Sustainability: key to enable next generation supersonic passenger flight

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Abstract. The 2020 global Covid-19 pandemic has shocked the aviation system to its core, showcasing what the loss of this economic engine can do to the world’s economies and societies. This crisis also presents an opportunity to create new capabilities and outlooks. Commercial supersonic flight is one such capability. The availability of advanced computational designs and propulsion systems, new materials, route optimization and alternative fuels means that supersonic aviation can be part of that future in a sustainable manner.

Boom’s ultimate goal is to mainstream supersonic air travel and make it accessible to millions of passengers per year. Long-term projections of business-class airline demand suggest a total market of 1,000 to 2,000 commercial supersonic aircraft operating on more than 500 primarily transoceanic routes that will benefit from speeds twice as fast as today’s aircraft.

Given the increased focus on mitigating aviation’s environmental impact, bringing a new aircraft to market in the 2020s requires a careful focus on sustainability. To ensure public acceptance supersonic aircraft manufacturers and operators will have to proactively engage with stakeholders to address their concerns and focus on integrating sustainability solutions across their business strategies.

Boom is the first commercial aviation OEM to build sustainability into its aircraft programmes from day one, ensuring that sustainability considerations form an integral part of every aspect of the production process. A sustainability commitment to cover every step in the aircraft development cycle, from design and test through in-service operations and end-of-life recycling is key to successfully reintroduce commercial supersonic flight in the years ahead.

1. Introduction

Within the timespan of a mere 44 years, during the first half of the 20th century, mankind witnessed the progression from the first controlled, sustained flight of a powered, heavier-than-air aircraft (1903) to breaking the sound barrier (Mach 1.06, in 1947). Another 29 years later, in 1976, Concorde became the first supersonic passenger-carrying commercial airplane. It exceeded Mach 2 with a maximum cruising speed of 2,179 km (1,354 miles) per hour.
Since then, commercial airplane speeds have actually seen a regression (see Figure 1). Today’s subsonic wide-body passenger aircraft attain maximum speeds in the range of Mach 0.89 (945km/h, A350XWB) compared to Mach 0.92 (969km/h, B747-100) in 1969, while commercial supersonic flight ceased altogether in 2003. In essence, the time required to fly from Paris to Rio de Janeiro or New York to London is no different today than it was almost half a century ago.

Figure 1 – Top airplane speeds

Unlike airplane speed, fuel efficiency and noise performance have dramatically improved for subsonic flight over the past decades. Modern airplanes produce about 80% less CO$_2$ per seat than the early jets of the 1960s. The combined application of evolutionary technologies (such as new high-bypass engine architectures, natural and hybrid laminar flow control) is expected to further improve fuel efficiency by roughly 25 to 30% compared to today’s subsonic aircraft (see Figure 2).

Figure 2 – Commercial aircraft fuel efficiencies 1960-2015

[1] Dourado E and Kotrous M 2016 Airplane Speeds Have Stagnated for 40 Years p 1
[2] International Air Transport Association (IATA) 2020 Aircraft Technology Roadmap to 2050 p 7
[3] Theis J 2018 Robust and Linear Parameter-Varying Control of Aeroservoelastic Systems p 1
Likewise, individual aircraft noise, measured in Effective Perceived Noise in Decibels (EPNdB), has seen a reduction of more than 90% since jet aircraft first entered service (see Figure 3).  

\[\text{Figure 3 – ICAO Annex 16 noise limits} \]

Given Concorde’s retirement, commercial supersonic flight has not benefitted from efficiency improvements and noise reductions associated with continuous technological advancements and fleet renewal - but this is about to change.

2. **Supersonic Passenger Flight – The First Generation**

Among the many aircraft types capable of supersonic flight, the vast majority were designed for military and research purposes. To date, Concorde (Mach 2.04, 4 Olympus 593 Mk610 turbojet engines with afterburners) remains the only supersonic passenger aircraft ever to enter full commercial service. It did so in January 1976, seven years after its maiden flight.

The Russian-built Tupolev Tu-144 (Mach 2.29, 4 Kuznetsov NK-144 turbofan engines with afterburners), was launched one year prior to Concorde, in 1968. Although 14 units were built, it only ever flew one route (Moscow to Almaty) and was retired from passenger service in 1978.

In spite of receiving 122 pre-orders from 26 airlines around the world, advanced plans for Boeing’s B2707 SST (Mach 2.7, 4 GE4/J5P turbojet engines with afterburners) were cancelled in 1971, largely due to the economic realities brought on by the first oil crisis.

Overall, first generation commercial supersonic flight, government-backed and with limited attention paid to economic viability, was characterized by heavy fuel costs and disproportionate noise and emission levels. Concorde’s takeoff noise, measured under FAR 36 conditions at Dallas Fort Worth in 1973, for example, registered at 115.4 EPNdB. With regard to fuel economy, Concorde managed about 17 passenger-miles to the Imperial gallon - or 16.6 litres per 100 passenger kilometres (pkm) – generating 0.42 kg CO₂/pkm.

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[4] https://www.nats.aero/environment/aircraft-noise/
[5] European Union Aviation Safety Agency (EASA) 2019 European Aviation Environmental Report 2019 p31
[6] US Environmental Protection Agency (EPA) 1974 Noise Measurement of Concorde 02 Approach and Takeoff at Dallas – FT.Worth and Dulles International Airports
[7] Rowell D 2003 Concorde: An Untimely and Unnecessary Demise
Among other destinations, Concorde flew regular transatlantic flights from London's Heathrow Airport and Paris' Charles de Gaulle Airport to John F. Kennedy International Airport in New York, Washington Dulles International Airport, and Grantley Adams International Airport in Barbados. Beginning 1977, British Airways and Singapore Airlines jointly operated Concorde flights on the London-Bahrain-Singapore route. The service operated for just 5 days before it had to be suspended as the Malaysian government had taken issue with the sonic boom over western parts of Malaysia and the Malacca Straits. Unable to find viable alternative routings, the service formally ceased in 1980. Following the AF4590 crash in July 2000, Concorde continued operations for three more years. Its final flight took place on 23 October 2003, drawing the first era of civilian supersonic transport to a definitive close.

3. A New Generation of Supersonic Commercial Passenger Aircraft

The same year the first Concorde took its maiden flight, mankind took its first steps on the moon. Just like Apollo 11, Concorde is widely considered to be a technological marvel of its time, designed and developed without digital simulators, computer-aided design software, or 3D modeling technology.

However, aerospace technologies have greatly advanced in recent decades and a new generation of supersonic OEMs and entrepreneurs, including Boom, are set to build on Concorde’s legacy having vastly improved computational design structures and materials, advanced propulsion systems and operations, and sustainable fuels at their disposal.

On 7 October 2020, Boom took the next step towards relaunching commercial supersonic flight with the unveiling of its XB-1 demonstrator, the first privately built supersonic airplane (see Figure 4). Measuring about 21.5 metres in length, a wingspan of 6.4 meters and powered by three GE J85-15 engines, XB-1 will be tested in 2021 as part of the development of Boom’s supersonic passenger aircraft, Overture.

Figure 4 - Boom’s supersonic demonstrator aircraft, XB-1

3.1 Structures and materials

Rather than the extensive use of costly and time-consuming physical models and wind tunnel testing, today’s computational fluid dynamics (CFD) and cloud computing capacity enables the analysis of millions of design points for thousands of virtual airplane designs in a relatively short time. Combined with artificial intelligence (AI) and machine learning (ML) algorithms, these data points allow engineers to continually optimize supersonic design processes.
The use of these multidisciplinary design optimization techniques enables manufacturers to shape aircraft very precisely around different performance requirements such as area ruling, minimizing pressure drag and skin friction, but also LTO and cruise noise and emissions.

The precise and economical manufacturing of aerostructures is further facilitated by the availability of new alloys, including carbon fibre composites, which offer both extreme strength and lightweight, have higher thermal stability than aluminium and are easier to mould into aerodynamically optimal shapes. These properties make the materials ideal for supersonic aircraft manufacturing. Their temperature capabilities also allow for a long airframe life with minimal maintenance, representing a significant cost-savings.

Additionally, many aircraft parts are now manufactured using 3D printing, instead of being milled out of solid blocks of metal. In the Boom XB-1 demonstrator, for example, the tertiary bracketry, clamp blocks, spacers, ducts, and fuel closeouts are primarily manufactured in-house using 3D-printed Ultem 9085 thermoplastic parts. This avoids materially-wasteful, transport-intensive design iterations thereby saving time and reducing research and development costs.

3.2 Advanced propulsion systems and operations

Concorde’s Olympus 593 turbojet engines, built by Rolls Royce/Sneema, were highly thermodynamically efficient machines, but they came with noisy, fuel-thirsty afterburners to produce the high thrust needed at takeoff and to achieve supersonic speeds in cruise.\(^8\)

Much like structure design and materials, however, the development of aircraft propulsion systems has seen significant benefits from technological advancements. For reasons of cost and performance, engine designs are typically closely tailored for each application. This also applies to new supersonic products. So, while with subsonic engines reductions in noise and fuel consumption can be achieved simultaneously by moving to larger-diameter, higher-bypass engines, this is not the case for supersonic engines which will rely more on thrust from the jet core than contemporary, high-bypass subsonic engines.\(^9\) It is expected, therefore, that Boom’s Overture will be equipped with low- to medium-bypass turbofan engines, which will eliminate the need for afterburners, resulting in vastly superior fuel and noise performance compared to conventional turbojet engines.

Operational measures provide additional potential for minimizing supersonic noise. For example, Overture will cruise at supersonic speeds only over water, which means that no sonic boom will reach those areas where people live and work. Also, coastal buffer zones are built into route planning assumptions and economic models, ensuring that Overture only cruises above Mach 1 once it reaches an acceptable distance from the shore.

With respect to departure noise, the use of programmed lapse rate (PLR), a computer-managed reduction in thrust after the takeoff roll, may offer significant noise benefits.\(^10\) Because supersonic engines tend to be sized for transonic acceleration and sustained supersonic cruise, they typically have a greater margin of excess thrust at departure than subsonic aircraft and should still be able to accelerate during the climb phase even after reducing power.\(^11\)

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[8] Leyman C 1986 A Review of the Technical Development of Concorde Progress in Aerospace Sciences 23 185
[9] Russell R, Maurice L and Devine R 2020 Supersonic Flight and Sustainability: A New Horizon NAE The Bridge 50 28
[10] Berton J, Jones S, Seidel J and Huff D 2017 Advanced Noise Abatement Procedures for a Supersonic Business Jet Int. Sym. on Air Breathing Engines (ISABE 2017) NASA Glenn Research Center, Cleveland, Ohio
[11] Russell R, Maurice L and Devine R 2020 Supersonic Flight and Sustainability: A New Horizon NAE The Bridge 50 28
Various studies have looked into potential propulsion systems for supersonic civil aircraft with some showing beneficial results from the application of a highly variable cycle (HVC) engine design in terms of reduced full burn and takeoff noise. New aircraft engines, however, are complex, costly and time consuming to engineer. Consisting of 20,000–40,000 parts, a new 30,000 lb thrust class engine for a single-aisle aircraft currently requires about 50 months and $ one billion to certify. Although perhaps not feasible yet, demand for new-generation commercial supersonic airplanes may encourage investment into variable-cycle engine designs.

4. Sustainable Fuels to Power New Supersonics

Being a young commercial aircraft manufacturer, Boom has been able to incorporate sustainability into its vehicle design from day one. The company’s approach encompasses aircraft testing, facility design, plans for aircraft end-of-life recycling, and more. Recognizing just how critical sustainability practices will be to the success of the new supersonic era, it is approaching the matter like any other engineering goal. One key focus area for Boom in the context of sustainability is the ability to design for net-zero carbon propulsion through the use of high-blend sustainable aviation fuels (SAF).

4.1 Sustainable Aviation Fuels (SAF)

Aircraft are ultra high-performance machines, subject to strict weight and volume limitations. These constraints are why jet fuel, with its high energy density, is uniquely suited for aviation. They are also the main hurdles to making electrification a viable solution for long distance flight. While current progress in electric propulsion may bring zero-carbon flights within reach for regional air travel in the next decade, designing batteries powerful enough for long-haul flights still poses an insurmountable challenge.

The SAF market has made huge progress from its invention just over a decade ago and it has the potential to make an important contribution to mitigating the current and expected future environmental impacts of aviation, including supersonics. In 2018, global airlines, through its representative body the International Air Transport Association (IATA), set out a target for one billion passengers to fly on aircraft using a blend of SAF and conventional (fossil) fuels by 2025. Still, only limited volumes of SAF are currently being produced and consumed – global production was estimated at 15 million litres in 2018, less than 0.1% of total aviation fuel consumption.

Early in 2020, a seventh technology pathway for SAF production was approved by the American Society for Materials Testing (ASTM): synthetic paraffinic kerosene derived from hydro-processed hydrocarbons, esters and fatty acids (HC HEFA SPK fuel). The corresponding new Annex to ASTM Standard D7566 was developed with support from the Commercial Aviation Alternative Fuels Initiative (CAAFI) - which Boom joined as a member in 2018 - and adds an additional avenue for SAF production.

[12] Smith H 2012 Innovation in Aeronautics Innovation in supersonic passenger air travel pp.155-196
[13] Sokhey J and Kube McDowell M 2008 Rolls-Royce low noise highly variable cycle nozzle for next generation supersonic aircraft
[14] Epstein A 2020 Aeropropulsion: Advances, Opportunities, and Challenges NAE The Bridge 50 8
[15] International Air Transport Association (IATA) 2018 Aim for 1 Billion Passengers to Fly on Sustainable Fuel Flights by 2025 Geneva, Switzerland
[16] International Energy Agency (IEA) 2019 Are Aviation Biofuels Ready For Take Off? Paris, France
[17] Annex A7 to ASTM’s SAF specification D7566
[18] Other ASTM-approved pathways are 1. Fischer-Tropsch (2 pathways) 2. Hydro-processed Esters and Fatty Acids (HEFA) 3. Alcohol to Jet 4. Hydroprocessed Fermented Sugars to Synthetic Isoparaffins and 5. Co-processing of vegetable oils in conventional refineries.
Boom believes that SAF alternatives, using hydrocarbon chains from non-fossil sources, offer an accessible solution for supersonic flight in the near- to mid-term. SAF engine ground tests for the Boom XB-1 supersonic demonstrator have been successfully conducted and Boom plans to incorporate SAF in its upcoming flight test programmes.

At the same time, Boom is partnering with forward-looking SAF providers, including Prometheus Fuels, to pursue the maximization of the carbon benefits from SAF, e.g. by supporting innovative, disruptive SAF technologies such as direct air capture (DAC) and collaborating to design and certify aircraft fuel systems for using SAF blends up to 100%.

Direct air capture (DAC) technology extracts CO\(_2\) from ambient air and delivers it as a purified, compressed gas to be used as feedstock for the production of SAF. In a separate process, electrolysis is used to split water into hydrogen (H\(_2\)) and oxygen (O\(_2\)). The hydrogen is then mixed with the captured CO\(_2\) to form syngas, which, using the Fischer-Tropsch process, can be transformed into jet fuel: synthetic paraffinic kerosene (SPK) which is certified for use in commercial aviation up to a 50% blend with conventional fuel.

DAC technology has matured significantly in recent years and provides a potential pathway to deliver net-zero carbon propulsion. Because atmospheric CO\(_2\) can be reused indefinitely, this effectively creates a closed loop, short-term carbon cycle. Life-cycle GHG emissions for this type of fuel have been estimated at 0.49 kg CO\(_2\) equivalents per litre (kg CO\(_2\)eq/l), i.e. a more than 80% emissions saving compared to conventional jet fuel for which overall GHG emissions have been estimated at 3.03 kg CO\(_2\)eq/l.\(^{19}\)

In addition to substantially lowering CO\(_2\) emissions, other DAC benefits that have been mentioned include its scalability, affordability and flexibility in terms of location and energy input\(^{20}\) while also offering energy storage potential for variable power sources. When renewable energy (solar, wind, hydro) is used for the DAC-process and electrolysis, the end-result is a virtually net zero-carbon jet fuel product, alternatively referred to as solar-, solar thermochemical-, or electro-fuel.

As with other sustainability levers, (structures, materials, propulsion systems and operations), the remaining barriers to scaling up the uptake of SAF are not necessarily of a technical nature, as various technologies are ready for or close to commercial deployment. Rather, the main obstacles lie with the economic, policy and market-related aspects, as SAF remains significantly more expensive than regular jet fuel, logistics chains often require modification, and effective, wide-spread policy incentives are slow to materialize. A package of policy measures to incentivise SAF production and uptake could be considered, including zero rating, reduced compliance obligations, mandates, credits, targets and direct funding.

4.3 CORSIA

In recent years, carbon offsetting programmes have been adopted throughout the aviation sector with a growing number of airlines offering their passengers the opportunity to offset CO\(_2\) emissions from their flight. In some cases, operators have themselves assumed the offset responsibility to offset flight emissions.

Internationally, the International Civil Aviation Organization (ICAO) has been implementing the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) since 2016. The

\(^{19}\) Falter C, Batteiger V, and Sizmann A (2016). Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production. Environmental Science & Technology, 50(1) pp 470

\(^{20}\) https://carbonengineering.com/our technology/
mechanism aims to address any annual increase in total CO₂ emissions from international civil aviation above 2019 levels. It will be implemented in three phases, starting with the early participation of countries on a voluntary basis from 2021 [21]. As of July 2020, 88 countries, representing over 75% of international aviation activity, have expressed their intention to voluntarily participate in the CORSIA mechanism from its outset. [22]

To complement the net-carbon benefits from SAF, future supersonic operators should be able to claim a reduction in offset obligations based on the use of CORSIA eligible SAF and offset any remaining CO₂ emissions from international flights through the purchase of CORSIA eligible emissions units. [23] The internalization of carbon costs through the use of SAF and CORSIA is an integral part of Boom’s sustainability analysis.

5 Conclusion

The return of commercial supersonic flight means spending less time in the air and more opportunities to enjoy moments on the ground. However, as global citizens we are reminded daily of the need to reduce the environmental impact of our economic activities, including air travel. In line with Boom’s vision to make Earth more accessible, therefore, it is fundamental that we take great care of it too.

While fuel efficiency and noise performance have continuously improved for subsonic aircraft, similar gains have not yet been realized to benefit civil supersonic aircraft development. The availability of advanced computational designs and propulsion systems, new materials, route optimization and alternative fuels have convinced a new generation of supersonic OEMs and entrepreneurs, including Boom, that the economic and environmental challenges that once plagued Concorde can be successfully overcome.

Overall, we have approaches to address the physics and economics of commercial supersonic aircraft. With safety always being Boom’s top priority, the main challenge now is to build an airliner that meets all other regulatory and sustainability requirements as well, including internationally agreed standards and recommended practices under ICAO for supersonic LTO noise and emissions, and CO₂ emissions. Boom is actively contributing to the ongoing work in ICAO and supports the timely development of standards to enable the inevitable return of commercial supersonic flight.

END

[21] Pilot Phase (2021-2023), First Phase (2024-2026), Second Phase (2027-2035). The pilot and first phases are voluntary while the second phase must be regarded as a compulsory one for those Member States with an individual share of international activities in the year 2018 above 0.5% of RTK or whose cumulative share is 90% of global RTK.
[22] https://www.icao.int/environmental-protection/CORSIA/Pages/state-pairs.aspx
[23] ICAO Annex 16 – Environmental Protection, Volume IV – Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).