NASA/CR–20220015464

Life Cycle Cost Modeling of High-speed Commercial Aircraft

Hayden R. Magill, John R. Olds, Mark G. Schaffer, and Ami N. Patel
SpaceWorks Enterprises, Inc., Atlanta, Georgia

September 2022

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

NASA/CR–20220015464

Life Cycle Cost Modeling of High-speed Commercial Aircraft

Hayden R. Magill, John R. Olds, Mark G. Schaffer, and Ami N. Patel
SpaceWorks Enterprises, Inc., Atlanta, Georgia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract 80NSSC22C0008

September 2022

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

SpaceWorks®

Life Cycle Cost Modeling of High-speed Commercial Aircraft
Final Report

National Aeronautics and Space Administration
Aeronautics Research Mission Directorate

NASA SBIR/STTR contract #80NSSC22C0008

September 2022

CONTENTS

1 - EXECUTIVE SUMMARY

SpaceWorks has concluded a 9-month research and development project aimed at addressing key questions in NASA's effort to anticipate, understand, and ultimately support the emerging high-speed commercial flight marketplace. The current project may be viewed as a follow-on to a 2021 study led by Deloitte and SpaceWorks entitled *Independent Market Study: Commercial Hypersonic Transportation*. Based in part on the recommendations of that prior study, the objectives of this current effort were to improve both flight performance and economic models, explore new model methodologies, and to leverage those to perform new and more complex trade studies and sensitivity studies.

The aircraft design space explored during this effort was cruise Mach between 2 and 5, maximum operating range between 3,500 and 7,000 nmi, passenger counts between 20 and 50, and fuel options of Jet-A, sustainable aviation fuel (SAF), liquified natural gas (LNG), and liquified hydrogen (LH2). To conduct rapid parametric sizing, cost estimation, and business case analysis for aircraft in this design space, SpaceWorks leveraged their internally developed Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA) modeling capability. The existing high-speed aircraft ROSETTA model used for the 2021 independent market study served as the starting point for model development under the current design effort.

First, SpaceWorks expanded the modeling capabilities of its existing ROSETTA model, used in the previous study to evaluate single aircraft design and operations scenarios, to simulate the business cases of up to two parallel aircraft developed and produced by exclusive manufacturers and then operated by a single Elite Airline as a mixed fleet. NASA provided SpaceWorks with a trade matrix of aircraft to evaluate mixed fleet solutions based on the assumption that a short-range aircraft servicing mostly transatlantic routes and a long-range aircraft servicing mostly transpacific routes would create a better business case solution. The results indicated that a mixed fleet could achieve a similar internal rate of return as the single aircraft cases and captured somewhat more of the high-speed passenger market. However, in these simulations, the long-range aircraft had a difficult time achieving sustainable production rates due to a higher percentage of the market being concentrated on shorter, transatlantic routes. Ticket prices increased on long range routes, and unit airframe and engine production dropped. SpaceWorks recommends future analysis of mixed fleets be segregated by route demand rather than route distance.

SpaceWorks re-examined the trade space assuming the use of alternative fuels (sustainable aviation fuel, liquid natural gas, and liquid hydrogen). Carbon-neutral SAF had very similar technical results to the previous Jet-A analysis but suffered economically due to higher cost SAF fuels at the beginning of the simulations. LNG had impressive business cases with relatively low fuel prices and higher fuel performance but had to overcome higher development and production costs. Zero-carbon LH2 struggled to meet the minimum internal rate of return requirements in the simulation due to the low density of the LH2 fuel (large aircraft volumes required) and the high development costs necessary to field a hydrogen engine and airframe. SpaceWorks recommends SAF as the best option going forward given its carbon neutral potential, minimal technical impact on existing aircraft, and current levels of integration into the existing infrastructure. LNG and LH2 have potential in the long-term but have too many technical and economic challenges to overcome in the short- to medium-term.

A sensitivity study was conducted to evaluate the economic impact if overland, high-speed flight restrictions were hypothetically lifted, and overland supersonic routes became available across the U.S. and North America. The significant market size unlocked by overland routes enables robust business cases where manufacturers achieve substantial engine and airframe production volumes. However, the Elite Airline was somewhat overwhelmed by the very high fleet acquisition costs. A staggered rollout of services to this larger market is recommended for future analysis. However, larger passenger counts proved to be better suited for the larger market and LH2 aircraft flying at Mach 2 could achieve successful business cases at shorter ranges (smaller aircraft). SpaceWorks recommends a "leader" / "follower" approach be investigated in future studies that evaluates a smaller, transoceanic aircraft to start and is followed by a larger aircraft that could service overland routes assuming restrictions have been lifted by that point.

A final sensitivity study was conducted to evaluate the impact of delaying initial operating capability and allowing the market and technology to grow and mature. SpaceWorks developed "k-factors" to project changes over time. Based on the results, market growth and improvements in propulsion areas proved to be the most beneficial to business cases. SpaceWorks recommends future NASA technology investments be focused in the propulsion area. Finally, SpaceWorks developed a new and more capable multi-method modeling and simulation tool using AnyLogic to provide greater insight and granularity into the high-speed flight industry and fleet operations. This model has been validated against the existing Excel-based ROSETTA model. SpaceWorks recommends future studies utilize the AnyLogic model going forward.

2 - STUDY OBJECTIVES & APPROACH

In recent years there has been a significant increase in the number of aerospace companies, both well-established and start-ups, that have proposed and even started to build and test aircraft concepts aimed at commercial point-to-point travel in the supersonic to hypersonic speed regime. Airline operators are starting to place orders for such aircraft, and even Wall Street has taken note, with several firms publishing reports on expected market size and viability. This growth in interest prompted the Hypersonic Technology Project (HTP) to hold a forum with stakeholders across government and industry in conjunction with the 2020 AIAA SciTech Conference. As a result of that meeting, HTP subsequently funded two studies to begin to examine the economic viability, regulatory barriers, and technical challenges associated with this high-speed commercial market.

This study serves as a follow-on to those efforts, with a goal of refining the life cycle modeling of high-speed commercial aircraft. Information developed under this activity will be used to guide the development of a series of reference vehicle concepts spanning the trade space of interest which will be used to guide future research and technology development aimed at eliminating barriers and enabling a sustainable, viable high-speed market.

2.1 - PREVIOUS STUDY REVIEW

Under one of the two previously sponsored study efforts, the team of Deloitte & Touche, LLP, the National Institute of Aerospace, and SpaceWorks Enterprises, Inc. (the Deloitte Team) executed an independent study for NASA entitled *Independent Market Study: Commercial Hypersonic Transportation* from August 2020 to April 2021 (National Aeronautics and Space Administration, Data and Technical Support Services (DATSS), TORFQ 36, Contract No. 80HQTR18A0010)[1].

The prior study had three primary objectives:

Define the market for high-speed commercial flight (Mach > 2)

The Deloitte Team surveyed traveling passengers and leading businesses to quantify annual demand for scheduled supersonic and/or hypersonic flight on select transatlantic and transpacific air routes, as a function of time savings and expected ticket premiums relative to today's subsonic travel on those same routes. This data was used to create predictive annual passenger demand curves for 90 representative over-water routes with origins or destinations in the United States.

Define the business cases for manufacturers and operators

SpaceWorks created a multidisciplinary ROSETTA (Reduced-order Spreadsheet for Evaluation of Technologies and Transportation Architectures) model to evaluate the potential business cases for supersonic/hypersonic engine manufacturers, airframe manufacturers, and airline operators. The model was used to explore a large trade space of different aircraft passenger capacities, unrefueled aircraft ranges, and maximum flight speeds (up to Mach 6). Conceptual aircraft throughout the trade space were sized using basic mission performance models and aircraft sizing relationships. For each candidate aircraft evaluated in the ROSETTA model, economic variables were optimized to create the best business cases for each player in the economy. The study objective was to identify the presence of any attractive regions of the design space where a high-speed aircraft design could be manufactured and operated with profitable business cases for all three players in the supply chain.

Identify and Understand Barriers to High-Speed Transportation

The Deloitte Team conducted independent research and interviewed leading business professionals to identify key barriers to future high-speed commercial flight (Mach > 2). Challenges were identified in aircraft emissions, overflight noise (sonic booms), takeoff noise, aircraft certification difficulties, and others. Even if future business models look attractive in a business model simulation, these challenges present serious barriers to future companies seeking to develop supersonic or hypersonic commercial aircraft.

Prior Findings and Recommendations

This previous study identified some encouraging solutions in the trade space. While several attractive economic solutions existed for aircraft with speeds above Mach 3, within the extensive assumptions made in the study, the most robust area of the trade space resulted from Mach 2 aircraft with 20-30 passengers and unrefueled ranges of 4,500-5,500 nmi. Aircraft designs in this region of the trade space had high production rates, high load factors, lower ticket prices, and were able to address most of the busiest trans-oceanic passenger routes. Aircraft of this size also had beneficial production and sales synergies with private-owner and charter aircraft markets.

Follow-on discussions with NASA personnel identified additional research questions of interest. How would the implementation of proposed alternate aviation fuels affect the results? Would a business solution with two supersonic/hypersonic aircraft types - one with a shorter range and one with a longer range - create a more optimum load factor across the mixed fleet? How would the introduction of new aircraft technologies affect the results, even if the supersonic/hypersonic service initiation date had to be delayed? Can the modeling and simulation tool be improved to create a more robust and capable tool?

These questions were the impetus of the present study effort, which serves as a logical extension of the Deloitte Team's foundational effort in 2020 – 2021.

---

[1] https://ntrs.nasa.gov/citations/20210014711

2.2 - CURRENT STUDY OBJECTIVES & OVERVIEW

Under this 9-month study for Life-Cycle Cost Modeling of High-Speed Commercial Aircraft, SpaceWorks was tasked with expanding the depth of analysis based on the results from the previous *Independent Market Study: Commercial Hypersonic Transportation* effort. The goal was to analyze the potential for high-speed flight from multiple technical and economic perspectives. Then, based on the results, provide recommendations for how NASA should support the overall high-speed flight industry. Seven main tasks were identified in the statement of work for the current study:

> *Task 1:*
> Beginning with the existing ROSETTA Model, develop a Two-Aircraft Type Model that evaluates the economic performance of a short-range aircraft design and a long-range aircraft[2] in their corresponding markets.
>
> *Task 2:*
> Develop and generate summary slides for conceptual aircraft designs of interest that display key technical and economic metrics.
>
> Task 3:
> Perform a trade space analysis of Jet-A aircraft to evaluate single aircraft economic performance against a mixed fleet solution that includes a short-range aircraft and long-range aircraft to address the transatlantic and transpacific markets, respectively.
>
> Task 4:
> Using the same trade matrix as described in Task 3, perform a trade space analysis of alternative fuels: Sustainable/Synthetic Aviation Fuel (SAF), Liquid Natural Gas (LNG), and Liquid Hydrogen (LH2).
>
> Task 5:
> Perform a sensitivity analysis of Jet-A aircraft assuming that regulatory constraints are not an issue and, therefore, supersonic overland routes are accessible.
>
> Task 6:
> Perform a sensitivity analysis of Jet-A aircraft evaluated at different Initial Operating Capability (IOC) dates to determine the economic impact of waiting for improved technology and/or larger addressable markets.
>
> Task 7:
> Develop a modeling and simulation (M&S) tool for enhanced economic analysis capabilities to provide greater insight into economic behaviors.

Except for Task 4, the alternative fuel trade study, all other tasks assumed the continued use of Jet-A hydrocarbon fuel when evaluating technical and economic parameters within each business case. More detail will be provided for each task in the Methodology and Assumptions section or in the Analysis and Results section as applicable.

The following section describes SpaceWorks' general methodology and major assumptions that stay consistent throughout the study.

2.3 - METHODOLOGY AND ASSUMPTIONS

2.3.1 - ROSETTA Model

Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA) models are fast-acting multi-disciplinary design optimization tools. Typically built in Microsoft Excel, a ROSETTA model is a representation of the design process for a specific aerospace vehicle or architecture. ROSETTA models are an early design tool used to support the rapid redesign of vehicle architectures for design space exploration and trade space analysis.

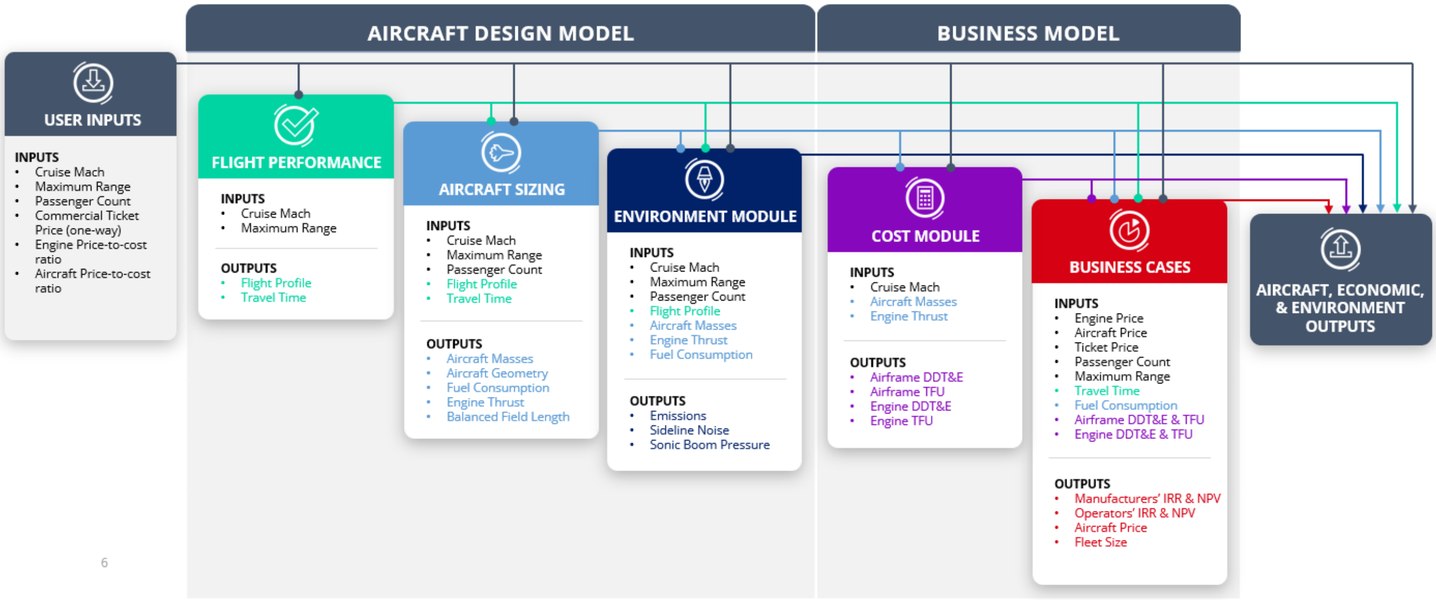
ROSETTA models fall into three categories. A Category 1 ROSETTA model produces traditional physics-based outputs such as system weight, size, range, and/or payload. A Category 2 ROSETTA model adds operations, cost, and economic analysis outputs such as turnaround time, life cycle cost, cost per flight, return on investment, internal rate of return (IRR), and the price per pound of payload. A Category 3 ROSETTA model adds parametric safety outputs such as catastrophic failure reliability, mission success reliability, and the probability of loss of passengers and/or crew. The existing Category 2 ROSETTA model from the previous *Independent Market Study: Commercial Hypersonic Transportation* effort was the starting point for the model used in this study. A screenshot of the ROSETTA model Excel workbook is shown in ***Figure 1***.

The ROSETTA model is comprised of two major models, the aircraft design model and the business model. The aircraft design model is comprised of flight performance, aircraft sizing, and environmental impacts modules. The business model is comprised of a cost module and business case module. Each module within these models is a single worksheet in the Excel workbook. The modules within each aircraft design model and business model are linked together using an interface worksheet. Finally, the aircraft design model and business model are themselves linked together between these interface worksheets. User inputs and model outputs are compiled from the interface worksheets and available to the user on a master inputs and outputs worksheet. The ROSETTA model data flow is shown in ***Figure 2.***

---

[2] Short and Long Range for the purposes of this study, are equivalent ranges to Medium (3-6 hours) and Long-Haul (6+ hours) commercial subsonic aircraft, recognizing the travel time relationships for subsonic aircraft are reduced significantly by the high-speed capabilities for the aircraft concepts in this study. https://www.themcggroup.com/blog/the-differences-between-longhaul-and-shorthaul-piloting/bp67

Figure 1: ROSETTA model Excel workbook



AIRCRAFT DESIGN MODEL

BUSINESS MODEL

USER INPUTS

INPUTS
- Cruise Mach
- Maximum Range
- Passenger Count
- Commercial Ticket Price (one-way)
- Engine Price-to-cost ratio
- Aircraft Price-to-cost ratio

FLIGHT PERFORMANCE

INPUTS
- Cruise Mach
- Maximum Range

OUTPUTS
- Flight Profile
- Travel Time

AIRCRAFT SIZING

INPUTS
- Cruise Mach
- Maximum Range
- Passenger Count
- Flight Profile
- Travel Time

OUTPUTS
- Aircraft Masses
- Aircraft Geometry
- Fuel Consumption
- Engine Thrust
- Balanced Field Length

ENVIRONMENT MODULE

INPUTS
- Cruise Mach
- Maximum Range
- Passenger Count
- Flight Profile
- Aircraft Masses
- Engine Thrust
- Fuel Consumption

OUTPUTS
- Emissions
- Sideline Noise
- Sonic Boom Pressure

COST MODULE

INPUTS
- Cruise Mach
- Aircraft Masses
- Engine Thrust

OUTPUTS
- Airframe DDT&E
- Airframe TFU
- Engine DDT&E
- Engine TFU

BUSINESS CASES

INPUTS
- Engine Price
- Aircraft Price
- Ticket Price
- Passenger Count
- Maximum Range
- Travel Time
- Fuel Consumption
- Airframe DDT&E & TFU
- Engine DDT&E & TFU

OUTPUTS
- Manufacturers' IRR & NPV
- Operators' IRR & NPV
- Aircraft Price
- Fleet Size

AIRCRAFT, ECONOMIC, & ENVIRONMENT OUTPUTS

Figure 2: Model data flow

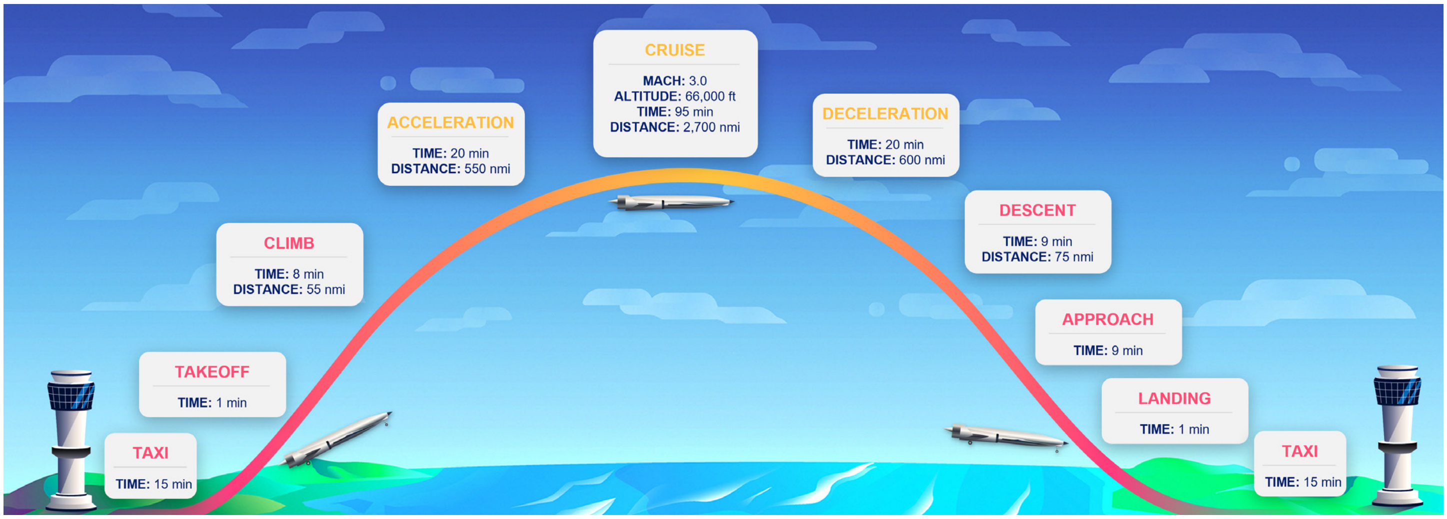


Figure 3: Flight segments with representative model results

2.3.1.1 - Flight Performance Module

The flight performance module calculates the flight times, velocities, and altitudes for each of the flight segments shown in ***Figure 3*** based on the aircraft maximum range and cruise Mach number. Climb and acceleration are estimated based on the aircraft's takeoff thrust-to-weight (T/W) capability. Aircraft cruise altitude and true airspeed are determined from the cruise Mach number and a cruise dynamic pressure of 500 psf. The total gate-to-gate time and flight profile are determined. An additional 45 minutes of contingency cruise at subsonic speed at the landing airport is also included.

2.3.1.2 - Aircraft Sizing Module

The aircraft sizing module calculates aircraft physical characteristics including manufacturer's empty weight (MEW) and operating empty weight (OEW), total fuel load, maximum takeoff weight (MTOW), fuselage length & diameter, wingspan & length, and engine sea-level static (SLS) thrust, from the aircraft cruise Mach, maximum range, passenger count, fuel type, and flight profile from the flight performance module. Aircraft thrust-specific fuel consumption (TSFC) at cruise condition is approximated from a curve-fit of representative high-Mach engines including the Rolls-Royce/Snecma Olympus 593, Pratt & Whitney J58, and Pratt & Whitney F119. Subsonic and supersonic lift-to-drag (L/D) ratio are estimated using Küchemann's equation with a knockdown to anchor results to existing flight vehicles including the Concorde and XB-70.

Aircraft L/D and TSFC are used to determine the fuel required for each flight segment using the Breguet range equation for cruise segments, basic flight mechanics for acceleration and deceleration segments, and time & throttle for taxi segments. Aircraft dry mass is determined from a series of mass estimating relationships for each major subsystem: structures, aerosurfaces, propulsion, thermal management, propellant management, avionics, power, crew cabin, and landing gear. A 25% mass growth allowance is applied to the resulting dry masses. The sizing module uses an iterative closure process, varying vehicle fuel load until the total available fuel load matches the mission required fuel load.

Once the aircraft design is closed, a balanced field length calculation is performed based on the vehicle mass, thrust, and subsonic L/D.

2.3.1.3 - Environmental Module

The environmental module calculates aircraft lateral, flyover, & approach noise, sonic boom perceived noise level, and emissions from the aircraft masses, geometry, engine thrust, and fuel consumption from the aircraft sizing module and the cruise altitude & velocity from the flight performance module. Lateral, flyover, and approach noise are estimated based on a curve fit of FAA-published data for operational and historical aircraft based on mass, geometry, and engine thrust. Sonic boom perceived noise level is determined from the overpressure, which is calculated based on the equations in NASA Technical Paper 3134, "A Loudness Calculation Procedure Applied to Shaped Sonic Booms". Emission calculations are based on SAE International standard AIR5715, with combustion product constituents determined from a curve-fit of CEA combustion calculations at different conditions.

2.3.1.4 - Cost Module

The cost module calculates design, development, test, and evaluation (DDT&E) and theoretical first unit (TFU) cost for the airframe and engine based on the aircraft physical characteristics from the aircraft sizing module. Airframe costs are estimated using a response surface model developed from Galorath's SEER for Hardware (SEER-H) software. Engine costs are estimated using thrust-based cost estimating relationships from "Analysis of Cost Drivers Impact on Direct Operating Costs Estimation of a Hypersonic Point-to-Point Vehicle", Margherita Pincini and Nicole Viola, March 2018[3], and "Valuation Techniques for Commercial Aircraft Program Design", Jacob Markish, June 2002[4].

---

[3] https://webthesis.biblio.polito.it/6856/1/tesi.pdf

[4] https://dspace.mit.edu/bitstream/handle/1721.1/16871/51679351-MIT.pdf?sequence=2&isAllowed=y

2.3.1.5 - Business Case Module

The business case module develops a full business model for each airframe manufacturer, engine manufacturer, and Elite Airline operator. Key outputs from the business model include internal rate of return (IRR), net present value (NPV), total sales of aircraft & engines, a schedule of expenses and revenues, and direct operating costs. Inputs to the model are the DDT&E and TFU costs for the airframe and engine from the cost module, and optimizer-selected ticket price, engine price, and airframe price from ROSETTA model inputs.

2.4 - Two-Aircraft Types Model Development (Task 1):

This task further developed and expanded the prior ROSETTA model to evaluate two different aircraft designs within a single economic trade space. The single aircraft model used in the prior study assumed one Engine Manufacturer, one Airframe Manufacturer / Aircraft Integrator, and one “Elite Airline” Operator. For the two aircraft-types model (also described as the “Mixed Fleet” model in this report), SpaceWorks simulated two exclusive and parallel engine manufacturers and two exclusive and parallel airframe manufacturers for the separate short- and long-range aircraft types. Therefore, no commonality or synergies existed between the two engines and the two airframes to establish a baseline, conservative economic approach reflective of competing manufacturing companies.

A single operator was assumed to operate both aircraft types, but with no route overlap or sharing between the two aircraft types. The short-range aircraft served routes up to its maximum unrefueled range. The long-range aircraft served routes from the limit of the short-range aircraft, up to its own maximum range. Therefore, a candidate point-to-point commercial route would be served by the Elite Airline using one aircraft type, or the other, for the duration of a single simulation.

While competition with subsonic airline operators is inherent in the market capture curves used in this study, it was assumed that there was no second Elite Airline that competed in the supersonic or hypersonic flight market. This assumption is somewhat optimistic for the operator in our simulations and reflects a first-mover advantage for the initial operator entering the high-speed service market. See ***Figure 4*** for how different manufacturers and operators interact.

For future, more advanced market studies that are less constrained by the limits of an Excel based-simulation tool, SpaceWorks would recommend business models incorporate the economic dynamics and realities of the air transportation industry by considering a variety of Original Equipment Manufacturers (OEMs) developing engine and aircraft “families” (e.g., Boeing 787-8/-9/-10, Airbus A 350-900/-1000) for exploiting production commonalities, shared technology developments, and economies of scale advancement. Multiple competitive or strategically aligned high-speed operators could also be simulated.

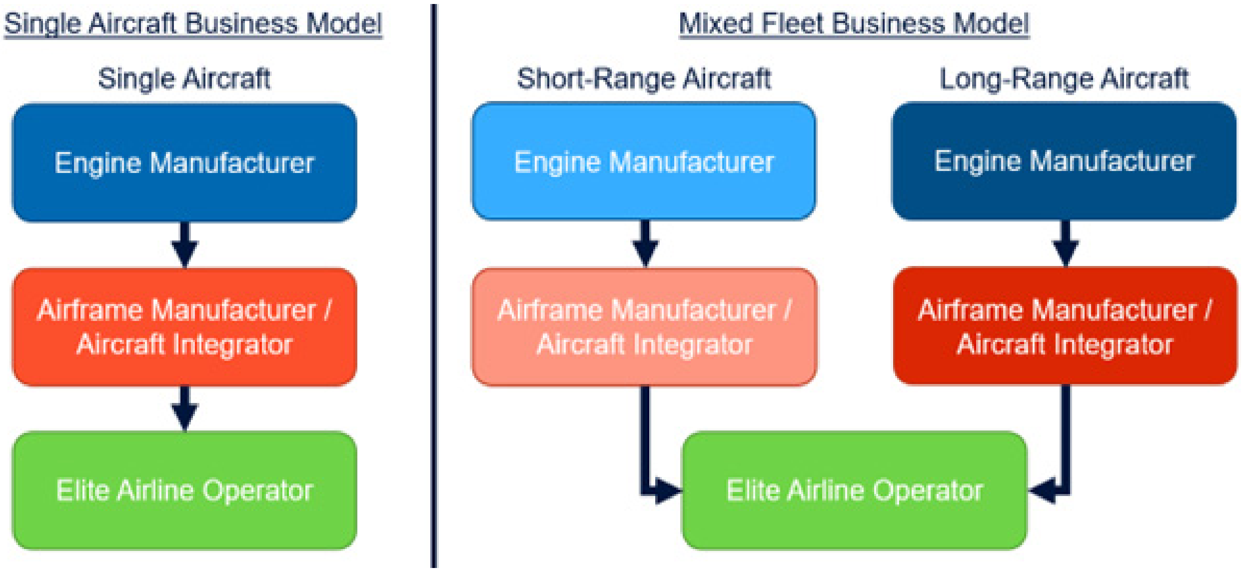


Figure 4: *Flow of goods and services from Engine Manufacturer(s) to Airframe Manufacturer(s) to the Operator for a single aircraft and a mixed fleet*

---

[3] Elite Airline is an airline engaged in a specialized network (high-speed point to point) offering first and/or business class seats to its customers. The Elite Airliner is assumed to be an FAA scheduled CAFR 14 -FAR part 121 certificated carrier or equivalent in foreign countries and compliant with the International civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPS) and applicable Annexes

The following describes key assumptions used throughout the model, unless otherwise specified.

Aircraft Design and Performance Assumptions

- Supersonic / hypersonic aircraft are sized for a maximum design range and offer a single passenger-class service that blends the market for current business and first-class travelers. On shorter than maximum routes, the aircraft fuel is partially offloaded.
- A low-bypass turbofan is used up to Mach 3. Aircraft able to fly Mach 3-5 will use a turboramjet and operate in ramjet mode above Mach 3.
- Aircraft are assumed to have a 15-year lifespan and are replaced upon retirement.

Market and Economic Assumptions

- The business model captures operations from 2022-2057
    - 10 years of development followed by 25 years of operations
- Engine manufacturers, airframe manufacturers, and the operator have individual business cases
- The United States Government purchases the first aircraft off the line for military, special service, and civil needs
    - “Anchor buy” concept used to establish minimum number of aircraft sold (max of 20 aircraft or $5B acquisition, whichever comes first)
- For a route to be serviceable, the route must be within range of the aircraft design range and the route must have enough demand for at least one flight per day at a load factor of 85%
- Belly cargo is included as additional revenue on all flights at $100/kg and up to 500 kg based on available space
- To approximate COVID recovery, 2019 market numbers are expected to be reached again by 2024. That is, 2024 transoceanic air travel markets are assumed to be the same as 2019 and are used as a point of departure for future growth.
    - Market growth rate of 0.94% is applied annually after 2024

SpaceWorks also used this opportunity to refine sizing and cost calculations. Given the calculation refinements and extensive model development to achieve two aircraft modeling capabilities, SpaceWorks revalidated sizing and cost results to historical and current high-speed aircraft. Concorde was used as the main anchoring data point since it has the most heritage and available information for an operationally proven and commercially flown high-speed aircraft by elite airlines.

The ROSETTA model used to support this analysis is a complex and highly coupled Excel workbook with multiple cross-linked worksheet tabs. The sizing portion of the model primarily depends on key trade space inputs associated with the aircraft design itself – maximum passenger count, maximum unrefueled range, and maximum cruise Mach number (here, Mach 2 to Mach 5). The aircraft sizing metrics behave as expected – larger passenger counts increase payload and cabin size, and therefore produce larger and heavier aircraft solutions. Longer range aircraft are larger and heavier. Aircraft with faster flight speeds have lower cruise lift-to-drag ratios, higher structural mass fractions lower engine efficiencies on average, and therefore produce larger aircraft. As a ground rule for this present study, SpaceWorks has eliminated any aircraft that close at a MTOW above one million pounds due to practical airport and runway considerations. Those aircraft are deleted from any plots or graphs of our results.

The economic portion of the model is even more complex, and it requires an optimizer to determine the “best” ticket prices, the unit sales price of an engine, and the unit sales price of an integrated aircraft in order to satisfy the positive business cases of one or two engine manufacturers, one or two airframe manufacturers, and the Elite Airline operator while capturing the largest possible share of the traveling public. In most cases, there is a tradeoff between the success of one company in the simulation and the success of another. For example, the engine manufacturer might wish to raise the average unit price of its engine to improve its economic return to pay for the nonrecurring and production costs associated with the engine. This in turn will pass along those costs to the airframe manufacture who must also raise the market price of the integrated aircraft to meet its own financial return goals. The operator then attempts to raise ticket prices, only to see demand for the service fall as a result of the price elasticity of that service to the traveling public. So, there is a delicate balance that must be achieved between the various participating companies. The ROSETTA model’s optimizer seeks that balance of a 25% minimum internal rate of return on this project for each participating company, while also seeking to maximize the number of participating travelers who would choose to fly supersonically to their destinations vs. opting for standard subsonic travel (typically 5% to 15% of total annual air travel demand for 2024 on the 90 transoceanic routes used as the baseline for this study). In some cases, the optimizer fails to achieve this balance, and the economic case “fails” to meet the threshold goals. But many cases have been evaluated as being “successful” within the trade space. Throughout this report, SpaceWorks will often present economic results that have failed to meet the 25% IRR threshold for one or more of the simulated companies, in an effort to show how close they were to achieving that bar. However, the recommended solutions will only be those that meet all of the objectives of the study.

Note that while the ROSETTA model does calculate and output results for aircraft emissions (CO2 equivalent exhaust products), estimated aircraft takeoff noise, and estimated sonic boom overpressure noise for each simulation, SpaceWorks has not attempted to constrain the recommended solutions based on those environmental parameters. It is understood that real-world regulations and public policies will further reduce the acceptable supersonic/hypersonic aircraft options (and could even eliminate all options entirely), but the goal is to explore the full market potential of these aircraft and present those results to regulators and policy makers as the upper range of economic possibilities. See ***Figure 5*** and ***Figure 6*** for ROSETTA model weight and pricing calibration results compared to available reference points.

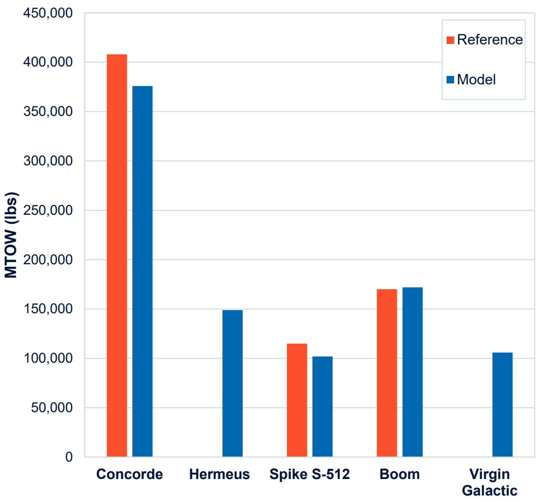


Figure 5: *Size comparisons between known or anticipated aircraft and the ROSETTA model's sizing outputs*

For each trade study and sensitivity study, the cruise Mach number for the candidate aircraft ranged from Mach 2 to Mach 5 and passenger counts were either 20 or 50[6]. Aircraft ranges varied for each task, but 4,000 nmi was identified as consistently performing well economically for short-range aircraft while 5,700 nmi was identified as a practical range representative of long-range aircraft in scheduled Elite Airline operations in the U.S. and worldwide. To reiterate, for extensive trade spaces, candidate aircraft that closed but resulted in a MTOW exceeding one million pounds were removed from further economic investigations for two reasons. First, these MTOWs typically exceed most airport runway weight limits (based on FAA Airport Diagrams[7]) and second, they typically resulted in an overly expensive aircraft (includes certification, manufacturing, airport-airspace infrastructure impact, and other life cycle costs) that likely would not be economically viable, based on well-known case studies (e.g., the Airbus A-380 case).

The objective function for optimizing the business cases required each manufacturer and operator to first achieve a 25% internal rate of return (IRR) as an optimization constraint and then to maximize the number of passengers served per year. IRR is a project-level economic measure that considers the annualized return a future revenue stream can achieve over a given number of years (positive cash flow), while also considering the amount of non-recurring investment it takes to initiate the project (negative cash flow). Positive values of IRR indicate that the subsequent financial margins on a project are sufficient to overcome its up-front investment cost.

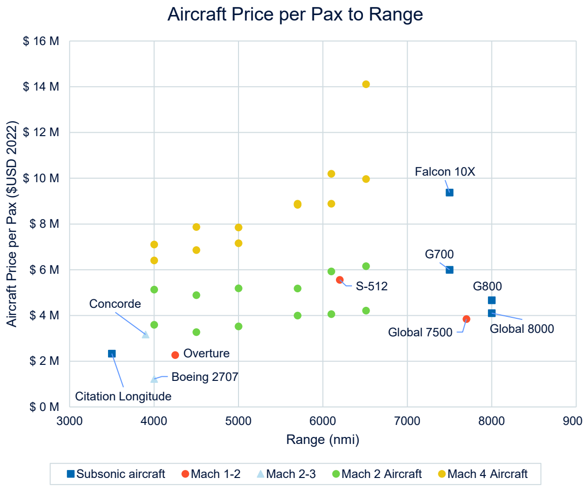


Figure 6: *Aircraft Price comparison between known or anticipated aircraft and the ROSETTA model's pricing outputs (normalized by passenger count)*

High-risk projects such as this will require a relatively healthy IRR in order to justify the risk in achieving the desired profit stream -- given that lower risk investment alternatives likely exist for aerospace manufacturers and operators. SpaceWorks considered a minimum 25% IRR to be commensurate with the risk associated with introducing supersonic or hypersonic commercial flight, and thus 25% was used as the minimum acceptable IRR for this study effort.

Maximizing market capture as an objective was intended to achieve a more robust business case with lower ticket prices and more aircraft produced. This drove the optimization to generate results that were more feasible for a larger portion of the flying public to fly with an elite airline offering premium seating as opposed to catering to high net-worth individuals (HNI) flying on a chartered, non-scheduled, and/or private aircraft. Higher production rates also align more with what a manufacturer's return on capital invested[8] would realistically require for them to invest in a high-speed aircraft program with the characteristics defined in this study. Finally, for post-processing, business cases that could not produce an IRR value were excluded from analysis (i.e., had all negative annual cash flows).

---

[6] Seat configuration assumes high end business and/or first-class seats; metrics are pitch, recline and quality comfort features in line with those of Elite airlines. https://www.airlinequality.com/info/seat-pitch-guide/

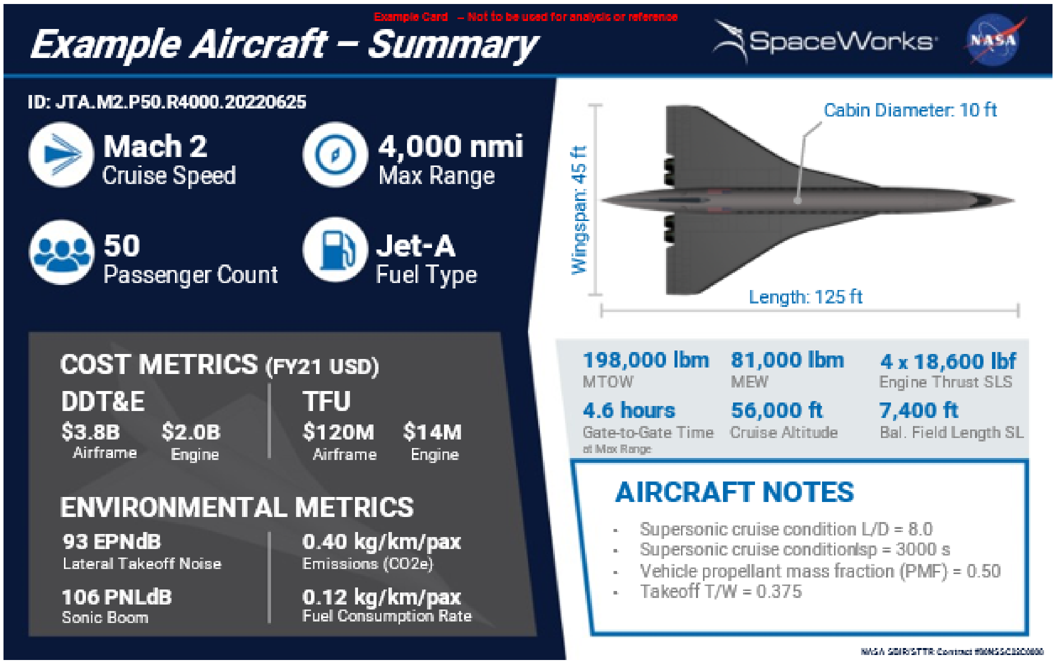
[7] https://www.faa.gov/airports/runway_safety/diagrams/

[8] https://www.iata.org/en/iata-repository/publications/economic-reports/new-study-on-airline-investor-returns/
https://www.icf.com/insights/transportation/aviation-return-on-invested-capital-tips#

2.5 - BASEBALL CARDS (TASK 2)

For Task 2, SpaceWorks was tasked to develop summary slides or "Baseball Cards" that displayed key design, environmental, cost, and business modeling metrics produced by the ROSETTA model. Two baseball card designs were developed by SpaceWorks' Studios team: a Technical Baseball Card and a Business Baseball Card.

The Technical Baseball Card highlights aircraft size, fuel load, non-recurring costs, emissions parameters, flight times, and similar parameters from the ROSETTA model as a function of passenger count, max unrefueled range, fuel type, and maximum cruise flight Mach number *(Figure 7)*. There is only a single Technical Baseball Card for a given aircraft design. However, there may be more than one Business Baseball Card *(Figure 8)* associated with the same aircraft design due to the various economic parameters that generate unique business case solutions. For example, higher or lower ticket prices, higher or lower fuel price assumptions, or a different set of potential routes will all generate different economic outcomes for the same conceptual aircraft.



Example Card – Not to be used for analysis or reference

Example Aircraft – Summary

ID: JTA.M2.P50.R4000.20220625

Mach 2 Cruise Speed

4,000 nmi Max Range

50 Passenger Count

Jet-A Fuel Type

198,000 lbm MTOW

81,000 lbm MEW

4 x 18,600 lbf Engine Thrust SLS

4.6 hours Gate-to-Gate Time at Max Range

56,000 ft Cruise Altitude

7,400 ft Bal. Field Length SL

COST METRICS (FY21 USD)

DDT&E		TFU	
$3.8B	$2.0B	$120M	$14M
Airframe	Engine	Airframe	Engine

ENVIRONMENTAL METRICS

93 EPNdB Lateral Takeoff Noise

0.40 kg/km/pax Emissions (CO2e)

106 PNLdB Sonic Boom

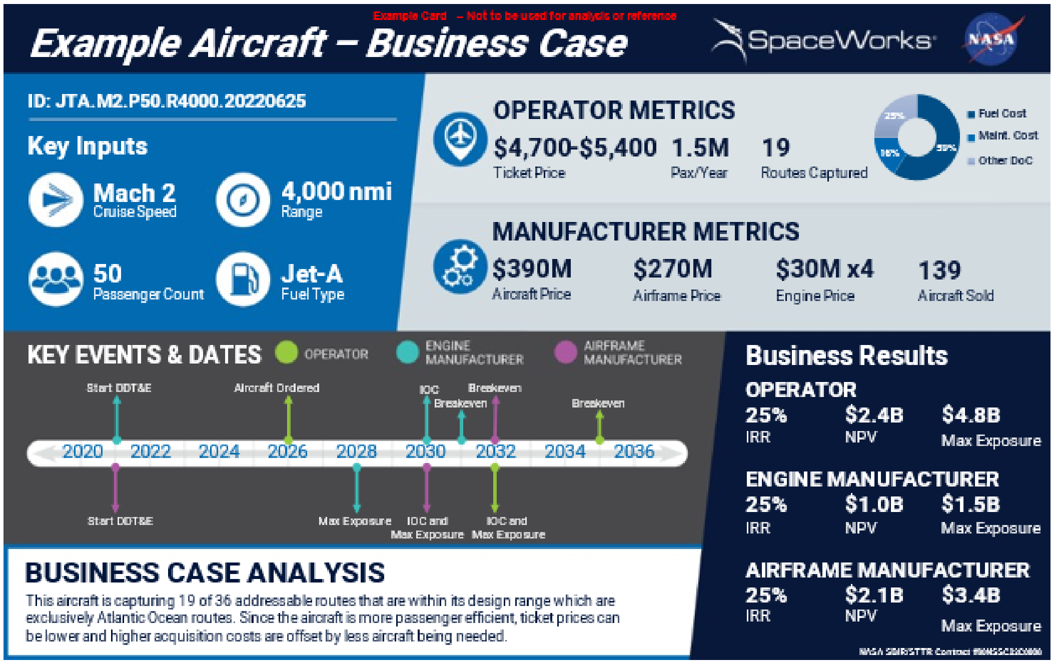
0.12 kg/km/pax Fuel Consumption Rate

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 8.0
- Supersonic cruise conditionIsp = 3000 s
- Vehicle propellant mass fraction (PMF) = 0.50
- Takeoff T/W = 0.375

NASA SBIR/STTR Contract #80NSSC22C0008

Figure 7: Technical Baseball Card to report key metrics regarding size, performance, environmental factors, and cost estimates



Example Card – Not to be used for analysis or reference

Example Aircraft – Business Case

ID: JTA.M2.P50.R4000.20220625

Key Inputs

Mach 2 Cruise Speed

4,000 nmi Range

50 Passenger Count

Jet-A Fuel Type

OPERATOR METRICS

$4,700-$5,400 Ticket Price

1.5M Pax/Year

19 Routes Captured

MANUFACTURER METRICS

$390M Aircraft Price

$270M Airframe Price

$30M x4 Engine Price

139 Aircraft Sold

KEY EVENTS & DATES

BUSINESS CASE ANALYSIS

This aircraft is capturing 19 of 36 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Since the aircraft is more passenger efficient, ticket prices can be lower and higher acquisition costs are offset by less aircraft being needed.

Business Results

	IRR	NPV	Max Exposure
OPERATOR	25%	$2.4B	$4.8B
ENGINE MANUFACTURER	25%	$1.0B	$1.5B
AIRFRAME MANUFACTURER	25%	$2.1B	$3.4B

NASA SBIR/STTR Contract #80NSSC22C0008

Figure 8: Business Baseball Card to report key metrics regarding financial performance, pricing, and market capture

3 - ANALYSIS & RESULTS

Under this study, SpaceWorks generated hundreds of candidate aircraft solutions and associated economic outcomes modeled using our ROSETTA model. The objective was to explore the trade space for supersonic and hypersonic commercial flight at a high level quickly and parametrically in order to identify any preferred regions of the design space that resulted in profitable solutions for manufacturers and operators. Each trade study was reduced to a matrix of candidate aircraft, and the economic business cases were then optimized for each. SpaceWorks' assumption is that more detailed design and analysis will follow once attractive areas of the trade space are identified. The complete set of trade matrix results can be found in Appendix A.

3.1 - MIXED FLEET TRADE STUDY (TASK 3)

The objective of the first trade study was to evaluate the economic performance of mixed fleet business cases compared to a single aircraft business case. The trade matrix in ***Table 1*** identified 18 aircraft to evaluate. Since range was not specified, the trade space was explored by varying range from 3,500-6,510 nmi so that a short- and long-range could be selected. Ultimately, 4,000 nmi was selected for the maximum unrefueled range of the short-range aircraft while multiple Mach-Range combinations were selected for the long-range aircraft. The varying maximum ranges for the long-range aircraft were necessary because the longer the design range, the harder it was for the aircraft to close technically and economically at higher Mach numbers.

Table 1: *Jet-A Trade Matrix*

Case	Range	PAX	Cruise Mach	Fuel Type
Baseline-A	Short	Best	Best	Jet-A
Baseline-B	Long	Best	Best	Jet-A
1	Short	20	2	Jet-A
2	Short	20	3	Jet-A
3	Short	20	4	Jet-A
4	Short	20	5	Jet-A
5	Short	50	2	Jet-A
6	Short	50	3	Jet-A
7	Short	50	4	Jet-A
8	Short	50	5	Jet-A
9	Long	20	2	Jet-A
10	Long	20	3	Jet-A
11	Long	20	4	Jet-A
12	Long	20	5	Jet-A
13	Long	50	2	Jet-A
14	Long	50	3	Jet-A
15	Long	50	4	Jet-A
16	Long	50	5	Jet-A

It should be noted that at the start of this study in January 2022, Jet-A fuel prices were around $2.60/gallon. After global economic and geopolitical issues arose, Jet-A fuel prices rose significantly. Given these conditions, SpaceWorks assumed a Jet-A fuel price of $4.06/gallon which was spot checked in June 2022 and was used for the remainder of the project. For the purposes of this study, fuel price remains constant, unless otherwise noted, and does not reflect any spikes or valleys in the economic cycle.

Single aircraft cases were run to establish a baseline, point of comparison for mixed fleet solutions. The results of these runs indicated that viable business cases existed at all Mach numbers, but slower Mach numbers and shorter design ranges enabled lower ticket prices which in turn generated more market capture and production volume. SpaceWorks considered cases with more demand and production to be more robust business cases and better serve the general public. In ***Figure 9***, key metrics for a 50-passenger aircraft are evaluated across Mach and design range.

In ***Figure 9***, market capture (number of passengers selecting supersonic / hypersonic flight annually) was not only dependent on ticket price, but also the number and size of the routes captured within the aircraft's design range. With that in mind, there were notable trends in that Figure. First, the greatest market capture was for a Mach 2 aircraft between 4,500 nmi and 5,700 nmi. These aircraft effectively captured most, if not all, the transatlantic routes as well as some of the shorter transpacific routes. This was also where the manufacturers saw the highest production volumes. The other notable region was for aircraft at 4,000 nmi. The market capture wasn't as high as in the first notable region, but the demand was not as affected by rising Mach number. Demand is relatively unchanged to about Mach 4 for a 4,000 nmi aircraft. For reference, the maximum number of passengers in the reference year, assuming 100% capture of the subsonic market, is approximately 39 million passenger-legs.

Based on these results, 5,700 nmi was determined to the "Best" design range for the single aircraft-type simulations and also for the long-range aircraft in the mixed fleet simulations due to its strong demand capture and because the design range captures significant transpacific market (e.g., LAX-TPE and SFO-TPE) as well as some longer transatlantic ones. For the short-range aircraft in the mixed fleet simulations, 4,000 nmi was select as the "Best" design range since it captured significant transatlantic routes and was less sensitive to changes in Mach number. Furthermore, 4,000 nmi was selected over 4,500 nmi to create a greater gap in design ranges between the short- and long-range aircraft in the mixed fleet simulations and therefore, enable the long-range aircraft to be able to service more routes.

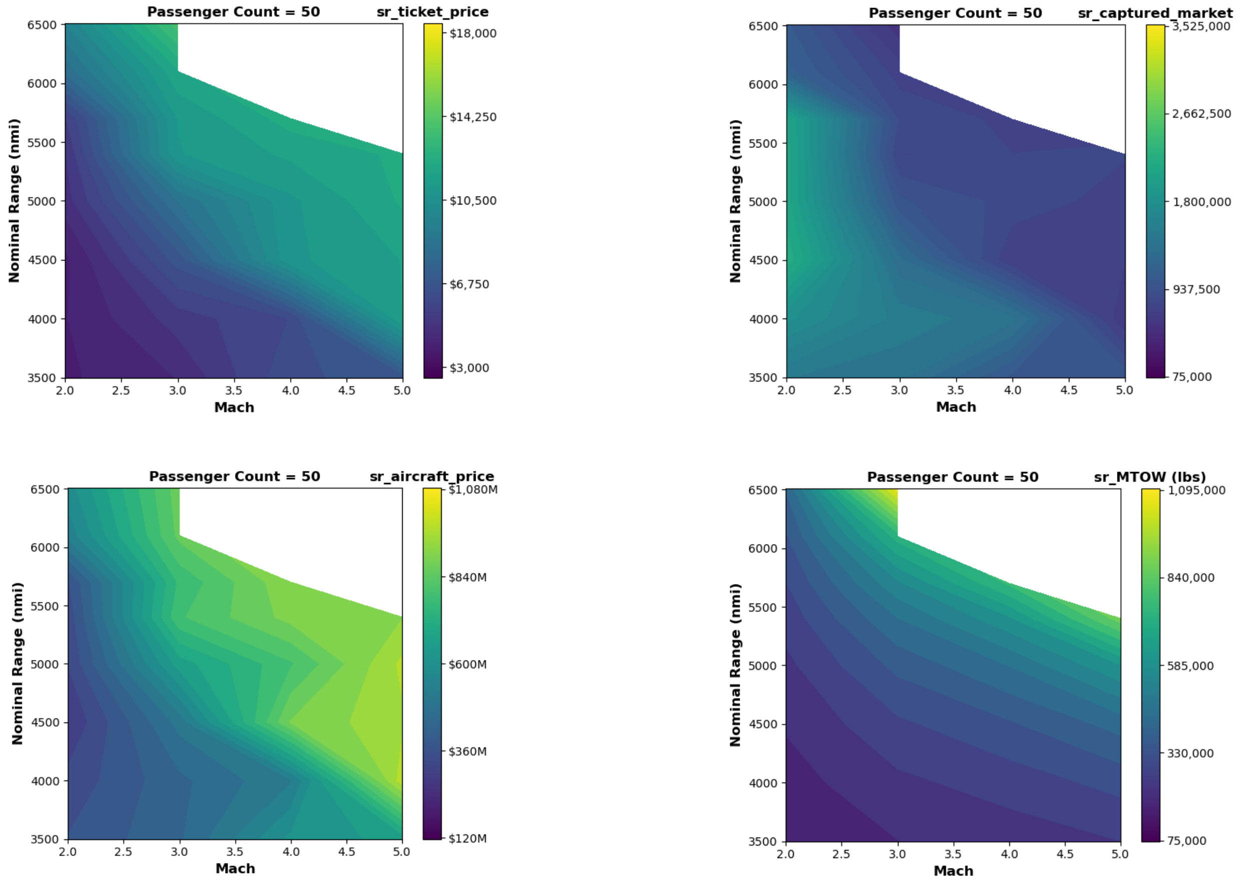


Figure 9: Key metric for 50-passenger aircraft across Mach and range

For mixed fleet solutions, the following assumptions were used to evaluate business cases:

- **Short-range aircraft service routes up to their design range while long-range aircraft service routes with distances between the two aircraft's design ranges**
- **Ticket prices are referenced to different baseline routes and are therefore different for short- and long-range aircraft (NYC to LHR vs. LAX to NRT). Ticket prices are more difficult to compare directly to each other due to the differences in the reference route distance used to report that variable in the mixed fleet simulations**
- **Each aircraft has an exclusive engine manufacturer and airframe manufacturer**
- **Both aircraft are utilized by a single operator**
- **Initial operating capability (IOC) dates are the same for both aircraft (~2030)**

In the ***Figures 10 and 11*** (following page), the market was heavily concentrated in the shorter transatlantic routes (mainly New York to European cities). In ***Figure 11***, the addressable market was roughly split in half at 4,000 nmi. This meant that for a mixed fleet operating on non-competitive routes divided by range, the long-range aircraft had to fly farther (more fuel) than the short-range aircraft to service the same amount of people. To counter the additional mass to carry more fuel, long-range aircraft in the mixed fleet analysis were ground ruled to be fixed at 20 passengers.

Looking at mixed fleet solutions, there were cases that performed better, worse, and about the same as single aircraft cases of the same design. The cases that performed better than the single aircraft cases (based on market capture) typically had a short-range aircraft with similar metrics to the single aircraft case with the long-range aircraft marginally increasing demand after that. However, the long-range aircraft in a mixed fleet solution almost always had worse metrics than that same aircraft operating in a single aircraft-type simulation where it is also allowed to service the short-range markets. Prices were significantly higher to compensate for the lost, transatlantic market demand. This in turn reduced the production volume for the manufacturer.

When comparing the best mixed fleet case identified to the best single aircraft case, the mixed fleet had marginally better market capture but that was caveated by greater investments for a short-range aircraft and a more expensive long-range aircraft. (See comparison in ***Table 2***, following page).

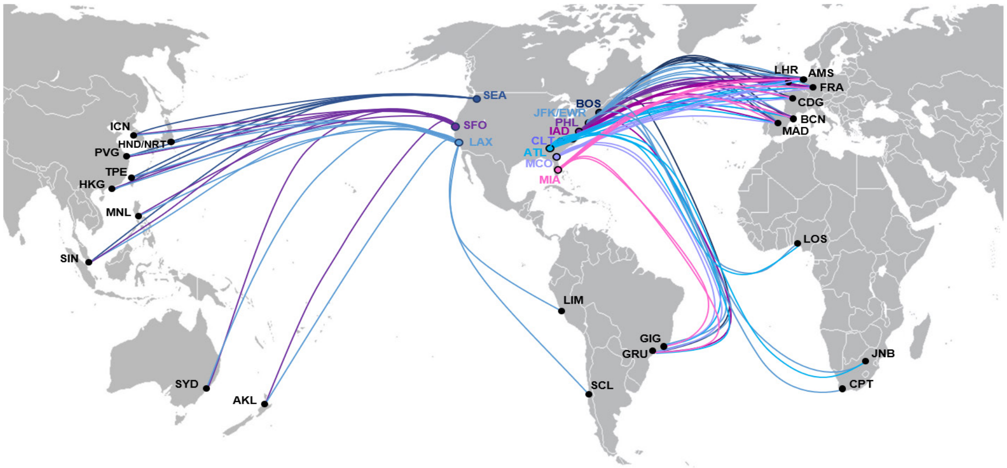


Figure 10: Available routes within the ROSETTA model

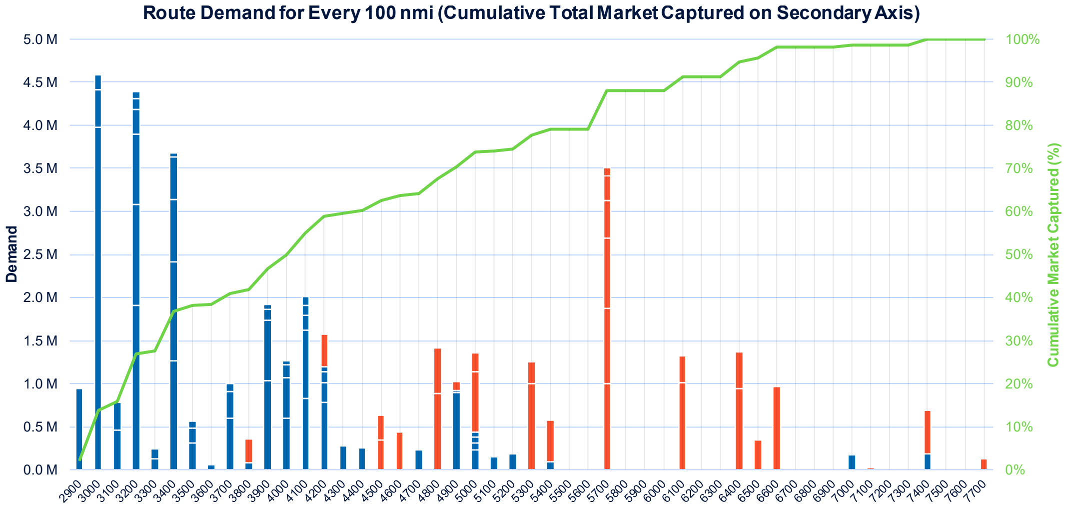


Figure 11: Demand and market capture across all routes in the ROSETTA model based on range (blue indicates transatlantic routes, orange indicates transpacific routes)

Table 2: Best mixed fleet case vs best single aircraft case

Key Metrics	Best Mixed Fleet Case		Best Single Case
Mach	3	2	2.4
Range (nmi)	3900	5700	4100
Passengers	50	20	38
Ticket Price	$1,925	$7,330	$2,064
Aircraft Price	$198M	$224M	$149M
Engine Price	$15.9 M x4	$18.9 M x4	$11.2 M x4
Aircraft Sold	369	199	455
PAX Market Capture	**4,080,000**	**700,000**	**4,210,000**
Total PAX Captured	**4,780,000**		**4,210,000**

Overall, mixed fleet cases performed notionally better, or were at least able to address more routes with similar market capture to a single aircraft business case. That is, segregating the markets into a short-range set of routes and a long-range set of routes and having a more catered aircraft designed to serve each segment did capture more of the available air travelers than would be captured with a single aircraft type that was sized to serve the overall design space. The most significant limiting factor to the mixed fleet business cases was the uneven demand distribution between short- and long-range markets. Long-range aircraft typically had to charge a much higher ticket price to be profitable while any extra demand capture came from slightly lower ticket prices for the short-range aircraft.

In a way, the long-range aircraft became more exclusive and expensive, and the short-range aircraft became less expensive and better utilized. In the single aircraft-type simulations, the resultant aircraft was optimized toward a compromise or middle ground, but in the mixed aircraft solution, the two solutions diverged economically. While it did result in marginally more participation among the traveling public, this solution that created an even more elite solution for long-range transpacific routes may not be preferred.

Considering these results, it’s hard to justify a mixed fleet solution with routes divided exclusively based on range. However, SpaceWorks sees potential for a mixed fleet solution based on demand that allows aircraft to be more catered for a group of routes that are distinguished by range and market size. So, rather than segregating the two aircraft types by route distance, they might better be segregated by factors such as route density. This approach could potentially keep load factors high on larger aircraft along the busiest routes, while using a small, and potentially faster, aircraft on less busy routes – even if the design range for the two aircraft was similar. Additional research is recommended.

The data and results generated under this task also provided a baseline for comparison of the following trade and sensitivity studies.

3.2 - ALTERNATIVE FUEL TRADE STUDIES (TASK 4)

The objective of the Alternative Fuels Trade Study is to evaluate the economic impact of using Sustainable/Synthetic Aviation Fuel (SAF), Liquid Natural Gas or methane (LNG), and Liquid Hydrogen (LH2). For this study, the same trade matrix used in Task 3 was used again for Task 4 with the only change being in the fuel column. The alternative fuel matrix is shown in ***Table 3***.

Table 3: *Alternative Fuel Trade Matrix*

Case	Range	PAX	Cruise Mach	Fuel Type
Baseline-A	Short	Best	Best	SAF/LNG/LH2
Baseline-B	Long	Best	Best	SAF/LNG/LH2
1	Short	20	2	SAF/LNG/LH2
2	Short	20	3	SAF/LNG/LH2
3	Short	20	4	SAF/LNG/LH2
4	Short	20	5	SAF/LNG/LH2
5	Short	50	2	SAF/LNG/LH2
6	Short	50	3	SAF/LNG/LH2
7	Short	50	4	SAF/LNG/LH2
8	Short	50	5	SAF/LNG/LH2
9	Long	20	2	SAF/LNG/LH2
10	Long	20	3	SAF/LNG/LH2
11	Long	20	4	SAF/LNG/LH2
12	Long	20	5	SAF/LNG/LH2
13	Long	50	2	SAF/LNG/LH2
14	Long	50	3	SAF/LNG/LH2
15	Long	50	4	SAF/LNG/LH2
16	Long	50	5	SAF/LNG/LH2

It should be noted that this study assumed parity in the availability and costs of the infrastructure upstream-midstream-downstream and into the vehicle for the four fuels considered. SpaceWorks’ primary focus was to assess the impact of alternative fuels on the performance of the aircraft (propulsive efficiency), size of the aircraft (fuel volumes required), the non-recurring development and production costs of the aircraft, the impact on carbon emissions associated with flight operations, and economic performance of the resultant simulation. While the costs of developing the production, supply, and distribution infrastructure for each fuel were not assessed, SpaceWorks recognizes the significant costs that will be required to achieve those distribution goals at the 90 major airports that we have evaluated. The following assumptions and considerations are foundational to the current study and will need to be further detailed in future studies.

This study assumed that by the entry into service of the high-speed aircraft, the infrastructure for production, storage, and distribution of biofuels and cryogenic fuels is well established and has reached good technical maturity in the subsonic air transportation industry. Although H2 is used in several industrial processes, the infrastructure for storing and transporting LH2 is not as mature as for LNG, partly because LH2 must be stored at very low temperatures (LH2 at 20 K and LNG at 111 K).

SpaceWorks assumed that the future infrastructure of airports will be fitted and suited for cryogenic fuels (LH2 and/or LNG), particularly at the major airports considered for this study. Operations also could be assumed to take place at smaller airports for private or charter aircraft (i.e New York-Teterboro, London-Biggin Hill, et al) given that these smaller airports typically supply fuel to the aircraft with tankers, rather than with built in ground infrastructure (i.e. New York-JFK and London-Heathrow), and thus, infrastructure could be modified to accommodate LH2/LNG tankers at smaller destinations. Both scenarios, however, still require substantial changes to the refueling protocols and requires investments.

The use of cryogenic fuels in aviation has several significant challenges, including the need for cryogenic storage where LH2, by its nature, requires a larger volume than kerosene, and boil-off losses come into play. Other aspects of hydrogen fuel, such as safety, logistics, passenger perception, etc., should be incorporated into future studies.

Additional focus and refinement were provided to the ROSETTA model’s emissions calculations and outputs. Jet-A, LNG, and LH2 are all relatively simple and straightforward calculations since their chemical compositions are known. SAF is not as defined given the variety of production methods. A surrogate molecule (C12H24/C12H26) was used to represent SAF’s chemical composition. Given SAF’s similarity to Jet-A though, differences between the fuels were minimal or insignificant on the technical and environmental outputs. ***Table 4*** provides all fuel characteristics that have design or economic impact as well as any notable assumption changes.

Table 4: *Fuel properties, characteristics, and economic factors*

PROPERTY	JET-A	SAF (100%)	LNG	LH2
Density (lb/gal)	6.66	6.58	3.91	0.55
Storage Temp	-40ºC	-40ºC	-163ºC	-249ºC
Subsonic Isp (s)	3,500	3,570	4,040	9,695
Supersonic Isp* (s)	3,000	3,060	3,470	7,200
Price	$4.06/gal	$6.70/gal	$1.30/gal	$3.60/gal
DDT&E Impact	0% Inc.	2.5% Inc.	30% Inc.	60% Inc
TFU Impact	0% Inc.	2.5% Inc.	5% Inc.	10% Inc.

Table 5: Jet-A Trade Matrix

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.01	40	25.0%	$3,900	4.6%	197	$250M	$19.8M	143,000	59,300	13,400	0.34
Best – LR	5,700	2.00	38	25.0%	$5,200	5.8%	300	$250M	$19.8M	222,000	77,000	20,900	0.49
1	4,000	2.0	20	25.1%	$5,000	3.7%	289	$170M	$13.5M	95,000	40,200	8,900	0.47
2	4,000	3.0		25.5%	$7,000	2.8%	207	$260M	$23.4M	135,000	51,600	12,700	0.75
3	4,000	4.0		25.0%	$10,000	1.9%	152	$380M	$37.1M	161,000	60,900	15,100	0.92
4	4,000	5.0		25.2%	$12,700	1.5%	123	$450M	$50.0M	186,000	71,600	17,500	1.06
5	4,000	2.0	50	25.0%	$4,300	4.1%	143	$350M	$27.8M	167,000	69,000	15,700	0.33
6	4,000	3.0		25.1%	$5,700	3.4%	111	$470M	$43.1M	236,000	87,700	22,100	0.53
7	4,000	4.0		24.9%	$11,500	1.5%	53	$990M	$97.6M	276,000	101,900	25,900	0.63
8	4,000	5.0		23.7%	$11,500	1.6%	61	$980M	$105.2M	313,000	117,400	29,300	0.71
9	6,100	2.0	20	25.0%	$8,200	3.4%	324	$210M	$17.0M	179,000	60,300	16,800	0.72
10	5,700	3.0		22.1%	$13,100	2.0%	188	$370M	$34.9M	317,000	96,500	29,700	1.48
11	5,400	4.0		19.0%	$15,500	1.1%	101	$520M	$57.0M	382,000	118,700	35,800	1.87
12	5,000	5.0		18.4%	$15,000	1.4%	120	$480M	$58.5M	381,000	126,000	35,700	1.96
13	6,100	2.0	50	25.0%	$8,300	2.9%	131	$530M	$41.9M	315,000	103,800	29,500	0.51
14	5,700	3.0		21.3%	$11,600	2.0%	81	$850M	$77.5M	545,000	163,500	51,100	1.02
15	5,400	4.0		18.6%	$11,600	2.0%	81	$870M	$90.8M	635,000	194,500	59,500	1.24
16	5,000	5.0		18.4%	$12,200	1.9%	74	$950M	$108.5M	616,000	200,400	57,700	1.26

For this study and for conservatism, SpaceWorks assumed that a candidate aircraft will only use a single fuel for the entirety of its flight profile and for all propulsive modes. For SAF, this meant the aircraft operated with 100% SAF instead of any SAF/Jet-A blends. For LNG & LH2, tank sizing had to accommodate the less dense fuels which meant the fuel volume requirements using the single fuel type were significant. For the higher speed aircraft in the simulation that use a ramjet operating mode above Mach 3, we made a simplifying assumption that ramjets could operate on Jet-A or SAF between Mach 3 and Mach 5, or at least up to the point that those aircraft failed to close technically or economically. If aircraft in that region of the trade space become attractive, then the assumption on ramjet fuel type needs to be more carefully reviewed and revised.

It should also be noted that fuel prices were allowed to change over time based on anticipated fuel industry trends. Annual fuel price changes were based on “k-factors” (see Task 6 for more information) generated from SpaceWorks subject matter experts (SMEs) and agreed to by NASA staff. The reasoning behind allowing fuel price to change over time was to give SAF an economic chance to outperform Jet-A business cases. It also helps the cryogenic fuel cases that must account for lower fuel densities.

Similar to the fuel k-factors, engine development and production complexity factors were internally determined through SME inputs. The factors were applied to account for the additional effort and challenges for developing an engine with minimal flight heritage and unproven technologies. Production factors weren’t as severe since it was assumed that most production challenges would have been addressed during development.

3.2.1 - Jet-A

To reestablish Jet-A baseline data, the trade space in Task 3 was rerun with the only difference being the change in fuel price over time ***(see Table 5)***.

3.2.2 - SAF

On the key metric of Market Capture, SAF performed similarly but slightly worse compared to Jet-A mainly due to the higher initial fuel prices. However, SAF does have a noticeable advantage over Jet-A which is the lack of production of sulfur oxides (SOx). Reduced SOx emissions would improve air quality, but they are not considered a greenhouse gas (GHG) that contributes to global warming. There are some slight improvements as well on the sizing side due to slightly higher fuel performance but nothing significant enough to be a differentiator to Jet-A. See ***Table 6*** for SAF results.

Table 6: SAF Trade Matrix

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.01	38	25.1%	$4,200	4.3%	200	$240M	$19.3M	135,000	56,500	12,600	0.34
Best – LR	5,700	2.00	50	25.0%	$5,500	5.3%	212	$330M	$26.8M	263,000	91,600	24,600	0.43
1	4,000	2.0	20	25.0%	$5,100	3.7%	298	$170M	$14.7M	92,000	39,700	8,700	0.45
2	4,000	3.0		25.0%	$7,100	2.7%	200	$250M	$22.6M	130,000	50,400	12,200	0.72
3	4,000	4.0		25.2%	$12,200	1.5%	120	$440M	$49.4M	154,000	59,300	14,500	0.87
4	4,000	5.0		25.1%	$12,800	1.5%	120	$440M	$49.0M	178,000	69,500	16,700	1.00
5	4,000	2.0	50	25.0%	$4,800	3.7%	131	$380M	$30.3M	163,000	68,000	15,300	0.32
6	4,000	3.0		25.0%	$6,900	2.6%	93	$540M	$49.9M	227,000	85,700	21,300	0.50
7	4,000	4.0		24.5%	$11,500	1.5%	54	$970M	$96.3M	265,000	99,200	24,800	0.60
8	4,000	5.0		23.5%	$11,500	1.6%	61	$950M	$104.1M	299,000	114,000	28,100	0.67
9	6,100	2.0	20	25.0%	$8,500	3.3%	314	$210M	$17.2M	170,000	58,300	16,000	0.68
10	5,700	3.0		22.5%	$15,400	1.2%	122	$420M	$41.7M	292,000	90,300	27,300	1.34
11	5,400	4.0		19.4%	$15,500	1.1%	101	$490M	$54.8M	347,000	109,700	32,500	1.68
12	5,000	5.0		18.4%	$15,000	1.4%	119	$460M	$56.6M	348,000	117,100	32,700	1.77
13	6,100	2.0	50	25.0%	$8,500	2.8%	129	$530M	$42.3M	299,000	100,300	28,100	0.48
14	5,700	3.0		21.3%	$11,600	2.0%	80	$810M	$75.9M	502,000	153,000	47,100	0.93
15	5,400	4.0		18.6%	$12,200	1.8%	71	$900M	$94.9M	579,000	180,300	54,300	1.12
16	5,000	5.0		18.3%	$12,400	1.8%	69	$950M	$109.8M	566,000	187,100	53,000	1.15

Table 7: LNG Trade Matrix

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.41	39	25.0%	$3,500	5.4%	204	$310M	$27.9M	170,000	72,700	16,000	0.38
Best – LR	5,700	2.00	39	25.1%	$4,900	6.2%	309	$310M	$25.7M	258,000	98,700	24,200	0.45
1	4,000	2.0	20	25.0%	$3,900	4.8%	374	$160M	$13.8M	99,000	45,200	9,300	0.40
2	4,000	3.0		25.1%	$5,300	4.0%	295	$240M	$23.0M	143,000	59,300	13,400	0.67
3	4,000	4.0		25.1%	$7,200	2.9%	214	$330M	$36.2M	167,000	68,500	15,600	0.80
4	4,000	5.0		25.4%	$12,600	1.5%	126	$530M	$66.2M	187,000	77,700	17,600	0.90
5	4,000	2.0	50	25.0%	$3,700	4.8%	165	$360M	$31.5M	175,000	77,700	16,400	0.29
6	4,000	3.0		25.0%	$5,200	3.8%	126	$500M	$50.7M	251,000	101,900	23,500	0.47
7	4,000	4.0		24.6%	$6,400	3.2%	106	$650M	$71.7M	290,000	117,000	27,200	0.55
8	4,000	5.0		23.5%	$10,400	1.8%	69	$990M	$117.0M	323,000	131,800	30,300	0.62
9	6,100	2.0	20	25.0%	$7,300	4.1%	381	$240M	$20.0M	207,000	77,400	19,400	0.70
10	5,700	3.0		21.9%	$15,200	1.3%	126	$560M	$57.6M	405,000	137,900	38,000	1.59
11	5,400	4.0		20.2%	$14,700	1.4%	128	$600M	$69.1M	457,000	157,800	42,900	1.89
12	5,000	5.0		20.8%	$15,000	1.4%	119	$640M	$80.7M	406,000	147,300	38,100	1.76
13	6,100	2.0	50	25.4%	$8,800	2.7%	128	$630M	$59.1M	364,000	133,900	34,100	0.49
14	5,700	3.0		19.7%	$11,000	2.2%	94	$940M	$91.5M	709,000	239,300	66,500	1.11
15	5,400	4.0		17.9%	$11,300	2.1%	88	$1.0B	$116.5M	795,000	272,100	74,500	1.31
16	5,000	5.0		18.8%	$11,500	2.1%	81	$1.1B	$137.0M	700,000	251,600	65,700	1.21

3.2.3 - LNG

LNG shows slightly more favorable business cases compared to Jet-A based on passenger market capture. The lower fuel price SpaceWorks assumed for LNG helps reduce annual costs to the operator which enables the operator to charge a lower ticket price while still maintaining its 25% IRR. LNG does suffer from higher aircraft and engine development and production costs which increases the LNG aircraft prices compared to Jet-A aircraft (prior to considering production rates of each alternative). The higher development costs result in higher financial exposure for the manufacturers and operator. Even though the business cases may generate better returns over the life cycle of the simulation, there is more financial risk to overcome in the early years when adopting LNG.

LNG cases also appear to have an inflection point for aircraft that have longer ranges and higher speeds. The additional development and production costs combined with the larger fuel quantities required for a lower density fuel start to outpace the benefits of using a lower cost fuel. See *Table 7* for LNG results.

Table 8: LH2 Trade Matrix

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/ pax)
Best – SR	4,000	2.28	30	19.0%	$10,300	1.6%	112	$270M	$28.1M	116,000	72,200	10,900	1.11E-03
Best – LR	5,700	2.00	38	17.2%	$14,100	1.2%	76	$470M	$45.7M	212,000	124,800	19,900	1.31E-03
1	4,000	2.0	20	18.2%	$9,800	1.7%	160	$190M	$18.5M	84,000	53,100	7,800	1.13E-03
2	4,000	3.0		15.0%	$15,200	0.8%	76	$300M	$34.0M	119,000	73,200	11,200	1.89E-03
3	4,000	4.0		11.0%	$16,700	0.6%	59	$300M	$38.4M	141,000	86,600	13,200	2.30E-03
4	4,000	5.0		6.7%	$17,900	0.3%	40	$300M	$43.4M	166,000	102,300	15,500	2.72E-03
5	4,000	2.0	50	17.3%	$7,400	2.1%	90	$330M	$32.5M	148,000	91,600	13,900	7.95E-04
6	4,000	3.0		14.3%	$12,400	1.1%	49	$560M	$62.8M	210,000	126,400	19,700	1.32E-03
7	4,000	4.0		14.9%	$14,700	0.7%	31	$670M	$89.6M	246,000	148,600	23,100	1.60E-03
8	4,000	5.0		12.1%	$15,700	0.6%	28	$630M	$94.2M	286,000	174,300	26,800	1.88E-03
9	6,100	2.0	20	10.2%	$16,700	0.7%	95	$210M	$20.4M	175,000	102,300	16,400	2.05E-03
10	5,700	3.0		**DNC**	$7,500	4.1%	332	$1.0B	$49.2M	374,000	211,700	35,100	5.25E-03
11	5,400	4.0		**DNC**	$7,500	4.1%	317	$1.4B	$76.6M	447,000	255,100	41,900	6.59E-03
12	5,000	5.0		**DNC**	$7,500	4.1%	317	$1.5B	$89.7M	416,000	243,400	39,000	6.40E-03
13	6,100	2.0	50	12.7%	$14,100	1.1%	60	$550M	$51.1M	307,000	177,700	28,800	1.45E-03
14	5,700	3.0		**DNC**	$7,500	3.5%	144	$1.8B	$86.1M	655,000	368,500	61,400	3.68E-03
15	5,400	4.0		**DNC**	$7,500	3.5%	130	$2.4B	$133.2M	777,000	441,300	72,800	4.58E-03
16	5,000	5.0		**DNC**	$7,500	3.7%	139	$2.5B	$154.6M	718,000	417,300	67,300	4.41E-03

3.2.4 - LH2

LH2 faces similar problems as LNG except the impact is significantly worse since LH2 is less dense and more expensive. No aircraft in the trade matrix achieved the required 25% IRR. This was mainly driven by the excessive amount of fuel needed for high-speed flight. The high fuel costs also drove up ticket prices which in turn, reduced market capture. The operator could not capture enough demand and continued to raise ticket prices to offset fuel costs. And with higher development and production cost, the manufacturers would need to achieve economies of scale to improve the business cases. See ***Table 8*** for LH2 results. Cases that did not economically close with a positive IRR are listed as DNC (Did Not Close) in ***Table 8*** ***.***

Overall, differences between the alternative fuel business cases were mostly driven by differences in fuel prices, regardless of improved technical performance or sizing.

Looking forward, alternative fuel prices will be dependent on the production process and by extension, the available supply. SAF offers a net-zero carbon alternative to Jet-A, but SAF supply is ambitiously hoping to produce 3 billion gallons per year by 2030. To put that in context, the global aviation industry used 95 billion gallons of aviation fuel in 2019 and SAF production in 2021 was only 6 million gallons, or approximately 0.6% of market. To achieve ICAO's 2050 Net Zero Objectives, the production of SAF would need to increase to 118 billion gallons[9].

LNG burns cleaner than Jet-A but it is still a hydrocarbon so much of the emissions remain the same. LH2 produces mostly water as a combustion product but water vapor is also considered a greenhouse gas (GHG). However, water quickly disperses in the atmosphere and is very transient due to the water cycle whereas other GHGs like CO2 will linger in the atmosphere, creating a higher concentration over time.

One thing is certain though, global industries and governments are looking to move away from Jet-A and other fossil fuels.

---

[9] https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact-sheet---us-and-eu-saf-policies.pdf

3.3 - OVERLAND ROUTES (TASK 5)

For the overland routes sensitivity study, SpaceWorks was tasked to evaluate the economic impact of expanding the 90 baseline transoceanic routes in the ROSETTA model to include additional U.S. domestic and U.S. international routes that are primarily overland. These routes were excluded up until this point because SpaceWorks has assumed that these routes would be unserviceable given current sonic boom and supersonic regulations. This is in line with the FAA's current position[10] on supersonic flight overland as well as NASA's[11], although both organizations are exploring options to possibly permit supersonic overland flight in the future.

Under the Task 5 sensitivity analysis, SpaceWorks assumed that any regulations and/or restrictions for supersonic or hypersonic flights overland could be lifted through some unspecified combination of new technologies, designated flight corridors, and other regulatory changes. The difficulty, cost, or even the likelihood of achieving such a significant policy change are not addressed here. SpaceWorks simply evaluated the impact of this scenario based on the increased number of routes and passengers that could be addressable if the change was allowed.

Overland domestic and international route market data was gathered from the *Bureau of Transportation Statistics: T-100 Domestic Market & T-100 International Market* data files for 2019. To be included in the ROSETTA model, routes had to meet certain criteria:

- **Domestic routes must fly between major U.S. airports (see Appendix C)**
- **International routes must fly from "large" U.S. airports**
- **Routes must have more than 100,000 passengers annually**

Given these criteria, the total available market in the model grew from the original 39 million passengers (90 routes) to roughly 331 million passengers (855 routes). With the substantial increase in routes, it was infeasible to model each route individually. To work around this, "representative" routes based on demand were created for both domestic routes and new international routes. Each route fell into one of three demand buckets:

- **100,000 to 499,999 passengers per year**
- **500,000 to 999,999 passengers per year**
- **1,000,000+ passengers per year**

Another consideration given to overland routes was a minimum distance that a high-speed aircraft would fly based on the maximum design Mach number. SpaceWorks and NASA agreed that it did not make sense for a high-speed commercial aircraft in the current trade space (Mach 2-5) to never reach its maximum cruise speed during a short, overland flight segment. That is, a Mach 5 aircraft would not be utilized to service a short route such as Atlanta to Orlando. Therefore, minimum route distances were determined for each Mach number that roughly correlated to a distance that had at least 30 minutes of cruise time at the aircraft's maximum cruise Mach. The following ***Table 9*** shows the minimum distance for each Mach and the resulting available market based on passengers per year in 2019.

Table 9: Minimum route distances for the respective Mach number and the resulting available market size

Mach	Minimum Distance	Addressable Domestic Market (Routes)	Addressable International Overland Market (Routes)
2	1,000 nmi	191,000,000 (381)	104,000,000 (384)
3	1,600 nmi	78,400,000 (161)	69,600,000 (268)
4	2,300 nmi	5,970,000 (20)	54,400,000 (209)
5	3,000 nmi	1,710,000 (8)	48,600,000 (184)

With all these conditions in place, the aforementioned representative routes used a weighted route distance based on demand and an average passenger demand. The representative routes were then put through the model and scaled accordingly based on the number of routes included within each representative route.

The final adjustment made to accommodate overland routes was to modify the traffic figures to mirror the current market passenger class distribution for the representative routes. The original 90 transoceanic routes had an economy-premium passenger class distribution of 84.7% & 15.3%, respectively, typical of international travel. For domestic routes, the distribution was adjusted to be 95% economy passengers & 5% premium passengers to be more reflective of cabin configurations on domestic aircraft/flights. For the added U.S. international routes that are overland, SpaceWorks assumed a slight shift towards economy passengers (88%) to reflect shorter North American routes to Canada and Mexico.

The simulation results from the overland routes study show significant improvements for the manufacturers. The significant increase in market size translates to higher production volumes for the engine and airframe manufacturers, and thus, a larger base of revenue over which to amortize their development costs. For the Elite Airline operator, the increased market size was beneficial but did result in relatively high initial fleet acquisition costs that drove the operator to increase ticket price in an effort to temper the demand and reduce its maximum financial exposure. Future studies should consider a controlled rollout of high-speed service over time as a way to spread the fleet acquisition costs for the airline operator. See ***Table 10*** for the overland route trade matrix results.

A separate sensitivity study was conducted to determine if an aircraft with a higher passenger count would be better suited for the expanded domestic and international markets that could derive from removing overland supersonic flight restrictions. A five-variable optimization of that simulation resulted in an 88-passenger aircraft as the best passenger count for the larger market model.

---

[10] https://www.faa.gov/newsroom/supersonic-flight

[11] https://www.nasa.gov/feature/supersonic-technologies

Table 10: Jet-A Overland Routes Trade Matrix Results

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.07	88	25.1%	$3,200	6.1%	1048	$210M	$18.5M	269,000	108,000	25,200	0.30
Best – LR	5,700	2.09	39	25.1%	$5,700	3.0%	1173	$180M	$16.7M	240,000	81,600	22,500	0.52
1	4,000	2.0	20	27.2%	$11,000	1.0%	966	$140M	$11.3M	95,000	40,200	8,900	0.47
2	4,000	3.0		28.2%	$10,200	1.1%	446	$210M	$19.2M	135,000	51,600	12,700	0.75
3	4,000	4.0		25.6%	$10,100	1.5%	206	$350M	$33.3M	161,000	60,900	15,100	0.92
4	4,000	5.0		25.0%	$10,700	1.7%	186	$380M	$39.4M	186,000	71,600	17,500	1.06
5	4,000	2.0	50	25.2%	$5,500	3.1%	1055	$200M	$14.3M	167,000	69,000	15,700	0.33
6	4,000	3.0		25.5%	$5,000	3.2%	485	$250M	$22.3M	236,000	87,700	22,100	0.53
7	4,000	4.0		25.0%	$8,400	1.5%	112	$550M	$55.6M	276,000	101,900	25,900	0.63
8	4,000	5.0		24.8%	$11,000	1.5%	92	$740M	$78.9M	313,000	117,400	29,300	0.71
9	6,100	2.0	20	25.3%	$9,200	1.3%	1159	$150M	$13.4M	179,000	60,300	16,800	0.72
10	5,700	3.0		24.1%	$14,000	0.7%	377	$300M	$28.8M	317,000	96,500	29,700	1.48
11	5,400	4.0		19.4%	$14,700	0.8%	207	$400M	$45.2M	382,000	118,700	35,800	1.87
12	5,000	5.0		18.0%	$15,000	0.9%	180	$450M	$56.6M	381,000	126,000	35,700	1.96
13	6,100	2.0	50	25.5%	$7,700	1.2%	616	$270M	$23.7M	315,000	103,800	29,500	0.51
14	5,700	3.0		22.3%	$12,900	0.4%	100	$750M	$68.7M	545,000	163,500	51,100	1.02
15	5,400	4.0		18.9%	$13,100	0.7%	79	$900M	$93.1M	635,000	194,500	59,500	1.24
16	5,000	5.0		18.4%	$12,800	1.2%	131	$700M	$91.5M	616,000	200,400	57,700	1.26

Given these two findings, SpaceWorks believes that a case could be made that a smaller aircraft (30-50 passengers) could service international routes to start while a larger passenger aircraft (60-90 passengers) could enter service later if/when overland restrictions are lifted, and the domestic market opens up. This “leader” and “follower” aircraft approach could open transoceanic routes first with a smaller and more affordable airplane, then expand to a larger and more expensive aircraft if/when the demand justifies it. This approach would delay the need to remove sonic boom overland flight restrictions for perhaps a decade and reduce near term demands on upfront capital for a larger aircraft development until the supersonic / hypersonic travel market has been better tested and understood.

SpaceWorks also conducted a focused sensitivity for overland routes considering LNG or LH2 as the fuel. The initial working theory was that reducing the design range of the aircraft and therefore, making the aircraft smaller, might be sufficient to improve the business case if demand for a cryogenic shorter range aircraft could be increased using overland routes. Previously, the shortest transoceanic route distance was New York to London at 3,000 nmi, so designing an aircraft for that range captured almost no other routes and did not have a large enough addressable market to satisfy the operator and the manufacturers. But with overland routes available, a smaller short-range aircraft using cryogenic fuels was viable. For this sensitivity study, 3,000 nmi and 3,500 nmi were used as candidate aircraft design ranges. The results of these cases can be seen in ***Table 11*** and ***Table 12***.

LNG showed improved business cases and had more cases reach the 25% IRR objective at higher Mach numbers. However, the biggest takeaway was that LH2 actually had cases that were successful, albeit all at a Mach 2 maximum aircraft design speed. Based on this finding, it may be feasible that Mach 2, LH2 aircraft may be well-enough suited to serve short-range domestic routes if overland markets become available. Such a scenario might be a viable first option to introduce hydrogen aircraft into the industry.

Table 11: LNG Overland Results

Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
3,000	2.0	20	28.4%	$12,000	0.8%	843	$130M	$12.3M	76,000	38,200	7,100	0.35
3,000	3.0		26.1%	$11,300	0.7%	323	$220M	$21.1M	97,000	45,500	9,100	0.52
3,000	4.0		21.6%	$6,600	1.8%	297	$200M	$20.1M	107,000	50,100	10,100	0.58
3,000	5.0		20.8%	$5,900	1.2%	80	$420M	$51.7M	114,000	54,400	10,700	0.61
3,000	2.0	50	25.1%	$6,100	2.5%	838	$250M	$14.3M	134,000	65,600	12,600	0.25
3,000	3.0		27.0%	$5,700	2.2%	364	$280M	$27.5M	170,000	77,800	16,000	0.36
3,000	4.0		19.9%	$5,300	1.4%	61	$590M	$68.2M	187,000	85,200	17,500	0.41
3,000	5.0		17.9%	$6,600	1.0%	33	$860M	$92.2M	197,000	91,600	18,500	0.42
3,500	2.0	20	26.1%	$11,600	0.9%	912	$140M	$8.4M	86,000	41,400	8,100	0.37
3,500	3.0		27.7%	$10,800	0.9%	393	$230M	$20.7M	116,000	51,300	10,900	0.58
3,500	4.0		25.3%	$10,300	1.2%	148	$440M	$44.0M	132,000	57,700	12,300	0.67
3,500	5.0		25.0%	$10,700	1.4%	129	$490M	$55.9M	143,000	63,700	13,400	0.72
3,500	2.0	50	25.8%	$5,800	2.8%	1047	$160M	$15.9M	152,000	71,100	14,300	0.26
3,500	3.0		27.3%	$5,400	2.9%	428	$290M	$24.9M	204,000	88,000	19,200	0.41
3,500	4.0		25.6%	$5,900	2.5%	126	$530M	$57.5M	229,000	98,300	21,500	0.47
3,500	5.0		24.2%	$6,400	2.6%	100	$660M	$77.8M	248,000	107,700	23,200	0.50

Table 12: LH2 Overland Results

Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
3,000	2.0	20	25.5%	$12,000	0.8%	849	$110	$9.3	65,000	43,100	6,100	9.65E-04
3,000	3.0		19.1%	$13,900	0.3%	176	$210	$21.5	82,000	52,900	7,700	1.43E-03
3,000	4.0		12.1%	$13,600	0.4%	65	$240	$30.7	91,000	59,000	8,600	1.63E-03
3,000	5.0		11.4%	$17,300	0.2%	22	$350	$48.8	100,000	65,100	9,300	1.76E-03
3,000	2.0	50	24.4%	$11,800	0.5%	403	$200	$16.9	116,000	74,200	10,800	6.84E-04
3,000	3.0		17.6%	$12,400	0.4%	158	$280	$29.2	144,000	90,900	13,500	1.00E-03
3,000	4.0		12.8%	$13,200	0.3%	25	$490	$62.2	159,000	100,700	14,900	1.13E-03
3,000	5.0		13.0%	$11,200	0.5%	23	$560	$84.3	172,000	110,200	16,100	1.22E-03
3,500	2.0	20	26.2%	$14,300	0.4%	465	$170	$14.1	73,000	47,600	6,900	1.03E-03
3,500	3.0		18.4%	$13,900	0.5%	234	$200	$19.7	98,000	61,400	9,200	1.61E-03
3,500	4.0		12.7%	$16,100	0.4%	85	$230	$29.2	112,000	70,200	10,500	1.89E-03
3,500	5.0		8.8%	$17,900	0.2%	37	$330	$47.1	125,000	79,500	11,700	2.13E-03
3,500	2.0	50	25.0%	$9,800	0.8%	441	$210	$17.2	130,000	82,000	12,200	7.31E-04
3,500	3.0		18.5%	$12,700	0.6%	188	$290	$29.7	172,000	105,800	16,100	1.13E-03
3,500	4.0		14.1%	$14,500	0.5%	31	$740	$75.9	194,000	120,000	18,200	1.32E-03
3,500	5.0		15.2%	$15,000	0.6%	28	$710	$104.9	216,000	135,000	20,300	1.47E-03

Ultimately, the additional market that comes with overland routes provides high production volume that makes the manufacturers' business cases profitable and robust. The Elite Airline operator can achieve robust business cases as well but the overwhelming fleet acquisition costs result in very high upfront investments. Better business cases were found outside the original 20-50 passenger trade space as an aircraft with more seats (88 passengers) was better suited for the large market size.

3.4 - IOC DATES (TASK 6)

For this task, SpaceWorks conducted a sensitivity study to evaluate the technical and economic impact of delaying the development and operations of a high-speed commercial aircraft. Technology advances over time and air travel markets are expected to continue to increase as world population and individual wealth grow. Assuming that no competition steps in to fill the void, it may be better to simply delay the service entry date of supersonic / hypersonic transportation for 10 years or more to allow the market and technology time to grow and mature.

In order to better understand progressions in technology and the changes in the economic landscape, SpaceWorks conducted an internal survey of subject matter experts (SMEs) across the company to gather their inputs for a variety of technology/ economic improvements or "k-factors", where a k-factor is a linear scaling relationship on key parameters within our ROSETTA model such as aircraft cruise lift-to-drag ratio. SMEs were asked to only evaluate k-factors that they had familiarity with (e.g., a structural engineer did not evaluate economic k-factors) and then responses were weighted before taking the average. These results were then approved by NASA before moving forward.

For analysis, k-factors were grouped into five major categories: Structures, Propulsion, Noise, Fuel, and Economics. See ***Tables 13 - 17*** for the list of k-factors and their anticipated impact. Delayed service date cases were also run with no k-factors applied (purely evaluating the impact of market growth) and with all k-factors applied.

Table 13: Structures k-factors

Structures k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Structures Mass Reduction	Mass	0%	-4%	-7%	-9%	-11.0%	-12.5%
TPS Mass Reduction	Mass	0%	-4%	-7.5%	-10.0%	-12.5%	-14.5%
L/D	L/D	0%	1%	3%	5%	6.0%	7.0%

Table 14: Propulsion k-factors

Propulsion k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Engine T/W	T/W	0%	4.0%	8%	11.5%	13.5%	15.5%
Isp	Fuel Eff.	0%	2.5%	5%	7.0%	8.5%	10%
Emissions	CO2e	0%	-2.5%	-4.0%	-7.0%	-8.0%	-9.0%

Table 15: Noise k-factors

Noise k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Sideline Noise	Takeoff Noise	0%	-3.0%	-6.0%	-7.0%	-9.0%	-10.0%
Overpressure	Overpressure	0%	-9.0%	-13.5%	-15.0%	-21.5%	-22.5%

Table 16: Fuel k-factors

Fuel k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Jet-A Prices	Fuel Cost	0%	9.0%	15.5%	27.5%	42.5%	53.0%
LNG Prices	Fuel Cost	0%	0.0%	2.5%	4.5%	8.0%	13.5%
SAF Prices	Fuel Cost	0%	-12.0%	-21.0%	-29.0%	-42.0%	-45.5%
LH2 Prices	Fuel Cost	0%	-5.5%	-8.0%	-16.0%	-28.0%	-62.0%

Table 17: Economic k-factors

Economic k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Maintenance	Maint. Costs	0%	-4.5%	-10.5%	-18.0%	-29.0%	-38.5%
Airframe Manufacturing	TFU	0%	-6.5%	-10.5%	-14.5%	-19.5%	-26.0%
Engine Manufacturing	TFU	0%	-6.5%	-10.5%	-14.5%	-19.5%	-26.0%
Tax Benefits / Detriments	Cost	0%	-7%	-5.0%	-3.5%	-2.5%	-2.0%

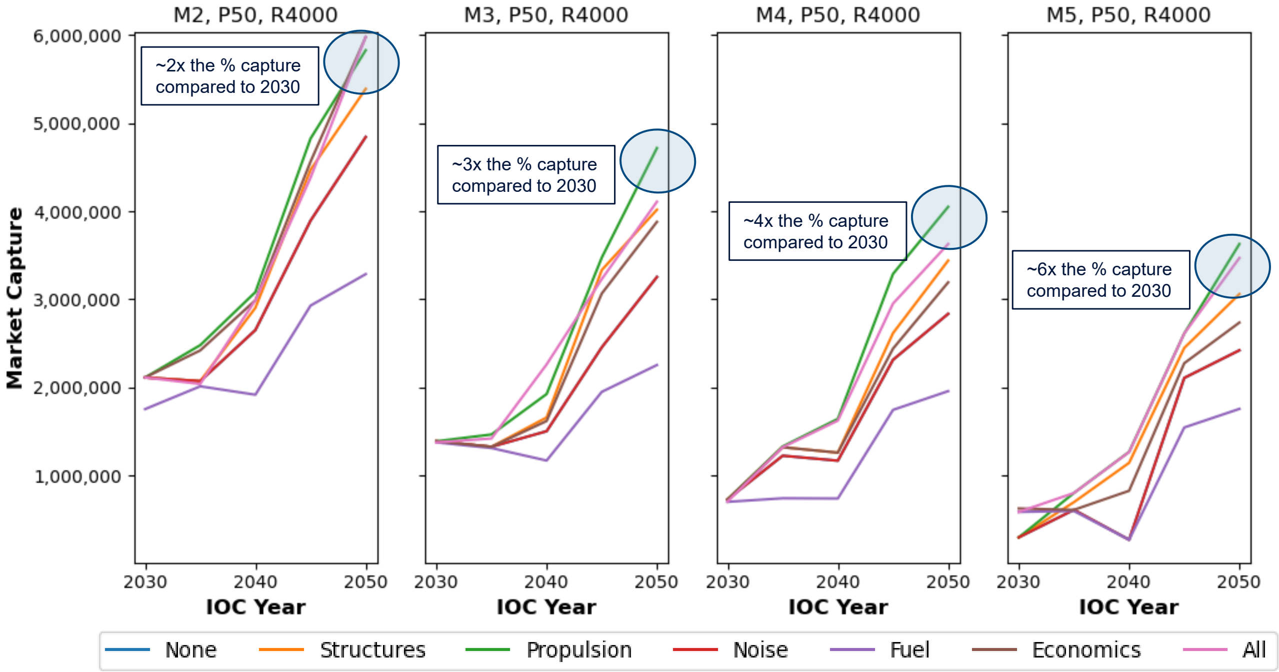


Figure 12: IOC Date Sensitivity Study Results for 50 passenger, 4,000 nmi, Mach 2-5 aircraft

To capture 25 years of operations for a given manufacturer or operator, a terminal value calculation was used in the final year of the model to account for projected cash flows. This took the years of operation remaining and multiplied it by the final year EBITDA. Terminal values were used in order to keep annual calculations aligned as initial operating capability (IOC) dates changed. This was particularly important for mixed fleet business cases when the operator had to account for a short- and long-range aircraft starting service at different times.

The results of IOC sensitivity study showed that the business cases generally improved as the IOC date shifted to later years ***(See Figure 12)***. Increasing the market size alone proved to be a significant improvement. Beyond that, propulsion k-factors had the greatest impact on the overall business case. On the other hand, fuel k-factors, specifically for Jet-A, were the most hindering to the business case as fossil-derived hydrocarbon fuel prices were projected to increase over time. However, business cases still saw some improvements which emphasizes the impact of the additional available market.

Demand has a two-fold effect here. By increasing the market size, more engine and airframe units need to be produced which unlocks additional manufacturing economies of scale. This yields lower acquisition costs for the operator who can then lower ticket prices and capture more demand, in a highly coupled iteration with the manufacturers. This loop ends when the total acquisition cost becomes too great and ticket prices don't generate enough revenue to balance out the costs.

It should also be noted that this IOC date sensitivity analysis assumes there are no other manufacturers or operators in this market space. Therefore, the manufacturers and operators always have a "first-mover" advantage and face zero risk of losing market share by waiting to start operations. This applies in mixed fleet analyses, too, where routes are non-competitive so there is no threat of cannibalization beyond the serviceable routes being split by distance.

Based on the results of this sensitivity study, SpaceWorks recommends NASA focus its technology investments into propulsion related projects. This recommendation may also lead to major engine manufacturers becoming more engaged in developing and producing engines for high-speed aircraft which currently does not seem to be the case[12].

---

[12] https://www.businessinsider.com/engine-makers-help-boom-build-supersonic-engine-overture-2022-9

4 - COMMERCIALIZATION EFFORTS UNDER PHASE III SBIR

4.1 - DES MODELING (TASK 7)

In parallel to the previous six tasks, SpaceWorks was tasked to develop an enhanced modeling and simulation (M&S) tool to eventually replace the existing ROSETTA model. There are two main reasons for moving towards an M&S tool. First, greater granularity and fidelity are achievable with the new M&S tool which enables more realistic economic modeling and greater insight into the model behavior. The other reason is that the scope and capability of the ROSETTA model is limited – practically or absolutely – by the specifications of Microsoft Excel. Recent additions to the model have resulted in noticeable increases in runtime, and therefore, reduce the overall practicality of utilizing the ROSETTA model as a software tool for such a large and complex technical and economic simulation.

After evaluating available options, SpaceWorks determined the AnyLogic® modeling and simulation application was the best option for advancing the modeling capabilities of this project. AnyLogic is a multi-method simulation software that enables any combination of discrete-event simulation (DES) modeling, agent-based modeling, and system dynamics modeling to be used within a simulation. To be an effective tool going forward, the objective of this task was to recreate the economic models from the ROSETTA model in AnyLogic and to verify the new AnyLogic model by comparison.

The sizing and performance models will not be integrated into the new AnyLogic-based model but will instead remain in Excel. However, the results from those models will be used to generate a database of aircraft to be fed into the AnyLogic model. The sizing and performance models can rapidly produce results and enable SpaceWorks to generate hundreds of unique aircraft for economic optimizations within AnyLogic.

Figure 13: AnyLogic multi-method simulation capabilities

It should be noted that results will not be identical between the ROSETTA model and the AnyLogic-based model due to subtle differences in how some behaviors are modeled. For example, in the ROSETTA model, aircraft are assumed to have a lifespan of 15 years, regardless of what route that aircraft flies on. In the higher-fidelity AnyLogic model, SpaceWorks can track individual aircraft metrics, such as flight hours, fuel consumed, passengers serviced, etc. Given this improved resolution within the model, aircraft are retired based on flight hours rather than a fixed lifespan. The timelines are roughly the same, but more realism has been introduced into the AnyLogic model.

Figures 14 -17 show the outputs of several validation cases against the optimized ROSETTA Model results. In general, the results between the ROSETTA and AnyLogic models were mostly consistent, and small discrepancies exist as a result of differences in modeling behavior.

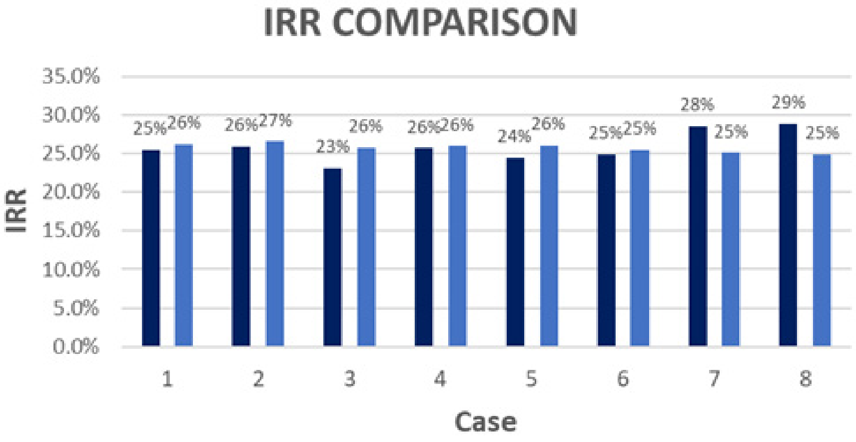


Figure 14: IRR results comparison of AnyLogic to ROSETTA

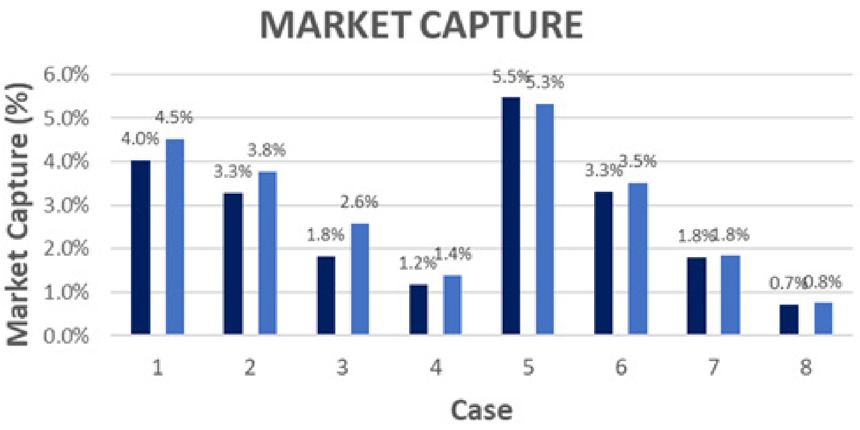


Figure 15: Market Capture results comparison of AnyLogic to ROSETTA

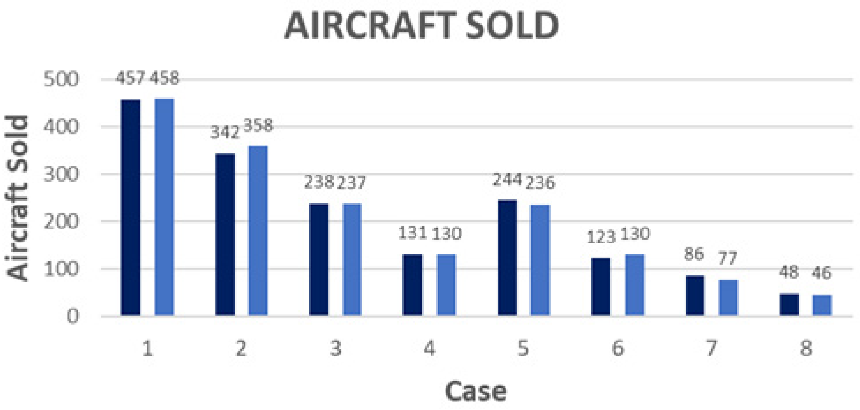


Figure 16: Aircraft Sold comparison of AnyLogic to ROSETTA

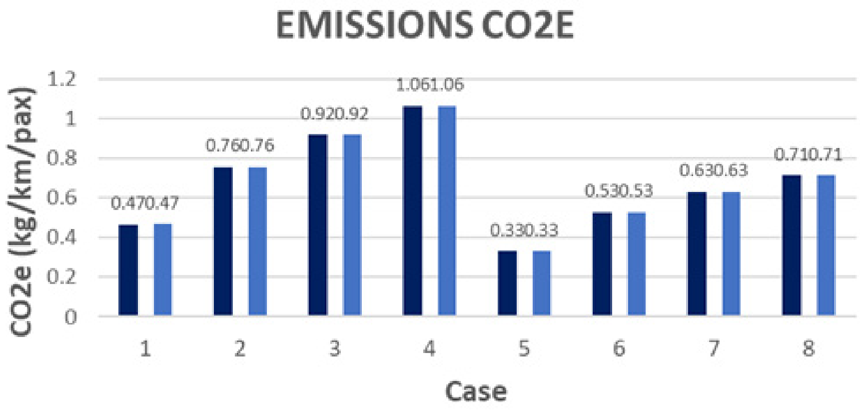


Figure 17: Emissions comparison of AnyLogic to ROSETTA

Given these results, SpaceWorks feels confident in the capabilities of the AnyLogic model and recommends that it replace the ROSETTA model for any future high-speed flight analysis work conducted by SpaceWorks. Improved fidelity can be implemented in several areas to further develop and enhance this model such as the manufacturing process, fuel production, and/or flight scheduling to start.

5 - CONCLUSIONS & RECOMMENDATIONS

5.1 - KEY CONCLUSIONS

1. Overall, when modeling a single Jet-A fueled aircraft type that serves a subset of the 90 candidate transoceanic passenger routes that lie within its unrefueled range, the Mach 2-3, 4,000-5,000 nmi, and 40-50 passenger aircraft had the best business cases. This conclusion is consistent with the results of the previous market study conducted with the Deloitte Team.

2. From the initial trade matrix study looking at Jet-A aircraft (Task 3), mixed fleet solutions that operated one aircraft type exclusively on shorter routes (under 4,000 nmi) and a second aircraft type exclusively on long-range routes (over 4,000 nmi) had marginally better solutions based on the metric of total passengers captured per year. However, the reduced addressable market for the long-range aircraft (only routes over 4,000 nmi) made it difficult for that side of the business case to close and typically had low production rates, high ticket prices, and lower demand. Based on these results, SpaceWorks believes a mixed fleet solution where the aircraft types are segregated based on range alone may not be the best approach.

3. In the simulation, SAF performed slightly worse than Jet-A economically, but overall the business cases were similar. Performance on the aircraft is almost identical, but the main differentiator was the initial price of SAF compared to Jet-A. SAF prices are currently very high (assuming it is even available in quantities needed) but prices are expected to decrease over time as the supply chain becomes more established. Jet-A is expected to have the opposite behavior. Its cost is expected to increase over time. If SAF prices can be brought down enough to be competitive with Jet-A, SAF could be a viable alternative going forward. The most obvious benefit to SAF, namely the carbon neutral life cycle of its production and use, is not explicitly modeled here, but is the strongest motivating factor in its adoption.

4. Looking at alternative cryogenic fuels, LNG benefitted from a relatively lower fuel price and improved energy content which produced some of the best business cases. However, aircraft prices tended to be higher due to additional complexity and larger tanks due to the lower density of the fuel. On the emissions side, LNG burns cleaner than Jet-A but still has the drawback of being a hydrocarbon, so it still produces some of the same harmful emissions as Jet-A.

5. The other cryogenic fuel, LH2, struggled to even achieve a 25% IRR. Even though LH2 has a high performance, the low density of LH2 meant the aircraft required very high volumes of fuel – an effect that increases aircraft size and drag. The high fuel costs incurred by the operator as well as higher aircraft prices make LH2 business cases hard to justify for the aircraft in the trade matrix analyzed. Despite this, Mach 2, LH2 aircraft were able to achieve 25% IRR when ranges were reduced to 3,000 nmi and 3,500 nmi. By reducing the required fuel capacity of aircraft, short range LH2 aircraft become feasible and may be viable options for domestic routes if overland restrictions are lifted. These cryogenic fuels may even be necessary for some high-speed engine cycles. However, these are both longer term options that need additional time to mature.

6. Overland routes provided a significant boost in available market size. The additional demand solidified the manufacturers' business cases with high production volumes. The operator also saw improved business cases but had high upfront costs to acquire all the aircraft needed to address the high demand. A controlled approach to service rollout might mitigate the capital needs from the operator and still benefit all players in the simulation.

7. In the IOC sensitivity study (delayed service entry dates), propulsion-focused k-factors and air travel market growth provided the greatest improvements to business cases. All technology sets considered offered improvements in the study metrics while fuel prices had a significant impact on the business cases of alternative fuels.

5.2 - FORWARD RECOMMENDATIONS

1. SpaceWorks recommends NASA and the FAA continue their technology and regulatory work to permit overland supersonic flight because of the increased market size that would result in more robust business cases for supersonic / hypersonic developers and operators.

2. As future work, SpaceWorks recommends assessing a mixed fleet solution that is based on route demand and/or density. In this scenario, one larger aircraft could service the higher density markets like New York to London while a smaller aircraft could be better suited for lower density markets and capture more routes. This approach could increase the load factors and utilization rates of both aircraft types and generate more robust mixed fleet solutions, even if the two aircraft have similar design ranges.

3. SpaceWorks also recommends that a small, fast, first-to-market transoceanic "leader" aircraft and a later, larger "follower" aircraft designed for also servicing the additional overland routes might be a good two-phased compromise strategy for government and commercial industry alike since it delays action on supersonic overland flight and reduces near-term capital requirements on aircraft developers.

4. For all the alternative fuels, current supply is limited. Their supply needs to be order of magnitudes greater than what it currently is to service future high-speed aircraft. Assuming those concerns can be addressed, SpaceWorks recommends continued investments in SAF as the way forward in future aviation fuels for high-speed aircraft. LNG shows promise based on its price and energy content and in limited cases, zero-carbon LH2 also finds some economically viable solutions in our simulation, so those too deserve additional investigation.

5. SpaceWorks recommends that NASA continue to focus government technology maturation investments into supersonic / hypersonic propulsion areas such as improved fuel efficiency and reduced takeoff noise, engine maintenance, emissions, and engine weight.

6. Finally, SpaceWorks' new AnyLogic-based model has demonstrated it can produce comparable results to our current Excel-based ROSETTA model. The enhanced modeling and simulation capabilities sets SpaceWorks up to provide improved business case analyses in the future. Given the confidence SpaceWorks has in the AnyLogic Model, it is recommended that it should replace the existing ROSETTA model in future studies, or at the very least, be used in parallel to ensure consistent results.

6 - APPENDICES

APPENDIX A – TRADE MATRIX RESULTS

APPENDIX B – K-FACTORS

APPENDIX C – AIRPORTS

Appendix A: Jet-A (Baseline)

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/ pax)
Best – SR	4,000	2.01	40	25.0%	$3,900	4.6%	197	$250M	$19.8M	143,000	59,300	13,400	0.34
Best – LR	5,700	2.00	38	25.0%	$5,200	5.8%	300	$250M	$19.8M	222,000	77,000	20,900	0.49
1	4,000	2.0	20	25.1%	$5,000	3.7%	289	$170M	$13.5M	95,000	40,200	8,900	0.47
2	4,000	3.0		25.5%	$7,000	2.8%	207	$260M	$23.4M	135,000	51,600	12,700	0.75
3	4,000	4.0		25.0%	$10,000	1.9%	152	$380M	$37.1M	161,000	60,900	15,100	0.92
4	4,000	5.0		25.2%	$12,700	1.5%	123	$450M	$50.0M	186,000	71,600	17,500	1.06
5	4,000	2.0	50	25.0%	$4,300	4.1%	143	$350M	$27.8M	167,000	69,000	15,700	0.33
6	4,000	3.0		25.1%	$5,700	3.4%	111	$470M	$43.1M	236,000	87,700	22,100	0.53
7	4,000	4.0		24.9%	$11,500	1.5%	53	$990M	$97.6M	276,000	101,900	25,900	0.63
8	4,000	5.0		23.7%	$11,500	1.6%	61	$980M	$105.2M	313,000	117,400	29,300	0.71
9	6,100	2.0	20	25.0%	$8,200	3.4%	324	$210M	$17.0M	179,000	60,300	16,800	0.72
10	5,700	3.0		22.1%	$13,100	2.0%	188	$370M	$34.9M	317,000	96,500	29,700	1.48
11	5,400	4.0		19.0%	$15,500	1.1%	101	$520M	$57.0M	382,000	118,700	35,800	1.87
12	5,000	5.0		18.4%	$15,000	1.4%	120	$480M	$58.5M	381,000	126,000	35,700	1.96
13	6,100	2.0	50	25.0%	$8,300	2.9%	131	$530M	$41.9M	315,000	103,800	29,500	0.51
14	5,700	3.0		21.3%	$11,600	2.0%	81	$850M	$77.5M	545,000	163,500	51,100	1.02
15	5,400	4.0		18.6%	$11,600	2.0%	81	$870M	$90.8M	635,000	194,500	59,500	1.24
16	5,000	5.0		18.4%	$12,200	1.9%	74	$950M	$108.5M	616,000	200,400	57,700	1.26

Appendix A: Jet-A (Overland Routes)

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/ pax)
Best – SR	4,000	2.07	88	25.1%	$3,200	6.1%	1048	$210M	$18.5M	269,000	108,000	25,200	0.30
Best – LR	5,700	2.09	39	25.1%	$5,700	3.0%	1173	$180M	$16.7M	240,000	81,600	22,500	0.52
1	4,000	2.0	20	27.2%	$11,000	1.0%	966	$140M	$11.3M	95,000	40,200	8,900	0.47
2	4,000	3.0		28.2%	$10,200	1.1%	446	$210M	$19.2M	135,000	51,600	12,700	0.75
3	4,000	4.0		25.6%	$10,100	1.5%	206	$350M	$33.3M	161,000	60,900	15,100	0.92
4	4,000	5.0		25.0%	$10,700	1.7%	186	$380M	$39.4M	186,000	71,600	17,500	1.06
5	4,000	2.0	50	25.2%	$5,500	3.1%	1055	$200M	$14.3M	167,000	69,000	15,700	0.33
6	4,000	3.0		25.5%	$5,000	3.2%	485	$250M	$22.3M	236,000	87,700	22,100	0.53
7	4,000	4.0		25.0%	$8,400	1.5%	112	$550M	$55.6M	276,000	101,900	25,900	0.63
8	4,000	5.0		24.8%	$11,000	1.5%	92	$740M	$78.9M	313,000	117,400	29,300	0.71
9	6,100	2.0	20	25.3%	$9,200	1.3%	1159	$150M	$13.4M	179,000	60,300	16,800	0.72
10	5,700	3.0		24.1%	$14,000	0.7%	377	$300M	$28.8M	317,000	96,500	29,700	1.48
11	5,400	4.0		19.4%	$14,700	0.8%	207	$400M	$45.2M	382,000	118,700	35,800	1.87
12	5,000	5.0		18.0%	$15,000	0.9%	180	$450M	$56.6M	381,000	126,000	35,700	1.96
13	6,100	2.0	50	25.5%	$7,700	1.2%	616	$270M	$23.7M	315,000	103,800	29,500	0.51
14	5,700	3.0		22.3%	$12,900	0.4%	100	$750M	$68.7M	545,000	163,500	51,100	1.02
15	5,400	4.0		18.9%	$13,100	0.7%	79	$900M	$93.1M	635,000	194,500	59,500	1.24
16	5,000	5.0		18.4%	$12,800	1.2%	131	$700M	$91.5M	616,000	200,400	57,700	1.26

Appendix A: Economic Comparison

				BASELINE						OVERLAND ROUTES					
Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price
1	4,000	2.0	20	25.1%	$5,000	1.5M	289	$170M	$13.5M	27.2%	$11,000	2.9M	966	$140M	$11.3M
2	4,000	3.0		25.5%	$7,000	1.1M	207	$260M	$23.4M	28.2%	$10,200	1.6M	446	$210M	$19.2M
3	4,000	4.0		25.0%	$10,000	0.77M	152	$380M	$37.1M	25.6%	$10,100	0.95M	206	$350M	$33.3M
4	4,000	5.0		25.2%	$12,700	0.60M	123	$450M	$50.0M	25.0%	$10,700	0.90M	186	$380M	$39.4M
5	4,000	2.0	50	25.0%	$4,300	1.6M	143	$350M	$27.8M	**25.2%**	**$5,500**	**9.4M**	**1055**	**$200M**	**$14.3M**
6	4,000	3.0		25.1%	$5,700	1.4M	111	$470M	$43.1M	25.5%	$5,000	4.8M	485	$250M	$22.3M
7	4,000	4.0		24.9%	$11,500	0.58M	53	$990M	$97.6M	25.0%	$8,400	0.98M	112	$550M	$55.6M
8	4,000	5.0		23.7%	$11,500	0.64M	61	$980M	$105.2M	24.8%	$11,000	0.80M	92	$740M	$78.9M
9	6,100	2.0	20	25.0%	$8,200	1.4M	324	$210M	$17.0M	25.3%	$9,200	4.2M	1159	$150M	$13.4M
10	5,700	3.0		22.1%	$13,100	0.81M	188	$370M	$34.9M	24.1%	$14,000	1.2M	377	$300M	$28.8M
11	5,400	4.0		19.0%	$15,500	0.45M	101	$520M	$57.0M	19.4%	$14,700	0.75M	207	$400M	$45.2M
12	5,000	5.0		18.4%	$15,000	0.54M	120	$480M	$58.5M	18.0%	$15,000	0.68M	180	$450M	$56.6M
13	6,100	2.0	50	25.0%	$8,300	1.1M	131	$530M	$41.9M	25.5%	$7,700	3.9M	616	$270M	$23.7M
14	5,700	3.0		21.3%	$11,600	0.78M	81	$850M	$77.5M	22.3%	$12,900	0.73M	100	$750M	$68.7M
15	5,400	4.0		18.6%	$11,600	0.80M	81	$870M	$90.8M	18.9%	$13,100	0.64M	79	$900M	$93.1M
16	5,000	5.0		18.4%	$12,200	0.75M	74	$950M	$108.5M	18.4%	$12,800	0.86M	131	$700M	$91.5M

Appendix A: SAF

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/ pax)
Best – SR	4,000	2.01	38	25.1%	$4,200	4.3%	200	$240M	$19.3M	135,000	56,500	12,600	0.34
Best – LR	5,700	2.00	50	25.0%	$5,500	5.3%	212	$330M	$26.8M	263,000	91,600	24,600	0.43
1	4,000	2.0	20	25.0%	$5,100	3.7%	298	$170M	$14.7M	92,000	39,700	8,700	0.45
2	4,000	3.0		25.0%	$7,100	2.7%	200	$250M	$22.6M	130,000	50,400	12,200	0.72
3	4,000	4.0		25.2%	$12,200	1.5%	120	$440M	$49.4M	154,000	59,300	14,500	0.87
4	4,000	5.0		25.1%	$12,800	1.5%	120	$440M	$49.0M	178,000	69,500	16,700	1.00
5	4,000	2.0	50	25.0%	$4,800	3.7%	131	$380M	$30.3M	163,000	68,000	15,300	0.32
6	4,000	3.0		25.0%	$6,900	2.6%	93	$540M	$49.9M	227,000	85,700	21,300	0.50
7	4,000	4.0		24.5%	$11,500	1.5%	54	$970M	$96.3M	265,000	99,200	24,800	0.60
8	4,000	5.0		23.5%	$11,500	1.6%	61	$950M	$104.1M	299,000	114,000	28,100	0.67
9	6,100	2.0	20	25.0%	$8,500	3.3%	314	$210M	$17.2M	170,000	58,300	16,000	0.68
10	5,700	3.0		22.5%	$15,400	1.2%	122	$420M	$41.7M	292,000	90,300	27,300	1.34
11	5,400	4.0		19.4%	$15,500	1.1%	101	$490M	$54.8M	347,000	109,700	32,500	1.68
12	5,000	5.0		18.4%	$15,000	1.4%	119	$460M	$56.6M	348,000	117,100	32,700	1.77
13	6,100	2.0	50	25.0%	$8,500	2.8%	129	$530M	$42.3M	299,000	100,300	28,100	0.48
14	5,700	3.0		21.3%	$11,600	2.0%	80	$810M	$75.9M	502,000	153,000	47,100	0.93
15	5,400	4.0		18.6%	$12,200	1.8%	71	$900M	$94.9M	579,000	180,300	54,300	1.12
16	5,000	5.0		18.3%	$12,400	1.8%	69	$950M	$109.8M	566,000	187,100	53,000	1.15

Appendix A: LNG (Baseline)

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/ pax)
Best – SR	4,000	2.41	39	25.0%	$3,500	5.4%	204	$310M	$27.9M	170,000	72,700	16,000	0.38
Best – LR	5,700	2.00	39	25.1%	$4,900	6.2%	309	$310M	$25.7M	258,000	98,700	24,200	0.45
1	4,000	2.0	20	25.0%	$3,900	4.8%	374	$160M	$13.8M	99,000	45,200	9,300	0.40
2	4,000	3.0		25.1%	$5,300	4.0%	295	$240M	$23.0M	143,000	59,300	13,400	0.67
3	4,000	4.0		25.1%	$7,200	2.9%	214	$330M	$36.2M	167,000	68,500	15,600	0.80
4	4,000	5.0		25.4%	$12,600	1.5%	126	$530M	$66.2M	187,000	77,700	17,600	0.90
5	4,000	2.0	50	25.0%	$3,700	4.8%	165	$360M	$31.5M	175,000	77,700	16,400	0.29
6	4,000	3.0		25.0%	$5,200	3.8%	126	$500M	$50.7M	251,000	101,900	23,500	0.47
7	4,000	4.0		24.6%	$6,400	3.2%	106	$650M	$71.7M	290,000	117,000	27,200	0.55
8	4,000	5.0		23.5%	$10,400	1.8%	69	$990M	$117.0M	323,000	131,800	30,300	0.62
9	6,100	2.0	20	25.0%	$7,300	4.1%	381	$240M	$20.0M	207,000	77,400	19,400	0.70
10	5,700	3.0		21.9%	$15,200	1.3%	126	$560M	$57.6M	405,000	137,900	38,000	1.59
11	5,400	4.0		20.2%	$14,700	1.4%	128	$600M	$69.1M	457,000	157,800	42,900	1.89
12	5,000	5.0		20.8%	$15,000	1.4%	119	$640M	$80.7M	406,000	147,300	38,100	1.76
13	6,100	2.0	50	25.4%	$8,800	2.7%	128	$630M	$59.1M	364,000	133,900	34,100	0.49
14	5,700	3.0		19.7%	$11,000	2.2%	94	$940M	$91.5M	709,000	239,300	66,500	1.11
15	5,400	4.0		17.9%	$11,300	2.1%	88	$1.0B	$116.5M	795,000	272,100	74,500	1.31
16	5,000	5.0		18.8%	$11,500	2.1%	81	$1.1B	$137.0M	700,000	251,600	65,700	1.21

Appendix A: LNG (Overland Routes)

Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
3,000	2.0	20	28.4%	$12,000	0.8%	843	$130M	$12.3M	76,000	38,200	7,100	0.35
3,000	3.0		26.1%	$11,300	0.7%	323	$220M	$21.1M	97,000	45,500	9,100	0.52
3,000	4.0		21.6%	$6,600	1.8%	297	$200M	$20.1M	107,000	50,100	10,100	0.58
3,000	5.0		20.8%	$5,900	1.2%	80	$420M	$51.7M	114,000	54,400	10,700	0.61
3,000	2.0	50	25.1%	$6,100	2.5%	838	$250M	$14.3M	134,000	65,600	12,600	0.25
3,000	3.0		27.0%	$5,700	2.2%	364	$280M	$27.5M	170,000	77,800	16,000	0.36
3,000	4.0		19.9%	$5,300	1.4%	61	$590M	$68.2M	187,000	85,200	17,500	0.41
3,000	5.0		17.9%	$6,600	1.0%	33	$860M	$92.2M	197,000	91,600	18,500	0.42
3,500	2.0	20	26.1%	$11,600	0.9%	912	$140M	$8.4M	86,000	41,400	8,100	0.37
3,500	3.0		27.7%	$10,800	0.9%	393	$230M	$20.7M	116,000	51,300	10,900	0.58
3,500	4.0		25.3%	$10,300	1.2%	148	$440M	$44.0M	132,000	57,700	12,300	0.67
3,500	5.0		25.0%	$10,700	1.4%	129	$490M	$55.9M	143,000	63,700	13,400	0.72
3,500	2.0	50	25.8%	$5,800	2.8%	1047	$160M	$15.9M	152,000	71,100	14,300	0.26
3,500	3.0		27.3%	$5,400	2.9%	428	$290M	$24.9M	204,000	88,000	19,200	0.41
3,500	4.0		25.6%	$5,900	2.5%	126	$530M	$57.5M	229,000	98,300	21,500	0.47
3,500	5.0		24.2%	$6,400	2.6%	100	$660M	$77.8M	248,000	107,700	23,200	0.50

Appendix A: LH2 (Baseline)

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/ pax)
Best – SR	4,000	2.28	30	19.0%	$10,300	1.6%	112	$270M	$28.1M	116,000	72,200	10,900	1.11E-03
Best – LR	5,700	2.00	38	17.2%	$14,100	1.2%	76	$470M	$45.7M	212,000	124,800	19,900	1.31E-03
1	4,000	2.0	20	18.2%	$9,800	1.7%	160	$190M	$18.5M	84,000	53,100	7,800	1.13E-03
2	4,000	3.0		15.0%	$15,200	0.8%	76	$300M	$34.0M	119,000	73,200	11,200	1.89E-03
3	4,000	4.0		11.0%	$16,700	0.6%	59	$300M	$38.4M	141,000	86,600	13,200	2.30E-03
4	4,000	5.0		6.7%	$17,900	0.3%	40	$300M	$43.4M	166,000	102,300	15,500	2.72E-03
5	4,000	2.0	50	17.3%	$7,400	2.1%	90	$330M	$32.5M	148,000	91,600	13,900	7.95E-04
6	4,000	3.0		14.3%	$12,400	1.1%	49	$560M	$62.8M	210,000	126,400	19,700	1.32E-03
7	4,000	4.0		14.9%	$14,700	0.7%	31	$670M	$89.6M	246,000	148,600	23,100	1.60E-03
8	4,000	5.0		12.1%	$15,700	0.6%	28	$630M	$94.2M	286,000	174,300	26,800	1.88E-03
9	6,100	2.0	20	10.2%	$16,700	0.7%	95	$210M	$20.4M	175,000	102,300	16,400	2.05E-03
10	5,700	3.0		**DNC**	$7,500	4.1%	332	$1.0B	$49.2M	374,000	211,700	35,100	5.25E-03
11	5,400	4.0		**DNC**	$7,500	4.1%	317	$1.4B	$76.6M	447,000	255,100	41,900	6.59E-03
12	5,000	5.0		**DNC**	$7,500	4.1%	317	$1.5B	$89.7M	416,000	243,400	39,000	6.40E-03
13	6,100	2.0	50	12.7%	$14,100	1.1%	60	$550M	$51.1M	307,000	177,700	28,800	1.45E-03
14	5,700	3.0		**DNC**	$7,500	3.5%	144	$1.8B	$86.1M	655,000	368,500	61,400	3.68E-03
15	5,400	4.0		**DNC**	$7,500	3.5%	130	$2.4B	$133.2M	777,000	441,300	72,800	4.58E-03
16	5,000	5.0		**DNC**	$7,500	3.7%	139	$2.5B	$154.6M	718,000	417,300	67,300	4.41E-03

Appendix A: LH2 (Overland Routes)

Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
3,000	2.0	20	25.5%	$12,000	0.8%	849	$110	$9.3	65,000	43,100	6,100	9.65E-04
3,000	3.0		19.1%	$13,900	0.3%	176	$210	$21.5	82,000	52,900	7,700	1.43E-03
3,000	4.0		12.1%	$13,600	0.4%	65	$240	$30.7	91,000	59,000	8,600	1.63E-03
3,000	5.0		11.4%	$17,300	0.2%	22	$350	$48.8	100,000	65,100	9,300	1.76E-03
3,000	2.0	50	24.4%	$11,800	0.5%	403	$200	$16.9	116,000	74,200	10,800	6.84E-04
3,000	3.0		17.6%	$12,400	0.4%	158	$280	$29.2	144,000	90,900	13,500	1.00E-03
3,000	4.0		12.8%	$13,200	0.3%	25	$490	$62.2	159,000	100,700	14,900	1.13E-03
3,000	5.0		13.0%	$11,200	0.5%	23	$560	$84.3	172,000	110,200	16,100	1.22E-03
3,500	2.0	20	26.2%	$14,300	0.4%	465	$170	$14.1	73,000	47,600	6,900	1.03E-03
3,500	3.0		18.4%	$13,900	0.5%	234	$200	$19.7	98,000	61,400	9,200	1.61E-03
3,500	4.0		12.7%	$16,100	0.4%	85	$230	$29.2	112,000	70,200	10,500	1.89E-03
3,500	5.0		8.8%	$17,900	0.2%	37	$330	$47.1	125,000	79,500	11,700	2.13E-03
3,500	2.0	50	25.0%	$9,800	0.8%	441	$210	$17.2	130,000	82,000	12,200	7.31E-04
3,500	3.0		18.5%	$12,700	0.6%	188	$290	$29.7	172,000	105,800	16,100	1.13E-03
3,500	4.0		14.1%	$14,500	0.5%	31	$740	$75.9	194,000	120,000	18,200	1.32E-03
3,500	5.0		15.2%	$15,000	0.6%	28	$710	$104.9	216,000	135,000	20,300	1.47E-03

Appendix B: Technical k-Factors

Structures k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Structures Mass Reduction	Mass	0%	-4%	-7%	-9%	-11.0%	-12.5%
TPS Mass Reduction	Mass	0%	-4%	-7.5%	-10.0%	-12.5%	-14.5%
L/D	L/D	0%	1%	3%	5%	6.0%	7.0%

Propulsion k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Engine T/W	T/W	0%	4.0%	8%	11.5%	13.5%	15.5%
Isp	Fuel Eff.	0%	2.5%	5%	7.0%	8.5%	10%
Emissions	CO2e	0%	-2.5%	-4.0%	-7.0%	-8.0%	-9.0%

Noise k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Sideline Noise	Takeoff Noise	0%	-3.0%	-6.0%	-7.0%	-9.0%	-10.0%
Overpressure	Overpressure	0%	-9.0%	-13.5%	-15.0%	-21.5%	-22.5%

Appendix B: Economic k-Factors

Fuel k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Jet-A Prices	Fuel Cost	0%	9.0%	15.5%	27.5%	42.5%	53.0%
LNG Prices	Fuel Cost	0%	0.0%	2.5%	4.5%	8.0%	13.5%
SAF Prices	Fuel Cost	0%	-12.0%	-21.0%	-29.0%	-42.0%	-45.5%
LH2 Prices	Fuel Cost	0%	-5.5%	-8.0%	-16.0%	-28.0%	-62.0%

Economic k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Maintenance	Maint. Costs	0%	-4.5%	-10.5%	-18.0%	-29.0%	-38.5%
Airframe Manufacturing	TFU	0%	-6.5%	-10.5%	-14.5%	-19.5%	-26.0%
Engine Manufacturing	TFU	0%	-6.5%	-10.5%	-14.5%	-19.5%	-26.0%
Tax Benefits / Detriments	Cost	0%	-7%	-5.0%	-3.5%	-2.5%	-2.0%

Appendix C: Airports

AIRPORT	AIRPORT NAME	ROUTES
ATL	Atlanta (GA) – Hartsfield-Jackson Atlanta International Airport	Domestic & International
DFW*	Dallas/Ft. Worth (TX) - Dallas/Fort Worth International	Domestic & International
DEN*	Denver (CO) - Denver International Airport	Domestic & International
ORD*	Chicago (IL), O'Hare International Airport	Domestic & International
LAX	Los Angeles (CA) - International	Domestic & International
CLT	Charlotte (NC)	Domestic & International
MCO	Orlando - International Airport (FL)	Domestic & International
LAS*	Las Vegas (NV)	Domestic & International
PHX*	Phoenix (AZ) - Sky Harbor International	Domestic & International
MIA	Miami (FL)	Domestic & International
SEA	Seattle/Tacoma (WA)	Domestic & International
IAH*	Houston, TX - George Bush Intercontinental Airport	Domestic & International
JFK	New York - John F. Kennedy (NY)	Domestic & International
EWR	New York - Newark (NJ)	Domestic & International
FLL*	Fort Lauderdale/Hollywood (FL)	Domestic & International
MSP*	Minneapolis - St. Paul International Airport (MN)	Domestic & International

*New airport to model for Overland Route Sensitivity Study

Appendix C: Airports

AIRPORT	AIRPORT NAME	ROUTES
SFO	San Francisco - International Airport, SA	Domestic & International
DTW*	Detroit (MI) , Wayne County Airport	Domestic & International
BOS	Boston (MA) - General Edward Lawrence Logan	Domestic & International
SLC*	Salt Lake City (UT)	Domestic & International
PHL	Philadelphia (PA) - International	Domestic & International
BWI*	Baltimore (MD) - Washington International Airport	Domestic & International
TPA*	Tampa - International (FL)	Domestic & International
SAN*	San Diego - Lindberg Field International (CA)	Domestic & International
LGA*	New York - LaGuardia (NY)	Domestic & International
MDW*	Chicago (IL), Midway	Domestic & International
BNA*	Nashville (TN)	Domestic & International
IAD	Washington DC - Dulles International	Domestic & International
DAL*	Dallas (TX) , Love Field	Domestic Only
DCA*	Washington DC - Ronald Reagan National	Domestic Only
PDX*	Portland International (OR)	Domestic Only
AUS*	Austin (TX) - Austin-Bergstrom Airport	Domestic Only

*New airport to model for Overland Route Sensitivity Study

Appendix C: Airports

AIRPORT	AIRPORT NAME	ROUTES
HOU*	Houston (TX) , Hobby	Domestic Only
HNL*	Honolulu (HI) - Honolulu International Airport	Domestic Only
STL*	St. Louis (MO) Lambert–St. Louis International Airport	Domestic Only
RSW*	Fort Myers, Southwest Florida Reg (FL)	Domestic Only
SMF*	Sacramento (CA)	Domestic Only
MSY*	New Orleans, La	Domestic Only
SJU*	San Juan - Luis Munoz Marin International Airport	Domestic Only
RDU*	Raleigh/Durham (NC)	Domestic Only
SJC*	San Jose (CA)	Domestic Only
OAK*	Oakland (CA)	Domestic Only
MCI*	Kansas City (MO) - Kansas City International Airport	Domestic Only
CLE*	Cleveland (OH) - Cleveland Hopkins International	Domestic Only
IND*	Indianapolis (IN) International	Domestic Only
SAT*	San Antonio (TX)	Domestic Only
SNA*	Orange County (Santa Ana) (CA)	Domestic Only
PIT*	Pittsburgh International Airport (PA)	Domestic Only

*New airport to model for Overland Route Sensitivity Study

Appendix C: Airports

AIRPORT	AIRPORT NAME	ROUTES
CVG*	Cincinnati (OH) - Cincinnati/Northern Kentucky Int'l	Domestic Only
CMH*	Columbus (OH) - Port Columbus International	Domestic Only
PBI*	West Palm Beach (FL)	Domestic Only
JAX*	Jacksonville (FL) - International	Domestic Only
MKE*	Milwaukee (WI)	Domestic Only
ONT*	Ontario (CA)	Domestic Only
ANC*	Anchorage (AK) - Ted Stevens Anchorage International	Domestic Only
BDL*	Hartford (CT) /Springfield (MA)	Domestic Only
OGG*	Kahului (HI)	Domestic Only
BUR*	Burbank (CA)	Domestic Only
OMA*	Omaha (NE)	Domestic Only
MEM*	Memphis (TN)	Domestic Only
BOI*	Boise (ID) - Boise Air Terminal	Domestic Only
RNO*	Reno (NV)	Domestic Only
CHS*	Charleston (SC)	Domestic Only
OKC*	Oklahoma City (OK) - Will Rogers World	Domestic Only

*New airport to model for Overland Route Sensitivity Study

SpaceWorks®

SPACE & FLIGHT SOLUTIONS FOR THE

NEXT GENERATION

www.spaceworks.aero