DECEMBER 2022

SUPERSONIC AIR TRAVEL FUEL CONSUMPTION

COMPARING FUEL CONSUMPTION IN TODAY'S PREMIUM SUBSONIC CABIN TO AN ALL-PREMIUM OVERTURE AIRCRAFT

About Boom Supersonic

Boom Supersonic is transforming air travel with Overture, the world's fastest airliner, optimized for speed, safety, and sustainability. Serving both civil and government markets, Overture will fly at twice the speed of today's airliners and is designed to run on 100% sustainable aviation fuel (SAF). Symphony™, a Boom-led collaboration with industry leaders, is the propulsion system that will power Overture. Overture's order book, including purchases and options from American Airlines, United Airlines, and Japan Airlines, stands at 130 aircraft. Boom is working with Northrop Grumman for government and defense applications of Overture. Suppliers and partners collaborating with Boom on the Overture program include Collins Aerospace, Eaton, Florida Turbine Technologies (FTT), a business unit of Kratos Defense & Security Solutions, Inc., GE Additive, Safran Landing Systems, StandardAero and the United States Air Force.

For more information, visit **www.boomsupersonic.com**.

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List of Acronyms

ASK: Available Seat Kilometers
CFD: Computational Fluid Dynamics
CO_2: Carbon Dioxide
IATA: International Air Transport Association
ICAO: International Civil Aviation Organization
ICCT: International Council on Clean Transportation
NO_x: Oxides of Nitrogen
RANS: Reynolds-Averaged Navier-Stokes
SABA: Sustainable Aviation Buyers Alliance
SAF: Sustainable Aviation Fuel
SBTi: Science Based Targets initiative
SSBJ: Supersonic Business Jet
SST: Supersonic Transport
U.S. DOT: United States Department of Transportation

Executive Summary

Air travel connects the world, linking people, culture, and ultimately enabling global economies to prosper. Supersonic air travel promises to amplify these benefits by reducing travel time even further. Boom Supersonic is building Overture, an airliner designed to operate sustainably at approximately twice the cruise speed of current aircraft while delivering a comfortable, enhanced cabin experience for 65 passengers.

At Boom, we are committed to delivering the benefits of high speed air travel sustainably, in a net zero carbon manner. Boom's sustainability strategy centers on the use of 100% sustainable aviation fuel (SAF) and efforts to rapidly advance and scale SAF production. This will enable net zero carbon operation of Overture while research and development efforts are undertaken to further mature supersonic technology, resulting in continued efficiency improvements.

Boom is also actively engaged and working with researchers and climate scientists to understand, quantify, and mitigate Overture's non-CO_2 climate impacts. We are designing Overture with circular economy principles in mind to minimize end-of-life waste, and are integrating sustainability throughout our supply chain. In addition to addressing climate impacts, we are also committed to addressing community noise impacts by adhering to Chapter 14 noise levels and flying at subsonic speeds over land and near coasts. Through these actions, Boom is committed to delivering supersonic travel in a sustainable manner, making sustainable aviation a reality for billions of passengers.

While Overture will operate with net zero carbon, and flying in the stratosphere will all but eliminate contrail impacts, supersonic flight has incremental fuel consumption needs relative to subsonic flight. This white paper shares an accurate comparison of the fuel consumption intensity of a seat on Overture to that of an equivalent premium class seat on a subsonic aircraft. The evaluation is performed for representative supersonic routes and includes detailed calculations on a route-by-route basis, using aircraft-specific cabin layout information and actual operational data for 2019 from U.S. Department of Transportation Form 41 and T-100 databases.

This study finds that supersonic air travel on Overture consumes 2-3 times as much fuel per seat than comparable premium class subsonic travel, depending on the routes evaluated, as well as various fuel consumption assumptions related to the subsonic fleet.

Section 1: Introduction

Air transport is one of the world's most important industries, providing vital social and economic benefits by linking continents and enabling trade across geographies. In 2018 alone, the industry transported 4.5 billion passengers, moved 35% of worldwide trade by value ($6.5 trillion), and contributed $3.5 trillion to the world economy (approximately 4% of global GDP).[1] These benefits are made possible by the speed of travel enabled by aviation, which provides transport capability at speeds and distances 1-2 orders of magnitude larger than road vehicles, ships, and trains.[2]

Supersonic air travel promises to deliver even greater benefits by reducing travel time even further compared to the current fleet of subsonic commercial aircraft. Boom's Overture airliner is designed to operate at Mach 1.7 (1,300 miles per hour), which is approximately twice the cruise speed of the current generation of subsonic aircraft, and is expected to be operated on over 600 routes. In its 65-passenger configuration, Overture's cabin is designed to deliver an enhanced, productive cabin experience that is similar to the premium class products (i.e., first and business-class cabins) offered on current subsonic aircraft. This will allow travelers to halve their travel time in the air, remain productive during travel, arrive at their destination refreshed, and conduct business trips in hours instead of days.

Traveling at supersonic speeds, however, involves additional energy requirements above subsonic flight. This is because supersonic aircraft operate in conditions that fundamentally differ from subsonic flight, resulting in greater fuel consumption for a given distance traveled. Recently published studies claim that supersonic aircraft result in between 5-9 times[3] as much fuel consumption per passenger than subsonic aircraft. However, these claims are based on non-comparable data which do not provide an accurate comparison of supersonic to subsonic aircraft. The studies compare the business class product of supersonic aircraft against a subsonic mixed class product (i.e., including economy class in addition to first and business class products),[4] and use project aircraft rather than the mature, wind tunnel validated aircraft data used by Boom.[5]

[1] Aviation Benefits Beyond Borders (2020). Global Fact Sheet.
[2] Varga et al. (2016). Further We Travel the Faster We Go.
[3] A 2018 ICCT study found that a 55-seat M2.2 SST burns between 5-7 times as much fuel per passenger as subsonic aircraft on selected routes. A more recent 2022 ICCT study concluded that a 15-seat M1.4 SSBJ and a 75-seat M1.7 SST burn 7-9 times more fuel per seat-km than subsonic aircraft.
[4] For instance, according to ICAO and IATA, premium cabin seats (which are more comparable to the product offered onboard supersonic aircraft) result in up to 5 times higher fuel consumption than an economy class seat on subsonic aircraft, when accounting for "the different weight and space associated with a passenger seat in different cabin classes."
[5] Boom has conducted a total of five wind tunnel tests over the course of 2021 and 2022, covering the following aspects: (1) low-speed aerodynamics, (2) low-speed airframe acoustics, (3) high-speed aerodynamics, (4) high-speed and static isolated inlet, and (5) low-speed nozzle acoustics.

Section 1: Introduction

This study presents a detailed evaluation of the fuel consumption per seat (referred to hereafter as fuel consumption intensity) for Boom's Overture airliner compared to that of premium cabin seats on subsonic aircraft currently in service. The evaluation is performed for representative supersonic routes from the transatlantic and transpacific markets. It includes detailed calculations of subsonic premium cabin fuel consumption intensity on a route-by-route basis using aircraft-specific cabin layout information and actual operational data from the U.S. Department of Transportation (U.S. DOT)[6] for 2019. Further, the study includes a detailed calculation of Overture's fuel consumption performance based on Boom's robust validated aircraft performance models.

Section 2 describes the data sources and methods used in our evaluations. Section 3 presents the results of the comparison. Section 4 contextualizes these results by providing a historical perspective on the evolution of aircraft fuel efficiency in the aviation industry. Finally, Section 5 summarizes the key findings of this work and outlines important steps that Boom is taking to address the increased energy requirements inherent in supersonic travel.

[6] Data on subsonic aircraft operations in 2019 was obtained from the U.S. DOT T-100 database, while operational fuel burn data was obtained from the Form 41 database.

Section 2: Methods and Data Sources

ROUTES EVALUATED

This study performed a fuel consumption intensity comparison for six representative routes that are expected to have high demand for supersonic travel on Overture based on customer engagement. These routes span both the transatlantic and transpacific markets, as shown in Figure 1 below. This allows a detailed calculation of fuel consumption intensity to be performed for subsonic flights on a route-by-route basis, with calculations based on aircraft-specific cabin layout information and the actual operational data for 2019 from U.S. DOT Form 41 and T-100 databases.

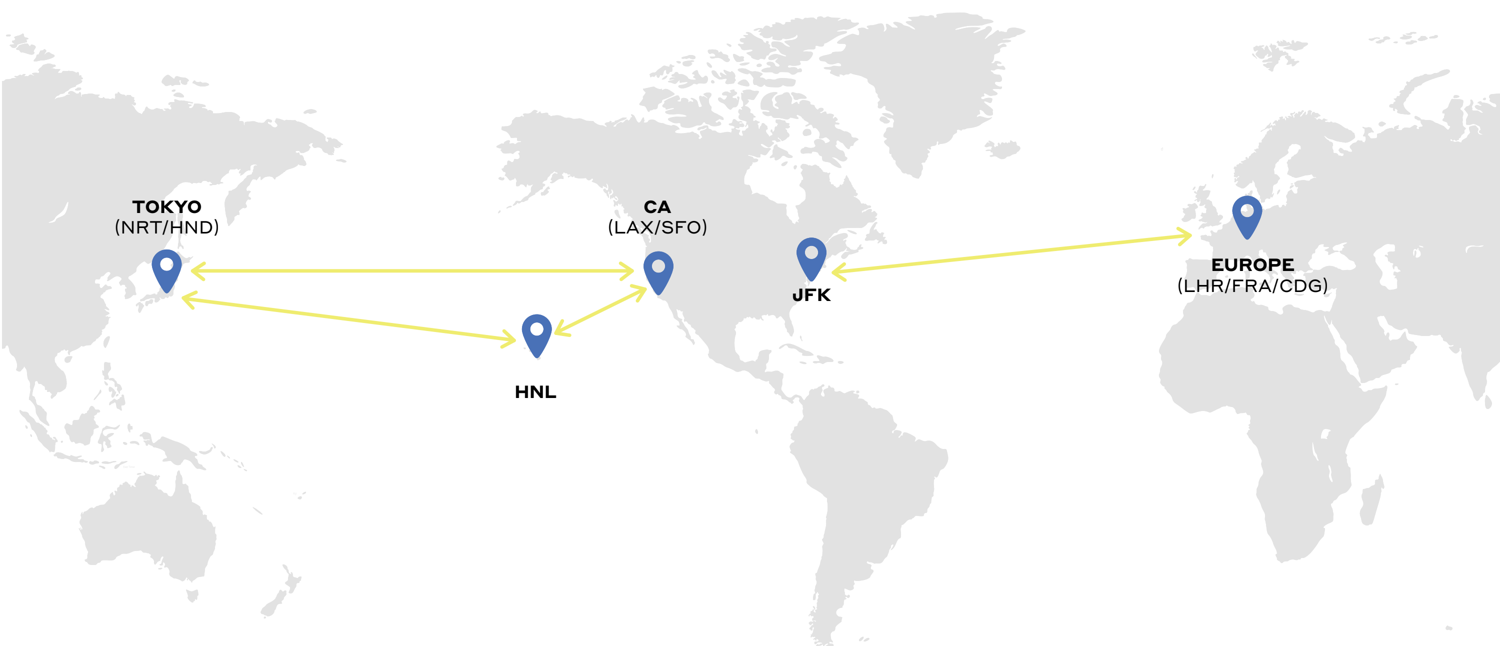
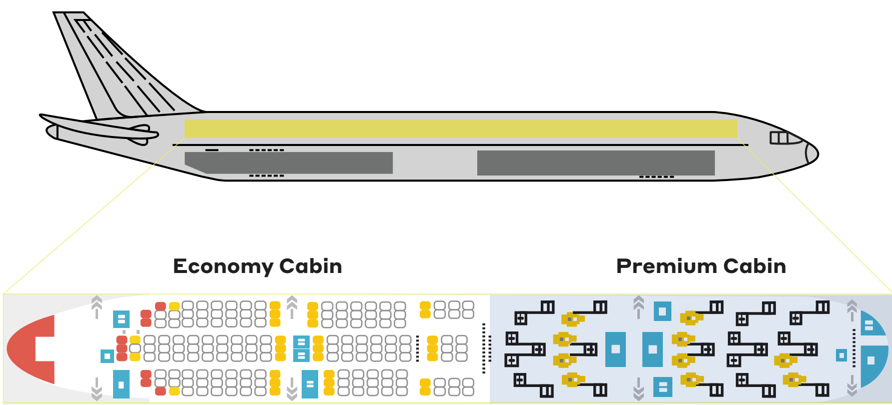


Figure 1: Transatlantic and transpacific markets evaluated to compare fuel consumption intensity between Overture and subsonic premium cabin travel.

SUBSONIC AIRCRAFT FUEL CONSUMPTION INTENSITY CALCULATIONS

The methodology used to calculate subsonic fuel consumption intensity per premium seat is as follows: for each route, fuel consumed by a given subsonic aircraft type is first apportioned to passenger transport according to the ratio of passenger and cargo weights transported, following industry standard practices.[7] Second, fuel consumption is attributed to the transport of premium cabin passengers on the basis of cabin area, allocated to each cabin type onboard the subsonic aircraft. Finally, the premium cabin fuel consumption is divided by the total number of premium cabin seats to obtain a fuel consumption intensity per premium seat. Figure 2 illustrates this methodology.



1. Passenger-attributable fuel consumption is apportioned based on **passenger** and **cargo** weights.
2. **Premium cabin** fuel consumption is calculated based on the relative proportions of the cabin floor area.
3. Fuel consumption intensity per **premium seat** is calculated by dividing premium cabin fuel consumption by the total number of premium seats

Image Credits:
(top) ANA Cargo, available online at: https://www.anacargo.jp/en/int/specification/b787_10.html
(bottom) SeatGuru, British Airways SeatMaps BoeingB787-8, available online at: https://www.seatguru.com/airlines/British_Airways/British_Airways_Boeing787-8.php

Figure 2: Illustration of the methodology used to calculate subsonic fuel consumption intensity per premium seat. The same process was repeated for each airline-aircraft combination that operated in 2019 on the representative routes studied.

Information on the subsonic widebody fleet that operated on the routes illustrated above was obtained from the U.S. DOT T-100 database for 2019 operations. Data included the airline operator code, aircraft type, number of departures, number of passengers, number of seats, total flight minutes,[8] and total weight of cargo transported, and represent non-directional values. A total of 45 different airline-aircraft combinations were evaluated across the six representative routes.

[7] Follows industry standard practices established by IATA and SBTi.
[8] The T-100 database does not provide flight times for flights operated by non-US airlines; in these cases, average flight times based on US airline flights contained in the database were substituted.

Fuel consumption for subsonic aircraft was based on U.S. DOT Form 41 data for 2019 operations. An average fuel consumption rate per flight hour was calculated for each aircraft type for Atlantic and Pacific operations, and used with flight times from the T-100 data to calculate total fuel consumption per flight. Since the Form 41 data only reports data for U.S. airlines, it does not contain data for aircraft types not operated by U.S. airlines (e.g., B747, A340, and A380). In these cases, the ICAO Carbon Emissions Calculator[9] was used to supplement fuel consumption information as needed.

Fuel consumption was apportioned to passenger transport according to the ratio of passenger and cargo weights transported, as shown in Figure 3. Following the methodology presented by IATA[10] and SBTi,[11] the weight of passengers transported was calculated assuming 100 kg/passenger and 50 kg/seat. Together with the weight of the cargo transported (which was obtained from the T-100 database), these figures were used to determine the share of fuel consumption associated with transporting passengers.

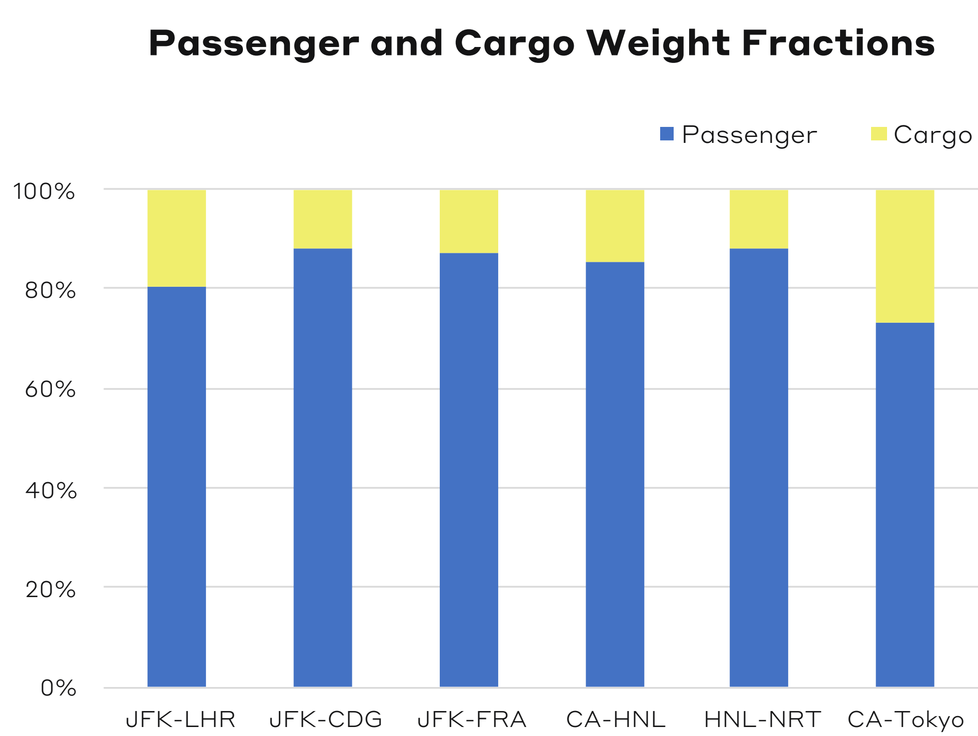


Figure 3: Average passenger and cargo weight fractions from 2019 subsonic aircraft operations on the routes evaluated in this study.

[9] ICAO (2018). Carbon Emissions Calculator Methodology, Version 11.
[10] IATA (2014). Recommended Practice 1678, CO2 Emissions Measurement Methodology.
[11] SBTi (2021). Science-based Target Setting for the Aviation Sector.

Fuel consumption attributed to premium cabin transport was calculated based on cabin area. The proportion of cabin floor area occupied by premium cabins was calculated for each airline and aircraft type using seat dimension data from SeatGuru, adjusted for aisle, galley, and amenities spaces based on cabin layout maps. Figure 4 illustrates the proportion of an aircraft's cabin area allocated to premium cabins, averaged over all operators studied in this work. Fuel consumption intensity per premium seat was calculated by dividing premium cabin fuel consumption by the number of premium class seats.

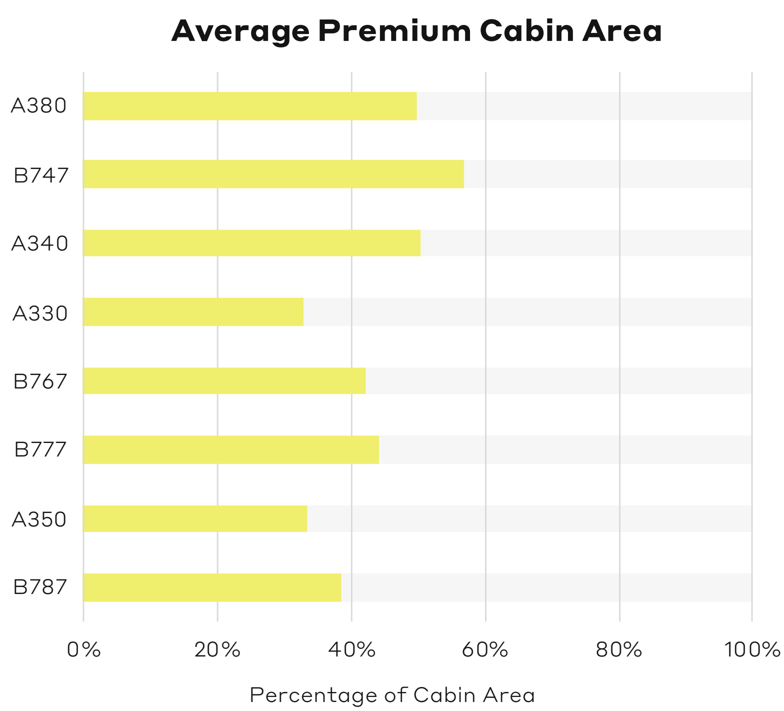


Figure 4: Proportion of subsonic aircraft floor areas allocated to premium class cabins. Results are shown by aircraft type, averaged across all operators from 2019 subsonic aircraft operations on the routes evaluated in this study.

Across all aircraft operations considered in this paper, the average subsonic fuel consumption intensity was found to be approximately 0.014 gallons per seat-mile (considering both economy class and premium class seats). The fuel consumption intensity for subsonic premium class seats was approximately three times larger than the average across all subsonic classes of travel, at 0.037 gallons per seat-mile.

OVERTURE AIRCRAFT FUEL CONSUMPTION INTENSITY CALCULATIONS

Fuel consumption for Overture was calculated using a suite of robust, high-fidelity, and patent-pending aircraft performance simulation tools developed at Boom. These tools incorporate high-fidelity Reynolds-Averaged Navier-Stokes computational fluid dynamics (RANS CFD) calculations and have been extensively validated using wind tunnel tests. Boom's aircraft performance modeling tools are coupled with a detailed Mission Analysis and Routing algorithm, which calculates Overture fuel consumption, inclusive of the following realisms:

- Median winds aloft
- Flight speed restrictions and routing to avoid sonic boom impacts over land masses, including secondary boom standoff distances
- Technical stops for refueling on long-range routes
- Fuel reserves for diversion, including climb and loiter for up to 30 minutes
- Capacity of 65 premium cabin passenger seats[12]

Though Overture has the ability to carry some cargo in addition to passenger bags, this analysis conservatively assumes that 100% of Overture's fuel consumption is attributed to passenger travel.

[12] Though significantly higher, Overture's maximum premium cabin seating configuration was not used in this analysis in order to represent how most operators are likely to deploy the aircraft and retain the objective of comparing similar cabins.

Section 3: Overture Fuel Consumption Intensity Findings

Supersonic air travel on Overture consumes 2-3 times as much fuel per seat when compared to premium class subsonic travel. This range captures the sensitivity of the evaluation to the different routes considered.

Figure 5 provides a relative comparison of Overture's fuel consumption intensity across the routes that were studied. For most routes, Overture's fuel consumption intensity is lower than 2.5 times the corresponding premium class subsonic fuel consumption intensity. Supersonic routes that have a greater proportion of overland flight tend to have a higher fuel consumption intensity than routes that originate from airports on the coasts due to speed and routing restrictions designed to eliminate sonic boom impacts over land. Differences in the subsonic aircraft fleet and amount of freight transported further contribute to variability in subsonic aircraft fuel consumption intensity across the routes evaluated. Finally, long-range routes (such as California to Tokyo) require Overture to perform a technical stop for refueling, leading to a fuel consumption intensity that is approximately three times higher than premium class subsonic travel.

The 2019 subsonic fleet that was evaluated in this analysis included a number of less fuel-efficient aircraft — that is, aircraft with relatively higher fuel consumption intensities on a premium seat basis, such as the Boeing 747, Airbus A340, and Airbus A380. Of the routes evaluated in this study, these aircraft were predominantly operated on the JFK-LHR, JFK-FRA, and HNL-NRT routes. As these aircraft are expected to be retired from the fleet in the coming years, an alternate assessment was performed excluding these aircraft types. The results of this alternate assessment are shown as gray symbols in Figure 5. Compared to premium cabin travel on a more efficient subsonic fleet (which excludes B747, A380, and A340 aircraft), Overture's fuel consumption intensity is approximately 2.5-3 times as high on those routes.

Comparison of Fuel Consumption Intensity on Overture with Subsonic Premium Cabin Travel

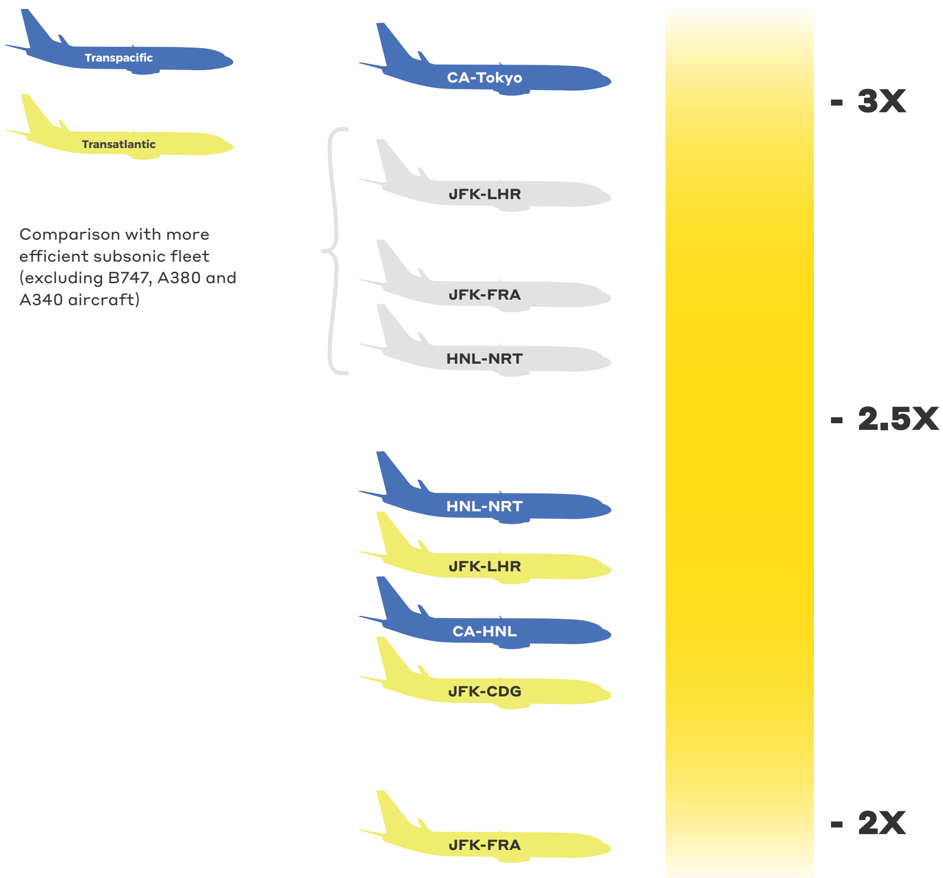


Figure 5: Comparison of fuel consumption intensity on Overture with subsonic premium cabin travel. Values are provided as a ratio of Overture relative to subsonic premium cabins. Grey icons denote a comparison of fuel consumption intensity relative to a subsonic fleet excluding fuel-inefficient B747, A380, and A340 aircraft.

[13] Peeters, P.M., Middel J., and Hoolhorst A. (2005). Fuel Efficiency of Commercial Aircraft: An Overview of Historical and Future Trends.
[14] Babikian R., Lukachko S.P., and Waitz I.A. (2001). The Historical Fuel Efficiency Characteristics of Regional Aircraft from Technological, Operational, and Cost Perspectives.

Section 4: Air Travel - A Historical Perspective on Fuel Efficiency

In aviation, step changes to increase the speed of travel often come at the cost of increased fuel consumption, at least in the initial stages. For example, while the jet engine doubled the speed of commercial air transport relative to piston-engine airliners in the 1960s, initial jet aircraft designs were approximately three times as fuel intensive as the technologically mature piston airliners of the time on a per seat kilometer basis. Similarly, early regional jets were approximately 2.5 times less fuel efficient than the turboprops operating in the same market. Over the span of 30 years of continued research and development into aircraft designs and jet engine technology, the fuel efficiency of commercial jet aircraft has improved to meet and even surpass those of piston-engine airliners. Figure 6 illustrates this historical trend.

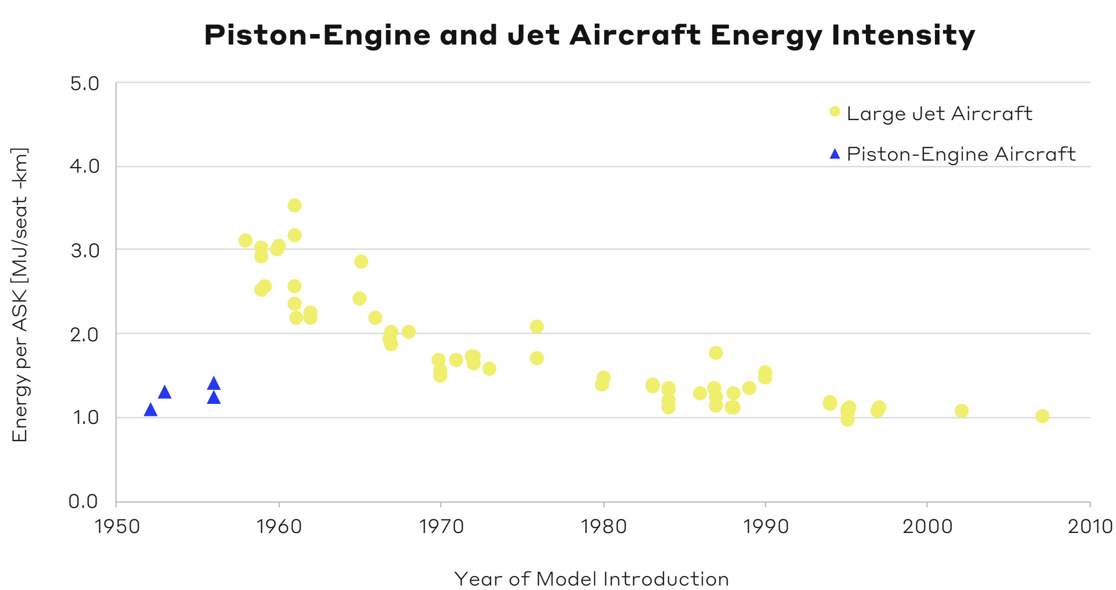


Figure 6: Subsonic aircraft energy intensities. Data for piston-engine airliners and large jet aircraft are taken from Peeters et al. (2005).[15]

Overture is the first commercial supersonic transport aircraft to be developed since the Concorde and Tupolev Tu-144 were designed in the late 1960s. As Overture enters airline fleets and begins service, and as other markets for supersonic travel are tapped into (including supersonic business jets, high-value cargo transport, and government executive transport), supersonic aircraft technology will continue to mature and could similarly deliver improvements to fuel efficiency relative to first-generation supersonic aircraft.

[15] Peeters P.M., Middel J., and Hoolhorst A. (2005). Fuel Efficiency of Commercial Aircraft: An Overview of Historical and Future Trends.

Section 5: Delivering Sustainable Supersonic Travel

At Boom Supersonic, we recognize the reality that supersonic travel is inherently more energy intensive than subsonic flight. In building Overture, we strive to deliver the benefits of speed in the most sustainable manner possible. The following section provides an overview of our efforts to understand and mitigate the climate impacts of designing, building, and flying Overture.

Boom's sustainability strategy centers on advancing and scaling SAF production and use. Overture and its engine, Symphony, are being designed to operate on 100% SAF and will achieve net zero carbon through advanced biofuels, waste-based fuels, and power-to-liquid (PtL) fuels, which offer up to 100% life cycle CO_2 reduction. Overture and Symphony are also being designed to accommodate future SAF specifications, which will feature improved performance characteristics and reduced environmental impacts compared to today's drop-in blended fuels. Use of 100% SAF will enable net zero carbon operation of Overture, as further research and development is undertaken to mature supersonic technology and improve fuel economy.[16]

Boom is partnering with airlines to enable net zero carbon Overture flights and SAF use. In 2021, Boom signed a commercial agreement with United Airlines for an order of 15 Overture aircraft. Boom is proud that, as part of this agreement, United intends to operate its Overture fleet at net zero carbon from day one. Boom is also actively engaging with airline customers and other partners across the SAF value chain. This includes a partnership with AIR COMPANY to supply PtL-based SAF for Overture flight tests and our membership in the Sustainable Aviation Buyers Alliance (SABA) to promote SAF production and use through book and claim systems.

[16] Examples of currently ongoing research activities include the U.S. Federal Aviation Administration Aviation Sustainability Center's (ASCENT) Project 10 and Project 47 (which investigate fuel burn and noise reductions from supersonic aircraft enabled by clean-sheet engine designs and assess the potential future evolution of the next-generation supersonic aircraft fleet). NASA is engaged in a similar study of assessing the environmental performance of several notional, near-term supersonic transports. Other research institutions such as the SENECA and MORE&LESS projects are attempting to conduct design optimization studies and environmental performance assessments of various supersonic concepts

In 2022, Boom conducted a study to understand how the rapid scaling of SAF production can be achieved, learning from drivers that enabled exponential growth of other renewable energy industries.[17] While continued progress across social, economic, and technical domains is needed, one of the most important drivers identified to achieve adequate supply of SAF and price parity with conventional fossil jet fuel is the importance of early buy-in and adoption of SAF. These crucial demand signals mark the beginning of a positive feedback loop between economies of scale and cost reductions from overcoming learning curves that will enable SAF to scale rapidly and drive the SAF market toward cost parity with conventional jet fuel.

Overture, with its premium product offering, presents a unique opportunity to support early SAF uptake. We believe that the relative price inelasticity of the premium cabin demand on Overture will be able to support the early price premiums associated with SAF. This will enable customers to minimize their carbon footprint while traveling on Overture and, at the same time, provide a strong demand signal to the SAF industry. Further, Boom's partnership with AIR COMPANY provides crucial early support to the development of PtL SAF technology (i.e., using CO_2 from the atmosphere and renewable electricity to produce near limitless zero carbon SAF).

At Boom, we recognize that the climate impacts of supersonic travel extend beyond its carbon footprint. Boom has taken an important first step in understanding Overture's non-CO_2 climate impacts by prioritizing and investing in climate science. In 2021, Boom engaged researchers at the University of Illinois Urbana-Champaign to better understand the atmospheric effects of Overture emissions — including impacts of NO_x emissions, water vapor, and contrails — in order to inform mitigation strategies. As the understanding of non-CO_2 climate effects continues to improve, Boom is already working to mitigate these impacts by investigating and incorporating broad emission-reducing technologies such as no- or low-aromatic SAF and low NO_x propulsion technologies.

As a company, Boom prioritizes transparency and accountability by voluntarily reporting on our emissions footprint annually and committing to science-based targets. Boom achieved carbon neutrality in 2021, and has set itself an ambitious goal to be net zero carbon by 2025. As outlined in our 2021 Environmental Sustainability Report,[18] this involves a transition to 100% renewable energy for Boom's facilities (already accomplished for Boom's Denver headquarters as of 2021), recycling facility waste, and maximizing landfill diversion. Furthermore, we strive to minimize design and construction resources, employing circular economy principles to minimize end-of-life waste, integrating sustainability throughout our supply chain, working with airline partners to ensure the net zero carbon operation of Overture, and managing residual emissions with high-quality offsets that prioritize carbon removal.

[17] Ashok and Murphy (2022). Scaling Sustainable Aviation Fuel Production: Lessons Learned from Exponential Growth in Renewable Energy Industries.
[18] Boom Supersonic (2022). 2021 Environmental Sustainability Report.

Section 6: Conclusion

Air travel enables vital personal and trade connections around the world, linking continents and enabling economies to prosper. These benefits are delivered because of the speed of travel enabled by aviation, and supersonic air travel promises to amplify these benefits by significantly reducing travel time even further. While it is a reality that supersonic travel does require more energy than subsonic flight, Boom, together with its industry and academic partners, continues to advance research and development into supersonic aircraft technology which is expected to deliver improvements both for Overture, the next generation of supersonic aircraft, and future iterations of commercial supersonic transport.

At Boom, we strive to deliver the benefits of speed in the most sustainable manner possible. Boom's sustainability strategy centers on advancing and scaling SAF production and use, beginning with Overture flight testing and net zero carbon airline operations, through to enabling widespread availability and eventual cost parity. Through this and other actions, Boom is committed to delivering supersonic air travel in a sustainable manner, making sustainable aviation a reality for billions of passengers.

BOOM

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