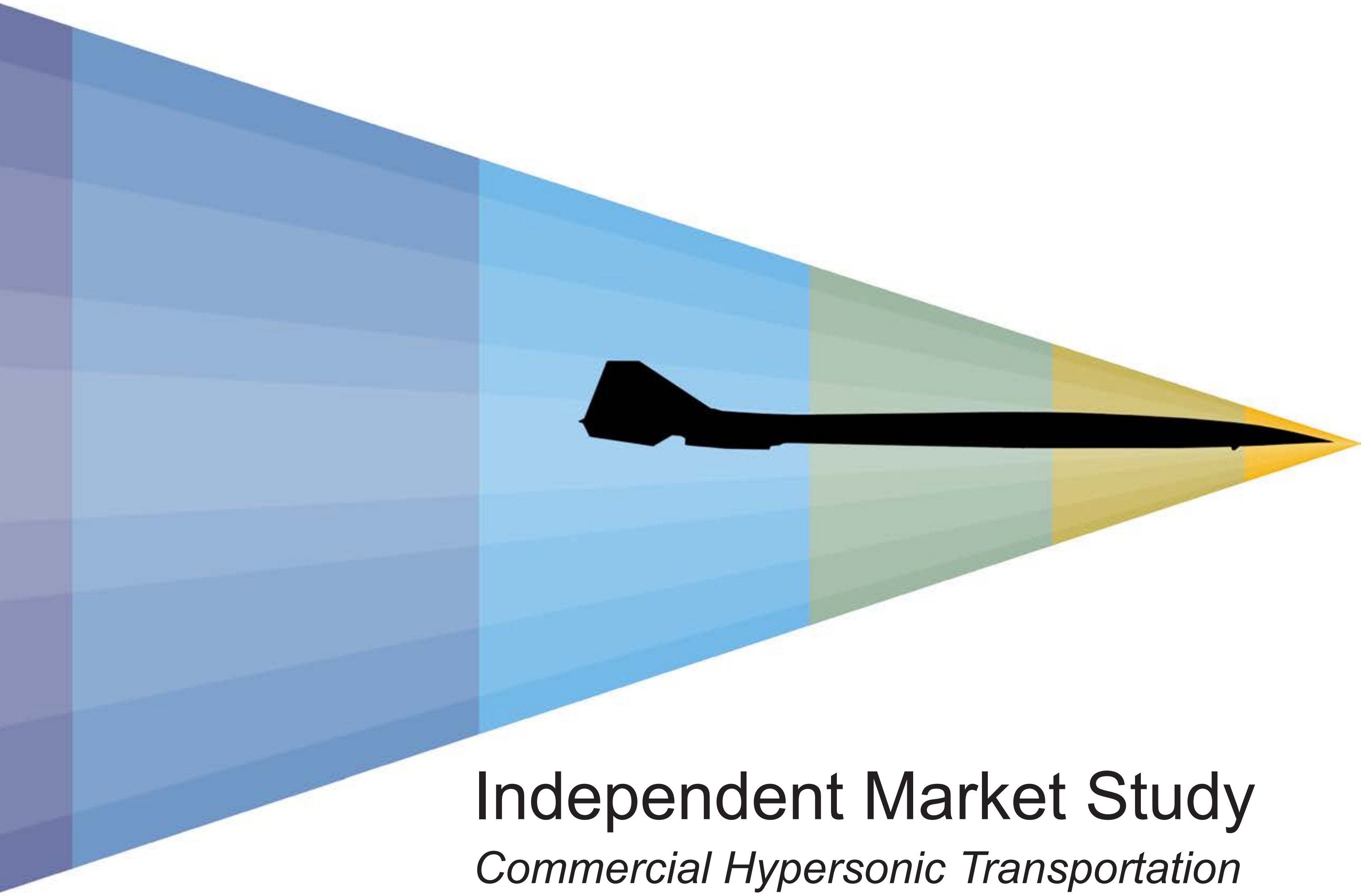


Independent Market Study

Commercial Hypersonic Transportation

April 2021

SAIC

BRYCE
TECH

The work in this report was conducted as part of NASA Delivery Order 80HQTR20F0177, Task Order #36 of the NASA Headquarters Data Analysis and Technical Support Services Contract 80HQTR18A0012.

Deliverable 5 – Final Report

The following individuals contributed to this publication:

BryceTech

Carissa Christensen, Susan Albert, Carie Mullins, Blake Ahadi,
Phil Smith, and Don Buley

SAIC

Dr. Ron Lehmer and Joe Smith

We would like to acknowledge the following NASA participants for their support of this contract:

Charles Leonard, Mary Jo Long-Davis, Eric Hendricks, Alan Linne,
John Martin, Jeff Robinson, Jon Seidel, and Andrea Storch

Subject matter experts who contributed to this study are listed on Page 8 of this document.

The work in this report was conducted as part of NASA Delivery Order 80HQTR20F0177, Task Order #36 of the NASA Headquarters Data Analysis and Technical Support Services Contract 80HQTR18A0012.

Deliverable 5 – Final Report

Contents

Executive Summary v
  Analysis and Modeling vi
  Findings vi
  Key Actions to Consider viii

Introduction 1

Methodology 2
  Data Sources 2
  Modeling Approach (Tasks 1 and 2) 4
    Demand (Task 1) 5
    Business Case (Task 2) 5
  Barriers (Task 3) 6

Market Definition (Task 1) 8
  Characterizing Future High-Speed Aircraft 8
    Fastest Commercial Subsonic Aircraft 9
    Historical Military and Commercial Aircraft Above Mach 1 9
    In Development Commercial Aircraft up to Mach 3 10
    In Development Commercial Aircraft Mach 4+ 11
    Effect of Commercial Supersonic Transportation on Commercial Hypersonic Market 12
    Representative Conceptual Aircraft Cases for Modeling and Analysis 13
  Estimating Passenger Demand and Revenue 15
    Forecasting Addressable Demand 15
    Willingness to Pay 16
    Other Factors Affecting Passenger Choices 18
    Total long-haul premium passengers 19
    Total long-haul premium passengers 19
  Estimating Revenue from Viable Routes 20
  Summary of Results 20
  Analysis and Comparison 20
  Commercial and General Aviation Services Demand at 1.5x Fare, All Cases 24
  Demand for High-speed Cargo Transportation 26

Business Case (Task 2) 27
  Estimating Revenue Based on Market Timing 28
  Estimating Costs 28

Operating Costs 28
Manufacturing Costs 31
Estimating Profit and Resale Value 31
Business Case Analysis Findings 33
Overview 33
Supported Acquisition Budget 33
Supported Available RDT&E: Commercial Aviation 34
Supported Available RDT&E: General Aviation Including Jet Sales 36
Supported Available RDT&E: Total. 37
Supported Available RDT&E: Best Case 37
Supported Available RDT&E: NASA-Defined Case 39
Sensitivity Analysis 39
Sensitivity Analysis Based on Optimized Case 39
Sensitivity of Cost per Seat Mile to Fuel Multiplier 40
Practical Business Case Considerations 41

Barriers (Task 3) 43
Identify and Catalog Barriers 44
Barrier Mitigation 49
Proposed NASA Mitigation Actions by Type of Mitigation and Barrier Group 51
Prioritize Barriers Based on Consequence of Barrier and Impact of Mitigation 52

Actions to Consider 56

Endnotes 57

Acronyms 59

Appendix 1: Analysis Results by Case 61

Appendix 2: Survey of High-Net-Worth Individuals 67

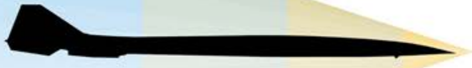
Appendix 3: Summary of High-Speed Commercial Aircraft (Conceptual and In Development). 70
Aerion Corporation AS2 70
Spike Aerospace S-512 70
Lockheed Martin Corp. QSTA 71
Exosonic Concept 71
Boom Technology Overture. 72
Virgin Galactic Concept. 72
Airbus Concorde 2 73
Boeing Concept 73

Hermeus Concept 74
EU Horizons 2020 Team STRATOFLY MR3 74
JAXA Concept 75
Stratolaunch Talon A 75
Generation Orbit X-60A 76

Appendix 4: Non-Technical Barriers to Commercial Hypersonic Transportation 77

Identification of Barriers and their Consequences 77
Mitigation of Barriers and their Impacts 91

This page intentionally left blank.



Executive Summary

For over five decades, the National Aeronautics and Space Administration (NASA) has been studying the fundamental physics and technologies to support the development of a hypersonic aircraft (vehicles flying in excess of Mach 5). Much of this research has logically focused on the fundamentals of propulsion, guidance, and control. In the past two decades, there has been a flurry of activity to field test air-launched hypersonic vehicles (NASA X-43 and X-51 platforms, for example) to integrate the knowledge and understanding gathered to date and as a precursor for the research and development (R&D) of various military applications of hypersonic flight, which other countries are pursuing as well.

In parallel with the vehicle testing by the United States (U.S.) and other countries, several commercial companies began to seriously evaluate and develop possible supersonic and hypersonic vehicle concepts to ultimately bring to the global commercial passenger aviation market. While this nascent market has benefited greatly from the long lineage of NASA research into hypersonics, it is now equally important to understand how future NASA research objectives can further enhance the development of these vehicle concepts into a viable transportation system.

In support of NASA's evaluation of its future research thrusts for its hypersonics program, NASA has been conducting "a year of due diligence." In addition to its own studies of the technical research needs and economics of hypersonic vehicles being done within the NASA organization, NASA has also commissioned independent studies of the market for commercial hypersonic transportation. SAIC and BryceTech (formerly Bryce Space and Technology) were awarded one of these independent studies to assist NASA in better understanding: (1) the passenger demand for high-speed aviation travel; (2) the pressures on the business case for developing and operating a hypersonic aircraft for the commercial aviation market; and (3) the non-technical (i.e., societal) barriers and challenges, including the steps NASA and the Government could take to overcome those barriers and challenges.

Table E1. Commercial high-speed aircraft in development.

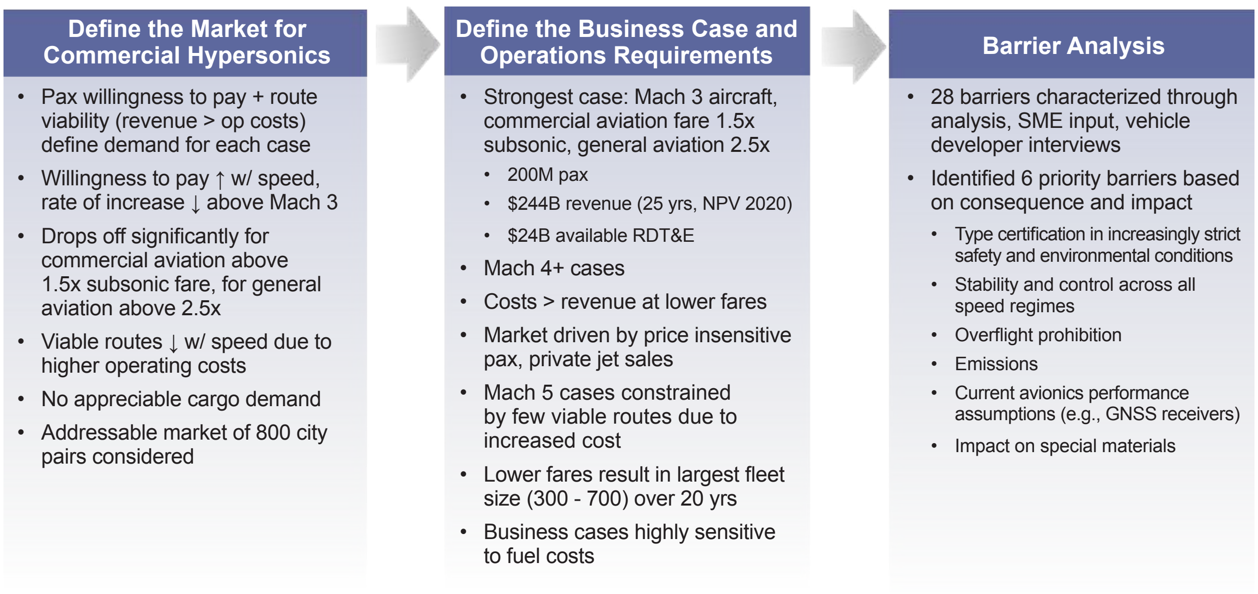
Vehicle	Actual or Estimated Entry into Service	Speed (Mach)
Aerion AS2	2027	1.4
Spike S-512	2023	1.5
Lockheed Martin QSTA (conceptual)	2030	1.8
Exosonic Concept	2029	1.8
Boom Overture	2029	2.2
Virgin Galactic TSC Concept	2029	3.0
Aerion AS3 (conceptual)	Undisclosed	4.3
Airbus Concorde 2 (conceptual)	Undisclosed	4.5
Boeing Concept (conceptual)	2040	5.0
Hermeus Concept	2035	5.0
JAXA Concept (conceptual)	Undisclosed	5.0
Reaction Engines LAPCAT A2 (conceptual)	Undisclosed	5.2
Stratolaunch Talon-A	2023	6.0
STRATOFLY MR3 (conceptual)	Undisclosed	8.0
Generation Orbit X-60A	2021	8.0
BlueEdge (conceptual)	Undisclosed	9.0+

Our approach to addressing these three tasks for NASA included modeling future demand and future business operations, considering global air transportation at speeds of Mach 2 to Mach 7. The team forecast premium air travel demand through 2060 and assessed the willingness of passengers of different income and wealth levels to pay to save time on flights between 800 city pairs. With the total addressable market defined, we examined industry-level business case viability for several aircraft speed and range cases. Considering operating and manufacturing costs for routes that could be serviced profitably, as well as typical profitability targets for the aviation industry, we quantified the level of RDT&E funding available to support each business case.

Analysis and Modeling

We conducted over 50 interviews to gather data from companies that are developing high-speed aircraft, experts on supersonic and hypersonic flight, and airline industry executives. We also used more than 70 reports and studies on air travel, high-speed aircraft, wealth, and other related topics in our research. Distinguished experts in high-speed flight technology and operations assessed our modeling approach and input assumptions for both realism and accuracy.

Figure E1. Summary results.



Define the Market for Commercial Hypersonics

- Pax willingness to pay + route viability (revenue > op costs) define demand for each case
- Willingness to pay ↑ w/ speed, rate of increase ↓ above Mach 3
- Drops off significantly for commercial aviation above 1.5x subsonic fare, for general aviation above 2.5x
- Viable routes ↓ w/ speed due to higher operating costs
- No appreciable cargo demand
- Addressable market of 800 city pairs considered

Define the Business Case and Operations Requirements

- Strongest case: Mach 3 aircraft, commercial aviation fare 1.5x subsonic, general aviation 2.5x
  - 200M pax
  - $244B revenue (25 yrs, NPV 2020)
  - $24B available RDT&E
- Mach 4+ cases
- Costs > revenue at lower fares
- Market driven by price insensitive pax, private jet sales
- Mach 5 cases constrained by few viable routes due to increased cost
- Lower fares result in largest fleet size (300 - 700) over 20 yrs
- Business cases highly sensitive to fuel costs

Barrier Analysis

- 28 barriers characterized through analysis, SME input, vehicle developer interviews
- Identified 6 priority barriers based on consequence and impact
  - Type certification in increasingly strict safety and environmental conditions
  - Stability and control across all speed regimes
  - Overflight prohibition
  - Emissions
  - Current avionics performance assumptions (e.g., GNSS receivers)
  - Impact on special materials

Findings

We found that a commercial high-speed transportation industry will justify significant research, development, test, and evaluation (RDT&E) funding, reaching levels in excess of $20B in 2020 dollars.

Figure E2. Top city pairs by estimated 2050 revenue.

Top 25 City Pairs (2050)

1. *London – Dubai*
2. *New York – London*
3. *San Francisco – Hong Kong*
4. *London – Mumbai*
5. *New York – Shanghai*
6. *London – Doha*
7. *London – Delhi*
8. *Paris – Dubai*
9. *Los Angeles – London*
10. *Anchorage – Hong Kong*
11. *New York – Beijing*
12. *Dubai – Beijing*
13. *Los Angeles – Hong Kong*
14. *Manchester – Dubai*
15. *New York – Paris*
16. *Los Angeles – Shanghai*
17. *New York – Hong Kong*
18. *London – Abu Dhabi*
19. *New York – Frankfurt*
20. *Frankfurt – Delhi*
21. *Birmingham – Dubai*
22. *New York – Tel Aviv*
23. *Chicago – London*
24. *New York – Delhi*
25. *Los Angeles – Beijing*

More than 300 city pairs can support high-speed commercial and general aviation. Many routes among the 800 city pairs we analyzed were too expensive to operate, compared to the revenue they would generate. Fuel was the most significant operating cost component. Generally, the number of viable routes decreased as aircraft speed increased, because operating costs increased with speed and so route revenue for certain routes became insufficient (even with the additional passengers attracted by the time savings associated with higher speed).

The best business case resulted from a Mach 3 aircraft and could support $24B in RDT&E. At Mach 3, the 7-hour flight from New York to London would be reduced by about 5 hours. This subsonic case resulted in $244B in revenue over 25 years (Net Present Value in 2020 dollars). Commercial aviation accounted for more than 60% of RDT&E resources and general aviation nearly 40%.

In the best case, the year 2050 saw 10M passengers, with a total of 200M passengers over 25 years. This is about 13% of today's premium passenger traffic on long-haul routes. On scheduled commercial flights, the best case resulted from fares at 150% of today's business and first-class fares. For general aviation (charter, fractional flights), the best business case resulted from prices at 250% of today's.

Lower fares result in the largest fleet size (about 300 to 700 aircraft) over 25 years. Fleet size represents the number of aircraft needed to service passenger demand on viable routes. Lower fares generated the highest levels of passenger demand, leading to the largest fleet sizes.

Cases at speeds above Mach 3 were constrained by diminishing time ad value savings from customers, fewer viable routes due to increased operating costs, and higher marginal manufacturing costs. Costs exceeded revenue at lower fares and fewer passengers were willing to pay higher fares (in the range of 5 or 10 times current subsonic fares). These cases were driven by a small number of price insensitive passengers and by private jet sales. Mach 5 cases were constrained by few viable routes due to increased cost.

The study found no appreciable cargo demand. While niche applications such as organ transplant, disaster aid, emergency repair parts, urgent documents, and perishable luxury goods may contribute to revenue, saving a matter of hours does not appear likely to command a significant price premium for cargo. Moreover, high-speed aircraft designs do not include much cargo space.

Findings were most sensitive to discount rate and fuel cost assumptions. Available RDT&E is sensitive to discount rate due to the 30-year time horizons assessed and sensitivity to discount rate increases as aircraft are introduced later. After discount rate, available RDT&E is most sensitive to fuel, which makes up roughly half of operating costs.

Significant, though not insurmountable, non-technical barriers challenge the development of a commercial industry. This study assessed barriers to the development of a high-speed transportation industry, specifically non-technical barriers. Of the 28 barriers we identified, the most critical barriers for NASA and others to address (based on seriousness of consequence as well as the highest likelihood

Subject Matter Experts

Pam Melroy
NASA Shuttle commander and USAF test pilot with expertise on supersonic and hypersonic technology and programs

Oscar Garcia
Three decades in commercial aviation as pilot and economics expert

Jim Free
Engineer and Director, NASA Glenn Research Center and Deputy AA NASA HEOMD with expertise in hypersonics

Stu Witt
42-year veteran of aerospace industry as pilot and airport director with expertise in disruptive flight technology

Natasha Heidenrich
Senior market analyst with expertise in airport business models

Virginia Stouffer
Electrical engineer specializing in aerospace communications and sensors

Rich Jennings
Former Assistant Manager, FAA Avionics Systems Branch with experties in certification and regulatory matters

Dr. Lafayette Taylor
Expert in aerospace analysis/ design and computational fluid dynamist

Jody Merritt
Founder lead USAF Reserve Hypersonics Task Force with 30+ years of aerospace experience

of effective mitigation) were related to type certification, stability and control of aircraft, prohibition of overflight, emissions, global navigation satellite system (GNSS) receivers, and special materials.

Key Actions to Consider

The study identified outcomes that would increase available R&D funding and reduce barriers to the development of the commercial high-speed air transportation industry, including improving performance and reducing costs, coordinating with and providing expertise to government regulators, and working with industry. In particular, based on this analysis, NASA should consider activities to improve performance and reduce costs, such as:

- Improving fuel efficiency,
- Improving maintainability to reduce cost of servicing and inspection,
- Reducing manufacturing costs at of high-speed aircraft, and
- Reducing/eliminating required cool down time for refueling and deplaning.

To reduce regulatory and other barriers to the development of commercial high-speed air transportation, NASA should consider facilitating working groups with the Federal Aviation Administration (FAA), the State Department, the Department of Defense (DOD), airport authorities, and industry to address certification, environmental, and other regulatory barriers. Providing NASA expertise in propulsion, materials, and the modeling and simulation of Air Traffic Management (ATM) scenarios to the FAA regarding the performance of critical technologies across a variety of environment conditions can reduce certification delays. Continued sonic boom reduction technology development, through NASA programs such as the Low Boom Flight Demonstration, and societal assessments of the issues and consequences relating to takeoff and landing noise and sound boom during cruise are also important. Finally, NASA's continued work with industry to leverage government programs on innovative alternative capabilities, technologies, and processes can reduce barriers and facilitate industry growth.

Figure E3. Actions to consider.

Checklist of Actions

✓ *Improve fuel efficiency*

✓ *Improve maintainability to reduce cost of servicing and inspection*

✓ *Reduce manufacturing costs*

✓ *Reduce/eliminate required vehicle cool down time post flight*

✓ *Reduce regulatory and other barriers to development of commercial high-speed air transportation*

✓ *Continue sonic boom reduction technology development*

✓ *Continue leverage of government programs supporting industry innovation designed to reduce barriers to entry and growth*

Introduction

For over five decades, NASA has been studying the fundamental physics and technologies to support the development of a hypersonic aircraft (vehicles flying in excess of Mach 5). Much of this research has logically focused on the fundamentals of propulsion, systems analysis, materials, and boundary layer transition. In the past two decades, there has been a flurry of activity to field test air-launched hypersonic vehicles (NASA X-43 and X-51 platforms, for example) to integrate the knowledge and understanding gathered to date and as a precursor for the R&D of various military applications of hypersonic flight, which other countries are pursuing as well.

In parallel with the vehicle testing by the U.S. and other countries, several commercial companies began to seriously evaluate and develop possible supersonic and hypersonic vehicle concepts to ultimately bring to the global commercial passenger aviation market. While this nascent market has benefited greatly from the long lineage of NASA research into hypersonics, it is now equally important to understand how future NASA research objectives can further enhance the development of these vehicle concepts into a viable transportation system.

In support of NASA's evaluation of its future research thrusts for its hypersonics program, NASA has been conducting "a year of due diligence." In addition to its own studies of the technical research needs and economics of hypersonic vehicles being done within the NASA organization, NASA has also commissioned independent studies of the market for commercial hypersonic transportation. SAIC and BryceTech (formerly Bryce Space and Technology) were awarded one of these independent studies to assist NASA in better understanding: (1) the passenger demand is for high-speed aviation travel; (2) the pressures on the business case for developing and operating a hypersonic aircraft for the commercial aviation market; and (3) the non-technical (i.e., societal) barriers and challenges exist, including the steps NASA and the Government could take to overcome those barriers and challenges.

Our approach to addressing these three tasks for NASA included modeling future demand and future business operations, considering global air transportation at speeds of Mach 2 to Mach 7. The team forecast premium air travel demand through 2060 and assessed the willingness of passengers of different income and wealth levels to pay to save time on flights between 800 city pairs. Based on this demand, we compared industry-level business cases for different aircraft, considering operating costs, manufacturing costs, and profitability for both general and commercial aviation.

Under contract to NASA, BryceTech and SAIC conducted a study of the future market for high-speed commercial air transportation. The study considered passenger and cargo demand, industry-level business dynamics, and non-technology barriers, such as regulatory dynamics, to the development of a viable market. The goal of the study was to determine the economic viability of commercial hypersonic point-to-point transportation, based on business models, markets, regulatory dynamics, and barriers that will affect technology investment and trades. NASA defined the relevant speed regime for the study, to provide full context for the assessment hypersonic market development, as covering the range Mach 2 to Mach 7.

BryceTech produced the analysis and this report, with SAIC providing overall project management oversight and subject matter expert (SME) input.

Methodology

This study assesses the economic viability of commercial high-speed air transportation by identifying business models, markets, regulatory dynamics, and barriers that will affect technology investment and trades. The study consisted of three areas of research and analysis. Bryce defined, characterized, and analyzed the:

- Market for commercial high-speed air transportation, considering speeds of Mach 2 to Mach 7 as part of this analysis (NASA Task 1),
- Business case and operations requirements for high-speed transportation, based on market dynamics (NASA Task 2), and
- Non-technology barriers to the development of a viable high-speed transportation industry (NASA Task 3).

The study approach consisted of:

- Research that included desk research, interviews, and survey data (data sources described below),
- Modeling of demand and business cases,
- Structured qualitative assessment of barriers to a commercial high-speed industry, and
- Analysis of results and synthesis of findings and recommendations.

Data Sources

This study incorporates desk research and a literature review of 70+ publications, the use of Bryce corporate intellectual property, including an econometric forecast model of the value of time saved for travelers in different demographic classes for 800 long-haul city-pairs, and Bryce survey data on 150 high net worth and ultra-high net worth flyers. This study also incorporates perspectives from SMEs, who provided technical expertise and data, reviewed findings, and offered insights into trends and dynamics. Table 1 provides a summary overview of the experience and qualifications of the primary SMEs who supported SAIC and Bryce's research.

Table 1. Study subject matter experts.

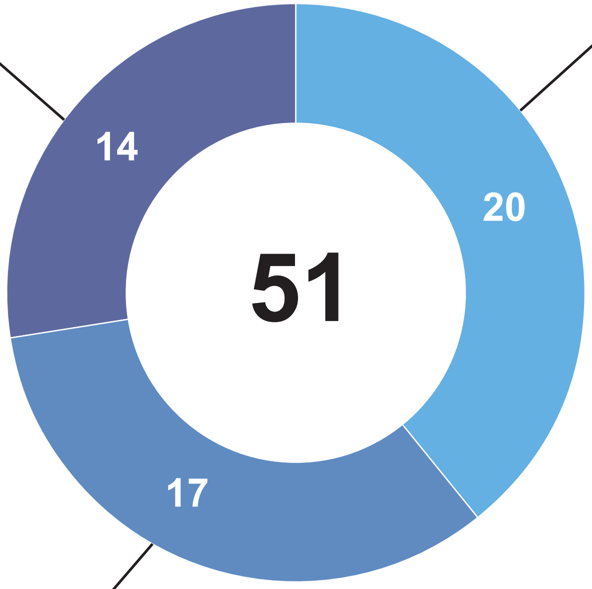
Pam Melroy *(for a part of the study project)*
NASA Shuttle commander, U.S. Air Force (USAF) test pilot
Defense Advanced Research Projects Agency (DARPA) Tactical Technology Office (TTO) Deputy Director
Space Council Users Advisory Group
Board of Directors, Aerospace Corp
Oscar Garcia
Advisor to airlines, aircraft operators, and government
FAA/Office of Commercial Space Transportation (AST), Commercial Space Transportation Advisory Committee
Expert in supersonic and hypersonic economics, certification
Former airline captain

Table 1. Study subject matter experts (continued).

Jim Free
Director Glenn Research Center, Deputy Associate Administrator NASA Human Exploration and Operations Mission Directorate (HEOMD)
11+ years as NASA executive program manager, space systems engineer
Hypersonics expertise
Stu Witt
Mojave Air and Space Port Director
Sought FAA approval for disruptive flight technology
42-year veteran of the aerospace industry
Military pilot
Natasha Heindrich
Senior market and competitive intelligence analyst
Expertise in airport business models
Virginia Stouffer
Engineer and project manager with 25 years of experience in aerospace
Transformational Electric Flight Symposia (Chair), American Institute of Aeronautics and Astronautics (AIAA) Transformational Flight Committee
Electrical engineer specializing in communications and sensors
Rich Jennings
Engineer, Manager FAA Avionics Systems Branch
30 years FAA Type Certification experience (Denver Aircraft Certification Office Manager)
Expertise in communications, navigation, and surveillance TSO equipment
Co-chair of RTCA Special Committee SC-186 Working Group 5 for Automatic Dependent Surveillance-Broadcast (ADS-B) Universal Access Transceiver (UAT) development (DO-282)
Dr. Lafayette Taylor
Fluid dynamics modeler – aerodynamics, hydrodynamics, propulsion
22 years of experience in developing and applying numerical models in the broad area of fluid dynamics including aerodynamics, hydrodynamics, and propulsion
Research professor, computational engineering and field simulation
Specialties: gas/fluid dynamics, fluid turbulence and turbulent flow modeling, algorithm development for physics-based simulations, and applied and computational mathematics
Jody Merritt
Chief solution architect, 30+ years aerospace experience
Military senior leader – Founder lead USAF Reserve Hypersonics Task Force, current lead Board of Advisors
Small business mentor, including hypersonics related industries

The study team conducted more than 50 interviews with C-suite executives and senior leaders at aircraft developers, engine manufacturers, and federal agencies, as well as a range of industry and technology experts. Most of the companies developing high-speed aircraft (Mach 1+) and relevant engines were interviewed, as shown in Figure 1 Number of interviewees by type.

Figure 1. Number of interviewees by type.



Engineering SME

AIAA
DoD, DDR&T
FAA
GE Aviation
LTA Research
Momentus
Northrop Grumman
Rolls-Royce
Smithsonian Institution
University of Colorado

Developer

Aerion
Boeing
Boom Technology
Exosonic
Hermeus
Lockheed Martin
Reaction Engines
SpaceX
The Spaceship Company

Industry Expert and Observer

Aerospace management consultant
AIAA
Apollo Global Management
Aviation Week
AXA XL
Bank of America
Embry-Riddle Aeronautical University
International Airlines Group
ITAR Attorney
Jetsuite X
Mojave Air and Spaceport
Smithsonian Institution
Southern Sky

Note: the pie chart counts the total number of individuals interviewed, while the table contains institutions of interviewees. Certain interviewees asked that their institution not be revealed, and in some cases multiple interviews were conducted at a single institution.

Modeling Approach (Tasks 1 and 2)

Bryce calculated passenger demand, revenue, and business case metrics using a macroeconomic, multi-year customer demand and travel preference model rather than on a specific aircraft design or feature set. The model incorporates existing Bryce models for forecasting airline passengers and assessing their purchase choices based on value of time saved. The full study model consists of two demand modules and an integrated business case module, addressing general aviation and commercial aviation. Our general aviation model includes on-demand commercially operated flights, including charters, fractional flights for passengers (priced by itinerary) and sales of privately owned aircraft (including individually owned and corporate-owned). Our commercial aviation model includes scheduled commercial flights for passengers (priced by seat). The two demand modules and business case module are:

- Demand Module: General aviation (private charter and fractional) demand
- Demand Module: Commercial aviation (first and business class) demand
- Business Case Module: Commercial aviation + general aviation + private jet sales business case

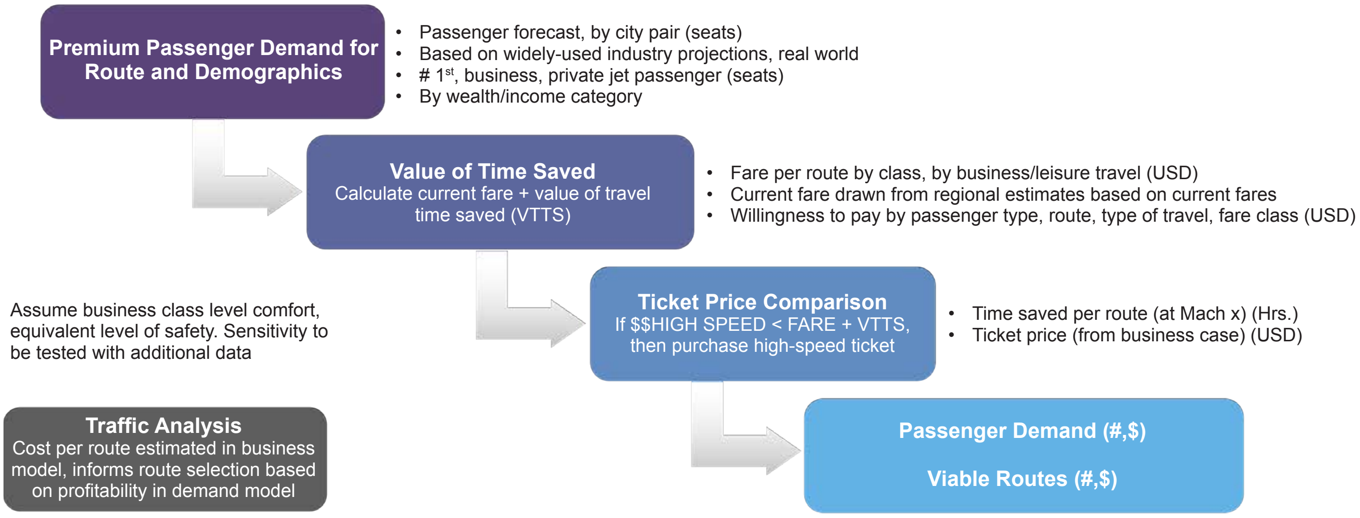
Market Definition, Commercial High-Speed Transportation

- *Market segments: commercial, private jet, cargo*
- *Passenger demand for high-net-worth individuals ($1M+) and executive travelers*
- *Over 800 long haul (5+ hours) city pairs considered, viable routes included*
- *Demand reaches 2019 (pre-COVID) rates in 2024*
- *Limited cargo market*

Demand (Task 1)

The commercial and general aviation demand modules evaluate the buying choices of each passenger with regard to willingness to purchase a high-speed ticket at a given fare based on passenger net worth or income. The modules comprising the demand model also identify viable long-haul air routes in future years based on demand for and cost of operating on each route. Each demand module was applied to five aircraft cases, representing a range of Mach numbers and service entry dates. Each case considered four prices per aircraft, for both a general aviation and a commercial aviation variant. The architecture of the overall demand model (commercial, first, and business class module, general aviation module) is shown in Figure 2.

Figure 2. Demand model architecture.



Business Case and Operations Requirements

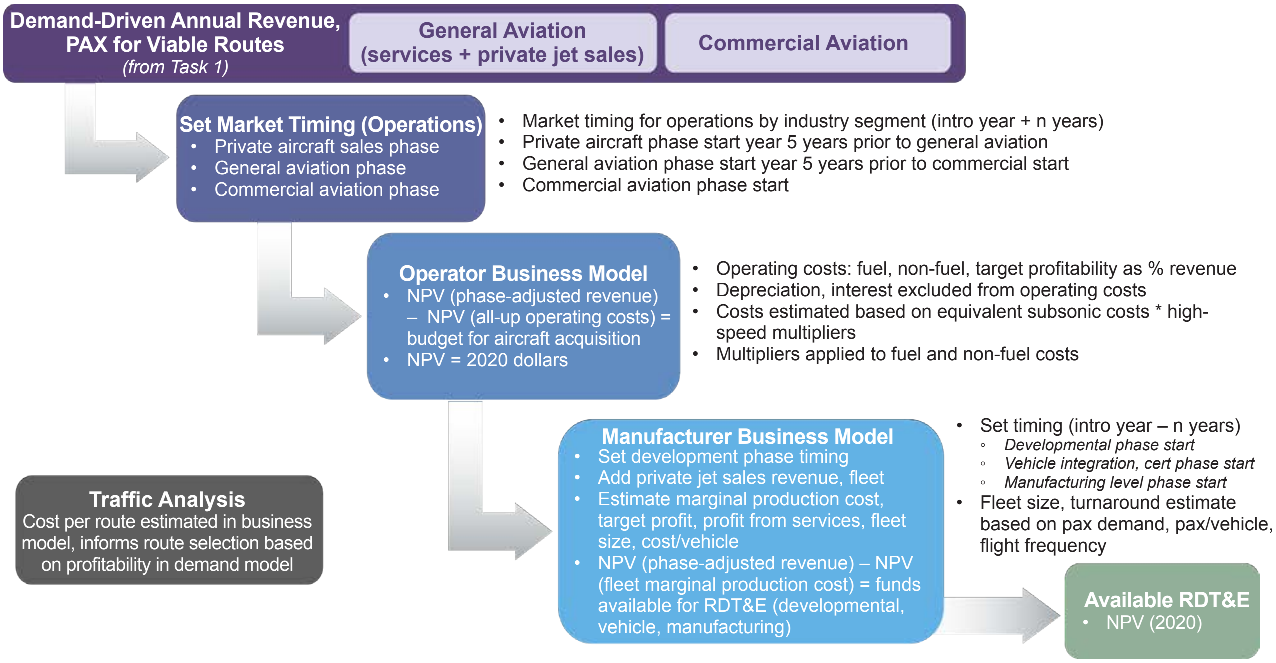
- *Compare increased revenue associated with value of time saved to increased cost associated with high-speed aircraft*
- *Consider manufacturer/airline dynamics*
- *Estimate supportable RDT&E*

Business Case (Task 2)

The business case model evaluates available RDT&E, based on demand-driven revenue and passengers on viable routes, market timing (when RDT&E expenditures are assumed to begin, start year of private aircraft sales, start year of general aviation and commercial services), and operating and manufacturing costs.

The business case module was applied to the five aircraft cases, each case considering four prices per aircraft, for a general aviation and a commercial aviation variant. The general architecture of the business case model is shown in Figure 3.

Figure 3. Business case model architecture.



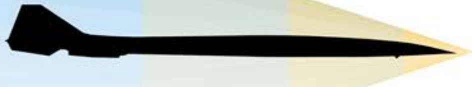
Non-Technology Barriers

- *Airport infrastructure*
- *Air traffic management*
- *Certification (U.S.)*
- *Environmental impacts*
- *Export control*
- *Insurance*
- *International legal and regulatory*
- *Societal*
- *Supply chain*
- *Weather*
- *Workforce*

Barriers (Task 3)

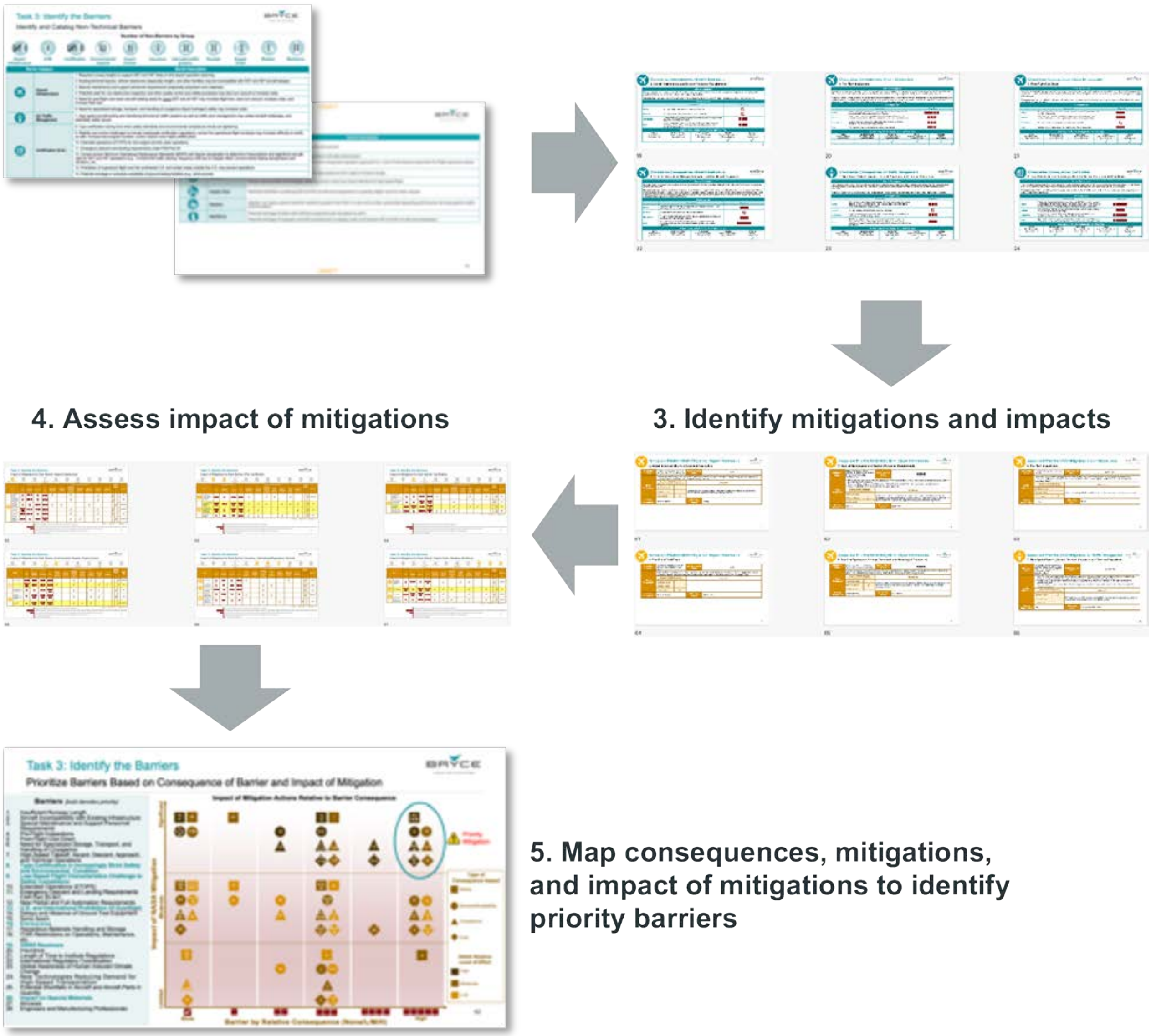
As shown in Figure 4, Bryce cataloged real and perceived non-technical barriers to commercial high-speed air transportation based on a review of articles, papers, studies, and reports identified in the literature review; interviews with industry professionals; and with Bryce and SAIC SMEs. Bryce's characterization of each barrier included an assessment of the magnitude of the barrier's impact on one of four potential consequences: safety, demand and availability, regulatory and policy compliance, and cost. Magnitude was expressed on a scale from no consequences identified to significant issues exist that, if not mitigated, would likely prevent a program from being approved or implemented. As an example, international certification is a potential barrier to hypersonic transportation systems, without this certification they would be unable to fly overseas routes. This study would illustrate this showing magnitude it effects demand as large since the number of routes which could be flown would be dramatically decreased.

Bryce mapped interdependencies among barriers and identified actions to mitigate each barrier, using tools such as a Bryce analysis of past government policy actions to support aerospace industry growth and barrier categorizations to elicit further insights from interviews. Bryce categorized mitigations by type and actor, and estimated mitigation impact based on the consequence of the barrier and on the predicted effectiveness of the mitigation.



Finally, Bryce assessed and prioritized mitigations based on the relative consequence of a barrier, impact of NASA mitigation, and NASA's relative level of effort. The resultant impact of NASA mitigation actions relative to barrier consequence identified six barriers requiring priority mitigation.

Figure 4. Methodology for identification, characterization, and mitigation of priority non-technical barriers to commercial hypersonic transportation.



1. Identify and characterize barriers

2. Characterize consequences

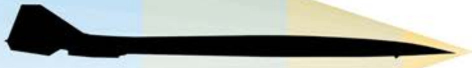
3. Identify mitigations and impacts

4. Assess impact of mitigations

5. Map consequences, mitigations, and impact of mitigations to identify priority barriers

Task 3: Identify the Barriers

Prioritize Barriers Based on Consequence of Barrier and Impact of Mitigation



Market Definition (Task 1)

KEY FINDINGS

Currently there 16 commercial high-speed vehicles in development from Mach 1.4 to Mach 5

Looking at all long-haul routes, passenger and revenue demand increases with speed but sees diminishing returns above Mach 3

Mach 3 aircraft generate the greatest revenue demand at 1.5x and 2.5x current premium fares on over 300 viable routes (demand revenue exceeds operating expenses)

North America to Europe routes generate the most revenue and passenger demand; North America to Asia is a substantially growing market

Today's air transportation industry consists of general aviation and commercial aviation business sectors operating under different regulatory regimes and often using different airports or different facilities within airports. General aviation aircraft are typically smaller and carry fewer passengers than scheduled commercial aircraft.

General aviation today includes subsonic, on-demand, commercially operated flights, such as charters, fractional flights for passengers (priced by itinerary), and cargo. General aviation also includes privately owned aircraft. Commercial aviation includes subsonic, scheduled, commercial flights for passengers (priced by seat) and cargo.

This analysis considers demand from both the general aviation and the commercial aviation sectors for future high-speed (Mach 2+) aircraft to estimate the commercial revenue future high-speed aircraft could generate.

To estimate demand from passengers and associated revenue, the study team:

- Characterized future high-speed aircraft in terms of speed and performance characteristics that affect the passenger experience, defining five representative conceptual cases and a baseline case representing a notional Mach 1 vehicle, not far removed from current fastest commercial aircraft, to be used in modeling future demand and business cases,
- Estimated passenger demand for high-speed flights using vehicles defined for each conceptual case at different fare levels compared to premium ticket prices today, and calculated revenue per route, and
- Estimated revenue associated with passenger demand by determining which routes could be operated such that revenue for a given route exceeded operating costs for that route. This estimate included only those routes in predicting future revenue.

Characterizing Future High-Speed Aircraft

The study team identified and characterized relevant aircraft (historical, operational, and in development). These aircraft included the fastest commercial subsonic aircraft operating today, historical military and commercial aircraft operated at speeds above Mach 1, and in-development commercial aircraft designed to operate at speeds above Mach 1. The team also considered the market interaction between commercial supersonic aircraft and hypersonic aircraft.

Based on the anticipated capabilities of high-speed aircraft in development, the team defined five study cases to reflect different types of future capability. The study cases range from Mach 2 to Mach 5, with an additional baseline case Mach 1, aircraft reflecting capabilities slightly above today's fastest aircraft. The team did not explore cases above Mach 5 as the marginal time saved over Mach 5 versus increasing costs at higher speeds result in less attractive business cases, additionally no current designs in development above Mach 5 for general or commercial passenger aviation.

Fastest Commercial Subsonic Aircraft

As shown in Table 2, several companies (Cessna, Gulfstream, Bombardier, and others) have introduced high-speed subsonic business jets that achieve maximum cruising speeds in the range of Mach 0.9 to Mach 0.94 and carry fewer than 20 passengers. The fastest commercial airliners in service, including the Boeing 787 and Airbus A350, achieve maximum cruising speed of about Mach 0.9, and are typically powered by very efficient turbofan engines and carry hundreds of passengers. Table 2 lists representative aircraft and is not meant to be comprehensive.

Table 2. Representative subsonic commercial aircraft with maximum cruising speeds approaching Mach 1.

	Vehicle	PAX	Hours of Utilization per Year	Number in Service	Performance				Financial	
					Speed (Mach)	Range (mi)	Takeoff Length (ft)	Maximum Cruise Altitude (ft)	RDT&E Investment	Unit Cost
Business Jet	Cessna Citation X+	12	Private: 400 – 600 Charter: 600 – 1,500	29	0.935	3,500	Undisclosed	51,000	Undisclosed	$24M
	Gulfstream G650/ G650ER	19	Private: 400 – 600 Charter: 600 – 1,500	400+	0.925	7,500	6,000	51,000	$1B	$72M
	Bombardier Global 6000	17	Private: 400 – 600 Charter: 600 – 1,500	816	0.9	6,000	5,540	51,000	Undisclosed	$62M
	Bombardier Global 7000	19	Private: 400 – 600 Charter: 600 – 1,500	22	0.925	7,500	5,900	51,000	$1B+	$72M
Airliner	Airbus A350	369	2,500 – 4,500	372	0.89	8,700	8,000	43,100	$15B	$370M
	Boeing 787	440	2,500 – 4,500	981	0.9	7,600	9,400	43,100	$32B	$200M

Historical Military and Commercial Aircraft Above Mach 1

Since the early 1950's, many military aircraft and munitions have achieved supersonic speeds, the fastest being the A-12, SR-71, and XB-70. Turbine engines (or simply jet engines) used to power aircraft were invented independently by the Germans and British during World War II (WWII). This technology was immediately improved upon for national security purposes by the U.S. and Soviet Union following WWII. Initially, the shapes of supersonic aircraft were investigated and tested using rocket-powered vehicles, a process later informed by experiences during the Korean War. The rocket-powered Bell X-1, piloted by Chuck Yeager, was the first aircraft to achieve supersonic speeds during level flight, breaking the so-called sound barrier (Mach 1) on October 14, 1947. Once it became clear that supersonic flight would not result in destruction of the airframe, development of air-breathing engines capable of propelling an aircraft beyond Mach 1 were pursued in earnest. The first military aircraft capable of sustained supersonic flight were the U.S. North American F-100 Super Sabre (first flight in 1953) and the Soviet MiG-21 (1955). Following losses of the subsonic U-2 spy plane in 1960 and 1962, Lockheed introduced the A-12 (1962) and a later variant called the SR-71 (1964), both representing the fastest jet-powered supersonic aircraft ever developed with speeds well in excess of Mach 3. These were used for intelligence gathering only. During this time, the Air Force introduced the Convair B-58 (1956), the world's first operational Mach 2 bomber. The Air Force also considered deployment of the Mach 3+ B-70 bomber, capable of penetrating deeply into Soviet territory. Despite conducting test flights from 1964 to 1969, the aircraft never entered service.

Leveraging design studies conducted in the 1950s, development of a commercial supersonic aircraft began in 1962 with Concorde. The vehicle was conceived as a cooperative technology development program between the governments of the United Kingdom and France; its genesis was embodied in a treaty, not because of market demand. Concorde flew for the first time on a test flight in 1969, the same year the Boeing 747 widebody airliner first took to the air. Notably, Boeing scrapped its commercial supersonic efforts during the 1960s to pursue the 747, correctly projecting greater demand for larger, more efficient airliners. Concorde entered service in 1976, five years after the introduction of widebody aircraft designed to fly large numbers of passengers economically. Though it carried an estimated 4 million passengers from 1967 to its retirement in 2003, it was not competitive with subsonic, widebody aircraft, being expensive to operate. Additionally, it was introduced during a time of high oil prices and the rise of a global environmental movement. Further, flights of Concorde were severely restricted by regulators due to the aircraft producing sonic booms when accelerating to a cruising speed of Mach 2. Only 20 aircraft were built, none operated by U.S. airlines. Two years after a fatal accident, Concorde was retired from service. Meanwhile, the Soviet design bureau led by Alexi Tupolev introduced a similar aircraft called the Tu-144. It was not a direct competitor to Concorde, having served mainly domestic routes, and even then it was used for a total of 100 passenger flights between 1975 and 1999. It did fly a variety of government-funded test and military missions, and even served a brief stint as a test platform in a cooperative program between Tupolev, Rockwell, and NASA (1996-1999). The aircraft was considered unreliable, a characteristic that led to two fatal crashes. Ultimately, all 16 Tu-144 aircraft were retired in 1999.

> ***'Military increasingly interested in taking advantage of private sector development.'***
>
> – Developer

Table 3. Historical commercial aircraft with speeds above Mach 1
(Sources: Concorde British Airways and Air France; Tu-144 - NASA Armstrong Fact Sheet.)

Vehicle	PAX	Actual or Estimated Entry into Service	Hours of Utilization per Year	Number in Service	Performance				Financial	
					Speed (Mach)	Range (mi)	Takeoff Length (ft)	Maximum Cruise Altitude (ft)	RDT&E Investment	Unit Cost
Concorde	100	1976 – 2003	70	20 *retired*	2.0	4,500	11,800	60,000	$15B – $22B	$160M
Tu-144	100	1968 – 1999	Undisclosed	16 *retired*	2.0	6,500	Undisclosed	66,000	Undisclosed	Undisclosed

In Development Commercial Aircraft up to Mach 3

Today, at least six companies have conducted detailed conceptual studies for or are actively developing commercial supersonic aircraft (listed in Table 4), with entry into service for most planned around the end of the decade. These aircraft aim at a mix of the executive passenger market and first/business class scheduled passenger services; none focus on cargo. Several aircraft are designed to operate within the existing air traffic regulatory environment, using oceanic routes or optimizing interaction with atmosphere to reduce sonic boom, as sonic boom is generally prohibited by regulators.

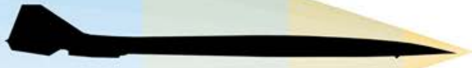


Table 4. In development commercial aircraft with maximum speeds of up to Mach 3.

Vehicle	PAX	Actual or Estimated Entry into Service	Performance		
			Speed (Mach)	**Range (mi)**	**Maximum Cruise Altitude (ft)**
Aerion AS2	8-10	2027	1.4	4,200	40,000
Spike S-512	18	2023	1.5	6,200	60,000
Lockheed Martin QSTA (conceptual)	40	2030	1.8	5,200	55,000
Exosonic Concept	70	2029	1.8	5,754	Undisclosed
Boom Overture	55	2029	2.2	4,500	60,000
Virgin Galactic TSC Concept	9-19	2029	3.0	4,000	60,000

> ***'Our goal is to make high-speed jets the cheapest option out there.'***
>
> – Developer

In Development Commercial Aircraft Mach 4+

Ten high-speed aircraft concepts have been introduced in recent years with cruising speeds exceeding Mach 4 (Table 5). At the lower end of the speed range is Aerion's AS3, with a maximum speed of Mach 4.3. Few details of the AS3 have been made public, including its passenger capacity and range, and its introduction is dependent on the success of the company's supersonic AS2. Airbus and Boeing have also indicated interest in developing airliners capable of exceeding Mach 4, with the companies having funded design studies but not yet advancing to the hardware stage. U.S.-based Hermeus, founded in 2018, has introduced a Mach 5 concept that received some mainstream attention when the company received a $1.5M contract from the U.S. Air Force for a presidential transport design study. The Japan Aerospace Exploration Agency (JAXA) has been pursuing design studies for a Mach 5 airliner concept that would presumably be operated as an airliner by a commercial provider. In Europe, two major efforts have been studied, none of which have advanced much beyond design studies. These include the LAPCAT-A2 conceived by United Kingdom (UK)-based Reaction Engines and the STRATOFLY-MR3 sponsored by the European Union's (EU) Horizon 2020 research and development grant program. The former appears more sophisticated in design, but Reaction Engines has emphasized it is focusing most of its energy on powerplant design, specifically development of the SABRE, a pre-cooled air-breathing rocket engine it hopes to market as a means to propel hypersonic and single-stage-to-orbit vehicles in the future. An interesting concept was presented as part of the International Civil Aviation Organization's (ICAO) annual innovation contest in 2020 and is featured on cargo transporter DHL's website. This system, called BlueEdge, was conceived by Canadian engineer Charles Bombardier and designer Drew Blair as a means to carry cargo at speeds of up to Mach 10 and a flight range of 10,000 miles, but appears largely a conceptual exercise.

Two concepts are planned as hypersonic test platforms available to government and commercial customers. Both are in advanced stages of development and expected to begin commercial services during the next few years. The first of these is Generation Orbit's X-60A, formerly the GOLauncher-1. This rocket-powered system is launched from a conventional Lear or Gulfstream aircraft and is designed to be capable of achieving speeds of Mach 8 to 10. Stratolaunch Systems is developing the Talon-A, which would be launched by the company's enormous twin-fuselage Stratolaunch Carrier. The company expects Talon-A to reach a maximum speed of Mach 6. In both cases, the test platforms can be used to conduct hypersonic research using a variety of experiment options.

> ***'The faster you can travel, the more it will induce even more travel.'***
>
> – Developer

Table 5. In development commercial aircraft with maximum speeds of Mach 4+.

Vehicle	PAX	Actual or Estimated Entry into Service	Performance		
			Speed (Mach)	Range (mi)	Maximum Cruise Altitude (ft)
Aerion AS3 (conceptual)	Undisclosed	Undisclosed	4.3	Undisclosed	Undisclosed
Airbus Concorde 2 (conceptual)	20	Undisclosed	4.5	Undisclosed	100,000
Boeing Concept (conceptual)	<100	2040	5.0	Undisclosed	95,000
Hermeus Concept	Undisclosed	2035	5.0	4,600	65,000
JAXA Concept (conceptual)	100	Undisclosed	5.0	5,600	82,000
Reaction Engines LAPCAT A2 (conceptual)	300	Undisclosed	5.2	12,000	92,000
Stratolaunch Talon-A	Test platform	2023	6.0	Undisclosed	35,000
STRATOFLY MR3 (conceptual)	300	Undisclosed	8.0	Undisclosed	98,425
Generation Orbit X-60A	Test platform	2021	8.0	Undisclosed	70,000-130,000
BlueEdge (conceptual)	Cargo only	Undisclosed	9.0+	10,000	125,000

Effect of Commercial Supersonic Transportation on Commercial Hypersonic Market

The evolution of a high-speed air transportation market from today's subsonic services and aircraft to a future hypersonic market will be significantly affected by commercial supersonic transportation.

As noted in Table 4 on Page 16, six companies are developing or assessing commercial supersonic (Mach 1+) aircraft with speeds up to Mach 3:

- Aerion AS2, Spike S-512, and Virgin Galactic/The Spaceship Company concept supersonic business jets,
- Boom Overture commercial passenger aircraft, similar to Concorde but with half the passenger complement, serving oceanic routes, and
- Unnamed vehicle systems by Lockheed Martin (a conceptual study dependent on results from the Lockheed Martin X-59 QueSST being developed under a NASA contract to investigate low boom flight characteristics) and Exosonic (an early development aircraft designed to carry 70 passengers at a speed of Mach 1.8)

These vehicles are generally designed to integrate with existing infrastructure, fit within existing certification structures, and require minimal modification to regulatory structures. Supersonic aircraft may be competitors to eventual commercial hypersonic aircraft, useful pathfinders for hypersonic aircraft, or both. Considering a competitive dynamic, the combination of flight time savings, operating, and manufacturing costs for commercial supersonic aircraft could generate a more attractive business case than hypersonic aircraft, given that hypersonic aircraft will likely cost more and will require new certification and regulatory structures. In such a case, the commercial incentive to pursue hypersonic aircraft could be diminished. Considering a pathfinder dynamic, the development and operation of aircraft at Mach 2 or 3 could identify cost reduction strategies for speed regimes above Mach 4, and so improve the hypersonic business case. Similarly, commercial supersonic aircraft could mitigate regulatory, environmental, and other key barriers to hypersonic travel and demonstrate market acceptance of high-speed flight.

Representative Conceptual Aircraft Cases for Modeling and Analysis

To assess the impact of differing aircraft capabilities on commercial high-speed transportation business dynamics, the study considered five conceptual aircraft, selected to reflect the range of potential future aircraft, along with a baseline aircraft representing current capability.

Cases 1 through 3 represent notional high-speed aircraft at Mach 2, 3, and 4, respectively. Cases 4 and 5, which describe notional hypersonic aircraft, are based on an assessment of key design characteristics and critical vehicle technologies. These are listed in Table 6.

The five aircraft cases vary by speed, fuel type, flight range, and year of introduction. All ranges shown are in miles rather than nautical miles to ensure consistency among all models. The conceptual aircraft analyzed here do not represent specific in-development vehicles; they do align with clusters of those vehicles to provide a realistic picture of future capability. Figure 5 maps the five cases used in this analysis to vehicles in development. The five aircraft cases used in this study, and the baseline case, are:

Table 6. Key design characteristics and critical vehicle technologies for hypersonic aircraft.

Subsystem	Key Hypersonic Design Characteristics	Critical Hypersonic Vehicle Technologies
Airframe	Thermal management to mitigate impact of frictional heat caused by high speeds, especially of the engine inlet area and leading edges Optimized to manage shock Capable of safely enabling low-speed flight (e.g., approach and landing) Use of techniques to reduce sonic boom	Optimal structural materials (nickel-based Inconel alloys, silicon-carbide ceramics, carbon-carbon composites) for wing and chine leading edges Optimal structural shapes and configurations to manage shock for optimal engine performance Development of unique or embedded flight control surfaces (e.g., wing morphing) to enable stability and control at low-speed regimes for takeoff and landing Enable low boom (not required for trans-oceanic routes) using fuselage shape changing or deployable surfaces
Propulsion	Capable of efficiently sustaining Mach 5+ speeds in rarified atmosphere Supplemented with capability to reduce thrust noise (especially takeoff) Capable of low-speed operations	Turboramjets and combined cycle scramjets—effectively new propulsion systems supported by little actual flight data, substantial RDT&E required Rocket—a proven technology that will likely need to be integrated with air-breathing systems to reduce weight and increase efficiency Noise—reduction of noise caused by high thrust at ground level during takeoffs represents a key technology area (e.g., noise cancellation, thrust saving diffusers, airflow transition technologies) Hydrogen and/or other cryogenic propellant including the technologies for cryogenic handling; fluid management and storage (both ground and flight) Synthetic fuels (e.g., higher enthalpy, higher density, performance across temperature regimes)
Flight Control Systems	Augmented by reaction control system (RCS) to enable attitude control in all altitudes and speeds Flight control surfaces capable of operating in very high temperatures	Reaction control systems to supplement/replace traditional flight control surfaces (e.g., cold gas thrusters optimized for aircraft) Flight control surface actuators that can operate in very hot environments (e.g., affordable metallic materials, wing morphing)
Autonomous Systems	Hardware and software capable of augmenting, enhancing, or replacing human control of aircraft	Reaction time will be essential, especially during emergencies, in order to respond to millisecond changes in vehicle performance (e.g., voting control logic, GNSS receiver response time, numerical simulation techniques)
Avionics	Communications, navigation, and other components capable of managing the system and its position, bearing, and flight path within the National Airspace System (NAS)	Systems integrated with enhanced and synthetic vision Navigation systems dependent on GNSS receivers currently controlled under International Traffic in Arms Regulations (ITAR)

Baseline Case: The case represents a notional Mach 1 vehicle, not far removed from current commercial aircraft capable of cruising speeds of Mach 0.95. This case represents aircraft powered by conventional air-breathing turbine engines burning hydrocarbon fuel (e.g., Jet A-1) and having a range of 8,000 miles.

Case 1: Aircraft with a speed of about Mach 2 are represented by this case, with an anticipated introduction year of 2025. Such aircraft would use relatively conventional powerplants burning hydrocarbon fuel and would be capable of carrying passengers to destinations within a 4,500-mile range. Concorde and the Tu-144 are historical examples of this type of aircraft.

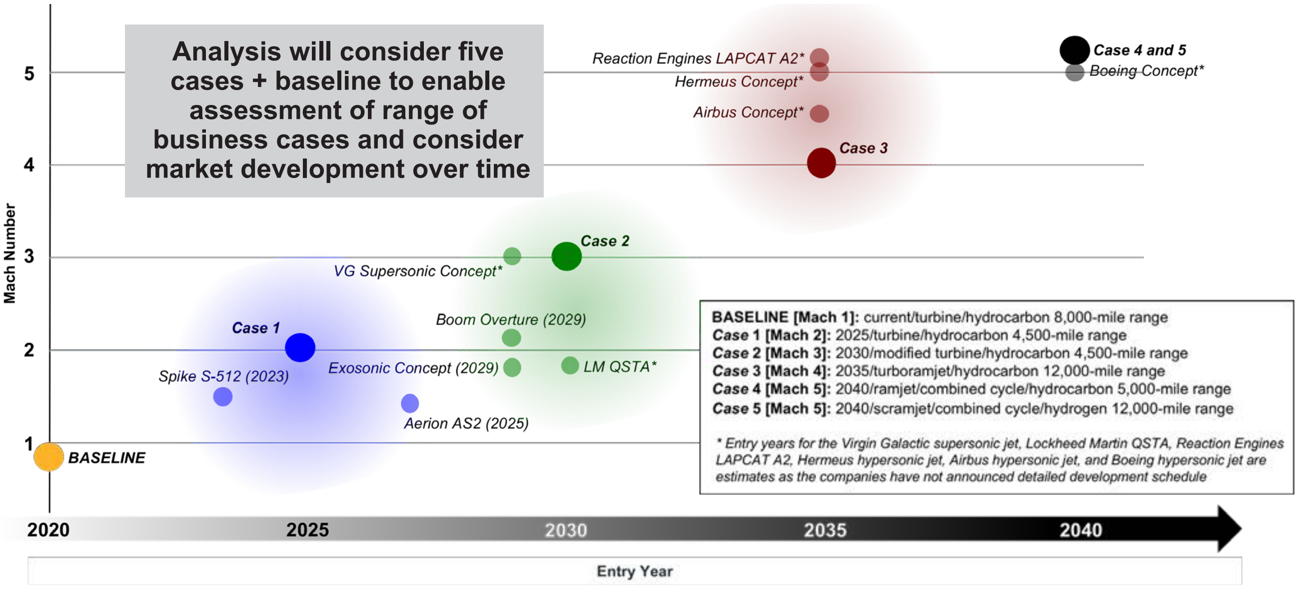
Case 2: This notional group consists of aircraft with a maximum cruising speed of Mach 3 and an introduction year of 2030. They would be powered by air-breathing turbine engines modified to enable long-duration, sustained use at high-thrust levels. These aircraft would have a range of about 4,500 miles. The A-12 and SR-71 are historical examples of this type of aircraft.

Case 3: Mach 4 aircraft with an introduction year of 2035 are represented by this case. Such aircraft would be powered by turboramjets, essentially a ramjet embedded in a turbojet, burning hydrocarbon fuel and having a maximum range of 12,000 miles.

Case 4: Aircraft in this case would use combined cycle ramjets burning hydrocarbon fuel to achieve a speed of Mach 5 or more and have a maximum range of 5,000 miles. The combined cycle aspect addresses the requirement that a ramjet be engaged at a certain optimal speed, in this case provided by a turbine engine-based propulsion system. The ramjet uses ram air to compress air, as opposed to an axial compressor used in conventional turbine engines, but the airflow is slowed to subsonic speeds prior to combustion. The projected entry year for this case is 2040.

Case 5: This case is very similar to Case 4, but instead of a ramjet, the aircraft employs a scramjet as part of a combined cycle system and burns hydrogen fuel. The scramjet is similar to a ramjet, but the airflow is *not* slowed to subsonic speeds prior to combustion. An additional difference is operational range, which for this case is 12,000 miles. The start year for this case is also 2040.

Figure 5. Analysis considered five cases plus a baseline to enable assessment of range of business cases and consider market development over time.



BASELINE [Mach 1]: current/turbine/hydrocarbon 8,000-mile range
***Case* 1 [Mach 2]:** 2025/turbine/hydrocarbon 4,500-mile range
***Case* 2 [Mach 3]:** 2030/modified turbine/hydrocarbon 4,500-mile range
***Case* 3 [Mach 4]:** 2035/turboramjet/hydrocarbon 12,000-mile range
***Case* 4 [Mach 5]:** 2040/ramjet/combined cycle/hydrocarbon 5,000-mile range
***Case* 5 [Mach 5]:** 2040/scramjet/combined cycle/hydrogen 12,000-mile range

** Entry years for the Virgin Galactic supersonic jet, Lockheed Martin QSTA, Reaction Engines LAPCAT A2, Hermeus hypersonic jet, Airbus hypersonic jet, and Boeing hypersonic jet are estimates as the companies have not announced detailed development schedule*

Estimating Passenger Demand and Revenue

To estimate passenger demand for future high-speed air transportation, we forecasted future passengers over the next decades and then modeled choices around how much passengers would be willing to pay for high-speed flights. We also considered other factors that might affect passenger decisions and demand for cargo.

Forecasting Addressable Demand

To forecast passengers and determine addressable passenger demand—that is, demand from passengers that might choose to pay higher prices than todays in order to fly on faster planes—we applied existing, well-known passenger forecasts through 2050, adapting them to the relevant time frame and relevant flights. The passenger forecast was developed with data from the FAA terminal area forecast[1] as well as Eurostat[2] data to capture European routes, totaling 800 long-haul (5+ hours) routes, representing all routes originating in North American and European. Other regional long-haul routes (like Middle East/China routes) were captured as possible from Airbus and Boeing forecasts. These forecasts were also analyzed to capture regional growth rates. This forecast demand was then adjusted to account for the downturn in air travel due to the 2020-2021 coronavirus pandemic.

> ***'Our goal is to fundamentally and sustainably redefine human connection by accelerating the global transportation network five times over.'***
>
> – Developer

The consensus regarding post-pandemic air travel is uncertain. While the airline industry has seen sustained profitability after previous disruptive global events (such as the 9/11 attacks on the U.S. and the 2008 financial crisis, for example generating $500B globally in revenue per year from 2010 to 2019), no event has matched the impact of coronavirus disease 2019 (COVID-19) on airlines. The world saw an unprecedented 60% decline in passengers in 2020, an estimated loss of $390B, and 197M lost jobs in travel and tourism sectors.[3]

> ***'For every plus 1 increase in Mach speed you need new materials and structures.'***
>
> – Developer

Airline industry organizations have said they expect domestic passenger traffic to recover before international passenger traffic; in fact, recovery was being observed in some markets in 2020.[4] Major forecasts indicate recovery to 2019 passenger levels by 2024/2025.[5,6] In 2019, ICAO and International Air Transport Association (IATA) projections showed steady growth in passenger, business, and cargo; ICAO projected fast growth in air passenger and cargo sector through 2040 (pre-COVID-19).[7,8]

Nearly half of respondents to a survey conducted by Bryce indicated they did not intend to change their travel patterns due to COVID-19; others said they would reduce business travel, drive rather than fly, or rely more on small planes/private flights, as shown in Figure 6.

For this analysis we used 2024 as the year passenger demand reaches 2019 levels. Regional and route growth rates were used from 2024 through 2050. Cases for aircraft with entry service dates of 2040 require the forecast to extend to 2070. For the period, 2050 through 2070 we extrapolated demand applying an overall growth rate based on the previous 25-year compound annual growth rate.

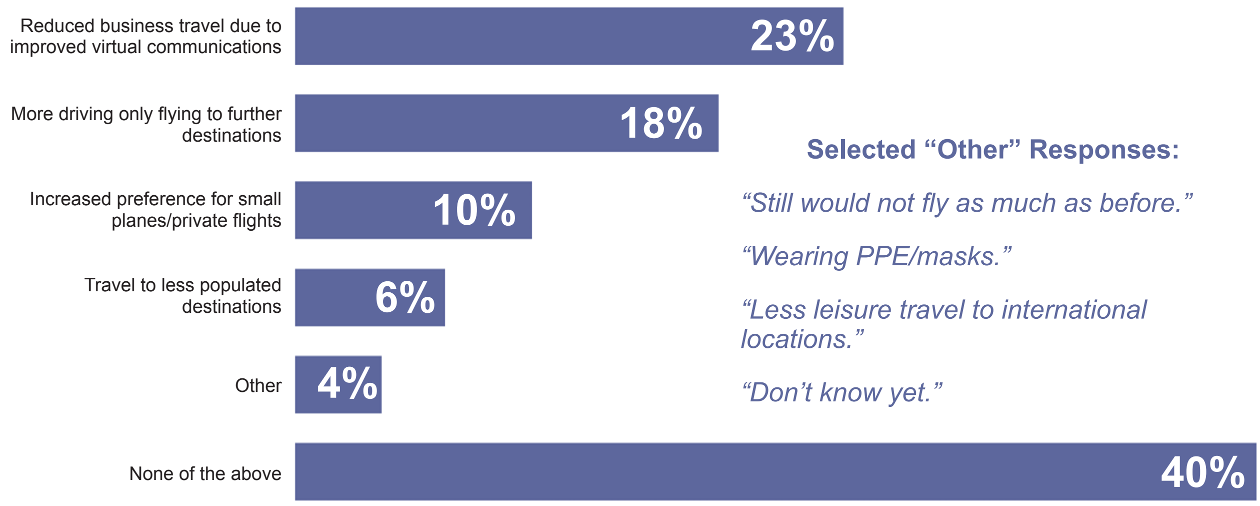
> ***'To the extent possible we're designing to work within existing infrastructure.'***
>
> – Developer

Using this overall passenger forecast, we forecast passenger traffic for flights between 800 long-haul city pairs where today's flight duration (i.e., subsonic flight) is five hours or more (roughly 2,500 miles), assessing both the general aviation and commercial aviation sectors. Long haul

flights greater than five hours represent routes long enough to allow flights of Mach 2+ to achieve cruising speed and save substantial time to the passenger. Flights greater than five hours ensure aircraft spend enough time at cruising speeds to achieve time savings of at least 2 hours.

For general aviation, addressable passenger demand was assumed to consist of the full range of general aviation passengers. For commercial aviation, addressable passenger demand was assumed to consist of premium passengers: passengers who purchase business or first-class seats (not those in business or first-class seats due to upgrades.) Based on historical costs for supersonic flight, tickets for high-speed aircraft are assumed here to be priced at least 50% higher than current premium class subsonic flight tickets (shown here as a 1.5x subsonic premium fare). These passengers represent the group most likely to purchase these more expensive flights to save time and participate in a more exclusive experience. We determined the percentage of passengers flying premium by analyzing the first and business class capacity of current aircraft flying long-haul routes resulting in 2% of passengers flying first class while 12% fly business class.

Figure 6. BryceTech HNWI survey respondents on pandemic-related concerns of air travel.



Selected "Other" Responses:

"Still would not fly as much as before."

"Wearing PPE/masks."

"Less leisure travel to international locations."

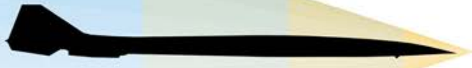
"Don't know yet."

Willingness to Pay

To predict passenger choices, we modeled passenger willingness to pay based on wealth demographics, flight duration and time savings compared to a subsonic flight today, and ticket price.

The study estimated the willingness of a passenger to pay for a faster flight by estimating the value of time saved for that passenger, using the 2016 U.S. Department of Transportation (DOT) "Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis"[9] methodology for calculating the value of time saved. The value of time saved for an individual varies based on that individual's financial situation, whether they are flying for business or leisure and whether they are flying private or commercial.

The study characterized passenger demographics as shown in Table 7. Leisure passenger demographics are based on wealth reports from Credit Suisse[10] and the Knight Frank Wealth Report[11] while executive business traveler income and demographics are based on data from government agency estimates including the Internal Revenue Service (IRS) and Securities and Exchange Commission (SEC) as well as an interview with an executive compensation expert, and research from Investopedia and Statista.

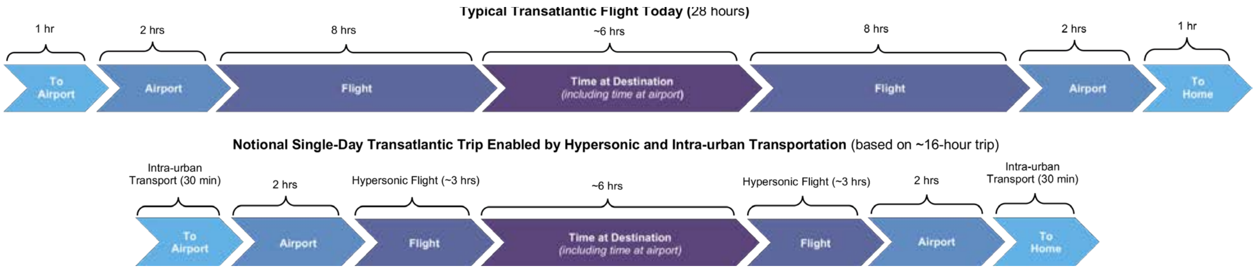


In the model developed for this study, time saved is calculated by analyzing door-to-door travel time for a passenger which includes travel to/from an airport, time in airport at both ends of the trip, and flight time. High-speed flight reduces flight time; other factors can affect overall time saved. For example, the model considers time saved at the airport for passengers flying general aviation, with separate terminals and faster check in and security screening, rather than commercial passenger service. Other factors could reduce total time as well; one that NASA specifically asked about is the introduction of intra-urban transportation services, a class of envisioned responsive flight services that save time from office or home to airport.

Intra-urban transportation or urban air mobility (UAM) is a highly automated passenger/cargo air transportation system flying at lower altitudes within urban and suburban areas. The services are projected to support large hub airports and regional airports. Current concepts plan to operate from existing airport infrastructure. These services would provide travel time savings to and from airport infrastructure for both high-speed and subsonic operators. However, if high-speed aircraft require unique facilities that result in additional travel time, intra-urban transport could be a significant enabler to compete with subsonic operators by mitigating the consequences of that extra travel time.

Additionally, in combination with hypersonic flight, UAM may induce demand by enabling single day round trips. As shown in Figure 7, a current transatlantic business trip requiring 6 hours at the destination would require 28 hours door-to-door. This same trip using intra-urban transport to and from the airport initial airport and hypersonic speed travel would require only 16 hours. Eliminating overnight stays or red-eye flights for executive business travels could encourage more trips due to the high value of executive time.

Figure 7. Single day transatlantic round trip.



Value of travel time saved (VTTS) as defined in the DOT model varies between business and leisure travel and flying commercial versus private. For commercial business passengers this methodology assumes a willingness to pay between 80%-120% of hourly income when saving an hour of travel time. This model assumes business travelers are willing to pay 100% of hourly income for each hour saved. The U.S. DOT methodology assumes leisure travelers are willing to pay 60% to 90% of estimated hourly household income for saving an hour, this model assumes a leisure traveler is willing to pay 75% of hourly household income for each hour saved.[12] These calculations are shown in Table 7. Private jet passengers show a willingness to pay to save time and for convenience and customer service. Based on analysis of private jet and commercial passenger fares, private jet costs are 3x that of commercial first-class fare, assuming at least 60% of the seats available on the aircraft are occupied. First class commercial long-haul flights have an average fare of about $5,000, resulting in an average long-haul private jet fare of $15,000. On-demand travel and airport convenience reduce travel time by roughly two hours, resulting in a willingness to pay $5,000 per hour for convenience of saving time.

As shown in Figure 8 and Figure 9, total long-haul, premium passengers reach nearly 140 million by 2070 while revenue reaches near $600B. For comparison, the subsonic market in 2019 was $870B representing 4 billion passengers, with about $130B from premium passengers.

For a given passenger on a given route, the model addressed these questions:

- How much time is saved on a route, compared to today's flight time, for a given aircraft case?
- How much is that time worth, based on the passenger's salary or net worth depending on traveling for business or leisure, respectively?
- Is the value of time saved, in addition to the current fare for the route under consideration, greater than a new, high-speed fare for the route?

If so, the passenger is assumed to purchase a ticket at the new, high-speed fare under consideration. High-speed fares were modeled as a function of current fares, with a range of 1.5x current premium fares to 10x current premium fares. Fare prices were chosen to model a broad trade space to determine price points that capture the most passengers as well as cover the increased manufacturing and operating costs of high-speed aircraft. The revenue from each passenger who chooses to purchase a ticket for that route, in a given year, is summed to estimate maximum addressable revenue on each route.

Passengers are allocated to demographic categories (shown in Table 8) based on their frequency in the greater population, using data from WealthX.[13] This allocation is used to determine the number of first and business class passengers within each demographic. Using the VTTS calculation, the model determines what a passenger in each demographic would be willing to pay for a given route, based on time saved on that route as determined by the speed of a given aircraft. While the model can analyze aircraft at any speed, we report here on analysis at the speeds associated with the five predetermined cases discussed above. The model compares the price a passenger is willing to pay to the fare for the route; route fares are set at 1.5x, 2.5x, 5x, or 10x subsonic premium fare prices for that route. If willingness to pay is greater than the calculated fare that passenger is assumed to choose to purchase a ticket for that route (assuming the route is available; as discussed above, some passengers that would elect to purchase a flight may not be able to, because the route is not viable due to operating costs exceeding maximum passenger revenue). Using this method, the model calculates the maximum number of passengers in each demographic for each route for a given fare and speed. The revenue for each route is calculated by multiplying the number of passengers willing to pay on each route by the price for the route.

Other Factors Affecting Passenger Choices

Bryce's survey of high-net-worth individuals identified comfort and convenience factors that affect passenger choices. Current high-speed aircraft developers have said they intend to achieve comfort similar to that of current business class accommodations, so passengers are assumed to find comfort and convenience acceptable on high-speed flights.

Telecommunications technologies continue to improve and have seen widespread use during 2020 as employees were required to work from home. NASA raised the question of whether this increased usage may continue past the pandemic, resulting in reduced overall business travel.

Current factors influencing adoption of telepresence are significant. Until relatively recently, cost of video conferencing equipment was high, personal computers were not equipped with webcams, and internet speeds were not high or consistent enough for many applications. Technology has caught up to needs in these areas. Moreover, new factors are at play: COVID-19 work-at-home mandates have increased telecommuting, with 62% of Americans working from home during the

Table 7. Value of travel time saved.

Demographics	Net Worth (Median)	Expected Annual Return (5%)	Annual Salary	VTTS/Hr. (2,000 hrs/yr)	Final VTTS	Private Jet
Net Worth						
HNWI $1M – $5M	$3M	$3M * 0.05 = $150K	$250K	$400K * 75%/2,000 = $150/hr.	$150	$5,000
HNWI $5M – $10M	$7.5M	$7.5M * 0.05 = $375M	$500K	$875K * 75%/2,000 = $330/hr.	$350	$5,000
UHNWI $10M – $50M	$30M	$30M * 0.05 = $1.5M	$1M	$2.5M * 75%/2,000 = $940/hr.	$1,000	$5,000
UHNWI $50M – $100M	$75M	$75M * 0.05 = $3.75M		$3.75M * 75%/2,000 = $1,400/hr.	$1,500	$5,000
UHNWI $100M – $500M	$300M	$300M * 0.05 = $15M		$15M * 75%/2,000 = $5,625/hr.	$6,000	$14,000
UHNWI $500M – $1B+	$750M	$750M * 0.05 = $37.5M		$37.5M * 75%/2,000 = $14,000/hr.	$14,000	$14,000
Salary						
Does not meet salary threshold				$0 above existing fare	$0	$5,000
Salary $100K – $500K ($200K Bonus)			$500K	$500K/2,000 = $250/hr.	$250	$0
Salary $500K – $1M ($500K Bonus)			$1.25M	$1.25M/2,000 = $500/hr.	$500	$5,000
Salary $1M – $5M			$3M	$3M/2,000 = $2,500/hr.	$2,500	$5,000
Salary $5M – $10M+			$7.5M	$7.5M/2,000 = $3,750/hr.	$3,750	$5,000

Figure 8. Demand for long-haul routes.

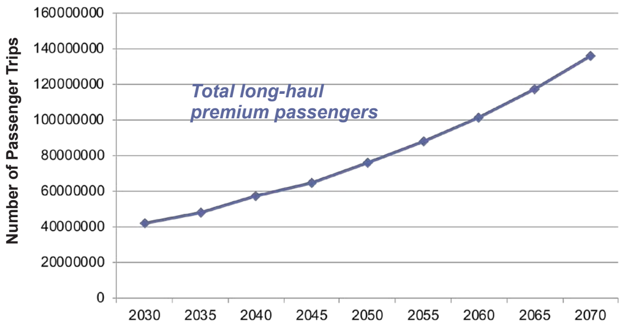
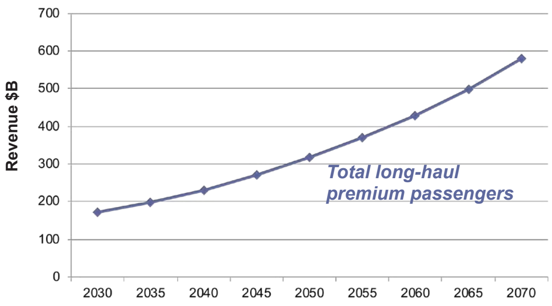


Figure 9. Revenue for long-haul routes.



pandemic.[14] Concern over climate change and impacts of air travel may reduce demand for air travel or increase costs. Finally, future technologies will influence growth in telepresence, including the fifth generation mobile network (5G) rollout of better connection speeds and reduced latency, virtual reality meetings that improve the quality of telework interaction, and artificial intelligence automation of administrative tasks that may reduce required humans.

While today's technology is more advanced and pervasive, it is important to note that previous projections that videoconferencing and other electronic communication technologies would dramatically diminish business air travel have been incorrect, as business air travel has continued to increase. For example, in late 2000s, aviation industry experts forecasted that the 2008 financial crisis would permanently increase use of videoconferencing as a replacement for expensive business travel (due to increases in airfares and cost-cutting measures at multi-national firms). Since 2008, spending on business travel has increased by about 5% annually, Related, incorrect projections were made due to the advent of fax machines and email. Air cargo has increased about 4% per year on average since 2009.

For purposes of this analysis, continued growth in demand for air travel, even given new technology, has been assumed.

Estimating Revenue from Viable Routes

To estimate annual revenue for a given case and ticket price in the future, we determined whether each of the 800+ city pair routes assessed was financially viable and aggregated passenger revenues from all viable routes.

To determine if a route was financially viable, we conducted a traffic analysis to estimate if a given route would attract sufficient passenger demand to make it worth operating. Specifically, the traffic analysis compared maximum annual route revenue to the operating cost for that route, for each vehicle case and at each fare level. Cost for each route was determined based on the per seat mile operating cost for the vehicle under consideration including fuel, maintenance, crew, insurance, ground, and system costs, and excluding any costs related to aircraft acquisition or lease. The determination of vehicle operating costs is described in the business case section.

If the maximum revenue equaled or exceeded operating cost for each route (specific to the vehicle and price level), the route was deemed viable and included in estimated revenue. Passengers on non-viable routes were excluded from the final estimate of passenger demand for each case and each price.

Summary of Results

Table 8 shows passenger demand for each fare and case evaluated. The number of passengers ranges from a low of 0 passengers willing to pay 10x subsonic fare over the study period for a Mach 2 flight to a maximum of more than 23 million willing to pay 1.5x subsonic fare in 2070 to fly Mach 2. The lack of passengers at 10x fare for Case 1 reflects the value passengers are willing to pay for time savings at Mach 2 exceeds the cost of 10x fare levels. Mach 5 Cases 4 and 5 garner the fewest passengers, with a maximum of about 10 million in 2070 for the long range, Mach 5 aircraft in Case 4. Cases 4 and 5 see fewer passengers because of the relatively few viable routes associated with those cases, driven by higher operating costs.

Table 9 shows the revenue for each fare and case evaluated. Note that the revenue reflects passenger demand on viable routes only. The greatest revenue is achieved by the Case 2, with Mach 3 aircraft generating nearly $38B in 2030 growing to about $180B in 2070. In case 5, Mach 5 aircraft generates the least revenue even at 1.5x fare, about $16B growing to about $80B in 2070. While passenger willingness to pay increases with time saved, the comparatively large operating costs of this aircraft reduce the number of viable routes and therefore overall revenue.

Analysis and Comparison

Figure 10 shows resulting passenger revenue and demand for the year 2050, used here to enable comparison because 2050 is considered in the time horizon for all cases.

In 2050, the number of passengers on viable routes is greatest for Case 1 (Mach 2 aircraft with a range of 4,500 miles), at 1.5x current subsonic fares. Viable route revenue is greatest for Case 2 (Mach 3 aircraft with a range of 4,500 miles), at 1.5x fare; while there are slightly fewer viable routes for Case 2 due to the increase in operating costs, they generate higher average revenue per route, reflecting how higher willingness to pay for time savings with incremental speed drives increased passenger demand for the highest subsonic fare routes.

Table 8. Passengers on viable long-haul routes (in thousands).

Number of Passengers on Viable Routes, Case 1									
	2030	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**	**2065**	**2070**
1.5x fare	5,224	6,413	7,637	9,215	10,983	13,225	15,926	19,177	23,093
2.5x fare	504	609	850	1,017	1,334	1,741	2,289	3,033	4,046
5x fare	48	73	84	112	179	249	345	478	663
10x fare	0	0	0	0	0	0	0	0	0
Number of Passengers on Viable Routes, Case 2									
	2030	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**	**2065**	**2070**
1.5x fare	4,905	5,870	7,084	8,447	10,112	12,117	14,519	17,397	20,846
2.5x fare	615	742	902	1,143	1,388	1,730	2,172	2,744	3,488
5x fare	77	100	121	181	233	307	406	535	706
10x fare	5	11	27	41	58	106	193	352	642
Number of Passengers on Viable Routes, Case 3									
	2030	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**	**2065**	**2070**
1.5x fare	4,087	4,896	5,850	6,881	8,180	9,731	11,577	13,773	16,387
2.5x fare	532	636	763	970	1,301	1,651	2,106	2,701	3,481
5x fare	188	244	299	379	484	622	804	1,045	1,365
10x fare	14	20	36	52	96	155	251	406	656
Number of Passengers on Viable Routes, Case 4									
	2030	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**	**2065**	**2070**
1.5x fare	2,198	2,723	3,214	3,813	4,609	5,547	6,675	8,033	9,667
2.5x fare	346	436	545	645	788	974	1,207	1,499	1,865
5x fare	80	103	149	216	263	359	493	678	937
10x fare	3	13	15	22	46	90	175	339	658
Number of Passengers on Viable Routes, Case 5									
	2030	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**	**2065**	**2070**
1.5x fare	1,896	2,410	2,876	3,436	4,142	5,036	6,122	7,443	9,049
2.5x fare	382	454	541	664	811	981	1,188	1,440	1,748
5x fare	102	151	193	255	356	512	748	1,108	1,663
10x fare	6	7	19	22	30	45	68	103	157

As fares increase, for a given case, the number of passengers decreases, as additional passengers fall into the category in which the value of time saved does not warrant paying the higher fare. For example, the sharp decline in passenger demand at the 2.5x fare level is driven by a loss in business traveler demand, the largest demographic group with the lowest willingness to pay (i.e., least wealthy). At the 5x fare level, a significant drop in general aviation passenger demand is observed.

Table 9. Revenue for viable long-haul routes (in billions $).

Revenue from Viable Routes, Case 1

	2030	2035	2040	2045	2050	2055	2060	2065	2070
1.5x fare	$35.6	$43.5	$51.7	$62.2	$74.2	$89.2	$107.1	$128.7	$154.6
2.5x fare	$9.8	$11.5	$14.2	$16.6	$20.5	$25.1	$30.9	$38.5	$48.3
5x fare	$1	$1.4	$1.6	$2.1	$3.1	$4.2	$5.5	$7.4	$9.9
10x fare	$0	$0	$0	$0	$0	$0	$0	$0	$0

Revenue from Viable Routes, Case 2

	2030	2035	2040	2045	2050	2055	2060	2065	2070
1.5x fare	$37.6	$45	$54.1	$64.7	$77.7	$93.1	$111.7	$133.9	$160.6
2.5x fare	$15.4	$17.8	$20.7	$24.6	$28.9	$34.2	$40.7	$48.7	$58.5
5x fare	$1.6	$2	$2.4	$3.4	$4.3	$5.6	$7.1	$9.2	$11.8
10x fare	$0.09	$0.2	$0.5	$0.8	$1.1	$2	$3.8	$7.1	$13.2

Revenue from Viable Routes, Case 3

	2030	2035	2040	2045	2050	2055	2060	2065	2070
1.5x fare	$32.6	$39.1	$46.9	$55.6	$66.7	$79.8	$95.4	$114.2	$136.7
2.5x fare	$12.8	$14.8	$17.2	$20.6	$25.4	$30.6	$37	$44.9	$54.9
5x fare	$7	$8.6	$10.3	$12.5	$15.3	$18.7	$23	$28.3	$35
10x fare	$0.4	$0.6	$0.9	$1.4	$2.4	$3.8	$5.9	$9.1	$14.3

Revenue from Viable Routes, Case 4

	2030	2035	2040	2045	2050	2055	2060	2065	2070
1.5x fare	$18.3	$23	$27.4	$32.6	$39.4	$47.7	$57.8	$70	$84.8
2.5x fare	$8.4	$10	$12	$14	$16.6	$19.9	$23.8	$28.5	$34.3
5x fare	$2.2	$2.8	$3.9	$5.2	$6.4	$8.4	$11.2	$14.9	$20
10x fare	$0.1	$0.4	$0.4	$0.6	$1.1	$1.9	$3.3	$5.6	$9.5

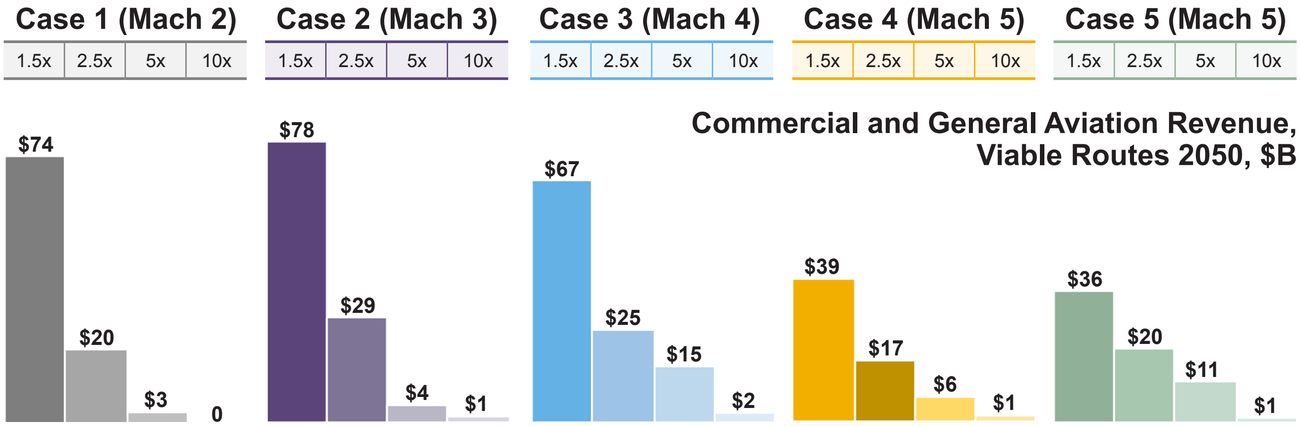
Revenue from Viable Routes, Case 5

	2030	2035	2040	2045	2050	2055	2060	2065	2070
1.5x fare	$16	$20.9	$25.1	$29.9	$36	$44.2	$54.1	$66.3	$81.2
2.5x fare	$10.3	$12.1	$14.3	$17	$20.2	$24	$28.4	$33.8	$40.1
5x fare	$4.3	$5.5	$6.8	$8.6	$10.9	$14.2	$18.7	$25	$33.7
10x fare	$0.2	$0.3	$0.6	$0.6	$0.9	$1.2	$1.7	$2.4	$3.5

Across all cases and fares, the maximum number of viable city pairs for general aviation is 382 in 2060 (Case 2, 2.5x fare), and for commercial aviation is 327 in 2055 (Case 1, 1.5x fare), of the total possible number of 800 city pairs.

Considering fares across all routes (that is, of the study population of 800+ city pairs with 5+ hour flights at current subsonic flight speeds), subsonic average premium base fares today are about $3,500. For Case 2, representing the overall best business case, the average subsonic fare for the 249 viable routes in 2050 is about $4,000, so the average fare for high-speed flight in Case 2 would be about $6,000 at 1.5x fare and $10,000 at 2.5x fare.

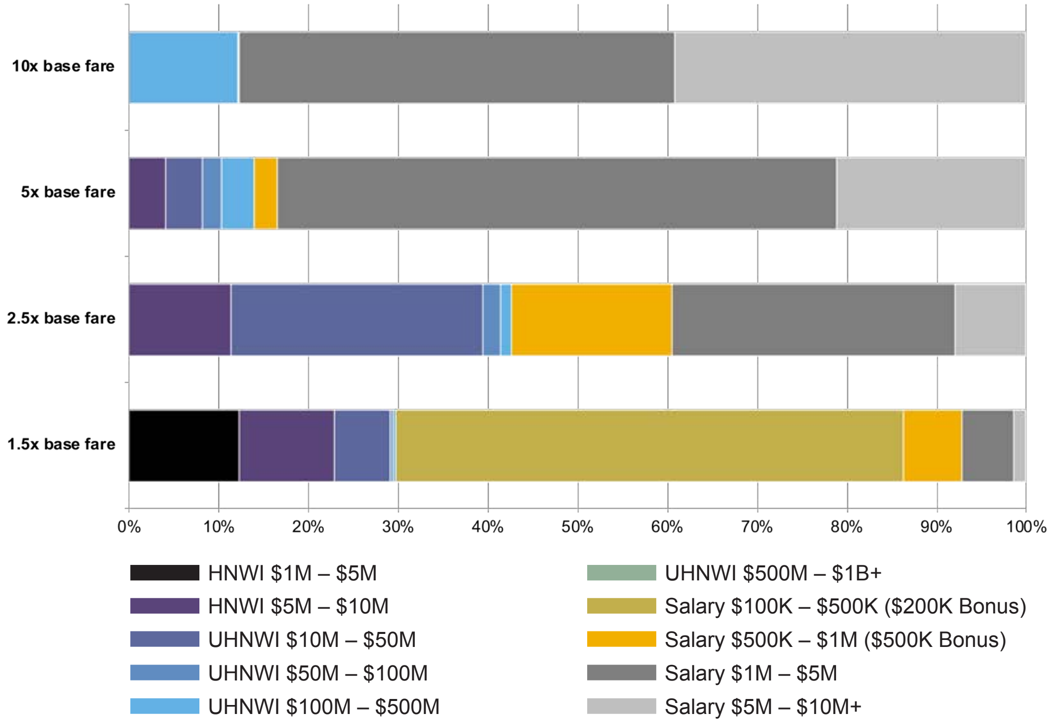
Figure 10. 2050 passenger and revenue demand for commercial and general aviation viable routes.



	Case 1 (Mach 2)				Case 2 (Mach 3)				Case 3 (Mach 4)				Case 4 (Mach 5)				Case 5 (Mach 5)			
	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x
# Profitable Routes	296	64	29	0	249	49	30	9	177	50	29	19	85	24	21	8	69	22	22	5
# PAX on Viable Routes	11M	1.3M	0.2M	0	10M	1.4M	0.2M	0.06M	8.2M	1.3M	0.5M	0.1M	4.6M	0.8M	0.3M	0.05M	4.1M	0.8M	0.3M	0.03M

Figure 11 illustrates the change in passenger demographics as seat prices increases for the Case 2 (Mach 3) aircraft which yields the highest passenger demand. As described above, the 1.5x subsonic premium (base) fare ticket price generates the most demand, the majority of this demand comes from the lowest income demographic categories of both business and leisure travelers. The most demand at this price is from business travelers with salaries between $100K and $500K. Both of these large demographics are unwilling to pay anything hire than that price. As fares continue to increase more demographic categories unwilling to pay higher prices. Once prices reach 10x base fare only the wealthiest leisure travelers and highest compensated executives continue to purchase flights.

Figure 11. Passengers by demographic categories for each fare.



Commercial and General Aviation Services Demand at 1.5x Fare, All Cases

Model outcomes over time are shown in Figure 12 and Figure 13, for all cases, at the 1.5x fare level. For the fare levels above 1.5x, the major difference, due to sensitivity to price, is the decrease in total passenger trips across all cases over the time horizon. The variance in total revenue between cases narrows for each subsequent fare above 1.5x since less passengers are willing to pay higher fares for better time savings. The time frame shown in Figure 12, 2030 through 2050, was selected to enable a like comparison among cases over time, and because extrapolated growth rates are applied beyond 2050 (as described above).

Figure 12. Demand at 1.5x fare.

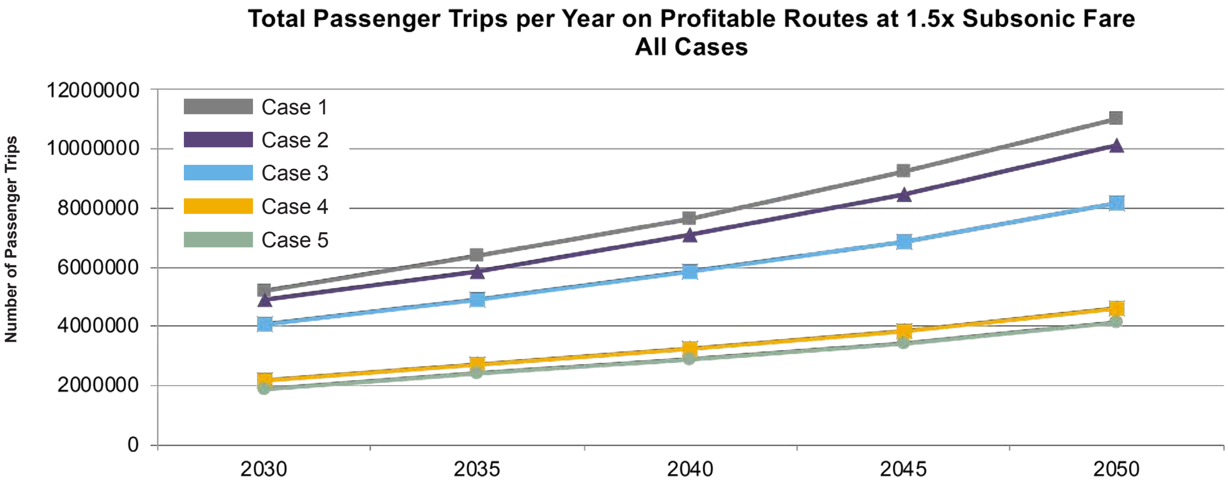
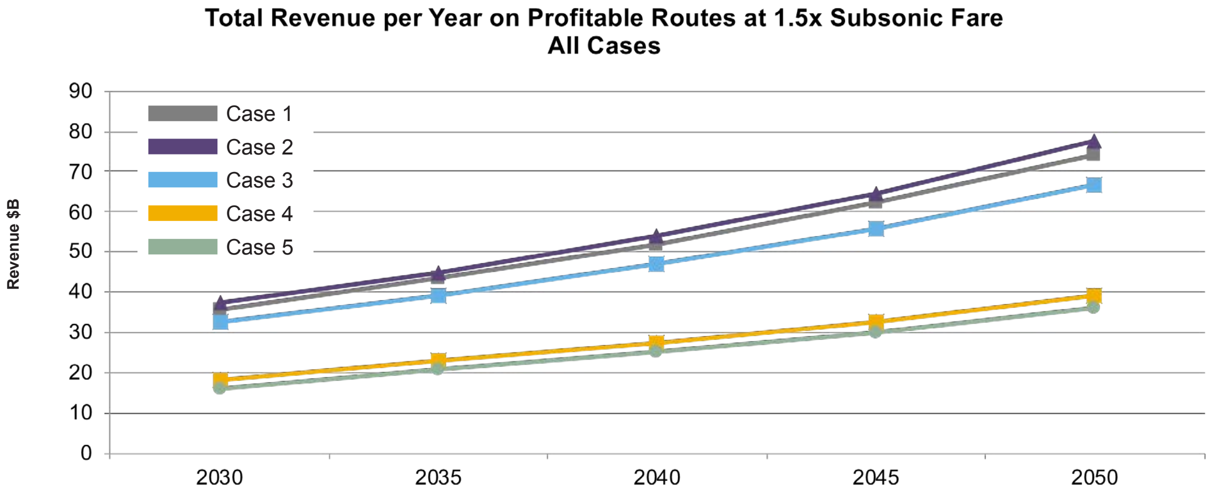


Figure 13. Revenue at 1.5x fare.



Case 1 yields most the most passenger trips, reaching 11 million passenger trips, ~15% of the 2050 addressable market of ~$75M passenger trips. Case 2 yields the highest revenue, reaching $78 billion or ~25% of the 2050 addressable market of revenue of ~$315B. For context, the subsonic industry in 2019 saw total airline industry revenue of $870B, representing 4 billion passengers, with roughly 15% of that revenue, or about $130B, from premium passengers on long haul routes.

For all aircraft cases assessed, passenger trips increase over time, and nearly double from 2030 to 2050. Growth in passenger trips over time is driven by both increased demand for existing viable routes as well as the emergence of additional viable routes. For the higher Mach cases, more passengers are willing to pay for trips overall, but operating cost constraints limit the number of viable routes to those with the highest average fares. This explains why the variance in total revenue between cases is lower than the variance in the total number of passenger trips (less passengers, but higher yields pre passenger). As detailed in the next section (business case), there is an inflection point where the benefits of added time savings exceed the loss in viable routes driven by operating costs for higher speed aircraft. For example, Case 2 has slightly less passenger trips per year than Case 1 but higher revenue per year due to the higher average fare across viable routes. And while Case 3 has a higher average route fare than Case 2, the reduction in the number of viable routes driven by operating costs outweighs the benefits of the added time savings. In summary, the ability to capture highly demanded routes with both medium and high fares makes Case 2 particularly attractive from a business case perspective.

Once again considering Case 2, the best business case for 2050, the top routes by revenue were those between the U.S. and Europe and the U.S. and China. Other strong regional routes included Europe to the Middle East, Europe/China, and Middle East/China. The breakdown of revenue by regional routes is shown in Figure 14. The top 25 routes based on revenue are shown in Figure 15 with the top three routes between London and Dubai, New York and London, and San Francisco and Hong Kong.

Figure 14. Revenue by regional route.

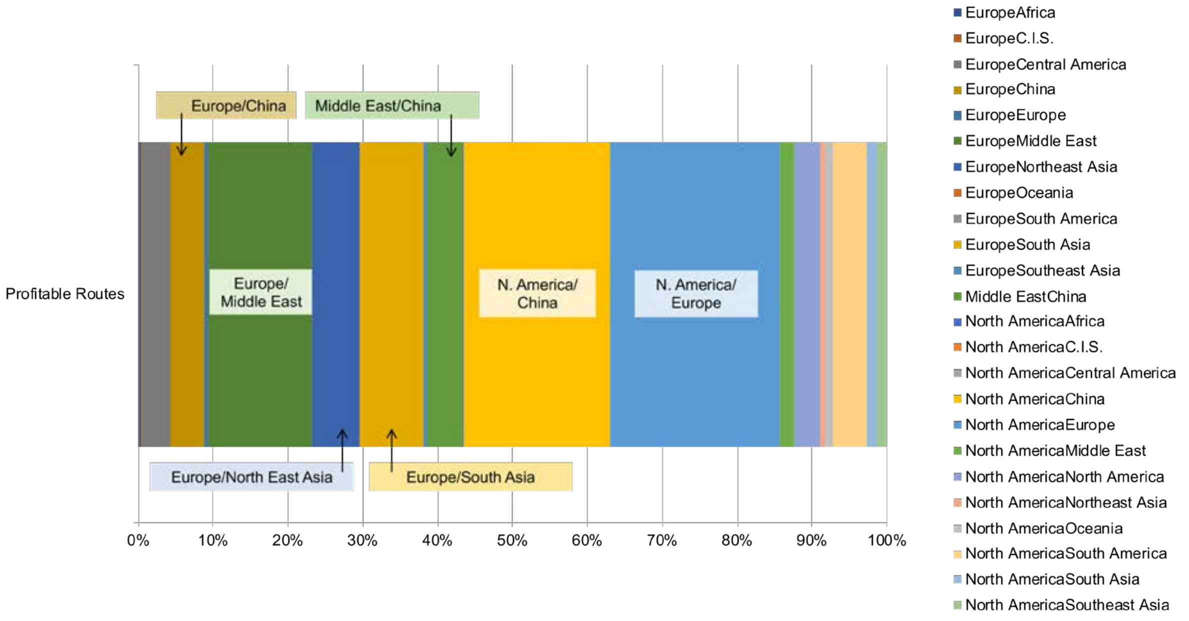
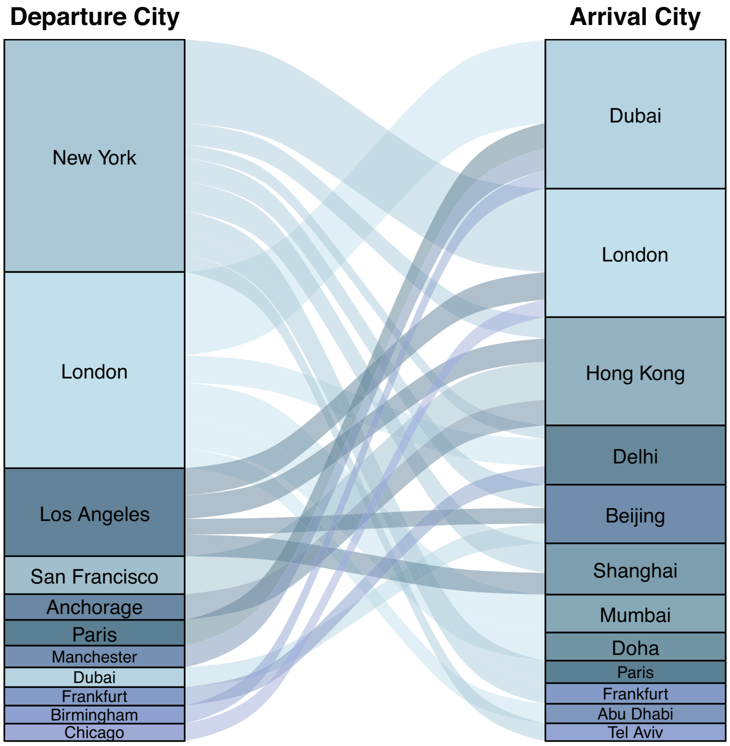


Figure 15. *Top city pairs by estimated 2050 revenue.*



Top 25 City Pairs (2050)

1. *London – Dubai*
2. *New York – London*
3. *San Francisco – Hong Kong*
4. *London – Mumbai*
5. *New York – Shanghai*
6. *London – Doha*
7. *London – Delhi*
8. *Paris – Dubai*
9. *Los Angeles – London*
10. *Anchorage – Hong Kong*
11. *New York – Beijing*
12. *Dubai – Beijing*
13. *Los Angeles – Hong Kong*
14. *Manchester – Dubai*
15. *New York – Paris*
16. *Los Angeles – Shanghai*
17. *New York – Hong Kong*
18. *London – Abu Dhabi*
19. *New York – Frankfurt*
20. *Frankfurt – Delhi*
21. *Birmingham – Dubai*
22. *New York – Tel Aviv*
23. *Chicago – London*
24. *New York – Delhi*
25. *Los Angeles – Beijing*

Demand for High-speed Cargo Transportation

Currently, air freight is dwarfed by maritime freight. Of the 108 trillion tonne-km of freight transported in 2015, 70% went by sea and less than 0.25% by air.[15]

About half of air freight by weight travels aboard passenger aircraft and this study considered whether cargo would be a significant market for high-speed aircraft.

Very few commercial markets for urgent cargo delivery are sensitive to changes of hours. Time-urgent applications identified in our research were organ transplants, disaster aid, perishable luxury goods, emergency repair parts, and urgent documents. The associated demand for such applications does not appear to be a significant revenue or business driver for high-speed aircraft in the future, due to factors such as the limited financial value of hours saved compared to cheaper subsonic options, critical applications requiring travel with a passenger (e.g., an organ handler), the small size of the potential market for some of these applications, and emerging technology substitutes to transportation, such as additive manufacturing for others. Moreover, high-speed aircraft typically are expected to have very limited cargo capacity.

> ***'Cargo market by itself doesn't make sense.'***
>
> – Developer

Given these factors and the fact that next-day shipping is available between every inhabited continent for small delivery fees, this analysis concludes that that some niche cargo revenue is likely for high-speed air transportation providers but is not a significant element of the business case.

A military hypersonic cargo market may emerge, separate from commercial demand. The U.S. Transportation Command signed a non-funded cooperative research and development agreement with SpaceX and XArc to study the use of space launch vehicles to transport supplies in emergencies. U.S. Army and Air Force officials have previously entered discussions with SpaceX regarding the possibility of using the Starship for point-to-point cargo transportation around Earth. However, this engagement is at a very early study phase and there is no clear characterization of military demand to date.

Business Case (Task 2)

KEY FINDINGS

Mach 3 identified as optimal business case; represents sweet spot between additional revenue enabled by time savings and increased cost of operation

Operating costs expected to increase significantly with speed regime, driven primarily by fuel and maintenance

Total fleet size limited at higher speed regimes as time savings reduce number of aircraft required to service passengers; constrains potential economies of scale in production

Efficient fleet utilization paramount to operator business case; serving routes with insufficient demand significantly reduces business case viability

Turnaround time limits productivity gains afforded by speed; higher number of daily takeoffs and landings results in more turnaround time, less total flight hours

To characterize and assess the business case viability of the future commercial high-speed air transportation market, the study team modeled the effects of key drivers for each case, including revenue (based on revenue associated with viable commercial and general aviation routes as well as private jet sales), timing of different product and service offerings, vehicle performance (passengers, utilization, speed, and range), costs, and profit and residual resale values.

> ***'Market is the business class, executive jet-type flier. Do not see this becoming a thing for the coach-class flier.'***
>
> – Developer

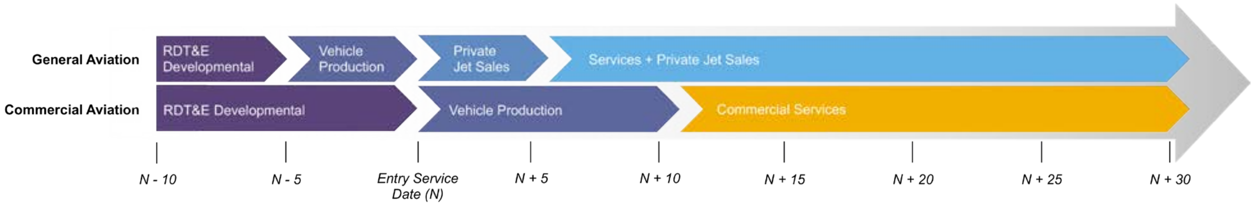
From these drivers, the model predicts fleet size, fleet cost, and ultimately total available RDT&E, by year, for each case and each fare level considered. Commercial air transportation business case dynamics vary between commercial and general aviation. The commercial aviation airline business case is driven by passenger and cargo revenue, with premium fare passengers (that is, business class and first-class passengers) generating a disproportionately high ~75% share of profits despite representing less than 20% of all passengers.[16] General aviation operators' business case is driven by revenues from charter operations, selling on-demand jet flights generally priced per itinerary, and from fractional ownership sales, where customers are allocated an allotment of flight hours commensurate with their share in the jet ownership/operating costs. Airlines, general aviation operators, and private individuals finance acquisition of aircraft from manufacturers or lease through an intermediary, incurring significant interest costs. Aircraft prices from manufacturers to airlines, general aviation operators, and private owners reflect the manufacturing costs, markup, and the RDT&E to certify the aircraft and its production line, typically allocated across an anticipated fleet size. Note that the model here addresses each of these elements separately; marginal manufacturing cost (excluding RDT&E) and markup are inputs. Available RDT&E is an output to inform the decision whether to launch a new type of high-speed aircraft.

Estimating Revenue Based on Market Timing

To estimate industry revenue over time for high-speed air transportation in the future, the study team first estimated passenger demand on viable routes for the period 2020 to 2070 (as described in the previous section). To apply this revenue estimate to each of the five aircraft cases, the business case analysis adjusted the demand-based revenue estimate to reflect market timing for each aircraft case and for both aircraft types considered within each case (a smaller general aviation aircraft and a larger commercial aviation aircraft). The characterization of market timing specified, for each aircraft considered, entry service date, associated RDT&E time frame, and associated operational timeframe for aircraft sales and entry into commercial airline or general aviation services.

The model assumed that, for general aviation aircraft, RDT&E (including RDT&E associated with preparation for vehicle production) would occur over ten years, prior to the entry service date of the aircraft. From the entry service date, the model assumed a 5-year period of general aviation private jet sales, followed by the introduction of general aviation services, during which private jet sales also continued, extending over 30 years from the entry service date. Figure 16 illustrates these timelines.

Figure 16. Market timing assumptions.



The model used the entry service date of a particular case's general aviation aircraft as the anchor date for characterizing the market timing of that case's commercial aviation aircraft. Commercial aviation services were assumed to begin ten years after the entry service date of the relevant general aviation aircraft. RDT&E was assumed to occur over the 20-year period prior to the start of commercial aviation services. Commercial services were modeled over a period of 20 years.

Estimating Costs

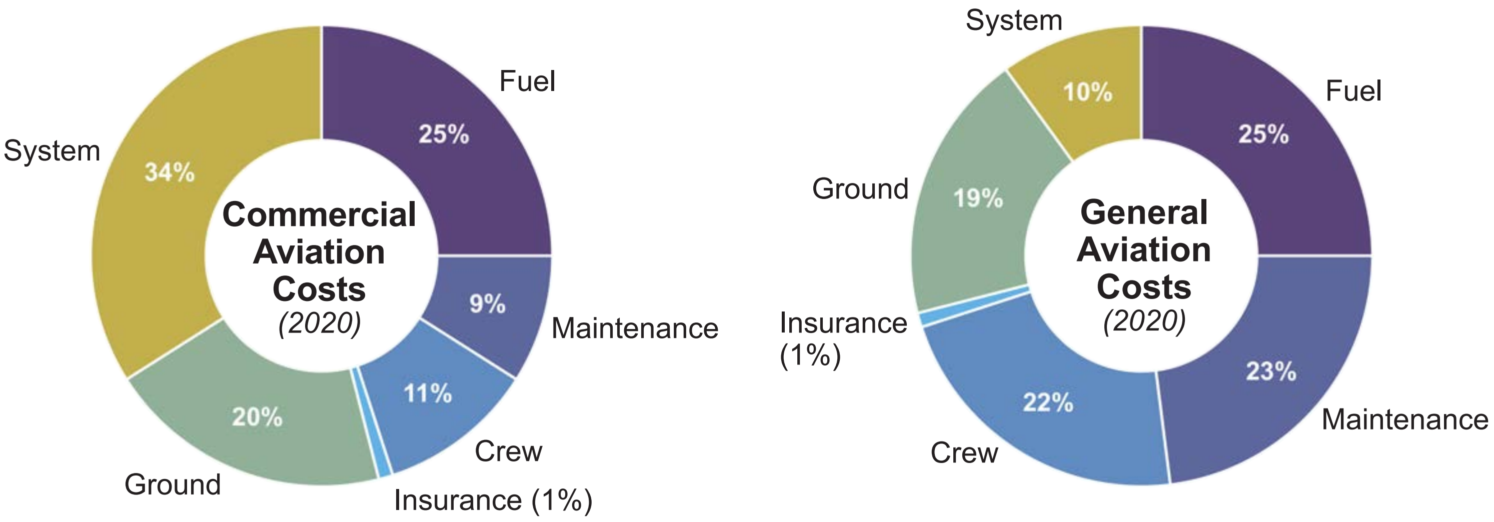
The business case analysis, at its most basic, subtracts costs from revenue to predict available RDT&E associated with a future high-speed air transportation industry. The costs considered are operating costs, marginal aircraft manufacturing costs, and industry ecosystem profit.

Operating Costs

To estimate operating costs (excluding the cost of acquiring aircraft through purchase or lease), Bryce developed multipliers to relate operating costs of high-speed aircraft to operating costs of current, subsonic aircraft. Multipliers were calculated and applied using the industry guiding metric of cost per seat mile.

Figure 17 shows the operating cost breakdown for commercial and general aviation market segments. Flight costs represent all costs related to aircraft flying operations, including fuel, maintenance, air crew, and insurance costs. Ground costs relate to the servicing of passengers and aircraft at airport stations, including aircraft landing fees and reservation/sales charges.

Figure 17. Relative magnitude of subsonic operating costs by market segment.



System costs occur independent of the type of aircraft used and the level of flying operations, comprised of marketing, administrative, and general overhead costs. While fuel price volatility drives variation in relative cost weights over time, the “rule of thumb” for commercial airlines is 50% flight costs, 30% ground, and 20% system.[17] The relative weight of system costs is the primary difference between commercial and general aviation. Operators of charter and fractional jets generally incur lower marketing, administrative, and general overhead costs relative to commercial airlines. For context, total cost per seat mile typically ranges from $0.10 to $0.15 for traditional airlines, $0.25 to $0.40 for airlines serving only premium passengers, and $0.70 to $1.00 for operators of general aviation aircraft.[18,19,20]

Cost multipliers used in this study were informed by insight from subject matter experts and aircraft developers on potential variance of specific factors, recent design studies evaluating operating costs for proposed high-speed aircraft, and historical data comparing *Concorde* with Boeing 747. Examples of recent design studies include the International Council on Clean Transportation (ICCT), which evaluated the fuel consumption of a 50-passenger supersonic commercial passenger aircraft, as well as the Polytechnic Institute of Turin (PIT), which analyzed the direct operating costs of a 300-passenger hypersonic commercial aircraft.[21,22] On average, the ICCT-modeled supersonic aircraft was estimated to burn 5 to 7 times as much fuel per passenger as subsonic aircraft on representative routes. For the PIT-modeled hypersonic aircraft, fuel cost ranged from about 8 to 12 times subsonic per seat mile depending on the hydrogen fuel price scenario considered.

In addition to considering these studies, the Bryce team developed a top-level cost estimating relationship (CER) using velocity, the slope of the effect curve, and drag to determine relative fuel consumption and cost. Results are shown in Table 10, denominated relative to subsonic per seat mile. The CER uses Mach 0.85 as the assumed velocity for subsonic aircraft, and the results consider refueling stops needed for Case 1, 2, and 4 on an average long-haul route due to limited range. Moreover, for Case 5, the result was increased to account for the price of liquid hydrogen relative to traditional hydrocarbon fuels.

For context on non-fuel cost multipliers, Bryce considered a Flight International–published cost analysis from 1972 comparing *Concorde* to

> ***‘Because turbojet engines used for supersonic flight will be operated at high throttle for duration of flight profile, engine maintenance and overhaul will be more challenging than for conventionally operated turbojet engines.’***
>
> – Developer

the Boeing 747. When considered on a per seat mile basis, fuel cost of *Concorde* was roughly 4 times that of the Boeing 747, maintenance costs about 3 times, and ground costs about 1.5 times.[23] In speaking with experts, there was a wide range of views around likely operating costs for advanced aircraft at higher Mach numbers. Due to the uncertainty, cost multipliers were determined with emphasis on the relative costs between the cases to evaluate the relationship between time savings and additional costs incurred with speed, and sensitivity analyses on several cost multipliers were conducted. Sensitivity analysis results are discussed in a later section.

Table 10. Operating cost multiplier breakdown.

		Fuel Multiplier			Non-Fuel Multiplier						
	Speed	**CER**	**Research**	**Model Input**	**Maintenance**	**Crew**	**Insurance**	**Ground**	**System**	**Model Input CA**	**Model Input GA**
Case 1	Mach 2	3x	5x to 7x (ICCT)	4.5x	3x	1x	10x	1.5x	1x	1.5x	1.9x
Case 2	Mach 3	5x		5.5x	4x	1x	10x	2x	1x	1.7x	2.3x
Case 3	Mach 4	7x		7x	5x	1x	10x	2.5x	1x	1.9x	2.7x
Case 4	Mach 5	10x	8x to 12x (PIT)	10x	6x	1x	10x	3x	1x	2.1x	3.2x
Case 5	Mach 5	11x		11x	7x	1x	10x	4x	1x	2.5x	3.7x

Table 11. Operating cost multiplier inputs.

	Propulsion	**Speed**	**Fuel Multiplier**	**Non-Fuel CA**	**Non-Fuel GA**
Case 1	Turbine	Mach 2	4.5x	1.5x	1.9x
Case 2	Modified Turbine	Mach 3	5.5x	1.7x	2.3x
Case 3	Turboramjet	Mach 4	7x	1.9x	2.7x
Case 4	Ramjet	Mach 5	10x	2.1x	3.2x
Case 5	Scramjet	Mach 5	11x	2.5x	3.7x

Based on the aircraft design and operating requirements, fuel, maintenance, insurance, and ground costs were assumed to increase with speed regime and vehicle complexity. Advanced fuels, such as hydrogen fuel, particularly results in increased costs. Operating cost multipliers used in the model are shown in Table 10 and Table 11, as they were applied to fuel, maintenance, insurance, and ground costs. The model input columns are a weighted average of the supporting columns, indicating the ultimate value used for fuel and non-fuel multipliers. Since the relative magnitude of non-fuel operating costs differ between commercial and general aviation, the non-fuel model input values differ:

- Fuel, the largest single operating cost for subsonic operators. Significant increases are anticipated for high-speed aircraft due to increased fuel burn caused by aerodynamic drag, as well as the expected adoption of synthetic hydrocarbon fuels to reduce emissions, and other advanced fuels like hydrogen (considered in Case 5).
- Non-fuel, includes flight costs other than fuel, as well as ground and system costs. Costs that were escalated are maintenance, insurance, and ground costs.
    - Maintenance includes the cost of materials for the airframe, engine, and system, as well as labor cost for performing maintenance and routine inspections. Expectations for increased flight frequency, engine thrust settings, thermal loads, as well as the use of advanced materials and need for specialized labor all contribute to an increase in projected maintenance burden.

> ***'The faster you go, the worse [tech challenges and costs] get.'***
>
> – Engine Developer

  - Insurance includes the flight and ground risk of airframe damage, passenger liability for death or injury, and the damage risk to cargo, and typically represent a small portion of subsonic operating costs. Significant increases are expected for high-speed aircraft due to the inherent risk and uncertainty related to high-speed aircraft relative to existing subsonic aircraft.
  - Ground costs include aircraft handling, airport fees, passenger/cargo processing, and ground/facility costs. Expectations for the development and operation of bespoke airport infrastructure to support high-speed aircraft (for example, specialized handling of cryogenic fuels for Case 5), as well as increased number of takeoffs and landings, contribute to an increase in projected ground costs.

- Non-fuel costs that were held constant are air crew, and system
  - Air crew costs include the total cost of the cockpit, including wages, training, and travel expenses. While it may be reasonable to expect increased compensation for air crew on high-speed aircraft, the reduction in flight time for a given route is assumed to mitigate this effect. In addition, trends toward autonomous piloting may further reduce the operating costs associated with air crew.
  - System costs include transport related, general and administrative, passenger service, and marketing costs. System costs are typically not correlated with aircraft type and thus are assumed to remain at the same level for high-speed operations.

Manufacturing Costs

To calculate total fleet manufacturing costs, the study team estimated the per-aircraft marginal manufacturing cost, excluding RDT&E and profit. As noted above, profit to the manufacturer is determined separately in the model, and available RDT&E is a model output. This distinction is important as aircraft sale prices are typically quoted inclusive of all costs, such as the recovery of non-recurring expenditures like RDT&E as well as the profit markup. Note that for subsonic aircraft, the marginal cost to manufacture an aircraft typically averages about 75% of the aircraft sale price.[24] Aircraft marginal manufacturing cost was assumed to increase with speed regime and vehicle complexity. Experts had a wide range of views around likely manufacturing costs for advanced aircraft at higher Mach numbers. Table 12 shows some factors identified by SMEs driving costs at higher Mach numbers, for both airframe and powerplant. The use of expensive advanced materials and optimized structures for high-speed airframes, as well as powerplant enhancements required for supersonic operation and turboramjet, ramjet, and scramjet technology, are expected to drive significant increases in manufacturing costs relative to subsonic aircraft. Table 13 shows the costs used in this analysis, for the general aviation and commercial aviation variant of each aircraft case, informed by Table 12 and additional factors such as the relatively limited economies of scale for high-speed aircraft production compared to subsonic aircraft. For example, considering a fixed level of daily utilization and passenger capacity, high-speed aircraft can service a greater number of passengers than subsonic due to the efficiencies afforded by high-speed flight (that is, one plane can fly more routes in a day because each route takes less time). As Mach regime increases, this effect limits the projected fleet sizes for high-speed aircraft.

Estimating Profit and Resale Value

To calculate profit across the high-speed air transportation ecosystem, the team assumed that total profit—to airlines, manufacturers, and lessors/financing organizations—was 25% of total passenger revenue. To develop this estimate, the team assessed profitability in the subsonic ecosystem for lessors, manufacturers, and airlines, based on annual reports and industry analysis. In this scenario, the lessors category includes all elements of aircraft ownership, capital needs, and financing. The team determined the dollar value of profit from

Table 12. Factors driving aircraft manufacturing cost.

Speed	Cost Element	Manufacturing Cost Drivers
0 to Mach 2.5	Airframe	No significant change in airframe manufacturing cost given use of conventional materials and shapes
	Powerplant	Due to enhancements required to enable operation of turbojet for supersonic transport (pre-cooling technology, variable inlets, augmented thrust, more robust components, etc.), cost is expected to be about 20-25% higher than for conventional turbojet engines
Mach 2.5 to Mach 4	Airframe	Due to use of titanium, Inconel, and other expensive materials, combined with optimized structures, the cost is expected to be about twice as much as for conventional airframes
	Powerplant	Relative cost to manufacture an enhanced turbojet for use in supersonic flight is about the same as would be for those operating up through Mach 2.5
Mach 4+	Airframe	Due to use of titanium, Inconel, and other expensive materials needed for shock surfaces like carbon-carbon and other ceramics, combined with optimized structures, the cost is expected to be about four times as much as for conventional airframes
	Powerplant	Turboramjet, ramjet, and scramjet technologies expected to inform manufacturing costs that are about 30% higher than for powerplants used for Mach 2-5 to Mach 4 regime

Table 13. Marginal manufacturing cost inputs.

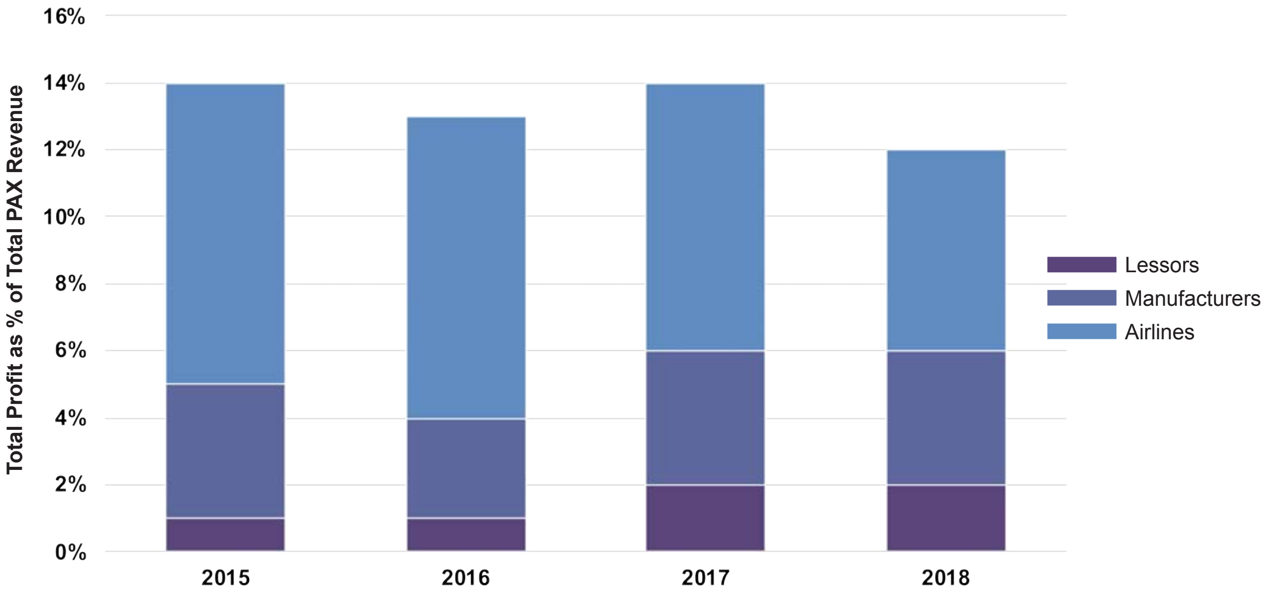
			Model Input: Unit Cost	
	Speed	Propulsion	10 PAX	50 PAX
Case 1	Mach 2	Turbine	$150M	$200M
Case 2	Mach 3	Modified Turbine	$200M	$300M
Case 3	Mach 4	Turboramjet	$250M	$400M
Case 4	Mach 5	Ramjet	$400M	$500M
Case 5	Mach 5	Scramjet	$450M	$500M

2015 through 2018 for all industry participants, considering passenger revenue and excluding cargo. The team then compared that value to total passenger revenue each year to develop the percentages shown in Figure 18. As a result, Figure 18 does not represent profit margin in the traditional sense; instead it relates profit for each entity as a proportion of total passenger revenue earned in the commercial aviation industry, resulting in a value of about 15%. In the general aviation market, profitability is typically about one-third higher than commercial aviation according to SME input. As this analysis is focused on characterizing premium passengers, and average profit earned by operators for first and business class passengers is significantly higher than economy passengers in the subsonic ecosystem, the model assumes that 25% of passenger revenue will be allocated as profit across the ecosystem.

In assessing market dynamics, we also considered potential resale value of high-speed aircraft. On average, today's subsonic aircraft can be assumed to have a 25-year depreciable life, with 15% residual value. These values vary with aircraft type, market conditions, and regulatory environment. The business case model for high-speed aircraft here assumes a 20-year depreciable life with 0% residual value. These lower values are due to uncertainty about the end state of advanced aircraft materials due to the highly demanding flight regime of high-speed aircraft.

Modeled results reported here therefore assume $0 resale revenue. It should be noted that realistically, an aircraft with 0% residual accounting book value will likely have some end-of-life part out value or even potential for continued operations. As a rough order of magnitude (ROM) estimate end-of-life part out value could reach as much as 5% of aircraft cost, including scrap value of specialty alloys and metals. As the value is relatively small, compared to total revenue, and highly uncertain it is not included in the business case.

Figure 18. Subsonic ecosystem profitablity for commercial aviation passengers.



Business Case Analysis Findings

Overview

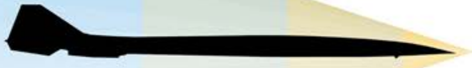
The business case analysis determines the available RDT&E across cases (1 through 5), fares (1.5x to 10x), and market segments (commercial and general aviation).

With few exceptions, available RDT&E was greater than $0 for all cases when considering only viable routes. Case 2 (Mach 3) generated the maximum available RDT&E of $24B in 2020 dollars. Beyond Case 2, available RDT&E declined with higher Mach cases. The number of viable routes was highest for Case 1 (Mach 2), falling with higher Mach cases due to increased operating and aircraft manufacturing costs. Required fleet sizes ranged from about 150 to 600 aircraft across cases. The 50-passenger commercial aircraft required 100 to 300 units at 1.5x fare, but fewer than 50 units at higher (2.5x, 5x, and 10x) fares due to the significant drop-off in passenger demand beyond 1.5x fare. The required fleet for the 10-passenger general aviation services jet ranged from 0 to 150 units across all fares, and private jet sales were estimated at 150 units total over 30 years for all cases. Manufacturers of subsonic aircraft typically seek production volume of several hundred, potentially as high as 500 to 1,000 for a single aircraft program for general aviation and commercial airliners, respectively, based on insight from SMEs.

In summary, Case 2 generated the highest level of available RDT&E across market segments, a total of $24B when considering 1.5x fare for commercial aviation ($15B) and 2.5x fare for general aviation ($9B). In this optimized case, by 2060, the end of the considered time horizon, 302 and 382 viable routes were identified for commercial and general aviation, respectively. A fleet size of 252 commercial aircraft (50-passenger) and 299 general aviation aircraft (10-passenger) would be required by 2060.

Supported Acquisition Budget

Figure 19 shows the acquisition budget, in 2020 dollars, across cases and fares. The acquisition budget is defined as the revenue generated from the forecasted fleet of aircraft in service

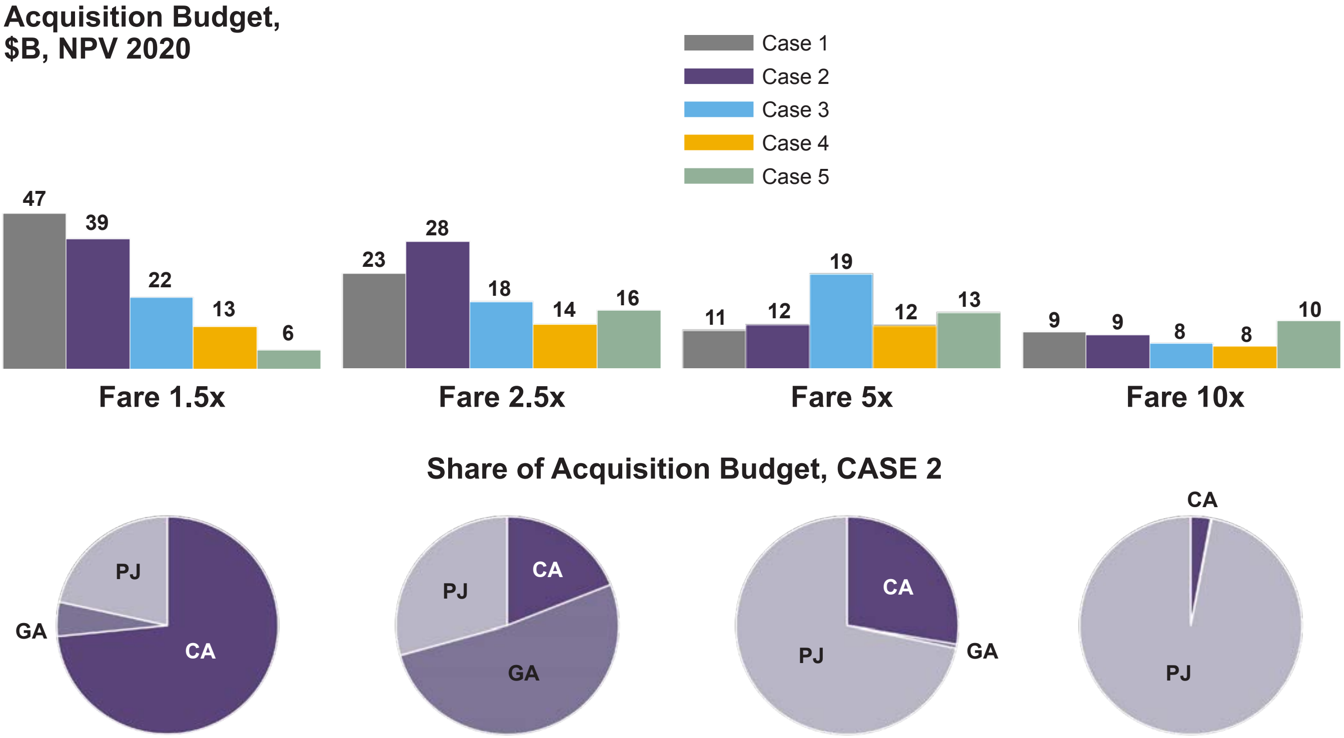


on viable routes, less operating costs and ecosystem profit. Available RDT&E is equal to the acquisition budget less fleet cost. The embedded pie charts show the relative contribution of each market segment to the acquisition budget for Case 2, our best case.

At the 1.5x fare, the acquisition budget is driven by commercial aviation demand, which is greater for Cases 1 and 2 than Cases 3, 4, and 5 as lower operating costs enable more viable routes, and thus more passenger revenue, at lower fares. Fewer passengers exist for higher Mach cases because operating costs exceed revenue generated for several highly trafficked routes. Passengers on these non-viable routes are not considered, constraining the acquisition budget. At the 2.5x, 5x, and 10x fares, the acquisition budget is driven by general aviation demand and jet sales, since only the wealthiest passengers are willing to pay.

The business case analysis uses 25% of passenger revenue for the base ecosystem profit across all cases. Varying the profit percentage has less effect at higher fares because revenue tends to be lower since fewer passengers can afford those fares.

Figure 19. Market-supported acquisition budget by case and fare.



Supported Available RDT&E: Commercial Aviation

Figure 20 shows available RDT&E in 2020 dollars for the commercial aviation market segment only. Data shown for passenger demand and revenue is cumulative over each case's respective time horizon.

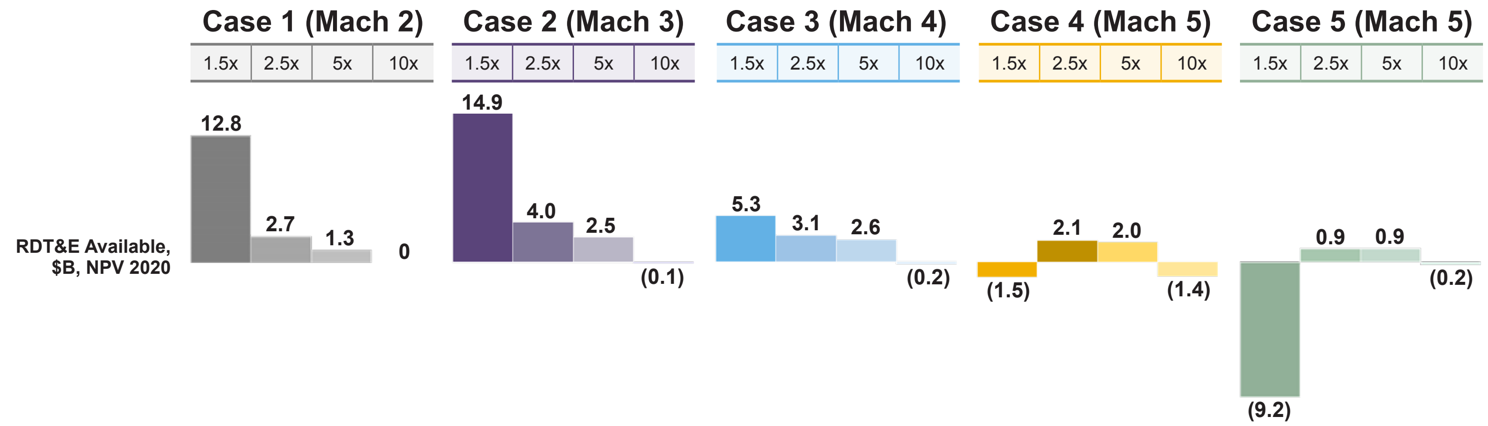
For Cases 1, 2, and 3, available RDT&E is highest at the 1.5x fare. Available RDT&E falls at higher fares due to significant loss of passenger demand and associated revenue.

For Cases 4 and 5 at the 1.5x fare, higher operating costs constrain the number of viable routes, and fleet marginal manufacturing cost and ecosystem profit drive available RDT&E below $0. Cases 4 and 5 generate positive available RDT&E for the 2.5x and 5x fares, but the upside is limited by the relatively lower passenger demand.

To be considered viable, revenue for a given route must exceed operating costs (as defined in this analysis, excluding RDT&E and the cost of aircraft acquisition). The number of viable routes is highest for Case 1 at the 1.5x fare, and for Case 3 at the 2.5x, 5x, and 10x fares. While operating costs for Case 3 are higher than Case 1, more passengers are willing to pay the 2.5x, 5x, and 10x fares due to the additional time savings, leading to higher revenue and number of viable routes. There is a break point between Case 3 and Case 4 where the additional route revenue generated by higher passenger demand does not exceed the additional operating costs incurred, resulting in a lower number of viable routes for Case 4. For Case 5, the 5x fare generates more viable routes than the 2.5x fare due to the relatively minor drop in passenger demand between the two fares.

Fleet required represents the number of aircraft needed to service passenger demand on viable routes. Across cases, Case 1 requires the greatest fleet size at the 1.5x and 2.5x fares (323 and 41), Case 5 at the 5x fare (29), and Case 4 at the 10x fare (24). For a constant level

Figure 20. Market-supported available RDT&E for commercial aviation by case and fare.



	Case 1 (Mach 2)				Case 2 (Mach 3)				Case 3 (Mach 4)				Case 4 (Mach 5)				Case 5 (Mach 5)			
	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x
Viable Routes	327	79	36	0	302	72	42	25	229	95	54	57	133	43	31	20	113	34	43	6
Fleet Required	323	41	16	0	252	29	15	10	198	37	19	20	127	20	18	24	123	20	29	6
PAX	177M	13M	3M	-	184M	15M	4M	2M	178M	24M	8M	4M	127M	17M	9M	5M	118M	15M	13M	2M
PAX Rev. ($B)	$1,012	$118	$46	-	$1,311	$157	$87	$28	$1,351	$239	$133	$81	$1,128	$205	$165	$75	$1,075	$198	$203	$33
PAX Rev. (NPV $B)	$179	$20	$8	-	$166	$19	$11	$3	$122	$21	$11	$6	$72	$13	$10	$4	$68	$12	$12	$2
Acq. Budget (%)	16%	23%	26%	-	17%	29%	31%	11%	13%	23%	30%	7%	6%	24%	27%	-23%	-5%	15%	14%	-4%
Cost Multiplier	2.3x				2.7x				3.3x				4.2x				4.8x			
Cost/Seat-Mile	$0.68				$0.81				$0.98				$1.27				$1.43			
Marginal Unit Cost	$200M				$300M				$400M				$500M				$500M			
Time Horizon	2035 – 2055				2040 – 2060				2045 – 2065				2050 – 2070				2050 – 2070			

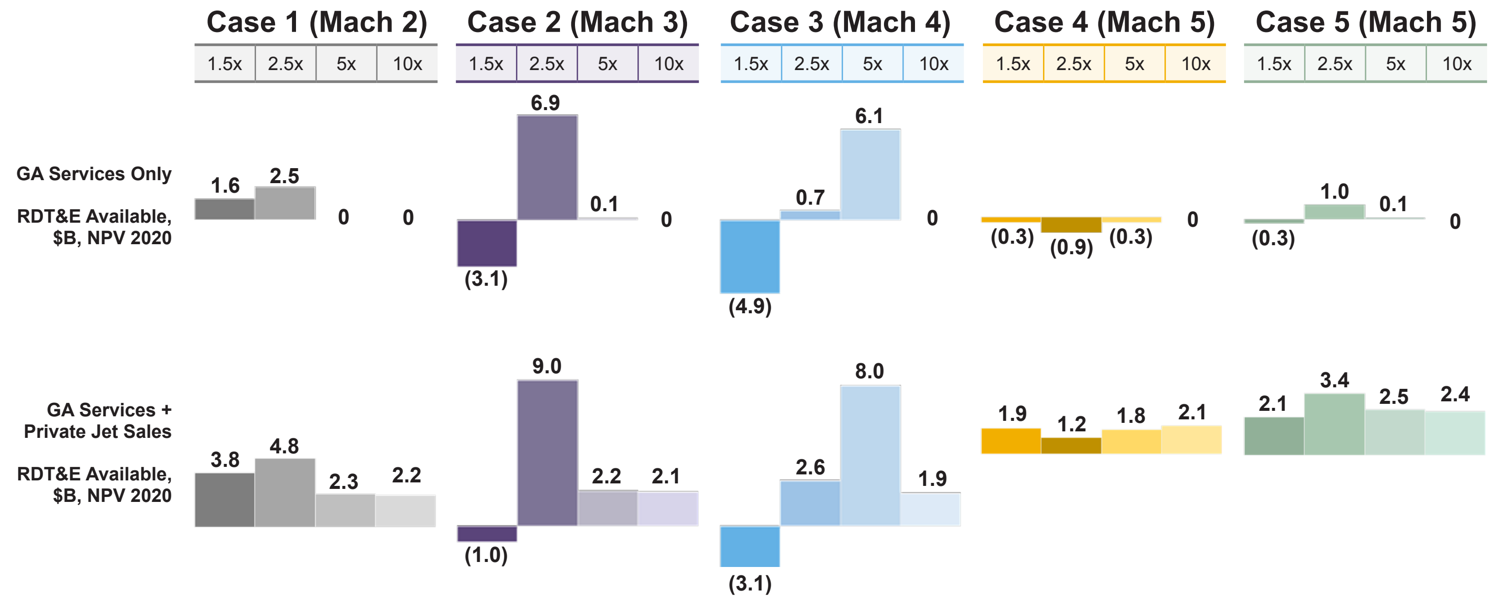
Aircraft capacity = 50 PAX
Profit % = 25%
Viable Routes = route PAX revenue > operating cost
Fleet required = aircraft required for viable routes (varies based on aircraft speed)
Acquisition Budget = % revenue, net of operating cost, profit
RDT&E available = acquisition budget - fleet cost
Cost multiplier = aggregate (fuel, non-fuel) multiplier applied to subsonic total cost/seat-mile
Time horizon = 20 years

of passenger demand, lower Mach cases require more aircraft relative to higher Mach cases; however, the productivity gains afforded by speed are limited by turnaround time. For example, a Case 3 aircraft completes almost twice as many flights per day as Case 1 but averages ~25% less daily flight hours due to additional time spend in turnaround. The net effect is positive, as shown at the 1.5x fare, where Case 1 requires 323 aircraft to service 177 million passengers, while Case 3 needs 198 aircraft to service 178 million passengers. This effect is also observed in the results for the general aviation market segment shown in Figure 20.

Supported Available RDT&E: General Aviation Including Jet Sales

Figure 21 shows available RDT&E in 2020 dollars for the general aviation and private jet sales market segments only. Data shown for passenger demand and revenue is cumulative over each case's respective time horizon.

Figure 21. Market-supported available RDT&E for general aviation by case and fare.



	Case 1 (Mach 2)				Case 2 (Mach 3)				Case 3 (Mach 4)				Case 4 (Mach 5)				Case 5 (Mach 5)			
	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x
Viable Routes	174	313	9	0	117	382	8	8	74	245	146	29	18	103	48	9	5	108	77	15
GA Fleet Req.	145	130	1	0	109	149	1	1	93	103	56	1	7	58	15	1	3	65	35	1
Jet Fleet Demand	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150
PAX	9M	9M	0	-	9M	14M	0	0	9M	12M	6M	0	1M	8M	2M	0	1M	8M	4M	0
PAX Rev. ($B)	$275	$263	$1	-	$290	$502	$1	$0	$290	$445	$287	$1	$44	$323	$78	$1	$22	$438	$217	$3
PAX Rev. (NPV $B)	$58	$57	$0	-	$42	$78	$0	$0	$29	$49	$31	$0	$3	$26	$6	$0	$2	$34	$16	$0
GA Acq. Budget (%)	15%	16%	48%	-	4%	19%	45%	35%	-5%	11%	27%	44%	3%	8%	7%	25%	-5%	14%	12%	39%
Cost Multiplier	2.5x				3.1x				3.8x				4.9x				5.5x			
Cost/Seat-Mile	$1.89				$2.32				$2.85				$3.65				$4.16			
Marginal Unit Cost	$150M				$200M				$250M				$400M				$450M			
GA Time Horizon	2030 – 2055				2035 – 2060				2040 – 2065				2045 – 2070				2045 – 2070			
Jet Time Horizon	2025 – 2055				2030 – 2060				2035 – 2065				2040 – 2070				2040 – 2070			

Aircraft capacity = 10 PAX
Profit % = 25%
Discount Rate = 7%
Viable Routes = route PAX revenue > operating cost
Fleet required = aircraft required for viable routes (varies based on aircraft speed)
Acquisition Budget = % revenue, net of operating cost, profit
RDT&E available = acquisition budget - fleet cost
Cost multiplier = aggregate (fuel, non-fuel) multiplier applied to subsonic total cost/seat-mile
Time horizon = 25 years for GA services, 30 years for private jet sales

Available RDT&E is highest for Cases 1, 2, and 5 at the 2.5x fare, for Case 3 at the 5x fare, and for Case 4 at the 10x fare. Across all cases, the 2.5x fare generates higher available RDT&E than the 1.5x. Since general aviation passengers are relatively price insensitive, total passenger demand increases from the 1.5x to 2.5x fare as the higher fares lead to more viable routes.

The number of viable routes is highest at the 2.5x fare for all cases. At the 5x fare, there is a significant rise in viable routes between Case 2 and Case 3 as more passengers are willing to pay a 5x fare due to greater time savings. Moving from Case 3 to Case 4 at the 5x fare, the additional revenue enabled by higher passenger demand does not exceed the additional operating costs incurred, so the number of viable routes falls for Case 4. This effect reverses between Case 4 and Case 5 at the 5x fare, as the additional time savings afforded by range (12,000 miles for Case 5 vs. 4,500 miles for Case 4) leads to greater passenger demand.

For general aviation services only, Case 1 requires the greatest fleet size at the 1.5x fares (145), Case 2 at the 2.5x fare (149), and Case 3 at the 5x fare (56). The 10x fare did not generate enough passenger demand for more than one dedicated aircraft in any case. Similar to commercial aviation, for a constant level of passenger demand, lower Mach cases require more aircraft relative to higher Mach cases. For example, at the 1.5x fare, Case 1 requires 145 aircraft to service 9 million passengers, while Case 3 needs 93 aircraft to service 9 million passengers.

Private jet sales are held constant across all cases and fares as this subset of the population is assumed to be relatively price insensitive. Across all cases and fares, the contribution of private jet sales to fleet size is 150 aircraft, as well as approximately $2B to available RDT&E.

Supported Available RDT&E: Total

Figure 22 shows available RDT&E in 2020 dollars aggregating commercial aviation, general aviation, and private jet sales.

Available RDT&E is greater than $0 across all cases and fares except Case 5 at the 1.5x fare. Case 1 achieves the highest available RDT&E for a given fare multiplier ($17B at 1.5x fare). Case 2 achieves the highest available RDT&E when optimizing for different fare multipliers between commercial and general aviation market segments ($15B at 1.5x fare for commercial aviation, $9B at 2.5x fare for general aviation). Case 3 generates the highest available RDT&E across cases at the 5x fare, driven mainly by the general aviation market segment. Cases 4 and 5 generate relatively low levels of available RDT&E as the combination of high operating and manufacturing costs constrain business case viability.

Supported Available RDT&E: Best Case

As discussed above, Case 2 (Mach 3 aircraft with 4,500-mile range) generates the highest level of available RDT&E when optimized across market segment and fare. Total available RDT&E is about $24B, comprised of $15B at the 1.5x fare for commercial aviation and $9B at the 2.5x fare for general aviation. Over the time horizon, total passenger demand is 198M with associated passenger revenue of $244B in 2020 dollars.

Figure 23 provides additional findings for the market segments comprising the optimized case. In this optimized case, 302 and 382 viable routes were identified for commercial and general aviation, respectively. The average viable route length for general aviation was 2.3 hours, compared to 2.6 hours for commercial aviation. As a result, the 10-passenger general aviation jet can fly slightly more routes per day than the 50-passenger commercial aircraft. Shorter routes and more frequent flights lead to more turnaround time, so the average annual utilization for the general aviation jet is below the commercial aircraft. A load factor of 50% was assumed for the general aviation jet as

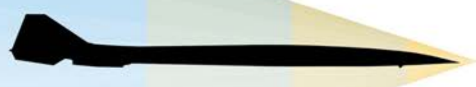
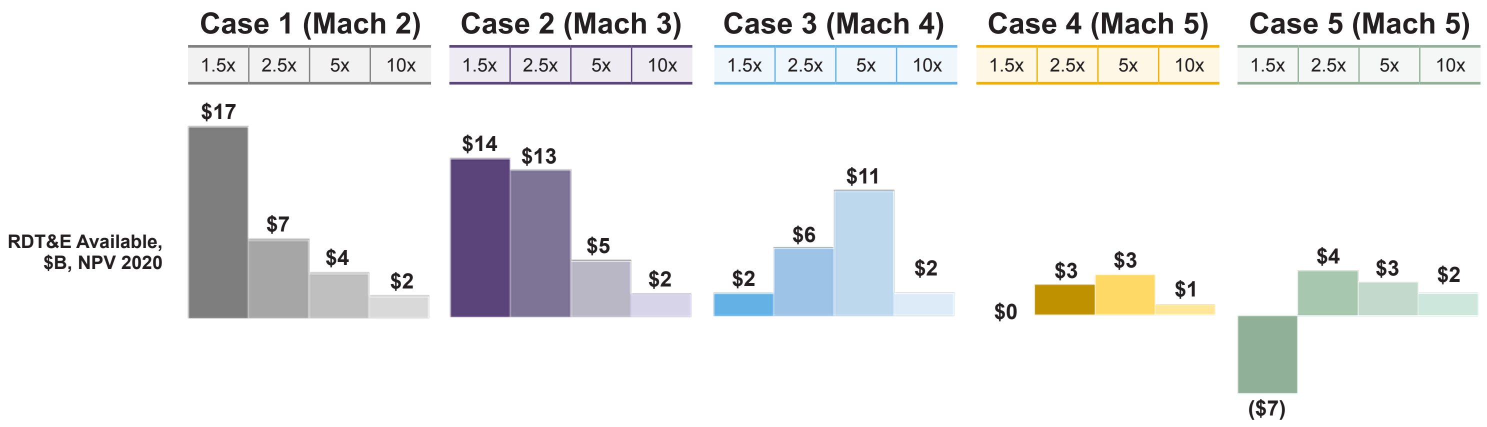


Figure 22. Total market supported available RDT&E by case and fare.



	Case 1 (Mach 2)				Case 2 (Mach 3)				Case 3 (Mach 4)				Case 4 (Mach 5)				Case 5 (Mach 5)			
	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x	1.5x	2.5x	5x	10x
CA	**$13**	$3	$1	$0	**$15**	$4	$3	$0	**$5**	$3	$3	$0	($2)	**$2**	$2	$0	($9)	**$1**	$1	$0
GA: Services	$2	**$3**	$0	$0	($3)	**$7**	$0	$0	($5)	$1	**$6**	$0	$0	($1)	$0	**$0**	$0	**$1**	$0	$0
GA: Jet Sales	$2	**$2**	$2	$2	$2	**$2**	$2	$24	$2	$2	**$2**	$2	$2	$2	$2	**$2**	$2	**$2**	$2	$2
CA	2035 – 2055				2040 – 2060				2045 – 2065				2050 – 2070				2050 – 2070			
GA: Services	2030 – 2055				2035 – 2060				2040 – 2065				2045 – 2070				2045 – 2070			
GA: Jet Sales	2025 – 2055				2030 – 2060				2035 – 2065				2040 – 2070				2040 – 2070			
Viable Routes	502	392	45	0	419	454	51	33	303	340	200	86	151	146	79	29	118	142	120	21
Fleet Required	618	320	166	150	512	329	166	161	441	290	224	171	285	229	184	175	277	235	213	157
Max RDT&E Available ($B, NPV 2020)	**$18B** CA 1.5x fare GA 2.5x fare				**$24B** CA 1.5x fare GA 2.5x fare				**$13B** CA 1.5x fare GA 5x fare				**$4B** CA 2.5x fare GA 10x fare				**$4B** CA 2.5 x fare GA 2.5x fare			

subsonic jets typically carry 4 to 6 passengers agnostic of total jet capacity according to jet operators interviewed. For the commercial aircraft, the load factor is an analytic output informed by the traffic analysis, correlated with the level of passenger demand across viable routes. A fleet size of 252 50-passenger commercial aircraft and 299 10-passenger general aviation jets is required by 2060.

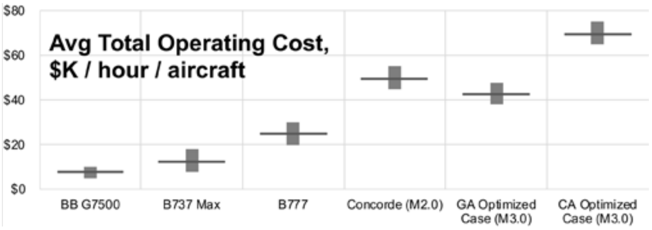
Figure 23 provides additional context on operating costs. Fuel represents 51% and 44% of total costs for commercial and general aviation, respectively, over the referenced time horizon. Subsonic fuel costs are typically around 25% of total operating costs. Maintenance represents a higher proportion of general aviation costs compared to commercial aviation, 30% to 15%, while system represents a higher proportion of commercial aviation costs compared to general, 12% to 3%. As mentioned previously, operators of charter and fractional jets generally incur lower marketing, administrative, and general overhead costs relative to commercial airlines. The cost per seat mile for commercial operators, or the cost to move one premium seat over one mile, is estimated to be $0.81. For general aviation operators, the cost per seat mile is estimated to be $2.32, or about $23 per aircraft flight mile. The graph below compares the hourly operating cost of the Mach 3 aircraft to aircraft on an average long-haul route.

Table 14. Case 2 (best case) findings by market segment.

	CA **1.5x Fare**	**GA** **2.5x Fare**
Total Viable Routes	302	382
Average Route Lengths (hrs)	2.6	2.3
Routes/Day	2.9	3.2
Flight Hours/Year	2,780	2,650
Implied Load Factor	94%	50%
Fleet Required	252	299
Available RDT&E ($B, NPV 2020)	**$14.9**	**$9.0**

Figure 23. Case 2 (best case) cost breakdown by market segment.

	CA	% Total	GA	% Total
Fuel	$385	51%	$126	44%
Maintenance	$112	15%	$84	30%
Crew	$34	4%	$20	7%
Insurance	$28	4%	$9	3%
Ground	$106	14%	$35	12%
System	$92	12%	$9	3%
Cost/Available Premium-Seat-Mile	**$0.81**		**$2.32**	



Supported Available RDT&E: NASA-Defined Case

In addition to the cases defined previously, NASA requested an analysis of a special case with defined parameters, referred to here as the NASA-Defined Case. The analysis considers a Mach 3 commercial aircraft with 50-passenger capacity and 3,500-mile range at the 2.5x fare. Per request, general aviation and private jet sales are not considered. NASA requested use of 100 aircraft as the defined fleet size, shown in Table 14 as the '100-fleet' scenario. In addition, the team assessed the NASA-Defined Case using the fleet-sizing methodology considered in the broader business case analysis (Cases 1 through 5), determining the available RDT&E for an optimized fleet serving only viable routes. The results are included to highlight the impact of fleet efficiency on business case viability for commercial operators.

As shown in Table 15, the 100-fleet scenario generates a negative level of available RDT&E, and the optimized scenario generates available RDT&E of about $4B in 2020 dollars. While the 100-fleet scenario enables the inclusion of more routes and passenger demand relative to the optimized scenario (311 routes to 60 routes), only a fraction of these routes are profitable. The remaining non-profitable routes drive available RDT&E to negative levels.

The implied load factor for the 100-fleet scenario is 35% compared to 78% for the optimized scenario, driven by the relatively low passenger demand generated for several of the 100-fleet routes. Since the optimized scenario only includes routes with sufficient passenger demand, the load factor is much higher. While the 100-fleet scenario assumes a fleet size of 100 aircraft, the optimized case requires only 21 aircraft to service the viable routes.

Table 15. NASA-defined case findings by scenario.

	100 Fleet	Optimized
Total Viable Routes	311	60
Average Route Lengths (hrs)	2.4	2.3
Routes/Day	3.1	3.2
Flight Hours/Year	2,678	2,626
Implied Load Factor	35%	78%
Fleet Required	100 input	21
Available RDT&E ($B, NPV 2020)	**($27)**	**$4.3**

Sensitivity Analysis

The inputs used throughout this analysis reflect predictions decades in the future; as noted, data is often limited and expert judgment varies. This section discusses the sensitivity of study findings to variations in inputs, to provide insight into uncertainty ranges.

Sensitivity Analysis Based on Optimized Case

Considering the best case identified, a Mach 3 aircraft with 4,500-mile range, at 1.5x fare for commercial aviation passengers and 2.5x fare for general aviation passengers, varying key inputs by about 10% results in changes in RDT&E from a drop in $6B to an increase of $9B.

The middle column of Table 16 shows the value of model inputs varied at a ~10% change in magnitude and supporting columns to the left and right show the resulting change in available RDT&E for commercial and general aviation.

Available RDT&E is most sensitive to discount rate for both market segments, due to the long horizons assessed. Sensitivity to discount rate increases for each subsequent case (highest for Cases 4 and 5) due to the increasingly distant time horizons. Other than the discount rate, available RDT&E is most sensitive to fuel (across all cases and both market segments), followed by maintenance. For example, a 10% increase in fuel multiplier would raise operating costs and reduce the number of viable routes, resulting in a $5B decrease in available RDT&E. Sensitivity to marginal manufacturing cost is correlated with the fleet required; low Mach regime cases are relatively more sensitive than higher Mach cases, which need fewer aircraft for the same number of passenger trips due to time savings.

> ***‘Military interest in reusability growing—dramatic change in the last 12 months—and as private capital becomes scarcer due to COVID-19 many companies will focus on military investment and this will impact designs accordingly.’***
>
> – Engineering SME

Table 16. Sensitivity analysis based on optimized case.

Total	GA	CA	**Sensitivity Analysis** *(~10% change in magnitude)*			CA	GA	Total
+$9B	+$3B	+$6B	6%	Discount Rate	8%	-$4B	-$2B	**-$6B**
+$2B	+$1B	+$1B	-$25M	Aircraft Unit Cost	+$25M	-$1B	-$1B	**-$2B**
+$6B	+$2B	+$3B	-0.5x	Fuel Multiplier	+0.5x	-$3B	-$2B	**-$5B**
+$3B	+$2B	+$1B	-0.4x	Maintenance Multiplier	+0.4x	-$1B	-$1B	**-$3B**
+$2B	+$1B	+$1B	-0.2x	Ground Multiplier	+0.2x	-$1B	-$1B	**-$2B**
+$5B	+$1B	+$4B	-0.2x	Non-Fuel Multiplier	+0.2x	-$3B	-$1B	**-$4B**

Totals may reflect rounding.

Sensitivity of Cost per Seat Mile to Fuel Multiplier

To further understand the sensitivity of model results to assumptions regarding fuel cost, the team assessed variation in available RDT&E as a function of fuel cost per seat mile for commercial aviation; the analysis shown here is for all cases at a 1.5x fare multiplier. In Figure 24, diamonds indicate the operating cost under the base fuel multiplier assumption for each case. The dotted line is included as a comparative reference point, showing the operating cost per seat mile needed to achieve available RDT&E of $10B in 2020 dollars.

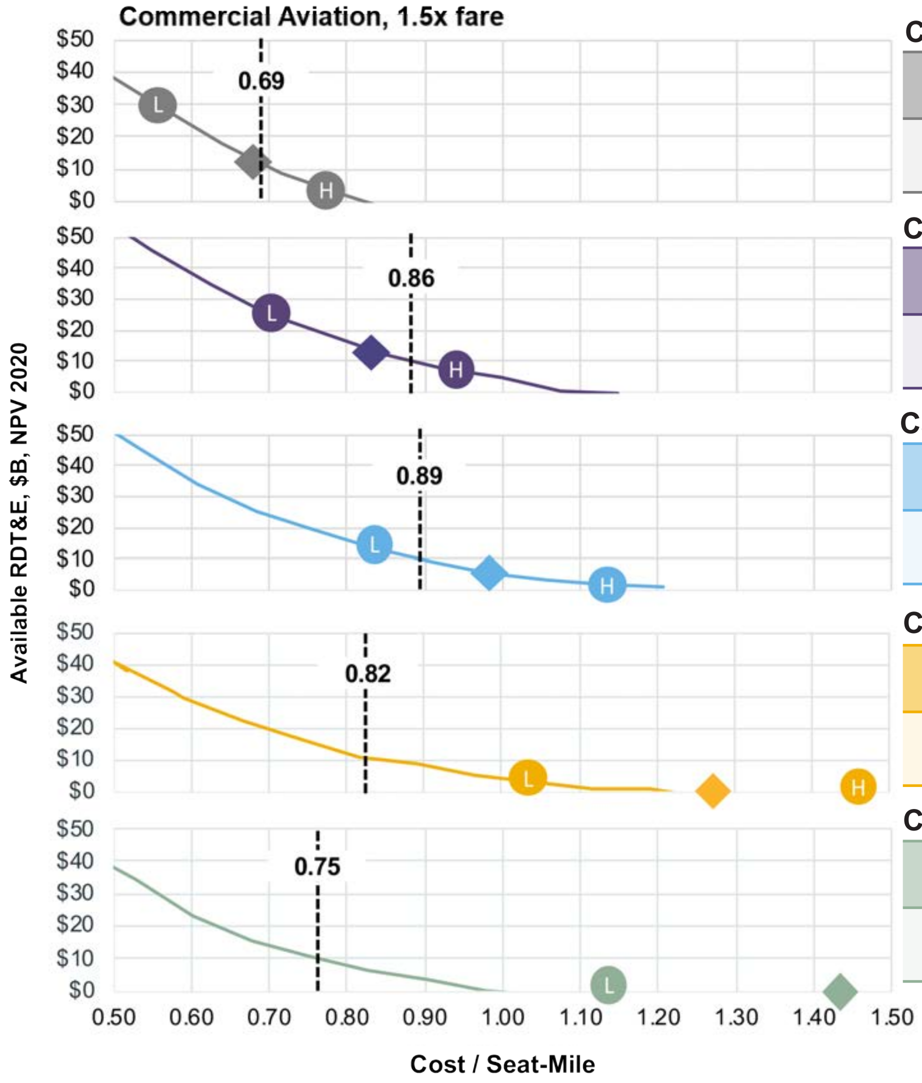
Figure 24 shows available RDT&E across cases under the base fuel multiplier assumptions used in modeling, and a high and low assumption based on a roughly 30% increase or decrease to the base multiplier. For example, an increase in the Case 1 fuel multiplier from 4.5x subsonic to 6x subsonic results in an $0.11 increase in the cost per seat mile, which reduces the number of viable routes and leads to a decrease of ~$10B in available RDT&E.

Cases 1, 2, and 3 generate positive available RDT&E under the low, base, and high scenarios. Case 4 generates positive available RDT&E for the low scenario only, while Case 5 generates negative available RDT&E in all scenarios. To achieve available RDT&E of $10B, Cases 1 and 2 succeed under the base scenario and Case 3 does under the low scenario. Cases 4 and 5 cannot achieve available RDT&E of $10B even under the low fuel multiplier scenario, highlighting how other business case factors, such as maintenance and market timing, must improve in tandem with fuel to improve the economic viability of these cases.

Practical Business Case Considerations

Predictive models abstract real-world dynamics to enable analysis. It is useful to highlight important pathways between model and reality, as there are some practical considerations that will require further study to understand their impact on this macroeconomic analysis.

Figure 24. Sensitivity analysis of cost-per-seat mile to fuel multiplier for 1.5x fare.



Case 1 (Mach 2)

L 3x	◆ 4.5x	H 6x	
			Input: Fuel Multiplier
1.9x	2.3x	2.6x	Output: Cost Multiplier
$0.57	$0.68	$0.79	Output: Cost/Seat-Mile

Case 2 (Mach 3)

L 3x	◆ 4.5x	H 6x	
			Input: Fuel Multiplier
2.3x	2.7x	3.1x	Output: Cost Multiplier
$0.70	$0.81	$0.92	Output: Cost/Seat-Mile

Case 3 (Mach 4)

L 3x	◆ 4.5x	H 6x	
			Input: Fuel Multiplier
2.8x	3.3x	3.8x	Output: Cost Multiplier
$0.83	$0.98	$1.13	Output: Cost/Seat-Mile

Case 4 (Mach 5)

L 3x	◆ 4.5x	H 6x	
			Input: Fuel Multiplier
3.5x	4.2x	5.0x	Output: Cost Multiplier
$1.04	$1.27	$1.49	Output: Cost/Seat-Mile

Case 5 (Mach 5)

L 3x	◆ 4.5x	H 6x	
			Input: Fuel Multiplier
3.8x	4.8x	5.3x	Output: Cost Multiplier
$1.13	$1.43	$1.58	Output: Cost/Seat-Mile

For example, the business case analysis in this study assumes high-speed aircraft capable of achieving annual flight hours comparable to subsonic aircraft despite the increased stresses of high-speed flight. If the ultimate performance of high-speed aircraft varies from the standard set by subsonic aircraft, more aircraft would be required across cases. Additionally, in soliciting feedback from industry experts and high-speed aircraft developers, there is significant uncertainty around the expected operating and manufacturing costs for the highest Mach regimes.

Another consideration is the alignment of fleet size with manufacturer economic motivation. For subsonic aircraft, the industry norm is 500+ for general aviation and 1,000+ for commercial aircraft over 20 years to achieve manufacturing viability. Below this threshold, economies of scale in production are limited, and recouping development costs becomes challenging. Across all cases considered, the maximum fleet required for the 50-passenger aircraft was 323 over 20 years, and 299 for 10-passenger aircraft over 30 years. While at least one high-speed aircraft start-up developer anticipates viability at roughly 100 units, it remains to be seen if the advent of high-speed aircraft will enable a break from industry norms.

A core uncertainty is whether available RDT&E is sufficient. This study specifically addressed the question of likely magnitude of available RDT&E enabled by a future industry, as opposed than on estimating likely requirements. For commercial aviation alone, available RDT&E reached a maximum of $15B in 2020 dollars (Case 2). For general aviation alone, this figure was $9B. It is uncertain whether these levels are adequate to support the full development campaign needed for high-speed aircraft. Media and anecdotal reports of high-speed aircraft developers (Mach 2) reference expected RDT&E below $10B, but these estimates are unvalidated. RDT&E cost for advanced subsonic aircraft, requiring less innovation than high-speed aircraft, have reportedly exceeded $10B (Airbus A350 and A380), up to $30+B (Boeing 787).[25]

Lastly, given NASA's interest specifically in future hypersonic commercial markets, the effect of commercial supersonic transportation on the potential commercial hypersonic market is uncertain. As discussed previously, the advent of commercial supersonic transportation could act as a competitor, pathfinder, or both, as it relates to a commercial hypersonic market (see Appendix).

Barriers (Task 3)

KEY FINDINGS

There are 28 non-technical barriers to commercial high-speed air transportation

Six barriers with significant government mitigation impact were identified:

- *Type certification during time when safety standards and environmental compliance trends are tightening*
- *Aircraft designed to fly at high Mach regimes may be more difficult to certify as safe, increase test program duration, and/or require more highly skilled pilots*
- *Prohibition of supersonic flight over the continental U.S. and certain areas outside the U.S.*
- *Aircraft emissions may prevent regulatory compliance*
- *Civil GNSS receiver operation above 600 m/s (Mach 1.8) is restricted under ITAR by the U.S. Munitions List*
- *Weather can impact special materials needed at greater than Mach 4 cruise*

In addition to sufficient demand and a viable business case, the emergence of a future commercial hypersonic transportation industry depends on the elimination or mitigation of different types of barriers to success. NASA specifically asked that this study consider business, regulatory, societal, and other non-technical barriers.

These barriers are affected and shaped by the technical challenges of hypersonic flight, including high thermal loads on structures and transmitted to structures; propulsion design, testing, materials, and manufacturing; advanced avionics and overall controllability; and complex data management for automated systems as well as substantial funding and investment requirements. Table 17 summarizes unique requirements for high-speed aircraft, in the form of a concept of operations, to provide a conceptual framework for identifying and characterizing the non-technical barriers that follow.

Using the concept of operations as context, we identified significant (non-technical) barriers to a future commercial hypersonic transportation industry, characterized their potential consequences, and assessed ways to address each barrier, predicting the likely impact of different approaches. Specifically, we:

- Identified a total of 28 barriers, their consequences, and the relative impact of these consequences to emerging commercial high-speed air transportation planning and development,
- Assessed each barrier and identified types of government mitigations (by NASA and other federal agencies) that might be employed and the relative impact the mitigation might have reducing or eliminating the barrier,
- Identified seven common NASA actions to mitigate multiple barriers, and
- Mapped the impact of potential NASA actions with relative consequence of barriers identifying six priority barriers and associated mitigations.

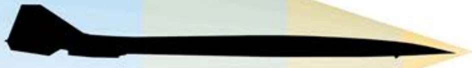
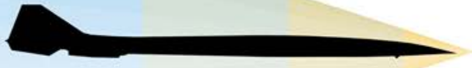


Table 17. Concept of operations reflecting unique requirements for a high-speed commercial aircraft.

Concept of Operations Level: System	
Airframe	Advanced airframe materials (nickel-based Inconel alloys, silicon-carbide ceramics, and carbon-carbon composites) are expensive, and the aircraft will require a cool-down period post-flight, requiring the identification of aircraft holding areas
Propulsion	Implementation of turbine-based combined cycle ramjet/scramjet or rocket-based combined cycle will impact development operational and maintenance capabilities and requirements
Propellant	Use of hydrogen, liquid oxygen (LOX), or other cryogenic propellants, as well as synthetic fuels, will require investment in new handling storage and transfer technologies
Emissions	Will require supporting changes to 14 CFR 34 and the Clean Air Act as well as public acceptance
Noise	Currently limited by 14 CFR 91.817 for sonic boom (any aircraft above Mach 1 over land). Note that 14 CFR 91.817 was revised in January 2021 (Amdt. 91-362, 86 FR 3792) to allow for an authorization to exceed Mach 1 under conditions and limitations. Will also require update/change to support continental travel routes (supersonic aircraft are also limited). Take-off noise may be prohibitively loud, potentially limiting operational times or locations
Autonomous Systems	Need for and implementation of fully automated flight controls with pilots only intervening under non-normal and emergency conditions
Testing	Use of special test facilities necessary for high-speed aircraft, components, and materials.
Concept of Operations Level: Airport Integration	
Runways and Taxiways	Aircraft may require increased runway lengths to support take-off and landing requirements
Terminal Interface	Commercial aircraft design, especially length, may require modification to existing terminal gate design, interfaces, and operations
Special Areas	Hypersonic aircraft may require cool-down and/or special fueling areas due to unique handling characteristics of propellants
Concept of Operations Level: National Airspace System (NAS)	
Flight Operations	Hypersonic aircraft will cruise in Upper Class E airspace (above 60,000 feet) requiring increased air traffic management capability to effectively manage exit from and entry into Class A airspace. Supersonic cruise likely to take place in high altitude Class A and lower altitude Upper Class E airspaces (55,000 – 65,000 feet)
Aircraft Ascent/ Descent	Hypersonic aircraft may require priority for decent and landing approval based on aircraft flight characteristics
Airport Size	Commercial hypersonic aircraft likely to be limited to high traffic airports managing Class B airspace. Supersonic aircraft likely to be capable of operating Class B, Class C, and possibly Class D airspaces

Identify and Catalog Barriers

The study team identified and cataloged 28 non-technical barriers to the development of a commercial hypersonic industry, grouping them into 11 categories. The barriers are summarized, in Table 18 on Page 48, and characterized in detail in Appendix 4. Each barrier is described in terms of their potential consequences and the magnitude of those consequences in terms of safety, demand, compliance, and cost using a five-point scale, with an indication of whether consequences vary significantly by vehicle configuration or fuel type.



The 28 non-technical barriers are:

1. **Runways.** Runways at desired airports may not be of sufficient length due to high landing speeds, a situation that could delay or impede supersonic and hypersonic operational planning and flights.
2. **Infrastructure.** Aircraft design and existing terminal layouts may not 1) meet the expectations of passengers paying a premium for tickets expect a high level of service and/or 2) be fully compatible with terminal clearances, runway and taxiway width, jet bridges, and other infrastructure elements.
3. **Special Maintenance, Personnel.** Complex high-speed aircraft may be more difficult to maintain, requiring special facilities and personnel knowledgeable and experienced with next generation structures, propulsion, avionics, data management, and automated computer flight systems.
4. **Pre-Flight Inspections.** Pre-flight visual inspections, or “pre-flight check,” are required by air crews prior to flight. Inspections as they are performed today may not be adequate for certain high-speed aircraft due to the unique environments these aircraft operate in. Non-destructive inspections (NDI) may be required to identify issues not visible by the naked eye.
5. **Post-Flight Cool Down.** Due to the result of kinetic heating caused by friction between the outside air and the skin of the rapidly moving aircraft the exterior structure will be extremely hot upon landing. In order to service the aircraft, the vehicle will require a standoff cool down period before it can be safely approached, and passengers and baggage safely off-loaded.
6. **Cryogenics.** Some hypersonic systems, especially those featuring a scramjet propulsion system, will require liquid hydrogen (LH2) for fuel, and possibly other cryogenic propellants, coolants, and pressurants.
7. **Air Traffic Systems.** Very high-speed aircraft may create handoff challenges and potentially safety issues (from routine tracking to wake turbulence).
8. **Type Certification.** Initially, the unique characteristics of some supersonic and all hypersonic aircraft and relative lack of statistic flight data will translate into certification delays. The very high bar set by the FAA and the aviation industry will be the standard, and environmental standards are expected to become stricter (e.g., emissions).[26]

> ***“[Certification is a] challenge, not an insurmountable barrier.’***
>
> – Developer

9. **Stability and Control.** Stability and control challenges across the operational flight envelope may increase difficulty to certify as safe, increase test program duration, and/or require more highly skilled pilots. High-speed aircraft will have to demonstrate safe and stable takeoff and landing and flight characteristics in a variety weather conditions at subsonic speeds.
10. **Extended Operations (ETOPS).** Extended-range Twin-engine Operational Performance Standards (ETOPS) for aircraft with two engines is currently 370 minutes flying time away from the nearest airport suitable for an emergency landing. This standard represents a significant barrier as high-speed aircraft will require 10-15 years of engine statistical data to support an ETOPS approach.[27]
11. **Emergency Descent and Landing.** For aircraft certified to operate above 25,000 feet, cabin pressure altitude must be less than 15,000 feet “after any probable failure condition in the pressurization system.” So for any “probable” failure, the aircraft must be able to descend to 15,000 feet before the cabin pressure is completely lost. For any failure not “extremely improbable,” the aircraft must be able to descend to 25,000 feet within 2 minutes of losing all cabin pressure.
12. **New Partial and Full Automation Requirements.** Current avionic Minimum Operating Performance Standards (MOPS) will require reevaluation and update for high-speed aircraft operations to address increased automation (e.g., simulated visual flight, complex data

> ***‘Commercial HST is most likely to fly autonomously.’***
>
> – Engineering SME

management systems, automated avionics). Current aircraft certification processes do not adequately address high-speed aircraft and engine design, testing, and certification processes and expertise.

13. **Prohibition of Overflight.** Prohibition of supersonic flight over the continental U.S. and certain areas outside the U.S. may prevent operations. Currently 14 CFR 91.817 prevents supersonic flight over the continental U.S. to prevent/eliminate sonic boom impacts (14 CFR 91.817 was updated in January 2021 to allow for operation of Mach 1 aircraft under certain conditions and limitations). Consensus on an acceptable level of noise and boom has not been reached. Current foreign government flight regulations may prevent supersonic flight over the continental U.S. to prevent/eliminate sonic boom impacts.
14. **Ground Test Equipment.** The relatively low number of supersonic and especially hypersonic engine test equipment and facilities poses a significant challenge for propulsion research.

> ***'Decarbonizing aviation industry will happen independent of high-speed aircraft, and high-speed aircraft designs will benefit from this more than anyone else.'***
>
> – Developer

15. **Noise.** High-speed aircraft will create sonic booms when transitioning from subsonic to supersonic flight. In addition, some turbojets create significant noise when using afterburners for takeoff and thrust reversers upon landing. While it is assumed that commercial super- and hypersonic aircraft will have to operate at similar noise levels as subsonic aircraft, they may generate more noise as a result of engines accelerating the aircraft at higher speeds to generate lift during takeoffs. Landing speeds may also be higher requiring greater use of thrust reversers.
16. **Emissions.** Carbon dioxide (CO_2), nitrogen oxides (NO_x), unburned hydrocarbons (UHC), and particulate emissions may prevent chemical emission compliance. Potential that high-speed aircraft using hydrocarbon fuels consume more than subsonic aircraft resulting in increased CO_2 emissions. In addition, aircraft operating above 60,000 feet using hydrocarbon fuels could potentially cause damage to the ozone layer.
17. **Hazardous Materials.** Hypersonic aircraft will likely require the use of cryogenics and other hazardous materials (beyond hydrocarbon fuels), necessitating special handling. The use of certain hazardous materials may create additional handling, transport, storage, disposal, and remediation issues and costs.
18. **ITAR Restrictions.** ITAR, Export Administration Regulations (EAR), and Missile Technology Control Regime (MTCR) may prevent international sales and export of certain technologies critical to supersonic and hypersonic systems. These may also impact operations, maintenance, and cyber security at non-U.S. facilities.
19. **GNSS Receivers.** High-speed aircraft require highly accurate GNSS receivers and supporting analytical software in order to accurately determine aircraft position. Civil GNSS receiver operation above 600 m/s (Mach 1.8) is restricted under ITAR by the U.S. Munitions List (22 CFR Part 121, Category XII (d)(2)). The sale and transfer of this technology may also be prohibited under Category 7 (Navigation and Avionics) of the EAR, as well as the MTCR.
20. **Insurance.** Obtaining insurance (hull and liability insurance, grounding insurance) for new vehicles and vehicle systems may be challenging and expensive due to historical caution experienced by underwriters with regards to new technologies and capabilities.
21. **Regulatory Timeline.** The development and approval of new regulations to support certain high-speed aircraft (especially those powered by unconventional powerplants like turboramjets, ramjets, and scramjets) will require years of dedicated effort and resources to implement.

> ***'Buyers of [our vehicle] will be among the wealthiest of the world, these folks have friends and enemies – the need for cyber defenses on these aircraft will present an ITAR issue.'***
>
> – Developer

22. **International Coordination.** International regulatory coordination has been identified as a challenge. For example, a lack of International agreement for flight operations above 60,000 feet may impede safe operations at this altitude (lack of high-speed corridors supporting safe flight 60,000+ feet above mean sea level, referred to by FAA as Upper Class E airspace operations). Another example: Noise and CO_2 emissions may prevent European Union Aviation Safety Agency (EASA) and ICAO noise and chemical emission compliance (aircraft noise and CO_2 emissions are a growing European concern). EASA follows ICAO Annex 16 Volumes I, II, and IV standards for noise and CO_2 standards. These standards continue to tighten and may become more restrictive than U.S. standards.
23. **Climate Concerns.** Increased public awareness of the environmental impact of CO_2, NO_x, UHC, and particulates emissions may create resistance to high-speed aircraft in light of human induced climate change. There is likely to be concern that high-speed aircraft using hydrocarbon-based fuels will significantly add to atmospheric CO_2, NO_x, UHC, and particulate levels adversely impacting the climate.
24. **Virtual Communications.** Virtual communications replacing certain travel may reduce demand for high-speed travel. Increased use of virtual communication tools and conferencing capabilities both internally and externally may reduce the requirement for travel and participation in face-to-face meetings.
25. **Aircraft, Parts in Quantity.** The use of exotic materials in some high-speed aircraft and specialized aircraft components will necessitate the establishment of new and scalable manufacturing capabilities and supporting supply chain in concert with aircraft development to support development, testing, delivery, and operation (including maintenance). Parts manufacturers may lack the financial resources to make the required investments in critical design and manufacturing technologies.

> ***'Advances in communications technologies, both to the cabin and to the office, are chipping away at the market for SST/HST.'***
>
> – Industry Expert

26. **Special Materials.** Weather (specifically rain erosion and effects of ice) can impact special materials (silicon-carbide, nickel-based alloys, other ceramics) needed at greater than Mach 4 cruise such as tiles (water droplets can erode delicate surfaces during high-speed flight), potentially degrading performance.
27. **Aircrews.** The introduction of high-speed aircraft will require the co-development and implementation of innovative simulation training capabilities to support the training and certification of qualified aircrews. The expectation is identifying aircrews with adequate experience (including military with experience flying high performance aircraft) but not likely to retire soon.
28. **Engineering, Manufacturing Skills.** There is a potential shortage of knowledgeable engineers and skilled manufacturers to design, build, integrate, and maintain high-speed aircraft and components.

The consequences—by type and magnitude—of each barrier are shown Table 18, and the format for characterizing each barrier is shown Table 19 on Page 49.

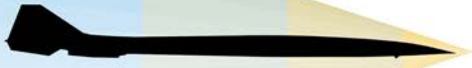


Table 18. Summary of barriers and consequences of barriers, by type and magnitude.

Barrier Category	Barrier	Magnitude of Consequence			
		Safety	Demand/ Availability	Compliance	Cost
Airport Infrastructure	1. Runway Length	☐	■■■	☐	■■■
	2. Infrastructure	☐	■■■	☐	■■■
	3. Special Maintenance, Personnel	☐	☐	■■■	■■■
	4. Pre-Flight Inspections	■■■■■	■■■	■■■	■■■
	5. Post-Flight Cool Down	■■■	■■■	☐	■■■
	6. Cryogenics	■■■	☐	■■■	■■■■■
ATM	7. Air Traffic Systems	■■■	☐	■■■	■■■
Certification (U.S.)	8. Type Certification	■■■■■	■■■	■■■■■	■■■■■
	9. Stability and Control	■■■■■	☐	■■■■■	■■■■■
	10. Extended Operations (ETOPS)	☐	■■	■■	■■■
	11. Emergency Descent and Landing	☐	☐	■■■	■■■
	12. New Partial and Full Automation Requirements	☐	☐	■■■■■	■■■■■
	13. Prohibition of Overflight	■■■	■■■■■	■■■	■■■■
	14. Ground Test Equipment	■■■	☐	■■■■	■■■■
Environmental Impacts	15. Noise	■■■	■■■	■■■	■■■
	16. Emissions	■■■■■	■■■	■■■	■■■
	17. Hazardous Materials	☐	☐	■■■	■■■■■
Export Control	18. ITAR Restrictions	■	■■■■■	■■■■■	■■■■■
	19. GNSS Receivers	■	■■■■■	■■■■■	■■■■■
Insurance	20. Insurance	☐	■■	☐	■■■
International Legal and Regulatory	21. Regulatory Timeline	☐	■	■■	■■■
	22. International Coordination	■■■	☐	■■■	■■■
Societal	23. Climate Concerns	☐	■■■	☐	☐
	24. Virtual Communications	☐	■■	☐	☐
Supply Chain	25. Aircraft, Parts in Quantity	☐	■■■	☐	■■■■
Weather	26. Special Materials	■■■■■	☐	■■■■■	■■■■■
Workforce	27. Aircrews	■■■■■	■■■	■■■■■	■■■
	28. Engineering, Manufacturing Skills	☐	☐	■■■	■■■

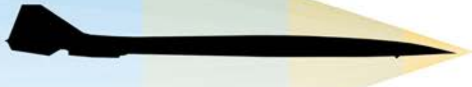


Table 19. *Format for characterization of each barrier (see Appendix).*

Barrier Description				
Brief description of barrier **Consequence(s):** Identification of perceived and/or actual consequences of this barrier to commercial high-speed air transportation				
Consequences				
Assessment				**Magnitude**
Safety	Explanation to support relative magnitude of barrier to safe operations of commercial high-speed air transportation. How does the barrier impact the safe operations of commercial high-speed air transportation?			*(See key below)*
Demand/Availability	Explanation to support relative magnitude of barrier in terms of its potential impact to commercial high-speed air transportation market demand. How does the barrier impact market demand for commercial high-speed air transportation?			*(See key below)*
Compliance	Explanation to support relative magnitude of barrier in terms of regulatory compliance. How does the barrier impact regulatory compliance?			*(See key below)*
Cost	Explanation to support relative magnitude of barrier in terms of costs. How does the barrier impact costs across the life cycle of commercial high-speed air transportation?			*(See key below)*
Relevance by Vehicle Configuration and Fuel Type				
Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
(Check as applies)	*(Check as applies)*	*(Check as applies)*	*(Check as applies)*	*(Check as applies)*

Key for Tables 18 and 20	
■■■■■	Significant public and/or passenger issues/concerns exist that are difficult to correct and if not fully corrected or mitigated, will likely prevent the program or solution from being approved or implemented
■■■	Few public and/or passenger issues/concerns exist but can be fully or partially mitigated to an extent that allows the program to continue or proceed
■	Minor public and/or passenger issues/concerns exist that require partial or no mitigation for the program to proceed
□	No consequences were identified

Barrier Mitigation

The study identified government actions that could mitigate these barriers and categorized those actions by type and by actor (that is, who would likely be responsible for completing the mitigation, such as NASA or another government agency). Past government actions to mitigate aerospace-related industry barriers largely fall into three categories: policies, financial resources, and programs. Policies have included overarching national policies, favoring domestic industry, third-party indemnification, informed consent, enabling public input, intra-government engagement, government-private industry partnerships, and government promotion of an industry. Examples of financial resources include tax incentives, direct financial resources (subsidies), export credit agency financing, and infrastructure support and advisory services. Finally, programs have included development programs (contract vehicles, for example), commercial off-the-shelf (COTS) purchases, grants, and contests and prizes.

Finally, the study assessed the benefits of different mitigation actions, in terms of probability of effectiveness and cost, and used this assessment to rank mitigations.

Table 20 shows the format used to capture mitigations for each barrier. Table 21 summarizes barriers and mitigations.

Table 20. Format for characterization of mitigations of each barrier (see Appendix).

Mitigation Types	Mitigation type from "Types of Government Mitigation Actions"	**NASA Level of Effort**	Priority to commercial high-speed air transportation stakeholders by high, moderate, or low, with supporting statement
NASA Mitigations	Brief description of the nature of NASA's mitigation		
	Impact of NASA Mitigation		Discussion
	Significant Impact	*(check if applicable)*	Explanation and source(s), as appropriate, to support relative magnitude of recommended mitigation in terms of impact to barrier being addressed
	Moderate Impact	*(check if applicable)*	
	Limited Impact	*(check if applicable)*	
Primary Implimenter	Primary entity with authority and/or capability to implement mitigation	**Other Key Actors**	Supporting entities, if necessary, with authority and/or capability to implement mitigation

Table 21. Impact of mitigations, by barrier.

Barrier	**Magnitude of Consequence** *(see key on Page 57)*				**Potential NASA Mitigation Actions** *(see footnote under table)*							**Impact of NASA Mitigation**			**NASA LOE**
	Safety	**Demand/ Availability**	**Compliance**	**Cost**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	*****	******	*******	
1. Runway Length	□	■■■	□	■■■	✓		✓			✓		✓			LOW
2. Infrastructure	□	■■■	□	■■■			✓			✓		✓			LOW
3. Special Maintenance, Personnel	□	□	■■■	■■■	✓	✓			✓				✓		MOD
4. Pre-Flight Inspections	■■■■	■■■	■■■	■■■			✓			✓		✓			MOD
5. Post-Flight Cool Down	■■■	■■■	□	■■■			✓			✓		✓			LOW
6. Cryogenics	■■■	□	■■■	■■■■■			✓	✓		✓			✓		MOD
7. Air Traffic Systems	■■■	□	■■■	■■■	✓		✓	✓		✓				✓	MOD
8. Type Certification	■■■■	■■■	■■■■■	■■■■■	✓	✓	✓		✓	✓	✓			✓	HIGH
9. Stability and Control	■■■■	□	■■■■■	■■■■■	✓	✓					✓			✓	HIGH
10. Extended Operations (ETOPS)	□	■■	■■	■■■	✓	✓			✓		✓			✓	HIGH
11. Emergency Descent and Landing	□	□	■■■	■■■	✓				✓		✓			✓	HIGH
12. New Partial and Full Automation Requirements	□	□	■■■■■	■■■■■			✓						✓		LOW
13. Prohibition of Overflight	■■■	■■■■■	■■■	■■■■			✓		✓	✓				✓	HIGH
14. Ground Test Equipment	■■■	□	■■■■	■■■■	✓	✓	✓							✓	HIGH
15. Noise	■■■	■■■	■■■	■■■			✓	✓	✓					✓	MOD
16. Emissions	■■■■	■■■	■■■	■■■	✓		✓			✓	✓			✓	HIGH
17. Hazardous Materials	□	□	■■■	■■■■■			✓		✓	✓			✓		LOW
18. ITAR Restrictions	■	■■■■■	■■■■■	■■■■■			✓		✓	✓			✓		LOW
19. GNSS Receivers	■	■■■■■	■■■■■	■■■■■			✓	✓	✓					✓	MOD
20. Insurance	□	■■	□	■■■	✓					✓			✓		LOW
21. Regulatory Timeline	□	■	■■	■■■			✓	✓					✓		LOW
22. International Coordination	■■■	□	■■■	■■■			✓						✓		LOW
23. Climate Concerns	□	■■■	□	□	✓		✓	✓					✓		MOD
24. Virtual Communications	□	■■	□	□			✓		✓			✓			LOW
25. Aircraft, Parts in Quantity	□	■■■	□	■■■■		✓		✓	✓				✓		MOD
26. Special Materials	■■■■	□	■■■■■	■■■■■	✓	✓	✓		✓		✓			✓	HIGH
27. Aircrews	■■■■	■■■	■■■■■	■■■	✓	✓			✓		✓		✓		MOD
28. Engineering, Manufacturing Skills	□	□	■■■	■■■	✓	✓	✓		✓		✓			✓	MOD

Key to Potential NASA Mitigation Actions: A = Modeling and Simulation Development; B = Test and Evaluation Support; C = Interagency, International, and Industry Facilitation and Coordination; D = Technical and Analytical Expertise; E = System Design and Development; F = Studies and Analysis Support; and G = Software Development.

Proposed NASA Mitigation Actions by Type of Mitigation and Barrier Group

For each barrier, between three and six mitigation actions were identified. Considering the full range of mitigation actions identified, potential NASA actions can be grouped into seven categories:

- **Modeling and Simulation**, or the development and execution of operationally based simulations and/or models to gather needed data to reduce and augment actual flight hours.
- **Test and Evaluation**, which includes the planning, development, and implementation of software and hardware assessment, and testing and evaluation as a component of a comprehensive R&D program, such as the use of facilities (wind tunnels, etc.)
- **Interagency, International, and Industry Facilitation and Coordination**, involving the planning, facilitation and implementation of briefings, meetings, working groups or product teams to identify issues/challenges and to develop and coordinate effective and timely solution.
- **Technical and Analytical Expertise**, with NASA providing individual or team expertise to support the planning, development, and execution of other government or industry R&D efforts.
- **System Design and Development** to support the design, develop and assess critical capabilities, components or systems to support government or industry R&D programs.
- **Studies and Analysis Support**, including the planning and implementation of R&D technology reviews, scientific studies related to high-speed aircraft design and operations and analysis of complex technical or engineering challenges, processes or methodologies.
- **Software Development**, including the development, modification, assessment, validation and verification of software to support the development, analysis, or assessment of high-speed aircraft design, technology or operations in complex environments.

Table 22. NASA mitigation action type by barrier type.

Barrier Category	Modeling and Simulation Development	Test and Evaluation Support	Interagency, International, and Industry Facilitation and Coordination	Technical and Analytical Expertise	System Design and Development	Studies and Analysis Support	Software Development
Airport Infrastructure	✓	✓	✓	✓	✓	✓	
Air Traffic Management	✓		✓	✓		✓	
Certification	✓	✓	✓	✓	✓	✓	✓
Environmental Impacts	✓		✓	✓	✓	✓	✓
Export Control			✓	✓	✓	✓	
Insurance	✓					✓	
Legal and Regulatory			✓	✓			
Societal	✓		✓	✓		✓	
Supply Chain		✓		✓	✓		
Weather	✓	✓	✓		✓		✓
Workforce	✓	✓	✓		✓		✓

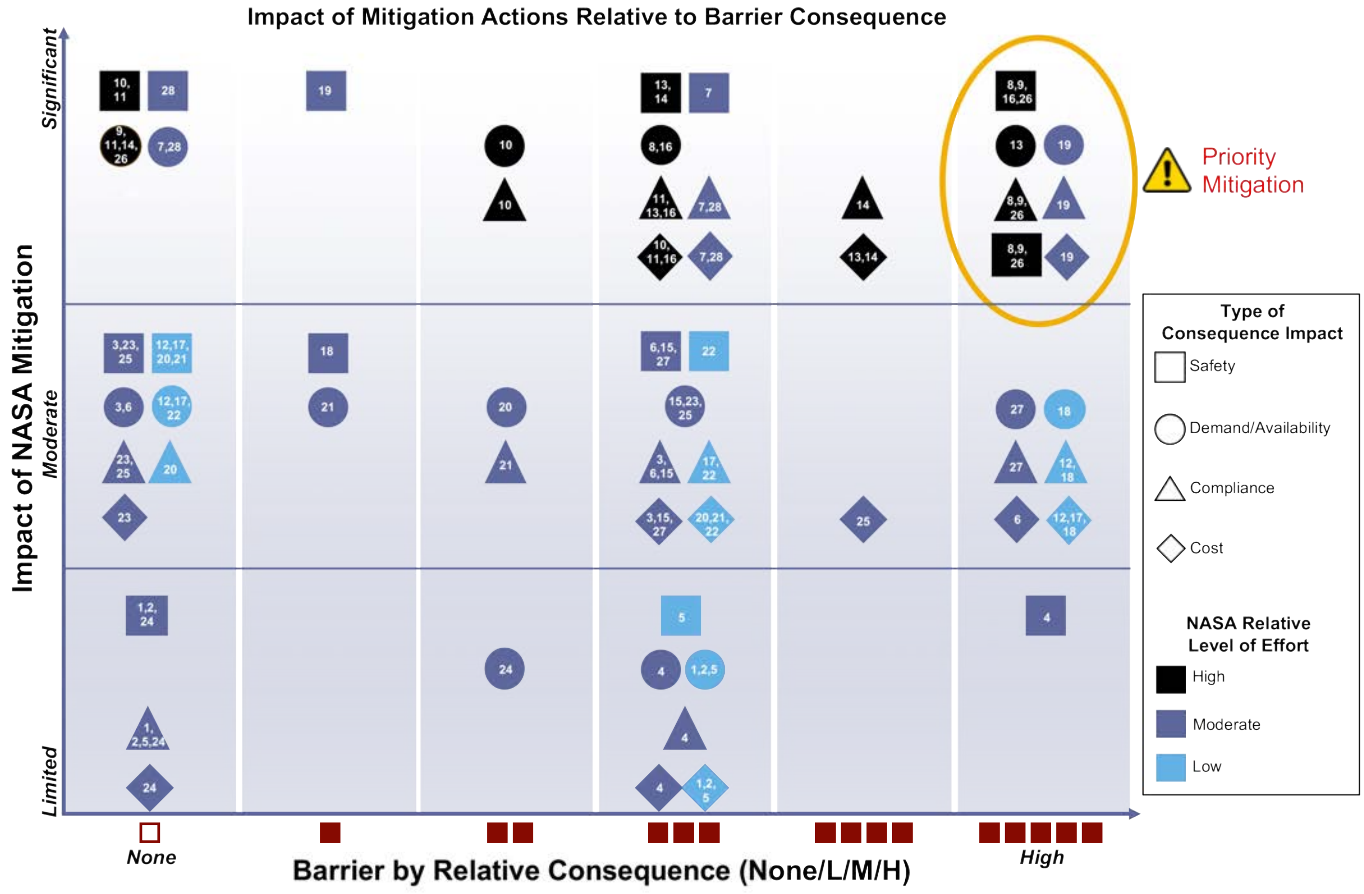
These actions are mapped to the categories of barrier, shown in Table 22. Specific mitigations for each barrier in each category are shown in Appendix 4.

Prioritize Barriers Based on Consequence of Barrier and Impact of Mitigation

Finally, the analysis selected the top barriers and prioritized six, based on the consequences of each barrier and the potential impact of mitigation, ranking most highly those barriers with high consequences where mitigation actions would have a significant impact. The mapping is shown in Figure 25.

- **Barrier 8: Type Certification.** Type certification during a time when safety standards and environmental compliance trends are tightening presents a significant challenge.
- **Barrier 9: Stability and Control.** Aircraft designed to fly at high Mach regimes across all weather conditions may be less stable and be more difficult to certify as safe, increase test program duration, and/or require more highly skilled pilots.
- **Barrier 13: Prohibition of Overflight.** Prohibition of supersonic flight over the continental U.S. and certain areas outside the U.S. may prevent operations.
- **Barrier 16: Emissions.** Emissions (CO_2, NO_x, UHC, and particulates) may prevent chemical emission compliance, especially at high altitudes.

Figure 25. Mapping of barriers by consequences and potential impact of mitigation. The numbers in the shapes represent the barriers themselves, number 1 through 28.



- **Barrier 19: GNSS Receivers.** ITAR restricts sale of GNSS receivers capable of providing navigational accuracy for aircraft exceeding 600 m/s (Mach 1.8), per 22 CFR Part 121 of the U.S. Munitions List.
- **Barrier 26: Special Materials.** Weather can impact special materials needed at greater than Mach 4 cruise such as tiles, potentially degrading performance. In addition, de-icing systems and/or ground support present related challenges. The availability of test facilities is an associated challenge.

The mitigation actions identified for these high priority barriers are discussed here; detail on mitigation actions for all barriers can be found in Appendix 4.

Barrier 8. Type certification during a time when safety standards and environmental compliance trends are tightening presents a significant challenge. Initially, the unique characteristics of some supersonic and all hypersonic aircraft, combined with the relative lack of statistical flight data will translate into certification delays. In addition, certification involves the maintenance plans the cover the life of the aircraft. The very high bar set by the FAA and the aviation industry will be the standard, and environmental standards, especially as they relate to emissions, are expected to become stricter.

The FAA would be the primary implementor of actions to mitigate this barrier. FAA issues and enforces regulations for the safety of civil aviation via certification, inspection, and other measures. In addition, FAA conducts RDT&E on systems and procedures needed for a safe and efficient system of air navigation and air traffic control (better aircraft, engines, and equipment; testing and evaluation of aviation systems, devices, materials, and procedures; and aeromedical research). The Environmental Protection Agency (EPA) and industry are also key stakeholders.

The FAA can leverage NASA expertise and capabilities to develop and implement aircraft flight simulations and testing across varied weather and environmental conditions and cruising altitudes. These mitigation actions would require a relatively high degree of NASA effort. Specifically, NASA can support FAA, by:

- Facilitating working groups to support the FAA, airport authorities, and aircraft developers and operators to assist in informing industry on FAA certification processes, procedures, and requirements;
- Providing modeling and analysis capabilities to the FAA to support the development; verification, validation, and accreditation (VV&A); and implementation of advanced simulation to help reduce certification delays,
- Making NASA test facilities available to industry to support the development of high-speed commercial aircraft; and
- Working closely with developers, providing technical expertise in the development of cleaner propulsion systems and fuels supporting safety capabilities.

Barrier 9. Aircraft designed to fly at high Mach regimes across all weather conditions may be less stable at lower speeds and be more difficult to certify as safe, increase test program duration, and/or require more highly skilled pilots. As above, FAA would be the primary implementor of actions to mitigate this barrier, in its regulatory role for civil aviation. Industry is also a key stakeholder.

The FAA can leverage NASA expertise and capabilities (including test facilities and equipment) in developing advanced modeling and simulation to support the analysis of low-speed flight characteristics in a wide variety of weather and environmental conditions early in the design process to significantly reduce actual flight time requirement. Mitigation actions would require a relatively high degree of NASA effort. Specifically, NASA can provide technical expertise and modeling and simulation to FAA and developers to investigate the development; Verification, Validation and Accreditation (VV&A); and implementation of subsonic, trans-sonic, supersonic, and hypersonic flight characteristics across a wide variety of weather and environmental conditions.

Barrier 13. Prohibition of supersonic flight over the continental U.S. and certain areas outside the U.S. may prevent operations. As above, FAA would be the primary implementor of actions to mitigate this barrier, in its regulatory role for civil aviation. The FAA globally conducts certain functions for safety in and outside the U.S., such as performing air traffic control handoffs, assessing whether a foreign civil aviation authority complies with international aviation standards, inspecting repair stations, and conducting oversight of navigation infrastructures. Industry is also a key stakeholder.

NASA could further offer a next tier of research in boundary layer and sonic boom research specific to the planned Mach range. The implementation of NASA's sonic boom reduction technologies and the FAA leveraging NASA technical expertise may significantly reduce certification barriers. Mitigation actions would require a relatively high degree of NASA effort. Specifically, NASA can:

- Continue to pursue sonic boom reduction technologies and social science experiments to determine the acceptable level of noise and sonic boom,
- Facilitate working groups for the FAA to identify and support updates to relevant 14 CFR chapters to support super- and hypersonic aircraft certification and to establish reasonable target noise levels that engine and airframe manufactures can work towards, and
- Facilitate working groups for the FAA, along with the Department of State and industry, to identify potential foreign regulation requirements potential issues and impediments, develop mitigation strategies, and pursue appropriate treaty/regulation adjustments.

Barrier 16: Emissions (CO_2, NO_x, UHC, and particulates) may prevent chemical emission compliance. As above, FAA would be the primary implementor of actions to mitigate this barrier, through its conduct of RDT&E on air systems. EPA and industry are also key stakeholders.

NASA's technical expertise and modeling capabilities will provide the FAA, EPA and industry significant environmental analytical support of alternative fuels and support industry in the modeling of those fuels impacts on propulsion system performance and potential environmental impacts. High-speed aircraft will be required to adhere to the Clean Air Act of 1963, Title II Part B, covering aircraft emissions and it adopts ICAO standards. The EPA sets emissions certification requirements. For any hydrocarbon-based fuels, it matters where the emissions are produced. Above 55,000 feet, the emissions will reside in atmosphere for extended period of time, presenting a functional barrier for some aircraft concepts. Mitigation actions would require a relatively high degree of NASA effort. Specifically, NASA can:

- Continue to work on cleaner burning engine technologies or emission mitigation techniques, providing technical expertise to the FAA and industry in the development of alternative fuel solutions to reduce CO_2 and other greenhouse gases, and
- Provide technical expertise and infrastructure to industry to develop supporting modeling to evaluate various non-hydrocarbon fuels emissions against propulsion system performance.

Barrier 19. ITAR restricts sale of GNSS receivers capable of providing navigational accuracy for aircraft exceeding 600 m/s (Mach 1.8), per 22 CFR Part 121 (U.S. Munitions List). Industry will likely be the lead to establish early coordination with the State Department's Directorate of Defense Trade Controls (DDTC) and the Department of Commerce to determine if GNSS receivers are an export restricted technology. FAA, DOD, and NASA are also key stakeholders. NASA can assist in the identification or development of alternative solutions, requiring a moderate level of effort. NASA can:

- Facilitate and coordinate meetings between industry and the State Department's DDTC and DOD early in the development cycle to identify potentially restricted technologies,
- Facilitate working groups with the DOD to identify/determine which DOD technologies would be helpful for industry to leverage and that would not represent ITAR challenges,
- Support industry in the RDT&E of alternative critical engine, avionics, and computer flight management systems to replace restricted components, and
- Work with industry to leverage the Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR), and grant programs to develop innovative alternative technologies.

Barrier 26. Weather can impact special materials needed at greater than Mach 4 cruise such as tiles, potentially degrading performance; de-icing systems and/or ground support. NASA's Aeronautics Research Mission Directorate (ARMD) is focused on the design, development, and testing of advanced technologies that can make aviation more environmentally friendly, maintain safety in more crowded skies, and ultimately modernize the aviation industry. NASA leadership, operational, and technical expertise will be critical to the development of effective assessment capabilities and processes and the development of supporting modeling and simulation environments. Industry is also a key stakeholder.

Additional mitigation actions NASA can undertake, requiring a relatively high level of effort, include efforts to:

- Provide technical assistance to perform testing/assessment of special material (for example, silicon carbide composites, nickel-based alloys, and carbon composites) performance in actual flight, in high-speed test chambers, and environmental chambers,
- Develop advanced simulations to evaluate the performance of special materials under a variety of environmental conditions reducing actual flight time and expensive chamber time, and
- Work with industry to leverage SBIR, STTR, and grant programs to support the development of innovative assessment capabilities and processes to accommodate special materials.

Actions to Consider

The study identified outcomes that would increase available R&D and reduce barriers to the development of the commercial high-speed air transportation industry, including improving performance and reducing costs, coordinating with government regulators and providing them with expertise, and working with industry. Based on this analysis, NASA should consider activities to improve performance and reduce costs, such as:

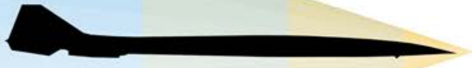
- Improving fuel efficiency,
- Improving maintainability to reduce cost of servicing and inspection,
- Reducing manufacturing costs at of high-speed aircraft, and
- Reducing/eliminating required cool down time for refueling and deplaning.

To reduce regulatory and other barriers to the development of commercial high-speed air transportation, NASA should consider facilitating working groups (FAA, State, DOD, airport authorities, industry) to address certification, environmental, and other regulatory barriers. Providing NASA expertise and modeling and simulation to the FAA regarding the performance of critical technologies across a variety of environment conditions can reduce certification delays. Continued sonic boom reduction technology development, through NASA programs such as Low Boom Flight Demonstration, and societal assessments of the issues and consequences relating to takeoff noise and boom are also important. Finally, NASA's continued work with industry to leverage government programs on innovative alternative capabilities, technologies, and processes can reduce barriers and facilitate industry growth.

Figure 26. Actions to consider.

Checklist of Actions

- ✓ *Improve fuel efficiency*
- ✓ *Improve maintainability to reduce cost of servicing and inspection*
- ✓ *Reduce manufacturing costs*
- ✓ *Reduce/eliminate required vehicle cool down time post flight*
- ✓ *Reduce regulatory and other barriers to development of commercial high-speed air transportation*
- ✓ *Continue sonic boom reduction technology development*
- ✓ *Continue leverage of government programs supporting industry innovation designed to reduce barriers to entry and growth*



Endnotes

[1] Federal Aviation Administration, *Terminal Area Forecast Summary*, FY 2016 - 2045.

[2] Eurostat, *Air Transport Forecast*, 2017.

[3] International Civil Aviation Organization, Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis, 7 Jan 2021.

[4] International Air Transportation Association, *COVID-19: Slow Expansion of Air Travel in July*, 1 September 2020.

[5] Airlines for America, *Tracking Impacts of COVID-19*, Updated 13 March 2021.

[6] International Air Transportation Association, Economics Chart of the Week: Five years to return to pre-pandemic level of passenger demand, 30 July 2020.

[7] International Civil Aviation Organization, *Forecast of Scheduled Passenger and Freight Traffic*, 2019, https://www.icao.int/sustainability/Pages/eap-fp-forecast-scheduled-passenger-traffic.aspx.

[8] International Air Transportation Association, *World Air Transportation Statistics 2019*.

[9] U.S Department of Transportation,*The Value of Travel Time Savings: Departmental Guidance for Conducting Economic Evaluations Revision 2* (2016 Update).

[10] Credit Suisse, *Global Wealth Report and Databook 2019*.

[11] Knight Frank, *The Wealth Report: The Global Perspective on Prime Property and Investment*.

[12] KKR Global Institute, The Wisdom of Compoundiing Capital, 2021. https://www.kkr.com/sites/default/files/The_Wisdom_of_Compounding_Capital_20210202.pdf.

[13] WealthX, *Global Wealth Outlook*, 2018.

[14] Gallup, *U.S. Workers Discovering Affinity for Remote Work*, 3 April 2020.

[15] OECD, *ITF Transport Outlook 2019*.

[16] Trondent Development Corporation, *Business Travel by the Numbers*, October 2020.

[17] ICAO, *Airline Operating Costs and Productivity*, February 2017.

[18] Oliver Wyman, *Airline Economic Analysis*, 26 April 2019.

[19] Institute of Transport Economics and Logistics, *Viability of the Premium Airline Business Model*, 7 November 2007.

[20] German Aerospace Center, *Market Environment for Supersonic Business Jets*, January 2011.

[21] ICCT, *Environmental Performance of Emerging Supersonic Transport Aircraft*, 17 July 2018.

[22] PIT, *Direct Operating Costs Estimation of a Hypersonic Point-to-Point Vehicle*, March 2018.

[23] Flight Global Archive, *Concorde and 747*, 5 October 1972.

[24] AIAA, *High Capacity Short Range Transport Aircraft*, 14 May 2020.

[25] IATA, *Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency*, June 2012.

[26] In the U.S., FAA provides requirments for type certification, production certification, and airworthiness certification in 14 CFR Part 21.

[27] ETOPS requirements are described for in 14 CFR Part 121 and Part 135 operations.

Acronyms

5G	Fifth generation mobile network
ADS-B	Automatic dependent surveillance–broadcast
AIAA	American Institute of Aeronautics and Astronautics
ARMD	Aeronautics Research Mission Directorate
AST	Office of Commercial Space Transportation
ATM	Air Traffic Management
CER	Cost estimating relationship
CFR	Code of Federal Regulations
CO2	Carbon dixoide
COTS	Commercial off-the-shelf
COVID-19	Coronavirus disease 2019
DARPA	Defense Advanced Research Projects Agency
DDTC	Directorate of Defense Trade Controls
DOD	Department of Defense
DOT	Department of Transportation
EAR	Export Administration Regulations
EASA	European Union Aviation Safety Agency
EPA	Environmental Protection Agency
ETOPS	Extended-range Twin-engine Operational Performance Standards
EU	European Union
FAA	Federal Aviation Administration
FR	Federal Register
GNSS	Global navigation satellite system
HEOMD	Human Exploration and Operations Mission Directorate
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IRS	Internal Revenue Service
ITAR	International Traffic in Arms Regulations
JAXA	Japan Aerospace Exploration Agency
LH2	Liquid hydrogen
LOX	Liquid oxygen
MOPS	Minimum Operating Performance Standards
MTCR	Missile Technology Control Regime
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NDI	Non-destructive inspections

NOx	Nitrogen oxides
NPV	Net present value
PIT	Polytechnic Institute of Turin
R&D	Research and development
RCS	Reaction control system
RDT&E	Research, development, test, and evaluation
ROM	Rough order of magnitude
SBIR	Small Business Innovation Research
SEC	Securities and Exchange Commission
SME	Subject Matter Expert
STTR	Small Business Technology Transfer
TSO	Technical Standard Orders
TTO	Tactical Technology Office
UAM	Urban air mobility
UAT	Universal Access Transceiver
UHC	Unburned hydrocarbons
UK	United Kingdom
U.S.	United States
USAF	U.S. Air Force
VTTS	Value of travel time saved
VV&A	Verification, Validation and Accreditation
WWII	World War II

Appendix 1: Analysis Results by Case

Table A1.1. Case 1 analysis results – commercial aviation.

Passengers on Viable Routes (M)						
	2030	2035	2040	2045	2050	2055
1.5X Fare	5.0	6.1	7.3	8.8	10.5	12.7
2.5X Fare	0.2	0.3	0.5	0.6	0.9	1.2
5X Fare	0.0	0.1	0.1	0.1	0.2	0.2
10X Fare	0.0	0.0	0.0	0.0	0.0	0.0
Revenue on Viable Routes ($B)						
	2030	2035	2040	2045	2050	2055
1.5X Fare	$28.6	$35.3	$41.9	$50.4	$60.0	$72.2
2.5X Fare	$2.2	$2.9	$4.5	$5.5	$7.8	$10.6
5X Fare	$1.0	$1.4	$1.6	$2.1	$3.1	$4.1
10X Fare	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Number of Viable Routes						
	2030	2035	2040	2045	2050	2055
1.5X Fare	180	219	241	272	296	335
2.5X Fare	23	27	42	46	64	83
5X Fare	10	15	15	19	29	38
10X Fare	0	0	0	0	0	0
Fleet Required						
	2030	2035	2040	2045	2050	2055
1.5X Fare	130	159	192	231	278	335
2.5X Fare	10	12	20	23	31	43
5X Fare	4	6	6	8	12	17
10x fare	3,240	13,127	15,001	21,684	46,305	89,918

Table A1.2. Case 1 analysis results – general aviation.

Passengers on Viable Routes (M)						
	2030	2035	2040	2045	2050	2055
1.5X Fare	0.2	0.3	0.3	0.4	0.5	0.6
2.5X Fare	0.3	0.3	0.3	0.4	0.4	0.5
5X Fare	0.0	0.0	0.0	0.0	0.0	0.0
10X Fare	0.0	0.0	0.0	0.0	0.0	0.0
Revenue on Viable Routes ($B)						
	2030	2035	2040	2045	2050	2055
1.5X Fare	$7.0	$8.3	$9.8	$11.8	$14.2	$16.9
2.5X Fare	$7.6	$8.6	$9.8	$11.1	$12.7	$14.5
5X Fare	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
10X Fare	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Number of Viable Routes						
	2030	2035	2040	2045	2050	2055
1.5X Fare	166	168	172	173	173	175
2.5X Fare	299	301	305	306	311	314
5X Fare	1	1	2	4	6	9
10X Fare	0	0	0	0	0	0
Fleet Required						
	2030	2035	2040	2045	2050	2055
1.5X Fare	63	74	88	105	126	150
2.5X Fare	69	79	89	102	117	133
5X Fare	1	1	1	1	1	1
10X Fare	0	0	0	0	0	0

Table A1.3. Case 2 analysis results – commercial aviation.

Passengers on Viable Routes (M)						
	2030	2035	2040	2045	2050	2055
1.5X Fare	5.6	6.8	8.1	9.7	11.6	13.9
2.5X Fare	0.3	0.4	0.6	0.8	1.0	1.4
5X Fare	0.1	0.1	0.2	0.2	0.3	0.4
10X Fare	0.0	0.0	0.0	0.1	0.1	0.2
Revenue on Viable Routes ($B)						
	2030	2035	2040	2045	2050	2055
1.5X Fare	$37.9	$45.6	$54.4	$65.1	$78.0	$93.4
2.5X Fare	$3.2	$4.2	$5.9	$7.6	$10.0	$13.3
5X Fare	$2.0	$2.4	$3.4	$4.3	$5.5	$7.1
10X Fare	$0.2	$0.5	$0.8	$1.1	$2.0	$3.8
Number of Viable Routes						
	2030	2035	2040	2045	2050	2055
1.5X Fare	184	209	228	249	277	308
2.5X Fare	25	31	42	49	61	75
5X Fare	16	19	26	30	36	44
10X Fare	2	5	7	9	16	27
Fleet Required						
	2030	2035	2040	2045	2050	2055
1.5X Fare	97	128	152	182	218	261
2.5X Fare	8	10	15	17	23	31
5X Fare	5	6	8	9	12	16
10X Fare	1	2	3	3	6	11

Table A1.4. Case 2 analysis results – general aviation.

Passengers on Viable Routes (M)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	0.2	0.3	0.3	0.4	0.5	0.6
2.5X Fare	0.4	0.5	0.5	0.6	0.7	0.8
5X Fare	0.0	0.0	0.0	0.0	0.0	0.0
10X Fare	0.0	0.0	0.0	0.0	0.0	0.0
Revenue on Viable Routes ($B)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	$7.1	$8.5	$10.3	$12.5	$15.1	$18.2
2.5X Fare	$14.6	$16.5	$18.7	$21.3	$24.2	$27.4
5X Fare	$0.0	$0.0	$0.0	$0.1	$0.1	$0.1
10X Fare	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Number of Viable Routes						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	109	113	114	114	116	118
2.5X Fare	368	374	374	375	379	383
5X Fare	2	3	5	8	8	8
10X Fare	0	1	2	3	5	9
Fleet Required						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	44	53	64	78	94	113
2.5X Fare	82	92	105	119	135	153
5X Fare	1	1	1	1	1	1
10X Fare	0	1	1	1	1	1

Table A1.5. Case 3 analysis results – commercial aviation.

Passengers on Viable Routes (M)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	5.6	6.6	7.9	9.3	11.1	13.2
2.5X Fare	0.4	0.6	0.9	1.2	1.5	2.1
5X Fare	0.1	0.2	0.3	0.4	0.5	0.7
10X Fare	0.0	0.1	0.1	0.2	0.2	0.4
Revenue on Viable Routes ($B)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	$40.2	$47.3	$56.4	$67.2	$80.1	$95.4
2.5X Fare	$4.5	$6.2	$8.9	$11.7	$15.5	$20.4
5X Fare	$2.9	$3.6	$4.9	$6.5	$8.5	$11.3
10X Fare	$0.9	$1.4	$2.4	$3.7	$5.7	$8.9
Number of Viable Routes						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	153	162	177	194	212	233
2.5X Fare	25	34	50	63	79	99
5X Fare	20	23	29	36	45	56
10X Fare	8	11	19	28	41	61
Fleet Required						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	73	103	122	145	172	205
2.5X Fare	7	10	16	22	29	39
5X Fare	5	6	8	11	15	20
10X Fare	2	3	5	9	14	22

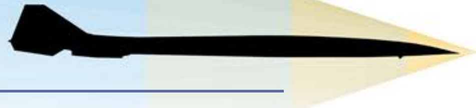


Table A1.6. Case 3 analysis results – general aviation.

Passengers on Viable Routes (M)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	0.2	0.3	0.3	0.4	0.5	0.6
2.5X Fare	0.3	0.4	0.4	0.5	0.6	0.6
5X Fare	0.2	0.2	0.2	0.3	0.3	0.3
10X Fare	0.0	0.0	0.0	0.0	0.0	0.0
Revenue on Viable Routes ($B)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	$6.7	$8.3	$10.2	$12.5	$15.4	$18.8
2.5X Fare	$12.7	$14.5	$16.6	$18.9	$21.5	$24.5
5X Fare	$7.5	$8.8	$10.4	$12.3	$14.5	$17.0
10X Fare	$0.0	$0.0	$0.0	$0.0	$0.1	$0.3
Number of Viable Routes						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	72	72	72	73	74	74
2.5X Fare	237	238	238	240	243	245
5X Fare	135	136	140	142	144	146
10X Fare	1	2	4	8	16	32
Fleet Required						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	34	42	52	64	79	97
2.5X Fare	55	63	72	81	93	105
5X Fare	25	30	35	42	49	58
10X Fare	1	1	1	1	1	1

Table A1.7. Case 4 analysis results – commercial aviation.

Passengers on Viable Routes (M)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	3.8	4.6	5.5	6.6	8.0	9.6
2.5X Fare	0.4	0.5	0.7	0.9	1.1	1.4
5X Fare	0.2	0.2	0.3	0.4	0.6	0.8
10X Fare	0.0	0.0	0.1	0.2	0.3	0.7
Revenue on Viable Routes ($B)						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	$31.3	$38.0	$46.1	$55.9	$67.8	$82.3
2.5X Fare	$4.9	$6.2	$7.9	$10.0	$12.8	$16.3
5X Fare	$3.3	$4.1	$5.6	$7.9	$11.0	$15.3
10X Fare	$0.6	$1.1	$1.9	$3.2	$5.5	$9.3
Number of Viable Routes						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	75	85	96	108	121	136
2.5X Fare	21	24	28	33	38	44
5X Fare	20	21	23	26	28	32
10X Fare	4	8	10	13	17	21
Fleet Required						
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	50	63	76	91	110	132
2.5X Fare	5	8	10	13	17	21
5X Fare	5	5	7	10	14	19
10X Fare	1	2	4	7	14	28

Table A1.8. Case 4 analysis results – general aviation.

	Passengers on Viable Routes (M)					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	0.0	0.0	0.0	0.0	0.0	0.1
2.5X Fare	0.2	0.2	0.3	0.3	0.4	0.4
5X Fare	0.0	0.1	0.1	0.1	0.1	0.1
10X Fare	0.0	0.0	0.0	0.0	0.0	0.0
	Revenue on Viable Routes ($B)					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	$1.2	$1.4	$1.6	$1.9	$2.1	$2.5
2.5X Fare	$9.1	$10.5	$12.0	$13.7	$15.7	$18.0
5X Fare	$1.9	$2.3	$2.8	$3.3	$4.0	$4.7
10X Fare	$0.0	$0.0	$0.0	$0.0	$0.1	$0.2
	Number of Viable Routes					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	17	17	17	18	18	18
2.5X Fare	99	99	100	101	102	103
5X Fare	43	45	46	47	47	48
10X Fare	2	3	4	5	7	9
	Fleet Required					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	4	4	5	6	7	8
2.5X Fare	30	35	40	46	52	60
5X Fare	7	8	10	11	13	16
10X Fare	1	1	1	1	1	1

Table A1.9. Case 5 analysis results – commercial aviation.

	Passengers on Viable Routes (M)					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	3.4	4.1	5.0	6.1	7.4	9.0
2.5X Fare	0.4	0.6	0.7	0.8	1.0	1.3
5X Fare	0.1	0.2	0.4	0.6	0.9	1.4
10X Fare	0.0	0.0	0.0	0.1	0.1	0.2
	Revenue on Viable Routes ($B)					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	$29.3	$35.3	$43.3	$53.2	$65.2	$80.0
2.5X Fare	$5.0	$6.3	$7.9	$9.8	$12.1	$15.0
5X Fare	$3.0	$4.3	$6.4	$9.4	$13.9	$20.6
10X Fare	$0.6	$0.9	$1.2	$1.6	$2.2	$2.9
	Number of Viable Routes					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	63	69	79	90	102	116
2.5X Fare	19	22	25	28	31	35
5X Fare	17	22	26	31	37	44
10X Fare	4	5	5	6	6	6
	Fleet Required					
	2030	**2035**	**2040**	**2045**	**2050**	**2055**
1.5X Fare	46	58	71	86	105	128
2.5X Fare	4	9	11	14	17	21
5X Fare	4	5	8	13	20	32
10X Fare	1	1	2	3	4	6

Table A1.10. Case 5 analysis results – general aviation.

Passengers on Viable Routes (M)

	2030	2035	2040	2045	2050	2055
1.5X Fare	0.0	0.0	0.0	0.0	0.0	0.0
2.5X Fare	0.2	0.3	0.3	0.3	0.4	0.5
5X Fare	0.1	0.1	0.1	0.2	0.2	0.2
10X Fare	0.0	0.0	0.0	0.0	0.0	0.0

Revenue on Viable Routes ($B)

	2030	2035	2040	2045	2050	2055
1.5X Fare	$0.6	$0.7	$0.8	$0.9	$1.1	$1.2
2.5X Fare	$11.9	$13.9	$16.1	$18.7	$21.6	$25.1
5X Fare	$5.6	$6.6	$7.8	$9.3	$11.0	$13.1
10X Fare	$0.0	$0.0	$0.0	$0.1	$0.3	$0.6

Number of Viable Routes

	2030	2035	2040	2045	2050	2055
1.5X Fare	5	5	5	5	5	5
2.5X Fare	103	103	104	106	107	108
5X Fare	72	74	75	76	76	77
10X Fare	2	4	6	8	11	16

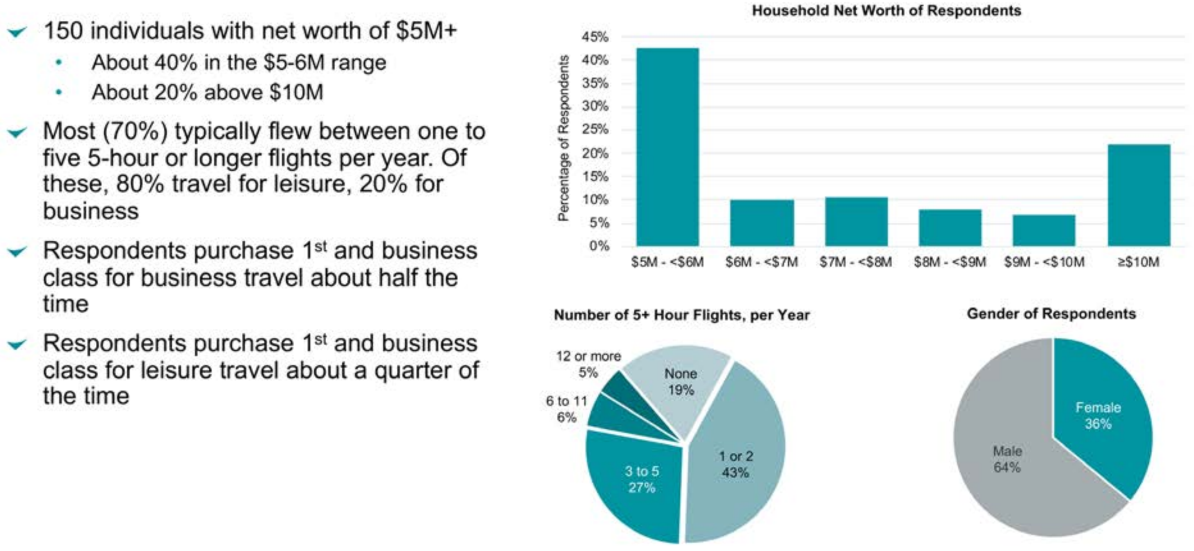
Fleet Required

	2030	2035	2040	2045	2050	2055
1.5X Fare	2	2	2	3	3	4
2.5X Fare	32	37	43	50	58	67
5X Fare	15	18	22	26	30	36
10X Fare	1	1	1	1	1	1

Appendix 2: Survey of High-Net-Worth Individuals

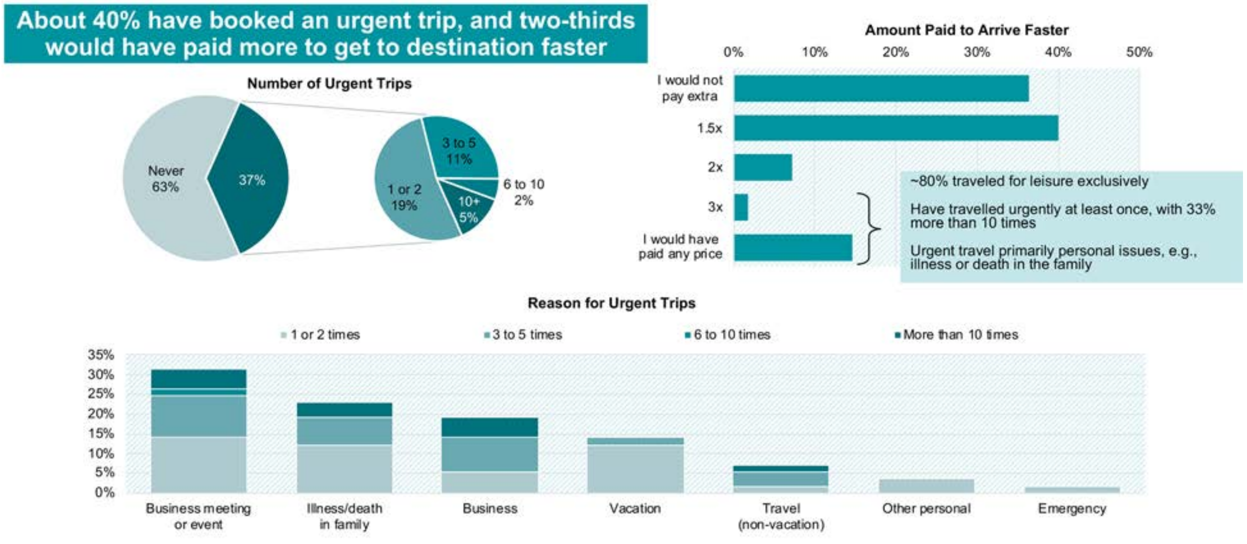
This appendix contains figures from the final presentation entitled *Independent Market Study: Commercial Hypersonic Transportation* (January 8, 2021) describing results of a survey of 150 high-net-worth individuals. The survey was commissioned by BryceTech in support of this study.

Figure A2.1. Survey demographics.



- 150 individuals with net worth of $5M+
  - About 40% in the $5-6M range
  - About 20% above $10M
- Most (70%) typically flew between one to five 5-hour or longer flights per year. Of these, 80% travel for leisure, 20% for business
- Respondents purchase 1st and business class for business travel about half the time
- Respondents purchase 1st and business class for leisure travel about a quarter of the time

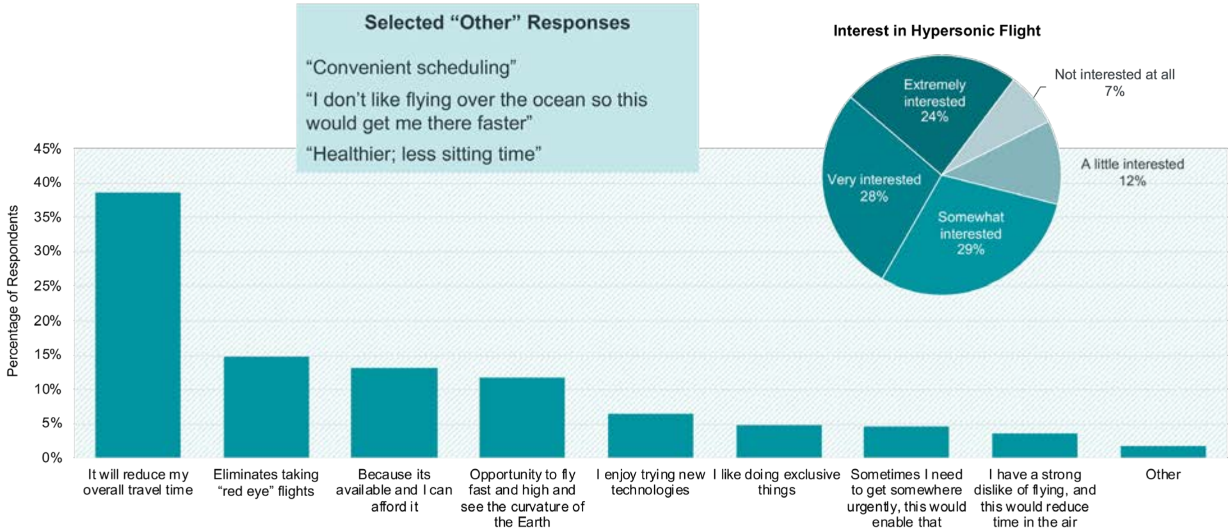
Figure A2.2. Urgent travel.



About 40% have booked an urgent trip, and two-thirds would have paid more to get to destination faster

- ~80% traveled for leisure exclusively
- Have travelled urgently at least once, with 33% more than 10 times
- Urgent travel primarily personal issues, e.g., illness or death in the family

Figure A2.3. Interest in high-speed commercial flight.


Selected "Other" Responses

"Convenient scheduling"

"I don't like flying over the ocean so this would get me there faster"

"Healthier; less sitting time"

Figure A2.4. Attitudes toward risk and other factors.

After learning about drawbacks (such as new technology, less cabin space, etc.), 17% respondents had decreased interest high-speed flight

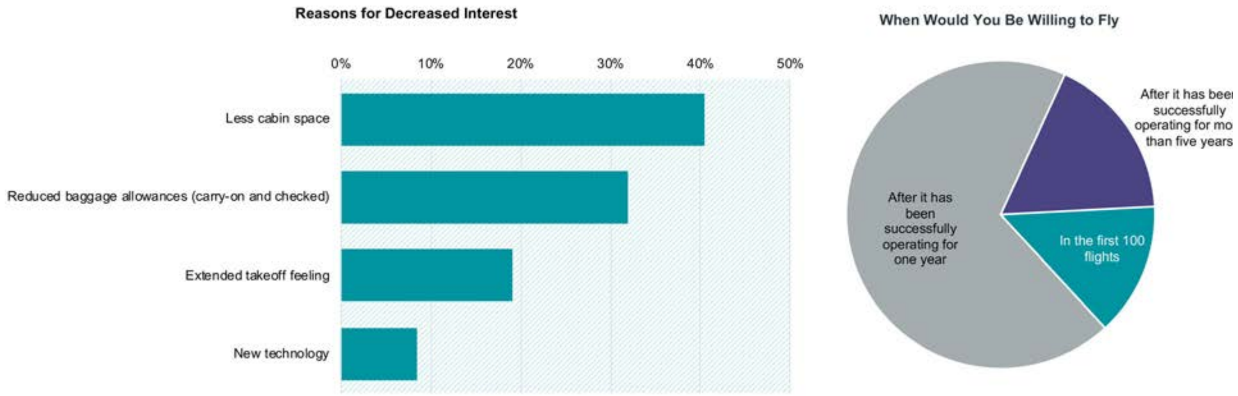


Figure A2.5. Time savings.

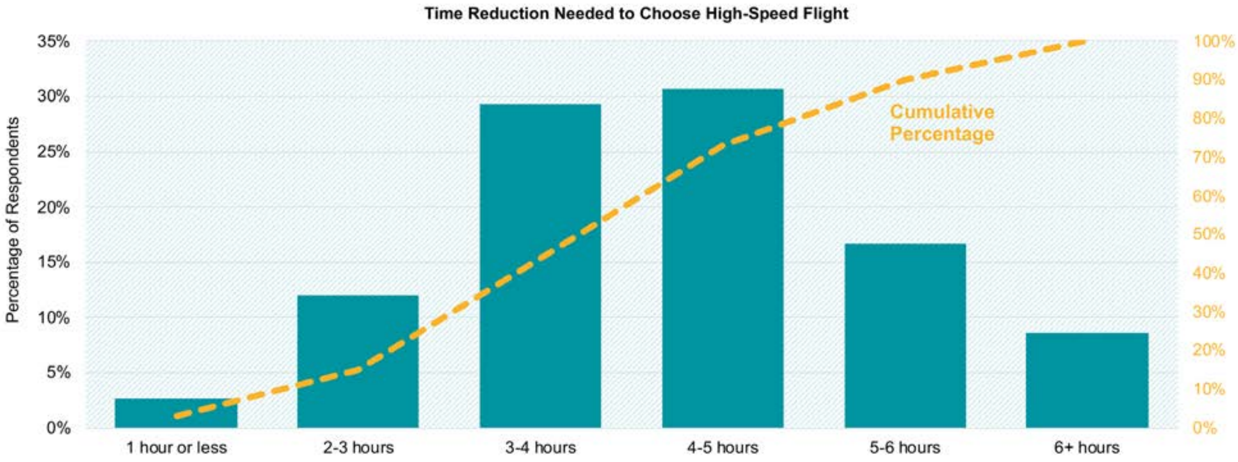
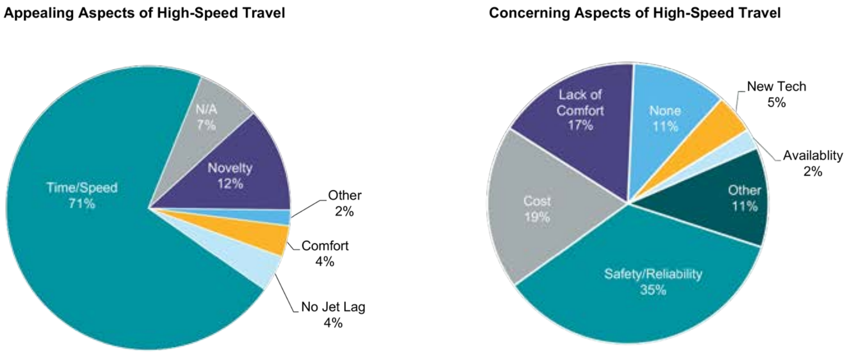


Figure A2.6. Open-ended question about high-speed travel.



Other Concerns

- Passenger Health
- Reliability
- Speed Vehicle
- Value
- Baggage load
- Carbon footprint
- COVID-19
- Practicality
- Travel concerns for surrounding travel (e.g., connecting to the hypersonic-capable airport

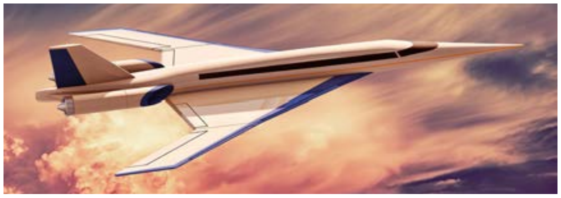
Appendix 3: Summary of High-Speed Commercial Aircraft (Conceptual and In Development)

Image courtesy of Aerion Supersonic LLC. Used with permission.

Aerion Corporation AS2

- U.S. company founded in 2002
- Originally pursued SBJ, a supersonic business jetcapable of carrying 12 passengers at Mach 1.6
- SBJ replaced by AS2 development project, a larger jet, still carrying 12 passengers, but featuring more accommodations
- AS2 team originally involved Airbus (2014-2017), but now Lockheed Martin Corp. (2017-2019), then Boeing (2019-)
- Aiming to serve UHNWIs with an estimated market of 300-500 aircraft
- RDT&E expected to be about $4B
- Propulsion: General Electric Affinity – Turbofan consisting of a CFM56 turbojet core and twin low pressure fans specifically designed for supersonic flight

Image: Spike Aerospace (www.SpikeAerospace.com)



Spike Aerospace S-512

- U.S.-based Spike Aerospacefounded in 2012
- Developing the S-512, asupersonic business jet
- Unique characteristic of cabin will be lack of windows; instead, cabin will feature flexible OLED or similar to display exterior environment
- Partnered with Seimens (manufacturing and systems engineering), MAYA (software), Greenport Technologies (aerospace equipment and manufacturing), BRPH (facilities), and Quartus Engineering (software)
- In 2018, announced a market study indicating 13 million people interested in supersonic flight
- Expects deliver production aircraft in 2023

Image: Lockheed Martin Corp.

Lockheed Martin Corp. QSTA

- Supersonic small airliner called the Quiet Supersonic Technology Airliner (QSTA)
- Leverages NASA-Lockheed Martin X-59 QueSSTProgram
- Selected number of passengers based on market research indicating this is a “sweet spot”
- Lockheed Martin has stated that there are no off-the-shelf jet engines available for this type of aircraft, so will pursue a new propulsion system
- No entry service date, but based on completion of QueSST program completion in 2023

Image: Exosonic, Inc.

Exosonic Concept

- U.S. start-up company founded in 2019
- Developing a low-boom, over land supersonic transport with a cruise speed of Mach 1.8
- 50-70 passengers
- Aiming for business class market, with ticketprices competitive with subsonic business class
- Seeking to use sustainable fuel for aircraft
- Design remains proprietary (image on right isnot the current configuration)
- Has partnered with the USAF Presidential and Executive Airlift Directorate for development of an executive jet
- $150,000 in seed funding from Y Combinator

Image: Copyright © 2021 Boom Supersonic.

Boom Technology Overture

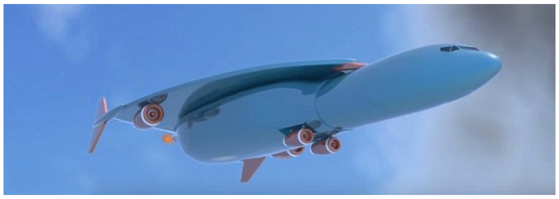
- U.S.-based Boom Technology founded in 2014
- Pursuing a supersonic airliner not unlike retired Concorde, but more efficient
- Will still create sonic boom, so flights limited to 500+ transoceanic routes
- Company started with $151M in venture capital
- About to introduce Boom XB-1 test vehicle, which is expected to conduct test flights in 2021 with a speed of Mach 2.2
- Is teaming with Virgin Galactic in development of vehicle; Virgin plans to acquire 10 XB-1 vehicles
- Overture expected to enter service by 2025, and believes there is a market for at least 1,000 units (commitments from nearly 100 companies)
- Business class fares expected

Image: Virgin Galactic

Virgin Galactic Concept

- Virgin Galactic founded in 2004 to develop andoffer commercial suborbital reusable launchvehicle, SpaceShipTwo, expected to beginoperations in 2021
- The Spaceship Company is Virgin Galactic’s advanced air and space vehicle manufacturer
- Announced in 2019 supersonic jet program to support business executive market designed tocarry up to 19 passengers to a speed of Mach 3(slightly less than SR-71 top speed)
- In partnership with Rolls-Royce for engine development
- Unclear how this relates to partnership withBoom Technology
- Note that Virgin Galactic has incurred significant business losses in 2019 ($73M) and 2020 ($60M) that will likely impact plans

Image: PatentYogi/Airbus.



Airbus Concorde 2

- Announced in 2015, but not much detail since
- Company reveal concept for a hypersonic business jet witha cruise speed of about Mach 4.5 and an altitude of100,000 feet
- Designed for 20 passengers
- Three separate propulsion systems, including turbojet,ramjet, and rocket, all burning different forms ofhydrogen for fuel (common source tankage)
- Indicated such a system could be used for military missions

Boeing Concept

- Boeing announced plans to pursue hypersonic airlinerin 2018, but with very few details. No updates since
- Hypersonic airline transport for passengers (40-70 based on number of windows shown in artwork)
- Would likely feature a combined cycle propulsion system not unlike that used on SR-71 (turbojet-ramjet)
- Can do two round trip flights from U.S. to London per day.This means the airline need not put its crew in hotels overnight – they sleep in their own homes. That usage rate drives down the cost and puts concept into the realm of economic feasibility, according to Boeing

Image: Hermeus

Hermeus Concept

- U.S.-based Hermeus founded in 2018
- Start up with a few seed rounds of investment (undisclosed)
- Conducted successful test of its prototype of its engine in March 2020
- In August 2020, via AFWERX, USAF Presidential and Executive Airlift Directorate awarded company an SBIR Phase II contract worth $1.5M in 2020 to develop a Mach 5 vehicle with range of 4,600 miles. The contract supports evaluation of potential hypersonic military transports for a 9-19-seat aircraft, including for the executive airlift mission
- Would presumably augment or even replace one or both 747 VC-25A aircraft the government is set to receive in 2021

Image: https://www.h2020-stratofly.eu/.

EU Horizons 2020 Team STRATOFLY MR3

- Multi-national European team pursuing feasibilityof high-speed passenger transport
- Funded via EU’s Horizons 2020 R&D program, but funding level is relatively low
- Leverages previous studies on LAPCAT-II MR2.4 concept vehicle
- Team consists of civil space agencies and companies
- Aiming for TRL6 by 2035 for the vehicle concept and 2050+ for operational “airliner” capable of carrying 300 passengers at altitude of 98,000 ft
- Consortium believes key technologies not likely to be ready until about 2035

JAXA Concept

- Mach 5 concept that may lead to commercial use
- Designed to carry 100 passengers
- Flat blended-body planform, with 10 rows of seats, each with 10 seats
- Ceiling of 82,000 feet
- Range of 5,600 miles
- Propulsion system will burn liquid hydrogen as fuel
- Testing of airframe subscale vehicle HIMICO aboardsounding rocket in 2021
- Development cost expected to be ¥2.4 trillion JPY

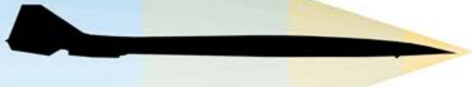
Stratolaunch Talon A

- Reusable Mach 6 uncrewed commercial test vehicle
- Designed as a hypersonic testbed available to a variety of users
- Designed to support research, experiments, and enabling operational missions
- Air–dropped from Roc aircraft once designed tocarry orbital launch vehicles

Image: Generation Orbit

Generation Orbit X-60A

- Expendable Mach 5-8 commercial uncrewed hypersonic test vehicle for testing purposes
- Based on GOLauncher-1 suborbital vehicle
- Designed as a hypersonic testbed available to a variety of users
- Designed to support research, experiments, and enabling operational missions
- Air–dropped from conventional aircraft



Appendix 4: Non-Technical Barriers to Commercial Hypersonic Transportation

This appendix contains detailed figures from the final presentation for each of the 28 non-technical barriers identified and characterized in this study. Figures A4.1 through A4.28 describe the barriers themselves and magnitude of their consequences in terms of safety, demand/availability, compliance, and cost. A second set of figures follows, each describing proposed NASA mitigative actions to address these barriers and their potential impact.

Identification of Barriers and their Consequences

Figure A4.1. Barrier 1 – Runway length, characterization and magnitude of consequences.

Barrier Description		
Runways at desired airports may not be of sufficient length due to high landing speeds, a situation that could delay or impede SST and HST operational planning and flights **Consequence(s):** Requirement for longer runways may limit city-pairs and increase costs (to support airport expansion)		
Consequences		
	Assessment	**Magnitude**
Safety	No major safety consequences or issues were identified; SST and HST aircraft will not operate from airports or FBOs with inadequate runway lengths	⧅
Demand	Insufficient runway length may limit the number of desirable airports/city pairs for scheduled and charter flights, adversely impacting passenger demand	■■■
Compliance	No major compliance consequences or issues were identified; SST and HST aircraft are expected to be designed to comply with existing runway lengths	⧅
Cost	Updates/expansions of existing airport runways are expensive and require extensive public and government funding	■■■

Relevance by Vehicle Configuration and Fuel Type				
Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.2. Barrier 2 – Infrastructure, characterization and magnitude of consequences.

Barrier Description		
Aircraft design and existing terminal layouts may not 1) meet the expectations of passengers paying a premium for tickets expect a high level of service and/or 2) be fully compatible with terminal clearances, runway and taxiway width, jet bridges, and other infrastructure elements **Consequence(s):** Possibly unmet expectations for premium support facilities could decrease demand and/or increase cost		
Consequences		
	Assessment	**Magnitude**
Safety	No major safety consequences or issues were identified: SST and HST aircraft will be certified and by definition safely comply with existing infrastructure	⧅
Demand	An inability to provide easily accessible premium services may adversely impact passenger expectations and reduce demand	■■■
Compliance	No major compliance consequences or issues were identified; SST and HST aircraft are expected to be designed to comply with existing infrastructure	⧅
Cost	Additional airport funding may be required to improve or add additional needed and desired support capabilities	■■■

Relevance by Vehicle Configuration and Fuel Type				
Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

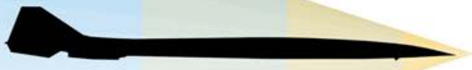


Figure A4.3. Barrier 3 – Special maintenance and personnel, characterization and magnitude of consequences.

Barrier Description
Complex high-speed aircraft may be more difficult to maintain, requiring special facilities and personnel knowledgeable and experienced with next generation propulsion, avionics, data management, and automated computer flight systems **Consequence(s):** Scheduled and unscheduled maintenance and repairs could result in delays, workforce requirements could be more difficult to meet

Consequences

	Assessment	Magnitude
Safety	No major safety consequences or issues were identified	☒
Demand	No major demand consequences or issues were identified	☒
Compliance	Documentation and validation of complex maintenance tasks and requirements may delay the certification process	🟥🟥🟥
Cost	Operators may need to plan for and commit additional funding to upgrade facilities and equipment, or obtain specialized maintenance personnel to sustain high-speed aircraft	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

Figure A4.4. Barrier 4 – Pre-flight inspections, characterization and magnitude of consequences.

Barrier Description
Pre-flight visual inspections, or “pre-flight check,” are required by air crews prior to flight. Such inspections may not be adequate for certain SST and HST due to the unique environments these aircraft operate in. Non-destructive inspections (NDI) may be required to identify issues not visible by the naked eye. **Consequence(s):** Continual thermal cycling of high-speed aircraft (repeated exposure to both extreme hot and cold temperatures) may require detailed post- and pre-flight inspection using NDI, beyond pre-flight checks, and this may slow turn around time and/or increase costs. Additional investment in maintenance equipment and facilities may be required to support timely operations and maintenance requirements

Consequences

	Assessment	Magnitude
Safety	Inability to identify microfractures or microscopic deterioration of materials and structures could lead to catastrophic failure of system	🟥🟥🟥🟥🟥
Demand	As operational experience is gained, costs relating to routine NDI costs and subsequent repairs will be shifted to customers in the form of higher ticket prices	🟥🟥🟥
Compliance	Documentation and validation of complex maintenance tasks and required equipment may delay the certification process	🟥🟥🟥
Cost	NDI inspection systems are expensive to procure and maintain	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

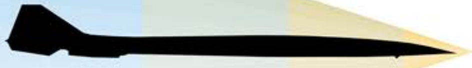


Figure A4.5. Barrier 5 – Post-flight cool down, characterization and magnitude of consequences.

Barrier Description

Due to the result of kinetic heating caused by friction between the outside air and the skin of the rapidly moving aircraft the exterior structure will be extremely hot upon landing. In order to service the aircraft, the vehicle will require a standoff cool down period before it can be safely approached, and passengers and baggage safely off-loaded

Consequence(s): Need for post-flight cool down aircraft holding areas may increase flight time, slow turn around, and increase costs. Potential air traffic delays and reduction of overall time saved

Consequences

	Assessment	Magnitude
Safety	Extremely hot surfaces represent a burn hazard and can ignite flammable materials (i.e., fuel, hydraulic fluid)	🟥🟥🟥
Demand	Aircraft cool down timelines in which passengers cannot safely disembark and reduce overall time savings to the passengers and negatively impact demand	🟥🟥🟥
Compliance	No major compliance consequences or issues were identified	☒
Cost	Additional aircraft holding areas may need to be identified or constructed	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
			✓	✓

Figure A4.6. Barrier 6 – Cryogenics, characterization and magnitude of consequences.

Barrier Description

Some HST systems, especially those featuring a scramjet propulsion system, will require liquid hydrogen (LH) for fuel, and possibly other cryogenic propellants, coolants, and pressurants

Consequence(s): Any need for specialized storage, transport, and handling of cryogenics will increase costs relative to traditional aircraft requirements. The use of LH in particular will require the procurement and installation of appropriate storage, transport, and handling facilities. Use of cryogenics will require airports and FBOs to plan for and invest in additional new supply channels, storage facilities, and transfer capabilities to meet servicing requirements while still maintaining current hydrocarbon capabilities to support subsonic fleets

Consequences

	Assessment	Magnitude
Safety	Cryogenics represent a hazard, causing burns when improperly handled. LH and liquid oxygen (LOX) are highly flammable	🟥🟥🟥
Demand	No major demand consequences or issues were identified	☒
Compliance	The ability to safely and effectively transfer and store specialized fuels aboard the aircraft may delay the certification process	🟥🟥🟥
Cost	Airports would need to identify additional funding to support the planning, procurement and installation of specialized storage, transport, and transfer capabilities	🟥🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
				✓

Figure A4.7. Barrier 7 – Air traffic systems, characterization and magnitude of consequences.

Barrier Description

Very high-speed SST and HST may create handoff challenges and potentially safety issues (from routine tracking to wake turbulence). High-speed aircraft will have to be capable of seamless integration into existing flight networks and air traffic management systems to facilitate safe aircraft handoff and landing approaches

Consequence(s): Need to upgrade navigation and information systems to appropriately track and identify aircraft operating at higher speeds and altitudes

Consequences

	Assessment	Magnitude
Safety	Very high-speed aircraft may create response time challenges for air crews and air traffic control centers. GNSS support may not be adequate to track HST during cruise. Wake turbulence may be an issue	■■■
Demand	No major demand consequences or issues were identified	⧅
Compliance	Delay in implementing appropriate air traffic management systems may delay the certification and initial operating timelines	■■■
Cost	The FAA and airports may need to upgrade existing air traffic management, information systems and supporting infrastructure (power, communications, response, etc.) to appropriately track and identify aircraft operating at higher speeds and altitudes	■■■

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

Figure A4.8. Barrier 8 – Type certification, characterization and magnitude of consequences.

Barrier Description

Initially, the unique characteristics of some SST and all HST aircraft and relative lack of statistic flight data will translate into certification delays. The very high bar set by the FAA and the aviation industry will be the standard, and environmental standards are expected to become stricter (i.e., emissions)

Consequence(s): RDT&E costs relating to flight component tests, requisite number of flight hours and, and compliance process may create delays measured in years, translating to increasing costs

Consequences

	Assessment	Magnitude
Safety	Flight testing features inherent risks to test pilots, and HST flight is a very new area of development. Ensuring safety around new vehicle systems under a testing regime and test environment, particularly during development of emergency procedures	■■■■■
Demand	Type certification delay will delay business plan execution, with costs transferred to the customer or absorbed by developer	■■■
Compliance	Type certification of certain SST and all HST will depend on modified or new regulations, often informed by flight data, and this will take years	■■■■■
Cost	High-speed aircraft lack supporting historical data requiring more actual flight hours, development, and use of complex simulations which will increase development time	■■■■■

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
	✓	✓	✓	✓

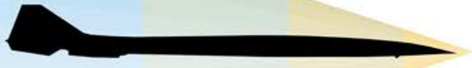


Figure A4.9. Barrier 9 – Stability and control, characterization and magnitude of consequences.

Barrier Description
Stability and control challenges to include inadequate certification regulations, across the operational flight envelope may increase difficulty to certify as safe, increase test program duration, and/or require more highly skilled pilots. High speed aircraft will have to demonstrate safe and stable takeoff and landing and flight flight characteristics in a variety weather conditions at subsonic speeds **Consequence(s):** RDT&E costs relating to flight component tests, requisite number of flight hours and, and compliance process may create delays measured in years, translating to increasing costs

Consequences	Assessment	Magnitude
Safety	Aircraft optimized to fly at very high speeds (the majority of their operational envelop) are at risk of becoming unstable at lower flight speeds, a condition that can lead to loss of aircraft	🟥🟥🟥🟥🟥
Demand	No major demand consequences or issues were identified	⧅
Compliance	Some SST and all HST aircraft lack supporting historical data requiring more actual flight hours, use of validated complex simulations which will increase certification timelines	🟥🟥🟥🟥🟥
Cost	Some SST and all HST aircraft lack supporting historical data requiring more actual flight hours, development and use of complex simulations which will increase development time	🟥🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
	✓	✓	✓	✓

Figure A4.10. Barrier 10 – Extended operations (ETOPS), characterization and magnitude of consequences.

Barrier Description
Extended-range Twin-engine Operational Performance Standards (ETOPS) for aircraft with two engines is currently 370 minutes flying time away from the nearest airport suitable for an emergency landing. This standard is assumed to apply to SST and HST aircraft **Consequence(s):** Suitable airports with 370 minutes flying time may be limited, impacting operational routes. Increasing ETOPS minutes will require greater engine reliability potentially increasing development and flight hours

Consequences	Assessment	Magnitude
Safety	No major safety consequences or issues were identified, since an SST or HST that cannot comply with ETOPS will not fly relevant routes	⧅
Demand	Shortened ETOPS flight time may limit city pairs reducing demand requirements	🟥🟥
Compliance	High speed aircraft propulsion systems lack supporting historical data requiring more actual flight hours, use of validated complex simulations which will increase ETOPS certification complexity and timelines	🟥🟥
Cost	High speed aircraft propulsion systems lack supporting historical operational and reliability data requiring longer development, testing (flight hours), and certification timelines	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.11. Barrier 11 – Emergency descent and landing, characterization and magnitude of consequences.

Barrier Description		
For aircraft certified to operate above 25,000 feet, cabin pressure altitude must be less than 15,000 feet "after any probable failure condition in the pressurization system.“ So for any "probable" failure, the aircraft must be able to descend to 15,000 feet before the cabin pressure is completely lost. For any failure not "extremely improbable," the aircraft must be able to descend to 25,000 feet within 2 minutes of losing all cabin pressure **Consequence(s):** Aircraft operating at 60,000 ft or higher will require advanced oxygen storage and/or generation systems to ensure passenger safety when executing emergency decent procedures from cruising altitudes. May impact development and certification timelines and cost		
Consequences		
	Assessment	**Magnitude**
Safety	No major safety consequences or issues were identified, since an SST or HST that cannot comply with emergency descent and landing requirements will not fly relevant routes	⊘
Demand	No major demand consequences or issues were identified	⊘
Compliance	No historical data exists for commercial aircraft operating/cruising at 60,000 ft and performing emergency decent procedures. Development of new or modification of existing certification processes will likely delay certification timelines	■■■
Cost	Advanced oxygen generation systems may have to be developed, tested, manufactured, and installed increasing aircraft development, manufacture, and integration costs	■■■

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.12. Barrier 12 – New partial and full automation requirements, characterization and magnitude of consequences.

Barrier Description		
Current avionic Minimum Operating Performance Standards (MOPS) will require reevaluation and update for SST and HST operations to address increased automation (e.g., simulated visual flight, complex data management systems, automated avionics). Current aircraft certification processes do not adequately address high-speed aircraft and engine design, testing, and certification processes and expertise. **Consequence(s):** Extended certification process impacting development timeline and costs		
Consequences		
	Assessment	**Magnitude**
Safety	No major safety consequences or issues were identified	⊘
Demand	No major demand consequences or issues were identified	⊘
Compliance	Current aircraft certification processes do not adequately address high-speed aircraft and engine design, testing, and certification	■■■■■
Cost	High-speed aircraft lack supporting historical data on non-visual flight and supporting avionics requiring additional flight hours and data and the use of validated complex simulations which will increase development costs	■■■■■

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
	✓	✓	✓	✓

Figure A4.13. Barrier 13 – Prohibition of overflight, characterization and magnitude of consequences.

Barrier Description
Prohibition of supersonic flight over the continental U.S. and certain areas outside the U.S. may prevent operations. Currently 14 CFR 91817 prevents supersonic flight over the continental US to prevent/eliminate sonic boom impacts. Consensus on an acceptable level of noise and boom has not been reached. Current foreign government flight regulations may prevent supersonic flight over the continental U.S. to prevent/eliminate sonic boom impacts
Consequence(s): Inability to leverage continental flight routes, increases development cost, limits potential major city pairs and reduces operator demand signal. Inability to leverage non-US continental flight routes, limits potential major city pairs and reduces operator demand signal

Consequences

	Assessment	Magnitude
Safety	Sonic boom impacts will need to be mitigated to prevent potential safety hazards to communities in the aircraft flight path	🟥🟥🟥
Demand	The prohibition of high-speed flight over the continental US and other international countries limits available city pairs to transoceanic routes reducing passenger demand	🟥🟥🟥🟥🟥
Compliance	Testing and validation of sonic boom mitigation will delay US and international certification timelines	🟥🟥🟥
Cost	Development of technologies to reduce or eliminate sonic boom impacts will drive development, testing and manufacturing costs while delaying program schedules	🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.14. Barrier 14 – Ground test equipment, characterization and magnitude of consequences.

Barrier Description
The relatively low number of supersonic and especially hypersonic engine test facilities represents a significant challenge for propulsion research
Consequence(s): Increased reliance on simulation, and delayed propulsion testing that result in overall RDT&E schedule slippage and increases in costs

Consequences

	Assessment	Magnitude
Safety	Lack of adequate ground test facilities requires greater reliance on actual flight time putting test flight crews and aircraft at greater risk	🟥🟥🟥
Demand	No major demand consequences or issues were identified	⧄
Compliance	Lack of adequate ground test facilities requires greater reliance on actual flight time increasing certification complexity and timelines	🟥🟥🟥🟥
Cost	The development, modification, or manufacture of experimental aircraft to provide flight hours to support high speed engine testing will increase development and testing costs and increase development and certification schedules	🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

Figure A4.15. Barrier 15 – Noise, characterization and magnitude of consequences.

Barrier Description

SST and HST aircraft will create sonic booms when transitioning from subsonic to supersonic flight. In addition, some turbojets create significant noise when using afterburners for takeoff and thrust reversers upon landing. While it is assumed that commercial SST and HST will have to operate at similar noise levels as subsonic aircraft, they may generate more noise as a result of engines operating at higher speeds to increase lift during takeoffs. Landing speeds may also be higher requiring greater use of thrust reversers

Consequence(s): Excessive noise generation may limit the major city pairs that aircraft have access to and times within which they can operate. Additional design requirements may result

Consequences

	Assessment	Magnitude
Safety	Loud, sustained jet noise present a hazard to hearing. Sonic booms can also shatter glass	🟥🟥🟥
Demand	Excessive noise may limit city pairs and flight times reducing passenger demand	🟥🟥🟥
Compliance	Aircraft will be required to comply with 14 CFR 36, Noise Standards: Aircraft Type and Airworthiness Certification, which may delay the certification process	🟥🟥🟥
Cost	Additional airframe and propulsion development time and cost may be required to meet 14 CFR 36 requirements	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.16. Barrier 16 – Emissions, characterization and magnitude of consequences.

Barrier Description

CO_2, NO_x, UHC, and particulate emissions may prevent chemical emission compliance. Potential that high-speed aircraft using hydrocarbon fuels consume more than subsonic aircraft resulting in increased CO_2 emissions. In addition, aircraft operating above 60,000 feet using hydrocarbon fuels could potentially cause damage to the ozone layer

Consequence(s): Potential limits to high-speed aircraft operational environments, increased certification/compliance issues, and additional design requirements. May also limit city-pairs based on regional requirements

Consequences

	Assessment	Magnitude
Safety	The magnitude of emissions (particularly NO_x) is highly dependent on the cruise altitude of the aircraft; the higher the altitude, the greater the potential damage to the ozone layer	🟥🟥🟥🟥🟥
Demand	Excessive emissions may have a major impact in terms of public perception, reducing passenger demand	🟥🟥🟥
Compliance	Propulsion systems will have to meet U.S. and international emissions standards delaying certification	🟥🟥🟥
Cost	Development of propulsion systems capable of meeting current and proposed U.S. and international emission standards will increase development and testing costs and may also delay schedule execution	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.17. Barrier 17 – Hazardous materials, characterization and magnitude of consequences.

Barrier Description

HST will likely require the use of cryogenics and other hazardous materials (beyond hydrocarbon fuels), requiring the need for special handling. The use of certain hazardous materials may create additional handling, transport, disposal, and remediation issues and costs

Consequence(s): Disposal and remediation of certain hazardous materials may be difficult, time consuming, and costly

Consequences

	Assessment	Magnitude
Safety	No major safety consequences or issues were identified; hazardous materials handling is covered through federal, state, and local regulations	☒
Demand	No major demand consequences or issues were identified	☒
Compliance	Aircraft exotic materials will need to be handled and disposed of IAW EPA standards and requirements. Development of appropriate procedures and processes to meet these standards may delay the certification process	🟥🟥🟥
Cost	The development, procurement and operation of specialized handling, transport, disposal, and remediation of exotic materials may create additional operating costs	🟥🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
			✓	✓

Figure A4.18. Barrier 18 – ITAR restrictions, characterization and magnitude of consequences.

Barrier Description

International Traffic in Arms Regulations (ITAR), Export Administration Regulations (EAR), and Missile Technology Control Regime (MTCR) may prevent international sales and export of certain technologies critical to SST and HST systems. These may also impact operations, maintenance, and cyber security at non-U.S. facilities

Consequence(s): There will be significant impact to the sale and export of advanced technologies and capabilities especially if developed in conjunction with DoD, or represent capabilities that could significantly improve a foreign countries military capabilities. This includes the sale and export of sensitive, advanced high- speed aircraft and supporting technologies that may be transferred to unauthorized or prohibited entities through illegal methods or that would support the the intended recipient's development of delivery systems for weapons of mass destruction

Consequences

	Assessment	Magnitude
Safety	Inability to sell critical components of an aircraft requiring parts and/or component substitution may impact overall aircraft safety	🟥
Demand	Export regulations may limit or prohibit the sale of high-speed aircraft in the international market limiting the availability to U.S. carriers, severely reducing overall demand	🟥🟥🟥🟥🟥
Compliance	Development of new capabilities or components may require additional testing and evaluation increasing certification timelines	🟥🟥🟥🟥🟥
Cost	Compliance of export regulations may require the development of critical technologies that are not reliant upon design, information or capabilities originally developed for national defense. This will significantly increase development costs and schedule timelines	🟥🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
	✓	✓	✓	✓

Figure A4.19. Barrier 19 – GNSS receivers, characterization and magnitude of consequences.

Barrier Description		
High supersonic and HST aircraft require highly accurate GNSS receivers and supporting analytical software in order to accurately determine aircraft position. Civil GNSS receiver operation above 600 m/s (Mach 1.8) is restricted by U.S. Munitions List (22 CFR Part 121, Category XII (d)(2)). The sale and transfer of this technology may also be prohibited under category 7 Navigation and Avionics of the EAR, as well as ITARS, and MTCR. **Consequence(s):** There may be significant challenges to the sale and export of sensitive, advanced high- speed aircraft and supporting technologies that may be transferred to unauthorized or prohibited entities through illegal methods		
Consequences		
	Assessment	**Magnitude**
Safety	Inability to sell critical components of an aircraft requiring parts and/or component substitution may impact overall aircraft safety	🟥
Demand	Export regulations may limit or prohibit the sale of advanced GNSS receivers in the international market limiting the availability to US carriers, severely reducing overall demand	🟥🟥🟥🟥🟥
Compliance	Development of new capabilities or components may require additional testing and evaluation increasing certification timelines	🟥🟥🟥🟥🟥
Cost	Compliance of export regulations may require the development of another technology that is not reliant upon design, information or capabilities originally developed for national defense or that may contribute to the enhancement of military capability of another nation. This will significantly increase development costs and schedule timelines	🟥🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type				
Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

Figure A4.20. Barrier 20 – Insurance, characterization and magnitude of consequences.

Barrier Description		
Obtaining insurance (hull and liability insurance, grounding insurance) for new vehicles and vehicle systems may be challenging and expensive due to historical caution experienced by underwriters in regards to new technologies and capabilities **Consequence(s):** The high cost of insurance may increase overall development costs		
Consequences		
	Assessment	**Magnitude**
Safety	No major safety consequences or issues were identified; SST and HST aircraft will be required to adhere to strict FAA standards for safety	☒
Demand	If deemed necessary, insurance costs could adversely impact overall ticket prices reducing passenger demand	🟥🟥
Compliance	No major compliance consequences or issues were identified	☒
Cost	Insurance for new SST and HST aircraft may be very expensive and may increase development cost	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type				
Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

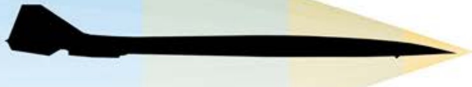


Figure A4.21. Barrier 21 – Regulatory timeline, characterization and magnitude of consequences.

Barrier Description

The development and approval of new regulations to support certain high-speed aircraft (especially those powered by unconventional powerplants like turboramjets, ramjets, and scramjets) will require extensive communications and coordination across a wide variety of government offices and congressional staff and will take years of dedicated effort and resources to implement

Consequence(s): Lack of approved supporting regulations may delay the development and implementation of high-speed aircraft operations. Manufactures and operators will need to commit resources to the development and approval process for an extended period of time

Consequences

	Assessment	Magnitude
Safety	No major safety consequences or issues were identified	⧅
Demand	Possible demand consequences include delay in delivery and operation of commercial SST and HST aircraft, even if length of time to certify and/or operate in an updated regulatory regime is factored into business plans	■
Compliance	Lengthy coordination and approval timelines of new regulations may adversely impact associated certification timelines	■■
Cost	Extensive coordination and approval times of supporting regulations may increase program schedules and increase cost (especially international coordination)	■■■

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

Figure A4.22. Barrier 22 – International coordination, characterization and magnitude of consequences.

Barrier Description

International regulatory coordination has been identified as a challenge. For example, a lack of International agreement for flight operations above 60,000 feet may impede safe operations at this altitude (lack of high-speed corridors supporting safe flight 60,000+ feet above mean sea level, referred to by FAA as Upper Class E airspace operations). Another example: Noise and CO_2 emissions may prevent European Union Aviation Safety Agency (EASA) and International Civil Aviation Organization (ICAO) noise and chemical emission compliance (aircraft noise and CO_2 emissions are a growing European concern). EASA follow ICAO Annex 16 Volumes I, II, and IV standards for noise and CO_2 standards. These standards continue to tighten and may become more restrictive than U.S. standards

Consequence(s): Increased speed makes the requirement for well defined flight corridors of even greater importance. Lack of an agreed to international agreement could delay service entry of high-speed aircraft, increase safety concerns. Potential limits to high-speed aircraft operational environments, increased certification/compliance issues, and additional design requirements. May also limit city-pairs based on regional requirements

Consequences

	Assessment	Magnitude
Safety	High speed cruising corridors will have to be identified and agreed upon to ensure safe fight operations	■■■
Demand	No major demand consequences or issues were identified	⧅
Compliance	Lack of or otherwise limited international compliance may restrict access to certain international markets	■■■
Cost	NASA may support the DoS and FAA in the development and coordination of required international agreements requiring on minimal additional resources	■■■

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.23. Barrier 23 – Climate concerns, characterization and magnitude of consequences.

Barrier Description		
Increased public awareness of the environmental impact of CO_2, NO_x, UHC, and particulates emissions may create resistance to high speed aircraft in light of human induced climate change. There is likely to be concern that high-speed aircraft using hydrocarbon-based fuels will significantly add to atmospheric CO_2, NO_x, UHC, and particulate levels adversely impacting the climate **Consequence(s):** May create resistance to high-speed aircraft use, especially if emissions exceed those of subsonic aircraft		
Consequences		
	Assessment	**Magnitude**
Safety	No major identified safety consequences or issues were identified	⧅
Demand	Perceived increases in CO_2 emissions and increased impact on climate change could adversely impact the requirement for seats and aircraft	■■■
Compliance	No major identified compliance consequences or issues were identified	⧅
Cost	No major identified cost consequences or issues were identified	⧅

Relevance by Vehicle Configuration and Fuel Type				
Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.24. Barrier 24 – Virtual communications, characterization and magnitude of consequences.

Barrier Description		
Virtual communications replacing certain travel may reduce demand for high-speed travel. Increased use of virtual communication tools and conferencing capabilities both internally and externally may reduce the requirement for travel and participation in face-to-face meetings. **Consequence(s):** Potential for reduced demand for business travel		
Consequences		
	Assessment	**Magnitude**
Safety	No major safety consequences or issues were identified	⧅
Demand	Increased use of virtual communication tools and conferencing capabilities both internally and externally may reduce the requirement for travel	■■
Compliance	No major compliance consequences or issues were identified	⧅
Cost	No major cost consequences or issues were identified	⧅

Relevance by Vehicle Configuration and Fuel Type				
Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Figure A4.25. Barrier 25 – Aircraft and parts in quantity, characterization and magnitude of consequences.

Barrier Description
The use of exotic materials in some SST and HST aircraft and their components will necessitate the establishment of new and scalable manufacturing capabilities in concert with aircraft development to support development, testing, delivery, and operation (including maintenance). Parts manufacturers may lack the financial resources to make the required investments in critical design and manufacturing technologies **Consequence(s):** Lack of supporting parts and/or component manufacturing will delay development, and delivery of aircraft. It will also limit the availability of aircraft, increase repair down time and decrease passenger demand

Consequences

	Assessment	Magnitude
Safety	No major safety consequences or issues were identified	☒
Demand	Lack of repair/spare parts will increase maintenance timelines, increasing turnaround times, delaying scheduled flights, and impacting customer satisfaction and demand	🟥🟥🟥
Compliance	No compliance consequences or issues were identified	☒
Cost	Parts manufactures may need to invest in advanced manufacturing capabilities and technologies to provide adequate and timely supply of parts to support airline operations	🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

Figure A4.26. Barrier 26 – Special materials, characterization and magnitude of consequences.

Barrier Description
Weather (specifically rain erosion and effects of ice) can impact special materials (silicon-carbide, nickel-based alloys, other ceramics) needed at greater than Mach 4 cruise such as tiles (water droplets can erode delicate surfaces during high-speed flight), potentially degrading performance **Consequence(s):** Additional investment may be required to ensure that aircraft designed to fly at Mach 4+ have stable flight characteristics in adverse weather conditions

Consequences

	Assessment	Magnitude
Safety	High-speed aircraft will have to demonstrate stable flight characteristics in adverse weather conditions	🟥🟥🟥🟥🟥
Demand	No major demand consequences or issues were identified	☒
Compliance	Adequate testing/assessment of special material performance at high speeds in varied weather conditions may require the use of limited high speed test chambers, environmental chambers, advanced simulation and an increase in flight hours delaying aircraft certification	🟥🟥🟥🟥🟥
Cost	Development and testing of special materials operating in adverse weather at high speed may drive additional development costs	🟥🟥🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

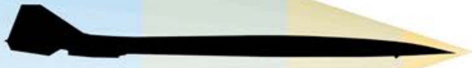


Figure A4.27. Barrier 27 – Aircrews, characterization and magnitude of consequences.

Barrier Description

The introduction of high-speed aircraft will require the co-development and implementation of innovative simulation training capabilities to support the training and certification of qualified aircrews. The expectation is identifying aircrews with adequate experience (including military with experience flying high performance aircraft) but not likely to retire soon

Consequence(s): The lack of trained and certified aircrews will limit the requirement for and the operation of high-speed aircraft. The development of required training capabilities and facilities will drive up operating costs and aircrew limitations will reduce aircraft availability and demand

Consequences

	Assessment	Magnitude
Safety	Aircrews flying advanced high-speed aircraft will require special training to handle supersonic and hypersonic emergency procedures	🟥🟥🟥🟥🟥
Demand	Lack of trained aircrews will limit the number of aircraft available, impacting seat availability and lowering demand	🟥🟥🟥
Compliance	The lack of regulations covering high speed SST and HST training and certification impedes recruitment beyond test pilots	🟥🟥🟥🟥🟥
Cost	Training may require the development and implementation of new training simulation capabilities include next generation simulators, software, and data management	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
		✓	✓	✓

Figure A4.28. Barrier 28 – Engineering and manufacturing skills, characterization and magnitude of consequences.

Barrier Description

There is a potential shortage of knowledgeable engineers and skilled manufacturers to design, build, integrate, and maintain SST and HST aircraft and components

Consequence(s): Qualified engineering staff will need to be trained resulting in potential delays and additional cost in the development, testing, integration and manufacture of high-speed aircraft and critical components

Consequences

	Assessment	Magnitude
Safety	No major safety consequences or issues were identified	⧅
Demand	No demand consequences or issues were identified	⧅
Compliance	Trained and qualified engineers will be required to support certification requirements and processes. Lack of engineers may delay the certification process	🟥🟥🟥
Cost	Training of required engineers and manufacturing professions will require the development and implementation of new training processes and capabilities. Development of an adequate and trained staff may delay development and increase costs	🟥🟥🟥

Relevance by Vehicle Configuration and Fuel Type

Turbine 0 to about Mach 2 Hydrocarbon fuel	**Modified Turbine** 0 to about Mach 3.5 Hydrocarbon fuel	**Turboramjet** 0 up to about Mach 5 Hydrocarbon fuel	**Ramjet** Mach 3 to about Mach 5 Hydrocarbon fuel	**Scramjet** Mach 5+ Hydrogen fuel
✓	✓	✓	✓	✓

Mitigation of Barriers and their Impacts

Figures A4.29 through A4.57 describe proposed NASA mitigative actions to address the previously defined barriers, their anticipated level of effort to the agency, and their potential impact.

Figure A4.29. Barrier 1 – Runway length, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Public-Private Partnership	**NASA Level of Effort**	LOW
NASA Mitigations	• Provide the FAA and airport authorities technical expertise to advise on potential runway limitations and facilitate discussions between aircraft developers and the FAA and airport authorities to understand facility limitations and design aircraft to operate within current airport operating restrictions • Support the modeling and analysis of aircraft design to improve lift to shorten takeoff and landing distance • Support the modeling and analysis of runway designs		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Airport authorities will identify potential runway extension solutions and can leverage NASA's technical expertise to analyze and optimize solutions
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	Airport Authorities	**Other Key Actors**	FAA, Industry

Figure A4.30. Barrier 2 – Infrastructure, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Direct Financial Resources	**NASA Level of Effort**	LOW
NASA Mitigations	Facilitate discussions between the FAA, airport authorities and aircraft developers to identify and analyze facility limitations and assist in designing aircraft to operate within current airport operating restrictions		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Airport authorities will identify potential infrastructure issues and limitations and can leverage NASA's technical expertise to analyze and optimize solutions
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	Airport Authorities	**Other Key Actors**	Industry

Figure A4.31. Barrier 3 – Special maintenance and personnel, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support, Direct Financial Resources, Direct Program, Public-Private Partnership, Seed/Prize/Grant	**NASA Level of Effort**	MODERATE
NASA Mitigations	• Provide technical expertise and modeling capability to the FAA to support the analysis of maintenance activities and processes to identify potential impacts and limitations. • Support the design, analysis and implementation of line replaceable modules to facilitate plug and play maintenance repairs • Support the development of training simulation for support personnel		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		NASA can support aircraft manufacturers and operators in comprehensively addressing and incorporating maintenance and support requirements early in the design process to reduce barriers to turn around time, environmental (disposal processes) and certification requirements
	Moderate Impact	✓	
	Limited Impact		
Primary Implementer	Industry	**Other Key Actors**	NASA, FAA

Figure A4.32. Barrier 4 – Pre-flight inspections, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and advisory Services	**NASA Level of Effort**	**MODERATE**
NASA Mitigations	Support the FAA to facilitate working groups and assist industry in the identification, analysis and development of comprehensive maintenance and logistics requirements and processes and ensure that the are incorporated early into the life cycle planning and development stages.		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Industry can leverage NASA capabilities to assist in the development of maintenance processes.
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	Industry	**Other Key Actors**	NASA

Figure A4.33. Barrier 5 – Post-flight cool down, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Direct Program Private Equity	**NASA Level of Effort**	**LOW**
NASA Mitigations	Assist the FAA in establishing and facilitating working groups including aircraft developers, operators and airport management to identify potential cool down timelines and to develop appropriate safety and aircraft handling procedures early in the design process		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	Airport Authorities	**Other Key Actors**	FAA, Industry

Figure A4.34. Barrier 6 – Cryogenics, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Public-Private Partnerships	**NASA Level of Effort**	**MODERATE**
NASA Mitigations	Facilitate working groups and provide technical expertise to support the FAA, Airport Authorities, and aircraft developers and operators to assist in the identification and analysis of storage, transport and handling requirements for cryogenic fuels		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Airport Authorities will require extensive technical and analytical support to identify and program for needed infrastructure improvements to support the inclusion of cryogenic fuels into existing refueling capabilities.
	Moderate Impact	✓	
	Limited Impact		
Primary Implementer	Airport Authorities	**Other Key Actors**	FAA, Industry

Figure A4.35. Barrier 7 – Air traffic systems, proposed NASA mitigation, level of effort, and potential impact.

<table>
<tr><td rowspan="1">Mitigation Types</td><td colspan="2">Infrastructure Support and Advisory Services, Grants, Seed/Prize/Grant Direct Financial Resources, COTS procurement, Grant, Seed/Prize/Grant</td><td>NASA Level of Effort</td><td>MODERATE</td></tr>
<tr><td rowspan="5">NASA Mitigations</td><td colspan="4">• Assist the FAA in planning and conducting of additional studies and analysis to examine potential flight operations in the future and identify needed processes and technology requirements to support SST/HST integration into the ecosystem.
• Provide modeling and simulation capabilities to support air space design to effectively incorporate non-conventional aircraft into operational air space
• Assist the FAA in the market research, identification, analysis and selection of more capable and automated future airport air traffic management systems</td></tr>
<tr><td colspan="2">Impact of NASA Mitigation
<i>(Does NASA action fully address barrier?)</i></td><td colspan="2">Discussion</td></tr>
<tr><td>Significant Impact</td><td>✓</td><td colspan="2" rowspan="3">FAA should leverage NASA expertise and capability to comprehensively plan, address, study and evaluate future flight operations early in the design process.</td></tr>
<tr><td>Moderate Impact</td><td></td></tr>
<tr><td>Limited Impact</td><td></td></tr>
<tr><td>Primary Implementer</td><td colspan="2">FAA</td><td>Other Key Actors</td><td>Industry, Airport Authorities</td></tr>
</table>

Figure A4.36. Barrier 8 – Type certification, proposed NASA mitigation, level of effort, and potential impact.

<table>
<tr><td>Mitigation Types</td><td colspan="2">Intra-governmental Engagement, Infrastructure Support and Advisory Services, Direct Financial Resources, Grants, Public-Private Partnerships</td><td>NASA Level of Effort</td><td>HIGH</td></tr>
<tr><td rowspan="5">NASA Mitigations</td><td colspan="4">• Facilitate working groups to support the FAA, airport authorities, and aircraft developers and operators to assist in informing industry on FAA certification processes, procedures, and requirements [Facilitation and Coordination]
• Provide modeling and analysis capabilities to the FAA to support the development, VV&A, and implementation of advanced simulation to help reduce certification delays [Modeling and Simulation, Test and Evaluation, Studies and Analysis, Software Development]
• Work closely with developers, providing technical expertise in the development of cleaner propulsion systems and fuels supporting safety capabilities [Design and Development]</td></tr>
<tr><td colspan="2">Impact of NASA Mitigation
<i>(Does NASA action fully address barrier?)</i></td><td colspan="2">Discussion</td></tr>
<tr><td>Significant Impact</td><td>✓</td><td colspan="2" rowspan="3">• The FAA can leverage NASA expertise and capabilities to develop and implement aircraft flight simulations and testing across varied weather and environmental conditions and cruising altitudes
• Primary Implementer Role: Issues and enforces regulations for the safety of civil aviation via certification, inspection, and other measures. In addition, FAA conducts RDT&E on systems and procedures needed for a safe and efficient system of air navigation and air traffic control (better aircraft, engines, and equipment; testing and evaluation of aviation systems, devices, materials, and procedures; and aeromedical research)</td></tr>
<tr><td>Moderate Impact</td><td></td></tr>
<tr><td>Limited Impact</td><td></td></tr>
<tr><td>Primary Implementer</td><td colspan="2">FAA</td><td>Other Key Actors</td><td>EPA, Industry</td></tr>
</table>

Figure A4.37. Barrier 9 – Stability and control, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Intragovernmental engagement, Infrastructure Support and Advisory Services, Direct Financial Resources, Grants, Public-Private Partnerships	**NASA Level of Effort**	**HIGH**
NASA Mitigations	Provide technical expertise and modeling and simulation to FAA and developers to investigate the development, VV&A, and implementation of subsonic, trans-sonic, supersonic, and hypersonic flight characteristics across a wide variety of weather and environmental conditions **[Modeling and Simulation, Test and Evaluation, Software Development]**		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact	✓	• FAA can leverage NASA expertise and capabilities in developing advanced modeling and simulation to support the analysis of low-speed flight characteristics in a wide variety of weather and environmental conditions early in the design process to significantly reduce actual flight time requirement • **Primary Implementer Role:** Issues and enforces regulations for the safety of civil aviation via certification, inspection, and other measures. In addition, FAA conducts RDT&E on systems and procedures needed for a safe and efficient system of air navigation and air traffic control (better aircraft, engines, and equipment; testing and evaluation of aviation systems, devices, materials, and procedures; and aeromedical research)
	Moderate Impact		
	Limited Impact		
Primary Implementer	FAA	**Other Key Actors**	Industry

Figure A4.38. Barrier 10 – Extended operations (ETOPS), proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Intra-governmental Engagement, Infrastructure Support and Advisory Services, Direct Financial Resources, Grants, Public-Private Partnerships	**NASA Level of Effort**	**HIGH**
NASA Mitigations	• Provide technical expertise and modeling and simulation develop capabilities to the FAA and developers to support the development, VV&A and implementation of advanced simulation to model single engine flight characteristics and ranges in a wide variety of weather and environmental conditions to help reduce actual flight hours. • Assist developers in the design, analysis and development of more reliable engines a wide variety of weather and environmental conditions to help reduce actual flight hours. • Assist developers (aircraft and engine) with simulation and accelerated engine life-cycle testing to determine component redundancy requirements and provide more confidence to certification authorities		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact	✓	FAA and NASA efforts in developing advanced modeling and simulation to support the analysis of Extended-range Twin-engine Operational Performance Standards in a wide variety of weather and environmental conditions early in the design process will significantly reduce ETOPS flight time barriers
	Moderate Impact		
	Limited Impact		
Primary Implementer	FAA	**Other Key Actors**	Industry

Figure A4.39. Barrier 11 – Emergency descent and landing, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Direct Financial Resources, Infrastructure Support and Advisory Services, Direct Program, Public-Private Partnership	**NASA Level of Effort**	**HIGH**
NASA Mitigations	• Provide technical expertise and analytical capability to the FAA and Industry to support the development, VV&A and implementation of advanced simulation to model emergency decent processes and characteristics from a variety of operational heights and under a wide variety of weather and environmental conditions to help reduce actual flight hours. • Assist developers with simulation in the design and development of advanced oxygen storage and generation systems to ensure passenger safety		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact	✓	The FAA working with NASA to develop and implement simulation and evaluation of emergency decent and landing processes in a wide variety of weather and environmental conditions early in the design process and will significantly reduce FAR Part 25.841 barriers
	Moderate Impact		
	Limited Impact		
Primary Implementer	FAA	**Other Key Actors**	Industry

Figure A4.40. Barrier 12 – New partial and full automation requirements, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, National Policy		**NASA Level of Effort**	**LOW**
NASA Mitigations	• Facilitate working groups for the FAA with industry to identify and support the update of critical 14 CFR chapters to support SST and HST Certification • Facilitate working groups for the FAA with avionics manufacturers and certification authorities to review applicable avionics standards to determine those that will require updating on supporting assumptions and algorithms to support high speed flight operations (e.g., TCAS/ACAS) • Provide interagency coordination support to the FAA to establish a new office to initiate the development of supporting certification processes of these emerging and unique capabilities			
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**	
	Significant Impact		NASA's technical expertise in full automation flight capabilities can assist the FAA and Industry in the development of an updated 14 CFR to accommodate full automation capability. These actions are not a core function of NASA and will only minimally impact their mission and capabilities	
	Moderate Impact	✓		
	Limited Impact			
Primary Implementer	FAA		**Other Key Actors**	NASA, Industry

Figure A4.41. Barrier 13 – Prohibition of overflight, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Direct Financial Resources National Policy, Enabling Public Input, Government Promotion, Infrastructure Support and Advisory Services		**NASA Level of Effort**	**HIGH**
NASA Mitigations	• Continue to pursue sonic boom reduction technologies and social science experiments to determine the acceptable level of noise and sonic boom **[System Design and Development]** • Facilitate working groups for the FAA to identify and support updates to relevant 14 CFR chapters to support SST and HST certification and to establish reasonable target noise levels that engine and airframe manufactures can work towards **[Interagency Facilitation and Coordination, Technical Expertise, Studies and Analysis]** • Facilitate working groups for the FAA with the DoS and industry to identify potential foreign regulation requirements potential issues and impediments, develop mitigation strategies, and pursue appropriate treaty/regulation adjustments **[Interagency Facilitation and Coordination, Technical Expertise, Studies and Analysis]**			
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**	
	Significant Impact	✓	• The FAA will lead the planning and update of 14 CFR and international regulations. The implementation of NASA's sonic boom reduction technologies and the FAA leveraging their technical expertise will significantly reduce certification barriers • **Primary Implementer Role:** Issues and enforces regulations for the safety of civil aviation via certification, inspection, and other measures. In addition, FAA conducts RDT&E on systems and procedures needed for a safe and efficient system of air navigation and air traffic control (better aircraft, engines, and equipment; testing and evaluation of aviation systems, devices, materials, and procedures; and aeromedical research)	
	Moderate Impact			
	Limited Impact			
Primary Implementer	FAA		**Other Key Actors**	Industry

Figure A4.42. Barrier 14 – Ground test equipment, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Direct Financial Resources, Public-Private Partnerships, Infrastructure Support and Advisory Services		**NASA Level of Effort**	**HIGH**
NASA Mitigations	• Provide technical expertise and development capabilities to the FAA, DoD and industry to support the development, VV&A and implementation of advanced simulation to model propulsion system performance at Mach speeds greater than 3 to 4 • Assist in identifying and coordinating for the use of limited ground test facilities/capabilities for speeds greater than Mach 3			
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**	
	Significant Impact	✓	Investment in and use of NASA's modeling and simulation capabilities to augment limited ground test facilities will significantly reduce testing barriers.	
	Moderate Impact			
	Limited Impact			
Primary Implementer	NASA		**Other Key Actors**	FAA, Industry

Figure A4.43. Barrier 15 – Noise, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services , Grants, Contests and Prizes, Public-Private Partnerships, Private Equity	**NASA Level of Effort**	**MODERATE**
NASA Mitigations	• Provide technical expertise to coordinate and assist industry in the continued development of quieter turbofan engine design to support the development of quieter combined engine propulsion systems • Support the modeling and analysis of aircraft design to improve lift to minimize the use of afterburners during takeoff and thrust reversers during landings • Leverage SBIR, STTR and grants to support the development of innovative technical solutions • Work with the FAA to establish an integrated industry development team and implementation of a systems of systems development approach		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Industry is leading the effort to develop and implement quitter turbo fan engines to meet tighter noise standards. NASA can play a significant support role in helping to identify and integrate innovative noise reduction technologies
	Moderate Impact	✓	
	Limited Impact		
Primary Implementer	Industry	**Other Key Actors**	FAA

Figure A4.45. Barrier 16 – Emissions, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Direct Financial Resources, Public-Private Partnerships	**NASA Level of Effort**	**HIGH**
NASA Mitigations	• Provide technical expertise to the FAA and industry to develop alternative fuel solutions to reduce CO_2 and other green house gases **[Studies and Analysis, Interagency/International/Industry Facilitation and Coordination]** • Provide technical expertise and infrastructure to industry to develop supporting modeling to evaluate various non-hydrocarbon fuels emissions against propulsion system performance **[Modeling and Simulation, Software Development]**		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact	✓	• NASA's technical expertise and modeling capabilities will provide the FAA, EPA and industry significant environmental analytical support of alternative fuels and support industry in the modeling of those fuels impacts on propulsion system performance and potential environmental impacts • SST and HST aircraft will be required to adhere to the Clean Air Act of 1963, Title II Part B covers aircraft emissions and it adopts ICAO standards. The EPA sets emissions certification requirements • For any hydrocarbon-based fuels, it matters where the emissions are produced. Above 55,000 feet, the emissions will reside in atmosphere for extended period of time, presenting a functional barrier for some SST and HST concepts • **Primary Implementer Role:** FAA conducts RDT&E on systems and procedures needed for a safe and efficient system of air navigation and air traffic control (better aircraft, engines, and equipment; testing and evaluation of aviation systems, devices, materials, and procedures; and aeromedical research)
	Moderate Impact		
	Limited Impact		
Primary Implementer	FAA	**Other Key Actors**	Industry, EPA

Figure A4.46. Barrier 17 – Hazardous materials, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Grants, Seed/Prizes/Grants	**NASA Level of Effort**	**LOW**
NASA Mitigations	• Coordinate with the EPA and industry to identify potentially hazardous materials, and develop handling, disposal and remediation processes • Leverage SBIR, STTB and Grants to support the development of handling, disposal and remediation processes and capabilities		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		NASA is expected to provide only minimal assistance to the EPA in the identification of hazardous materials and development of remediation processes
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	EPA	**Other Key Actors**	NASA, Industry

Figure A4.47. Barrier 18 – ITAR restrictions, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	National Policy, Infrastructure Support and Advisory Services, Public-Private Partnerships	**NASA Level of Effort**	**LOW**
NASA Mitigations	• Facilitate and coordinate meetings between industry and the State Department's Directorate of Defense Trade Controls (DDTC) early in the development cycle to identify potentially restricted technologies • Facilitate working groups with the DoD to identify/determine which DoD technologies would be helpful for industry to leverage and that would not represent ITARS challenges • Support industry in the research, development and design of alternative critical engine, avionics and computer flight management systems to replace restricted components		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Industry will be the lead to establish early coordination with DDTC to determine ITAR restrictions and to develop appropriate strategies to resolve potential issues and restrictions. Software and cyber security also identified as a potential ITAR issues. NASA can provide technical and operational support
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	Industry	**Other Key Actors**	Dos (DDTC), DoD, NASA

Figure A4.48. Barrier 19 – GNSS receivers, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	National Policy, Infrastructure Support and Advisory Services, Public-Private Partnership, Seed/Prize/Grant	**NASA Level of Effort**	**MODERATE**
NASA Mitigations	• Facilitate and coordinate meetings between industry and the State Department's Directorate of Defense Trade Controls (DDTC) and DoD early in the development cycle to identify potentially restricted technologies **[Interagency/Industrial Facilitation and Coordination]** • Facilitate working groups with the DoD to identify/determine which DoD technologies would be helpful for industry to leverage and that would not represent ITARS challenges **[Interagency/Industry Facilitation and Coordination]** • Support industry in the RDT&E of alternative critical engine, avionics, and computer flight management systems to replace restricted components **[System Design and Development, Technical and Analytical Expertise]** • Work with industry to leverage the SBIR, STTR, and grant programs to develop innovative alternative technologies **[Interagency/Industry Facilitation and Coordination]**		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		**Primary Implementer Role:** Industry will be the lead to establish early coordination with DDTC and DoC to determine if GNSS receivers are an export restricted technology. NASA can assist in the identification or development of alternative solutions
	Moderate Impact	✓	
	Limited Impact		
Primary Implementer	Industry	**Other Key Actors**	DoS (DDTC), FAA, DoD, DoC, NASA

Figure A4.49. Barrier 20 – Insurance, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services	**NASA Level of Effort**	**LOW**
NASA Mitigations	Provide simulation support combined with the manufactures flight hours to help demonstrate the overall safety and performance of experimental aircraft to help reduce insurance costs		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Industry will be responsible for determining and obtaining the supporting analytical requirements
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	Industry	**Other Key Actors**	FAA, NASA

Figure A4.50. Barrier 21 – Regulatory timeline, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	National Policy, Infrastructure Support and Advisory Services	**NASA Level of Effort**	**LOW**
NASA Mitigations	Provide technical expertise to the FAA and facilitate working groups with other Government agencies, congressional staff and industry to support the more rapid development, coordination, communication and approval of new regulations to support the certification of high-speed aircraft		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		FAA is the lead for the development, update and approval of regulations related to the operations and certification of high-speed aircraft. These actions are not a core function of NASA and will only minimally impact their mission and capabilities
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	FAA	**Other Key Actors**	NASA, Industry

Figure A4.51. Barrier 22 – International coordination, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	National Policy, Government Promotion	**NASA Level of Effort**	**LOW**
NASA Mitigations	Facilitate working groups with the DoS, FAA and industry to identify potential foreign regulation requirements, potential issues and impediments, develop mitigation strategies and pursue appropriate treaty/regulation adjustments		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		DoS will need to lead the effort to identify and negotiate acceptable solutions potentially restrictive international regulations. NASA will be able to provide supporting technical and operational expertise to the working group
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	DoS	**Other Key Actors**	FAA, NASA

Figure A4.52. Barrier 23 – Climate concerns, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Direct Financial Resources, Infrastructure Support and Advisory Services, Grants, National Policy	**NASA Level of Effort**	**MODERATE**
NASA Mitigations	• Provide technical expertise to the FAA, EPA, DoS and industry to support the analysis and development of alternative fuel solutions (e.g., hydrogen fuel) to reduce CO_2 and other green house gases • Work with the EPA to develop supporting modeling to evaluate various non-hydrocarbon fuels emissions against propulsion system performance • Work with the EPA, DoS and industry to identify future environmental trends and requirements and develop modeling to evaluate the potential impacts and develop mitigation strategies		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		EPA will lead in the development of future U.S. emission standards, while DoS will be responsible for coordinating and negotiating international emission standards. NASA can provide key analytical capabilities to determine potential impacts of high-speed aircraft operations on the environment
	Moderate Impact	✓	
	Limited Impact		
Primary Implementer	EPA	**Other Key Actors**	FAA, NASA, DoS

Figure A4.53. Barrier 24 – Virtual communications, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Government Promotion, Public-Private Partnerships	**NASA Level of Effort**	**LOW**
NASA Mitigations	• Support manufacturers and operators to develop aggressive marketing campaigns to draw back business customers and expand the leisure market • Assist in the development of improved aircraft mobile digital platforms to allow travelers to be constantly connected		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		Industry will have to lead the effort to development and implement an effective marketing that will help to maintain and expand the passenger market reducing the barrier to commercialization. These actions are not a core function of NASA and will only minimally impact their mission and capabilities
	Moderate Impact		
	Limited Impact	✓	
Primary Implementer	Industry	**Other Key Actors**	NASA

Figure A4.54. Barrier 25 – Aircraft and parts in quantity, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Seed/Prize/Grants	**NASA Level of Effort**	**MODERATE**
NASA Mitigations	• Leverage their technical expertise in processing and manufacturing exotic materials to support industry in the development, assessment, prototyping and validation of new and scalable manufacturing processes • Provide grants and leverage SBIR and STTR programs for the development of innovative scalable manufacturing technologies and processes		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact		While NASA can significantly support the effort it will require that manufactures work with suppliers to identify requirements, capabilities and to establish new supply channels if required
	Moderate Impact	✓	
	Limited Impact		
Primary Implementer	Industry	**Other Key Actors**	NASA, Industry (Small Business)

Figure A4.55. Barrier 26 – Special materials, proposed NASA mitigation, level of effort, and potential impact.

Mitigation Types	Infrastructure Support and Advisory Services, Direct Financial Resources, Direct Program, Seed/Prize/Grants	**NASA Level of Effort**	**HIGH**
NASA Mitigations	• Provide technical assessment to perform testing/assessment of special material (for example, silicon carbide composites, nickel-based alloys, and carbon composites) performance in actual flight, in high-speed test chambers, and environmental chambers **[Modeling and Simulation, Test and Evaluation, System Design and Development]** • Develop advanced simulations to evaluate the performance of special materials under a variety of environmental conditions reducing actual flight time and expensive chamber time **[Modeling and Simulation, Test and Evaluation, Software Development]** • Work with industry leverage SBIR, STTR, and grant programs to support the development of innovative assessment capabilities and processes to accommodate special materials **[Interagency/Industry Facilitation and Coordination]**		
	Impact of NASA Mitigation *(Does NASA action fully address barrier?)*		**Discussion**
	Significant Impact	✓	• NASA leadership, operational, and technical expertise will be critical to the development of effective assessment capabilities and processes and the development of supporting modeling and simulation environments • **Primary Implementer Role:** NASA ARMD is focused on the design, development, and testing of advanced technologies that can make aviation more environmentally friendly, maintain safety in more crowded skies, and ultimately modernize the aviation industry
	Moderate Impact		
	Limited Impact		
Primary Implementer	NASA	**Other Key Actors**	Industry (Small Business)

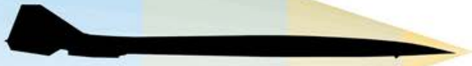


Figure A4.56. Barrier 27 – Aircrews, proposed NASA mitigation, level of effort, and potential impact.

<table>
<tr><td>Mitigation Types</td><td colspan="2">Direct Financial Resources, Seed/Prize/Grants</td><td>NASA Level of Effort</td><td>MODERATE</td></tr>
<tr><td rowspan="5">NASA Mitigations</td><td colspan="4">• Leverage their technical expertise to assist the FAA and industry in the development, assessment and implementation of innovative simulation-based flight training capabilities to support the training and certification of qualified aircrews
• Leverage SBIR, STTR and Grant programs to develop innovative alternative training and simulation technologies</td></tr>
<tr><td colspan="2">Impact of NASA Mitigation
<i>(Does NASA action fully address barrier?)</i></td><td colspan="2">Discussion</td></tr>
<tr><td>Significant Impact</td><td></td><td colspan="2" rowspan="3">While NASA can significantly support the effort it will require that the FAA and industry develop the operational and training requirements and standards that must be simulated/modeled</td></tr>
<tr><td>Moderate Impact</td><td>✓</td></tr>
<tr><td>Limited Impact</td><td></td></tr>
<tr><td>Primary Implementer</td><td colspan="2">FAA</td><td>Other Key Actors</td><td>NASA, Industry, Academia</td></tr>
</table>

Figure A4.57. Barrier 28 – Engineering and manufacturing skills, proposed NASA mitigation, level of effort, and potential impact.

<table>
<tr><td>Mitigation Types</td><td colspan="2">Direct Financial Resources Grants, Seed/Prize/Grants, Infrastructure support and Advisory Services</td><td>NASA Level of Effort</td><td>MODERATE</td></tr>
<tr><td rowspan="5">NASA Mitigations</td><td colspan="4">• Leverage their technical expertise to assist industry in the development, assessment and implementation of innovative simulation-based engineer training capabilities to support the training and certification of qualified engineer and manufacturing professionals
• Leverage SBIR, STTR and Grant programs to develop innovative alternative training and simulation technologies
• Coordinate with industry and academia to develop and establish engineering specialties with a focus on high-speed aircraft design, operations and maintenance</td></tr>
<tr><td colspan="2">Impact of NASA Mitigation
<i>(Does NASA action fully address barrier?)</i></td><td colspan="2">Discussion</td></tr>
<tr><td>Significant Impact</td><td>✓</td><td colspan="2" rowspan="3">NASA leadership and technical expertise will be critical to the development of educational and training standards and to the development of supporting simulation capabilities</td></tr>
<tr><td>Moderate Impact</td><td></td></tr>
<tr><td>Limited Impact</td><td></td></tr>
<tr><td>Primary Implementer</td><td colspan="2">NASA</td><td>Other Key Actors</td><td>Industry, Academia</td></tr>
</table>