Project 010 Aircraft Technology Modeling and Assessment

Georgia Institute of Technology and Purdue University

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Executive Summary

Georgia Tech and Purdue partnered to investigate the future demand for supersonic air travel and the environmental impact of supersonic aircraft. In the context of this research, environmental impacts includes direct CO_2 emissions and fuel consumption. The research was conducted as a collaborative effort in order to leverage capabilities and knowledge available from the multiple entities that make up the ASCENT university partners and advisory committee. The primary objective of this research project was to support the Federal Aviation Administration (FAA) in modeling and assessing the potential future evolution of the next generation supersonic aircraft fleet. Research under this project consisted of four integrated focus areas: (1) Developing a set of harmonized fleet assumptions for use in future fleet assessments; (2) Modeling environmental impact of supersonic vehicles expected to enter the fleet through 2050; (3) Analyzing supersonic vehicle performance using AEDT and (4) Performing vehicle and fleet level assessments based on input from the FAA and the results of (1) and (2).

To develop suitable assumptions for the fleet level analysis incorporating new supersonic vehicles, it is necessary to forecast the future demand for supersonic air travel. Georgia Tech followed a two-step approach that first examines historical data to identify current premium demand (business and first class), and then estimates how such demand would scale for supersonic travel. The first step relied heavily on data derived from the Bureau of Transportation Statistics (BTS) databases, especially the Airline Origin and Destination Survey (DB1B) database, which provided information on passenger itineraries based on a 10% sampling of airline tickets from reporting carriers. For the second step, cost data documented by Airlines for America (A4A) was utilized. The A4A Passenger Airline Cost Index (PACI) was used to establish a baseline airline cost structure based on current operating costs. That structure was then scaled to estimate that of a supersonic airliner. Together, the two steps provided a better understanding of potential demand for future commercial supersonic travel from both a passenger and an airline perspective.

In an independent, but complementary, approach to consider demand and routes for supersonic aircraft, the Purdue team developed a ticket pricing model for possible future supersonic aircraft that relies upon current as-offered business class and above fares for routes that could have passenger demand for supersonic aircraft. Via an approach that considered the size of the potential business class and above demand on a city pair route, the distance of that city pair route, and an adjustment to allow for the shortest trip time by increasing overwater distance of the route, the Purdue team identified 26 potential routes for supersonic aircraft. By providing these potential routes to the FLEET (Fleet-Level Environmental Evaluation Tool) simulation, the allocation problem in FLEET then determines how many supersonic aircraft operate on these routes, giving a prediction of which routes would see supersonic aircraft use and an idea of the number of supersonic flights operated on those routes.

To provide a preliminary estimate for the performance of supersonic vehicles, the Georgia Tech team started by establishing a reference performance for a subsonic vehicle. Quantitative estimates for the impact of supersonic vehicles on the various KEIs, especially fuel efficiency, were then derived based on literature review, future performance targets set by NASA, and engineering judgement. For an appropriate estimation, performance parameters such as cruise lift-to-drag ratio and engine-specific fuel consumption (SFC) values were required. Those values could be determined from preliminary constraint, mission and utilization analyses conducted based on the vehicle's design mission requirements. Georgia Tech developed rapid, interactive tools that incorporated such analyses. They were calibrated using publicly available data for the Concorde and utilized to estimate the impact for two concept supersonic vehicles. The first vehicle represents a 10-12 passenger business jet, while the second represents a 50-60 passenger airliner.

In order to facilitate environmental impact prediction of supersonic aircraft, it was necessary to identify modeling capabilities and potential gaps in existing tools. Georgia Tech identified existing supersonic aircraft models in the AEDT vehicle database, including the Concorde and some military aircraft. These models were reviewed as to how these aircraft were modeled. Coefficients in the AEDT vehicle modeling definitions were identified that pertain to the specifics and peculiarities of those vehicles. Publicly available data were used to gauge the accuracy of AEDT.

Georgia Tech and Purdue exercised their respective fleet analysis tools (GREAT and FLEET and produced for estimates of the fleet level impact of a potential fleet of supersonic aircraft operating in the future.

The outcome of this study is intended to provide a glimpse into the future potential state of supersonic air travel using preliminary estimates of supersonic vehicle performance. Future works should build on the current estimates to conduct more detailed vehicle and fleet performance analyses.

Table of Acronyms

AEDT	Aviation Environmental Design Tool
ANGIM	Airport Noise Grid Integration Model
APU	Auxiliary Power Unit
ASPM	Airspace System Performance Metrics
BADA	Base of Aircraft Data
BPR	Bypass Ratio
BTS	Bureau of Transportation Statistics
CAEP	Committee on Aviation Environmental Protection
CLEEN	Continuous Lower Energy, Emissions, and Noise
CMC	Ceramic Matrix Composite
CMO	Current Market Outlook
DNL	Day-Night Level
DOE	Design of Experiments
ECU	Electronic Control Unit
EDS	Environmental Design Space
EIA	Energy Information Administration
EIS	Entry into Service
EPNL	Effective Perceived Noise Level
ETS	Emissions Trading System
EU	European Union
FAA	Federal Aviation Administration
FLOPS	Flight Optimization System
FPR	Fan Pressure Ratio
GDP	Gross Domestic Product
GMF	Global Market Forecast
GREAT	Global and Regional Environmental Analysis Tool
GTF	Geared Turbofan
HPC	High Pressure Compressor
HPCPR	High Pressure Compressor Pressure Ratio
HPT	High Pressure Turbine
HWB	Hybrid Wing Body
ICAO	International Civil Aviation Organization
LPC	Low Pressure Compressor
LPCPR	Low Pressure Compressor Pressure Ratio
LSA	Large Single Aisle
LTA	Large Twin Aisle
MSC	Mission Specification Changes
NEE	Noise Equivalent Energy
NPSS	Numerical Propulsion System Simulation
nvPM	Non-volatile Particulate Matter
OEM	Original Equipment Manufacturer
OPR	Overall Pressure Ratio
PAI	Propulsion Airframe Integration
R&D	Research and Development
RJ	Regional Jet
RPM	Revenue Passenger Miles
SA	Single-Aisle (Includes both SSA and LSA Classes)
SSA	Small Single Aisle
STA	Small Twin Aisle
TRL	Technology Readiness Level
TSFC	Thrust Specific Fuel Consumption
UHC	Unburned Hydocarbons
USD	U.S. Dollars
VLA	Very Large Aircraft
WWLMINET	World Wide Logistics Management Institute Network

University Participants

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P.I.(s): Dr. Dimitri Mavris (PI), Dr. Jimmy Tai (Co-PI)
FAA Award Number: 13-C-AJFE-GIT-006, -012, -022, -031, -041
Period of Performance: August 1, 2014 – August 31, 2018

Purdue University

P.I.(s): Dr. Daniel DeLaurentis (PI), Dr. William A. Crossley (Co-PI)
FAA Award Number: 13-C-AJFE-PU-004, -008, -013, -018, -026
Period of Performance: August 1, 2014 – August 31, 2018

Project Funding Level

The project was funded at the following levels: Georgia Institute of Technology ($1,547,500); Purdue University ($431,231). Cost share details for each university are below:

The Georgia Institute of Technology has agreed to a total of $1,547,500 in matching funds. This total includes salaries for the project director, research engineers, graduate research assistants and computing, financial and administrative support, including meeting arrangements. The institute has also agreed to provide tuition remission for the students paid for by state funds.

Purdue University provides matching support through salary support of the faculty PIs and through salary support and tuition and fee waivers for one of the graduate research assistants working on this project. While Purdue University provides the majority of the 1:1 cost share for the Aviation Sustainability Center of Excellence (ASCENT) 10-Purdue, an in-kind matching contribution of just under $20,000 came from a gift of the RDSwin-Pro aircraft design software from Conceptual Research Corp.

Investigation Team

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Principal Investigator: Dimitri Mavris
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Project Overview

Georgia Tech and Purdue partnered to investigate the impact of supersonic aircraft on future environmental impacts of aviation. Impacts assessed at the fleet level include direct CO_2 emissions and fuel consumption. The research was conducted as a collaborative effort in order to leverage capabilities and knowledge available from the multiple entities that make up the ASCENT university partners and advisory committee.

The primary objective of this research project was to support the Federal Aviation Administration (FAA) in modeling and assessing the potential future evolution of the next generation supersonic aircraft fleet. Research under this project consisted of four integrated focus areas: (1) Developing a set of harmonized fleet assumptions for use in future fleet assessments; (2) Modeling environmental impact of supersonic vehicles expected to enter the fleet through 2050; (3) Analyzing supersonic vehicle performance using AEDT and (4) Performing vehicle and fleet level assessments based on input from the FAA and the results of (1) and (2).

Due to extensive experience assessing the FAA Continuous Lower Energy, Emissions, and Noise project (CLEEN I), Georgia Tech was selected as the lead for all four objectives described above. Purdue supported the objectives as shown in Table 1, listing the high-level division of responsibilities.

Table 1. University Contributions

Objectives		Georgia Tech	Purdue
1	Fleet Assumptions & Demand Assessment	Identify supersonic demand drivers and supporting airports	Estimate latent demand and flight schedules for supersonic aircraft
2	Preliminary Vehicle Environmental Impact Prediction	(a) Develop estimates of Key Environmental Indicators (KEI) for supersonic aircraft relative to current technology subsonic; (b) Develop estimates of likely operating altitudes (U.S)	Support with expert knowledge
3	AEDT Vehicle Definition	Test current version of AEDT ability to analyze existing supersonic models	N/A
4	Vehicle and Fleet Assessments	Apply GREAT to estimate impact of supersonics in terms of fuel burn, water vapor, and LTO NOx	Apply FLEET to estimate impact of supersonics in terms of fuel burn, water vapor, and LTO NOx

Georgia Tech led the process of conducting literature review on potential future demand for supersonic travel for fleet and technology evolution and evaluation. This work was performed under objective 1 and the outcome was used to support objective 4. Under objective 2, Georgia Tech developed conceptual design tools to estimate the environmental impact of supersonic vehicles relative to subsonic ones. In addition, Georgia Tech used AEDT to its ability to analyze supersonic aircraft performance under objective 3. Georgia Tech also ran GREAT for multiple scenarios to assess the fleet-level impacts of supersonic vehicles.

Purdue applied their FLEET tool under objective 4, using a subset of the fleet assumptions defined in objective 1 and preliminary vehicle impact estimates from objective 2. This activity demonstrated the capabilities of FLEET for assessment of fleet-level environmental impacts as a result of new aircraft technologies and distinct operational scenarios.

Major Accomplishments

The following were the major tasks completed under ASCENT Project 10:

Fleet Assumptions & Demand Assessment

The Georgia Tech team developed preliminary estimates of potential markets and routes for supersonic aircraft based on existing market and demand data as well as a ticket price analysis. Additionally, an airline operating cost model and a parametric aircraft cost scale model was developed in order to estimate the potential required ticket premium for airlines to be able to profitably operate a fleet of supersonic aircraft.

The Purdue team developed the approach to determine what the team calls "supersonic-eligible" routes, with several different filters that can identify routes based on distance between airports, predicted demand for supersonic flights, and percentage of the flight over water. This will provide a flexible and fast way to identify these routes.

Preliminary Vehicle Environmental Impact Prediction
Georgia Tech developed a parametric constraint and sizing environment that allows the user to define key mission parameters as well as capabilities and estimate the required engine and aircraft size and the resulting performance. This was used to estimate preliminary environmental performance metrics for several potential future concept aircraft.

AEDT Vehicle Definition
Georgia Tech investigated and identified the existing gaps in modeling supersonic aircraft in AEDT. The result was a white paper in modeling requirements and potentially required changes to the AEDT code and the associated modeling standards to improve and enable modeling specific aspects of supersonic aircraft and their environmental impacts.

Vehicle and Fleet Assessments
Georgia Tech used the GREAT and IDEA models to simulate the impact of potential supersonic vehicles on the fleet-level performance. Such impact was determined for a number of scenarios with varying underlying assumptions.

The Purdue team has also developed an approach to identify the price of currently offered business and above class tickets and then use this to develop a price for the supersonic aircraft tickets. This is important because of the inability to access reported international ticket price data of any kind. With this approach, the supersonic ticket price model allows the profit-seeking airline module and the passenger price-elasticity module to function in our FLEET simulation.

Milestone(s)

Georgia Tech had four milestones covered this year of performance.

1) The drivers of supersonic demand were identified in Task 1.
2) Using the demand estimate, a list of airports and routes that could support future supersonic aircraft was produced in Task 1.
3) Preliminary Key Environmental Indicators (KEI) for future supersonic aircraft were produced in Task 2.
4) A white paper assessing the ability of AEDT to model supersonic aircraft was developed along with a number of potential improvements needed to improve the accuracy of modeling supersonic aircraft in AEDT.

For Purdue the proposal covering this year of performances listed two milestones:

1) Complete modeling of chosen contractor's technologies.
2) Updated fleet assessment.

The Purdue team is using our own placeholder description of a potential, new supersonic transport aircraft; the representation of this in FLEET matches the most early proposed supersonic aircraft, one that will fly at Mach 2.2 but only during overwater portions of flight.

The Purdue team has also incorporated the supersonic aircraft model and performed initial fleet-level assessments of CO_2 emissions for the single "Current Trends, Best Guess" scenario.

Task 1- Fleet-Level Assumptions Setting and Demand Assessment

Georgia Institute of Technology and Purdue University

Objective(s)

This task focused on identifying and predicting significant drivers of commercial supersonic travel demand. For this year, focus was on U.S. operations. Using scenarios from prior ASCENT Project 10 work, Georgia Tech was to identify drivers of supersonic demand to and from the U.S., including domestic operations and international flight connections arriving to or departing from U.S. airports. In parallel, Purdue was to predict the latent demand for supersonic travel using the same

ASCENT 10 scenarios to bound the potential future demand. Georgia Tech was to use this latent demand to identify specific airports within the U.S. that are likely to support supersonic operations under the various previously defined scenarios. Georgia Tech was to pass this information to Purdue to generate flight schedules (# of ops) for each identified airport. This information would then be used in Task 4 to estimate the impact of supersonic travel on the U.S. aerospace system.

Research Approach – Georgia Tech

To investigate demand for commercial supersonic travel, Georgia Tech followed a two-step approach that first examines historical data to identify current premium demand (business and first class), and then estimates how such demand would scale for supersonic travel. The first step relied heavily on data derived from the Bureau of Transportation Statistics (BTS) databases, especially the Airline Origin and Destination Survey (DB1B) database, which provided information on passenger itineraries based on a 10% sampling of airline tickets from reporting carriers. For the second step, cost data documented by Airlines for America (A4A) was utilized. The A4A Passenger Airline Cost Index (PACI) was used to establish a baseline airline cost structure based on current operating costs. That structure was then scaled to estimate that of a supersonic airliner. Together, the two steps provided a better understanding of potential demand for future commercial supersonic travel from both a passenger and an airline perspective.

Current Demand for Premium Seats

In gauging demand for commercial supersonic travel, Georgia Tech attempted to identify current demand for premium seats. This is because supersonic travel, especially in the near term, is expected to cost more than subsonic travel (due to the increased time savings and increased associated costs). Historical performance of the Concorde also supports that assumption. As a result, identifying current premium passengers became a priority. The 2016 BTS DB1B database provided important information to begin this process. The database not only includes basic travel information such as origin, destination, miles flown, etc., but also includes important information such as number of passengers, fare class, fare per mile, etc. Premium passengers were identified as those who flew in the business and first classes (i.e., BTS DB1B fare classes C: unrestricted business class, D: restricted business class, F: unrestricted first class and G: restricted first class). However, there were some limitations in using the DB1B database. First, the data provided only represents a 10% sample of actual demand and not a full representation of the flying public. It was assumed that such sample was large enough to be representative of total demand. Second, the DB1B database is restricted to U.S. domestic flights only and does not include any information regarding international travel. This was a major limitation since most supersonic operations, especially in the near term, are expected to be transoceanic (for the U.S., this means the majority of international travel across the Atlantic and Pacific oceans). The Georgia Tech team inquired about a more inclusive dataset from the BTS; however, such dataset has restricted access due to proprietary concerns. To overcome this limitation, the team relied on an additional inventory of global flights for which it has access. The inventory provides information on all flights in 2015 including number of seats and number of operations, but unlike the DB1B database, does not specify fare class or number of passengers. Assumptions regarding passenger load factor and premium passenger share had to be made to conduct a preliminary demand assessment. Results for U.S. domestic (using 2016 BTS DB1B database) and global international (using 2015 inventory) demand for premium seats are presented below.

For domestic demand, the cumulative average daily premium passengers was aggregated by fare paid using the DB1B data. This was done by first filtering out all non-premium passengers (BTS DB1B fare classes U: unknown, X: restricted coach class and Y: unrestricted coach class), multiplying the number of passengers by 10 (since the DB1B is a 10% sample of total passengers) and then finally dividing by 365 (since the DB1B is annual). The x-axis of Figure 1represents the fare per mile in 2016 US dollars (calculated by dividing total fare by trip distance). The y-axis represents the cumulative average daily passengers that paid a certain fare per mile or higher. For example, the plot shows that approximately nine daily passengers paid three dollars per mile or higher in 2016 (orange square). The general trend is plotted in blue. Overall, the trend is sensible as it suggests that demand decreases as price increases. For current subsonic operations, it is estimated that the average fare per mile is in the order of 20 cents (shown in green on the plot). It is also estimated that future supersonic operations will target an average fare per mile of 100 cents (shown in red on the plot). This suggests, at least for 2016 operations, supersonic airlines can capture a daily demand of approximately 100 premium passengers (red dotted line).

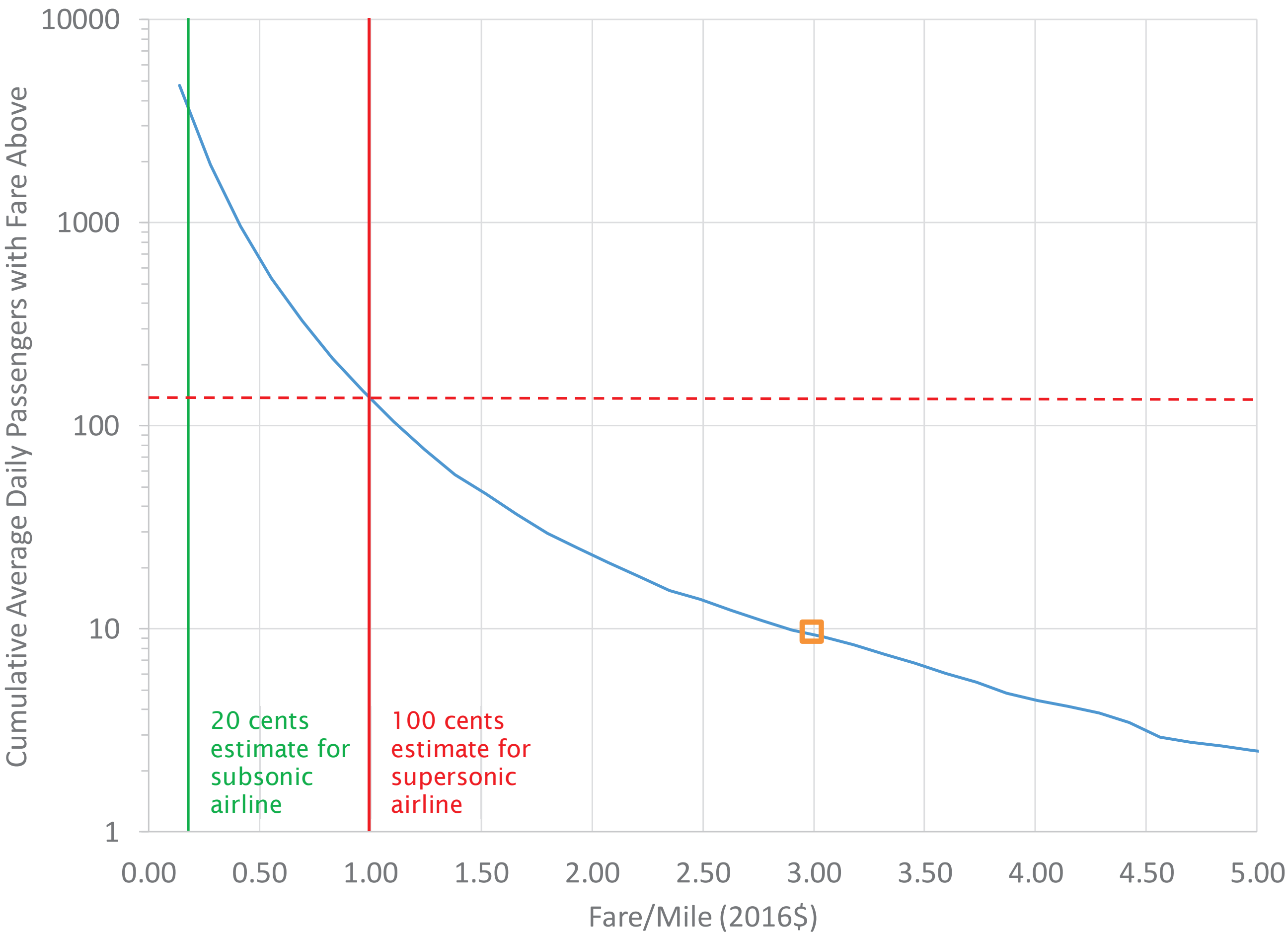

FIGURE 1. DEMAND CURVE ESTIMATION

For international demand, the premium Passengers Daily Each Way (PDEW) was plotted against flight distance for all flights (Figure 2). This was done by utilizing appropriate assumptions for passenger load factor and premium seat share to determine the number of premium passengers (since the inventory only includes number of seats) and then dividing by 365 to compute PDEW. Results from domestic demand analysis were used as a reference to estimate international demand. It is estimated that international demand for supersonic travel would target routes with PDEW values greater than 100 (area above the horizontal orange line). This would provide enough demand to fill a single 100 seat plane with a single flight per day or a 50 seat plane with two flights per day. Furthermore this shows the potential size of the market and it is therefore advisable to target markets that are large enough to support a high load factor without having to capture all of the existing potential demand because that would be unrealistic. It is estimated that supersonic flights, especially in the near term, will be long-haul ones of distances greater than 2000 nmi (area to the right of the vertical orange line). Hence, it is estimated that international supersonic demand would be for routes that lie in the shaded orange area. These routes are listed in Table 2 and plotted on the map shown in Figure 3. The thickness of the lines in the map correspond to PDEW (thicker lines indicate routes with higher PDEW).

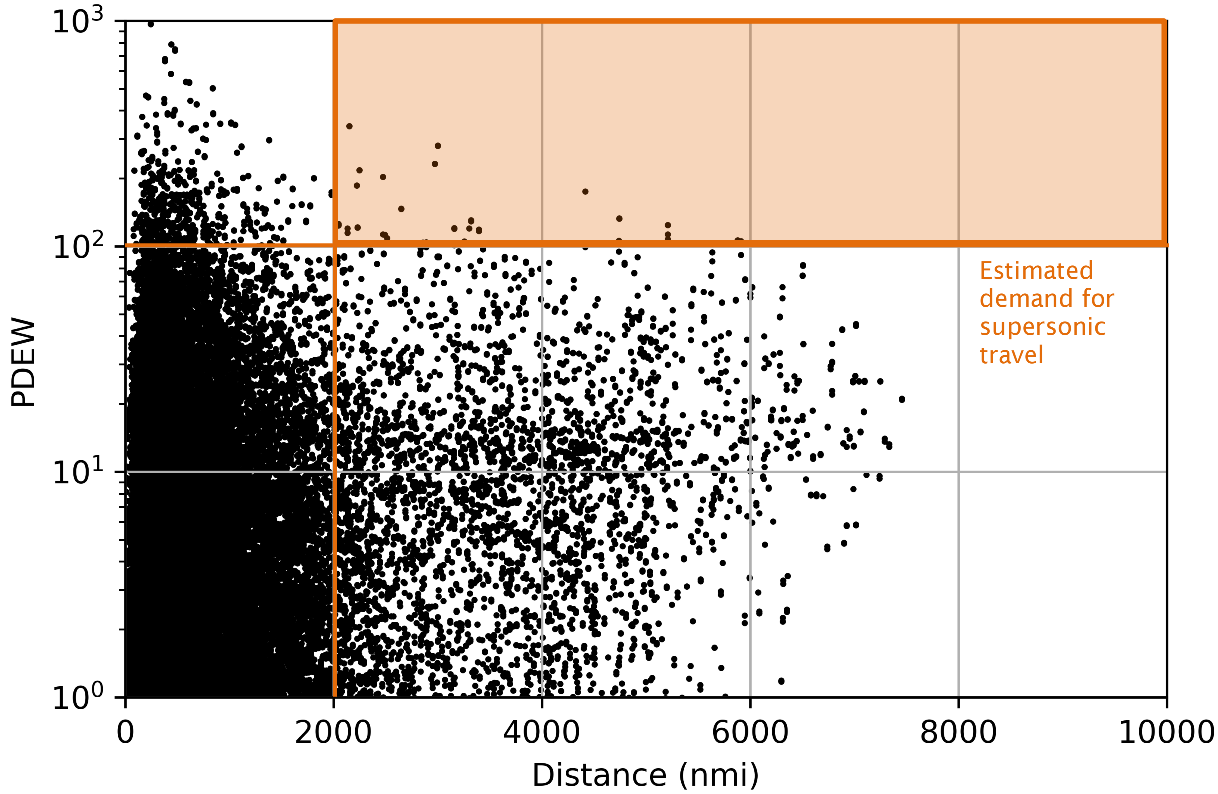

Figure 2. Market Selection

Table 2. List of 50 Airport Pairs with over 100 PDEW and over 2000nmi Great Circle Distance

OPS	SUM_SEATS	GRT_CIRC_DIST	DEP_APT_CODE	ARR_APT_CODE
13372	342	2151	KJFK	KLAX
13372	341	2151	KLAX	KJFK
6946	279	2999	KJFK	EGLL
6925	279	2999	EGLL	KJFK
4144	232	2973	OMDB	EGLL
4139	232	2973	EGLL	OMDB
9186	218	2247	KSFO	KJFK
9177	218	2247	KJFK	KSFO
4802	203	2473	PANC	KORD
6923	186	2221	KLAX	PHNL
7168	186	2221	PHNL	KLAX
4228	175	4415	VHHH	PANC
2545	147	2650	OMDB	VTBS
2541	146	2650	VTBS	OMDB
2965	133	4741	KLAX	EGLL
2946	133	4741	EGLL	KLAX
3476	131	3318	PHNL	RJAA
3452	129	3318	RJAA	PHNL
4092	126	2048	ZSPD	WSSS

2853	124	5209	EGLL	VHHH
2850	124	5209	VHHH	EGLL
3589	124	2048	WSSS	ZSPD
5471	122	2229	KEWR	KSFO
5498	121	2229	KSFO	KEWR
2956	121	3158	KJFK	LFPG
5451	120	2133	KEWR	KLAX
3270	120	3301	RKSI	PANC
2919	120	3158	LFPG	KJFK
3178	119	3395	WSSS	YSSY
2741	117	3395	YSSY	WSSS
5202	115	2133	KLAX	KEWR
2750	113	2473	KORD	PANC
2257	113	5209	KLAX	RKSI
2995	113	2491	RKSI	WSSS
2897	112	2491	WSSS	RKSI
3123	109	2511	VTBS	RJAA
2180	107	5209	RKSI	KLAX
2167	106	5879	WSSS	EGLL
2167	106	5879	EGLL	WSSS
2626	106	4737	RJAA	KLAX
2363	105	5909	RCGM	KLAX
2657	105	3253	YMML	WSSS
2552	105	3253	WSSS	YMML
2520	105	2511	RJAA	VTBS
2695	104	2889	WSSS	RJAA
2547	104	2857	WSSS	RJTT
2545	104	2857	RJTT	WSSS
1987	101	3157	WSSS	OMDB
1990	101	3157	OMDB	WSSS

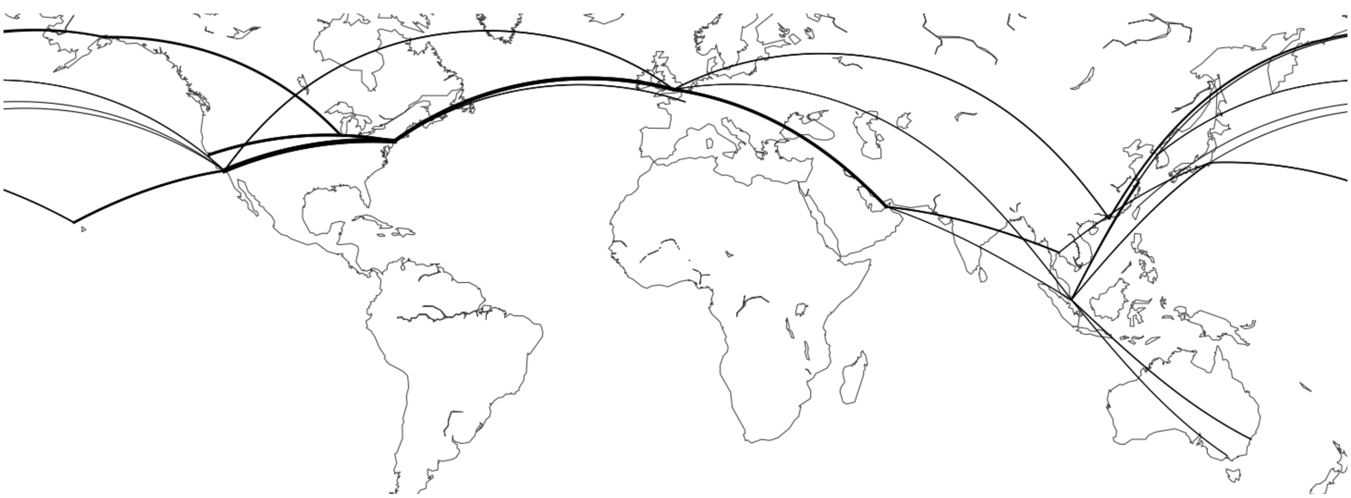

Figure 3. Selected Routes

Potential Airline Market for Supersonic Travel

After analyzing the potential demand from a passenger perspective, the Georgia Tech team investigated the market for supersonic travel from an airline perspective. A4A data for airline operating costs were used to establish a baseline airline cost structure representative of subsonic operations. Specifically, Passenger Airline Cost Index (PACI) data for the fourth quarter of 2016 were used to establish the structure shown in Figure 4. As shown in the figure, 'labor' and 'fuel' costs account for approximately 50% of all airline operating costs. Other major contributors include 'aircraft rents and ownership' and 'professional services'. This baseline structure was assumed to be representative of that for a currently operational reference subsonic aircraft with certain specifications. To estimate a similar cost structure representative of operating costs for a concept supersonic aircraft, the specifications of the latter needed to be estimated relative to those of the reference aircraft. Engineering judgement was exercised, along with some feedback input based on the results of Task 2, to define the specifications of the concept supersonic vehicle. The specifications for both the subsonic and supersonic vehicles are tabulated in Table 3. Using these specifications, and by normalizing the cost structure by flight hour, the baseline airline structure could be adjusted to reflect the differences in various component costs (e.g., fuel and maintenance).

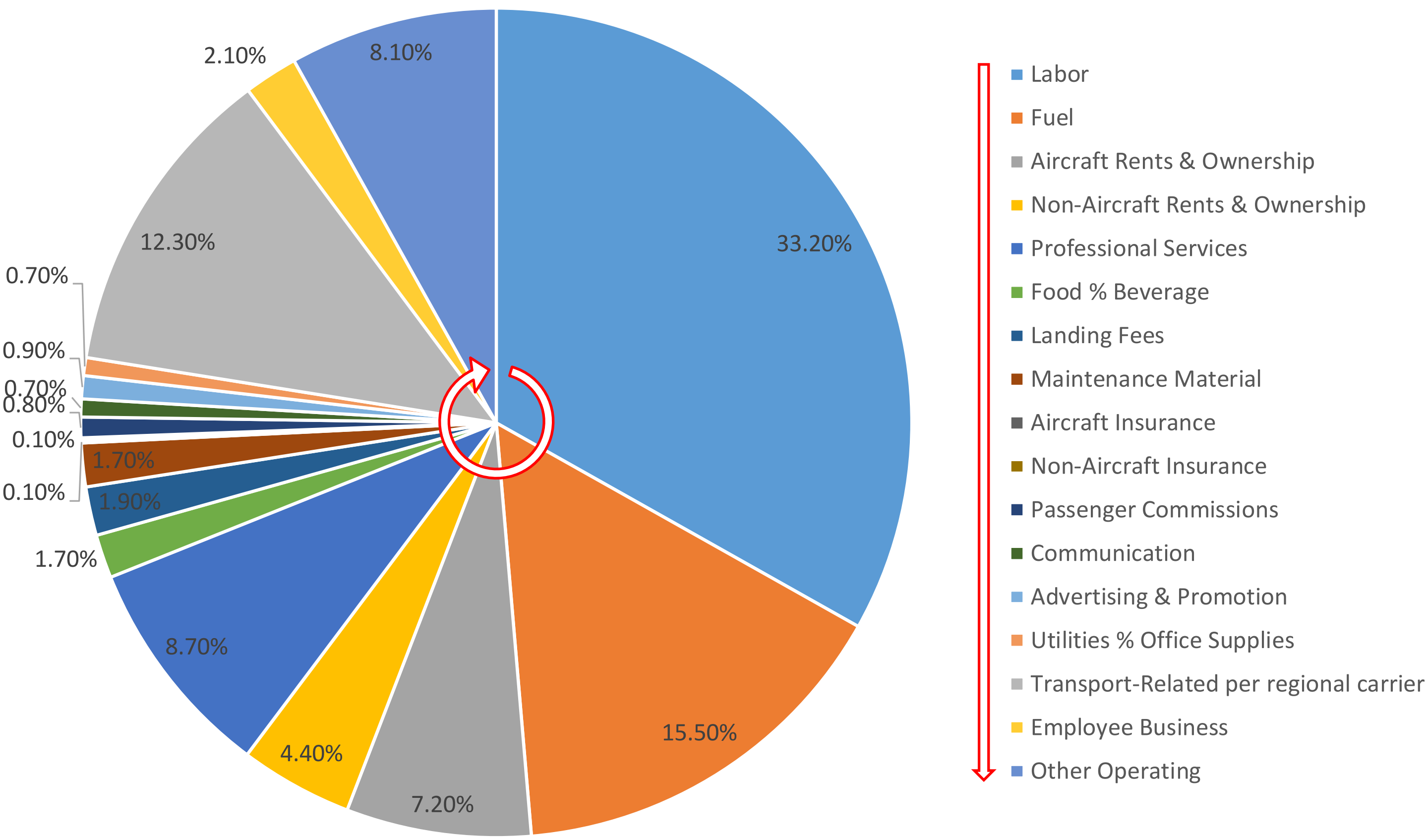

FIGURE 4. COMMERCIAL AIRLINE COST INDEX

An important parameter that was estimated using this procedure was the required yield per seat mile (i.e., the average fare per seat mile). Assuming airline profit margins remain the same as that for subsonic operations, yield directly correlates with operating costs. This parameter was estimated for different utilization and fuel consumption scaling values (Figure 5). The plot above shows the resulting trends. Generally, the more fuel is consumed, the higher the required yield should be to maintain the same profit margins. Alternatively, higher utilization allows for lower required yield values. For the concept supersonic aircraft characteristics assumed (fuel consumption 8 times that of subsonic aircraft and utilization of 1000 hours per year), it was found that required yield would have to be almost 4.5 times that of subsonic operations for airlines to maintain the same profit margins (red square). This means that, on average, airlines would have to charge passengers of supersonic flights 4.5 times more than passengers of subsonic flights.

TABLE 3. RELATIVE COST INDEX ADJUSTMENTS

	Reference Subsonic Aircraft	Concept Supersonic Aircraft
Number of Seats	180	100
Load Factor	0.8	0.8
Block Speed (miles per hour)	500	1350
Utilization (hours per year)	4500	1000
Fuel Consumption (relative per block hour)	1.0	8.0
Maintenance Costs (relative)	1.0	3.0
Acquisition Costs (relative)	1.0	2.0

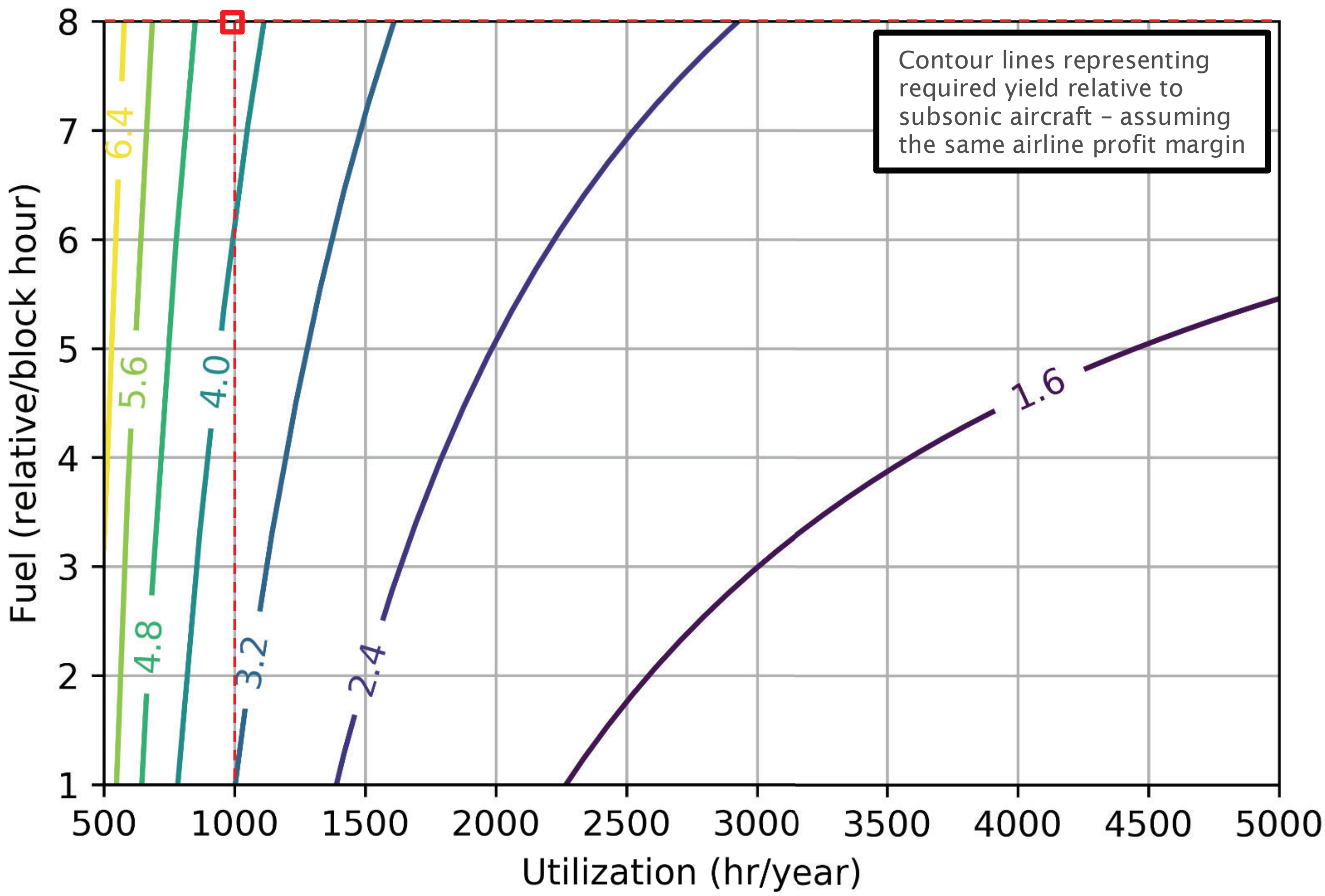

FIGURE 5: RELATIVE REQUIRED YIELD AS FUNCTION OF FUEL MULTIPLIER AND UTILIZATION

Research Approach – Purdue

FLEET Supersonic Simulation Requirements

Supersonic Ticket Price Modeling

One of the first steps in determining ticket prices for supersonic flights is identifying the potential routes where the supersonic aircraft might operate and then use available pricing information about those routes. Considering that the Boom Aerospace concept is a possible first supersonic passenger-carrying entrant that does not make an attempt at low boom flight, the initial supersonic aircraft are most likely to operate on over-ocean routes, where they can fly supersonically over the water. This means that mostly international routes will be “supersonic eligible”. Following discussion from Boom’s website that indicates their aircraft could operate with a ticket price similar to current business class tickets, the Purdue team assumes that the supersonic ticket price would be similar to the current business class ticket prices. With data about historical ticket prices paid for international routes difficult to obtain, the Purdue team is dependent on the current (2017) offered “business class or above” ticket pricing data to model supersonic ticket prices for FLEET simulations.

Supersonic Ticket Price Modeling Components

The Purdue team uses offered “business class or above” ticket price data in 2018 to model the supersonic ticket fare for supersonic eligible routes. However, to use the current (2018) offered “business class or above” ticket price for supersonic aircraft on the eligible routes, FLEET needs a “reference” 2018 supersonic aircraft operating cost. With the no actual supersonic aircraft models currently available, the Purdue team has developed two placeholder strategies to estimate the supersonic aircraft operating cost using a fictitious “reference” aircraft operating cost. These placeholder approaches to model the supersonic aircraft operating cost will be replaced by the actual operating cost incurred by the supersonic aircraft model to be provided by the project partners from Georgia Institute of Technology.

Offered “business class or above” ticket price in 2018

In this work, it is assumed that the supersonic ticket price is similar to the current business ticket fare. The Purdue team employs offered “business class or above” pricing data for modeling the supersonic ticket fares in FLEET. This approach is different from the one being currently employed to model the subsonic ticket fares. In particular, the current approach used for subsonic ticket pricing utilizes data from the Bureau of Transportation Statistics (BTS) Airline Origin and Destination Survey (DB1B) [1] for finding routes with nearly homogenous aircraft size to develop a curve that estimates yield (profitability on a ticket sold to a passenger) as a function of range for each size-class of subsonic aircraft. However, this approach does not translate to supersonic aircraft, because the historical ticket prices paid for international flights from BTS DB1B database is not publicly available. Therefore, the Purdue team’s FLEET model currently calculates the supersonic aircraft ticket pricing by using offered “business class or above” pricing data obtained from the ITA software website [2]. The Purdue team has collected roundtrip offered “business class or above” ticket fare data for all the origin-destination pairs (and destination-origin pairs) of the supersonic eligible routes for 02/09/2018 and selected the median of the ticket price data for every route as the current offered “business class or above” ticket fare.

Reference supersonic aircraft operating cost

To utilize the offered “business class or above” ticket fare data to model the supersonic ticket price in FLEET, a “reference” 2018 supersonic aircraft operating cost is required. The current work utilizes FLEET’s existing class 5 subsonic aircraft as the “reference” aircraft to estimate the supersonic aircraft operating cost. The class 5 aircraft corresponds to a twin-aisle aircraft, which has a much larger seat capacity (approximately 250 seats) than the envisioned first-entry supersonic transports. However, the reason to select FLEET’s class 5 subsonic aircraft as the “reference" aircraft is because of its ability to operate on transoceanic ranges, allowing the Purdue team to get a fairly rough estimate of an inflated operating cost per passenger fora supersonic aircraft with a much smaller payload compared to FLEET’s subsonic class 5 aircraft. Currently, with the reference aircraft selected, two different placeholder ideas have been developed to estimate the supersonic aircraft operating cost.

1. The first placeholder approach assumes that the 2018 supersonic aircraft direct operating cost is equal to the direct operating cost of new-in-class 5 subsonic aircraft in FLEET.

$$DOCpax_{ref\_sup,\,route} = DOC_{new-in-class\,5,\ route}/seats_{supersonic}$$

2. The alternate placeholder approach assumes that the 2018 supersonic aircraft direct operating cost is equal to the average direct operating cost of best-in-class 5 and new-in-class 5 subsonic aircraft.

$$DOCpax_{ref\_sup,\,route} = \frac{\left[\left(DOC_{best-in-class\,5,\ route} + DOC_{new-in-class\,5,\ route}\right)\Big/_{2}\right]}{seats_{supersonic}}$$

In the simulation year 2018, FLEET has both best-in-class 5 and new-in-class 5 subsonic aircraft in service at the same time, leading to the development of the two different placeholder approaches described above. The current simulation results use the second placeholder approach to select the "reference" supersonic aircraft operating cost as an average of the best-in- and new-in-class 5 direct operating costs.

Supersonic Ticket Price Margin Calculation Strategies

The Purdue team has developed three different strategies to model the supersonic ticket price margin. As discussed earlier, the "reference" 2018 supersonic aircraft operating cost is required to use offered "business class or above" ticket fare for calculating the supersonic flight fare margin on each route. The supersonic ticket price margin so calculated is used to determine the supersonic ticket fare for every route using one of the following ticket price models:

Ticket price margin per route

i. This approach uses a route-specific ticket price margin. The margin per passenger for a given route is calculated as the offered 2018 "business class or above" ticket fare for that route, less the fictitious 2018 "reference" supersonic aircraft direct operating cost per passenger for the route.

$$margin_{route} = CurrentOfferFare_{route} - DOCpax_{ref\_sup,\,route}$$

ii. For each supersonic eligible route, the addition of the calculated margin per passenger with the direct operating cost per passenger gives the supersonic ticket fare.

$$Fare_{sup\_ac,\,route} = margin_{route} + DOCpax_{sup\_ac,\,route}$$

Here, the sup_ac index allows for best-in-class supersonic aircraft (EIS 2025), new-in-class supersonic aircraft (EIS 2035), and future-in-class supersonic aircraft (EIS 2045).

iii. This approach ensures that the margin for every route is independent of the other supersonic eligible routes in FLEET. This approach should potentially be able to take care of the variability in ticket fares due to the popularity/ high demand on different routes, mimicking the market behavior fairly. However, as FLEET simulation does not model the competition between different airlines (instead FLEET simulation currently models a single airline), this ticket price model could possibly lead to unrealistic results.

Constant margin across routes

i. This approach is the simplest to implement among all approaches as it is based on average margin that is independent of the route length.

ii. The average margin per passenger for all the routes is calculated as the difference between the offered 2018 "business class or above" ticket fare and the fictitious 2018 "reference" supersonic aircraft direct operating cost per passenger, averaged over all the supersonic routes.

$$margin_{avg} = \Sigma\,(CurrentOfferFare_{route} - DOCpax_{ref\_sup,\,route})/n_{routes}$$

iii. For each supersonic eligible route, the sum of the average margin per passenger with the direct operating cost per passenger gives the supersonic ticket fare.

$$Fare_{sup\_ac,\,route} = margin_{avg} + DOCpax_{sup\_ac,\,route}$$

Here, the sup_ac index allows for best-in-class supersonic aircraft (EIS 2025), new-in-class supersonic aircraft (EIS 2035), and future-in-class supersonic aircraft (EIS 2045).

iv. This approach ensures that the margin is independent of range; the supersonic ticket fare varies only according to the direct operating cost per passenger for different routes. This implies that the profit margin for every route remains constant.

Average margin per passenger-nautical mile

i. This approach is based on using an average margin per passenger–nautical mile metric to estimate the supersonic ticket fare.

ii. The average margin per passenger–nautical mile is calculated as the difference between the offered 2018 "business class or above" ticket fare and the fictitious 2018 "reference" supersonic aircraft direct operating cost per passenger, per route length of every route, averaged over all the supersonic eligible routes.

$$margin\ per\ nm_{avg} = \Sigma \frac{CurrentOfferFare_{route} - DOCpax_{ref\_sup,\,route}}{Range_{route}} / n_{routes}$$

iii. The supersonic ticket fare for every supersonic eligible route is calculated as the sum of the direct operating cost per passenger for the route, and the average margin per passenger–nautical mile multiplied by the route length for every route.

$$Fare_{\sup\_ac,\,route} = \left(margin\ per\ nm_{avg} \times Range_{route}\right) + DOCpax_{\sup\_ac,\,route}$$

Here, the sup_ac index allows for best-in-class supersonic aircraft (EIS 2025), new-in-class supersonic aircraft (EIS 2035), and future-in-class supersonic aircraft (EIS 2045).

iv. In this approach, the supersonic ticket fare is directly dependent on the supersonic route length. This implies that operating a supersonic aircraft on a longer route would lead to a higher profit margin than on a shorter route, reflecting that passengers would be willing to pay more to save more time; therefore, the allocation problem might favor supersonic aircraft on longer routes, if aircraft count, capacity and demand constraints are satisfied, to maximize profit.

Current ticket price model and future work

The Purdue team selected the third ticket price calculation strategy (average margin per nautical mile) exclusively to determine the supersonic ticket fares for eligible routes in the current FLEET simulations. The supersonic ticket prices accommodate the effect of supersonic operation range on an airline's profit margin, as this ticket price model is dependent on the route length. This implies that a supersonic passenger would be willing to pay more for a longer-range flight as there would be more time savings compared to a shorter-range flight. The team investigated and compared the fleet allocation (both subsonic and supersonic), class-wise carbon emissions, and the route-wise airline profit margin for all three ticket price models and concluded that the average margin per nautical mile ticket price estimation model is the most plausible choice for Purdue's simulation of supersonic commercial travel in FLEET. Subsequently, the development of a passenger choice model (i.e., a model that accounts for the "value of travel time" of passengers as a foundation for modeling their choice on routes when both supersonic and subsonic aircraft are available, discussed later on) will accommodate for the effect of passenger time savings on ticket pricing.

Supersonic aircraft cost and performance modeling

The supersonic aircraft modeling task is currently underway and primarily performed by Georgia Tech. In the meanwhile, to produce the initial supersonic scenario simulation results using FLEET, supersonic aircraft models are required. The Purdue team has currently developed 'placeholder' supersonic aircraft models to conduct these initial FLEET simulations. These 'placeholder' supersonic aircraft models will later be replaced by the supersonic aircraft models to be provided by the project partners from Georgia Institute of Technology.

Current supersonic aircraft model 'placeholder'

The Purdue team has developed a 'placeholder' aircraft model that enables the representation of a supersonic aircraft in the FLEET simulations using the existing subsonic aircraft models. In the 'placeholder' model, the aircraft cost and performance modeling are currently accomplished by using 'multipliers' to modify the cost and performance parameter outputs of already existing subsonic aircraft to mimic the operation of a supersonic aircraft.

Current 'multipliers' for aircraft performance

The 'placeholder' supersonic aircraft developed by the Purdue team has a seat capacity of 69 passengers, which matches the seat capacity of a subsonic class 2 aircraft in FLEET. The proposed concept from BOOM would have 55 seats; so applying an appropriate load factor limits the supersonic to 55 seats in the results that will appear below. The fuel burn for the 'placeholder' supersonic aircraft is set to be equivalent to the fuel burn of FLEET's existing class 5 subsonic aircraft. This translates to the supersonic aircraft having approximately 3.5 times more average fuel burn per passenger-nautical mile when compared to a subsonic class 5 aircraft (refer to Table 1). This is done to account for an increased fuel burn expected for a supersonic aircraft when compared to a subsonic aircraft of the same size/class. The supersonic aircraft are expected to require increased maintenance hours, which are represented in the 'placeholder' model by implementing a multiplier of 1.5 times the subsonic class 5 maintenance hours requirement. Table 2 summarizes the 'multipliers' implemented for developing the 'placeholder' supersonic aircraft model for FLEET.

TABLE 4. COMPARISON OF AVERAGE FUEL BURN PER PASSENGER NAUTICAL MILE BETWEEN SUPERSONIC AIRCRAFT AND CLASS 5 SUBSONIC AIRCRAFT

	Representative-in-Class	Best-in-Class	New-in-Class	Future-in-Class
'Placeholder' Supersonic Aircraft [lb/nmi]	0.4745	0.4225	0.4212	0.2312
FLEET's Class 5 Subsonic Aircraft [lb/nmi]	0.1255	0.1346	0.1188	0.0652

TABLE 5. SUMMARY OF 'MULTIPLIERS' USED FOR DEVELOPING THE 'PLACEHOLDER' SUPERSONIC AIRCRAFT MODEL IN FLEET

Cost and Performance Parameters of 'Placeholder' Supersonic Aircraft	Multipliers / Modeling Characteristics
Seat Capacity	Subsonic class 2 aircraft (69 seats)
Fuel Burn	Subsonic class 5 aircraft
Block Time	Overwater calculations and subsonic class 5 aircraft (for overland segment only)
Turnaround Time	1 hour
Crew Cost	Block time calculations and subsonic class 5 aircraft
Maintenance Hours	1.5 times of subsonic Class 5 aircraft
Insurance	Subsonic Class 5 aircraft Insurance
Indirect Operating Cost	Subsonic Class 5 aircraft
Acquisition Cost	Subsonic Class 6 aircraft

In this current work, the supersonic aircraft is expected to fly supersonically overwater only, so the block time for the current 'placeholder' supersonic aircraft is computed according to how much of the flight is overwater. The placeholder model presumes that the supersonic aircraft cruises at Mach 2.2 overwater and Mach 0.95 overland; hence, the total block time considers the time contributions for both its overwater and overland flight sub-segments. For the overland flight (subsonic flight segment), the block time of the supersonic aircraft is equivalent to the block time of class 5 subsonic aircraft already existing in FLEET. The percentage of overwater flight for the supersonic aircraft is calculated using the overwater calculations detailed in the next section. The modified block time equation appears below.

$$Blocktime_{sup} = \left[Blocktime_{sub\_class5}^{min\_time\_route} \times (1 - \%_{overwater})\right] + \left[\%_{overwater} \times \frac{min\_time\_distance}{Sup\_cruise\_spd}\right]$$

Here, the $Blocktime_{sub\_class5}^{min\_time\_route}$ represents the block time of subsonic class 5 aircraft on the minimum time route identified using the supersonic route path adjustment strategy and overwater calculation for supersonic aircraft operation, described in the following section.

Using the updated block time calculations described above, the crew cost for the ‘placeholder’ supersonic aircraft is also modified to incorporate the block time reduction occurring during the supersonic overwater flight segment. The updated crew cost is a factor of the FLEET’s subsonic class 5 aircraft crew cost, with the modified equation appearing below.

$$Crewcost_{sup} = Crewcost_{sub\_class5} \times \frac{SeatCap_{sup}}{SeatCap_{sub\_class5}} \times \frac{Blocktime_{sup}}{Blocktime_{sub\_class5}^{min\ \_time\_route}}$$

As with the previous case, the $Blocktime_{sub\_class5}^{min\ \_time\_route}$ represents the block time of subsonic class 5 aircraft on the minimum time route identified using the supersonic route path adjustment strategy and overwater calculation for supersonic aircraft operation.

Characterizing Supersonic Eligible Routes in FLEET

As part of the first-year effort to include supersonic aircraft, the Purdue team has developed approaches to characterize what the team calls “supersonic eligible” routes. A set of filters was developed to identify which of the 1,940 routes in the FLEET network have enough total passenger demand to support a plausible number of business class or above travelers and are within bounds on minimum range (where there is sufficient range to accelerate to supersonic speed for meaningful block time reduction) and maximum range (to reflect the projected maximum range of proposed supersonic transports). The team has also developed a simple, but credible approach to consider the percentage of each route that is “overwater”. This facilitates scenarios where the supersonic aircraft can only operate above Mach 1.0 during the overwater segment. This overwater approach also considers a simple re-routing that might increase distance flown between airports over that of the great circle distance, but that resulting route minimizes flight time to take advantage of the supersonic speeds.

Route Filters based on 2016 BTS database

The Purdue team has implemented demand and World-Wide Logistics Management Institute Network (WWLMINET) airport [3] filters to determine potential supersonic eligible routes from the 2016 Bureau of Transportation Statistics (BTS) T-100 database. These filters lead to a set of 127 supersonic eligible routes for FLEET simulations. The supersonic route set will be the intersection of the subsonic route set from 2005 BTS T-100 data and the 127 supersonic eligible route set with overwater percentage filter.

Demand filter

The demand filter assumes that the potential supersonic passengers are the current “business class or above” passengers. In FLEET, the travel demand is split such that supersonic (“business class or above”) demand is a fixed percentage (5%) of the total travel demand with subsonic for the remainder. In addition, the supersonic daily demand (5% of the total travel demand) should correspond to 50 passengers or more to make the route supersonic aircraft operation eligible. To determine the number of potential business-class-or-above paying passengers, the Purdue team considered typical aircraft currently flying transoceanic routes. Those aircraft have enough seats in business and above cabins that are roughly 10% of the total seat capacity, albeit with fairly significant variation. Then, the Purdue team assumes that 50% of the daily “business class or above” passengers would be willing to fly supersonic, as a coarse approximation that half of the passengers flying in business class or above cabin are paying that fare (the other half are using upgrades or similar). With the daily demand for “business class or above” travel being set to 10% of the total travel demand, the supersonic daily demand turns out as 5% of the total travel demand. Because the Bureau of Transportation Statistics provides the DB1B Coupon database sample of ticket prices paid only for domestic routes, a direct comparison is not possible. However, an indirect comparison indicates that for all domestic routes in the DB1B for 2016, 4.82% of the reported tickets were business class or above; focusing on domestic flights between 2350 nmi and 4500 nmi, 6.89% of the reported tickets were business class or above. This supports that the 5% travel demand assumption.

Supersonic route path adjustment and overwater calculation (to represent the no supersonic over-land limitation)

The current work considers that the supersonic aircraft can only operate over Mach 1.0 when it is flying overwater. The Purdue team has developed a method to estimate the overwater portion for the supersonic eligible routes, this allows the team to further identify supersonic routes that have a certain percentage of route path overwater (for example, some of our recent studies have used 75% overwater as this additional filter for supersonic eligible routes). This method includes adjusting the supersonic eligible route path from its great circle path to allow the aircraft to operate at supersonic speeds for the longest overwater route segment possible. The re-routing facilitates the selection of the supersonic eligible route path along which minimum flight time is possible (using supersonic speeds overwater and subsonic speeds over-land).

The overwater portion calculations with re-routing technique have the following characteristics:

1. These calculations consider the longest route portion over water without any land portions. The great circle distance is based on the longitudes and latitudes of airports on a spherical earth model.
2. In case small islands lie under the flight path (in the great circle path or during path re-routing), the algorithm checks if the sum of path length before and after the island is greater than 40% of the total flight path. If yes, then the small island is ignored, because we assume that an aircraft can avoid the island by flying around it (and we are interested in the longest overwater route segment).
3. The re-routing technique finds 14 alternate flight path deviations above and below the great circle path. For generating the alternate flight path, the coordinates of the mid-point of the great circle path are determined, followed by incrementing (or decrementing) the mid-point latitude by 1° for each alternate flight path, ultimately changing the departure heading of the aircraft. The 14 alternate routes generated in this study correspond to incremental deviations in departure heading to a maximum of +7° and –7° from the great circle path.
4. Among the great circle path and all the alternate flight paths generated for a route, the minimum time flight path is selected for the supersonic aircraft. The flight time is determined using different flight speeds for overwater and over-land flight operation. The minimum time flight path is hence optimal because of the discrete departure deviations. The flight time for every route is calculated using a supersonic flight speed of Mach 2.2 (at 55,000 ft) for the longest segment overwater and subsonic flight speed of Mach 0.95 (at 35,000 ft) for remaining segments. These simplistic calculations are performed using the following equation:

$$t_{flight} = \frac{P_{overwater}/100}{vel_{sup}} + \frac{1-(P_{overwater}/100)}{vel_{sub}}$$

where, t_{flight} denotes the flight time, $P_{overwater}$ is the percentage of flight overwater, vel_{sup} is the supersonic aircraft speed (Mach 2.2 at 55,000 ft), and vel_{sub} is the subsonic aircraft speed (Mach 0.95 at 35,000 ft).

For example, considering the JFK – NRT route shown in Figure 6, the overwater portion calculation technique finds a minimum time flight path (denoted by red dotted line) with a deviation from the great circle flight path (denoted by solid red line). In this case, the minimum flight time path also has the longest segment overwater amongst all the route path deviations generated by the technique.

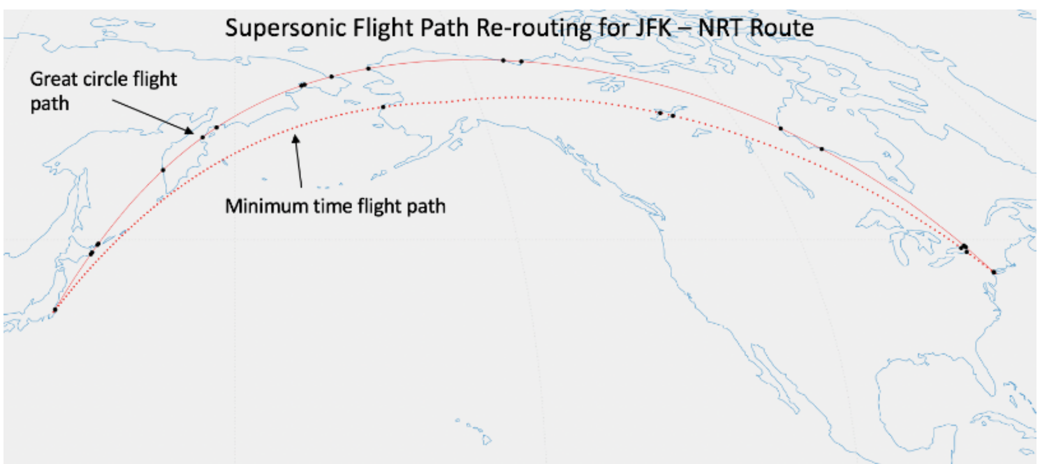

FIGURE 6. DEMONSTRATION OF SUPERSONIC FLIGHT PATH RE-ROUTING FOR JFK-NRT ROUTE TO FIND THE MINIMUM FLIGHT TIME PATH

Supersonic route network with overwater filter

In FLEET, the set of 127 supersonic eligible routes obtained after implementing the demand and airport filters undergo additional filtering with respect to their presence in the existing FLEET route network and their range. FLEET's existing route network of 1,940 routes is based on the 2005 BTS T-100 reported operations. The routes filtered from the 2016 BTS T-100 database are compared to the existing FLEET network to ensure that the supersonic eligible routes are a subset of the 1,940 routes in FLEET. This work considers routes with route lengths between 1,500 nmi and 4,500 nmi. This leads to the inclusion of transoceanic routes, because they meet the required range and have a considerable portion of the flight path over water. The set of 127 supersonic eligible routes reduces to 96 after the application of these additional filters.

For the initial studies, the simulations allow supersonic operation over water only, so the overwater calculations are employed to filter the 96 supersonic eligible routes to give routes that have more than or equal to 75% of flight path overwater. This leads to a set of 26 supersonic eligible routes, which appear on a global projection in Figure 7 where some of the simple latitude deviations for minimum flight time are visible. Table 6 lists all of these routes with distance and overwater percentages. The Purdue team has utilized this set of 26 supersonic eligible routes for producing the current simulation results. As with all routes in FLEET, the aircraft will travel a round trip on the route, so the Amsterdam Schiphol (AMS) to New York – John F. Kennedy (JFK) route also covers flights from JFK to AMS.

FIGURE 7. POTENTIAL SUPERSONIC ROUTES WITH > 75% OF FLIGHT OVER WATER IN FLEET

TABLE 6. FLEET SUPERSONIC-ELIGIBLE ROUTES WITH OVERWATER FILTER AT 75% OR MORE

Airport A	Airport B	Route Length Min Time [nmi]	Percentage of flight path overwater
AMS	JFK	3227.86	76.44
ATL	CDG	3864.97	81.71
BOS	LHR	2939.35	83.75
CDG	IAD	3413.89	88.19
CDG	JFK	3182.62	88.43
CDG	MIA	3981.58	95.40
EWR	FRA	3445.46	78.36
FCO	JFK	3769.93	80.49
FRA	IAD	3622.24	79.73
FRA	JFK	3409.91	78.64
HNL	KIX	3618.86	96.50
HNL	LAS	2397.70	88.07
HNL	LAX	2227.44	99.13
HNL	NRT	3329.67	98.32
HNL	PHX	2531.75	89.12
HNL	SEA	2326.19	96.01
HNL	SFO	2082.62	99.24

HNL	SYD	4412.18	99.27
IAD	LHR	3255.82	81.82
JFK	LHR	3093.34	87.12
JFK	MAD	3120.04	89.26
JFK	MXP	3553.73	83.03
JFK	ZRH	3454.17	81.58
LHR	MIA	3859.46	96.05
MAD	MIA	3837.72	93.71
NRT	SFO	4442.36	99.47

Task 2- Preliminary Vehicle-Level Environmental Impact Prediction

Georgia Institute of Technology and Purdue University

Objective

This task focused on providing a preliminary estimate of the environmental impact of supersonic travel. The likely performance of supersonic aircraft *relative* to existing subsonic transports, for which performance is known, was to be identified. This relative estimation was performed for a number of Key Environmental Indicators (KEI) including fuel burn, emissions, water vapor, likely cruise altitudes, and noise. KEI information was to be compiled for three supersonic aircraft types:

1. Type 1: aircraft that operate at supersonic speeds in unrestricted areas and subsonic speeds over other areas
2. Type 2: same aircraft as Type 1 except that they also have technology to fly at Mach cut-off speeds over prohibited areas. Mach cut-off is a phenomenon that takes advantage of atmospheric characteristics to prevent sonic booms from propagating to the ground (typically works from Mach 1.1 to 1.15)
3. Type 3: aircraft specifically designed to produce very low sonic boom levels during all phases of supersonic flight.

Quantitative estimates for each KEI were to be generated through an extensive literature search of previously developed concepts and active projects in industry and government using sources such as NASA contractor reports, journal and conference publications, and press releases pertaining to concepts under active development. Georgia Tech was to estimate fuel burn, noise, water vapor, and emissions as a function of vehicle size, mission, and passenger capability, using publicly available resources. These estimates were to be compared to baseline aircraft in the subsonic transport category with the goal of establishing an equivalency in each of the KEI metrics.

Research Approach

To provide a preliminary estimate for the performance of supersonic vehicles, the Georgia Tech team started by establishing a reference performance for a subsonic vehicle. Quantitative estimates for the impact of supersonic vehicles on the various KEIs, especially fuel efficiency, were then derived based on literature review, future performance targets set by NASA, and engineering judgement. The subsonic vehicle that was selected as reference was the Boeing 737-800. This aircraft was chosen based on its similar payload-range capabilities compared to both the Concorde and future supersonic vehicles. The KEIs selected were primarily fuel burn, CO_2 emissions, NO_x emissions and noise. The first two KEIs correlate with each other to a great extent. For NO_x, a distinction was made between emissions released during cruise and emissions released in the vicinity of airports at low altitudes during Landing and Take Off (LTO). Similarly for noise, a distinction was made between airport noise and sonic boom noise. The latter is only a characteristic of supersonic vehicles since it is only produced in regimes of supersonic flow. As for targeted performance, NASA goals for supersonic vehicles were used as reference. NASA set vehicle performance goals for the mid-term (business jet size) and far-term (airliner size). Table 7 summarizes the findings.

TABLE 7. COMPARISON OF ENVIRONMENTAL METRICS FOR SUBSONIC AND SUPERSONIC AIRCRAFT

	1976 Concorde	1998 Boeing 737-800	Current Tech. Estimate	2025 NASA N+2	2035 NASA N+3	2035+ NASA N+3 Stretch
Fuel Efficiency (lb/seat/nmi)	0.53	0.10		0.30	0.29	0.22
Cruise NOx Emissions (g/kg of fuel)	23.3	-		<10.0	<5.0	<5.0
LTO NOx Emissions (g)	29,995	8,466		-	-	-
Cumulative Airport Noise Margin Stage 3 (EPNdB)	− 43.2	+ 13.0		-	20	30
Sonic Boom Noise (PLdB)	105	N/A		N/A	70-80	65-75
	Historical Performance		Supersonic	Targeted Performance		

The historical values in the table were derived from various sources. For the Concorde, flight manuals were utilized to determine fuel efficiency in terms of pounds of fuel per seat per nautical mile. Values for cruise NOx emissions and sonic boom noise were determined based on a literature search. As for LTO NOx emissions, the value was determined using the ICAO engine databank. Last, for airport noise, it was determined based on Maximum Take Off Mass (MTOM) relative to Stage 3 certification standards. It is to be noted that the Concorde did not need to meet any noise certification standards. Nevertheless, the noise margin (relative to Stage 3) was calculated for reference. For the Boeing 737-800, similar sources were utilized to gather the required information.

Once values for the Concorde and the Boeing 737-800 were gathered, preliminary estimates for current technology supersonic vehicles (Types 1/2/3) needed to be established. However, for an appropriate estimation, performance parameters such as cruise lift-to-drag ratio and engine specific fuel consumption (SFC) values were required. Those values could be determined from preliminary constraint, mission and utilization analyses conducted based on the vehicle's design mission requirements.

Constraint and Mission Analyses

Preliminary constraint and mission analyses can be conducted based on aircraft mission requirements. A constraint analysis translates a design's performance requirements into constraints on a thrust loading versus wing loading plot. It results in the definition of a feasible design space within which a design point may be selected. Alternatively, a mission analysis flies the chosen design through a mission to determine parameters such as aircraft takeoff weight, thrust requirement and wing area. Both analyses followed the methods outlined by Mattingly et al. in the "Aircraft Engine Design" book. Mission requirements for supersonic vehicles considered in the analyses were as follows:

1. Takeoff ground roll (constraint and mission analyses)
2. Initial climb with One Engine Inoperative (constraint analysis)
3. Accelerated climb (mission analysis)
4. Constant speed climb – subsonic (constraint and mission analyses)
5. Transonic acceleration (constraint and mission analyses)
6. Constant speed climb – supersonic (constraint and mission analyses)
7. Supersonic cruise (constraint and mission analyses)
8. Deceleration and descent (mission analysis)
9. Landing ground roll (constraint analysis)

For constraint analysis, the goal is to establish a relationship between the aircraft's thrust loading (defined as the ratio between sea-level thrust and take-off weight) and wing loading (defined as the ratio between take-off weight and wing area) for every mission requirement. Such relationship is typically of the following form:

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha}\left\{\frac{qS}{\beta W_{TO}}\left[K_1\left(\frac{n\beta W_{TO}}{qS}\right)^2 + K_2\left(\frac{n\beta W_{TO}}{qS}\right) + C_{D_0} + C_{D_R}\right] + \frac{P_S}{V}\right\}$$

where T_{SL} is sea-level thrust, W_{TO} is take-off weight, S is wing area, n is load factor, $\alpha = T/T_{SL}$ is the installed full throttle thrust lapse, $\beta = W/W_{TO}$ is the ratio of instantaneous weight to takeoff weight, q is dynamic pressure, $[K_1; K_2; C_{D_0}]$ are the coefficients of the parabolic lift-drag polar, C_{D_R} represents additional drag caused by, for example, flaps or ground friction, P_S is the weight specific excess power, and V is velocity. When relationships for all mission requirements are plotted together on a thrust loading versus wing loading plot, a design space is defined in which any point selected is a feasible design that meets all requirements. An example plot is shown in Figure 8.

For mission analysis, the goal is to utilize the results of constraint analysis (mainly the selected design point in terms of thrust loading and wing loading) and calculate takeoff weight, sea-level thrust and wing area. This is done by determining the aircraft's fuel consumption throughout the different segments of a design mission:

$$\frac{W_f}{W_i} \approx \begin{cases} \exp\left\{-\frac{TSFC \cdot (D+R)}{W}\Delta t\right\}, & \text{if } P_S = 0 \\ \exp\left\{-\frac{TSFC \cdot T}{V \cdot (T-(D+R))}\Delta z_e\right\}, & \text{if } P_S > 0 \end{cases}$$

where W_f/W_i is the ratio of aircraft final weight at the end of the segment to its initial weight at the beginning of that segment, is the thrust specific fuel consumption, $[T; W; (D+R)]$ are the instantaneous thrust, weight and drag forces, respectively, V is velocity, Δt is the total segment flight time, and Δz_e is the total change in segment energy height. For segments of the first type ($P_S = 0$), all thrust work is dissipated resulting in no speed and/or altitude variation. Examples include constant speed cruise, best cruise Mach number and altitude, and loiter. For segments of the second type ($P_S > 0$), some thrust work is converted to mechanical energy in order to vary speed and/or altitude. Examples include constant speed climb, takeoff acceleration, and horizontal acceleration. An example plot of the progression in aircraft weight due to fuel consumption throughout the design mission is shown in Figure 9.

The ratio of aircraft fuel weight to takeoff weight can be determined using the fuel consumption relations of the different mission segments and accordingly, aircraft takeoff weight can be determined:

$$\frac{W_F}{W_{TO}} = 1 - \prod_{k=1}^{n}\left[\frac{W_f}{W_i}\right]_k \quad ; \quad W_{TO} = {W_P}\Big/\left(1 - \frac{W_E}{W_{TO}} - \frac{W_F}{W_{TO}}\right)$$

where n is the total number of mission segments, W_P is the payload weight and W_E/W_{TO} is the ratio of aircraft empty weight to takeoff weight (typically estimated using empirical relations). Once the aircraft takeoff weight is known, sea-level thrust and wing area can be determined using the design point value in terms of thrust loading and wing loading.

Constraint and mission analyses were integrated in the form of an interactive dashboard that allows the user to parametrically vary mission requirements and underlying assumptions (Figure 10). It was created using 'Bokeh', an interactive library that allows the creation of web front-end visualizations without requiring a large amount of html or javascript development. A screenshot of the dashboard is shown below. Concorde design point and weights are embedded for reference.

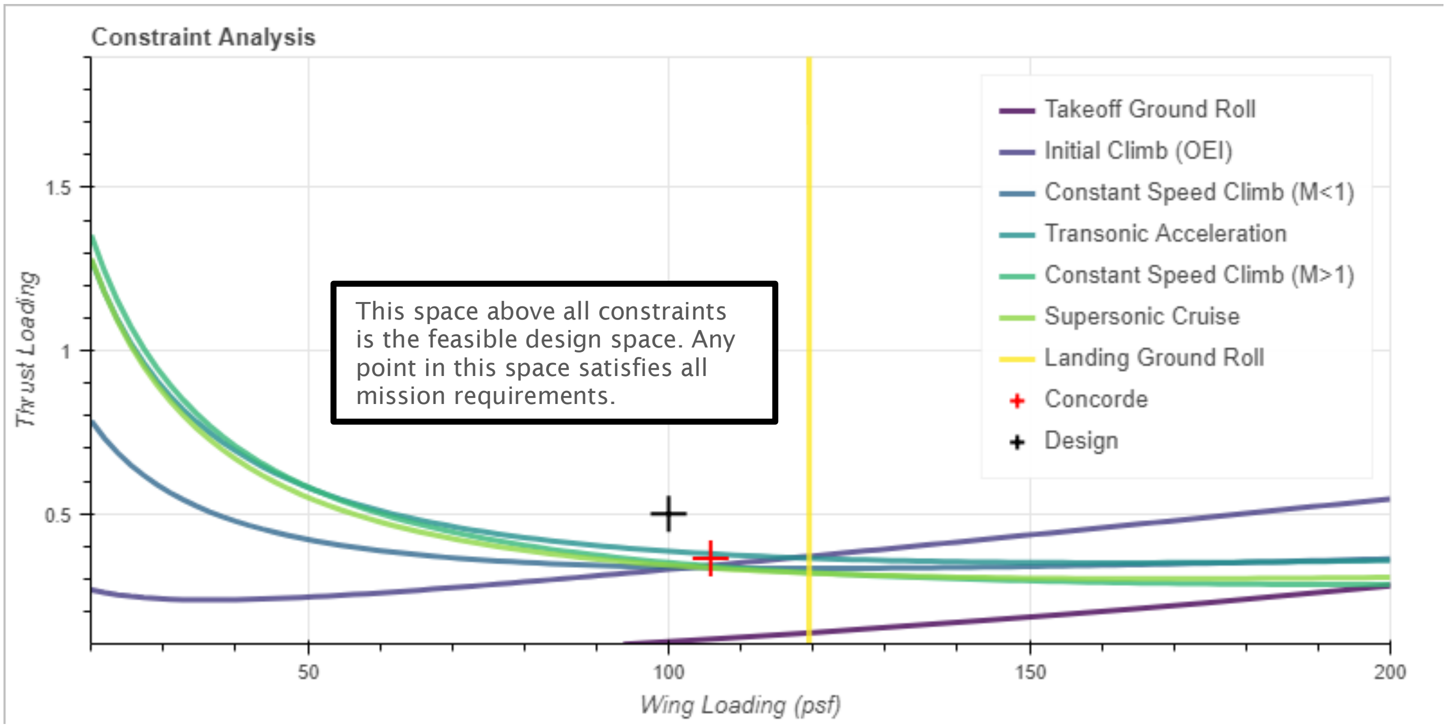

FIGURE 8. CONSTRAINT PLOT

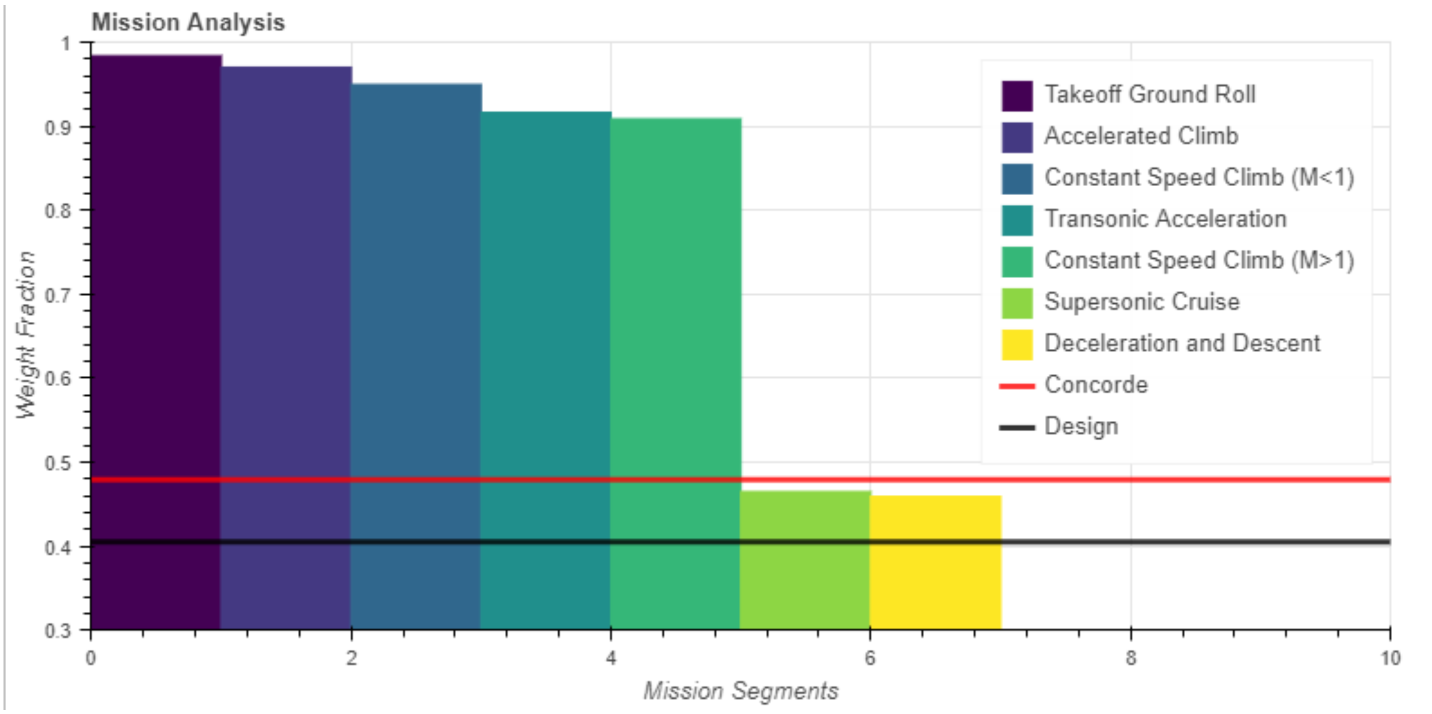

FIGURE 9. WEIGHT FRACTION ANALYSIS

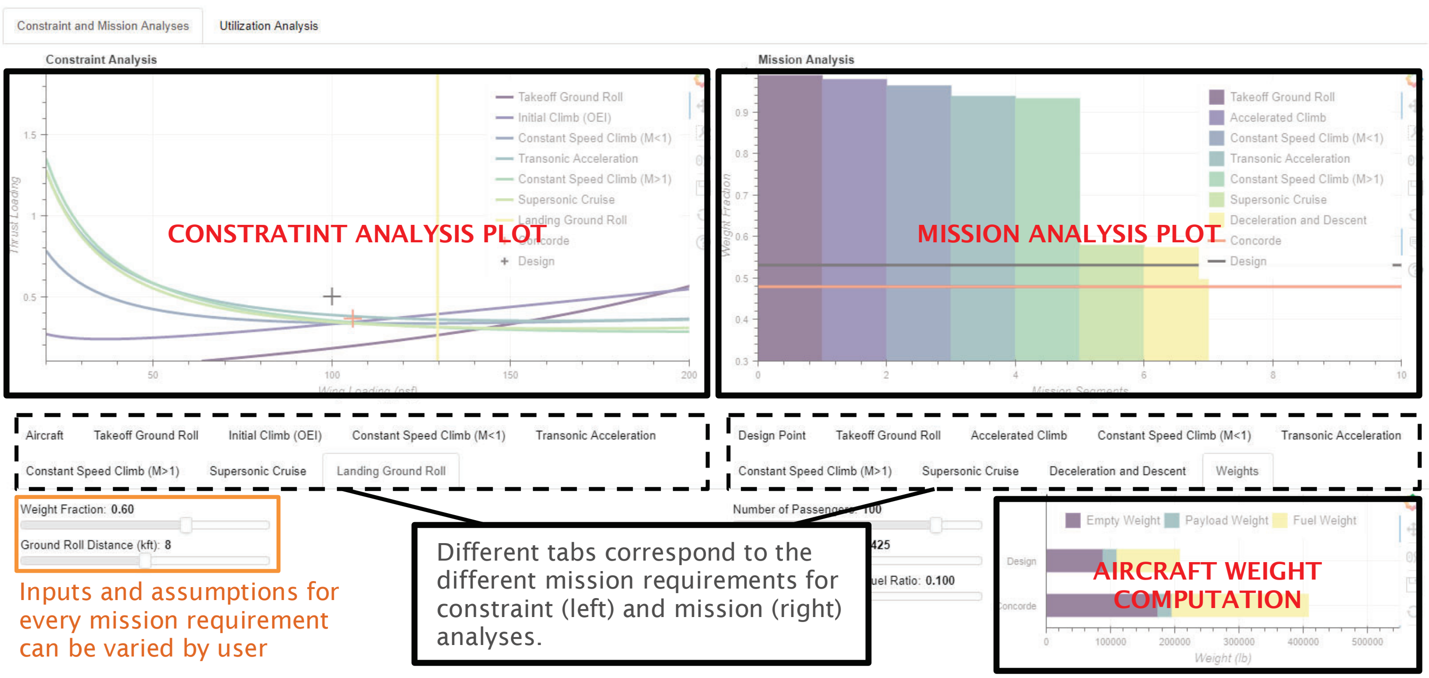

FIGURE 10. SYNTHESIS AND SIZING OVERVIEW

Using publicly available Concorde data (such as cruise lift-to-drag ratio and SFC), the underlying models of the dashboard were calibrated such that the design point and weights of the Concorde were matched (refer to the snapshot below).

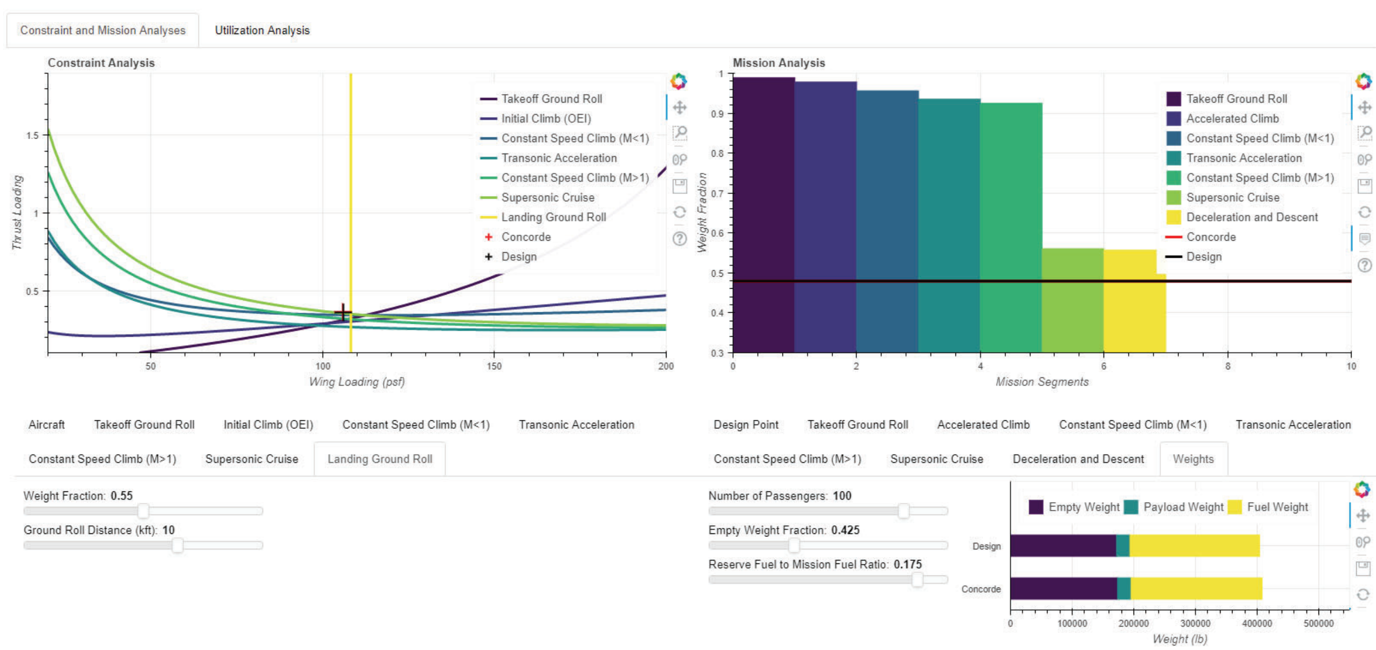

FIGURE 11. MATCHING CONCORDE DESIGN

Next, using the calibrated models, and by utilizing appropriate assumptions to account for efficiency gains in terms of aerodynamics (drag polar), propulsion (SFC) and structures (empty weight fraction), a preliminary assessment of two concept supersonic vehicles was conducted. The first vehicle represents a 10-12 passenger business jet, while the second represents a 50-60 passenger airliner. The two snapshots in Figure 12 and Figure 13 show the results for both vehicles, respectively.

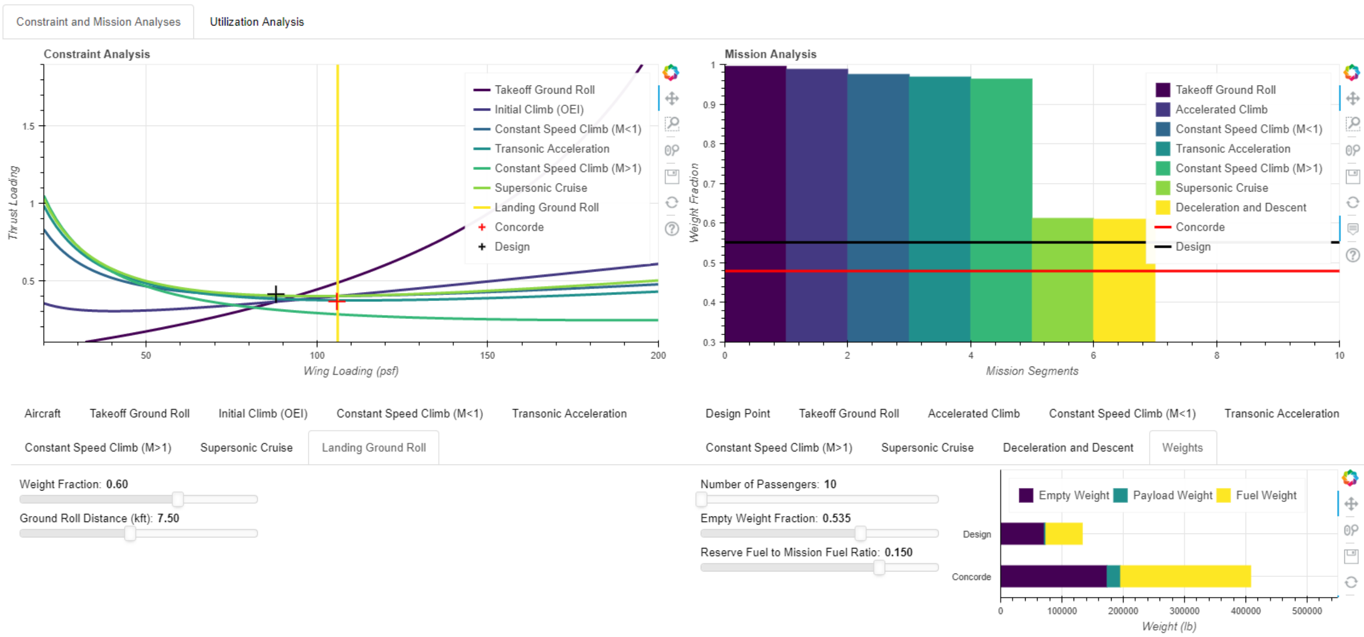

FIGURE 12. EXPLORING A SUPERSONIC BUSINESS JET DESIGN

FIGURE 13. EXPLORING A 55 SEAT SUPERSONIC AIRLINER DESIGN

Aircraft Utilization

Aircraft utilization can be analyzed using general flight and aircraft characteristics. The goal of a utilization analysis is to gauge the potential productivity of an aircraft. For supersonic vehicles, productivity is assessed in terms of the potential time savings per flight (relative to a subsonic vehicle) and the maximum aircraft utilization possible within a 24-hr period. Similar to constraint and mission analyses, utilization analysis was integrated in an interactive dashboard that allows the user to parametrically vary flight and aircraft characteristics. A screenshot of the dashboard is shown in Figure 14.

Total flight time is broken into four components: time to takeoff and climb, time to descend and land, cruise time, and turnaround time (in cases where flight range exceeds maximum design range). The first two are user inputs and are assumed the same for both subsonic and supersonic vehicles. Cruise time for the subsonic vehicle is simply computed as cruise range divided by cruise speed (which is derived from user input Mach number and cruising altitude). However, for supersonic vehicles, cruise time also depends on the percentage of flight over water. This is because supersonic vehicles may be restricted to fly at subsonic speeds over land. Therefore, the percentage of flight over water along with the subsonic cruise settings (for portions of the flight over land) have been embedded in the dashboard as inputs that the user may vary, as shown in orange in Figure 15 (note: to simulate unrestricted operations, percentage over water should be set to 100).

Cruise flight time is hence calculated as:

$$t_{C,sub} = S_C/V_C$$
$$t_{C,sup} = x \cdot (S_C/V_{C,sup}) + (1-x) \cdot (S_C/V_{C,sub})$$

where $[t_{C,sub}; t_{C,sup}]$ are cruise times for the subsonic vehicle and supersonic vehicle, respectively, $[V_C; V_{C,sub}; V_{C,sup}]$ are the cruise speeds for the subsonic vehicle, supersonic vehicle flying subsonically, and supersonic vehicle flying supersonically, respectively, x is the percentage of flight over water, S_C is the cruise range, and $R_{C,max}$ is the maximum cruise range of the supersonic vehicle. For flights that exceed the maximum cruise range of the supersonic vehicle, it is necessary for the vehicle to descend and land, refuel and turnaround, then takeoff and climb back to cruising altitude. Therefore, for every stop that the vehicle needs to make, total flight time is increased by these additional components. The time to turnaround is also a user input (shown in green in Figure 15).

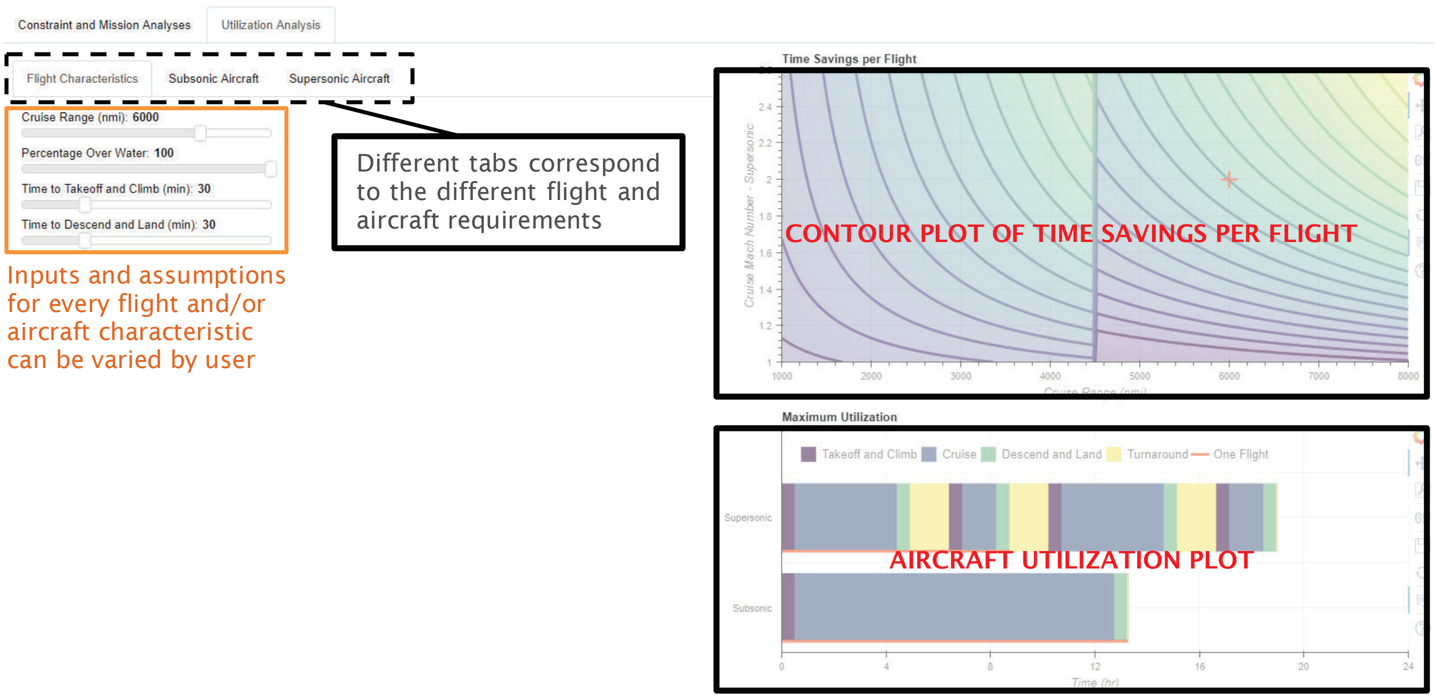

FIGURE 14. EXPLORING MISSION FREQUENCY AND UTILIZATION

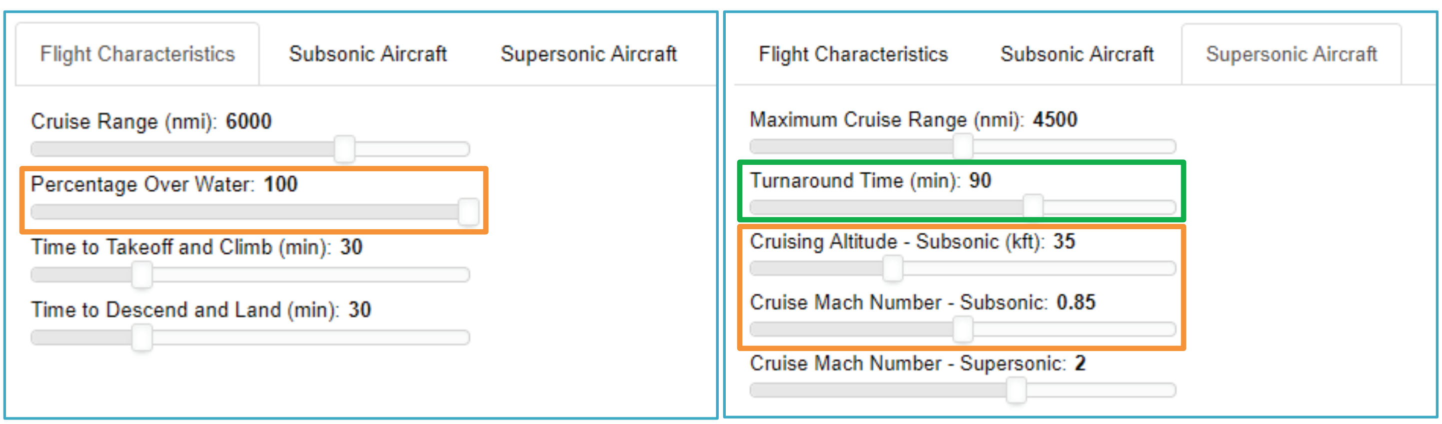

FIGURE 15. AIRLINE OPERATION ASSUMPTIONS

Based on the previous, a contour plot of time savings per flight ($t_{total,sub} - t_{total,sup}$) can be constructed as a function of cruise Mach number of the supersonic vehicle and cruise range. Figure 16and Figure 17 show two example cases (percentage over water is 100 for both). In the first example, the cruise Mach number and cruise range are set to be 2.0 and 6000 nmi, respectively (shown as the red cross in the figure), while the maximum range of the supersonic vehicle is set at 4500 nmi. This is the reason a vertical distortion in the contour lines appears at 4500 nmi since additional time is required to make a refueling stop for any range beyond that value. In this example, total time savings was 4.5 hours. In the second example, the cruise Mach number and cruise range are set to be 2.0 and 7000 nmi, respectively (again shown as the red cross in the figure), while the maximum range of the supersonic vehicle is set at 3000 nmi. In this case, two vertical distortions appear in the contour lines because one refueling stop would be required for any range between 3000 nmi and 6000 nmi and another stop would be required for any range greater than 6000 nmi. In this example, total time savings were 3.2 hours (note: time savings per flight are displayed when the user hovers the mouse pointer over any point in the plot).

Aircraft utilization within a 24-hour period for both subsonic and supersonic vehicles can also be determined using the user input flight and aircraft characteristics. Based on the total flight time per trip, and taking into account the turnaround time on the ground, the maximum utilization can be determined. Aircraft utilization corresponding to the two example cases are shown in the figures below. As shown in the Figure 18 andFigure 19, a supersonic return flight is possible in the first case with an overall utilization of approximately 19 hours (including turnaround time). In the second case however, the supersonic aircraft requires two refueling stops to accomplish its mission in approximately 12 hours, with no time left to turnaround and complete a return flight.

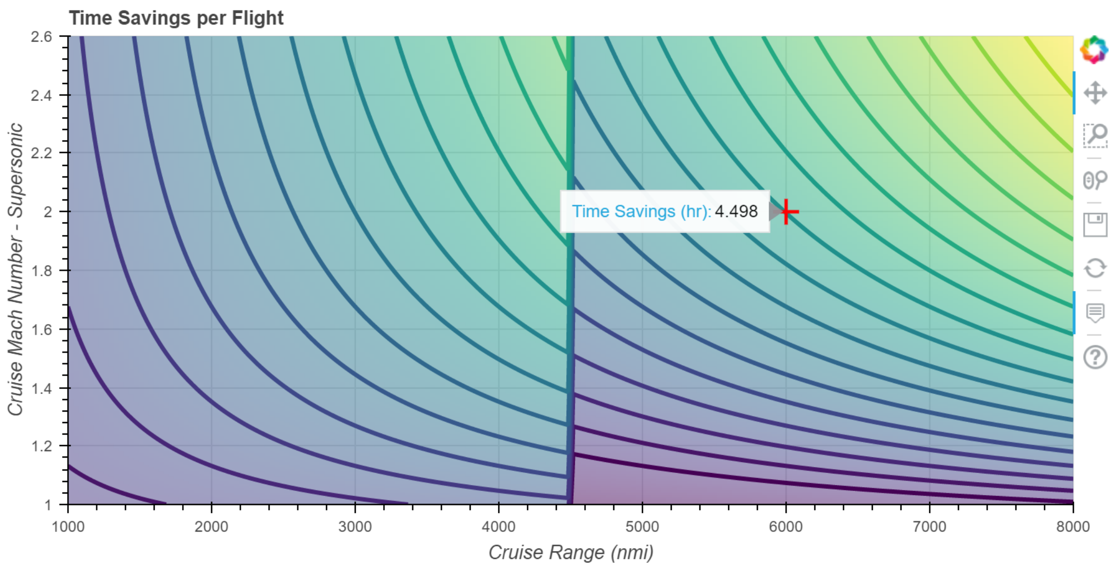

FIGURE 16. TIME SAVINGS FOR MACH 2.2 AND 4500 NMI MAXIMUM RANGE

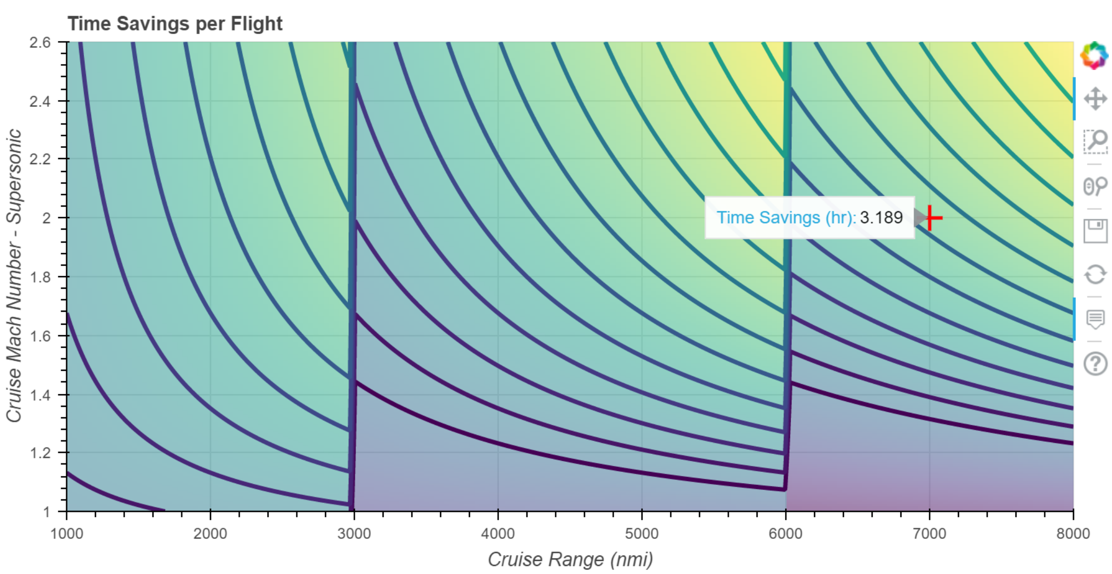

FIGURE 17. TIME SAVINGS FOR MACH 2.0 AND 3000 NMI MAXIMUM RANGE

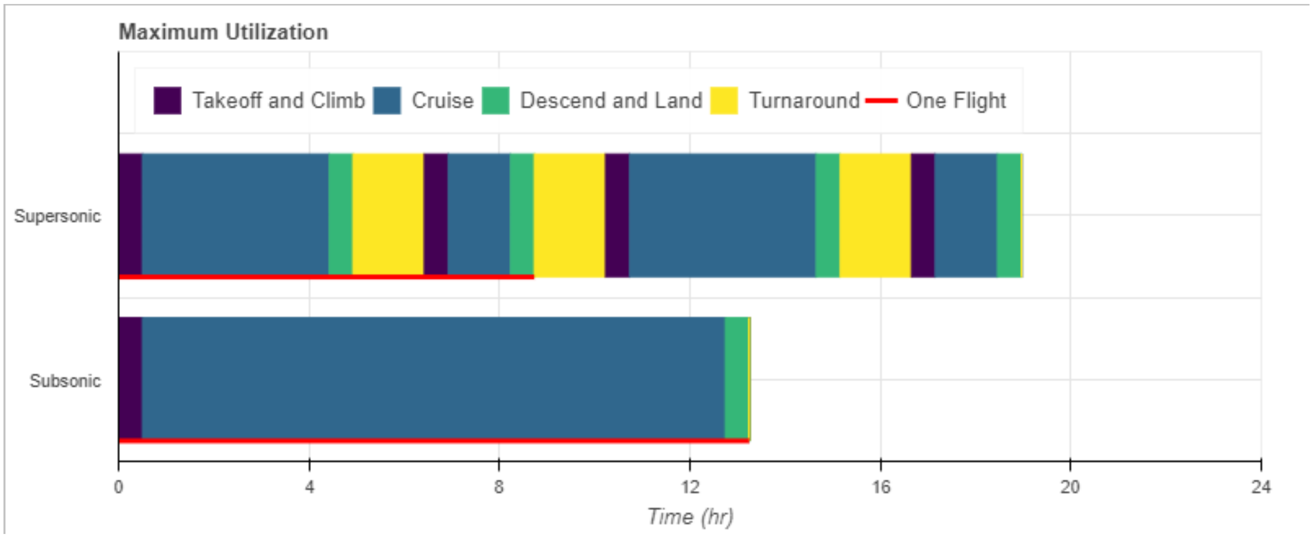

FIGURE 18. UTILIZATION FOR SUPERSONIC VS SUBSONIC MACH 1.4

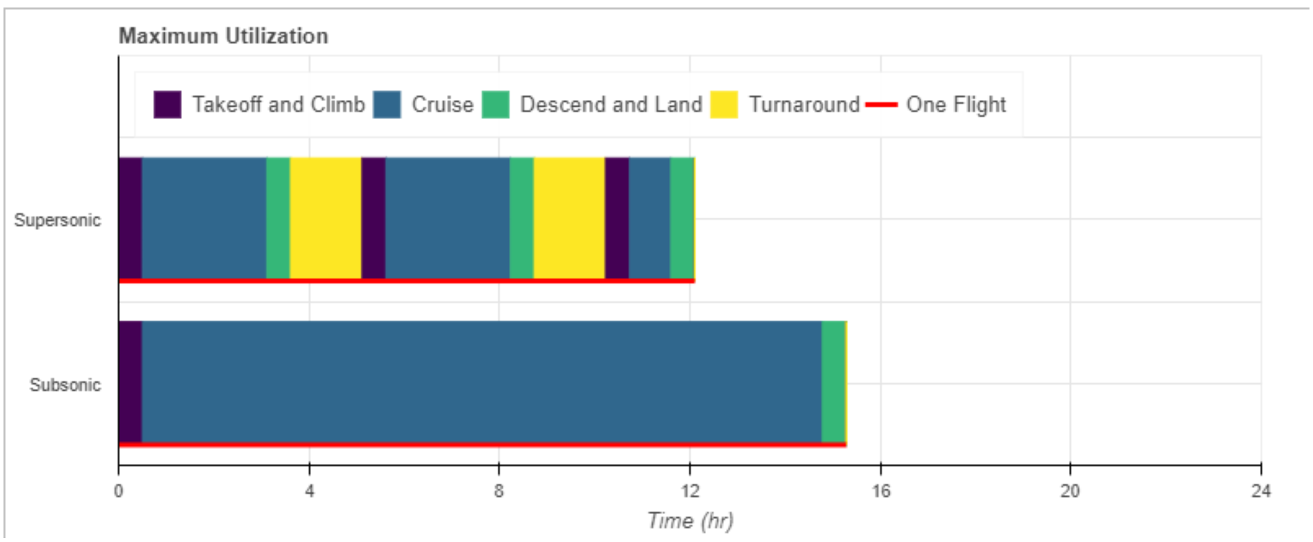

FIGURE 19. UTILIZATION FOR SUPERSONIC VS SUBSONIC MACH 2.2

A utilization analysis was conducted for the two concept supersonic vehicles that were assessed using constraint and mission analyses. For the 10-12 passenger business jet, with a cruise Mach number of 1.4 and a maximum range of 4000 nmi, a design range equal to its maximum provides aircraft utilization of approximately 21 hours (assuming percentage over water is 100). The supersonic business jet provided 3.1 hours of time savings per flight relative to the subsonic vehicle. It was able to complete three flights within a 24-hour period compared to just two for the subsonic vehicle. Similarly, for the 50-60 passenger airliner, with a cruise Mach number of 2.2 and maximum range of 4500 nmi, a design range equal to its maximum provides aircraft utilization of approximately 22.5 hours (assuming percentage over water is 100). The supersonic airliner provided 5.6 hours of time savings per flight relative to the subsonic vehicle. It was able to complete four flights (two round trips) within a 24-hour period compared to just two (one round trip) for the subsonic vehicle. The utilization plots for the two concept vehicles are shown in the figures below. The results show that for their respective design mission ranges, the two concept supersonic vehicles offer high productivity from a utilization standpoint. Both vehicles managed to perform more flights and resulted in higher utilization within 24 hours compared to their subsonic references (Figure 20 and 21).

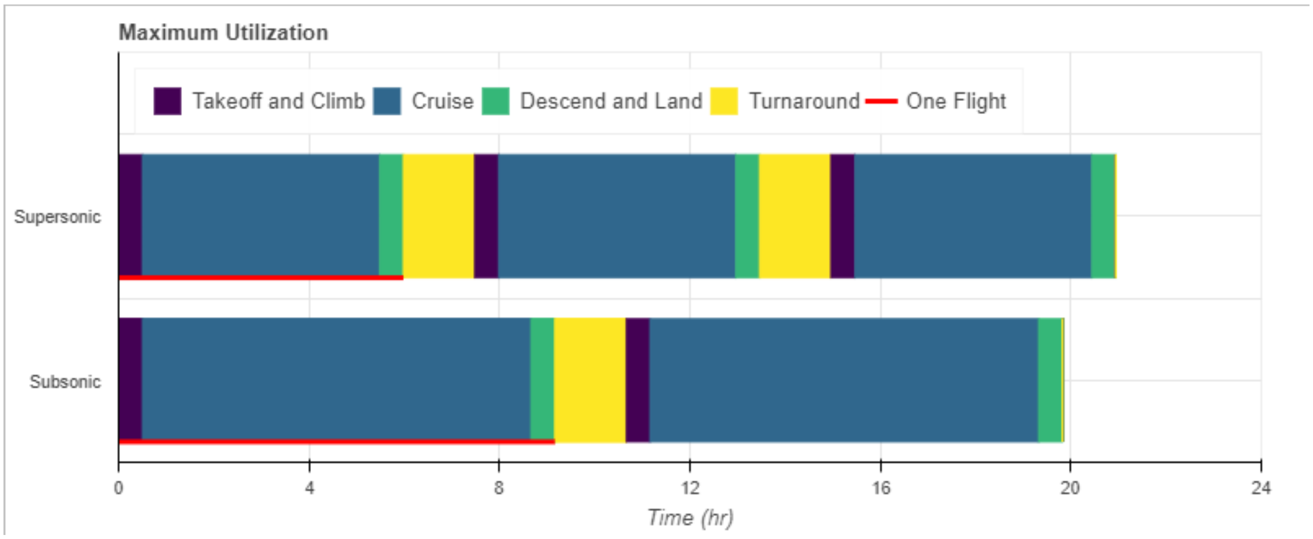

FIGURE 20. UTILIZATION FOR SUPERSONIC VS SUBSONIC MACH 1.4

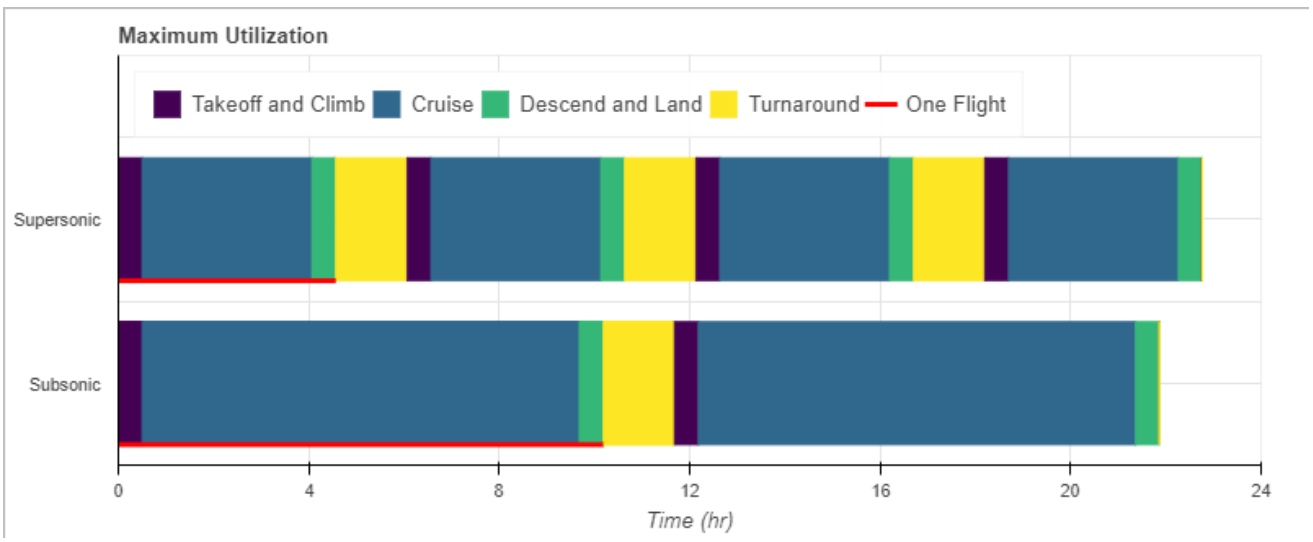

FIGURE 21. UTILIZATION FOR SUPERSONIC VS SUBSONIC MACH 2.2

Preliminary Estimates
For the two concept supersonic vehicles considered in the previous constraint, mission and utilization analyses, a preliminary estimate of fuel efficiency can be determined using number of passengers, design range and block fuel. For the supersonic business jet, fuel efficiency was computed to be 1.275 lb/seat/nmi. This value is more than double of that of the Concorde. However, that was expected based on the low number of seats. Alternatively, for the supersonic airliner, fuel efficiency was computed to be 0.275 lb/seat/nmi. This value is almost half of that of the Concorde and is in perfect alignment with the NASA near- and mid-term goals. Results for fuel efficiency are summarized in Table 8.

As for preliminary estimates for the other KEIs, such as cruise NOx emissions and airport noise, those remain to be investigated. The bulk of the effort for Task 2 was dedicated to the construction of the interactive and parametric conceptual design tools (dashboard), and the analysis of fuel efficiency. Surely, the developed tools will be utilized in a similar manner to assess the remaining KEIs in future work.

TABLE 8. SUMMARY OF CHARACTERISTICS FOR TWO SUPERSONIC AIRCRAFT CONCEPTS

	Supersonic Business Jet	Supersonic Airliner
Number of Seats	10	55
Design Ranger (nautical miles)	4000	4500
Block Fuel (pounds)	51000	68000
Fuel Efficiency (pounds per seat per nautical mile)	1.275	0.275

Task 3- Investigation of AEDT Ability to Analyze Supersonic Vehicles

Georgia Institute of Technology and Purdue University

Objective

Fleet Level Technology Assessment

This task focused on identifying the modeling capabilities and potential gaps in the tools used for aircraft environmental predictions. Georgia Tech was to identify existing models of supersonic aircraft in the AEDT vehicle database, including the Concorde and some military aircraft. AEDT studies were to be created on some routes of interest to generate single flight results for these vehicles, and their modeled KEIs were to be documented. Additionally, Georgia Tech was to update and attempt to import and generate the same information for AEDT vehicle coefficients for a 100 passenger supersonic aircraft that was previously developed for the NASA NRA "Integration of Advanced Vehicle Concepts into the NAS". In this process any potential errors or gaps in the capability were to be documented. In order to identify potential modeling gaps, coefficients in the AEDT vehicle modeling definitions that pertain to the specifics and peculiarities of those vehicles were identified. An existing known subsonic aircraft with general characteristics close to the vehicles under study were to be duplicated and coefficients used in certain aspects of modeling and phases of flight were to be adjusted to possible values for that particular supersonic aircraft. The resulting definition of this adjusted vehicle were to be run through AEDT to identify potential errors or gaps in modeling capability. This was to be documented, along with potential solutions for addressing the particular requirements of modeling supersonic aircraft.

Research Approach

To facilitate environmental impact prediction of supersonic aircraft, it is necessary to identify the modeling capabilities and potential gaps in the tools used for these predictions. As part of this task we identified existing models of supersonic aircraft in the AEDT vehicle database, including the Concorde and some military aircraft. These models were then reviewed as to how these aircraft were modeled. The next step will be to create AEDT studies on some routes of interest to generate single flight results for these vehicles and document the modeled KEI information for these aircraft types. In order to identify potential modeling gaps, coefficients in the AEDT vehicle modeling definitions were identified that pertain to the specifics and peculiarities of those vehicles.

Supersonic Vehicles in AEDT

The first step of the task was to test one of the current supersonic models existing in the AEDT database. The primary civilian aircraft that exists in AEDT's fleet database is the Concorde.

For this, a study was created in AEDT to plot the noise contour generated by a take-off of the Concorde at JFK airport. The first step is selecting the adequate equipment, which is the CONCORDE/OLY593 in the AEDT database.

TABLE 9. DEFAULT CONFIGURATION OF CONCORDE IN AEDT

Max gross landing weight (lb)	245000
Max landing distance (ft)	10600
Max gross take-off weight (lb)	400000
Number of engines	4
Max sea level static thrust (lbs/engine)	38100
Max operating speed (knots)	500
Max operating Mach number	1.2
Max operating altitude (ft)	41000
Wing surface area	181.2

To test out the Concorde noise estimates in AEDT it is necessary to select an airport in AEDT. JFK airport (KJFK), with default layout was chosen for this purpose. The operation has to be defined for the aircraft; here take-off is chosen, for the North-East track. An annualization for this operation is then defined (i.e. the frequency of such an operation). We wish to plot the contours for a single flight, so we do not repeat the operation over time. It should be noted that historically the
Next, a receptor grid has to be generated. We chose a 120x120 receptor grid, spaced out by 1.5 nautical miles each. The grid has to be centered on the airport and large enough to allow the noise contours to be closed, otherwise they will not be plotted by AEDT.

In this case the most relevant metric for noise of an aircraft c was the Single Event Level (SEL), which is the most appropriate for a noise metric for a single flight, because it is the metric that is used in aggregated form in the Day-Night-Level (DNL) for regulatory purposes. With these parameters, the simulation on AEDT gives the following noise contours shown in Figure 22. It should be noted that this is for a specific straight departure from JFK only. This does not represent in any way the departures that Concorde performed in the past, which were cognizant of the fact that in order to minimize noise exposure over land the actual tracks were heavily biased to be over water. Furthermore, this straight path does not follow any currently used tracks at JFK or in the New York airspace.

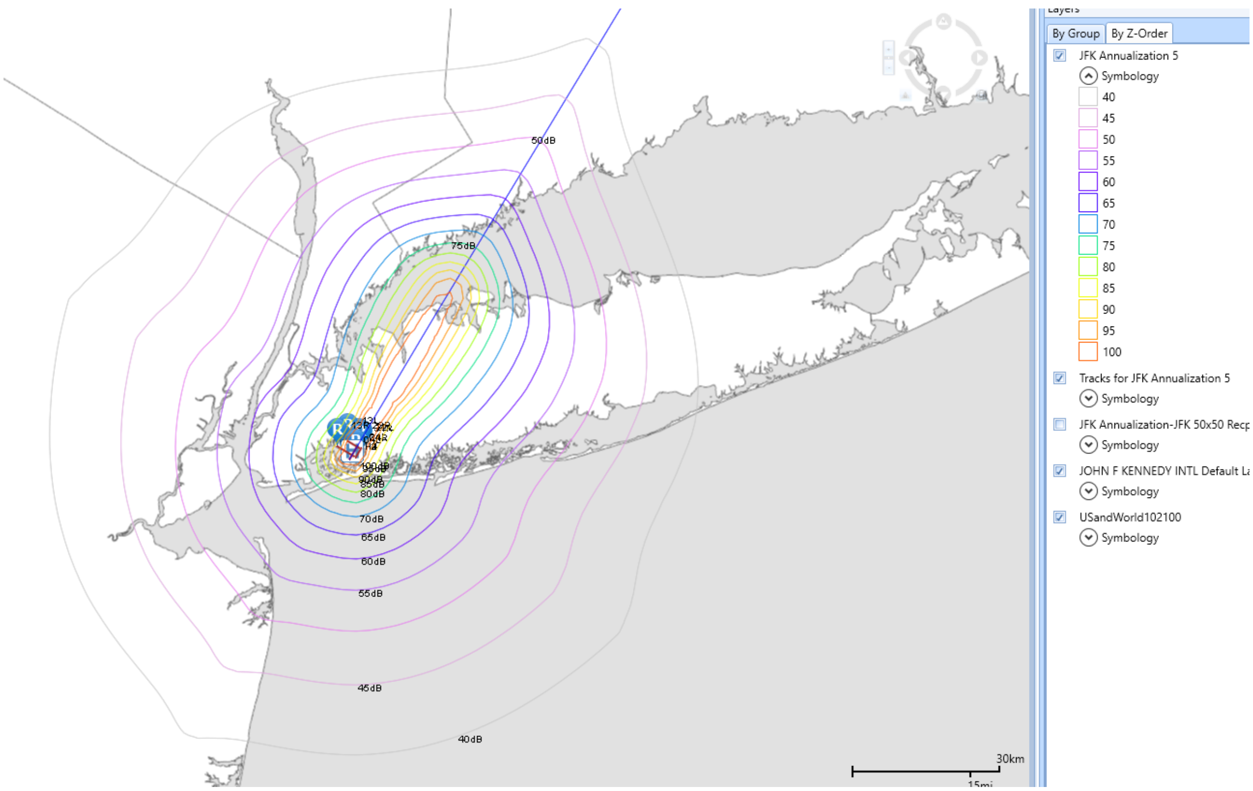

FIGURE 22. NOISE CONTOURS FOR CONCORDE TAKE-OFF AT JFK

A simulation for several flights of the Concorde were performed through the AEDT tester developed by ASDL. The tester takes all the flights combinations from AEDT database and performs the calculation for the flights suitable for the chosen aircraft.

AEDT model of the Concorde

Aircraft Noise Performance (ANP) Model

The ANP model data contain a Concorde model. This is not surprising, given that the Concorde was one of the first aircraft to undergo noise certification, which provides the necessary data to create the ANP model. The model has a few interesting features, likely due to the age of the model data. First, it only includes STANDARD procedures and no ICAO procedures, even though the Concorde did use noise abatement procedures. Another feature of the ANP model is that it includes a standard climb power thrust curve and a reheat thrust curve, which are both used in the procedures. However, it does not include alternate thrust curves for temperature variations as found in most current ANP models.

Looking and the noise model for the Concorde, there are only three thrust settings for which noise curves exist. Additionally, the highest departure thrust noise curve is at 32klbf thrust per engine, whereas the Concorde produced close to 38klbf per engine with reheat. This means that if the thrust exceeds the value of the highest thrust noise curve, the noise values will be extrapolated. In this case, even at 32klbf thrust, the noise at 200ft distance is 138db SEL, which is without reheat. Extrapolating this would push the noise close to 140dB. The spectral classes that are being used in the noise modeling for atmospheric adjustments are 106 and 206, which are the low bypass relative frequency loudness adjustments.

BADA 3

The BADA model database is used in AEDT for aircraft modeling over 10,000 ft above field elevation and especially during cruise phases. Since this model and database is relatively new, having been introduced after the retirement of the Concorde, it does not contain a Concorde model. The AEDT fleet database default substitution model is the “FGTL” (generic heavy fighter) model, which is based off the Rockwell B1 Lancer using a cruise Mach of 0.8. This substitution is likely based of the closeness in the MTOW (180,000 kgs vs 186,000 kgs) and the same number of engines with similar SLS thrust.

Engine Emissions Databank (EEDB)

The latest versions of the EEDB do not contain any information of the Olympus engines. However, the AEDT fleet database does contain an entry, which is marked “EDMS 4.5 – Rolls Royce”. Therefore, we can presume that the engine at one point existed in the EEDB and was eventually removed after the retirement of the Concorde. It should also be noted that the data does not include thrust information and it is therefore not possible to conclude from this whether the data does or does not include reheat information. Additionally, the entry contains four values for fuel flow and each emissions species. This, however, does not match the expected five sets of values for the certification of supersonic engines. Additionally, the thrust levels for each sets of points are define considerably differently and also depend on the presence of reheat capability. Therefore, it is unclear what the values represent. It is possible to assume that these values represent subsonic engine equivalents that are designed to match the definition of the four subsonic point values. This is consistent with how AEDT will interpret these values.

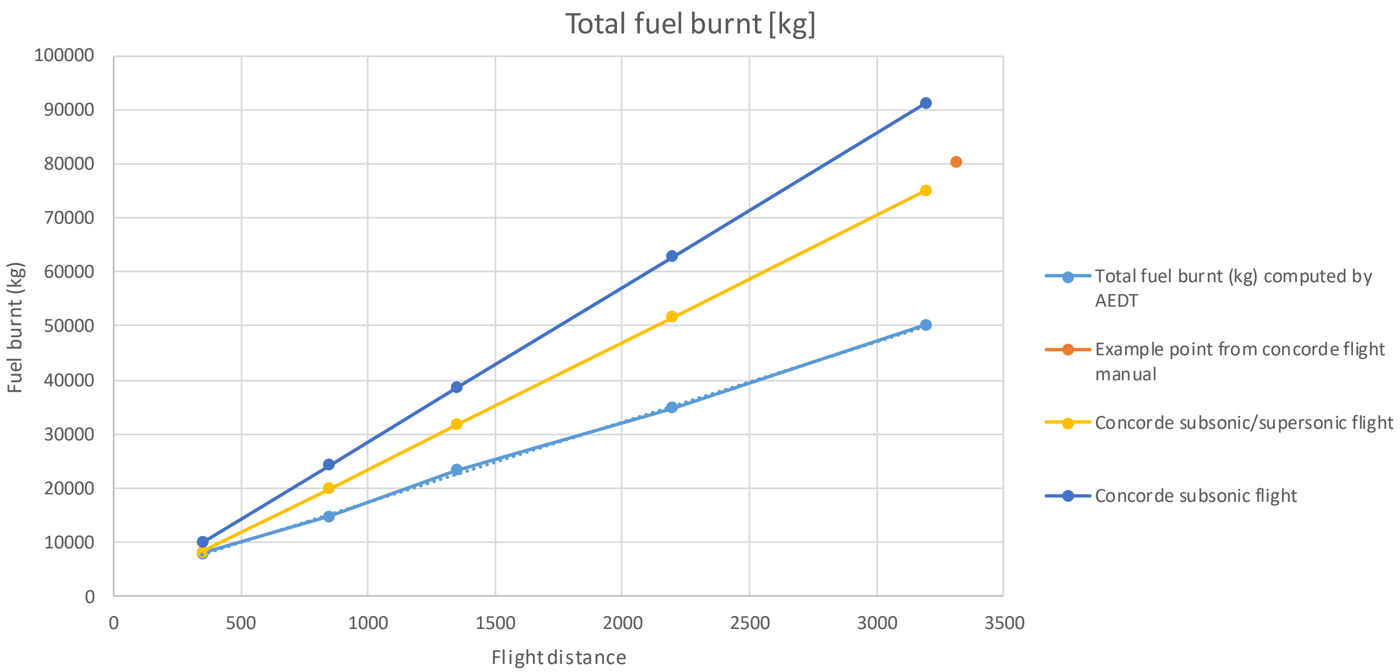

FIGURE 23. CONCORDE FUELBURN ESTIMATES BASED ON FLIGHT DISTANCE

Modeling by phase of flight

Aircraft Noise Performance (ANP) Model

The current way of modeling take-off and landing performance under 10,000 ft field elevation is to use the ANP models and the modeling methods described in ICAE Doc 9911 and previously described in SAE 1845, as well as the INM Manual. Since the modeling is derived from also modeling military aircraft, it does include provisions for aircraft whose performance characteristics are somewhat similar to high speed military aircraft, at least in the take-off and landing characteristics. Specifically, these characteristics include:

- Possible use of reheat
- Aerodynamic optimization for high speed
- Aircraft configuration changes

The possible use of reheat is addressed in a later section. The aircraft shape optimization for high efficiency at supersonic Mach numbers usually require a significant trade-off in efficiency at low speed flight. Therefore, many supersonic aircraft struggle to produce enough lift at low speeds in order to sustain flight. This means that in addition to very high angles of attack and deployable surfaces, it is often necessary to have increased speeds at take-off, such as V_1, V_R and V_2, in addition to higher speeds at low altitudes potentially in excess of 250 knots under 10,000 ft. Additionally, higher landing speeds can also be necessary. This means that the default reference speeds used in the performance modeling, but especially in the source noise modeling and data are potentially too low. The effects of this are currently being investigated in ASCENT Projects 43 and 45. Aerodynamic configurations such as additional moveable surfaces and other features that change the configuration and aerodynamics of the aircraft are implementable by defining these as additional entries into the FLAPS table and then making use of them in the corresponding procedure steps. This means that it is necessary for the manufacturer to supply this information so that it can be used during modeling.

BADA

BADA is currently used for modeling the aircraft performance over 10,000 ft above field elevation. It also only includes a single thrust and fuel curve, which might not be adequate enough to model the aircraft engine performance over a wide variety of Mach numbers and inlet and nozzle configurations, especially in a linear fashion as is currently the standard in version 3. While the model does not explicitly cover supersonic flight, it could potentially be adopted to allow this, given additional configuration data. The current implemented version explicitly forbids Mach numbers greater than 1.0. Additionally, BADA 3 currently only provisions a single cruise configuration. This would have to be expanded to account for the difference in subsonic and supersonic configurations of the aircraft.

The climb procedure over 10,000 ft, by default, uses a defined energy share (share of potential energy contribution to altitude vs speed increases), while following a constant calibrated air speed (CAS). This is continued until a transition altitude, where the climb CAS speed equals the climb Mach number. The climb to the initial cruise altitude then continues at that constant Mach number. This mimics a relatively standard way in which conventional subsonic passenger aircraft are flown.

For supersonic aircraft, however, it is possible in the aircraft procedure coefficients to specify a second segment climb and cruise speed and Mach number such that the transition altitude occurs at a projected altitude at which the transition from subsonic to supersonic flight is expected to take place. This was tested on the 100 seat airliner model created for NASA in a previous project [4]. The result is that the current version of AEDT will handle the transition to supersonic cruise as long as the drag polar for cruise as well as the TSFC curves are designed to match cruise conditions correctly. The transition itself is handled not very well. It tends to consist of a very brief jump from subsonic to supersonic that completely misses the drag rise as well as the fuelburn and associated emissions caused by the transition. This can cause an additional modeling error on the order of a few percent of mission block fuel. However, considering the system was never designed for modeling these conditions as well as the lack of any other modeling standards, it is probably acceptable for the short term future.

Figure 24 shows that this is too simplistic for a supersonic passenger aircraft, at least the way the Concorde was supposed to be flown. Specifically, there are different procedures depending on whether a subsonic cruise or a supersonic cruise will be performed and whether or not the climb to supersonic cruise has to be delayed for overland noise rules. Additionally, the transition from subsonic flight to supersonic flight typically has to be achieved as quickly as possible in order to minimize time in very high drag conditions while not violating flight envelope and center of gravity constraints. The current number of coefficients present in the BADA procedure definition is insufficient to describe the details of this, especially if this is materially different between potential future supersonic aircraft.

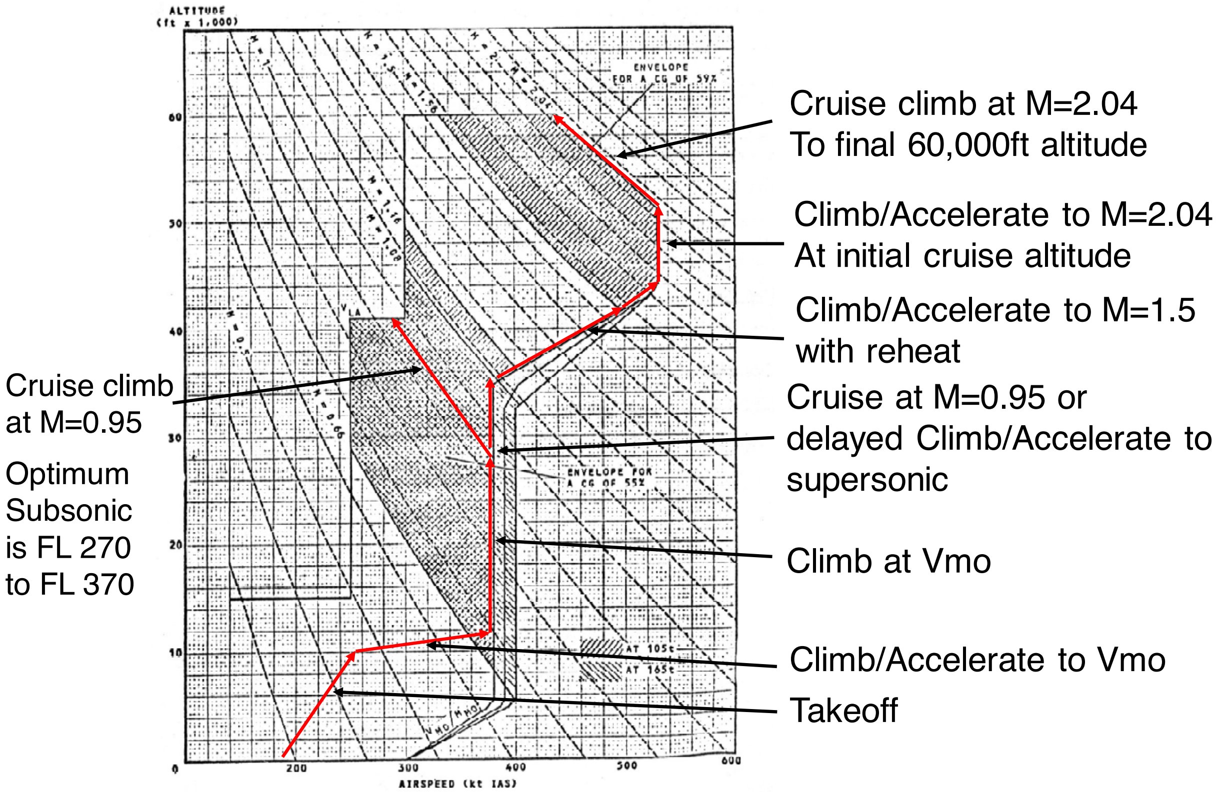

FIGURE 24. CONCORDE OPERATIONAL ENVELOPE (ALTITUDE IN FEET VERSUS INDICATED AIRSPEED IN KNOTS) WITH STANDARD CLIMB TO CRUISE PROCEDURE SHOWN[5]

Noise Modeling

The current state of noise modeling in AEDT is entirely limited to the use of Noise-Power-Distance (NPD) curves, which describe the aircraft noise signature as a function of engine thrust (power) and distance of the observer. The distance data is limited from 200 ft to 25,000 ft, but can be extrapolated – if required – using a linear method. This method is probably sufficient to properly capture the noise generated by a supersonic aircraft near and around airports but is not suited to propagating the boom noise created by the shock waves from high altitudes, nor does it capture any potential focusing or dissipating effects due to trajectory or atmospheric effects. However, there are a few research codes (such as PCBOOM), that currently allow the calculation of the boom effects on the ground. These methods and the required data will have to be integrated in AEDT, if such functionality is desired.

Emissions Modeling

AEDT uses the Fuel Flow Method v26 in order to use the ground test data obtained during engine certification and publish in the ICAO Engine Emissions Databank (EEDB). This method uses four defined throttle settings with fuel flow end emissions index (EI) values to interpolate the values over the entire flight envelope. It also adjusts the equivalent combustor inlet conditions from the sea-level static (SLS) data to the appropriate conditions at any altitude. The altitude adjustment is based on adjusting the changes in free stream conditions to equivalent changes in combustor inlet conditions using isentropic relations. Therefore, an aircraft in supersonic flight will violate this assumption due to the shocks produced by the nose and the inlet compression shocks during supersonic flight. Supersonic inlets tend to have a number of moving surfaces to optimally adjust to the required conditions and to allow the engine to operate normally and effectively during a wide range of Mach numbers. This means that the required conditions heavily depend on the specifics of the situation and the inlet configuration required. However, since it is an objective of the inlet to slow the free stream to acceptable subsonic conditions at the face of the engine inlet at all times and to minimize losses as much as possible, it is potentially possible to assign an additional inlet correction factor based the inlet total pressure recovery. This correction factor can take the form of an ideal number based on Mach number or if available actual inlet performance. It is possible that the current combustor correction coefficients, which are based on a 1990s era CFM56 empirical correlation, have to be updated similar to the required updates for modern stage combustion engines.

The nozzle performance is an additional potential issue. Supersonic aircraft will require a much more complex nozzle compared to a simple subsonic converging exit. The Concorde utilized a secondary set of nozzles on each engine designed to improve subsonic performance. The current modeling method adjusts for installed effects with simple fixed multipliers from the ground test data. It is unclear how these multipliers will have to be adjusted due to the much larger installed effects that an integrated engine of a supersonic aircraft will present. Another potential issue is that the adjustments for speed and altitude effects compared to the static ground tests will probably have to be adjusted. The specifics of this will depend on how and which equipment will be included in the ground tests. Unlike the military aircraft noise modeling that lends itself to be adopted to supersonic passenger aircraft, there is no emissions certification requirement for military aircraft.

Reheat

The Concorde made use of reheat during take-off in order to meet certification requirements in case of engine failure, but would terminate reheat below 1000 ft if all engines continued to operate nominally. Additionally, the Concorde made use of reheat in order to minimize time spent in the transonic drag rise region during the climb to supersonic cruise.

Modern supersonic aircraft are not expected to require or include reheat due to better engine thrust and efficiency and the potential fuel penalty for not using reheat either being completely eliminated or small enough to outweigh a host of other issues, such as maintenance cost, regulatory complexity and others. It is unlikely that the capability of properly representing reheat beyond the current capabilities are required in the future.

Accomplishments

This work identified the key issues that will need to be addressed in improving the modeling of supersonic aircraft in AEDT, which are:

- Transition from subsonic to supersonic
- Supersonic cruise
- Emissions modeling
- Noise modeling
- Boom modeling

A key element in modeling a supersonic aircraft is to be able to model the transition from subsonic flight to supersonic flight. This involves crossing the highest drag regime of flight and contributes a significant amount of the fuel burn and emissions. As investigated this can currently be approximated by a sudden jump but this neglects this portion of flight almost completely. This will require modeling either through a generic transonic drag rise approximation or additional aircraft specific coefficients.

The modeling of supersonic cruise currently does work but can be improved. The atmosphere model that is used potentially has to include more sophisticated data about the actual altitudes of the atmospheric layers. Additionally, an aircraft model is currently limited to either subsonic or supersonic flight but cannot accommodate both. This is potentially necessary because supersonic cruise is currently prohibited over land and the model needs to be able to accommodate that.

After performance modeling, emissions modeling is another area for improvements. Specifically the current full flight emissions modeling method – the Boeing Fuel Flow Method (BFFM) – which is used because it avoids requiring detailed engine performance parameters. It relies on first principles physics relations for atmospheric and engine cycle approximations and empirical fits for combustor properties. This needs to be update in order to accommodate the cycle differences and the differences in operating conditions at altitude.

Finally, the modeling of aircraft noise needs to be addressed. The airport noise is not specifically different for supersonic aircraft, but will be dominated by jet noise due to the potentially high exhaust speeds that are requires for supersonic cruise. This will potentially require the de-rating for take-off in order to meet stringent noise limits. This will have to be addressed in potentially a similar way as subsonic de-rating is handled in AEDT. It will become necessary to integrate supersonic boom modeling with AEDT. This can be accomplished either through the validation and integration with existing tools – such as PcBOOM and others – or alternatively direct integration of modeling methods or code into AEDT. There is some work required before AEDT will be able to model supersonic aircraft with good fidelity, but the issues have been identified.

Task 4- Fleet-Level Environmental Assessments

Objective

This task was to quantify the fleet-level impact of supersonic aircraft. Georgia Tech was to use the GREAT fleet prediction tool to perform a preliminary assessment of the impact of supersonic aircraft using a subset of scenarios from prior ASCENT 10 work and for a subset of the KEIs and aircraft types evaluated in Task 2. Similarly, Purdue was to utilize their FLEET capability to analyze such impact.

Research Approach – Georgia Tech

To prepare modeling supersonic aircraft several changes to the modeling toolchain had to be made. First, inside GREAT and IDEA the current subsonic fleet is divided into seat classes in order to track the different sizes as well as payload-range capabilities of the current fleet of aircraft in operation. In order to model a supersonic fleet, the team decided to add a new seat class “SST”, in order to track these new aircraft separately. It should be noted, however, that this means that for now there is only a single type of supersonic aircraft that is being tracked. For now this was a 55 seat commercial jet with a maximum range of approximately 4500nmi that tries to mimic one of the potential new market entrants that could enter service in the next few years. For now it was decided to set the earliest entry into service date (EIS) to 2025.

The model was also altered in two ways in order to model the potential amount of supersonic flights. First, it is now possible to simply specify an amount of the fleet that would be switched or replaced by supersonic flights. It should be noted that it is possible to specify this for all modeled regions: Domestic, Atlantic, Pacific, Latin-America, Other. Therefore, it becomes possible to investigate the implications of switching a certain amount of passengers or flights in those regions. This is especially important with regards to investigating the potential of allowing overland supersonic flights or not, since most domestic flights are almost 100% overland flights in the U.S. This also has an effect of what missions and markets a potential supersonic aircraft would be used on.

The second method that was added to the models builds on this capability by partially reusing the logic of converting production numbers into potential replacement aircraft and therefore the ability to replace a certain share of the projected operations. This allows the user to specify aircraft production rates. The produced aircraft are then inserted into the fleet to be used to replace existing aircraft. This also necessitates assuming a productivity per aircraft. This is normally a function of primarily utilization since subsonic fleet block times and speeds (the gate to gate time and average speed based on it) have been relatively constant over the last decades. However, supersonic aircraft by definition have a much higher block speed. They therefore in theory would be potentially capable of flying many more mission than a subsonic aircraft. However, based on the analysis in Task 2. It seems likely that keeping a high utilization would become a significant challenge and therefore it seems unlikely that supersonic aircraft would yield an increased productivity. So for now the assumptions were set to have an increased block speed with a lower utilization and therefore only a small change in the number of flights possible in a given time period per aircraft in the supersonic fleet. An example of the production assumption based on a study from Boyd Consulting Group [7] estimating a potential 10 year demand of up to 1300 supersonic airliners is shown in Figure 25. For the purposes of this it was also assumed that the manufacturer would face a four year production ramp up to the targeted production rate of eleven aircraft per month. The result is shown as a share of the overall fleet. The curve bends down significantly due to the large increases in the conventional fleet forecasts in the coming decades such that a constant production rate yields a diminishing share of the overall fleet.

The standard fleet turnover model applicable to all seat classes was also brought forward. This means the models have the capability to replace aircraft within their seat class with potential improved future aircraft with similar capabilities. For now it was assumed that a supersonic aircraft would be operated more similar to current wide-body aircraft in terms of time of ownership and the underlying financing and leasing durations and the expected useful economic life.

Using these production rate assumptions along with the vehicle specific performance estimates from Task 2 allows running of the fleet analysis. The scenarios develop for the subsonic projections of commercial aviation environmental impact can be used as a basis for analyzing the effect of a potential supersonic fleet. It should be noted that it is possible to independently vary the supersonic specific assumptions in terms of market share, production rate, passenger demand, and aircraft technology. This can serve as a guide as to the potential variability of these assumptions and is what was done for this phase of work. However, it is indeed plausible that those assumptions are not wholly independent of the assumptions developed for the subsonic only scenarios. For example, it is definitely plausible that engine and aircraft technology for both subsonic and supersonic vehicles would at least partly develop in tandem. It is also expected that passenger demand for air travel with affect both subsonic and supersonic together and not be completely decoupled, except for some very specific cases.

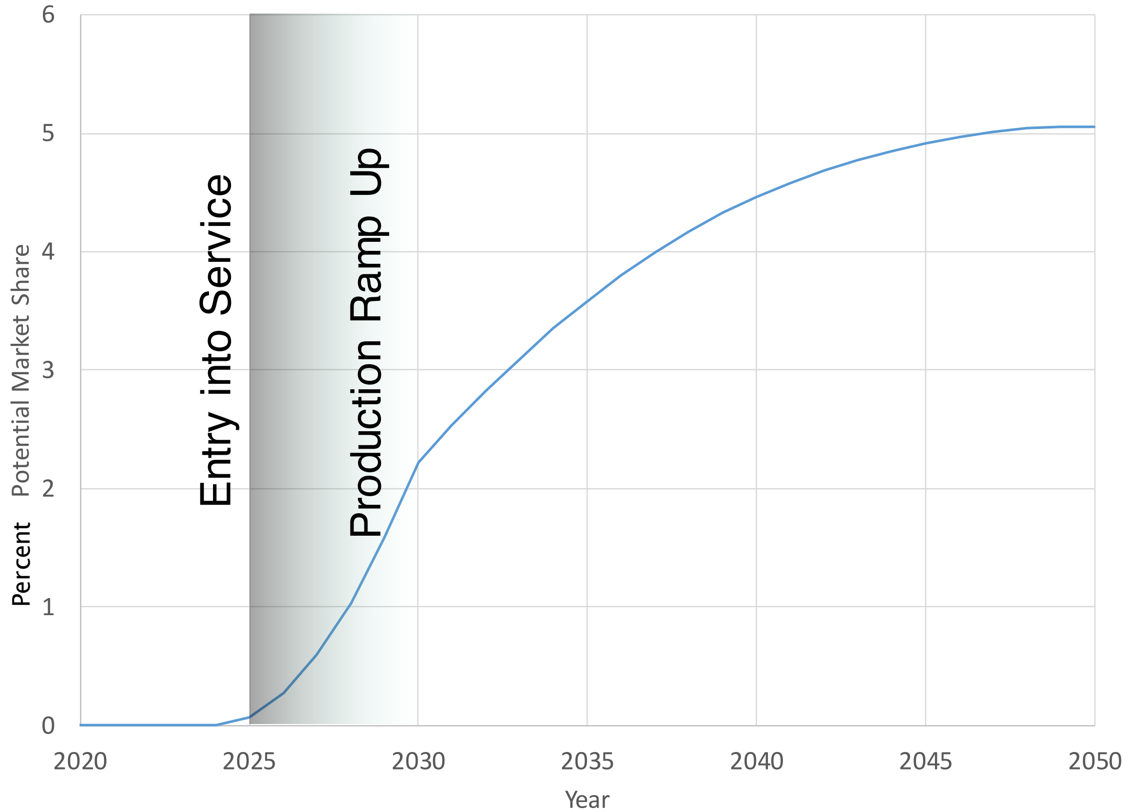

FIGURE 25. PERCENT POTENTIAL MARKET SHARE OF SUPERSONIC FLEET

The results presented here should be taken as a guide to the range of variability in the results instead of wholly consistent scenarios of the future. An example is shown in Figure 26, which shows the relative CO_2 emissions trajectories for the "Current Trends Best Guess" scenario as well as the same scenario but instead with a large fleet of operational supersonic commercial aircraft starting in 2025 using the production rate assumptions explained before.

Similar results were produced for most of the subsonic scenarios with and without supersonic aircraft being introduced. Additional metrics such as specific fleet make up as well as passenger demand and airline operating cost structure were generated in addition to the fuel burn and CO_2 emissions results. In order to summarize the results of these runs, they were aggregated as ranges of the fleet-wide delta in CO_2 emissions in 2050 that is the emissions with a supersonic fleet minus the emissions without a supersonic fleet. This shows the potential size of the resulting additional emissions a fleet of supersonic airliners could potentially produce. This is shown in Figure 27. The primary drivers of assumptions for the supersonic fleet are summarized in the three rows shown. The first row shows the impact of the market size assumption. This could range from a very limited adoption of around a dozen aircraft that only fly one to two round trips per day to the potential switch of the entire premium ticket market that is paying business, first-class, and higher passengers. This would require a large fleet of supersonic airliners, which at a multiple of fuel burn and therefore emissions would drive a significant increase in emissions. The second row shows the impact of vehicle technologies on the 2050 emissions. The worst case would be a significant fleet of current technology only aircraft – with estimates as developed in Task 2 – and the best case based on the aggressive mid- and far-term technology goals defined by NASA's supersonic vehicle project. The third row attempts to show the interaction of the primary subsonic aviation growth rates on the resultant supersonic demand. This is in effect a scaling that happens due to the overall increase or decrease – or better, high growth or low growth – of aviation travel as a whole, of which supersonic airliners are expected to only capture a small portion. Nonetheless, it shows significant variation depending on the underlying assumptions provided by those specific scenarios.

Additionally, these ranges represent only a one-at-a-time sensitivity. There are potentially significant interactions that could take place. This means not only interactions between the scenario assumptions for subsonic and supersonic demand, technology, operations, etc, but also the interactions between the supersonic market adoption rate, aviation growth, as well as vehicle technology. This was not studied at this stage of the project, but it is envisioned to do so once better vehicle performance and demand estimates have been developed.

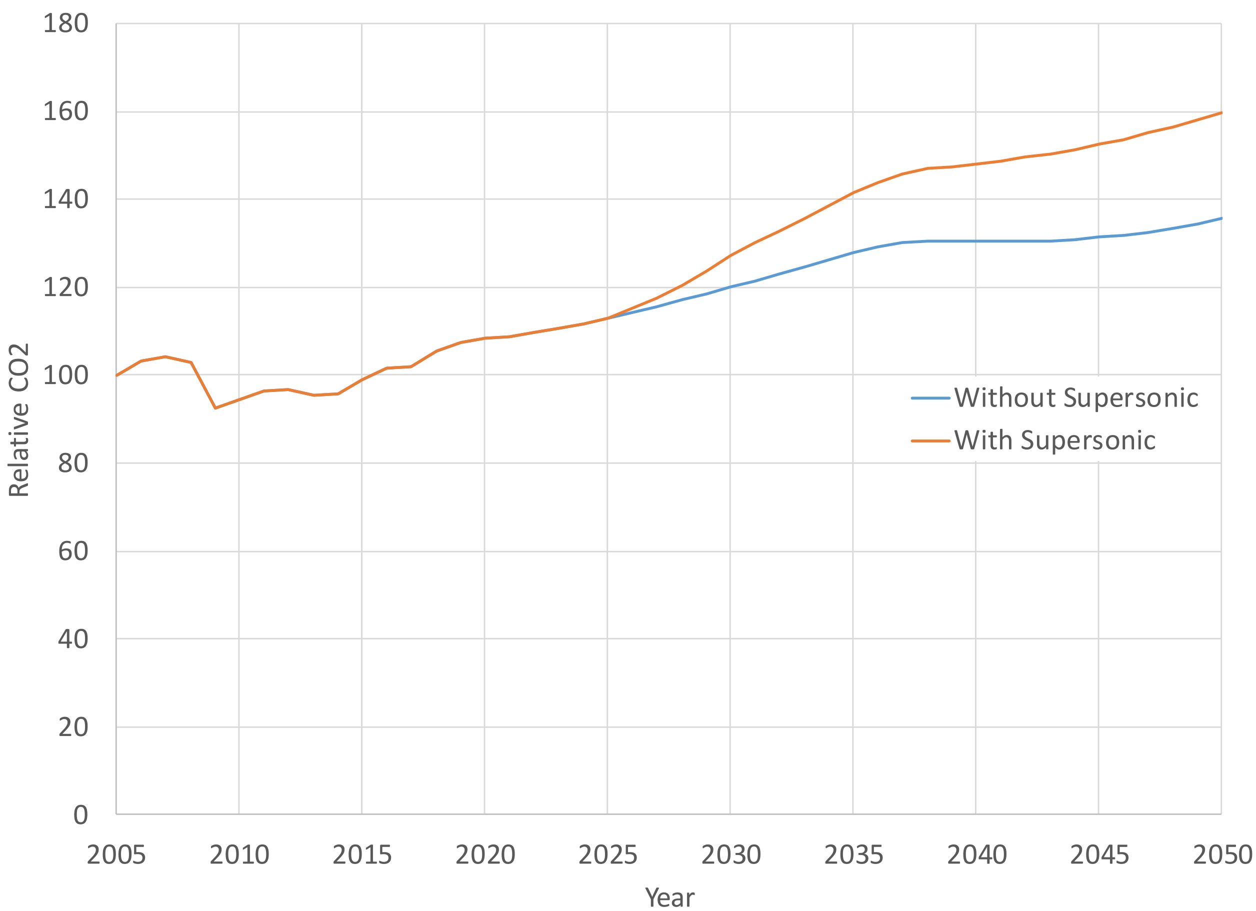

FIGURE 26. CURRENT TRENDS BEST GUESS SCENARIO EFFECT OF INCLUDING LARGE SUPERSONIC FLEET (FIGURE 25)

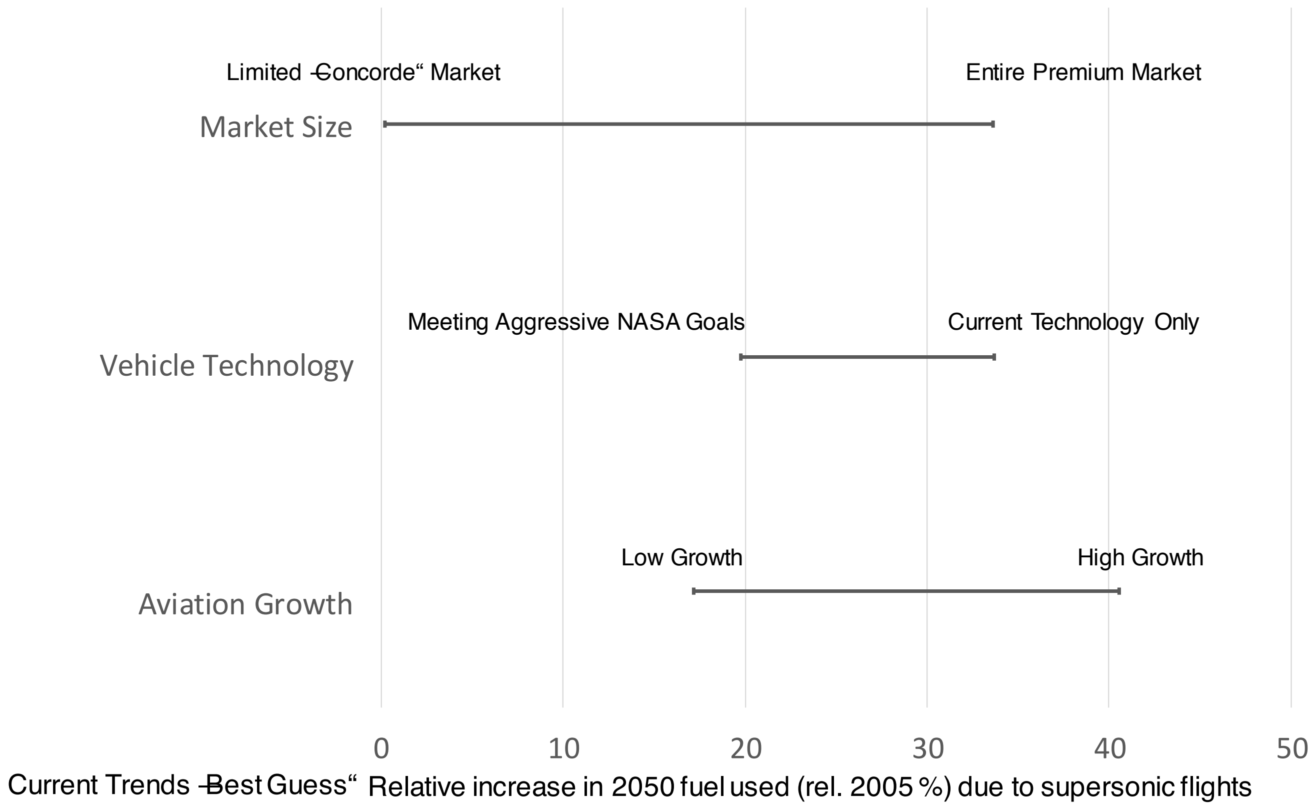

Figure 27. Range of Results due to Possible Assumptions for Supersonic Aircraft

Research Approach – Purdue

Vehicle and Fleet Assessments

Incorporating Supersonic Aircraft in FLEET Allocation Problem

In FLEET, there are two ways to conduct the airline aircraft allocation with supersonic aircraft in the airline's fleet, the sequential approach and the simultaneous approach. In the sequential allocation approach, FLEET allocated the airline's supersonic aircraft first to satisfy the identified supersonic flight demand. Then, it uses subsonic aircraft to carry the unsatisfied supersonic flight demand remaining from the supersonic allocation along with all of the subsonic demand. For both subsonic and supersonic demands, the airline cannot carry passenger more than the available market demands. This approach is consistent with the assumptions that the supersonic ticket fares are similar to the current business and first classes ticket fares, so that the supersonic flight demand come from the business and first classes demand. Passengers would generally choose a supersonic flight first because of the shorter block hours, if the supersonic ticket fare is similar to the business and first classes fares on subsonic flights. In the simultaneous allocation approach, the airline allocates the supersonic and subsonic aircraft at the same time to satisfy both supersonic and subsonic flight demands. The simultaneous approach is slightly more complicated to implement, but this would provide a more holistic approach to enforcing noise and/or airport capacity constraints, if those are desired.

Subsonic and supersonic aircraft sequential allocation approach

Figure 28 shows the flowchart of subsonic and supersonic aircraft sequential allocation approach. In each simulation year, FLEET predicts the inherent airline passenger demand growth due to the economic growth and adopts the price-demand elasticity to show the influences of airline ticket price changes from last year on demand. Subsequently, the total demand is split into subsonic demand and supersonic demand. In the work to date, the team has been using the notion that proposed supersonic transport aircraft will operate with a ticket price roughly equivalent to business class fares. FLEET uses the assumption that 5% of the total demand on a route is the business and first-class passengers; this represents the potential supersonic aircraft demand. In FLEET, the airline first allocates its supersonic aircraft to satisfy the supersonic demand and then any unsatisfied supersonic demand is combined with the subsonic demand, and the subsonic aircraft allocation meets this demand. Finally, the airline acquires and retires aircraft based on the operations of supersonic and subsonic aircraft operations from the allocation problem.

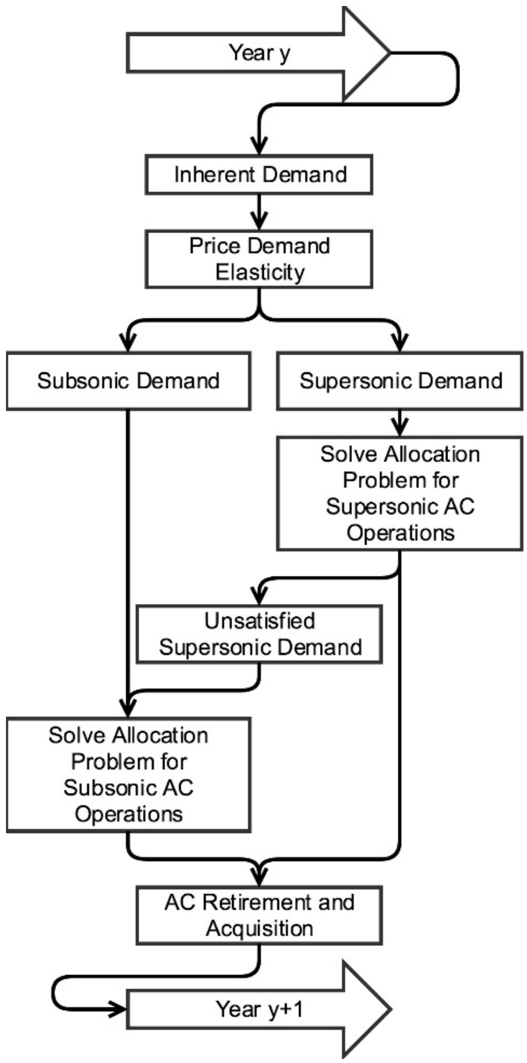

FIGURE 28. FLOWCHART OF SUBSONIC AND SUPERSONIC AIRCRAFT SEQUENTIAL ALLOCATION APPROACH

The sequential allocation approach has three advantages: it is easy to implement in FLEET; it can ensure that assumptions about the supersonic flight ticket fare and supersonic flight demand can be held; simulation results are relatively easy to analyze and provide reasoning.

The drawbacks of the sequential allocation approach include two points. The first involves implementation of airport traffic capacity constraints or airport noise constraints. Both types of constraints limit the number of aircraft operations in FLEET's aircraft allocation problem. The traffic capacity constraint limits the number of take-offs and landings, while the airport noise constraint limits the size of the predicted total area inside a DNL contour of 65 dB. The predicted noise area is also a function of the number of operations of each type of aircraft in the airline's fleet. With the supersonic aircraft allocated before the subsonic fleet but the capacity and noise area requiring the total number of operations (meaning supersonic and subsonic aircraft) at an airport, these constraints either allow unrestricted supersonic operations (i.e., once the supersonic fleet is allocated, the subsonic fleet is limited to meet the constraints) or require an a priori estimate of how limits should be applied to the supersonic aircraft before they are allocated. The second disadvantage of the sequential approach is that this approach favors supersonic aircraft operations. The airline always allocates the supersonic aircraft on the most profitable routes to optimize revenues from only the supersonic route network instead of from the entire fleet network because the sequential allocation approach separates the consideration of supersonic and subsonic aircraft fleets. It is possible that the sum of profits from the supersonic allocation and the subsonic allocation approach could be less than the profit from the simultaneous approach, and the major reason for including the allocation model in FLEET is to represent how a profit-seeking airline would use its aircraft.

Subsonic and supersonic aircraft simultaneous allocation approach

Figure 29 shows the flowchart of a proposed subsonic and supersonic aircraft simultaneous allocation approach. After calculating the inherent demand growth with price-demand elasticity effect, FLEET evaluates the subsonic demand and supersonic demand on each route. Both demands are inputs for the simultaneous allocation problem. Subsequently, the simultaneous aircraft allocation problem evaluates both subsonic and supersonic aircraft operations. Based on the supersonic and subsonic aircraft operations, the airline in FLEET makes strategies of aircraft acquisition and retirement.

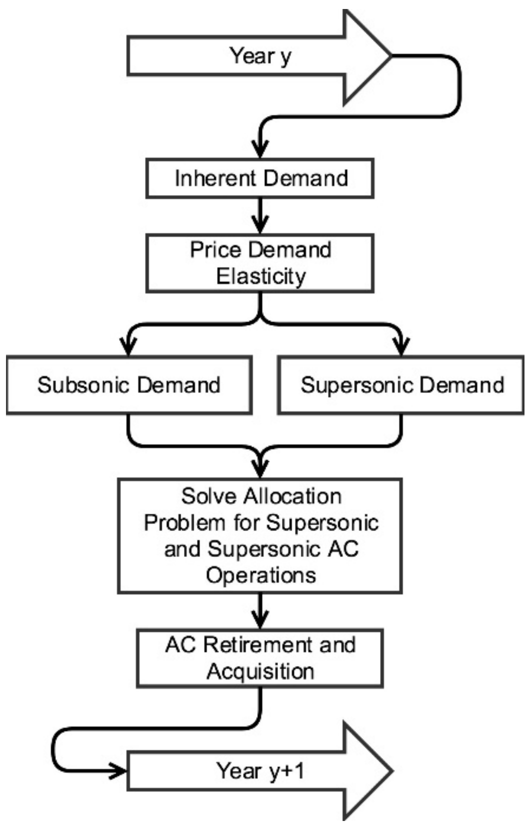

Figure 29. Flowchart of Subsonic and Supersonic Aircraft Simultaneous Allocation Approach

The simultaneous aircraft allocation problem is shown as follows.

Objective function:

$$\sum_{a1,r1}(\boldsymbol{PaxSub_{a1,r1}PSub_{a1,r1} - xSub_{a1,r1}CSub_{a1,r1}}) + \sum_{a2,r2}(\boldsymbol{PaxSup_{a2,r2}PSup_{a2,r2} - xSup_{a2,r2}CSup_{a2,r2}})$$

Equation 1

Constraint functions:

$$\sum_{r} 2xSub_{a,r}(BHSub_{a,r} + MHSub_{a,r} + tSub_{a,r}) \leq 24 \times 3fleetSub_a, \forall a, r \in r1$$

Equation 2

$$\sum_{r} 2xSup_{a,r}(BHSup_{a,r} + MHSup_{a,r} + tSup_{a,r}) \leq 24 \times 3fleetSup_a, \forall a, r \in r2$$

Equation 3

$$tranPax_r = \begin{cases} DemSup_r - \sum_{a2} PaxSup_{a2,r}, \ \forall r \in r1 \cap r2 \\ 0, \forall r \notin r1 \cap r2 \end{cases}$$

Equation 4

$$\sum_{a2} Paxsup_{a2,r2} \leq DemSup_{r2}, \forall r2$$

Equation 5

$$0.2(DemSub_{r1}) + tranPax_{r1} \leq \sum_{a1} PaxSub_{a1,r1} \leq DemSub_{r1} + tranPax_{r1}, \forall r1$$

Equation 6

$$paxsup_{a,r} \leq xSup_{a,r} \times SupSeat_a \ , \forall a, r$$

Equation 7

$$paxsub_{a,r} \leq xSub_{a,r} \times SubSeat_a \ , \forall a, r$$

Equation 8

Equation 1 shows the objective function of the simultaneous allocation problem. $r1$ and $r2$ are sets of subsonic and supersonic routes, respectively. $PaxSub_{a1,r1}$ and $PaxSup_{a2,r2}$ show the number of passenger carried by subsonic aircraft $a1$ and supersonic aircraft $a2$ on routes $r1$ and $r2$, respectively; while $xSub_{a1,r1}$ and $xSup_{a2,r2}$ represent the number of flights of subsonic aircraft $a1$ and supersonic aircraft $a2$ on routes $r1$ and $r2$. $PSub_{a1,r1}$ and $PSup_{a2,r2}$ are the subsonic and supersonic ticket fares for taking subsonic aircraft $a1$ and supersonic aircraft $a2$ on routes $r1$ and $r2$, respectively. Finally, $CSub_{a1,r1}$ and $CSup_{a2,r2}$ are the operation costs per flight of using subsonic aircraft $a1$ and supersonic aircraft $a2$ on routes $r1$ and $r2$.

Equation 2 and Equation 3 check that the total operation hours of subsonic aircraft and supersonic aircraft are less than 72 hours, respectively. The operating hours include block hours ($BHSub_{a,r}$ and $BHSup_{a,r}$), maintenance hours ($MHSub_{a,r}$ and $MHSup_{a,r}$), and aircraft turn-over time ($tSub_{a,r}$ and $tSup_{a,r}$) for both subsonic and supersonic aircraft. $fleetSub_a$ and $fleetSup_a$ represent number of subsonic and supersonic aircraft type a in the airline's fleet. The 72-hour time window allows for completion of the longest trans-Pacific roundtrips.

Equation 4 shows the definition of the redundant variable, $tranPax_r$, to simplify the expression of Equation 6 and show the unsatisfied supersonic flight passenger demand. The unsatisfied supersonic flight passenger demand equals to the carried supersonic flight passenger demand, $PaxSup_{a2,r2}$, subtracts from the total supersonic flight demand, $DemSup_r$, on the intersection of subsonic and supersonic route sets.

Equation 5 ensures that the carried supersonic flight passengers are less than the supersonic flight market demand, $DemSup_{r2}$. The unsatisfied supersonic flight demand will be included in the subsonic flight market demand. Equation 6 ensures that the airline can satisfy all unsatisfied supersonic flight demand and, at a minimum, twenty percent of the subsonic demand. This 20% limitation makes the constraint easier to address in the allocation problem; in practice, very high percentages of the available demand are satisfied (95% and above). Also, the carried subsonic flight passenger should be less than the total subsonic market demand.

Finally, both Equations 7 and 8 ensure that the carried passenger is less than the total available seats for subsonic and supersonic flight, respectively. $SupSeat_a$ and $SubSeat_a$ are the supersonic aircraft a seat capacity and subsonic aircraft a seat capacity, respectively.

The strength of the simultaneous allocation problem is that constraints for the entire airline fleet are readily incorporated in the allocation problem. Hence, it is easy to implement both the airport noise constraint and the airport operation capacity constraint without introducing biases for one type of aircraft. Also, this formulation can guarantee that the aircraft allocation is optimal for the overall airline's operations instead of optimizing for supersonic aircraft operations first and then serving remaining demand via subsonic aircraft operations.

The simultaneous allocation problem renders the choices of business class or first-class passengers to the airline. The redundant variable in Equation 4 represents numbers of business class or first-class passengers who buy the subsonic ticket price. The airline can optimize its overall profits by making the decisions for those passengers to either take the supersonic or subsonic flights.

Future Work: Allocation Problem Selection

An immediate future item for work is to determine which allocation approach to use for supersonic studies moving forward. The Purdue team will develop a passenger choice model (i.e., account for the "value of travel time" of passengers as a foundation for modeling their choice on routes when both supersonic and subsonic aircraft are available) and integrate it into the subsonic and supersonic aircraft simultaneous allocation approach, so that the business or first-class passengers have the option to choose between either supersonic or subsonic flights based on the airlines' schedules. The team will continue to utilize the supersonic and subsonic aircraft sequential allocation approach if the quality of the passenger choice model developed does not meet reasonable expectations about the choice between supersonic or subsonic travel, or if the team receives feedback that the sequential allocation might match how airlines might schedule supersonic aircraft when they enter the fleet.

Preliminary Simulation Results

Figure 29 shows a subset of scenarios developed from the first phase of the ASCENT 10 project [8] that can be readily simulated in FLEET, based upon the fidelity of the current supersonic aircraft modelling approach and the relevance of the availability of supersonic aircraft. The scenarios are listed by row in dark blue boxes, whereas the columns list the final worldview descriptors with specific settings for each scenario. Each cell is colored from low to nominal to high settings. Scenarios that we studied for the subsonic-only fleet mix with noise limitations are not part of the set of scenarios shown in Figure 29 because of the current lack of noise models for supersonic aircraft. The rest of this section describes Purdue's preliminary results from a simulation study in which supersonic aircraft become available for serving commercial air travel demand by the FLEET profit-seeking airline. The "Current Trend Best Guess" (CTBG) scenario with an all-subsonic aircraft fleet, characterized from the first phase of the ASCENT 10 project, was used to enable the comparison to the fleet mix with supersonic aircraft. Since the modeling and assumptions are still under continuous refinement and improvement, these preliminary results are primarily useful for understanding the workings of the model, the kinds of sensitivities we see when supersonic aircraft are introduced to the fleet and improving the diagnostic and analysis of the simulation data.

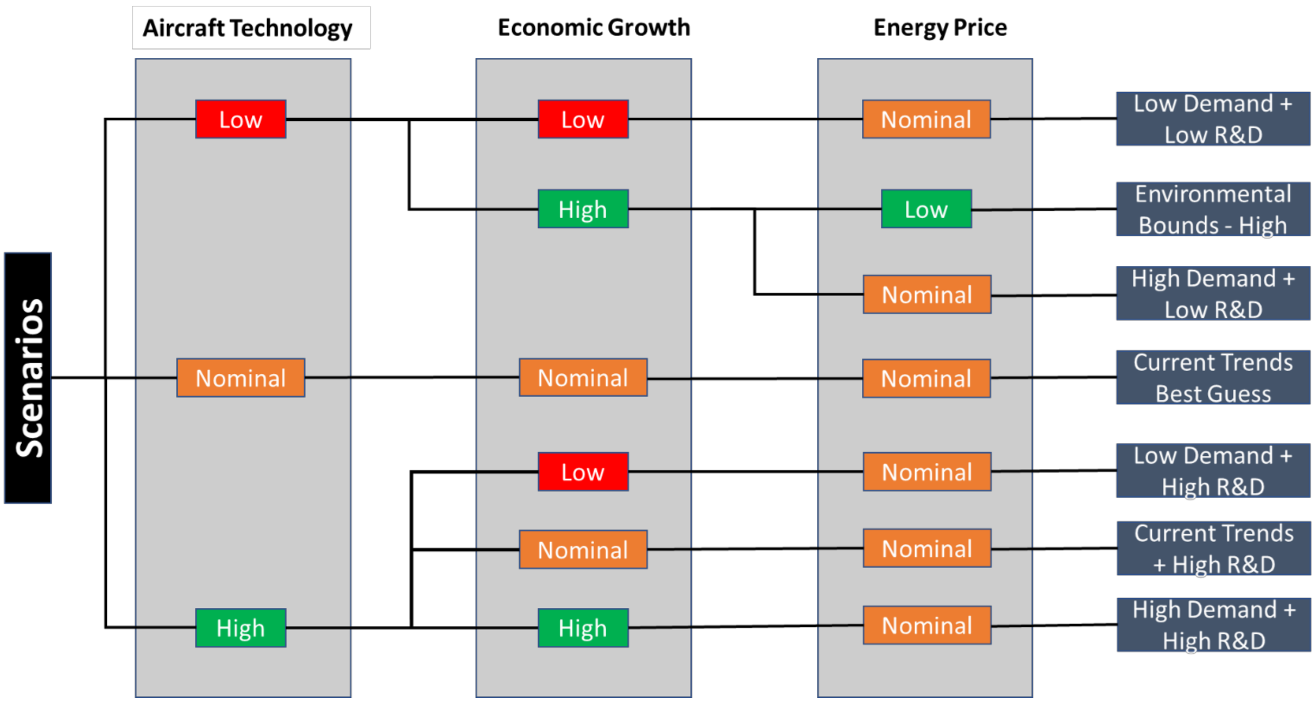

FIGURE 30. SCENARIO TREE OVERVIEW FOR SUPERSONIC STUDY

The FLEET setup for the CTBG scenario is defined as follows:

- A network of 169 airports including U.S. domestic routes and international routes that have either their origin or destination in the U.S.
- The annual gross domestic product (GDP) grows at a constant value of 4.3% in Asia, 4.2% in Latin America, 2.4% in Europe, and 2.8% for airports in the United States.
- The annual population growth rate at a constant value of 1.1% in Asia, 1.26% in Latin America, 0% in Europe, and 0.58% for the United States.
- Jet fuel prices grow according to the Energy Information Administration (EIA) reference fuel price [9] case and adjusted it to meet the ASCENT survey fuel price, $77.08/bbl, by 2050.
- Carbon emission prices grow linearly from $0/MT in 2020 to $21/MT by 2050.

TABLE 10. SUBSONIC AIRCRAFT TYPES USED IN SIMULATION

Subsonic Aircraft Types in Study				
	Representative-in-Class	Best-in-Class	New-in-Class	Future-in-Class
Class 1 (SRJ)	Canadair RJ200/RJ440	Embraer ERJ145		
Class 2 (RJ)	Canadair RJ700	Canadair RJ900	GT Gen1 DD RJ (2020)	GT Gen2 DD RJ (2030)
Class 3 (SA)	Boeing 737-300	Boeing 737-700	GT Gen1 DD SA (2017)	GT Gen2 DD SA (2035)
Class 4 (STA)	Boeing 757-200	Boeing 737-800	GT Gen1 DD STA (2025)	GT Gen2 DD STA (2040)
Class 5 (LTA)	Boeing 767-300ER	Airbus A330-200	GT Gen1 DD LTA (2020)	GT Gen2 DD LTA (2030)
Class 6 (VLA)	Boeing 747-400	Boeing 777-200LR	GT Gen1 DD VLA (2025)	GT Gen2 DD VLA (2040)

In Table 10 the aircraft labeled with “GT Gen1 DD” are the Generation 1 aircraft modeled by Georgia Tech with a ‘Direct Drive’ engine. The Generation 2 aircraft are labeled as “GT Gen2 DD”. These include aircraft that belong to the following classes - regional jet (RJ), single aisle (SA), small twin aisle (STA), large twin aisle (LTA), and very large aircraft (VLA). Based on the amount and speed of technology incorporated into aircraft, in each of the scenarios, the New-in-Class and Best-in-Class aircraft models will vary. Given the observation that new orders for 50-seat regional jet aircraft have diminished to zero, there are no small regional jet (SRJ) aircraft in the new- and future-in-class technology ages.

The Purdue Team tests the simulation with different supersonic ticket price models and supersonic aircraft allocation problems to assess which models result in the most possible carbon emission trends and commercial aviation industry behaviors. In this report, Purdue Team uses the previous ASCENT 10 project all-subsonic CTBG simulation results as the reference. Then, the CTBG supersonic aircraft scenario with 1) average margin per nautical mile ticket price model and 2) sequential supersonic aircraft allocation approach is used to compare the results with the all-subsonic CTBG scenario. The following sections include the simulation results and discussions.

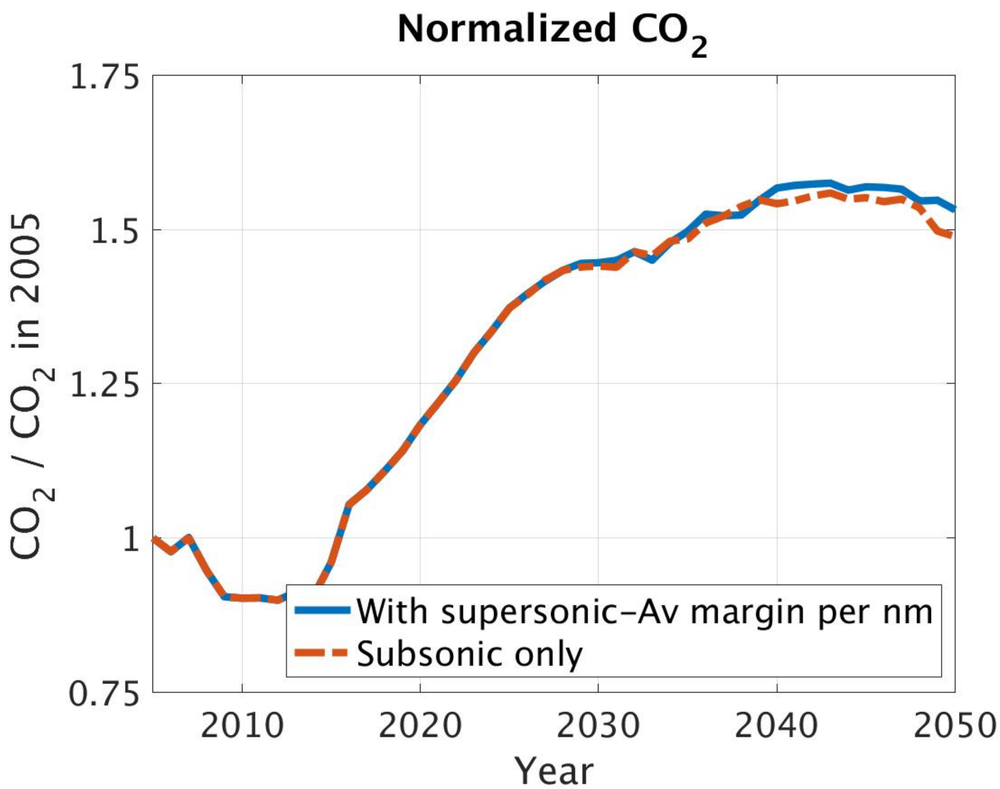

FIGURE 31. NORMALIZED FLEET-LEVEL CO_2 EMISSIONS FROM 2005 TO 2050

Figure 31 shows the predicted fleet-level CO_2 emission values for the subsonic-only airline fleet, which is the same result as in the previous phase of ASCENT 10 for the CTBG scenario definition, along with predictions for the airline fleet including the introduction of supersonic aircraft. The CO_2 emission for each year during the FLEET simulation period is normalized by the CO_2 emission value in the first simulation year of 2005. The dashed orange line represents CO_2 emission trend for the scenario in which there are no supersonic aircraft available (i.e., all subsonic aircraft only fleet) to the airline, while the solid blue line represents the CO_2 emission trend for the scenario where supersonic aircraft with cruise a Mach of 2.2 is available to the airline after year 2025. By 2050, the CO_2 emission in the subsonic-only fleet scenario increased to 1.5 times of the CO_2 emission value in 2005, while the carbon emission from the scenario with supersonic aircraft available resulted in about 1.51 times of the carbon emission in 2005. Although the scenario with supersonic aircraft available has a higher CO_2 emission value than the subsonic fleet only scenario by 2050, the scenario with supersonic aircraft has a slightly lower CO_2 emissions than the all subsonic fleet scenario at different times in the 2030s.

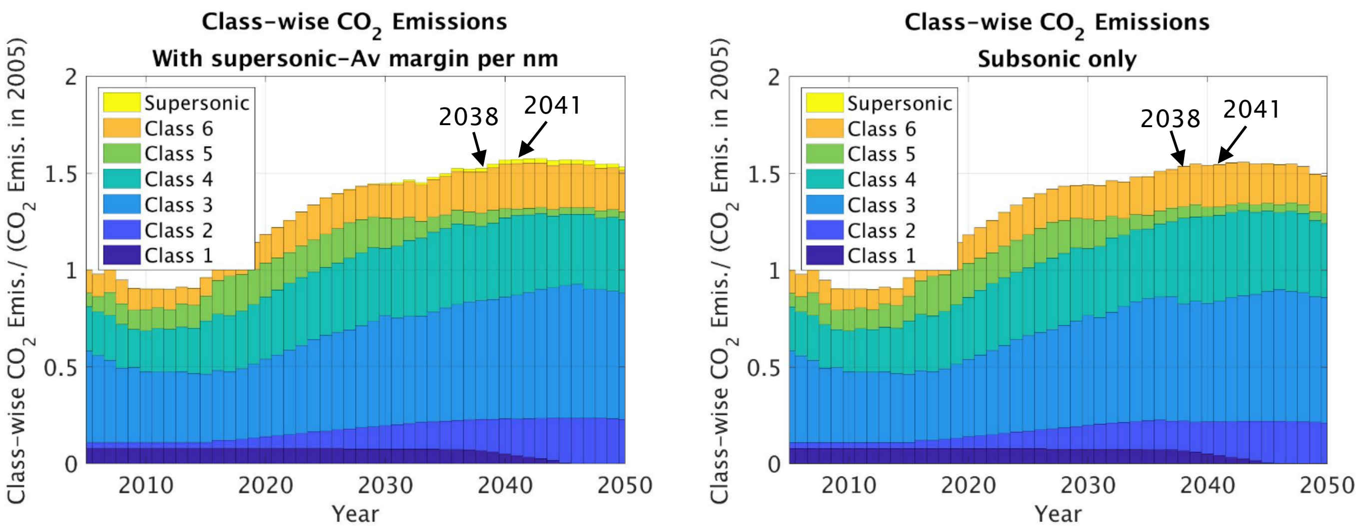

FIGURE 32. NORMALIZED CO_2 EMISSIONS BY AIRCRAFT CLASS

Figure 32 shows the CO_2 emission composition by each aircraft class in the airline fleet throughout the simulation period. Similar to Figure 30, the CO_2 emission values for each aircraft class in both scenarios are normalized by their corresponding carbon emission values for each aircraft class in 2005. Also consistent with Figure 31, Figure 32 shows that the CO_2 emission in the simulation for the scenario with available supersonic aircraft (left plot) was lower than the CO_2 emission in the all-subsonic aircraft fleet scenario (right plot) in some years in the 2030s. Conversely, the scenario with supersonic aircraft available consistently yielded a higher CO_2 emission than the all-subsonic fleet scenario after 2040. The carbon emission reduction observed in the scenario with supersonic aircraft available, when compared to the subsonic-only fleet scenario for years 2034 and 2038, is due to the different manner in which the FLEET airline utilizes its subsonic aircraft (i.e. classes 1 to 6) when supersonic aircraft are available.

Figure 33 shows the number of trips flown daily, over a three-day period by different aircraft types on supersonic-eligible routes in the FLEET airline network for both “subsonic only” and “with supersonic” fleet-mix schemes in 2038. The three-day period allows for subsonic aircraft to complete the longest round-trip trans-Pacific flights in the FLEET network. Low to high number of aircraft trips are represented by a spectrum of light blue to deep blue shades respectively, while the red-shaded cells indicate city pairs with no utilization of a certain aircraft type. For instance, of the 26 supersonic-eligible routes indicated in Figure 33, the Honolulu to Los Angeles (i.e., HNL to LAX, route number 13) has the most average number of daily trips (as evidenced by the blue shaded cells) by both subsonic and supersonic aircraft in 2038. This behavior stems from a FLEET modeling abstraction that ensures that only the travel demand by all U.S. air carriers is characterized. A lot of real-world travel demand on the HNL-LAX route are predominantly served by U.S. carriers, thus a high fraction of this demand is captured in the FLEET simulation. For routes like New York to London (i.e., JFK to LHR, route number 20) in FLEET, served by other multiple carriers from Europe and other continents, the fraction of real-world demand served by U.S. air carriers is smaller compared to the total demand served by all carriers operating on the route, thus the lower number of aircraft trips as compared to the HNL-LAX route.

Figure 33 also reveals that the FLEET airline does not utilize any subsonic best-in-class aircraft on any of the supersonic-eligible routes in 2038, for the fleet-mix scheme where supersonic aircraft is made available to the airline. In addition, unlike the fleet-mix scheme with subsonic-only aircraft where most future-in-class 3 aircraft utilization predominantly occurs on Honolulu to Osaka (i.e. HNL to KIX, route number 11), the FLEET airline utilizes future-in-class 3 aircraft, which is comparatively more fuel efficient and has more seats than older generation class 3 aircraft, in the fleet-mix scheme with supersonic aircraft available on almost all of the 26 eligible supersonic routes in 2038. The combined effect of the sparse utilization of the moderately fuel-efficient new-in-class 5 aircraft and more fuel-efficient future-in-class 3 aircraft across multiple supersonic-eligible routes in the fleet-mix scheme with supersonic aircraft available, as compared to the high density route-specific utilization observed in the subsonic-only fleet scheme, consequently results in a lower total CO_2 emission in 2038 for the scenario where supersonic aircraft is available and used by the airline.

FLEET Airline City Pair			Fleet-mix Scheme with Supersonic Aircraft: Subsonic, Future Class 3	Subsonic, New Class 4	Subsonic, New Class 5	Subsonic, New Class 6	Supersonic, Best
1	AMS	JFK	0.00	3.33	0.00	0.00	0.00
2	ATL	CDG	0.67	0.67	0.67	4.00	1.33
3	BOS	LHR	0.67	5.33	1.33	0.00	1.33
4	CDG	IAD	0.00	2.67	0.67	0.67	0.67
5	CDG	JFK	0.67	11.33	0.67	0.00	2.00
6	CDG	MIA	0.67	0.00	1.33	1.33	0.00
7	EWR	FRA	0.67	2.67	0.67	0.00	0.00
8	FCO	JFK	0.67	0.00	0.67	2.67	0.67
9	FRA	IAD	0.00	8.67	1.33	0.00	1.33
10	FRA	JFK	0.67	2.00	0.67	0.00	0.00
11	HNL	KIX	0.00	0.67	1.33	7.33	0.00
12	HNL	LAS	1.33	8.00	0.67	0.00	1.33
13	HNL	LAX	3.33	56.00	0.00	0.00	8.67
14	HNL	NRT	0.00	26.00	0.67	0.67	0.00
15	HNL	PHX	1.33	6.00	0.00	0.00	1.33
16	HNL	SEA	0.67	9.33	1.33	0.00	2.00
17	HNL	SFO	1.33	33.33	0.67	0.00	5.33
18	HNL	SYD	0.00	0.67	1.33	0.00	0.00
19	IAD	LHR	0.67	12.00	0.67	0.00	2.00
20	JFK	LHR	0.67	26.67	0.00	0.00	4.00
21	JFK	MAD	0.67	2.00	0.67	0.00	0.00
22	JFK	MXP	0.67	0.67	0.67	0.67	0.00
23	JFK	ZRH	0.67	2.00	0.67	0.00	0.00
24	LHR	MIA	0.67	0.67	0.67	2.00	0.67
25	MAD	MIA	0.67	0.67	0.67	1.33	0.00
26	NRT	SFO	0.00	0.67	0.00	14.00	0.00

FLEET Airline City Pair			Fleet-mix Scheme with Subsonic-Only Aircraft: Subsonic, Future Class 3	New Class 4	New Class 5	New Class 6
1	AMS	JFK	0.00	3.33	0.00	0.00
2	ATL	CDG	0.00	0.00	7.33	0.00
3	BOS	LHR	0.00	7.33	0.00	0.00
4	CDG	IAD	0.00	4.67	0.00	0.00
5	CDG	JFK	0.00	13.33	0.00	0.00
6	CDG	MIA	0.00	0.00	3.33	0.00
7	EWR	FRA	0.00	4.67	0.00	0.00
8	FCO	JFK	0.00	3.33	0.00	2.00
9	FRA	IAD	0.00	10.67	0.00	0.00
10	FRA	JFK	0.00	3.33	0.00	0.00
11	HNL	KIX	20.67	0.00	0.00	0.00
12	HNL	LAS	0.00	10.00	0.00	0.00
13	HNL	LAX	0.00	61.33	0.00	0.00
14	HNL	NRT	0.00	28.67	0.00	0.00
15	HNL	PHX	0.00	7.33	0.00	0.00
16	HNL	SEA	0.00	12.00	0.00	0.00
17	HNL	SFO	0.00	36.67	0.00	0.00
18	HNL	SYD	0.00	0.00	2.00	0.00
19	IAD	LHR	0.00	14.67	0.00	0.00
20	JFK	LHR	0.00	28.67	0.00	0.00
21	JFK	MAD	0.00	3.33	0.00	0.00
22	JFK	MXP	0.00	0.00	2.67	0.00
23	JFK	ZRH	4.67	0.00	0.00	0.00
24	LHR	MIA	0.00	0.00	2.00	2.00
25	MAD	MIA	0.00	0.00	0.00	2.00
26	NRT	SFO	0.00	0.00	0.00	15.33

FIGURE 33. NUMBER OF TRIPS ALLOCATED BETWEEN CITY PAIRS PER DAY OVER A REPRESENTATIVE THREE-DAY PERIOD IN 2038

Figure 34 shows the number of daily trips (over a 3-day period) flown by different aircraft types on supersonic-eligible routes in the FLEET airline network for both fleet-mix schemes in 2041. Similar to Figure 33, low to high number of aircraft trips are represented by a spectrum of light blue to deep blue shades respectively, while the red-shaded cells indicate city pairs with no utilization of a certain aircraft type. Similar to 2038 (Figure 33), Figure 34 shows that the FLEET airline utilizes a similar mix of subsonic aircraft class across different technology ages in both schemes that results in a significantly higher fleet-level carbon emissions in 2041 for the scheme with supersonic aircraft available. Furthermore, the airline also allocates available next-generation new-in-class supersonic aircraft to serve demand on different routes, thereby using more supersonic aircraft in 2041 as compared to the total supersonic aircraft utilization in 2038.

FLEET Airline City Pair			Fleet-mix Scheme with Supersonic Aircraft: Subsonic, Future Class 3	Subsonic, New Class 4	Subsonic, New Class 5	Subsonic, Future Class 5	Subsonic, New Class 6	Supersonic, Best	Supersonic, New
1	AMS	JFK	0.00	2.67	0.67	0.00	0.00	0.00	0.67
2	ATL	CDG	0.67	0.00	0.00	0.67	4.67	0.00	1.33
3	BOS	LHR	0.67	7.33	0.00	0.00	0.00	1.33	0.00
4	CDG	IAD	0.67	3.33	0.67	0.00	0.00	0.67	0.00
5	CDG	JFK	0.67	12.67	0.67	0.00	0.00	0.67	1.33
6	CDG	MIA	0.67	0.00	0.00	0.00	1.33	0.00	0.67
7	EWR	FRA	0.67	3.33	0.67	0.00	0.00	0.67	0.00
8	FCO	JFK	0.67	0.67	0.00	0.67	2.67	0.67	0.00
9	FRA	IAD	1.33	9.33	0.00	0.00	0.67	2.00	0.00
10	FRA	JFK	3.33	1.33	0.00	0.00	0.00	0.00	0.67
11	HNL	KIX	0.67	0.00	0.00	0.67	8.67	0.00	2.67
12	HNL	LAS	7.33	5.33	0.00	0.00	0.00	1.33	0.00
13	HNL	LAX	13.33	52.00	0.00	0.00	0.00	9.33	0.00
14	HNL	NRT	1.33	29.33	0.67	0.00	0.00	0.00	4.67
15	HNL	PHX	2.00	4.67	0.00	0.00	0.00	1.33	0.00
16	HNL	SEA	10.67	4.00	0.00	0.00	0.00	2.00	0.00
17	HNL	SFO	1.33	34.00	0.00	0.00	0.00	6.00	0.00
18	HNL	SYD	0.00	0.00	0.00	2.00	0.00	0.00	0.67
19	IAD	LHR	1.33	14.00	0.00	0.00	0.00	2.67	0.00
20	JFK	LHR	3.33	27.33	0.00	0.00	0.00	4.67	0.00
21	JFK	MAD	0.00	2.00	1.33	0.00	0.00	0.67	0.00
22	JFK	MXP	0.00	2.00	0.00	0.00	0.67	0.00	0.67
23	JFK	ZRH	0.67	2.00	0.00	0.00	0.67	0.00	0.67
24	LHR	MIA	0.67	0.00	0.00	0.67	2.67	0.00	0.67
25	MAD	MIA	0.67	0.67	0.00	0.00	2.00	0.00	0.67
26	NRT	SFO	0.00	0.67	0.00	0.67	16.00	0.00	4.00

FLEET Airline City Pair			Fleet-mix Scheme with Subsonic-Only Aircraft: Subsonic, Future Class 3	New Class 4	New Class 5	Future Class 5	New Class 6
1	AMS	JFK	0.67	2.00	0.67	0.00	0.00
2	ATL	CDG	1.33	0.00	0.00	0.00	5.33
3	BOS	LHR	1.33	7.33	0.00	0.00	0.00
4	CDG	IAD	1.33	3.33	0.67	0.00	0.00
5	CDG	JFK	1.33	12.67	0.67	0.00	0.00
6	CDG	MIA	0.00	0.00	0.00	0.67	2.00
7	EWR	FRA	0.00	4.00	0.67	0.00	0.00
8	FCO	JFK	0.67	0.00	0.00	0.67	3.33
9	FRA	IAD	0.00	9.33	0.00	2.00	0.00
10	FRA	JFK	0.67	3.33	0.00	0.00	0.00
11	HNL	KIX	0.00	14.00	0.00	1.33	0.00
12	HNL	LAS	0.00	10.00	0.67	0.00	0.00
13	HNL	LAX	13.33	55.33	0.00	0.00	0.00
14	HNL	NRT	0.67	30.67	0.00	1.33	0.00
15	HNL	PHX	1.33	6.00	0.00	0.00	0.00
16	HNL	SEA	1.33	10.67	0.67	0.00	0.00
17	HNL	SFO	2.00	37.33	0.00	0.00	0.00
18	HNL	SYD	0.00	1.33	0.00	0.00	0.67
19	IAD	LHR	1.33	14.00	0.67	0.00	0.00
20	JFK	LHR	1.33	30.00	0.00	0.00	0.00
21	JFK	MAD	1.33	2.00	0.67	0.00	0.00
22	JFK	MXP	0.67	2.00	0.67	0.00	0.00
23	JFK	ZRH	1.33	2.00	0.00	0.67	0.00
24	LHR	MIA	0.67	0.67	0.00	0.00	2.67
25	MAD	MIA	1.33	0.00	0.00	0.00	2.00
26	NRT	SFO	0.00	0.67	0.00	1.33	16.00

FIGURE 34. NUMBER OF TRIPS ALLOCATED BETWEEN CITY PAIRS PER DAY OVER A REPRESENTATIVE 3-DAY PERIOD IN 2041

Summary and Future Work

Georgia Tech

The Georgia Tech team investigated routes that would be capable to carry enough demand to fill a 50 to 60 seat supersonic aircraft with significant time advantages. It was also demonstrated that an estimate of vehicle demand can be converted to equivalent passenger traffic in GREAT.

The preliminary modeling of supersonic vehicles developed a parametric capability to explore the design constraints for potential future supersonic aircraft design. This is valuable because it allows the user to explore specific aircraft capabilities or mission requirements and their influence on the engine and aerodynamic efficiency of the aircraft as well as a simplified mission performance and weight analysis that results in preliminary estimates of fuel efficiency for a potential aircraft. These results in multipliers of a couple of new aircraft concepts relative to a reference subsonic aircraft type. The resulting fuel intensity of these new types is in the several multiples of a standard single aisle reference aircraft.

This phase of the effort investigated the ability of AEDT to model supersonic aircraft - which it can – but is not well supported. The results obtained from existing or other aircraft developed for other research efforts show specific modeling gaps that influence the accuracy of any potential supersonic aircraft model in AEDT. These modeling gaps resulted in specific recommendations for improving the future modeling capabilities of AEDT.

The fleet analysis tools were expanded to specifically include a separate category for supersonic aircraft. The results for the fleet analysis obtained from GREAT/IDEA, which include several of the supersonic concept aircraft for the first time, are first attempts at incorporating potential supersonic aircraft into the fleet analysis frameworks. The range of the results show a relatively modest impact of CO_2 emissions for only a few daily flights on a very limited number of routes. However, following some prior market assessments of a potential demand of over a thousand supersonic aircraft over a ten year period, the results show a potentially very significant increase in CO_2 emissions of aviation.

Future work – shown in the second year proposal for the current supersonic effort – will focus on reducing the modeling uncertainty in the demand for supersonic aircraft as well as expanding the estimates for supersonic aircraft in the key environmental indicators. The team will also work with the AEDT developers in order to improve the modeling of supersonic aircraft and enable to accurate representation of them in the software. Additionally, the fleet level modeling of supersonic aircraft will focus on expanding the environmental metrics as well as incorporating new models. Finally, the team will develop high fidelity EDS models of two potential supersonic aircraft that will allow a much higher fidelity of the environmental performance of these aircraft. This also will allow investigations into the optimum design and operation of these potential new aircraft.

Purdue

The Purdue team successfully demonstrated FLEET's capabilities for modeling and analyzing the introduction of commercial supersonic aircraft to an existing all-subsonic airline fleet model. This demonstration has shown that FLEET is capable of adjusting scenarios developed by ASCENT 10 Project partners (in the first phase of the ASCENT 10 project) to accommodate for the availability of supersonic aircraft in the airline fleet, and as such, provides some unique features that benefit the FAA in tackling challenging fleet-level emissions forecasting problems.

The preliminary results from FLEET – using the placeholder supersonic aircraft model – indicate some seemingly counterintuitive trends for fleet level CO_2 emissions when comparing the subsonic only fleet mix to a mix that includes some supersonic aircraft along with subsonic aircraft. In the fleet-mix scheme where supersonic aircraft become available, the future CO_2 emissions drop below the values predicted in the corresponding scheme with all-subsonic aircraft fleet for some of the years of the simulation. In other year, the predicted fleet-level CO_2 emissions for the with supersonic fleet scheme exceeds that predicted for the subsonic only fleet by an amount that is larger than one would expect for the number of supersonic aircraft operated by the airline. The FLEET approach to use an allocation problem to represent scheduling and assignment decisions of a profit-seeking airline, combined with a retirement model to represent when the airline would retire an existing aircraft from its fleet and an acquisition model for adding new aircraft – both to replace retiring aircraft and to meet growing demand – provides a model-based coupling of these considerations. When the allocation approach first satisfies business class and above passenger demand with supersonic aircraft and subsequently satisfies remaining demand with the subsonic fleet, this coupling shows a different use, retirement and acquisition of the subsonic fleet from that predicted in the subsonic-only fleet mix scheme. These changes lead to the (at least initially) counterintuitive fleet-level CO_2 results. At this time, the results still rely upon the simplistic placeholder supersonic aircraft model, so the predicted values for fuel burn / CO2 emissions should not be viewed with high support; the ability to find these trends via FLEET is the more important conclusion at this point in the effort.

The preliminary results presented in this report are based on the allocation approach which satisfies travel demand first by using supersonic aircraft and next by using subsonic aircraft. In the near term, the Purdue team intends to perform additional studies for the "with supersonic" fleet-mix scheme for several of the economic / technology factor scenarios described as part of the previous ASCENT 10 efforts. When the supersonic aircraft vehicle description becomes available from our Georgia Tech colleagues, we will replace our current placeholder description and repeat the various studies.

Future work (elucidated in detail in the second-year proposal for the current supersonic effort) will assess the fleet-level advantage of having different types of supersonic aircraft, defined by certain operational specifications (e.g. Mach cut-off overland), available to the FLEET airline to improve model fidelity, upon developing and revamping necessary FLEET modules to accommodate for supersonic aircraft, before subsequently running FLEET for different ASCENT 10 Project scenarios.

Publications

Ogunsina, K., Chao, H., Kolencherry, N., Jain, S., Moolchandani, K., Crossley, W. A., and DeLaurentis, D. A., "Fleet-Level Environmental Assessments for Feasibility of Aviation Emission Reduction Goals," Proceedings of CESUN Global Conference 2018, Tokyo, Japan.

Outreach Efforts

Multiple interactions with government, industry, and academia have occurred during the course of project.

ASCENT 10: Aircraft Technology Modeling and Assessment, oral presentation to ASCENT Spring Advisory Committee Meeting, MIT, Cambridge MA, April 4, 2018.

Awards

None

Student Involvement

Of the Georgia Tech students, Eugene Mangortey performed significant work under Task 2. He conducted an extensive literature search on the Concorde's historical performance and operation, and investigated the special policies and provisions that were put in place when the Concorde came into service. He analyzed the research findings and helped formulate specific recommendations and design considerations for future supersonic vehicles. Eugene is currently a Graduate Research Assistant at Georgia Tech and is expected to graduate with his Master's degree in 2019.

Manon Huguenin performed significant work under Task 3. She learned how to use AEDT and ran the required studies for the Concorde. She also analyzed AEDT outcomes and researched actual Concorde performance to identify discrepancies and help formulate recommendations for further development of AEDT. Manon is currently a Graduate Research Assistant at Georgia Tech and is expected to graduate with her Master's degree in 2019.

The Purdue team includes three graduate students in the effort, all three have been conducting tasks in support of the effort. One has just obtained his MS degree and is continuing at Purdue for PhD studies. The other two students are continuing as PhD students.

Plans for Next Period

Table 11 shows the expected objective and contributions developed between Georgia Tech, Purdue, and FAA. It shows the expected contributions by task and university.

TABLE 11. UNIVERSITY CONTRIBUTIONS FOR YEAR 2

Objectives		Georgia Tech	Purdue
1	Fleet Assumptions & Demand Assessment	Identify supersonic demand drivers and supporting airports and project demand for all scenarios Expand to international airports	Estimate latent demand and flight schedules for supersonic aircraft
2	Preliminary Vehicle Environmental Impact Prediction	Develop estimates of Key Environmental Indicators (KEI) for supersonic aircraft relative to current technology subsonic aircraft, Develop estimates of likely operating altitudes	Support with expert knowledge
3	AEDT Vehicle Definition	Test current version of AEDT ability to analyze existing supersonic models Work with AEDT developers to understand the required modifications to support supersonic vehicles	N/A
4	Vehicle and Fleet Assessments	Apply GREAT to estimate impact of supersonics in terms of fuel burn, water vapor, and LTO NOx for a combination of vehicles and scenarios	Apply FLEET to estimate impact of supersonics in terms of fuel burn, water vapor, and LTO NOx
5	EDS Vehicle Modeling	Create 2 EDS supersonic vehicle models with boom signatures	Support with expert knowledge

Table 12 highlights the plans for the next research period for Georgia Tech. Full details on these plans can be found in the second year proposal submitted earlier in the summer.

TABLE 12. LIST OF ANTICIPATED MILESTONES FOR THE NEXT RESEARCH PERIOD (GT)

Milestone	Planned Due Date
Documentation of the updated projected supersonic demand for the A10 scenarios	12/2018
Documentation of the development of key environmental Indicators (KEI) for the list of current and future subsonic aircraft by type and size class	03/2019
Updated Fleet Level Environmental Impacts for each scenario in APMT compatible format	08/2019
EDS aircraft descriptions and characteristics in Powerpoint format including fuel burn, emissions, and noise, and FLOPS output files and also engine descriptions including NPSS and Wate output files.	08/2019
A Report documenting the results of the interdependency tasks	2/2019

Table 13 highlights the plans for the next research period for Purdue. Full details on these plans can be found in the second-year proposal submitted earlier in the summer.

TABLE 13. LIST OF ANTICIPATED MILESTONES FOR THE NEXT RESEARCH PERIOD (PURDUE)

Milestone	Planned Due Date
• Develop and test passenger choice model and ticket price model; update FLEET allocation problem and supersonic route network • Document the results of these changes using a variant of the current trends best guess scenario from the subsonic-only studies as an initial view of how introducing supersonic aircraft might change fleet-level CO_2 emissions	12/2018
• Employ aircraft representations from Georgia Tech teammates – using Key Environmental Indicators and the multiplier approach – into FLEET and demonstrate FLEET studies with these models; begin to measure additional environmental metrics (e.g., NO_x, H_2O) • Document these FLEET studies to show the impact of introducing supersonic aircraft with higher resolution than the studies described above	02/2019
• Develop coefficients, estimates, and additional modules for assessing fleet-level environmental impact; study additional scenarios with FLEET, building upon the previous subsonic-only study scenarios. Incorporate improved vehicle models from Georgia Tech teammates as they become available • Document these FLEET scenario studies to show predictions of how the various environmental metrics (CO_2, NO_x, H_2O) may evolve when supersonic aircraft are available in these future scenarios	04/2019
• Conduct sensitivity studies for drivers (ticket price, passenger choice model parameters, regional fuel prices, etc.) that impact supersonic travel. • Document the sensitivity in the fleet-level environmental metrics to these parameters, which are not typically varied as part of the future scenarios	06/2019
• Coordinate with colleagues at Georgia Tech to provide a project report summarizing this second phase of work studying the introduction of supersonic aircraft	08/2019

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