A Methodology for Supersonic Commercial Market Estimation and Environmental Impact Evaluation (Part I)

Colby J. Weit (1), Jiajie (Terry) Wen (2), Akshay Anand (3), Madhukar P. Mayakonda (4), Turab A. Zaidi (5), and Dimitri N. Mavris (6)

(1) Researcher, Aerospace Systems Design Laboratory at Georgia Tech Lorraine (ASDL@GTL) and Centre National de la Recherche Scientifique (CNRS), 57070 Metz, France. Email: cweit3@gatech.edu
(2) Researcher, ASDL@GTL and CNRS, 57070 Metz, France. Email: jwen2@georgiatech-metz.fr
(3) Researcher, ASDL@GTL and CNRS, 57070 Metz, France. Email: aanand@georgiatech-metz.fr
(4) Researcher, ASDL@GTL and CNRS, 57070 Metz, France. Email: m.mayakonda@gatech.edu
(5) Head of ASDL@GTL, 57070 Metz, France. Email: turab@gatech.edu
(6) Director of Aerospace Systems Design Laboratory (ASDL), School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, United States. Email: dimitri.mavris@aerospace.gatech.edu

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ABSTRACT

Interest and effort in re-introducing civil supersonic transport (SST) airplanes as a means of travel have surged in the past decade. Current major endeavours are underway for both commercial and business supersonic vehicles. The value proposition for these aircraft exists for high-net-worth individuals and business-class travellers who value time savings more than the potential cost associated with supersonic travel. Although these new SSTs in development will be more fuel-efficient than the SSTs of the past, they will have higher relative fuel burn (FB) than current subsonic aircraft flying the same routes. Burning more fuel while having less passengers (pax) on board per trip yields significantly higher FB per passenger for these operations. However, the relatively small market capturable by supersonic commercial operations means that in the broader scope of global aviation, the effect of increased FB per pax on fleet-level carbon dioxide (CO_2) emissions is unknown. In addition, due to uncertainties in the effectiveness of sonic boom reduction technologies, it remains unclear whether supersonic over-land flight will be permitted in the future. Part I of this two-part study aims to formulate a methodology that employs a bottom-up approach for estimating the demand of supersonic commercial operations in coming decades, using only publicly available subsonic baseline-fleet data. The constraints and limitations identified while using publicly available data is key to understanding the data requirements for executing market assessment studies of this type. Part II of two-part study will fill many of the gaps identified in this public-data-only Part I, in order to refine the study process and results. After proposing the bottom-up methodology for estimating demand, the procedure is implemented and the environmental impact of the estimated market is determined. The results identify a supersonic commercial flight demand of 47 to 786 daily, global flights in 2035, growing to 71 to 1,180 daily, global flights in 2050, corresponding to low and high demand scenarios, respectively. These fleets will contribute an approximate 1.96 to 28.61 megatonnes (MT) of CO_2 to global aviation emissions in 2035, growing to 3.01 to 43.08 MT of CO_2 in 2050. These emissions in 2035 and 2050 represent a 0.21 to 3.12% and 0.33 to 4.69% increase in CO_2 emissions with respect to the 2018 global subsonic commercial aviation fleet.

1 INTRODUCTION

Nearly two decades after the Concorde ceased operations, efforts to reintroduce supersonic flight have become stronger than ever. Companies like Boom and Aerion are bringing vastly different designs to the market, but they both claim compelling business cases. Recent market studies have shown promising demand for commercial SSTs and supersonic business jets (SSBJs) [1, 2]. Although the business cases for these vehicles target the small population of ultra-high-net-worth individuals and business executives, the number of supersonic vehicles required to meet the market demand is not insignificant. Some studies expect up to 2,000 SSTs [3, 4] and up to 600 SSBJs by 2035 [5]. Despite the excitement and believed outstanding demand for the revival of supersonic travel, many regulatory hurdles and operational constraints are present, and they impose clear limitations on supersonic flight. There are currently no active standards for the certification of new civil supersonic airplanes or supersonic aircraft engines. Additionally, the International Civil Aviation Organization (ICAO), the agency responsible for setting standards of global aviation, has no provision in its current noise certification standard for supersonic aircraft [6]. Furthermore, the United States' Federal Aviation Administration (FAA), a leader in aviation policy and regulation, has an active ban on over-land supersonic flight. Many other countries throughout the world also have similar restrictions on civil supersonic flight. The impact of these restrictions on flight path will vary depending on the geographical location of an origin-destination (O/D) pair. For example, flying supersonically from Honolulu to Los Angeles is much more likely to be feasible than from Los Angeles to New York. As a result, to reliably forecast the commercial supersonic flight demand, fleet and network models are needed to consider the impact of these constraints [7].

Although current civil SSTs in development will be more efficient than their predecessor and bench-mark, the Aerospatiale/BAC Concorde, these aircraft will still have higher relative fuel burn (FB) than subsonic aircraft on the same routes [8]. Unfortunately, this will be true for both supersonic and subsonic cruise conditions. The supersonic cruise operations require much more thrust to overcome supersonic drag, and supersonic aircraft designed for high-speed, high-altitude flight are less efficient during subsonic operation due to their aerodynamic characteristics. In addition to fuel burn and the related CO_2 emissions of SSTs, other emissions such as nitrogen oxides (NO_x) and water vapour are impactful to the global environment. While there are existing regulations for some emissions in landing and take-off operations, no current standards exist for cruise emissions [9]. The high-altitude NO_x emissions of supersonic aircraft have a strong, negative effect on the stratospheric ozone layer, the layer which filters ultraviolet radiation from reaching and harming life on earth [10]. Furthermore, water emissions similarly contribute to high-altitude ozone depletion due to their effects on aerosol reactions that provide a source of ozone loss-related hydrogen oxides [11].

The overall environmental effects of reintroducing supersonics are highly dependent on the forecasted demand of the commercial supersonic operations. This paper is the first of a two-part study that provides a methodology for estimating the commercial SST market demand and evaluating the associated CO_2 emissions due to SST operations. Part I relies solely on publicly available subsonic baseline-fleet data, and Part II utilizes proprietary baseline-fleet data, in an effort to compare the outcomes, identify the validity of underlying assumptions, and understand the key modelling decisions required complete the study with the differing data sets. The following sections in this paper provide background information regarding the assumptions made to develop the forecasting scenarios, a detailed discussion and implementation of the forecasting methodology developed for this research, and an analysis of the results.

2 BACKGROUND

2.1 Need for Global Commercial Passenger Flight Data

One common approach for estimating the demand for future supersonic commercial operations is based on the analysis of current and projected subsonic commercial aviation data [7]. There are two main reasons for this approach preference: First, supersonic commercial service provided by the Concorde between 1976 and 2003 was very limited in terms of routes offered and frequency of the flights, yielding limited insight from the historical data of its operations. Second, since the proposed supersonic commercial aircraft will enter a strong and continually-growing subsonic aviation market, having a precise understanding of the existing market is crucial.

To estimate supersonic operations' environmental impact, it is important to have a representative sample of the expected O/D pairs that will offer supersonic service. By specifying an O/D pair, a mission profile can be generated depending on the scenario (for example, a SST will likely be rerouted to fly a longer path if supersonic flight over-land is prohibited in the low demand scenario). Some assumptions on the performance of proposed vehicle are needed to estimate the fuel consumption during these supersonic fights. O/D pair information is necessary because high level parameters for air traffic measures such as revenue passenger kilometres (RPK) given on a regional basis will not provide enough granularity to enable reasonable estimates on the fuel burn and resulting environmental impact.

The two-part study approach is devised to identify the data gaps that need to be filled if public baseline-fleet data is used, and to understand the value added by using proprietary subsonic baseline-fleet data. In Part I, the commercial supersonic travel demand and environmental impact are estimated based on publicly available information provided by OAG (presented in this paper). In Part II, global, proprietary data acquired from the International Air Transport Association (IATA) is used.

2.2 Gathering Publicly Available Data

As explained previously, the supersonic commercial operations demand forecasting methodology requires O/D-level revenue passenger kilometre (RPK) information. RPKs for a single flight are calculated by multiplying the number of revenue-paying passengers aboard the plane by the distance travelled. RPKs can be aggregated for a segment, timeframe, etc. by multiplying the RPKs by the number of flights in the domain of interest. RPKs for all flights of one aircraft type on a given route can be calculated using Eq. 1:

$$RPK = \#Flights \cdot \#Seats \cdot LF \cdot D \qquad (1)$$

where LF represents passenger load factor (the fraction of seats filled by revenue-generating passengers), and D is distance in kilometres. To calculate annual revenue passenger kilometres on a given O/D pair, the annual number of flights is used for that O/D. Data from various public sources were used to aggregate the information needed to analyse the existing commercial aviation market, and the process is described in this subsection.

2.2.1 O/D Level Data

The first public data source is Routes, part of the Aviation Week Network. Routes publishes the top 100 busiest routes in the world based on the number of passengers [12]. However, the majority of these routes have relatively short flight distances. Only six of the 100 have distances longer than 2,500 km. It is unlikely that routes shorter than 2,500 km will allow a supersonic aircraft to provide enough time savings to warrant operation on that route.

The second source is OAG. The publicly available OAG data provides information of the world's busiest routes by number of flights between March 2018 and February 2019 [13], this year of data will be referred to in this paper as 2018 reference data. The OAG dataset divides the world into 5 geographic regions (Europe, Asia-Pacific, Middle East and Africa, North America, and Latin America). For each region, the top 10 flights are ranked by flight frequency for each of three flight distance categories: short-haul (less than 1,500 km), medium-haul (between 1,501 and 4,000 km) and long-haul (more than 4,000 km). When combined, the data provides 150 routes globally, 50 of which have distances greater than 2,500 km, the assumed minimum distance required for SST viability. This range is a key filtering requirement for SST viability that will be discussed later in section 3. Compared to Routes, OAG has a larger breadth of suitable SST routes. Furthermore, the six Routes O/Ds that are suitable for SST operations are also included in the OAG data. As such, the OAG data is selected as the baseline data set. On a given O/D pair, the OAG data aggregates all flights into a single number that accounts for both airport A to airport B and airport B to airport A cumulatively.

2.2.2 Aircraft Type Data

OAG data provides information on number of flights for each O/D pair. To calculate RPK, the average number of seats per flight on each O/D segment is needed. FlightAware's database [14] is queried to track the different aircraft types flown on every OAG O/D pair during a three-day period. An average seating capacity for every family of aircraft is estimated by accounting for higher percentages of more recent and more common variants of an aircraft family. With the frequency of flights for each type of aircraft on each O/D pair known from the FlightAware data, a weighted average for number of seats is calculated.

2.2.3 Passenger Load Factor Data

Passenger load factor is an important metric for airlines, as it represents the capacity utilization of an aircraft. Average load factor at the fleet-level can be affected by factors such as airline business model, time of year, and geographic regions. In 2019, IATA published statistics on load factor for 2018 based on 6 geographic regions [15]. The values shown in Tab. 1 are applied in each region-based RPK calculation. For flights between regions, the average load factor between those regions is used.

Table 1. Passenger load factor in 2018

Region	Passenger Load Factor
Asia-Pacific	80.6%
Europe	85.0%
Middle East	74.7%
North America	82.6%
Latin America	81.8%
Africa	71.0%

2.2.4 Global Subsonic Passenger RPK Data

Every year, Airbus and Boeing publish their market forecasts for the next two decades [16, 17]. These market forecasts provide insights from the industry on the dynamic global aviation market. To account for the differences in regional economic development and other influential factors, region groupings are introduced. Boeing's approach for region grouping is used for this study because it offers a good balance between simplicity and necessary granularity. Boeing's grouping has 42 total region pairs, which appropriately differentiates different socio-economic regions (e.g. China separate from Southeast Asia). Airbus also differentiates different socio-economic regions but includes more than 150 total region pairs, offering too much granularity for the study at hand.

In addition to region grouping, Boeing's market outlook provides forecasted region pair RPKs and the associated annual growth for the next two decades. This data includes 41 region pairs and an aggregate "rest of the world" catch-all for what falls outside of those pairs.

2.3 Scenario Generation

The generation of scenarios takes the approach of varying selected input parameters and evaluating their effects or sensitivities. This study targets two scenario outcomes, each corresponding to either low or high market penetration, which refers to the difference in resulting demand upon introduction of supersonic commercial services. The first factor that will affect market penetration is the regulation on supersonic over-land flight. With an existing ban of sonic booms over land [18] in the United States and most countries, many O/D pairs with majority over-land flight are not feasible routes. However, if en-route noise standards are introduced in parallel with low-boom technology, the future operability of over-land flight can become feasible. The low demand scenario assumes that low boom technology will not be mature enough for supersonic commercial services in the 2035 window of interest for this study. In this scenario, the supersonic over-land flight ban remains in place. The high demand scenario assumes that the low boom technology and noise standards have matured enough, as previously discussed, such that supersonic over-land flight ban would be lifted by 2035.

The other main scenario drivers are the aforementioned switching percentage of premium class passengers to supersonic service and the required travel time savings to warrant a passenger's switch. Past studies provide limited guidance on these parameters, providing a large range of possible switching percentages to calculate demand [7] or assuming a total demand and attributing that the entire demand is filled by switching or filled by induced demand [19]. Additionally, Liebhardt et al. and Rutherford et al. make different assumptions on the required travel time savings for viable routes (2 hours for [7], 1 hour for [19]), a critical value parameter in identifying a supersonic commercial network. The sensitivities of these scenario drivers are explored further in the research and will be discussed in the results section.

2.4 Commercial SST Vehicle Assumptions

When identifying routes for supersonic operations, all potential routes in the baseline network are evaluated for feasibility and viability given the capabilities of a representative vehicle. Additionally, the fuel burn characteristics of this representative vehicle is required to quantify the scenario-based environmental impact of the vehicle's operations in the identified network. A method for quantifying fuel burn on a given route and aggregating the route-based fuel burn to a global fuel burn is discussed in section 3.

In order to choose a reasonable representative vehicle for this analysis, a survey is conducted of existing vehicles and proposed vehicles that could operate the missions of interest. The two historical SSTs are the Aerospatiale/BAC Concorde and the Tupolev Tu-144. Three companies in the United States are developing new civil supersonic vehicles: Aerion Corporation, Spike Aerospace, and Boom Technology. Aerion and Spike have targeted SSBJ models while Boom is developing a commercial SST. Of the three in-development vehicles, only the Boom Overture is targeting commercial operation. Additionally, it makes more sense to use the airplane closest to future operations (the Boom Overture SST) in the proposed network rather than the vehicles designed and manufactured a half-century ago (the Concorde and Tu-144). As such, this paper will assume a representative commercial SST vehicle similar to the Boom Overture to evaluate the network and will provide the appropriate vehicle-level assumptions [20].

The Boom Overture is a commercial SST in-development capable of operating at Mach 2.2 with a design range of 4,500 nmi (8,300 km). Boom is targeting an entry-into-service of 2023, however, the authors believe that 2025 may be a more realistic entry-into-service (2025 is the assumed base year of SST operations in this study). The expectation of Boom entry-into-service of 2025 is due to delays in the debut of the Boom Technology XB-1 "Baby Boom", a one-third-scale model of the Boom Overture. The scaled demonstrator is a two-seater model, and it will provide Boom Technology with vital knowledge and data in regards to aerodynamic design and calibration, stability and control, avionics. The SST is not specifically a "new technology airplane", but rather is relying on the generations of incremental improvements in computational design, modelling and simulation, materials, and manufacturing processes since its predecessor SSTs to improve performance, noise, and emissions. The quoted Boom Overture maximum-take-off-weight (MTOW) is 77.1 tonnes. The authors believe this number is rather optimistic and have assumed accordingly that this value will be closer to 120 tonnes upon entry-into-service for fuel burn analysis, splitting the difference between the quoted Boom number and Concorde. Further, the ratio of maximum fuel weight (MFW) to MTOW is assumed to be 50%, similar to that of Concorde (51.7%). This assumption gives an MFW of 60 tonnes, as summarized in Tab. 2.

Table 2. Vehicle-level assumptions for the representative commercial SST

Max Range	4500 nmi (8,300 km)
MTOW	120 tonnes
MFW	60 tonnes

2.5 Commercial Supersonic Operation Assumptions

In addition to discussing vehicle-level performance assumptions, vehicle-level operation assumptions are required to evaluate potential network routes. Regarding the integration into existing global airport infrastructure, this research assumes that sufficient runway length exists at major airports of interest for SST operations or that major airports will make appropriate modifications to support commercial SST operations driven by market demand. The take-off field length (TOFL) of the representative SST is non-restrictive for global commercial airport access. This assumption simplifies the need to make a TOFL capability assumption and investigate every airport under consideration to qualify their suitability for supporting SST operations. The assumption of airport compatibility also includes no restrictions due to saturation of landing and take-off time-slots or terminal space.

Since the SST design range is limited to 4,500 nmi (8,300 km), there will be cases within the perspective global network where the route distance of a high-demand O/D pair is beyond the capability of the representative SST. This research approach does not disqualify those routes but rather requires a refuelling stop within the 4,500 nmi requisite range to break the total flight into at most two legs. The time required for refuelling does not invalidate the time savings needed to warrant SST demand.

3 METHODOLOGY

This section describes the methodology used to forecast supersonic service provided by the proposed new commercial SST and its environmental impact. This methodology needs to consider not only the constraints on vehicle and operation, but also the growth of existing commercial passenger market. This forecasting methodology is transparent and can be replicated using publicly available data. It will also serve as a baseline for comparison in the second part of this two-part study where an alternate data set is utilized.

3.1 Global Flight Demand Forecast

Since the period of interest for this study is between 2035 and 2050, and Boeing's current market outlook forecasts the next two decades up to 2038, growth for the following decades are extrapolated based on Eq. 2, where g_i represents growth rate g of the i^{th} decade:

$$g_{i+2} = g_{i+1} + \frac{g_{i+1} - g_i}{2} \qquad (2)$$

When linear extrapolation is used, growth rate of certain regions will become negative, which is unlikely given historical trends. On the other hand, this approach assumes that the growth rate will stabilize over time, important to account for far-future uncertainty. This forecasted subsonic baseline-fleet data to 2050 from the 2018 baseline provides the basis from which the SST market assessment is initiated.

3.2 Supersonic Flight Routing

As mentioned previously, the approach for this study will identify a high demand and low demand scenario relating to market penetration of SST services upon entry-into-service. The high demand scenario assumes no supersonic over-land flight restrictions, implying that a SST can follow great circle distance (GCD) trajectory, the shortest path on the Earth's surface between origin and destination. For the fuel burn method explained in section 3.5.1, a basic mission profile of flight distance versus flight Mach number is needed. In the high demand scenario, this process is very simple because the trajectory of the flight is uninterrupted by ground-track geography.

The low demand scenario, reflecting the contemporaneous situation of prohibited supersonic over-land flight, makes the trajectory mapping more complicated. First, the over-land flight ban means that an SST will likely need to cover extra distance to fly over water to maximize its supersonic trajectory, often deviating from the ideal, unrestricted path. Then, for situations where it is more efficient to simply fly over-land instead of re-routing the trajectory overwater, the plane must slow down to subsonic speed. If this trajectory also includes getting back to a feasible supersonic path, then the aircraft must accelerate up to supersonic cruise speed again – an expensive effort of fuel burn. Identifying feasible SST trajectories requires trade-off between fuel consumption due to re-routing and additional accelerations and time savings.

To accurately calculate the time savings of supersonic flight under restrictions, the team used a path planning algorithm developed by members of the Aerospace System Design Laboratory (ASDL), with which the authors are affiliated. It is based on the A* search algorithm, and modified with Bresenham's Line of Sight algorithm [21]. This method is expected to be published by ASDL soon.

3.3 Identification of Feasible Routes

A list of requirements is needed to identify the set of subsonic routes that is feasible and viable for supersonic service. The requirements that make a route feasible for supersonic service are mainly related to vehicle attributes, but requirements for viability can also depend on factors such as flight operations and economics. The supersonic vehicle and operation assumptions are detailed in section 2.4 and section 2.5, respectively. In addition, the list of routes will differ between the high and low demand scenarios due to the presence of over-land supersonic flight restrictions for low demand. Since the subsonic global flight movement is growing over time, the identified supersonic flight frequency will also evolve. After specific flight movements have been obtained, the final step is to analyse the environmental impact of these supersonic flights.

Four requirements are imposed to filter out routes (O/D pairs) that are infeasible or impractical for the low demand, restricted supersonic scenario:

1. Great circle distance greater than 1,500 nmi (2,500 km)
2. Absolute time savings greater than 1.5 hours
3. Relative time savings (time savings relative to overall subsonic trip reference time) greater than 20%
4. Total number of subsonic to supersonic accelerations less than 3

The first requirement will filter out most of the short-haul routes that cannot substantially benefit from SST's higher speed. The absolute time savings requires that the re-routed flight deviating from great circle distance trajectory still saves sufficient time even if it has a long enough distance to hypothetically support SST operations. The relative time savings requirement filters out particular long-haul flights that do not benefit significantly from SSTs because the re-routing over-water enables time savings but not enough. The last requirement on number of accelerations is imposed so that the fuel consumption does not become excessive as a result of many accelerations. The high demand scenario kept criterion one, but criteria two through four are not applicable due to their specificity to restricted, re-routed trajectories. Using the aforementioned requirements, 27 OAG routes for the low demand scenario and 43 routes for the high demand scenario remained.

3.4 Estimating the Market Share of Supersonic Operations

The overarching assumption of this methodology is that the 150 OAG busiest routes are representative of the global commercial passenger flight movements. This assumption implies that total OAG RPKs per region pair are directly proportional to global RPKs in those region pairs, and the market capture (MC), the ratio of RPKs of routes feasible for supersonic flight to the RPKs of all OAG routes, is representative of the proportion of all feasible supersonic routes in the global market. This assumption is necessary due to the limited availability of aggregated O/D flight movements from public data sources, and will be one of the main contrasting factors in Part II of this study.

A majority of future demand for supersonic commercial transport will come from existing subsonic premium class patrons switching to supersonic service, because their time-savings is worth as much or more than the associated increased price of supersonic service. An ancillary, small part of demand will be "induced", coming from two sources. New customers could arise due to the notoriety, prestige, or experience of travelling supersonically. Also, the shortened flight duration means that the number of available trips could increase, allowing premium class patrons to travel more frequently.

The difference between the high and low demand scenarios arises from differing assumptions on the feasibility of supersonic flight routes. Market capture ratio for each scenario is calculated by dividing the sum of high demand and low demand OAG RPKs feasible for SST operations by the total number of OAG RPKs for the 2018 reference data provided by OAG. The regional feasible supersonic RPKs (RPK_{RF}), shown in Eq. 3, would be the market capture ratio for that scenario (low or high) multiplied by the RPKs per region (RPK_{PR}), the latter number provided in Boeing's subsonic market outlook for 2018 and forecasted to 2050 with five year increments from 2020 to 2050.

$$RPK_{RF} = MC \cdot RPK_{PR} \tag{3}$$

The regional actual RPKs (RPK_{RA}) for supersonic operations is calculated using Eq. 4:

$$RPK_{RA} = RPK_{RF} \cdot P \cdot S \cdot (1 + ID) \tag{4}$$

P represents the average percentage of premium passengers on any given subsonic flight, S represents the switching percentage of premium passengers who replace their subsonic patronage with supersonic service, and ID accounts for induced demand.

The number of flights per year between a region pair is calculated using Eq. 5:

$$\#Flights = \frac{RPK_{RA}}{\#Seats \cdot LF \cdot D} \tag{5}$$

This equation requires a distance metric representing the average distance between an O/D in a given region pair. An artefact arising from the OAG data used in this study is an inconsistent distribution of representative O/D pairs across the 42 different region pairs from Boeing's market outlook. Some region pairs have zero, one, or more than one representative O/D pair(s) that come from the OAG busiest routes data. To come up with the distance metric in the above equation, a set of three cases is devised to fill the gap presented by the sparsity of data. A weighted average method is used.

1. When only one flight in the OAG routes list belongs to a particular region pair, that flight is considered as the representative flight of that region pair. This flight distance is then used to estimate the number of flights in Eq. 5.
2. When multiple flights belong to a region pair, the representative flight distance is estimated by the weighted average method based on frequency of each flight provided in the OAG busiest routes data, shown in Eq. 6:

$$D_w = \frac{\sum_{i=1}^{n} \#Flights_i \cdot D_i}{\sum_{i=1}^{n} \#Flights_i} \quad (6)$$

   where D_w is the weighted average distance of that region pair, and i is the index of each O/D flight, and n is the total number of flights in that region pair
3. When no flights belong to a region pair, the representative flight distance is taken to be the global weighted average distance based on all forecasted SST flights. An alternative approach would be to pick one or more representative mission(s), but the choice would be rather arbitrary and the outcome of the restricted scenario will be highly sensitive to the missions chosen

Once the number of annual flights per region pair is estimated, fuel burn is estimated for the available routes that have been identified.

3.5 Environmental Impact Analysis

Without the rigor of physics-based modelling and simulation, a projection-type approach based on historical data is used to estimate the fuel burn of the new generation of commercial SSTs. Combined with global O/D pair data and flight demand growth, fuel burn for each flight movement can be calculated and aggregated. Lastly, pump to wake (PTW) CO_2 emission on a global scale can then be obtained to convert fuel burn metrics to CO_2 metrics.

High fidelity mission analysis based on aircraft modelling is deemed unnecessary for two reasons. There is significant uncertainty regarding the performance and efficiency of currently proposed commercial SST. Additionally, a large number of flights need to be analysed, which could become intractable for a physics-based simulation requiring non-trivial computation. To overcome these issues, a methodology is devised for estimating the fuel burn of a hypothetical commercial SST based on historical data, assumptions on the aircraft's maximum take-off weight, and other high level parameters. Regarding historical data on operated commercial supersonic transport vehicles, only flight manuals from the Concorde are available in the public domain. These flight manuals and their data are used to formulate the FB estimation method.

3.5.1 Method for Fuel Burn Calculation

For a typical supersonic flight route that contains a mixture of subsonic and supersonic segments, this method for fuel burn calculation requires the information in Tab. 3 on fuel consumption.

Table 3. Required inputs for mission fuel burn

Cruise (Specific Distance in nmi/tonne)	
Subsonic	$f(D_{sg}, m_i)$
Supersonic	$f(D_{sg}, m_i)$
Acceleration (Fuel Burn in tonne)	
M = 0 - 0.95	$f(m_i)$
M = 0.95 - 2.0	$f(m_i)$

Average specific distance d_s during cruise is a function of distance of that segment, D_{sg}, and initial mass of that segment normalized by MTOW, denoted by m_i. Absolute fuel burn depends on m_i. Fuel burn during decelerations is assumed to be negligible.

3.5.2 Gathering Historical Data

The first step involves the gathering of historic data. Due to the limited number of historical commercial supersonic aircraft, subsonic commercial aircraft are considered first. While the fundamental tube and wing architecture of subsonic configurations has remained unchanged for decades, incremental technology advancements have chipped away at their remaining inefficiencies. After surveying a diverse set of current and recent-past subsonic airliners serving medium-haul flights (on the range of 1500 – 3500 nmi), a clear linear trend is observed between specific distance, measured in nmi per tonne, and the natural log of MTOW.

This trend is depicted in Fig. 1. The next step is to obtain Concorde's specific distance during subsonic and supersonic cruise. From the Concorde flight manual published by Air France [22], specific distance for most efficient subsonic and supersonic cruise climb are obtained. With this data, the relationship between specific distance and the aircraft's instantaneous weight can be correlated.

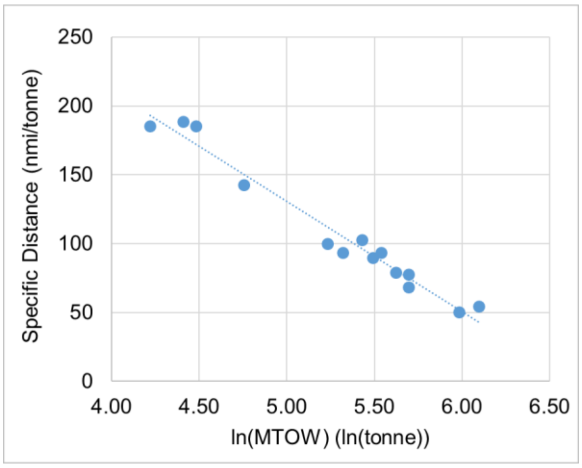

Figure 1. Specific distance vs. ln(MTOW) for airliners serving medium-haul routes

If initial mass M_i and final mass M_f are known (the difference being the mass of the fuel consumed), the distance of a segment, D_{sg}, can be estimated using Eq. 7. Fig. 2 shows the relationship between specific distance (d_s) and mass (M) for Concorde.

$$D_{sg} = \int_{M_i}^{M_f} d_s \, dM \quad (7)$$

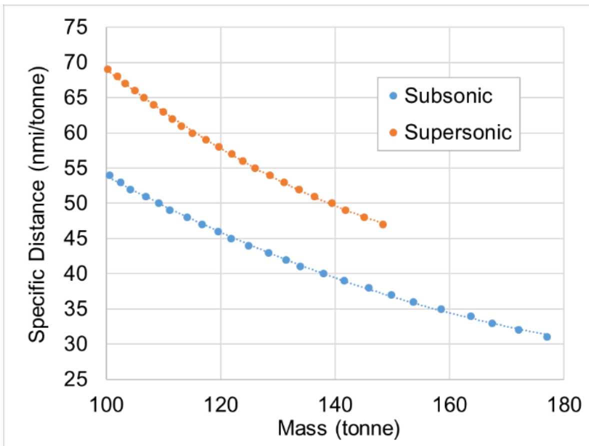

Figure 2. Specific distance vs. instantaneous mass for Concorde's optimal cruise condition

In typical aircraft performance analyses, flight distance is specified and fuel burn is determined, rather than vice-versa. A challenge of using this approach is that not only is FB for a given range unknown, but its value also changes depending on the initial mass of the aircraft. To simplify the calculation, specific distance look-up tables for subsonic and supersonic cruise are created. These tables are referred to as specific distance maps. For any combination of weight fraction of the aircraft (normalized with MTOW) and flight distance, a corresponding specific distance value can be determined. Given a mission profile, the fuel burn for each cruise segment is found using these look-up tables.

In addition, estimates for fuel consumption due to acceleration can also be deduced from Concorde's flight manual. The first type of acceleration is take-off to subsonic cruise (M = 0.95), and the second is subsonic cruise to supersonic cruise (M = 2.0). These values are assumed to vary linearly with the airplane's weight fraction.

3.5.3 Scaling the Fuel Burn Maps

The proposed new generation of supersonic commercial transport will be smaller than Concorde and has a lower MTOW. It is difficult to generate a new trend line for SSTs due to limited historical data. Thus, the trend line for subsonic aircraft, developed previously, is used to estimate the specific distance for the new commercial SST with Concorde being the reference aircraft. The slope of the new trend line is assumed to be same but with a shift in the intercept. This shift can be attributed to differences in engine type, aerodynamics, and other supersonic design factors. This process is shown in Fig 3. for scaling one pair of data points from Concorde.

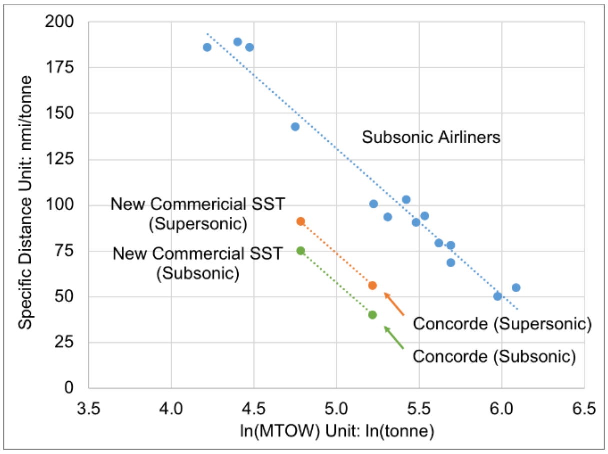

Figure 3. Estimating specific distance of future commercial SST based on historic data

In addition to the two specific distance maps for subsonic and supersonic cruise, acceleration fuel burn values are adjusted by scaling with the ratio of MTOW between the new SST and Concorde. To obtain enough thrust during take-off and transonic acceleration, Concorde's Rolls-Royce/Snecma Olympus 593 turbojet engines use afterburners that are extremely inefficient. According to Boom [23], during take-off Concorde's afterburners increase fuel consumption by 78% while adding only 17% extra thrust. This might represent a worst-case scenario, but it speaks to how inefficient the Concorde's afterburners were. Due to the introduction of new engine technologies, future commercial SSTs will not use engines with afterburners. A 60% reduction in fuel consumption is applied to the scaled acceleration fuel burn values. This reduction is a reasonable estimate for typical non-afterburning engines.

3.5.4 Incorporating Technology Improvements

Benefiting from more than 50 years of technology advancement, the proposed commercial SST will be more efficient than Concorde. After the specific range maps are scaled by MTOW, a percentage improvement is applied to achieve the design range. For the new SST with MTOW of 120 tonnes and 4,500 nmi of max range, the efficiency improvement (for specific range) is 7%.

3.5.5 CO_2 Estimation

It is important to understand the impact of supersonic commercial service on greenhouse gas emissions on a global scale. Since this is a new type of vehicle with considerably higher fuel burn per passenger on a given trip, the associated emissions are of strong interest to environmental regulators and climate scientists. For conventional jet fuel, the commonly accepted value for carbon dioxide generated by the aircraft is 3.15 kg of CO_2 per kilogram of jet fuel burnt [24]. Due to the lack of a representative O/D for every region pair in the public domain data set (discussed previously in section 3.4), fuel burn cannot be calculated for a representative O/D for every region pair. A similar weighted average method is implemented such that region pairs with representative O/Ds have fuel burn calculated using the fuel burn map method described. The region pairs without representative O/Ds use the global average fuel burn per flight from the list of filtered OAG O/Ds.

4 RESULTS AND DISCUSSIONS

The outputs of the implementation of the overall methodology for market estimation and fuel burn assessment are flights per day and annual carbon dioxide emissions in target years of 2035 and 2050. Tab. 4 provides the resulting data for these scenarios on daily flights, while Tab. 5 and Tab. 6 provide the data for CO_2 emissions. The first two rows of data in Tab. 4 represent the percentage of total RPKs globally on routes that are feasible for SST operations. These percentages are derived from the OAG data as described previously and will be verified and refined as needed in Part II of this study when more extensive data is incorporated into the analysis.

Table 4. Results for flights per day for target years and high & low cases for switching %

	Year	**2035**	**2050**
	% High Demand	4.66%	4.58%
	% Low Demand	3.15%	3.15%
5% Switching Factor	**# Flights Per Day (High Demand)**	79	118
	# Flights Per Day (Low Demand)	47	71
50% Switching Factor	**# Flights Per Day (High Demand)**	786	1180
	# Flights Per Day (Low Demand)	465	711
Assumed Percentage Premium Passengers: 15%			

The percentage of subsonic passenger RPKs that are generated by premium passengers capable of switching to SST operations is set to 15% for the sake of reporting results and the induced passenger demand percentage is set to a 1% increment on total SST demand. The percent premium pax is an assumed value in the first part of this study, but this number will be verified and updated as needed using more detailed data in Part II. Additionally, high and low cases of the ratio of premium class passengers that actually switch to SST operations are provided in the tables as 50% and 5%, respectively. Tab. 4 shows the outcome of these factor settings to have a range of 47 to 786 daily flights of SSTs globally in 2035 depending on the switching factor and scenario. For 2050, this range increases to 71 to 1,180 daily flights. The wide range of possible outcomes allude to the input uncertainty and scenarios. The range represents a set of possible outcomes, not a deterministic value, to reflect the uncertainty and sensitivities included. The data shows that the over-land flight restriction inherent in the low demand scenario leads to a 34% decrease in demand, manifested in a reduced number of flights per day by the same percentage. These daily flight numbers are quite low relative to claims from other sources, although the other sources do not propose a bottom-up market estimation but rather claim a value that comes from proprietary market studies. Rutherford et al.'s [19] analysis claims 5,000 daily flights per day for an unrestricted (i.e. high demand) scenario in 2035 compared to the 786 daily flights estimated in this study. The disparity is partially due to the assumptions required in this study given the utilized public data set, and will be verified or changed in the second part of this study. However, none of the assumptions in this study are extraordinary to the extent which could be directly ascribed to the order of magnitude difference. This outcome suggests that the 5,000 flights per day number is most likely to be overly optimistic for what the market will actually demand in 2035.

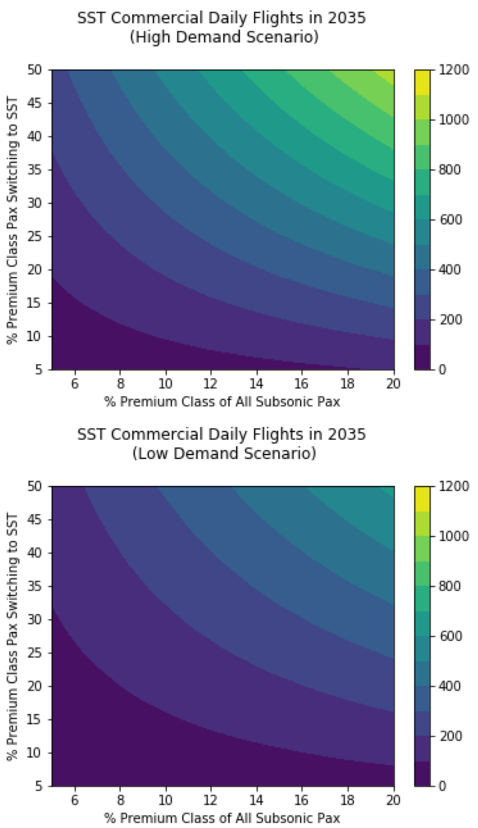

Figure 4. Sensitivity of assumed % on flights per day outcome in 2035 (both scenarios)

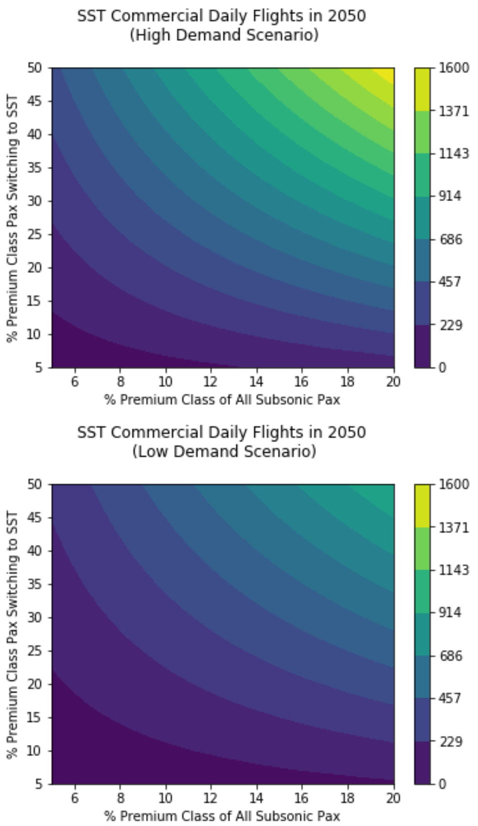

Figure 5. Sensitivity of assumed % on flights per day outcome in 2050 (both scenarios)

Fig. 4 and Fig. 5 provide contour plots of the sensitivity of the assumed percentage factors to the overall number of flights predicted in 2035 and 2050 years. Intuitively, as the fraction of subsonic passengers capable of switching and the fraction of premium passengers that actually switch increase, the overall demand (and therefore daily flights) increase. Both of these parameters have a linear effect on the outcome number of daily flights such that a unit change in the parameter will create a unit change in the number of daily flights. This result implies that the assumptions used for each parameter should be considered with equal weight due to their equal influence.

Tab. 5 shows the data corresponding to the carbon dioxide impacts of the associated estimated market demand for SST flights. Tab. 6 shows the relative CO_2 in the target years of operation for SSTs with respect to 2018 value of 918 MT for global subsonic commercial aviation as reported by [25]. In 2035, the predicted CO_2 emissions are 1.96 to 28.61 MT of CO_2. In 2050, the predicted CO_2 emissions are 3.01 to 43.08 MT. Referring to Tab. 6, the 2035 values correspond to a 0.21 to 3.12% increase over the 2018 reference emissions, and the 2050 values correspond to a 0.33 to 4.69% increase over the 2018 reference emissions, depending on the outcome of the high demand and low demand scenarios. These percent contributions to global aviation emissions on the high demand scenarios are not insignificant. Given the multiple hundreds of thousands of flights per day in 2020, only growing as time moves forward, an increase in emissions by a few percent due to approximately 500-1,000 additional flights per day is quite meaningful, and satisfies the Part I objectives of estimating the market demand and associated environmental impact of future SST operations.

Table 5. Results for yearly CO_2 emissions for target years and high & low cases for switching %

	Year	2035	2050
5% Switching Factor	**CO_2 Emissions (MT) (High Demand)**	2.86	4.31
	CO_2 Emissions (MT) (Low Demand)	1.96	3.01
50% Switching Factor	**CO_2 Emissions (MT) (High Demand)**	28.61	43.08
	CO_2 Emissions (MT) (Low Demand)	19.58	30.05
Assumed Percentage Premium Passengers: 15%			

Table 6. Results for relative CO_2 of SST operations in target years relative to 2018 global CO_2

	Year	2035	2050
5% Switching Factor	**% Relative CO_2 Emissions (High Demand)**	0.31%	0.47%
	% Relative CO_2 Emissions (Low Demand)	0.21%	0.33%
50% Switching Factor	**% Relative CO_2 Emissions (High Demand)**	3.12%	4.69%
	% Relative CO_2 Emissions (Low Demand)	2.13%	3.27%
Assumed Percentage Premium Passengers: 15%			
2018 CO_2 Emissions Subsonic Fleet Reference: 918 MT			

5 CONCLUSION

Reiterating the constraints posed in Part I of this two-part study, the motivation for using public data while developing the methodology for market estimation and environmental impact assessment enabled the authors to clearly understand the key, driving parameters required in pursuing the target outcome. The gaps bridged from the baseline data set to the target outcome and the resolutions or concessions made in the process are described in the next subsection. Part II of the study will employ a more sophisticated, proprietary data set to understand the validity of the assumptions made and how the results would change given more complete reference data.

5.1 Identified Gaps and Assumptions Made

While processing the public flight movement data from OAG, the key assumption is that the list of 150 routes is representative of the global aviation market. In Part II of the study, this assumption is removed and replaced with O/D-level data to evaluate global routes suitable for SST operations. When identifying supersonic flight demand, the critical assumptions are:

1. The percentage of premium passengers on a given flight is assumed and is made parametric to study sensitivities
2. The percentage of premium passengers switching to supersonic service is assumed and is made parametric to study sensitivities
3. The percentage of induced demand is estimated and the value remains constant

Part II of this study will remove assumption 1 in the supersonic flight demand list above, as premium class data will be used for all global O/D pairs. When modelling the fuel burn of a representative future supersonic commercial transport:

1. The trend between specific distance and log-transformed maximum take-off weight obtained for subsonic airliners is assumed to be suitable for future commercial SSTs
2. The overall design of future commercial SSTs is assumed to be similar to the aircraft configuration of the Concorde such that the fuel burn methodology is applicable using Concorde as a baseline vehicle
3. Engines on future commercial SSTs will not have afterburners
4. Incremental improvements in aviation design and technology will enable future commercial SSTs to achieve the 4,500 nmi of range as claimed

Part II of this study will maintain the fuel burn modelling assumptions, as the proprietary data that will be infused specifically targets the subsonic baseline fleet information for market assessment.

The gaps in flight movement data that were filled during this study are:

1. For RPK calculation, seating capacity is estimated based on the distribution of aircraft types flown on a given route during a sample period
2. Load factor is estimated based on data for six geographic regions and is assumed to be constant throughout the forecast period
3. If a region pair does not have a representative O/D pair from the OAG data, the global weighted average values assessed from the OAG data are used for flight distance and fuel burn

Part II of this study will remove these flight movement data assumptions, as this information is known in the proprietary data set and will be calculated at the O/D-level, withdrawing the need to aggregate O/Ds to their region pair for distance, RPKs, and fuel burn assessments

5.2 Final Summary

Although the main contribution of this paper is in developing the methodology for market estimation and environmental impact assessment by means of a fuel burn analysis, the outcomes of the implementation, detailed in the previous section, are also meaningful. The results derived from this implementation conclude that the high demand scenario of SST operations in the future can have a non-trivial environmental impact as quantified by 2035 and 2050 CO_2 emissions on the order of 3-5% of 2018 reference emissions. These emissions do not consider the additional noise, NO_x, etc. emissions discussed in the introduction that also result from SST operations. Furthermore, the results of the current approach do not corroborate existing claims that there is demand for 5,000 daily flights in 2035, but rather a small fraction of that. With the conclusion of Part I, the authors will follow this paper with Part II, discussing the process and outcomes with the application of more holistic data.

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