and captured carbon.

Table 3. Fuel characteristics, 2035

Parameter	Jet A	e-kerosene	% change
Cost (in 2035) (2011 $/kg)	$1.00	$3.30	+230%
WTT emissions (g CO_2e/MJ)	17	-62	-464%
TTW emissions (g CO_2e/MJ)	72	72	0%
WTW emissions (g CO_2e/MJ)	89	10	-89%
Sulfur content (ppm)	600	15	-98%
Black carbon emissions (mg C/kg)	300	30	-90%
Water vapor emissions (g/kg)	1231	1366	+11%

E-kerosene fuel prices are estimated as a minimum selling price based on Isaacs et al. (2021), assuming a reverse water gas shift (RWGS) reaction using dedicated wind electricity and direct air capture as a carbon source. Jet A is anticipated to cost $1.00 per kilogram (Speth et al., 2021), compared to $3.30 per kilogram for e-kerosene in the base case (all in 2011 dollars). Baseline CO_2 intensity for the fossil Jet A is about 90 grams of CO_2e per megajoule (g CO_2e /MJ), with e-kerosene reducing that by almost 90%, to 10 g CO_2e /MJ. Expected black carbon emissions and sulfur content are consistent with measured BC emissions and fuel sulfur contents from paraffinic alternative fuels (Moore et al., 2015; Speth et al., 2015). E-kerosene is expected to be near-zero sulfur and to emit 90% less black carbon as a result of its low aromatic content. Water vapor emissions, conversely, are expected to increase by 11% as a result of fewer unsaturated hydrocarbons.

A complete description of our modeling approach is provided in Speth et al. (2021) and summarized here. Market modeling is performed by projecting the global subsonic civil aviation market based on regional market forecasts from Boeing, with growth assumed to take place largely on existing routes as described by the OAG flight schedule.[5] Supersonic demand is projected based on the willingness-to-pay (WTP) of passengers for travel time savings based on data for the projected WTP distributions of passengers at the origin and destination of each route. These distributions are derived through a demand-side model described in detail in Speth et al. (2021). We account for both substitution of existing subsonic to supersonic demand (passengers who would already fly a given route but choose to take a faster option), and new demand induced by the availability of faster supersonic aviation (passengers who only choose to fly this route because there is now a sufficiently fast option). Demand is sensitive to aircraft performance since less fuel-efficient aircraft will cost passengers more per hour of time saved.

For each supersonic aircraft under consideration, aircraft performance (including cruise altitude) is estimated using a model which was calibrated using data from the Concorde and NASA's Supersonic Technology Concept Aeroplane (STCA). The model estimates fuel burn and NO_x emissions in each flight segment, allowing determination of uptake—and therefore annual number of flights—for each origin-destination pair. For this work, the performance model described in Speth et al. (2021) was updated to incorporate the Numerical Propulsion System Simulation (NPSS) engine model and more realistic wing loading limitations (Sanz-Morère et al., 2021).

5 https://www.oag.com/airline-schedules-data

The market model uses a number of uncertain economic parameters, including income elasticity of demand and the median value of time for different passenger classes. When evaluating the effect of economic uncertainty, three "economic scenarios" are determined by varying all of the economic parameters across three values (low, medium, high) and simulating every possible combination of values. This includes both fuel prices, which are varied between 80%, 100%, and 120% of the values provided in Table 3. Thus, e-kerosene price was varied by +/- 20% (from $2.64 to $3.96 per kg) from the base cost when exploring its market potential. The low, medium, and high economic cases were defined as the 10th, 50th, and 90th percentile results of the 2,187 possible combinations of global operations.

Once the number of flights on each route is known, the performance model estimates total emissions averaged over the course of each month. These emissions were included in simulations using the GEOS-Chem global chemistry transport model v11, which includes the Unified Chemistry eXtension or UCX (Eastham et al., 2014). The UCX allows GEOS-Chem to calculate changes in global ozone that result from supersonic aircraft emissions by simulating interactions between the stratosphere and troposphere. Simulations are performed for a baseline year of 2035, including background subsonic aviation emissions as projected by our market model and non-aviation emissions from the Intergovernmental Panel on Climate Change's (IPCC) RCP 4.5 scenario. Each simulation covers a fourteen-year period, of which the final four years are averaged when deriving results. This means that the impacts presented in this work are based on a "steady-state" estimate of the effect of supersonic aviation of aircraft in operation in 2035.

Medium-term climate impacts are quantified during the final four years through the Rapid Radiative Transfer Model for Global applications (RRTMG) embedded in GEOS-Chem. All calculations include the effect of methane feedbacks. When simulating the effects of supersonic aviation, we perform two simulations: once with, and once without, the inclusion of the supersonic fleet emissions. The difference in outcomes (e.g., ozone column) is then taken as the effect of the supersonic fleet. We include both substitution and induced demand with regard to the total emissions from supersonic aircraft. However, we do not model any reduction in subsonic flights, which is marginal (less than 1%).

We can theoretically simulate each combination of fleet and fuel based on the predicted market for that combination. However, for cases in which the projected SST market is very small, this approach would conflate the change in environmental impact due to a change in fuel composition with that due to a change in market size or distribution. Furthermore, under the base climate-constrained case (3a), virtually no market was predicted. We therefore developed a second climate-constrained scenario with lower fuel cost assumptions (3b) to simulate the same fuel burn distribution in the unconstrained case (1) for Jet A but with the emission characteristics of e-kerosene summarized in Table 3.

The drier atmosphere at cruise altitudes typical of supersonic aircraft means that few contrails are expected to form, suggesting that supersonic aircraft may have smaller contrail-related climate impacts per unit of distance flown than is the case for subsonic aircraft. However, in light of the low level of certainty in contrail modeling, the greater level of uncertainty around actual supersonic operations, and the difficulty of accurately simulating or observing humidity at high altitudes (Agarwal et al., 2021), contrail impacts are not considered in this work.

Results

The following sections summarize the results of the market and atmospheric modeling for the supersonic aircraft in 2035. We start with results from the market model for four scenarios—the subsonic baseline, the unrestricted supersonic, and the two restricted cases. A key result is that virtually no market is predicted for either aircraft under overland flight restrictions or with e-kerosene use. We then present the atmospheric modeling for the base subsonic (Case 0), unconstrained (Case 1), and ultralow-cost e-kerosene (Case 3b) supersonic cases.

Market modeling

Table 4 summarizes the market modeling for the unconstrained case. Without overland flight restrictions or requirements for e-kerosene use, we find a base market of 130 to 240 supersonic aircraft in 2035, providing between 0.1% and 0.6% of the baseline subsonic available seat kilometers (ASKs), for the Small SST and Large SST, respectively. The Large SST market is about one-ninth of that envisioned by Boom, which has a goal of selling up to 2000 of its "Overture" aircraft (Bellamy III, 2018).

Table 4. Potential SST market in 2035, unconstrained case

Parameter	Base subsonic (Case 0)	Unconstrained supersonic (Case 1)	
		Small SST	Large SST
Fleet size (# of aircraft)	—	130 to 140	230 to 240
Annual number of roundtrips (thousand)	37,091	92.6	192
Annual available seat-km (billion)	18,818	11.4	108
Average stage length (km)	—	4,120	3,760
Average share of ASKs (%)	—	0.1%	0.6%
Average value of time threshold ($/hour)	—	650	301
Average flight time saving per roundtrip (hours)	—	4	4.5
Average time saving in percentage of subsonic flight	—	38%	46%

Also shown on the table are the average value of time threshold, the average number of hours saved, and the percentage of flight time saved for each design. The Large SST saves about 4.5 hours roundtrip flight time on a 3800 km one-way route, or about 45% of the total trip time. Note that this figure does not include taxi time, boarding/deplaning time, and airport transit time; these are not expected to vary between supersonic and subsonic designs and would therefore dilute these time savings. Flying on the slower Small SST saves less time, on the order of 4 hours roundtrip on a somewhat longer (4100 km) trip.[6] The value of time threshold, which indicates how much customers would need to value an hour of time savings in order to accept the additional costs of flying supersonic, is about $300 per hour for the Large SST vs $650 per hour for the smaller design. This indicates higher potential profitability and a larger pool of customers for the Large SST.

Table 5 summarizes the fuel burn results for the unconstrained supersonic case. The two SSTs investigated are expected to be fuel intensive—burning 7 to 9 times more fuel

6 For this work, both reference aircraft were modeled on commercial routes. This introduces somewhat of a mismatch between the operations that the Small SST was modeled on and those of its reference aircraft, Aerion's AS2 business jet. Thus, the market findings outlined here should not be extrapolated to a supersonic business jet, which would be used on a different set of missions and whose market would likely respond to economic factors beyond those represented here.

per seat-km than the subsonic fleet in 2035[7]—but due to their small market share are unlikely to be a major source of total CO_2. In total, they could emit between 0.5% and 4% of subsonic CO_2 in 2035, while satisfying demand for 0.1% to 0.6% of available seat kilometers in that year.

Table 5. Fuel burn, unconstrained case

Parameter	Subsonic fleet (Case 0)	Unconstrained supersonic case (Case 1)	
		Small SST	Large SST
Fuel burn (Mt)	428	2.23	17.1
Fuel burn SST as share of subsonic BAU	—	0.52%	3.99%
Fuel intensity (kg/100 available seat-km)	2.27	19.5	15.7
Fuel intensity relative to subsonic	—	8.6	6.9

The market model also predicts the routes and markets that supersonic aircraft would be operated on in the unconstrained case. Figure 1 shows which markets the Large SST is likely to be operated on. Three types of data are shown. The thickness of each arrow is proportional to the absolute number of SST operations, while the numerical label indicates the share of global SST operations by region. The coloring of each arrow shows the SST share of all seats, including from subsonic operations.

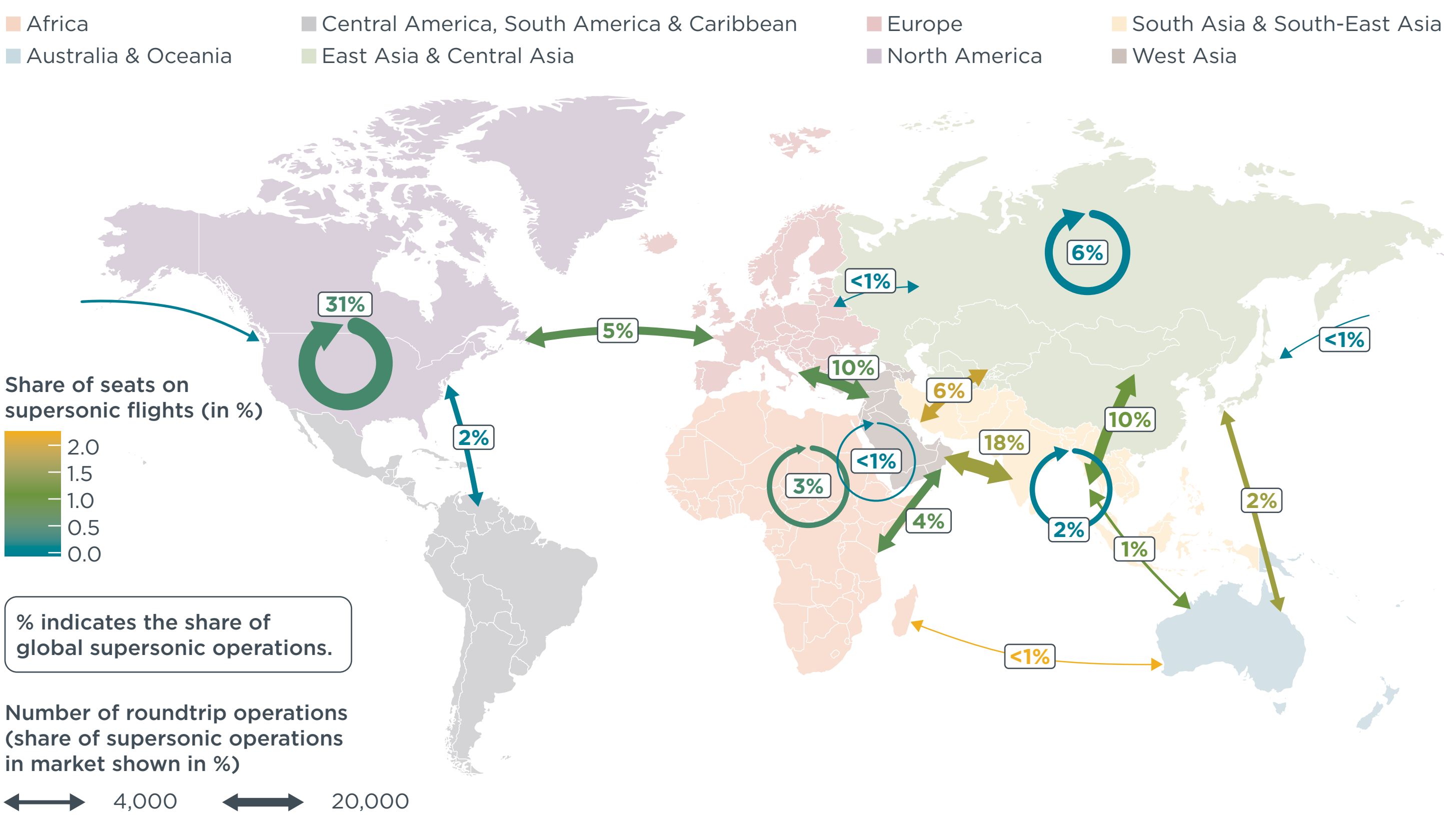

Figure 1. Geographic breakdown of large SST operations by market, unconstrained case

7 This supersonic to subsonic fuel burn multiple falls in the high range of previous work by Kharina et al. (2018) of 5 to 7 times more fuel per passenger and for Speth et al. (2021), of 4 to 10 times more fuel per ASK. The first study modeled a faster (MN 2.2) 55-seat design using Boom's preliminary estimate of 77 tonnes MTOM. The MTOM of the MN 1.7, 75-seat design in this study has grown to 191 tonnes, as a point of reference.

As highlighted, there are two large potential markets for the Large SST, each accounting for about 40% of all flights. The first is in the Middle East, where Gulf carriers are expected to operate flights to South Asia/Oceania, Europe, and Asia. North America is the second largest market, with a large majority (31% of the global total) of flights being intracontinental. These two markets have the highest estimated willingness to pay for time savings and trip lengths that can be made without additional refueling stops. The North Atlantic is expected to be the major transoceanic market, consistent with Concorde operations between New York and London/Paris. Interestingly, no intra-EU market is expected, along with few operations to Japan. The latter finding is surprising given that Japan Airlines is a declared Boom launch customer.

The results above are specific to the unconstrained supersonic case (Case 1). The majority of the potential market is overland, not over water, making those markets vulnerable to overland flight restrictions. The market model was also used to predict the potential market for supersonics under the two constrained cases: first, by assuming that existing overland flight restrictions are retained (Case 2); second, by assuming that supersonics would be operated on e-kerosene (case 3a) costing $3.30 per kg of fuel. Figure 2 summarizes the potential market, in terms of the number of aircraft in service in 2035. The central economic case is shown as the blue bars, while the error bars depict the low and high economic cases. Other market indicators, including the number of operations, share of ASKs, and fuel burn, scale approximately to the number of aircraft in service.

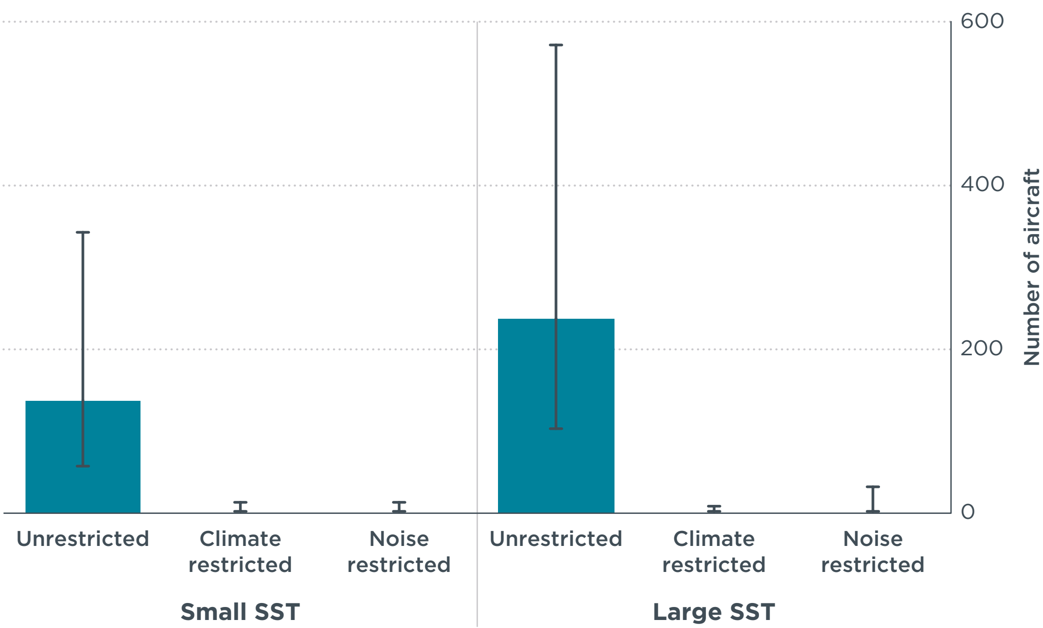

Figure 2. Unconstrained vs. constrained market case

As shown, both the simulated overland flight ban and use of e-kerosene dramatically reduce the potential supersonic market. Only the high economic case generates a constrained supersonic market; even then, the fleet size falls by 95% to 99% for the Large SST under the noise and climate constraints, respectively. The potential Small SST fleet size shrinks to only 3% of the original market for both constrained cases under the high economic case. The lack of a constrained supersonic market is explained by the fact that airlines aren't expected to profitably operate supersonic aircraft either due to insufficient time savings (overland flight ban) or high fuel costs (e-kerosene). Because the SSTs are expected to burn 7 to 9 times more fuel per ASK, operating them on e-kerosene with a high (+230%) price premium inflates SST fuel costs per seat kilometer to around 25 times the subsonic baseline.

Atmospheric modeling

The lack of a viable market under Case 3a makes it challenging to model the atmospheric impacts of e-kerosene use. Accordingly, Case 3b was developed assuming ultralow-cost e-kerosene (cost parity with Jet A) to allow direct comparison to the unconstrained supersonic case (Case 1) using Jet A. We then ran atmospheric simulations to estimate steady-state effects of supersonic air pollutants in 2035.

Table 6 presents the relative emissions intensity by aircraft type and fuel for CO_2, ozone, and nitrogen oxides (NO_x).

Table 6. Emission intensity by aircraft type and fuel

Aircraft type	CO_2				Ozone				NO_x			
	kg CO_2/100 seat-km		SST e-kerosene change vs. Jet A		mDU/bn seat-km		SST e-kerosene change vs. Jet A		g NO_x/100 seat-km		SST e-kerosene change vs. Jet A	
	Jet A	e-kerosene	Δ Supersonic[a]	Δ Subsonic[b]	Jet A	e-kerosene	Δ Supersonic	Δ Subsonic	Jet A	e-kerosene	Δ Supersonic	Δ Subsonic
Subsonic	7.2	—	—	—	0.061	—	—	—	34.5	—	—	—
Small SST	61.6	6.78	-89%	-6%	-14.3	-12.8	1.50	-12.86	350	350	0%	+910%
Large SST	49.6	5.46	-89%	-24%	-7.08	-6.65	0.43	-6.71	356	356	0%	+930%

[a] Δ supersonic is the change in a given value (e.g. kg CO_2/100 seat-km) for a supersonic aircraft burning e-kerosene compared to that same aircraft burning Jet A.
[b] Δ subsonic is the difference in that value for a supersonic aircraft burning e-kerosene relative to that value for a subsonic aircraft burning Jet A.

Overall, we find that e-kerosene can reduce the long-term (CO_2) climate impact of supersonics but has only limited impacts on other pollutants. If generated using dedicated renewable electricity, the lifecycle CO_2 emissions per seat-km from supersonics could be cut by 6% and 24% for the Small and Large SST, respectively, compared to the subsonic Jet A baseline. This reduction is smaller than from the fuel itself (-89%) due to the underlying fuel intensity of SSTs. E-kerosene would only modestly reduce ozone depletion from supersonics by 0.43 to 1.50 milliDobson Units (mDU)/billion seat-km, or 6 to 10% of the total. It would not impact NO_x emissions, which would remain elevated at around 10 times the subsonic per seat-km baseline.

To put the ozone depletion figure into context, current estimates of the total global average ozone depletion resulting from CFCs peaked at between 10 and 20 DU (Chipperfield et al, 2017). The projected supersonic fleet, in comparison, would cause between 0.16 DU and 0.76 DU of ozone depletion for the Small and Large SST fleets, respectively. This means that a small fleet of supersonic aircraft, providing between 0.1% and 0.6% of the total number of seat-km of the projected subsonic fleet, could cause ozone depletion equivalent to up to 8% of the total impact of CFC emissions.

Because e-kerosene will be very low in sulfur (see Table 3) and largely paraffinic, it should reduce both sulfate and black carbon aerosols during combustion. Along with ozone, water vapor, and methane, these particulates help determine the medium-term (non-CO_2, non-contrail cirrus) impacts of supersonic aircraft. Figure 3 summarizes the expected radiative forcing (RF), in milliwatts per square meter (mW/m^2) per billion seat-km of both SSTs on fossil Jet A and e-kerosene. Warming impacts are shown in red; cooling impacts are shown in blue while the net warming impact is shown in green. Note that, due to some non-linearity in the radiative forcing estimation, the net RF of a given aircraft/fuel combination may vary somewhat from the sum of its individual components.

The top two graphs present data for the Small SST, while the bottom two graphics show the Large SST. The Jet A case is shown at left, while the e-kerosene constrained case is shown at right. Note that the scale of the Small SST panels is twice that of the Large SST, demonstrating larger per seat-km climate impacts.

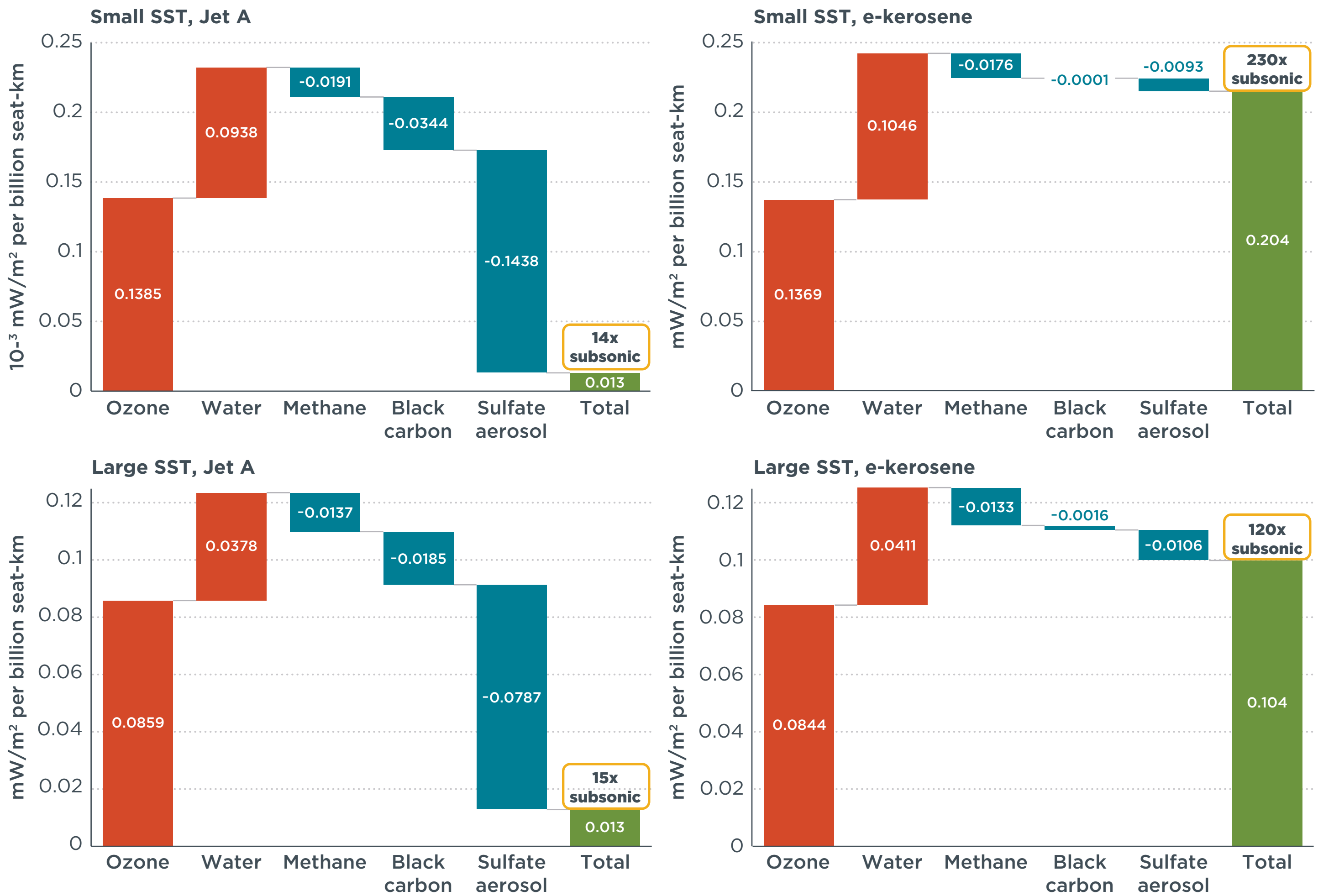

Figure 3. Medium-term radiative forcing by SST and fuel

As shown, the use of e-kerosene is expected to increase the net warming impact of medium-term climate forcers from supersonic aircraft. While the warming impact of ozone changes and water vapor are largely insensitive to the fuel used, e-kerosene use would dramatically cut emissions of black carbon and sulfate aerosols, which cool the stratosphere.[8] This results in a net increase in the RF of SSTs operated on e-kerosene by unmasking the warming of other pollutants. Net supersonic RF per seat-km rises from about 15 times that of the subsonic baseline (0.0009 milliWatts/m² per billion seat-km) under Jet A to 120 to 230 times that when operated under e-kerosene.

8 At lower altitudes, black carbon is a potent climate warmer. In the stratosphere, it has the opposite effect, by absorbing and re-radiating incoming light from the sun before that light reaches the troposphere.

To this point, this discussion has focused on impacts per seat-km. Figure 4 plots the total fleetwide medium-term radiative forcing by case and aircraft type, taking into account both the intensity (10^{-3} mW/m^2 per billion seat-km) and operations (billion seat-km) of each aircraft type. The total medium-term subsonic RF in 2035, shown in blue, is about 17 mW/m^2. Warming associated with supersonic operations on Jet A for the unconstrained case (case 1) is shown in green. The larger net warming due to e-kerosene use in Case 3b is shown in red. The total medium-term RF from e-kerosene use varies from 2.3 to 11 mW/m^2 for the Small and Large SST, respectively. In other words, if the Large SST were operated on e-kerosene, the medium-term RF of commercial aviation could increase by two-thirds despite covering less than 1% of all traffic in ASKs. This finding is largely hypothetical, though, because e-kerosene is expected to be cost-prohibitive for supersonic aircraft in 2035.

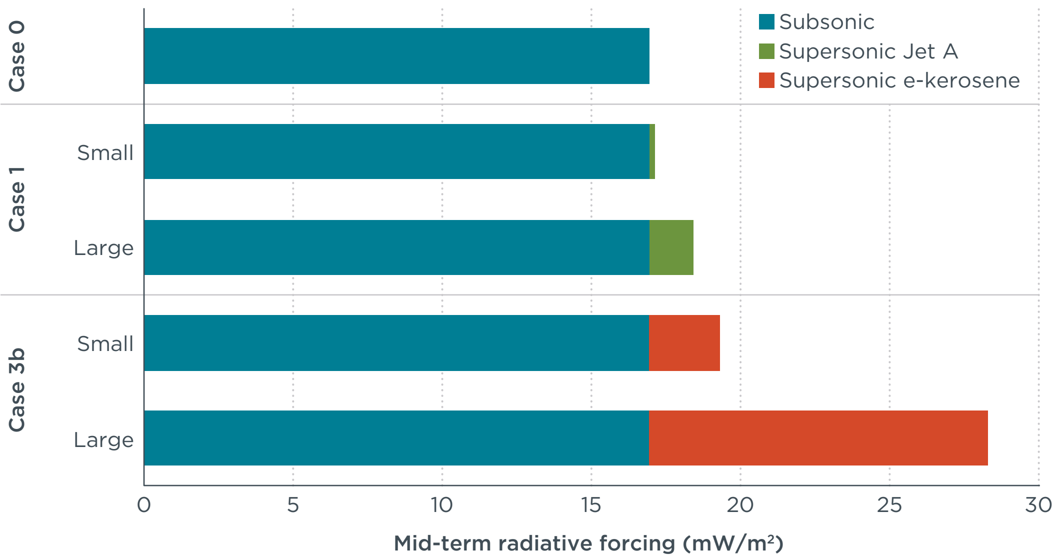

Figure 4. Fleetwide medium-term radiative forcing by case and SST

Given their very different residence times in the atmosphere, and also the differing altitudes of supersonic vs. subsonic operations, it is challenging to compare the total (CO_2 and non-CO_2) climate impacts of supersonic versus subsonic aircraft on a consistent basis. Still, this research is broadly consistent with Zhang et al. (2021), who concluded that radiative forcing from supersonic ozone destruction and water vapor is likely to exceed that of CO_2 alone.

Conclusions

This study investigated the potential market for and atmospheric impacts of near-term supersonic designs. We conclude that environmental limits like an overland flight ban and requirements to operate aircraft on synthetic aviation fuels would sharply constrain potential supersonic markets. For the unconstrained case, we find a potential market for 130 to 240 supersonic aircraft in 2035, providing up to 0.6% of available seat-miles that year. Under noise and climate constraints, the 2035 potential market falls by 95% to 100%; for all but the most optimistic economic case, airlines are unable to operate SSTs profitably under environmental constraints. The fuel intensity of the designs (7 to 9 times that of subsonics) combined with the high price of e-kerosene (3.3 times that of fossil jet fuel), generates a 25-fold increase in fuel costs relative to the subsonic baseline.

Considering the hypothetical case where ultracheap e-fuels become available at price parity with Jet A, we find tradeoffs in their use in supersonic aircraft. E-fuels could modestly reduce the long-term CO_2 impact of supersonics compared to subsonics operated on fossil fuels but could increase medium-term climate impacts by 120 to 230 times that of the subsonic baseline. Emissions of pollutants like NO_x would remain elevated, and even the small number of operations could significantly impact the ozone layer. Synthetic fuels with dramatically reduced lifecycle CO_2 intensity will still drive climate change when burned in supersonic aircraft because of the high fuel intensity of those designs and the altitudes at which they operate.

These findings hold important implications for future supersonic aircraft designs; namely that both low-boom designs approved for overland flight and ultralow-cost SAFs will be needed for a sizeable supersonic market to develop. Even then, other atmospheric impacts like NO_x emissions and ozone depletion would be largely unaddressed. Finally, because SST manufacturers develop and sell planes but do not purchase their fuel, it is likely that supersonic aircraft will be operated on fossil fuels, not e-kerosene, in pursuit of profitability.

This points to several policy recommendations. First, environmental standards are needed to ensure that supersonic aircraft have acceptable emissions on their own merits, independent of the fuels they burn. Second, given that the climate benefits of using e-kerosene in supersonics are unclear, SAF subsidies and tax credits should exclude supersonic designs. Finally, in order to meet net-zero targets, governments, manufacturers, and airlines should pursue measures to promote new zero-emission aircraft, including hydrogen and regional electric designs.

As manufacturers continue to develop supersonic designs, we envision future work on their economic and environmental merits. Research on other sustainable aviation fuels, notably advanced biofuels, that could have differing costs and emission profiles compared to e-kerosene, may be needed. Research into contrail cirrus impacts, which were beyond the scope of this work, may be needed. The operational implications of reintroducing supersonic aircraft at airports, in particular how that might impact airport congestion and safety, should be investigated. Finally, a detailed study of viable routes and how these aircraft might fit into existing airline operations is recommended.

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