Life Cycle Cost Modeling of High-Speed Commercial Aircraft

Final Review – Executive Summary

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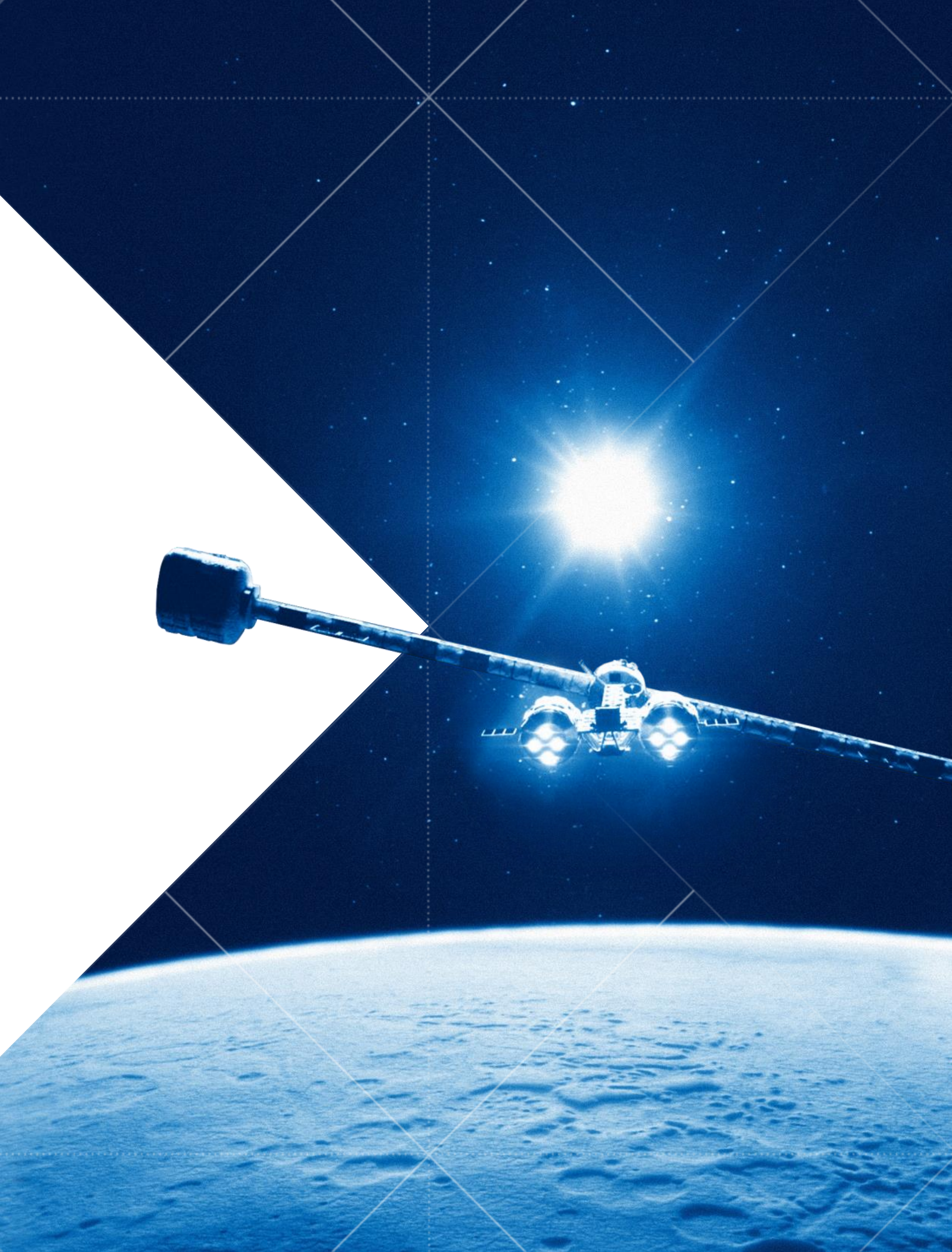


NASA SBIR/STTR Contract #80NSSC22C0008

Agenda

8:00 – 9:00	**Executive Summary**	**John Olds**
9:00 – 10:00	AnyLogic Model Development	Ami Patel
10:00 – 10:15	*Break*	
10:15 – 11:30	Trade Study Details	Hayden Magill
11:30 – 12:00	Data Exploration and Discussion	Mark Schaffer

Introduction

- **For several years, SpaceWorks has been supporting NASA's effort to better understand the future passenger market and potential economic business cases for supersonic and/or hypersonic commercial flight.**
  - Does a reliable passenger demand exist for commercial supersonic / hypersonic flight?
  - If so, can it result in profitable business case for various players in the manufacturing and operating economy?

- **The presentation is the culmination of a 9-month research and development SBIR project that follows the 2021 Commercial Hypersonic Transportation Market Study study led by Deloitte, the NIA, and SpaceWorks**

- **Based in part on the recommendations of that prior study, the objectives if this current effort were to:**
  - Improve both flight performance and economic models
  - Reexamine the results of the prior effort in light if any updates
  - Conduct a series of four new trade studies related aircraft operating models, fuels, market growth, and service entry date
  - Explore new modeling methodologies and tools to increase modeling and simulation capabilities in the future

2021 Commercial Hypersonic Transportation Market Study

Deloitte Tasks

- Market Segmentation – analyzed current trends in the aviation market for scheduled service, private-owner operations, and air cargo
- City Pairing - determined the most viable routes for high-speed passenger travel by analyzing industry data and selected routes based on route-by-route economic and technical viability. Emphasis was placed on transoceanic routes die to sonic boom challenges for overland flight
- Market Demand – developed ticket price elasticity curves based on direct customer surveys to quantify passenger willingness to pay for high-speed travel
- Barriers Assessment – characterize key policy, regulatory, and technical barriers to future high-speed flight operations

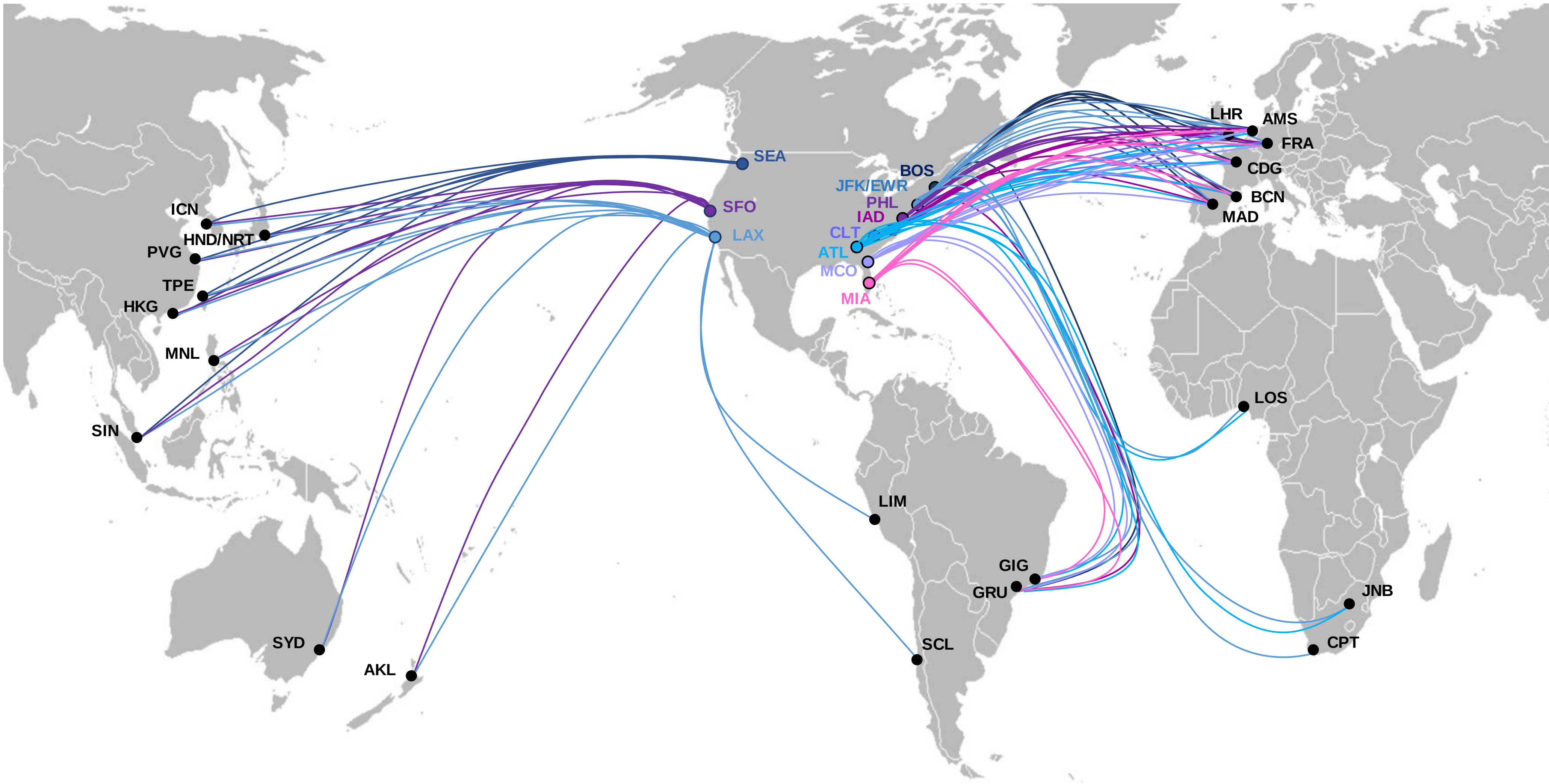
SpaceWorks Tasks

- ROSETTA Model Development – built on existing ROSETTA model to integrate flight performance, aircraft sizing environment impact, airframe costing, engine costing, manufacturer and operator economic modules
- Optimize Business Cases – implemented ticket price elasticity curves from Deloitte and optimize model inputs to determine best business cases across Mach, range, and passenger count
- Investigate Sensitivities – characterized sensitivity of aircraft design parameters and business case assumptions

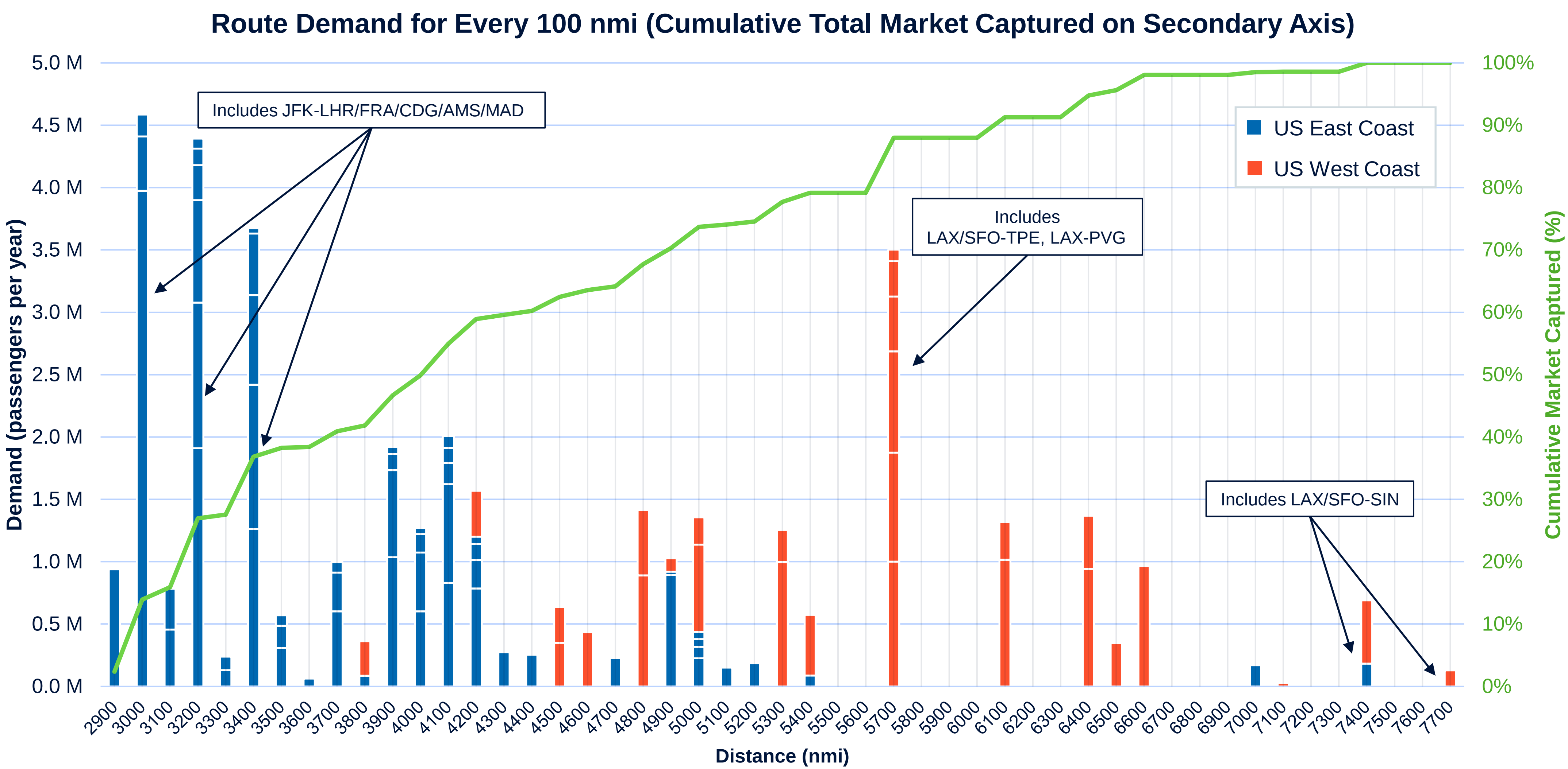
National Institute of Aerospace Tasks

- Project Review and Guidance– provided expert review and study guidance throughout the study

Baseline US-Based Transoceanic Flight Routes (90 routes)



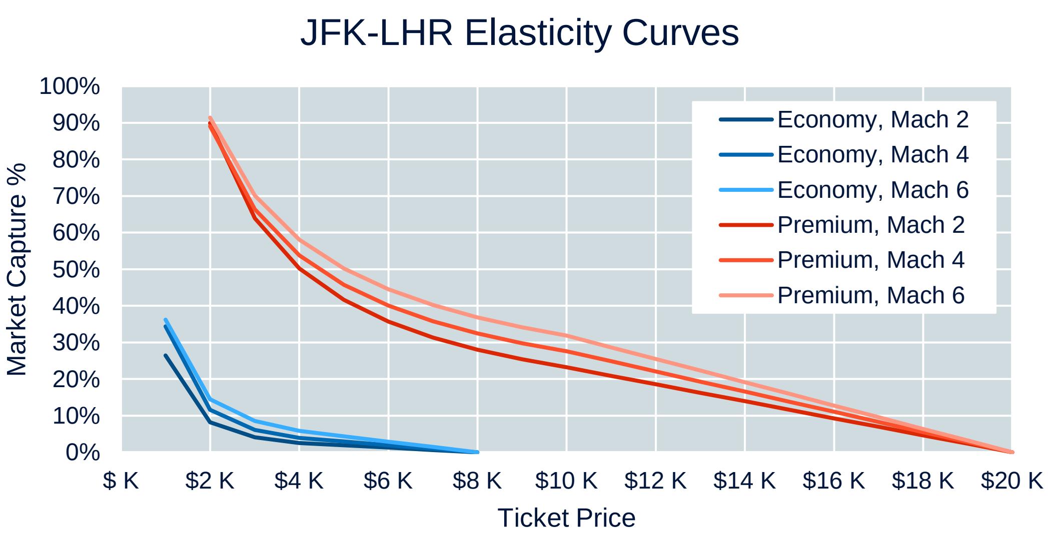
Annual Passenger Market by Route Distance

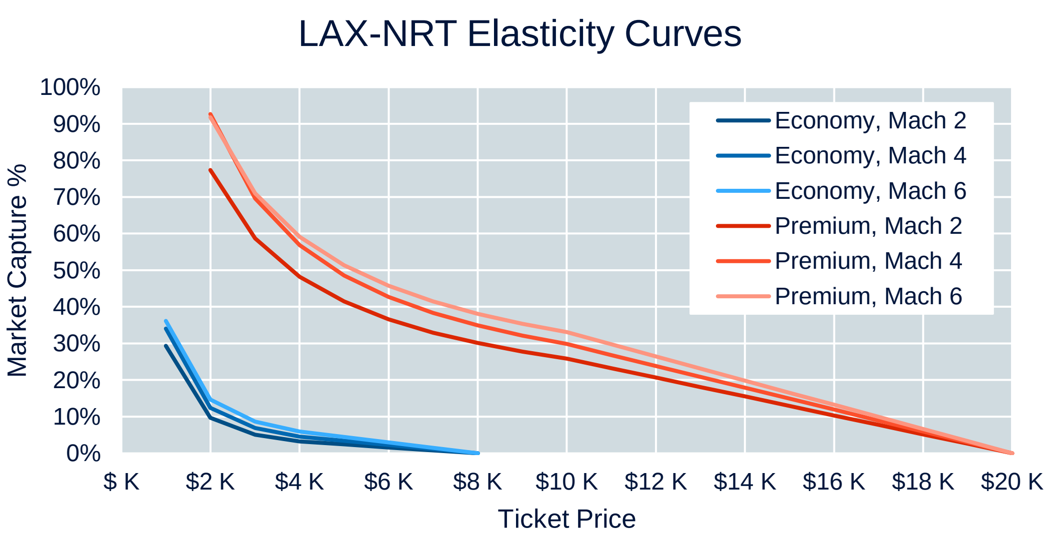


Price Elasticity Results (Prior and Current Study)

- **Deloitte surveyed passengers' willingness to pay for speed for for three representative routes: JFK-LHR, LAX-NRT, & LAX-SIN**
  - Data for economy and premium passengers was collected

- **SpaceWorks generated smooth price elasticity curves from the survey data for implementation into the ROSETTA model**
  - Separate curves for market capture versus ticket price are used for economy and premium passengers, with the total passenger capture determined from percent of market capture for each class
  - Market capture is ground ruled to be 0% for economy ticket prices above $8K and premium ticket prices above $20K





Point-to-Point ROSETTA Model Overview

- **<u>Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA)</u> models are fast-acting multi-disciplinary design optimization tools**

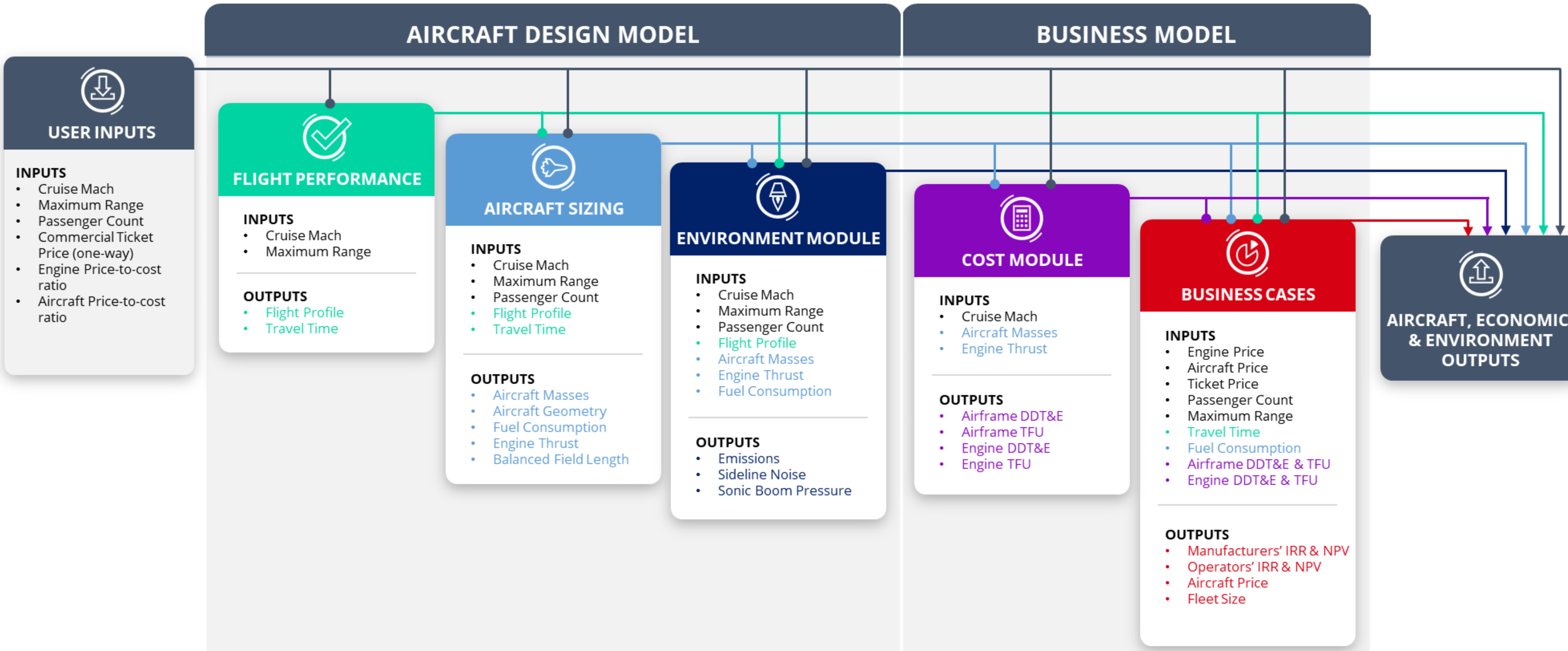
- **Spreadsheet-based ROSETTA model is a representation of the design process for a specific vehicle or architecture**
  - ROSETTAs use spreadsheet-based tools such as NextSizer or AFWAT directly, but create meta-models of dedicated disciplinary codes such as QuickShot, Manta, NPSS, and CBAero
  - Goal is to be fast-acting, accurate, and robust to support rapid redesign of vehicle architectures

ROSETTA Model Methodology

- **The Aircraft Design Model sizes the aircraft and determines the development and production cost**
  - Inputs: cruise Mach, maximum range, and passenger count
  - Outputs: aircraft masses and geometry, engine performance, airframe and engine development cost, airframe and engine production cost

- **The Business Model evaluates the business cases for the engine manufacturer, airframe manufacturer, and airline operator**
  - Inputs: ticket price (to the passenger), aircraft price (to the operator), and engine price (to the airframe manufacturer)
  - Data from Aircraft Design Model: airframe and engine development and production cost
  - Outputs: engine manufacturer, airframe manufacture, and airline operator IRR, NPV, and maximum exposure

ROSETTA Model Data Flow



2021 Study Findings

- **There are multiple aircraft configurations and market approaches that result in positive business cases for their manufacturers and operators (assumed as IRR > 25%)**
  - Smaller aircraft (20-50 pax) tend to be favored over larger aircraft for several factors, including sales synergies with the private/charter market and higher average passenger load factors on thin routes
  - Slower cruise speed aircraft (Mach 2-3) in the 4,000-4,500 nmi class are also slightly favored and result in lower ticket prices and therefore larger market sizes. This seems to be a more robust part of the market
  - North-Atlantic markets remain the largest economic prize, but longer trans-Pacific ranges remain interesting for smaller Mach 2-3 vehicles that can reach to 6,000 nmi+

- **Results are most sensitive to potential reductions in estimated passenger market size**
  - Fuel cost increases, engine development cost increases, and lost of private/charter sales are also important

- **Government contributions via non-recurring offsets or "anchor buys" are helpful**
  - More beneficial for 1) smaller overall aircraft development program (gov't contributes a larger percentage of the total cost) or 2) higher speed aircraft where predicted annual airframe sales are not as large. However, government contributions are not required for success

Current Study Objectives

Based on the 2021 study findings, the objectives for the current effort were:

1. **Improve ROSETTA optimization methods and refine aircraft performance, cost, and business modeling**

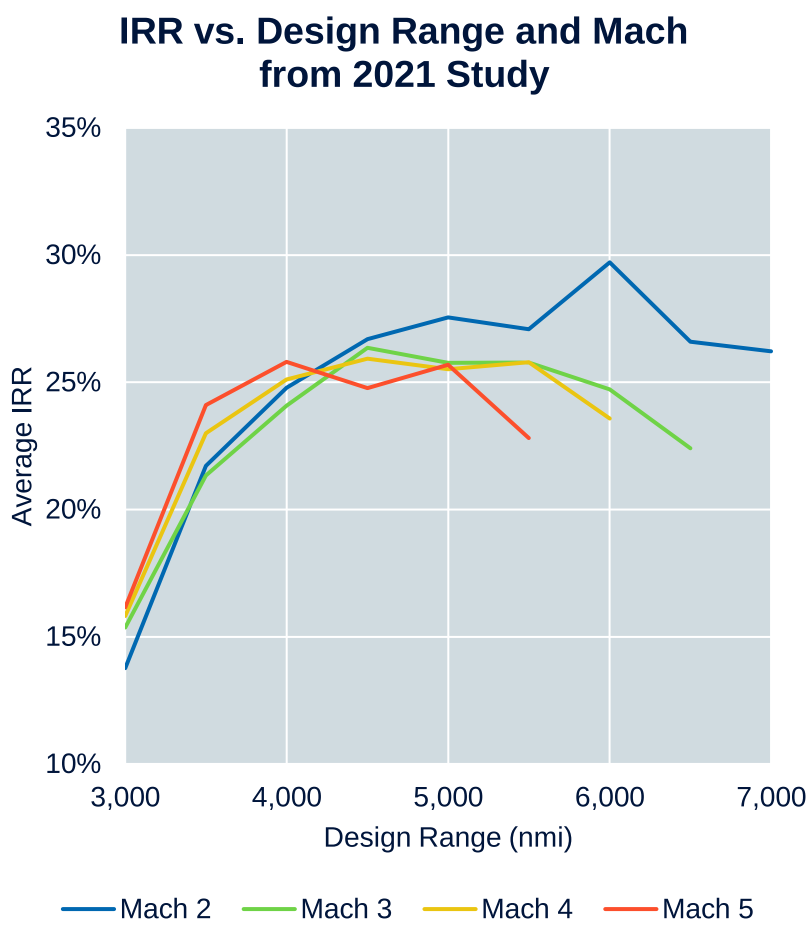
2. **Further characterize business case viability in the Mach 2-5, 20-50 passenger, 3500-7000 nmi design space**
   - Develop baseball cards with details on individual point designs in this space

3. **Explore alternative scenarios**
   - Consider allowing the airline operator to have a <u>mixed fleet</u> of short-range and long-range aircraft
   - Consider <u>alternative fuels</u> to Jet-A: sustainable aviation fuel (SAF), liquified natural gas (LNG), and liquified hydrogen (LH2)
   - Evaluate the impact of allowing <u>overland routes</u> over the continental United States
   - Assess the impact of delaying <u>initial operating capability</u> (IOC) date

4. **Develop a new Discrete Event Simulation (DES) to expand business modeling capabilities beyond the limitations of the Excel-based ROSETTA implementation**
   - Improve the fidelity of the route-by-route and aircraft-by-aircraft modeling

Optimization Method Redesign

- **During the 2021 study, the ROSETTA model optimizer was set up:**
  - Objective function: Maximize the minimum IRR of the (1) engine manufacturer, (2) airframe manufacturer, and (3) airline operator
  - Control variables: Ticket price (to the passenger), aircraft price (to the operator), and engine price (to the airframe manufacturer)
- **A key finding of that study was that all three entities could achieve >25% IRR across many Mach and range design points**
  - However, to achieve the maximum IRR, the optimizer often raised ticket prices at the expense of market capture in order to make minor improvements to airline IRR
- **In response, SpaceWorks and NASA agreed to change the objective function of the current study to maximize market capture while constraining all entities to achieve 25% IRR**



Commentary on IRR

- **Internal Rate of Return (IRR) is:**
  - A useful financial metric used by corporations for comparing future capital projects in terms of rate of return over time
  - Accounts for the "time value of money" in a project cash flow by discounting income in the project's out years relative to near term investment expenses
  - Mathematically, IRR is the discount rate that makes the Net Present Value (NPV) of all cash flows equal to zero. So, if IRR is greater than the company's capital discount rate (e.g. cost of money), it will add value to the company

Competing projects can have dramatically different investments or marginal returns, but the same IRR. The following two $5000 projects and their projected returns would be evaluated as equivalent based on IRR

Capital Project 1 (10 yrs)

Year 1	Years 2-10
$ (5,000)	$ 1,000

IRR: 13.7%

Nominal Revenue: $9,000
NPV@10%: $690

VS.

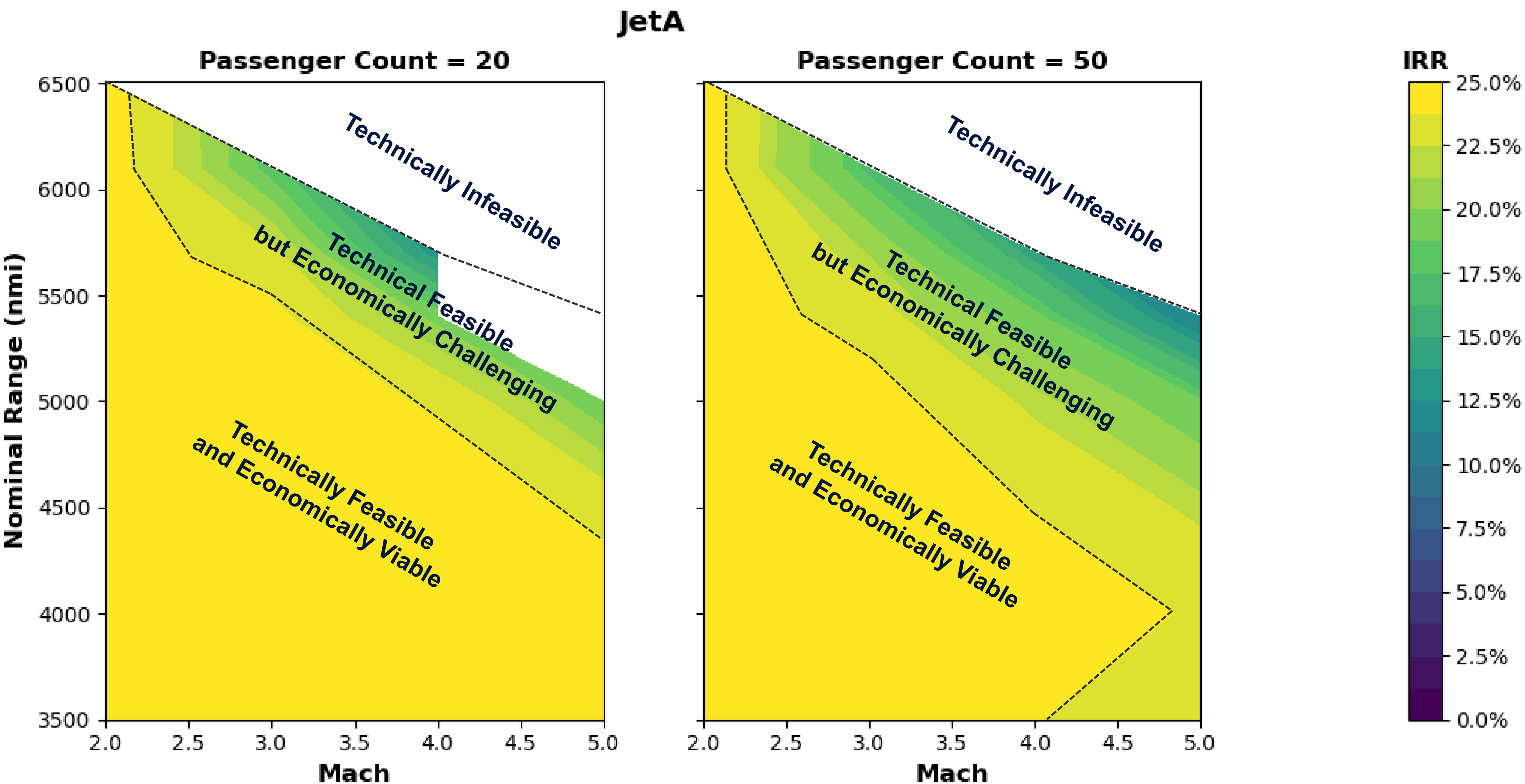
Capital Project 2 (20 yrs)

Years 1-5	Years 6-20
$ (1000)	$ 1,055

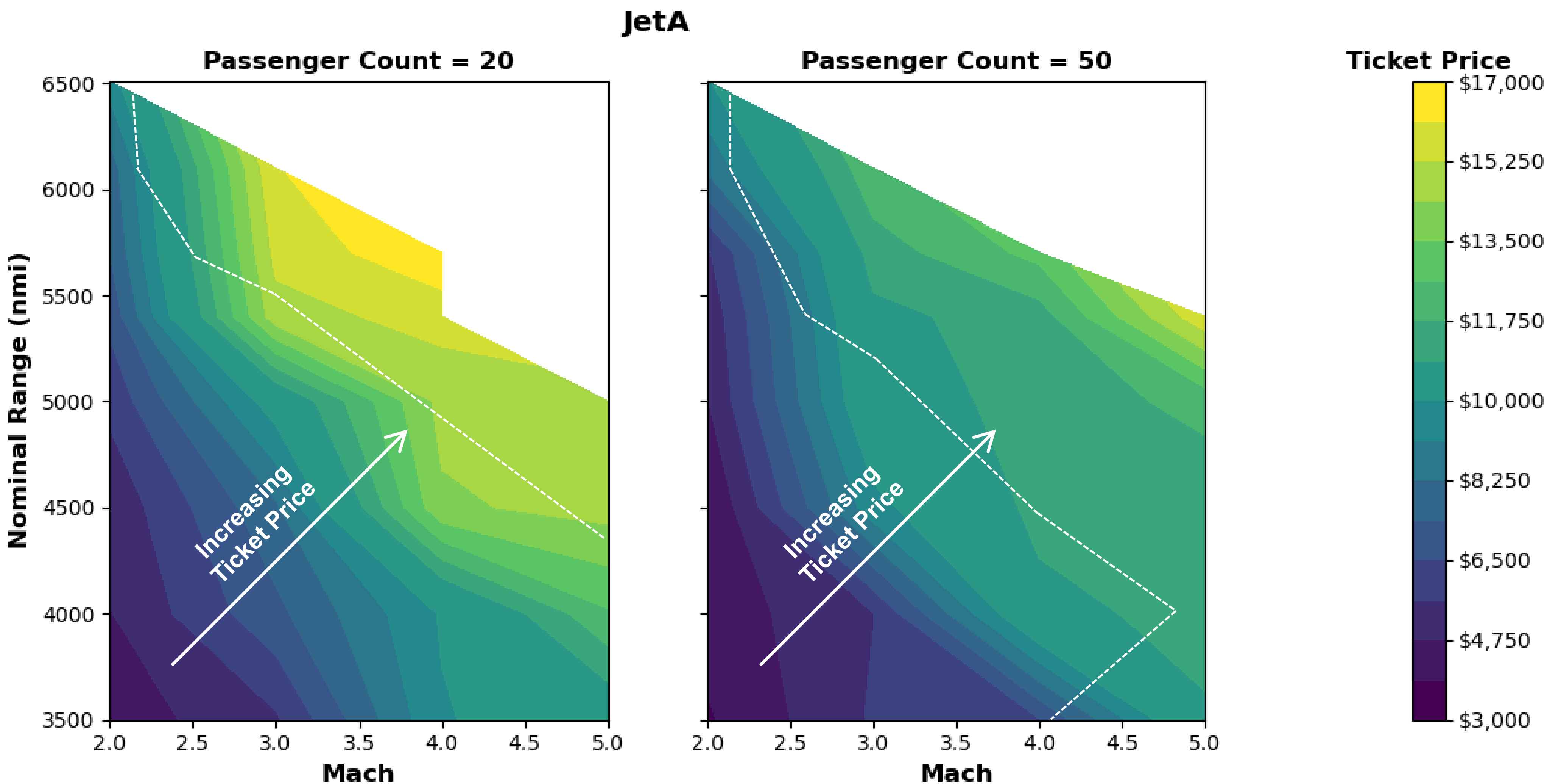
IRR: 13.7%

Nominal Revenue: $15,825
NPV@10%: $1,192

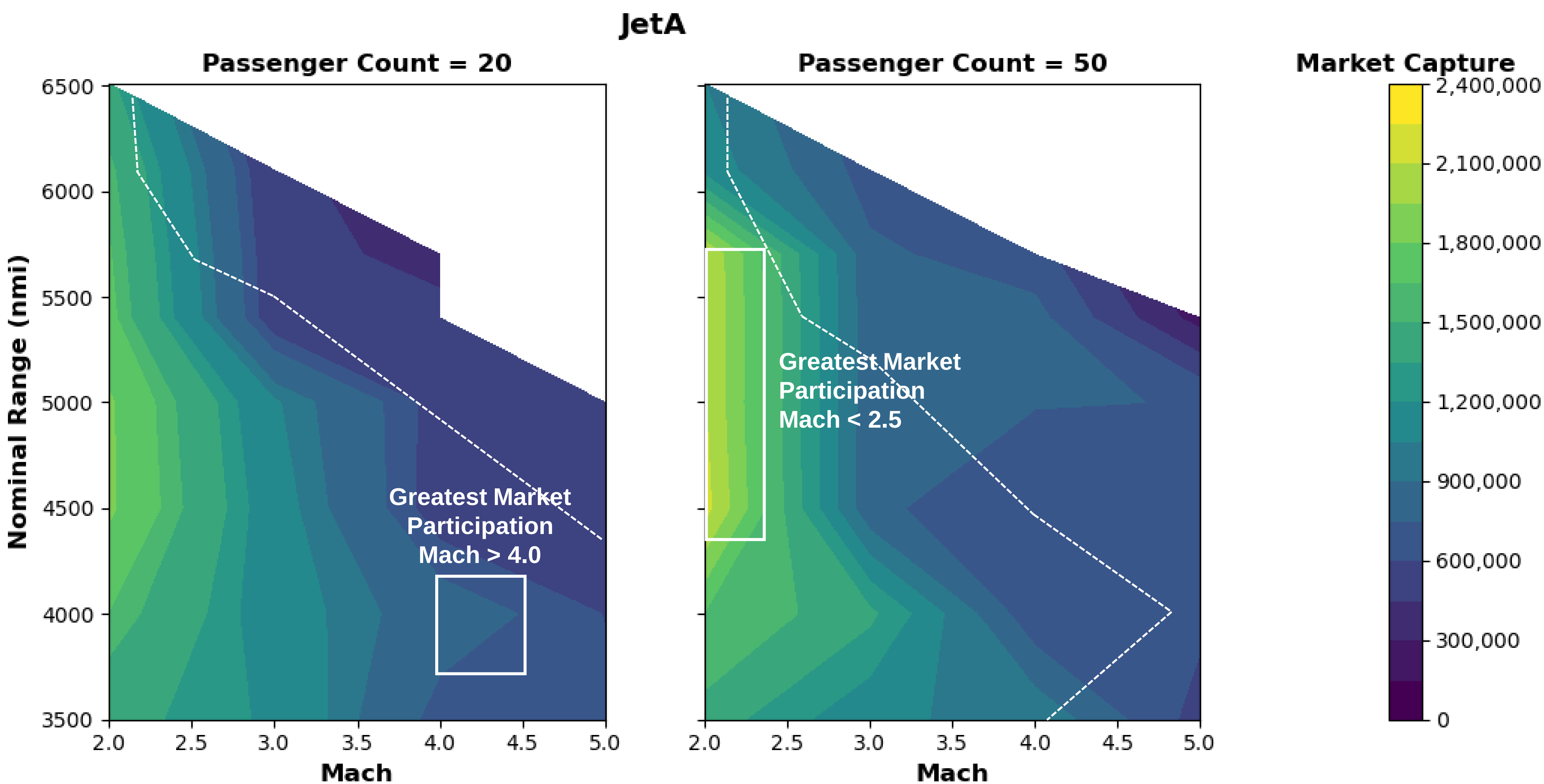
Results – Technical and Economic Design Space



Results – Ticket Price



Results – Market Participation



Jet-A Mach 2 Long Range

SpaceWorks® NASA

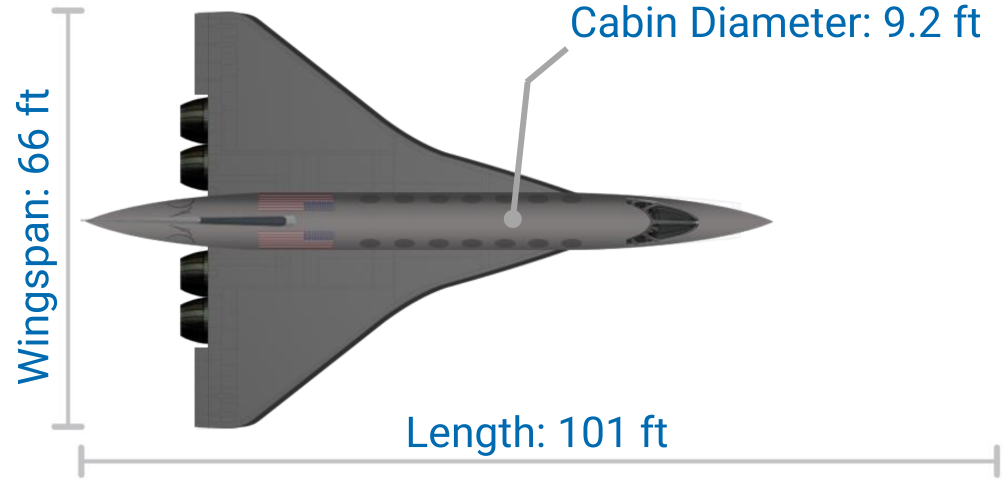
ID: JTA.M2.00.P38.R5700.20220810

Mach 2
Cruise Speed

5,700 nmi
Max Range

38
Passenger Count

JetA
Fuel Type



COST METRICS (FY21 USD)

DDT&E		TFU	
$4.1B	$2.3B	$109M	$15M
Airframe	Engine	Airframe	Engine

ENVIRONMENTAL METRICS

92 EPNdB
Lateral Takeoff Noise

105 PNLdB
Sonic Boom

0.49 kg/km/pax
Emissions (CO2e)

0.15 kg/km/pax
Fuel Consumption Rate

222,000 lbm
MTOW

77,000 lbm
MEW

4 x 20,900 lbf
Engine Thrust SLS

5.8 hours
Gate-to-Gate Time
at Max Range

56,400 ft
Cruise Altitude

6,600 ft
Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 8
- Supersonic cruise condition Isp = 3000 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

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Jet-A Mach 2 Long Range

SpaceWorks NASA

ID: JTA.M2.00.P38.R5700.20220810

Key Inputs

Mach 2
Cruise Speed

5,700 nmi
Range

38
Passenger Count

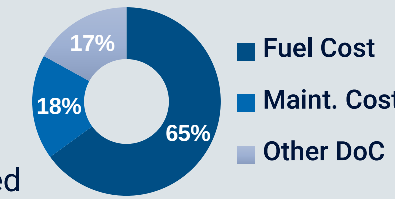
JetA
Fuel Type

OPERATOR METRICS

$5,200-$6,700
Ticket Price

2.3M
Pax/Year

49
Routes Captured



MANUFACTURER METRICS

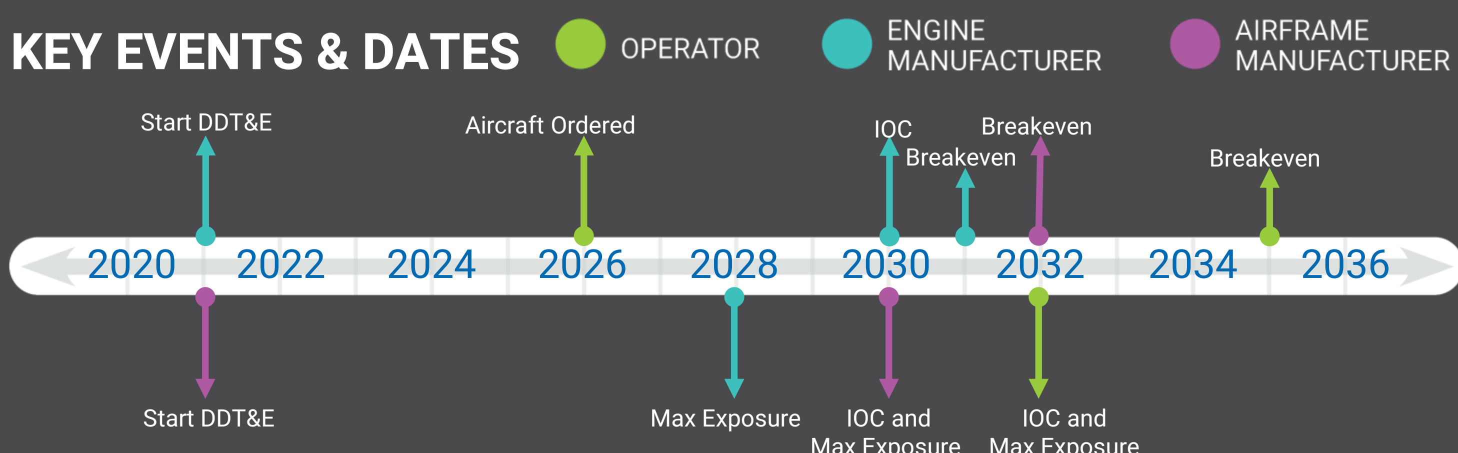
$251M
Aircraft Price

$172M
Airframe Price

$20M x4
Engine Price

300
Aircraft Sold

KEY EVENTS & DATES



Business Results

OPERATOR

25%	$3.5B	$7.2B
IRR	NPV	Max Exposure

ENGINE MANUFACTURER

25%	$1.0B	$1.2B
IRR	NPV	Max Exposure

AIRFRAME MANUFACTURER

25%	$2.1B	$2.9B
IRR	NPV	Max Exposure

BUSINESS CASE ANALYSIS

This aircraft is capturing 49 of 78 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Since the aircraft is more passenger efficient, ticket prices don't become overly expensive, enabling higher demand capture overall.

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Jet-A Mach 4 Short Range

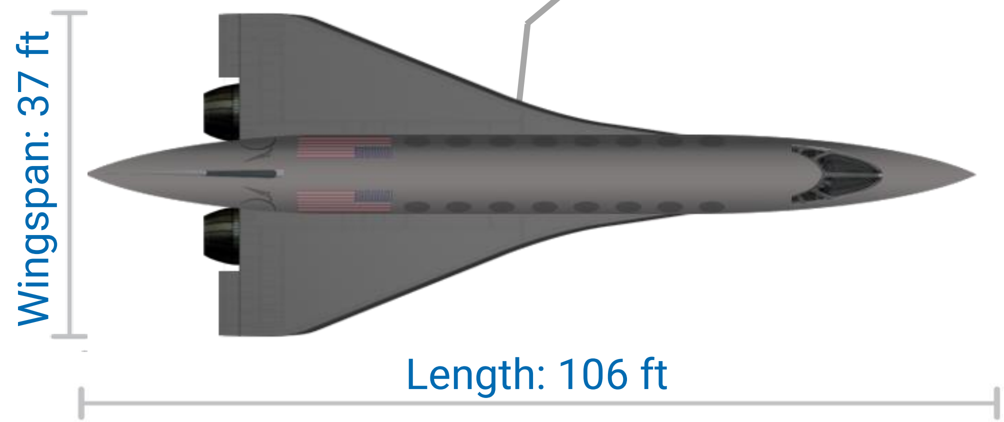
ID: JTA.M4.P20.R4000.20220722

Mach 4
Cruise Speed

4,000 nmi
Max Range

20
Passenger Count

JetA
Fuel Type



COST METRICS (FY21 USD)

	DDT&E		TFU	
	$3.7B	$2.7B	$93M	$19M
	Airframe	Engine	Airframe	Engine

ENVIRONMENTAL METRICS

91 EPNdB
Lateral Takeoff Noise

0.92 kg/km/pax
Emissions (CO2e)

101 PNLdB
Sonic Boom

0.28 kg/km/pax
Fuel Consumption Rate

161,000 lbm
MTOW

60,900 lbm
MEW

4 x 15,100 lbf
Engine Thrust SLS

2.5 hours
Gate-to-Gate Time
at Max Range

85,500 ft
Cruise Altitude

9,100 ft
Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 5.6
- Supersonic cruise condition Isp = 1600 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

NASA SBIR/STTR Contract #80NSSC22C0008

Jet-A Mach 4 Short Range

SpaceWorks® NASA

ID: JTA.M4.P20.R4000.20220809

Key Inputs

Mach 4
Cruise Speed

4,000 nmi
Range

20
Passenger Count

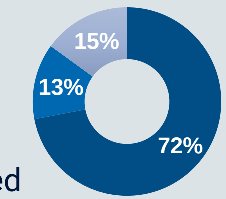
JetA
Fuel Type

OPERATOR METRICS

$10,000-$11,300
Ticket Price

0.8M
Pax/Year

23
Routes Captured



MANUFACTURER METRICS

$376M
Aircraft Price

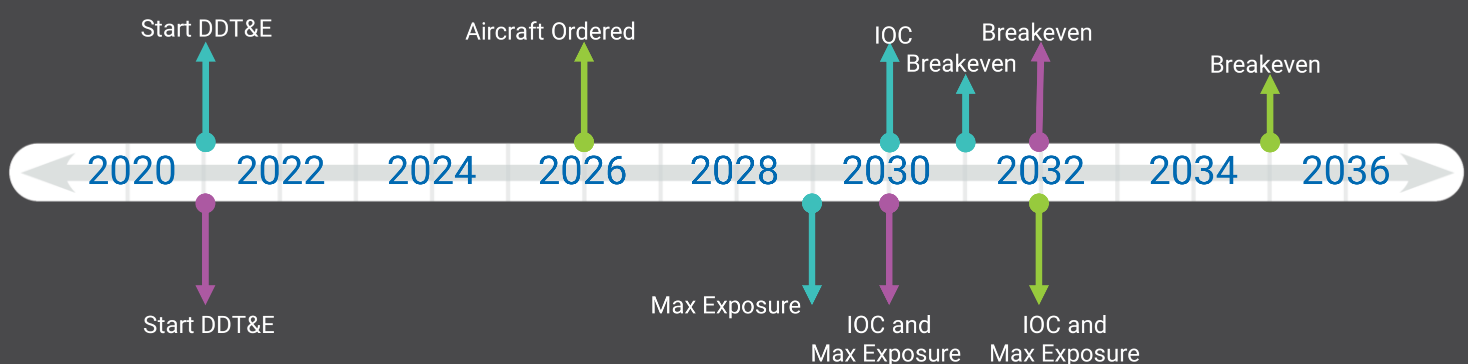
$227M
Airframe Price

$37M x4
Engine Price

152
Aircraft Sold

KEY EVENTS & DATES

OPERATOR ENGINE MANUFACTURER AIRFRAME MANUFACTURER



Business Results

OPERATOR

25%	$2.7B	$5.8B
IRR	NPV	Max Exposure

ENGINE MANUFACTURER

25%	$1.4B	$1.8B
IRR	NPV	Max Exposure

AIRFRAME MANUFACTURER

25%	$2.4B	$3.4B
IRR	NPV	Max Exposure

BUSINESS CASE ANALYSIS

This aircraft is capturing 23 of 37 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. High ticket prices and aircraft prices drive this business case to cater more to an elite airliner. It is less robust but still viable.

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Key Findings – Overall

- **Overall, when modeling a single Jet-A fueled aircraft type that serves a subset of our 90 candidate transoceanic passenger routes that lie within its unrefueled range, the Mach 2-2.5, 4,500-5,500 nmi, and 40-50 passenger aircraft had the best business cases**
  - This conclusion is mostly consistent with the results of the 2021 market study, but slightly revised due to changes in the model and objective function
  - The current study favored slightly larger aircraft, which reduce ticket prices and capture more of the traveling public, because the optimizer was set to maximize market capture

- **Our overall position is unchanged from our prior study. We believe that there are viable economic markets for future high-speed (supersonic and hypersonic) aircraft**

- **However, we acknowledge that safety, noise compliance, emission, compliance, and sonic boom remain significant challenges to this industry**
  - While our simulations report environmental variables as outputs, we did not attempt to restrict our design space based on current government guidance or regulations on exhaust emissions or takeoff noise.
  - Adding restrictions based on environmental factors will certainly reduce, or even eliminate, the viable options for high-speed commercial flight. Additional research is needed in these areas.

Key Findings – Mixed Fleet

Mixed fleet based on short- and long-range segregated aircraft types not the best approach

- Only marginally improved annual passenger capture
- Resulted in poorer than anticipated business cases for the long-range aircraft due to low production rates, high ticket prices, and reduced demand. It lost most of the market to the short-range aircraft
- Lesson learned: we need to take another look at this mixed-fleet simulation so that both aircraft types are used more effectively

Recommend assessing a mixed fleet solution based on route demand and/or density

- A larger aircraft operating on high density routes (e.g. NYC – LHR) and a smaller one for low density markets could capture more routes, increase load factors, and allow higher utilization rates of both aircraft types, even if those two aircraft types might have similar maximum ranges
- Likely generates a more robust solution for both aircraft manufacturers as well
- Recommended for future investigation with our DES model

Key Findings – Alternative Fuels

SAF and Jet-A were very similar in terms of economic and airplane performance

- SAF is currently much more expensive than Jet-A. That gap is expected to narrow over time as the SAF supply chain scales while Jet-A prices increase
- SAF will become a viable alternative fuel as the price continues to decrease due to its status as net-zero carbon fuel
- We conclude that SAF the preferred long-term solution for high-speed aircraft applications, but we recognize that the significant investment in production and distribution infrastructure is a major barrier to adoption

LNG produced some of the best business cases

- LNG has a lower initial fuel price relative to Jet-A and improved energy density are good
- However, LNG yields higher aircraft development and manufacturing costs due to additional complexity and larger tanks
- LNG burns cleaner than Jet-A but is still a carbon producer. Sustainability might be an issue as LNG prices increase

LH2 struggled to achieve the required 25% IRR in most of the trade space

- High performance but low density meant very high onboard volumes of fuel, increasing aircraft size and drag
- High operator fuel costs and high aircraft prices make LH2 business cases hard to justify for most of the trade space
- Only at Mach 2, were our simulated LH2 aircraft able to achieve 25% IRR at 3,000 nmi and 3,500 nmi overland ranges
- We conclude that short range LH2 aircraft are feasible and may be viable options for domestic routes

Key Findings – Overland Routes

- **Addition of overland routes significantly boosts the available market and demand**
  - The impact of overland flight on the model is significant and the number of passengers participating in supersonic / hypersonic flight annually increases by ~5X compared to our transoceanic baseline model
  - Initial capital outlays could be a financial hurdle for operators and manufacturers, but a controlled service rollout might mitigate the capital needs and benefit all stakeholders

- **High production volumes solidify the manufacturers' business cases**
  - Number of aircraft produced could increase from less than 200 to nearly 1000 aircraft in certain simulations

- **Operator's business case also improved**
  - Optimal aircraft size can increase (to 88 pax), and ticket prices can be reduced while still meeting the 25% IRR
  - Increased upfront acquisition costs are needed to address the high demand, but controlled service rollout might mitigate the capital needs and benefit all stakeholders

- **However, we did not address "how" overland sonic boom restrictions might be eliminated**
  - This is a highly complex political and environmental issue
  - The inclusion of a much larger number of supersonic overland routes should be seen as a bounding case on the potential for the high-speed flight commercial market

Key Findings – IOC Dates

- **All the considered technology sets offered improvements in the study metrics over time**
  - Assuming that no competitors will enter the market first, simply waiting for the increase in the elite air travel market size and leveraging advancements in technology is a preferred strategy. However, waiting might not be possible
  - SAF will become a viable alternative fuel as the price continues to decrease due to its status as net-zero carbon fuel

- **Propulsion performance and air travel market growth offered the most benefits in economics**
  - Propulsion technologies have the potential to improve engine Isp, lower engine weight (and therefore aircraft weight), reduce emissions, reduce engine maintenance costs, and reduce noise
  - Structures and noise reduction technologies were also valuable in a government technology investment portfolio

- **Fuel prices significantly influence the business cases for alternative fuels**
  - Jet-A and LNG prices are expected to increase over time, while SAF and LH2 prices are expected to become more competitive over time (assuming that production and distribution infrastructures advance as assumed)
  - We recommend baselining SAF for future high-speed aircraft, while continuing to evaluate LNG and LH2, especially for the highest speed aircraft whose ramjet or scramjet propulsion systems may require these fuels

Recommendations

1. **NASA and FAA continue their efforts to permit overland supersonic flight**
   - Drastically increased market size
   - More robust business cases for supersonic / hypersonic developers and operators

2. **In the meantime, a two-phased “leader-follower” compromise strategy for government and commercial**
   - Small fast first-to-market transoceanic “leader” aircraft
   - Larger slower “follower” aircraft designed for additional overland routes
   - Delays action on supersonic overland flight and reduces near-term capital requirements

3. **Continued investments in supersonic and hypersonic propulsion technology, particularly in the areas of:**
   - Engine fuel efficiency and emissions
   - Takeoff noise
   - Engine maintenance costs
   - Engine weight

4. **Continued investment in SAF with further exploration of LNG and LH2 viability**
   - Supply of all alternative fuels needs to be orders of magnitudes greater
   - LNG shows promise while LH2 is economically viable for some simulated solutions

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