Life Cycle Cost Modeling of High-Speed Commercial Aircraft

Final Review – Key Findings Detailed

August 3rd, 2023 | NASA Langley Research Center | Revision A

Hayden Magill
PI & Economic Analyst
hayden.magill@spaceworks.aero | 770-415-1157

Aaron Boysen
Sr. Economic Analyst

Ami Patel
Software Technical Director & Senior Software Engineer

John Bradford
Principal Engineer

NASA SBIR Contract #80NSSC22C0008

Agenda

11:00 – 12:15	Executive Summary	John Bradford
12:15 – 1:00	*Lunch*	
1:00 – 1:45	MIDAS Developments & Demo	Ami Patel
1:45 – 4:00	**Key Findings Detailed**	
1:45 – 2:15	**Market**	**Aaron Boysen**
2:15 – 2:45	**Aircraft**	**Hayden Magill**
2:45 – 3:00	*Break*	
3:00 – 3:30	**Financial**	**Aaron Boysen / Hayden Magill**
3:30 – 4:00	**Environmental**	**Hayden Magill**
4:00 – 4:30	**Recommendations & Discussion**	**Hayden Magill / All**

All times Eastern

Key Findings | Overall

- **Economic metrics resulted in ticket price premiums of 2 to 2.5 times over business class tickets in order to capture ~10% of the market currently serviced by hundreds of subsonic aircraft.**

- **Given our key findings with respect to market demand, aircraft technical specifications/capabilities, financial considerations, and various environment factors:**

  - ***We believe there is a high-speed PTP market, but it is <u>relatively small</u> for the foreseeable future due to a combination of challenging factors***

  - ***The <u>environmental issues must be solved</u> without significantly impacting the design and capabilities of the aircraft in order for this market to be realized***

  - ***Small improvements in the aircraft (i.e., engine TSFC, structural mass reductions, etc.) can have a <u>significant positive impact on financial viability</u> due to impacts on $/RPM***

Market

Research Overview

The average airline passenger remains too price sensitive for high-speed flight, but premium passengers are still willing to pay for speed/time

Process

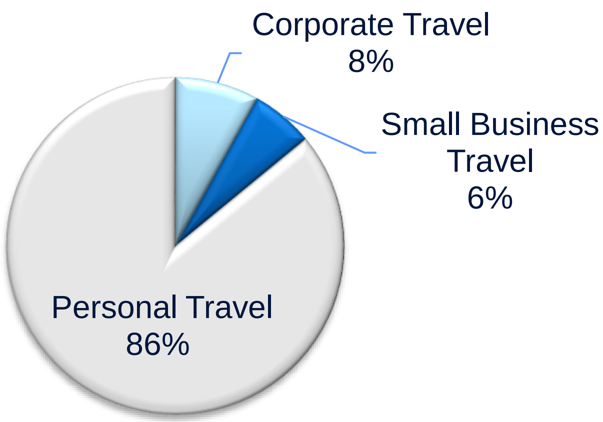
- Dynamic survey developed with skip logic to customized questions based on travel purpose (Personal vs. Busn.)
- Questions developed to ensure data is representative of the flying public and to gain further market insights
  - Environmental importance
  - Urgent travel frequency
  - Cabin amenity importance and more
- Distribute survey to individual travelers (SurveyMonkey) and corporate travel managers (GBTA)
- Conducted extensive data clean-up and analysis to produce updated elasticity curves and market insights

Survey Audiences Sources

SurveyMonkey

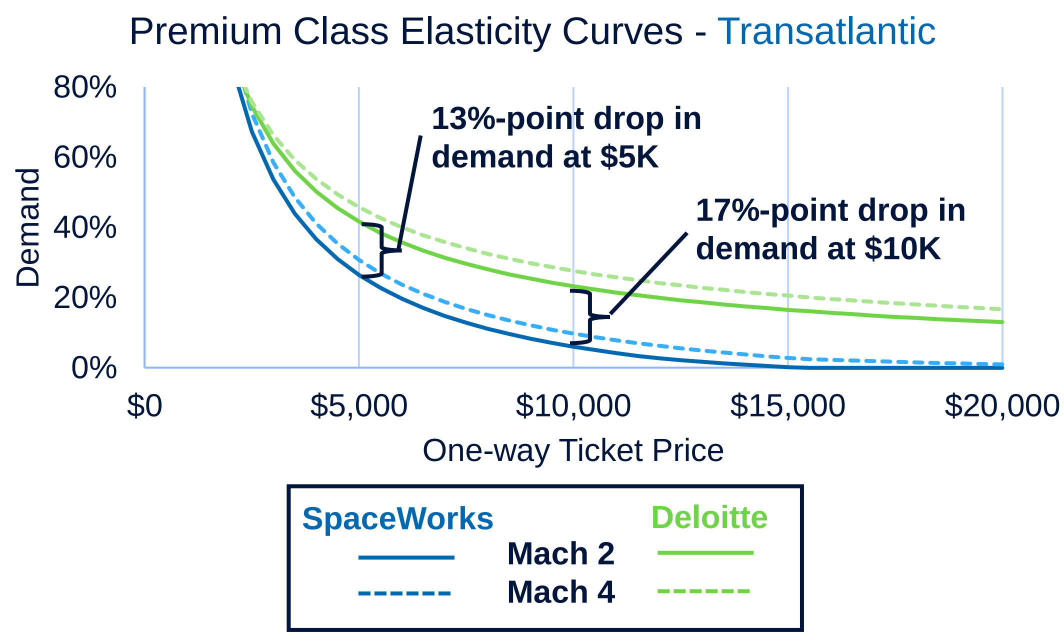
GBTA

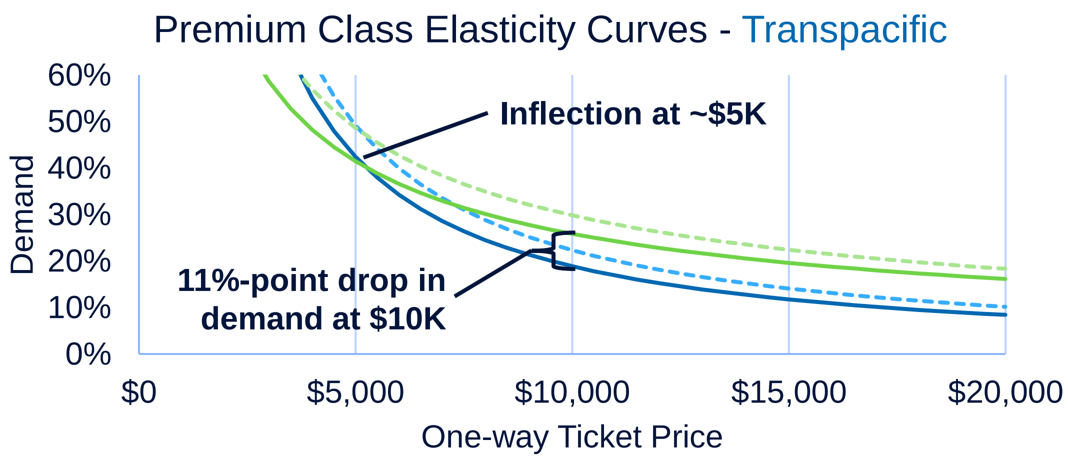
Elasticity Curve Data Blend



Price Elasticity Curve Differences

- **New results indicate an overall reduction in willingness to pay**
  - Most passengers were only willing to pay 1.5x to 2.5x the normal ticket price
  - Reduction was more pronounced in the transatlantic market
- **Price is more elastic compared to previous data**
  - Premium class less elastic at lower prices and much more elastic at higher prices
  - Economy class maintained similar behavior both at low and high prices
- **Corporate travel manager curve is more elastic than individual business travelers**
  - Likely due to corporate travel managers being more aware of travel budget limitations
- **These curves offer more insight into willingness to pay but still include some uncertainty and bias**





Macroeconomic Differences Between Surveys

- **Consumer Price Index (CPI) measures overall change in consumer prices and is a direct indicator of purchasing power**

- **Sept. 2020 (Deloitte survey)**
  - Consumer Price Index for all goods - 1.4%
  - Avg. Airline Fare - $197 (lowest in 10 years)
  - Purchasing power for airline tickets was at a 10-year high (27% different from 10-year Avg.)

- **Jan. 2023 (SpaceWorks survey)**
  - Consumer Price Index for all goods - 6.4%
  - Avg. Airline Fares $265
  - Purchasing power for airline tickets only 3% from 10-year Avg.

- **Global annual industry annual growth rate improved to 3.8% through 2031**

Consumer Price Index (CPI)

Average US Air Fares ($)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2013	307	309	315	319	327	325	316	304	301	310	318	301
2014	292	298	302	318	342	343	315	296	292	301	306	287
2015	283	289	287	295	319	325	297	278	275	286	294	279
2016	278	284	284	296	310	310	284	268	267	[illegible]	[illegible]	[illegible]
2017	269	281	284	294	301	296	276	259	259	[illegible]	[illegible]	[illegible]
2018	255	265	267	274	281	279	265	256	258	[illegible]	[illegible]	[illegible]
2019	248	259	260	269	283	283	268	260	263	270	269	252
2020	255	265	232	203	202	206	205	199	197	216	223	206
2021	201	197	197	223	250	257	244	213	199	206	215	209
2022	211	222	244	297	345	344	311	284	284	294	293	269
2023	265	281										

High / Low

Sept. 2020 Survey

Jan. 2023 Survey

10-year Avg. - $272

Unique Same Day Travel Enabled by High-speed Flight

Same-day Transatlantic Travel Premium

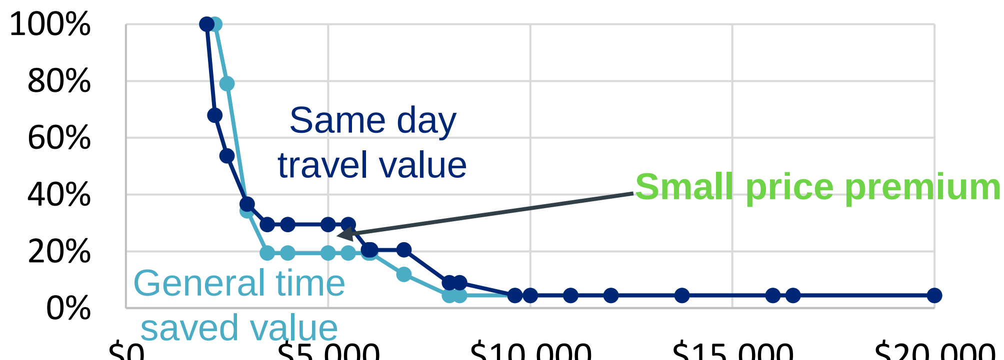
- **Dedicated survey question posed to determine what premium (if any) there was for same-day round trip transatlantic travel**

- **Respondents place value on variable amount of time to conduct business and then return home**

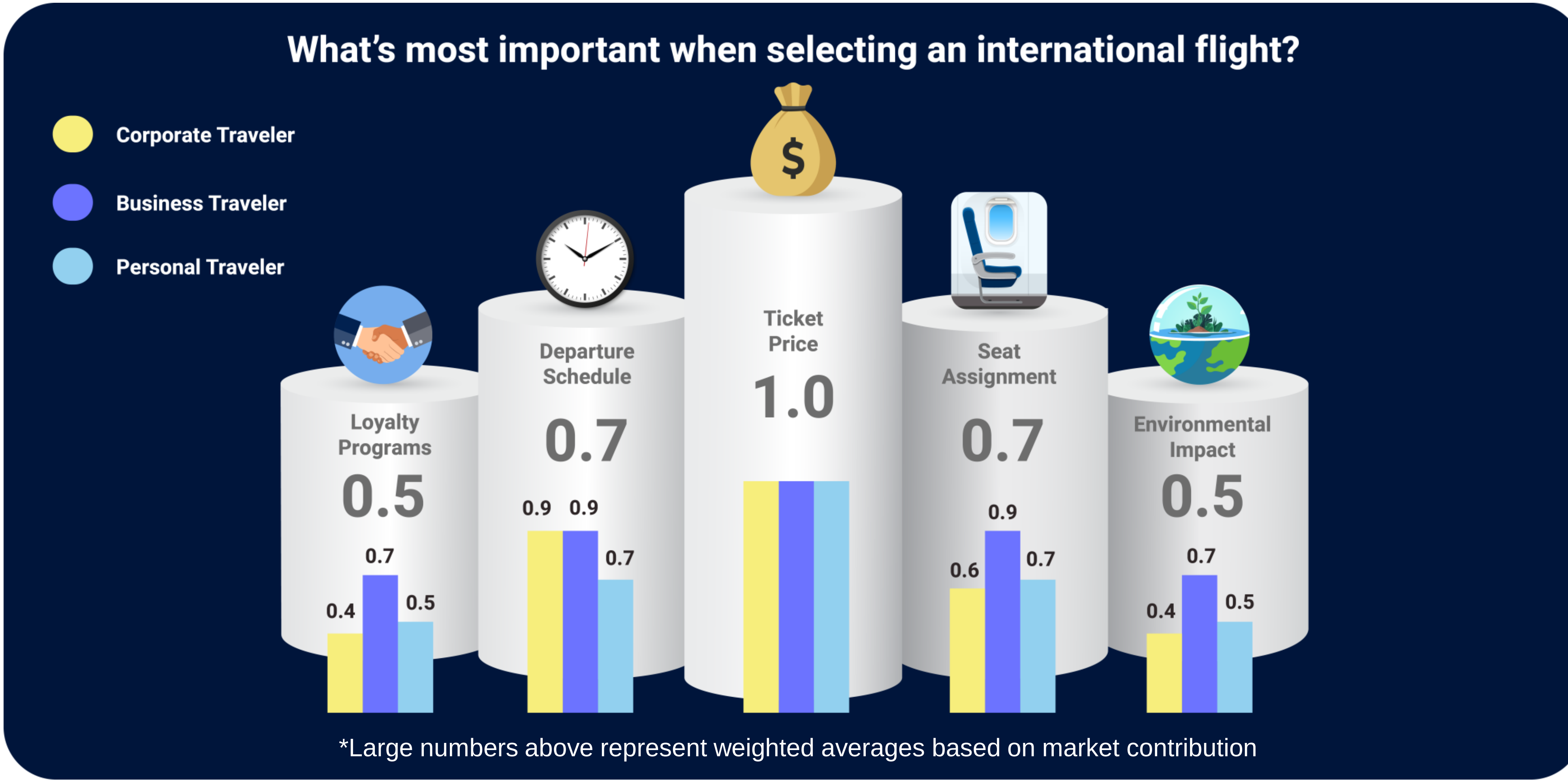
- **No premium was discerned when personal, business, and seat class travel data sets were blended**
  - Value of same day travel diminished by added time needed for customs/bags and local transportation
  - Value overlaps with value of general time savings
  - Small premium observed for Business and 1st class travelers specifically traveling for business at $3500-$9500 ticket price

Activity	Hours Required			
Total Travel Day	**13**	**13**	**13**	**13**
Conduct Business	2	3	4	5
Local Transportation	1	1	1	1
Customs/Bags	2	2	2	2
Flight to destination	4	3.5	3	2.5
Flight to origin	4	3.5	3	2.5
Required Flight Mach	*2.1*	*2.3*	*3.5*	*5.3*
Equivalent Time Saved	3.5	4.0	4.5	5.0

1st/Business Class Travelers – Flying for Business

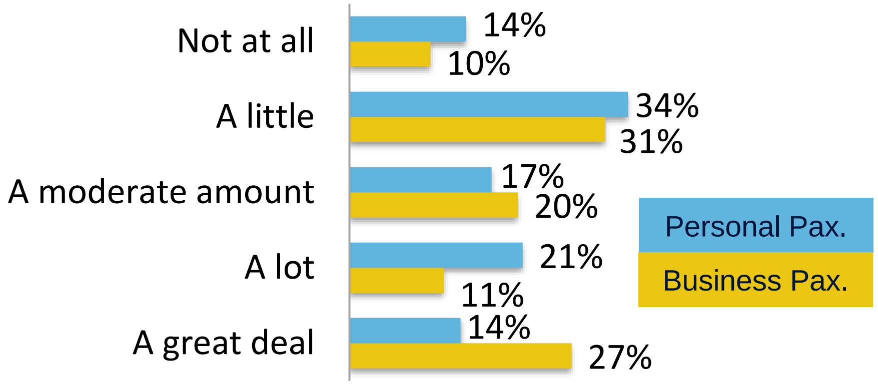


Relative Value of Influential Ticket Purchase Factors



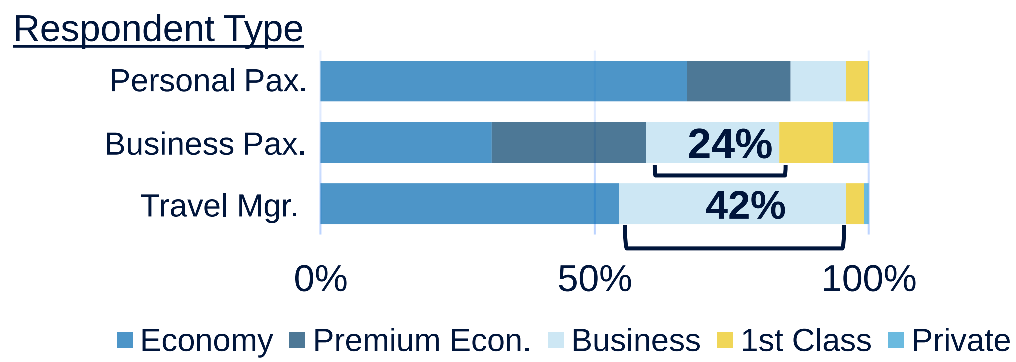
Other High-Speed Passenger Insights and Market Trends

Cabin Amenity Importance



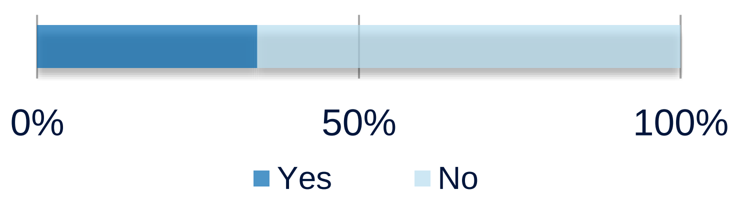
Business travelers place more value on cabin amenities

Seat Class Preference



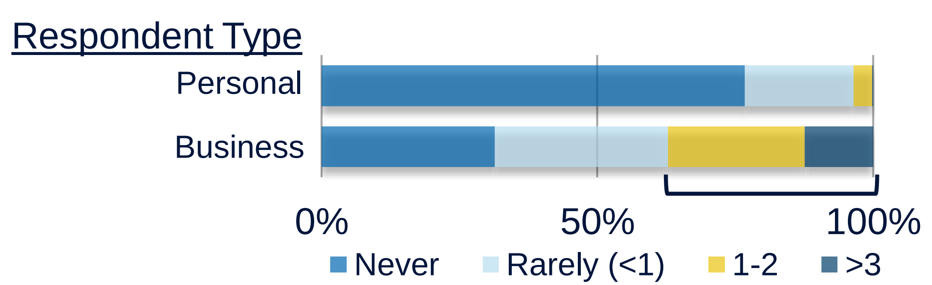
Travel managers chose a much higher percentage of business class passengers

Tech Stop Sensitivity



1/3 of travelers would rather endure a longer flight than sit on the tarmac

Urgent Travel Frequency



37% of business pax. urgently need to travel annually

Overland Route Market Growth Potential

- **Analysis conducted to determine potential market growth if US-based overland routes were available**
- **Minimum cruise distance based on route length and Mach needed to achieve 30 minutes of cruise time**
- **The Market potential increases substantially due for lower Mach aircraft**

Mach	Min. Cruise Distance nmi	Additional Domestic Market Annual Pax* (Routes)	Approx. Increase from Ref.	Additional Int. Overland Market Annual Pax* (Routes)	Approx. Increase from Ref.
2	**1,000**	**191M (381)**	**6x**	**104M (384)**	**4x**
3	1,600	78.4M (161)	3x	69.6M (268)	3x
4	2,300	6.0M (20)	1x	54.4M (209)	2x
5	3,000	1.7M (8)	1x	48.6M (184)	2x

*minimum potential market for additional US based routes only

Tech Stop Market Growth Potential

- **Tech stops offer a slight increase in market potential for short-range AC**

Design Range	Total Addressable Routes	Via Direct	Via Tech Stops	Additional Enabled Market	Approx. Increase
3,500 nmi	9	0	9	~4.55M Pax	**1.1x**
4,000 nmi	15*	1	14	~6.86M Pax	**1.2x**
4,500 nmi	23*	5	18	~11.3M Pax	**1.3x**

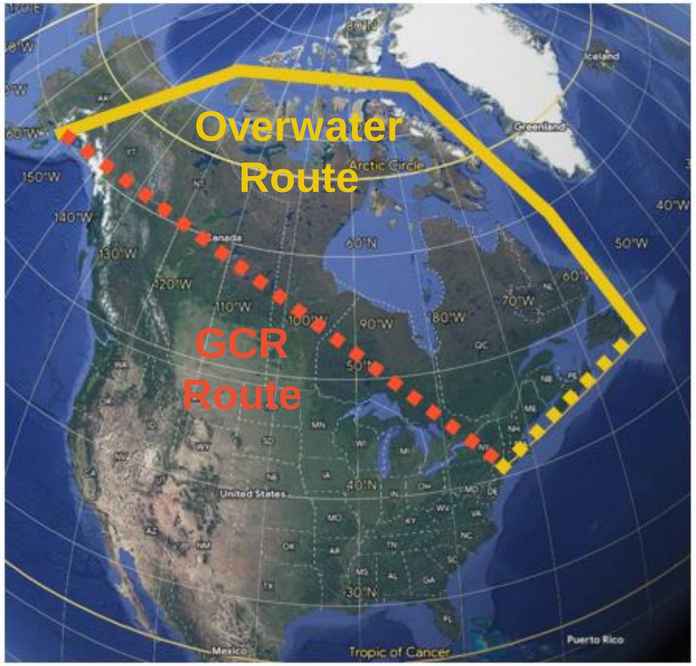
**Includes 29 transpacific routes that were modeled as well as LAX-LIM as a direct route*

- **Even more market potential can be realized by connecting the east coast cities to transpacific markets or vice versa**

AC Design Range (nmi)➔	**Water Overflight Only**			**Great Circle Routes (GCR)**		
	3,500	**4,000**	**4,500**	**3,500**	**4,000**	**4,500**
Possible Routes	0	6	18	11	23	**36**
Total Market Potential (pax/yr)	**+0.0M**	**+4.08M**	**+7.84M**	**+2.69M**	**+7.60M**	**+12.3M**
Top Route	N/A	LAX–LHR **(38%)**	LAX–LHR **(20%)**	JFK–ICN **(25%)**	LAX– LHR **(21%)**	**LAX–LHR (13%)**

Percentages based on route contribution to Total Modeled Market Potential for each range

Example Route (JFK – ANC)



Aircraft

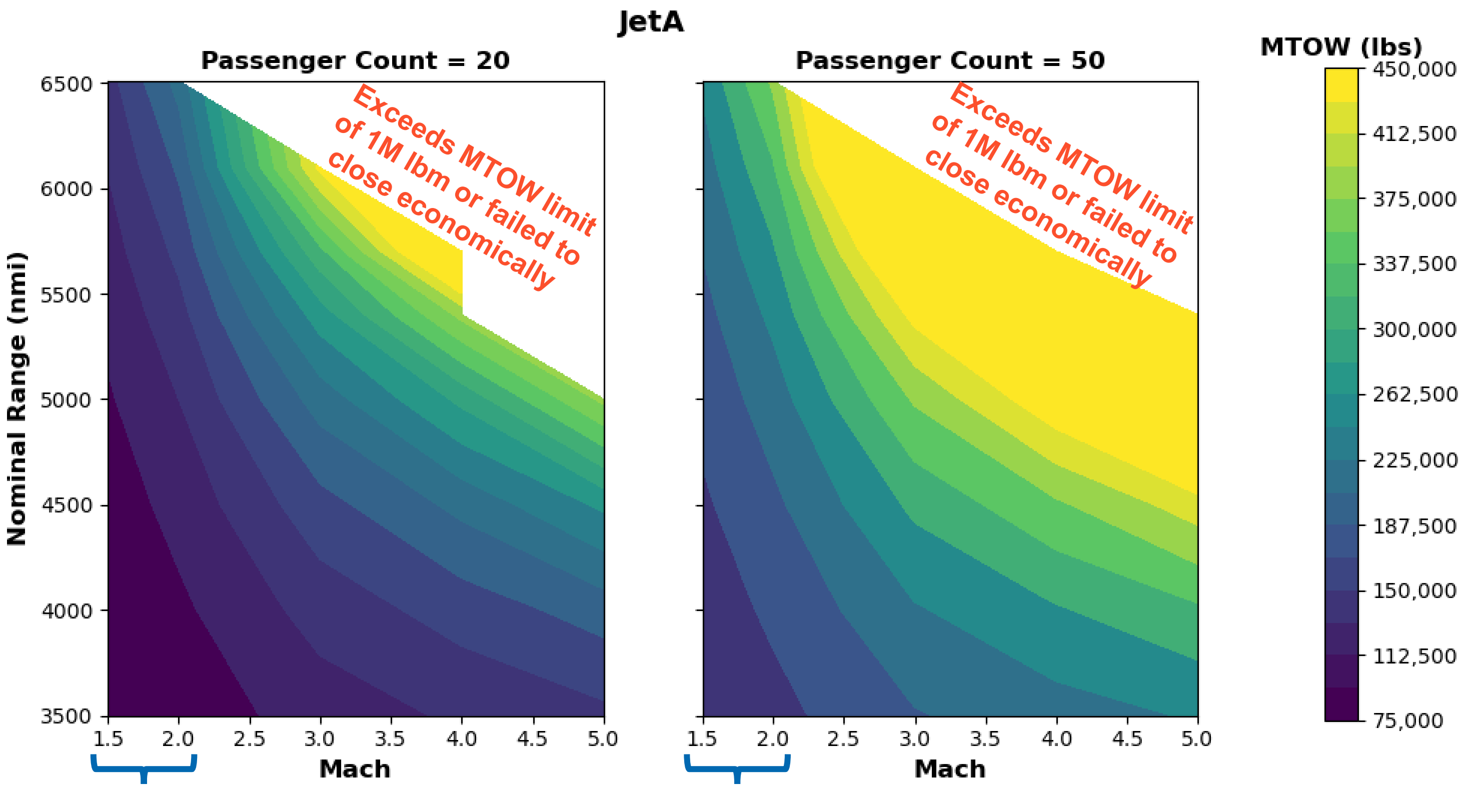
NASA SBIR Contract #80NSSC22C0008

Key Finding | Aircraft

Mach 1.5-2, 40-50 pax, 4,500-5,700 nmi range were the preferred aircraft configuration that kept masses and complexity low, enabling lower development and production costs

<u>**Key Features of Mach 1.5-2 Aircraft**</u>

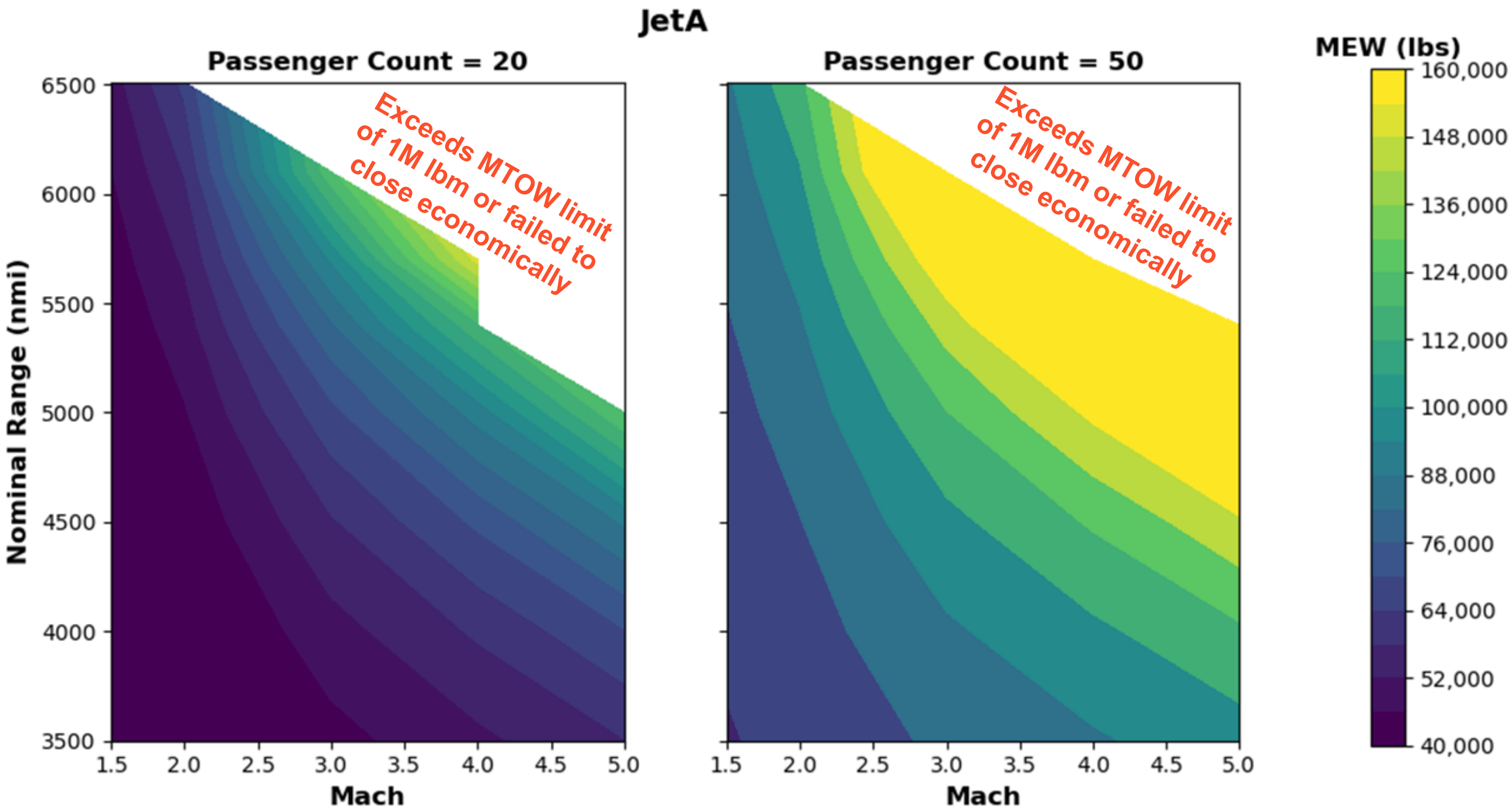
- **"Best" fuel option of JetA to SAF or straight to SAF, relative to LNG or hydrogen**
- **Least technical hurdles and complexity**
- **Lower masses**
  - < 200klb MTOW
  - < 90klb MEW
- **Long ranges more feasible from vehicle closure sensitivity**
  - Up to 5,700-6,100 nmi
- **Lowest emissions**
  - 0.25 - 0.40 CO_2e kg/km/pax (still ~5x higher than subsonic A/C)
- **Lowest noise level for takeoff**
  - < 92 EPNdB



Lower Masses at Slower Speeds

- **The Manufacturing Empty Weight (MEW) better represents the subsystem masses that drive the CERs**

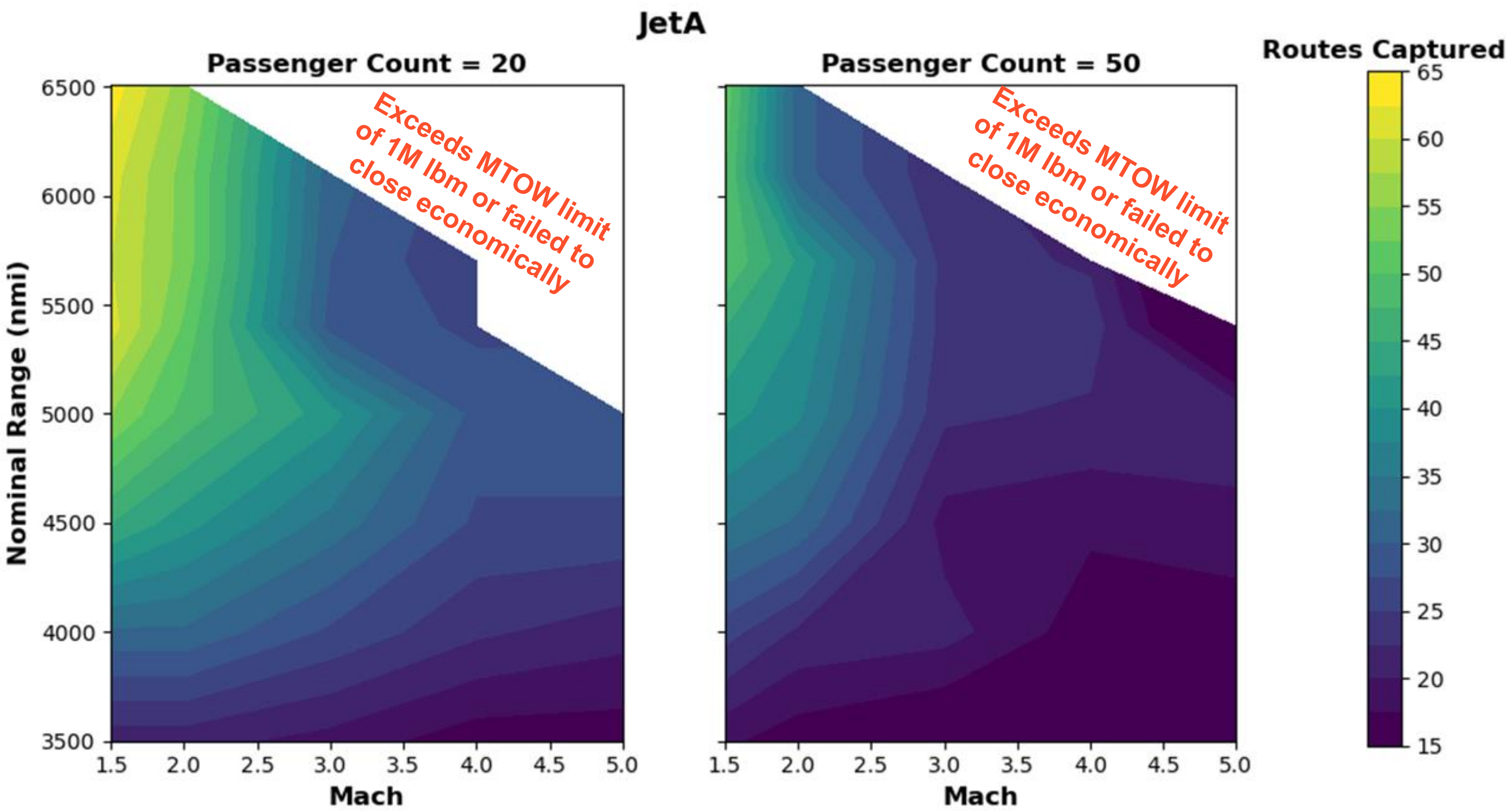
- **Range becomes a bigger factor as Mach number increases**



Note: Aircraft designs do not account for additional accommodations for TOL noise, sonic boom, or emission reduction technology. Current predicted levels are outputs of the analyses and no attempts to comply with existing or proposed regulations have been made to date.

Lower Speeds enable Longer Ranges

- **Because the masses weren't as impacted by range at lower speeds, its easier to design the aircraft to reach more cities**
  - This enables more opportunities for people to travel at high-speeds
- **This specifically enables the transpacific markets that start becoming available around 4,500 nmi**



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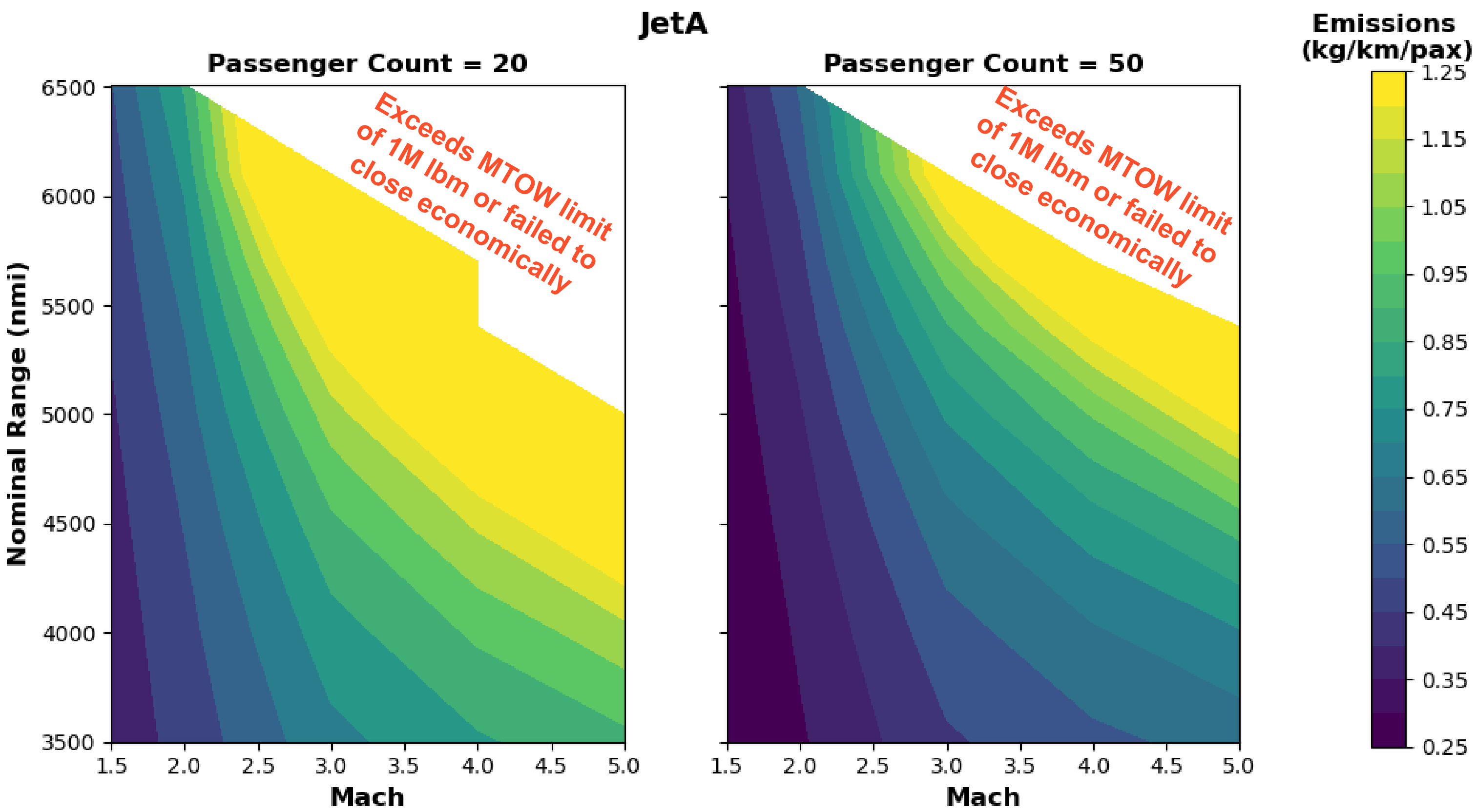
Lower Speeds mitigate Emissions

- **At lower speeds, less fuel is needed per flight which reduces the total emissions**
  - These values are still well above current subsonic levels (~0.08 kg/km/pax)
- **Takeoff noise is also reduced and close to current takeoff noise regulations**



Note: Aircraft designs do not account for additional accommodations for TOL noise, sonic boom, or emission reduction technology. Current predicted levels are outputs of the analyses and no attempts to comply with existing or proposed regulations have been made to date.

Break

- 10-15 minutes

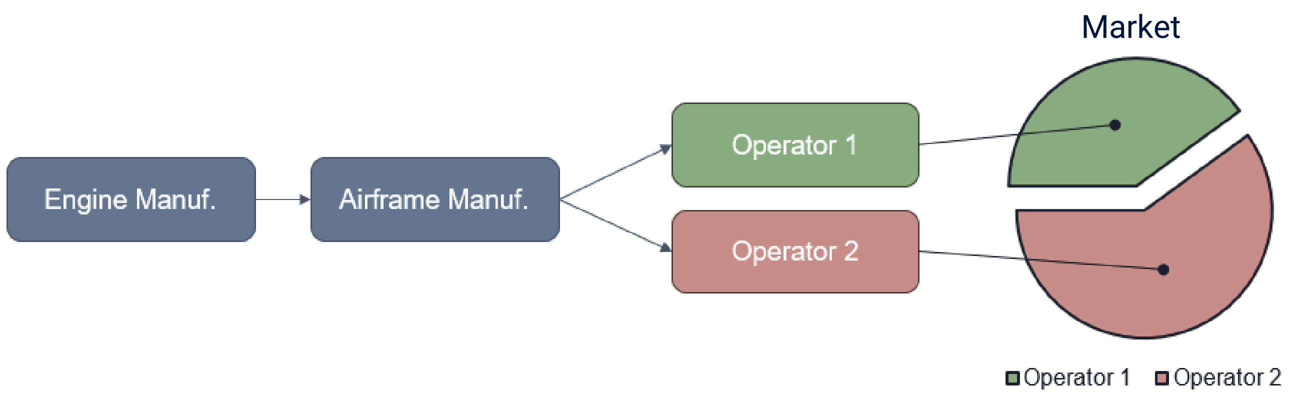
Financials

Key Finding | Financials

For the optimal aircraft configuration, spreading the financial risk between multiple operators enables improved business cases for all stakeholders

- **Splitting demand tempers initial investments by the operators while still enabling high production rates by the manufacturer**
  - Reduces maximum exposures for both operators and is therefore a less risky venture overall

- **This enables the engine and airframe manufacturer to reduce their list prices, resulting in operators breaking even sooner**
  - Faster break-even points are driven by lower ticket prices that generate higher market capture and revenue



DDT&E Historical Analysis & Cost Analysis Deep-dive

- **Research conducted on historical major commercial development airplane programs**

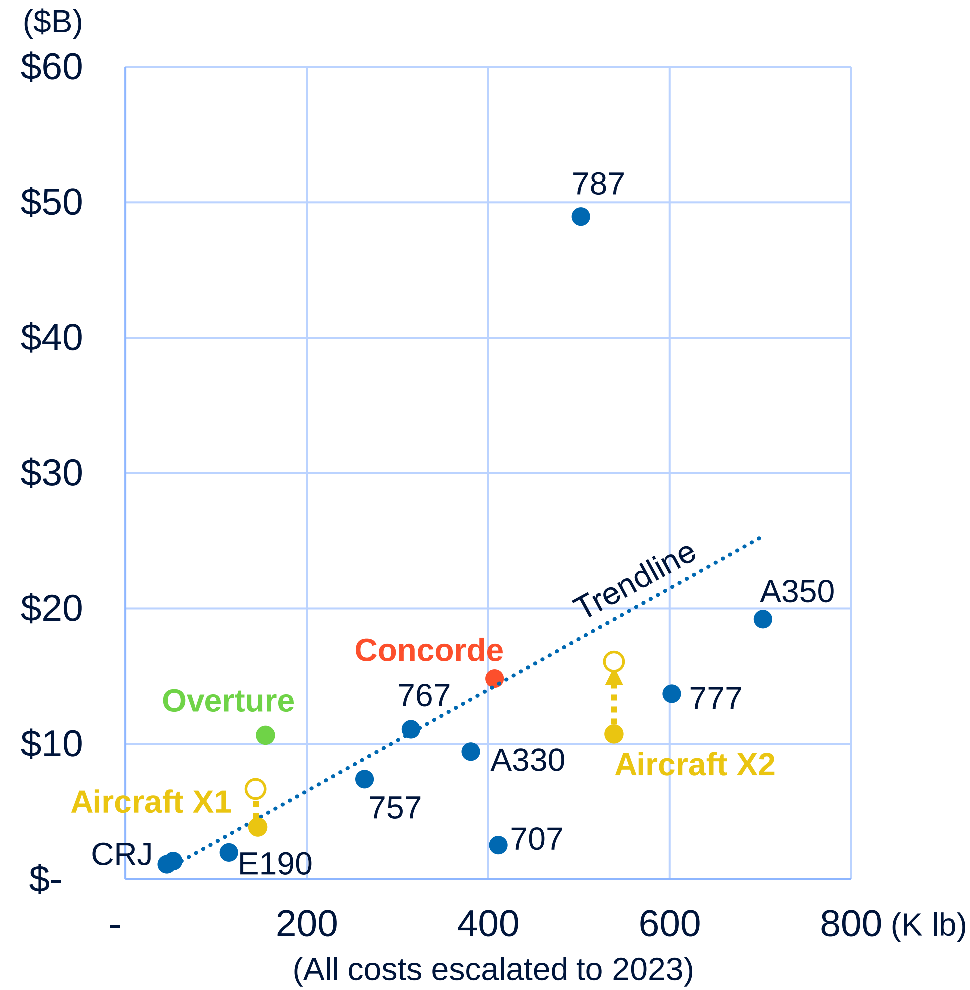
- **Design development test and evaluation cost correlates with airframe mass (P = 0.6)**

- **Other major factors**
  - Technology complexity
  - Design / Infrastructure inheritance
  - Certification environment

- **Aircraft X1**
  - Mach = 2
  - Range = 4000
  - Capacity = 50 Pax
  - MTOW = 168K lbs

- **Aircraft X2**
  - Mach = 3
  - Range = 5700
  - Capacity = 50 Pax
  - MTOW = 546K lbs

Historic DDT&E Cost vs MTOW



Jet-A Matrix – X1

SpaceWorks® NASA

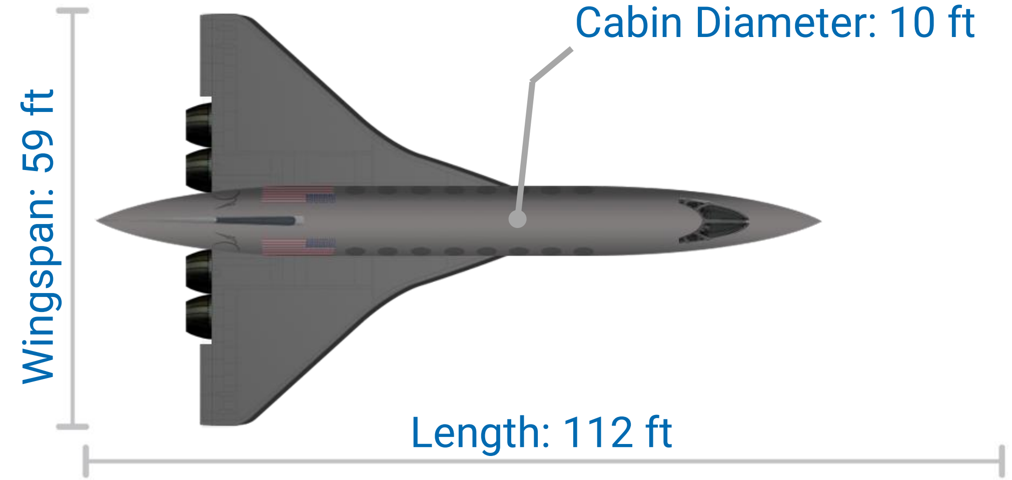
ID: JTA.M2.P50.R4000.20230518

Mach 2
Cruise Speed

4,000 nmi
Max Range

50
Passenger Count

JetA
Fuel Type



167,000 lbm MTOW	**69,000 lbm** MEW	**4 x 15,700 lbf** Engine Thrust SLS
4.4 hours Gate-to-Gate Time at Max Range	**56,300 ft** Cruise Altitude	**6,600 ft** Bal. Field Length SL

COST METRICS (FY21 USD)

DDT&E
- **$6.9B** Airframe
- **$2.5B** Engine

TFU
- **$95M** Airframe
- **$11M** Engine

ENVIRONMENTAL METRICS

91 EPNdB
Lateral Takeoff Noise

104 PNLdB
Sonic Boom

0.33 kg/km/pax
Emissions (CO_2e)

0.1 kg/km/pax
Fuel Consumption Rate

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
- Effective Dose Rate (51° Lat.) = 9.0 μSv/hr

NASA SBIR Contract #80NSSC22C0008

Jet-A Matrix – X1

SpaceWorks® NASA

ID: JTA.M2.P50.R4000.20230518

Key Inputs

Mach 2
Cruise Speed

4,000 nmi
Range

50
Passenger Count

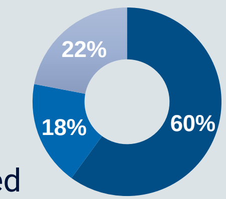
JetA
Fuel Type

OPERATOR METRICS

$5,700-$6,400
Ticket Price

0.5M
Pax/Year

16
Routes Captured



MANUFACTURER METRICS

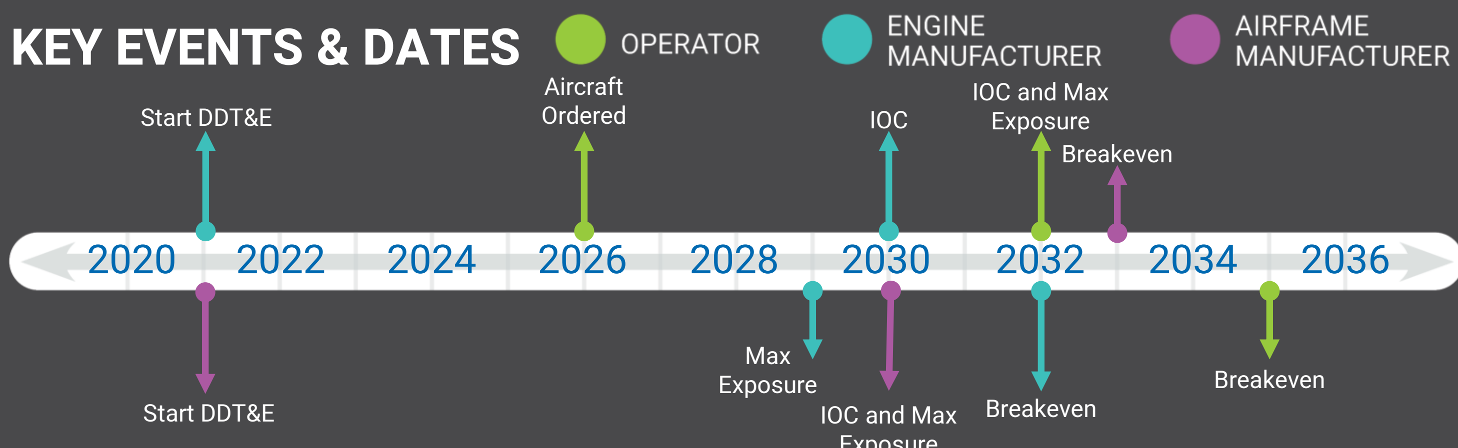
$667M
Aircraft Price

$513M
Airframe Price

$38M x4
Engine Price

97
Aircraft Sold

KEY EVENTS & DATES



Business Results

OPERATOR

10%	$1.2B	$3.6B
ROIC (avg)	NPV	Max Exposure

ENGINE MANUFACTURER

19%	$544M	$2.5B
IRR	NPV	Max Exposure

AIRFRAME MANUFACTURER

19%	$1.8B	$8.2B
IRR	NPV	Max Exposure

BUSINESS CASE ANALYSIS

This aircraft is capturing 16 of 37 addressable routes that are within its design range which are exclusively Atlantic Ocean routes.

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Jet-A Matrix – X2

SpaceWorks NASA

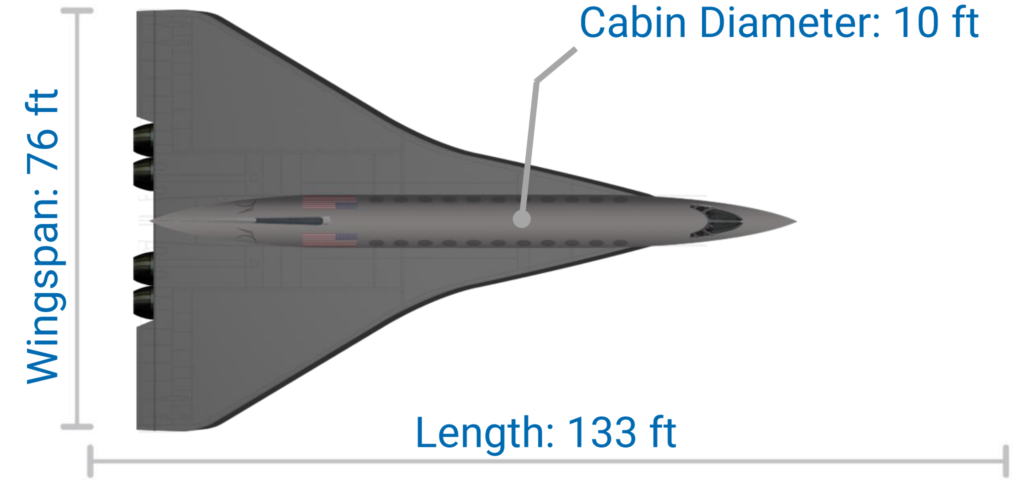
ID: JTA.M3.P50.R5700.20230518

Mach 3
Cruise Speed

5,700 nmi
Max Range

50
Passenger Count

JetA
Fuel Type



COST METRICS (FY21 USD)

DDT&E

$14B	$5.0B
Airframe	Engine

TFU

$220M	$49M
Airframe	Engine

ENVIRONMENTAL METRICS

97 EPNdB
Lateral Takeoff Noise

1.02 kg/km/pax
Emissions (CO2e)

106 PNLdB
Sonic Boom

0.32 kg/km/pax
Fuel Consumption Rate

546,000 lbm	**163,500 lbm**	**4 x 51,100 lbf**
MTOW	MEW	Engine Thrust SLS
4.1 hours	**73,300 ft**	**7,800 ft**
Gate-to-Gate Time at Max Range	Cruise Altitude	Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 6.4
- Supersonic cruise condition Isp = 2000 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375
- Effective Dose Rate (51º Lat.) = 9.1 μSv/hr

NASA SBIR Contract #80NSSC22C0008

Jet-A Matrix – X2

SpaceWorks NASA

ID: JTA.M3.P50.R5700.20230518

Key Inputs

Mach 3
Cruise Speed

5,700 nmi
Range

50
Passenger Count

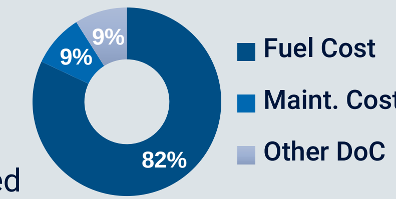
JetA
Fuel Type

OPERATOR METRICS

$11,600-$14,800
Ticket Price

0.2M
Pax/Year

9
Routes Captured



MANUFACTURER METRICS

$745M
Aircraft Price

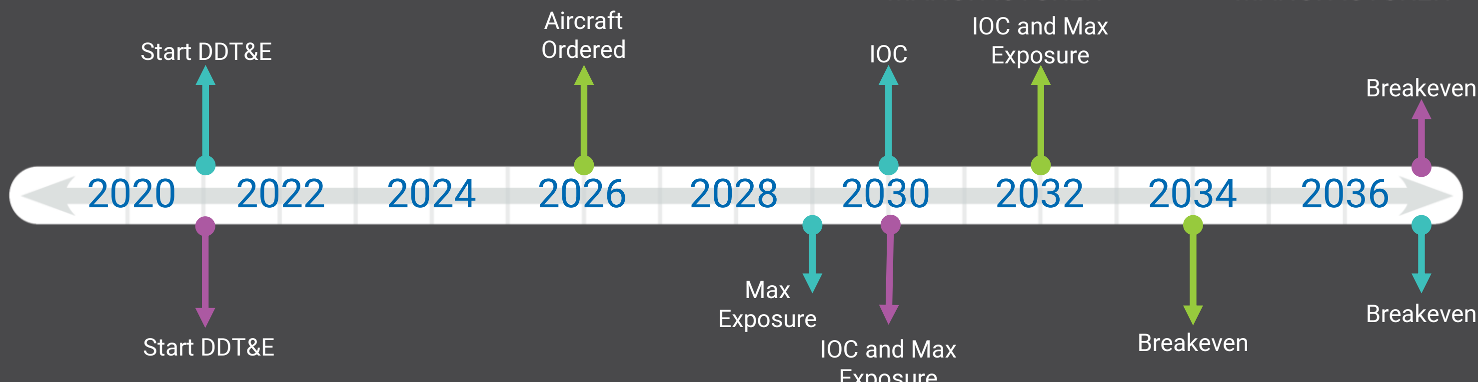
$495M
Airframe Price

$62M x4
Engine Price

50
Aircraft Sold

KEY EVENTS & DATES

OPERATOR — ENGINE MANUFACTURER — AIRFRAME MANUFACTURER



Business Results

OPERATOR

4%	$557M	$1.9B
ROIC (avg)	NPV	Max Exposure

ENGINE MANUFACTURER

9%	$-1.1B	$5.7B
IRR	NPV	Max Exposure

AIRFRAME MANUFACTURER

9%	$-3.4B	$18B
IRR	NPV	Max Exposure

BUSINESS CASE ANALYSIS

This aircraft is capturing 9 of 78 addressable routes that are within its design range which are a mix of Atlantic & Pacific Ocean routes.

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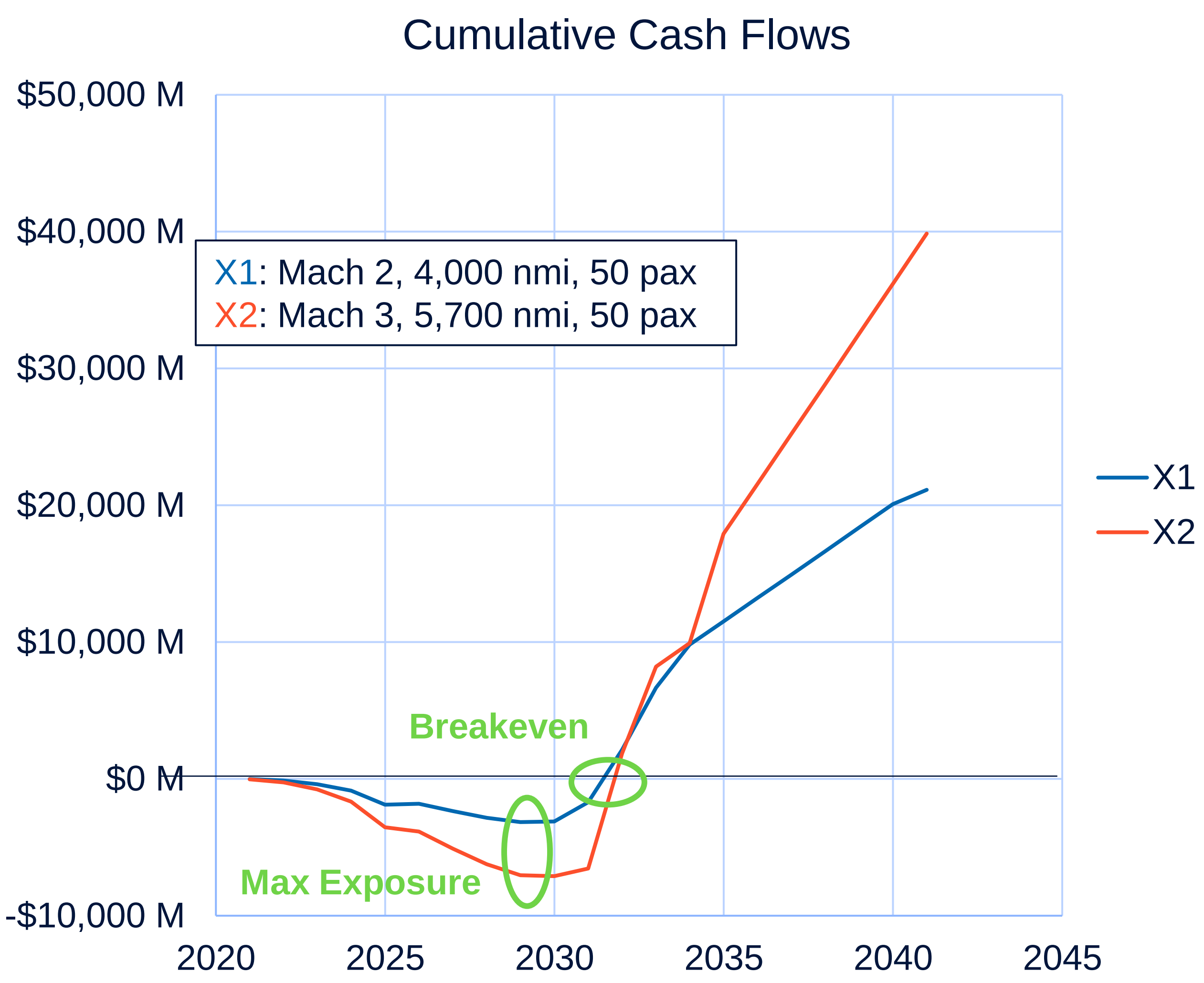
Airframe Manufacturer Financials

- **The more complex X2 aircraft fails to reach the initial objective using either set of market data**
- **Greater development costs drive higher aircraft prices that result in greater profits but hurt the operator's financial metrics**

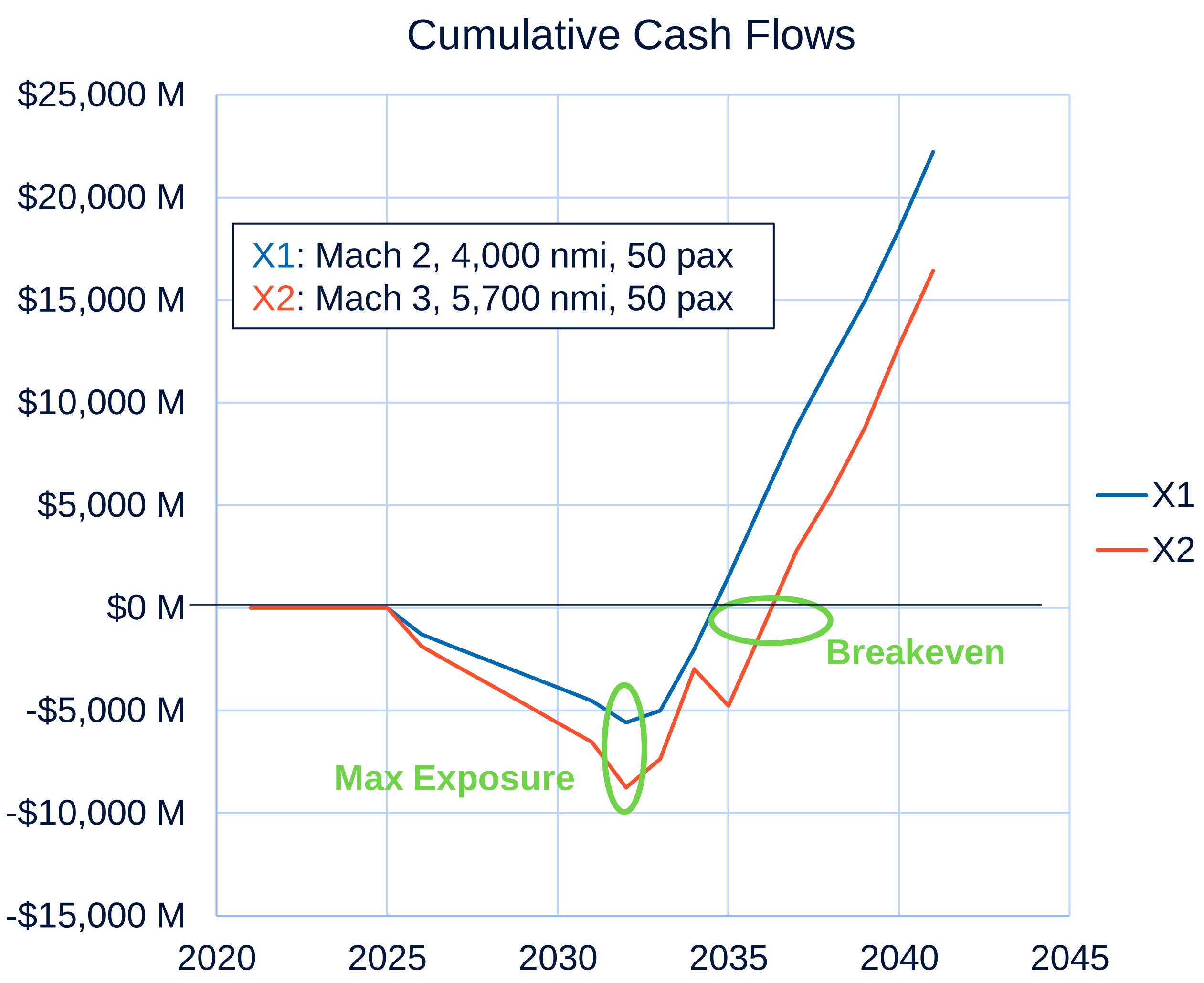
	X1	X2
IRR	25.0%	21.5%
Max Exposure	$3.3B	$7.5B
Breakeven	2032	2032
Aircraft Price	$350M	$850M
Engine Price	$28M	$78M
Aircraft Sold	143	81



Operator Financials

- **Operator cash flows indicate how X1 can generate quicker returns with lower ticket prices**
  - Although revenues may be lower, costs are also lower compared to X2
    - X1 is less expensive and requires less fuel
  - Max exposure also reflects the aircraft prices and how X1 has less upfront costs (even with more aircraft ordered)

	X1	X2
IRR	25.0%	21.5%
Max Exposure	$5.1B	$7.5B
Breakeven	2035	2036
Ticket Price	$4,300	$11,500
Market Capture	1.6M	780k



RASM & CASM Comparison with Subsonic Industry

- **Analyzed hypothetical highspeed airline "Airdromeda" for comparison with industry**
  - 20 pax airplane
  - Average airfare $4400
  - Average route length 3300 nmi
- **Compared with publicly available US DOT Form 41 Data**
- **Changes in RASM/CASM attributed to Airdromeda's unique operations**
  - RASM
    - ~10x increase in airfare
    - Route length and load factor variance
  - CASM
    - 7x-11x increases in fuel/maint./crew labor CASM
    - Smaller increases in other cost categories
- **Highspeed industry margins are much higher (~56%) but the volume is much lower**
  - Represents ~1% of US international market
  - British Airways reported 43% margins with Concorde

RASM

Typical Subsonic Airline	Highspeed Airline
$0.11 - $0.16	$1.83

~13x increase

CASM

Typical Subsonic Airline	Highspeed Airline
$0.10 - $0.15	$0.80

~6x increase

Relative Financial Differences between Market Approaches

- **X1 and X2 both reflect single operator, single aircraft scenarios**
- **However, when multiple manufacturers and/or multiple operators are considered, notable trends emerge**
  - Multiple operators could reduce their max exposures and enable improved economics
  - Multiple manufactures can provide a more balanced fleet, but the production rates are insufficient to generate notable cost savings

Stakeholder	Metric	Single Operator	Multiple Manufacturers	Multiple Operators
All	IRR	-	-	-
Operator	Max Exposure	-	▲	▼
	Breakeven	-	▲	▼
	Ticket Prices	-	▼	▼
	Market Capture	-	▲	▲
	Annual Revenue	-	▲	▼
	Annual Cost	-	▲	▼
Manufacturers	Max Exposure	-	▼	▼
	Breakeven	-	▲	▼
	Aircraft Price	-	▲	▼
	Aircraft Sold	-	▼	▲
	Engine Price	-	▲	▼
	Engines Sold	-	▼	▲

Multiple Operators

- **Comparing X1 for single aircraft business case against the multiple operator solution shows improvements across the board when demand is split between operators**
  - Ticket prices are lower, aircraft prices are lower with over 2x more aircraft sold, market capture increases by over 50%, and max exposures are both lower

Case	Min IRR	Mach	Range	Pax	Ticket Price	Aircraft Price	Aircraft Sold	Routes	Pax/Yr	Max Exp.
Subsonic					$2,000*	~$100M*				
Single	25.0%	2	4,000	50	$4,300	$350M	143	22	2.2M	$5.1B
Multiple Ops	25.4%	2	4,000	50	$3,400 | $4,000	$235M	323	10 | 30	2.2M | 1.3M	$4.1B | $2.6B

- **Comparing the same cases with updated market data shows greater advantages with this approach**
  - Max exposure is greater while all other metrics are the same, or better than, single operator (including IRR)

Case	Min IRR	Mach	Range	Pax	Ticket Price	Aircraft Price	Aircraft Sold	Routes	Pax/Yr	Max Exp.
Subsonic					$2,000*	~$100M*				
Single	19%	2	4,000	50	$5,700	$665M	97	16	1.1M	$3.6B
Multiple Ops	25%	2	4,000	50	$3,300 | $5,700	$530M	166	10 | 22	1.5M | 0.52M	$8.4B | $5.3B

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Key Finding - Environmental

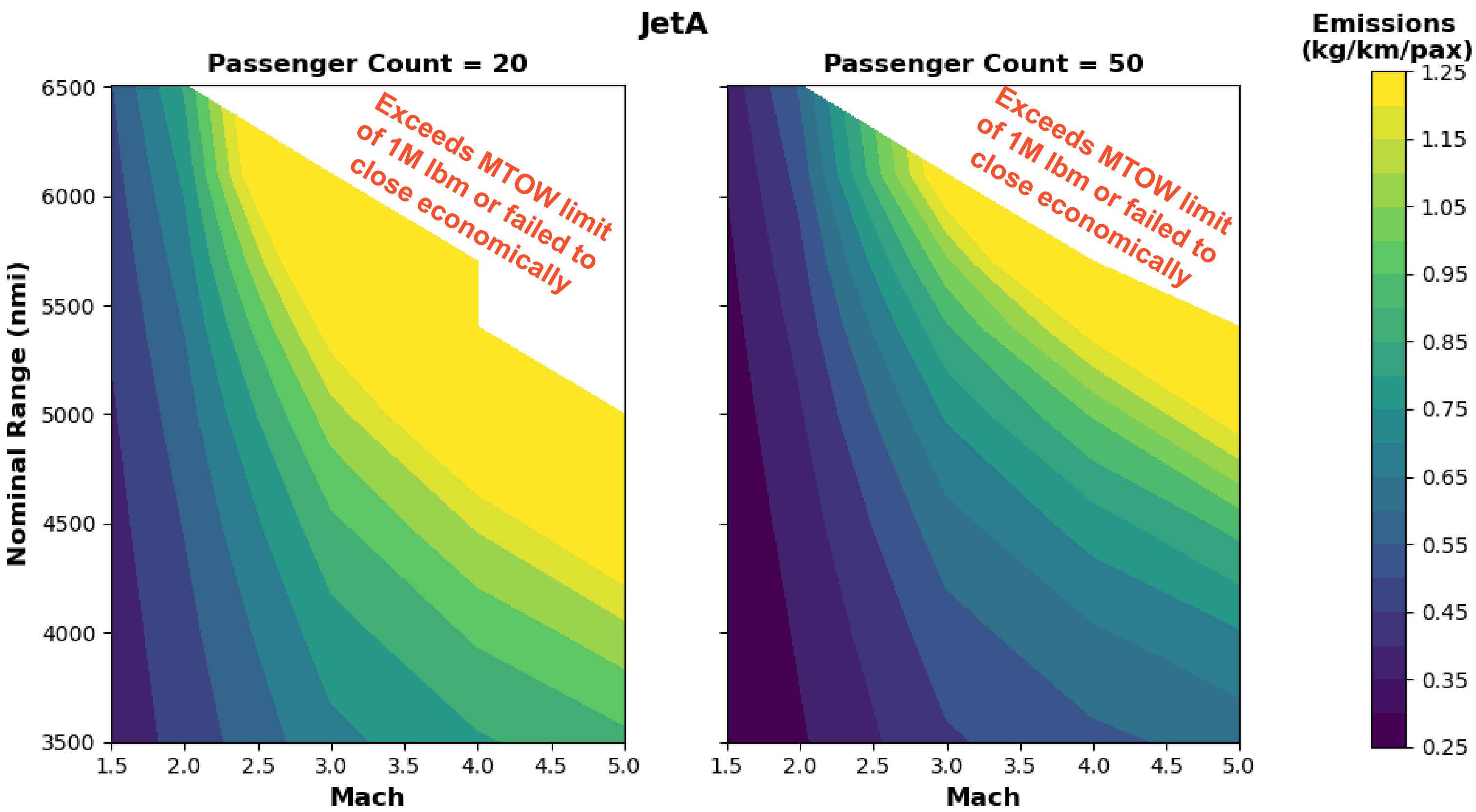
Key Finding - Environment

Takeoff noise, sonic booms, and emissions continue to pose a major challenge to high-speed flight and will need to be addressed before a high-speed market can be realized

- High-speed aircraft are chasing regulations that continue to become more stringent as climate concerns become more prevalent
- Advanced technology would help address these issues but that requires time and money
- Alternative fuels could solve the emissions challenge, but production scale of these fuels need to be significantly higher
- Shorter flights do offer benefits against radiation exposure

Lower Speeds mitigate Emissions

- **At lower speeds, less fuel is needed per flight which reduces the total emissions**
  - These values are still well above current subsonic levels (~0.08 kg/km/pax)
- **Takeoff noise is also reduced and close to current takeoff noise regulations**



Note: Aircraft designs do not account for additional accommodations for TOL noise, sonic boom, or emission reduction technology. Current predicted levels are outputs of the analyses and no attempts to comply with existing or proposed regulations have been made to date.

Emissions Comparison

- **At lower speeds, less fuel is needed per flight which reduces the total emissions**
  - These values are still well above current subsonic levels (~0.08 CO2e kg/km/pax)
- **Comparing alternative fuels offers some insight into their benefits**
  - However, the benefits for these fuels may only be realized when evaluating the entire life cycle of the fuel, especially for SAF which produces similar emissions to Jet-A
- **The table below captures X1 metrics for each fuel type and compares it to model outputs for known aircraft**

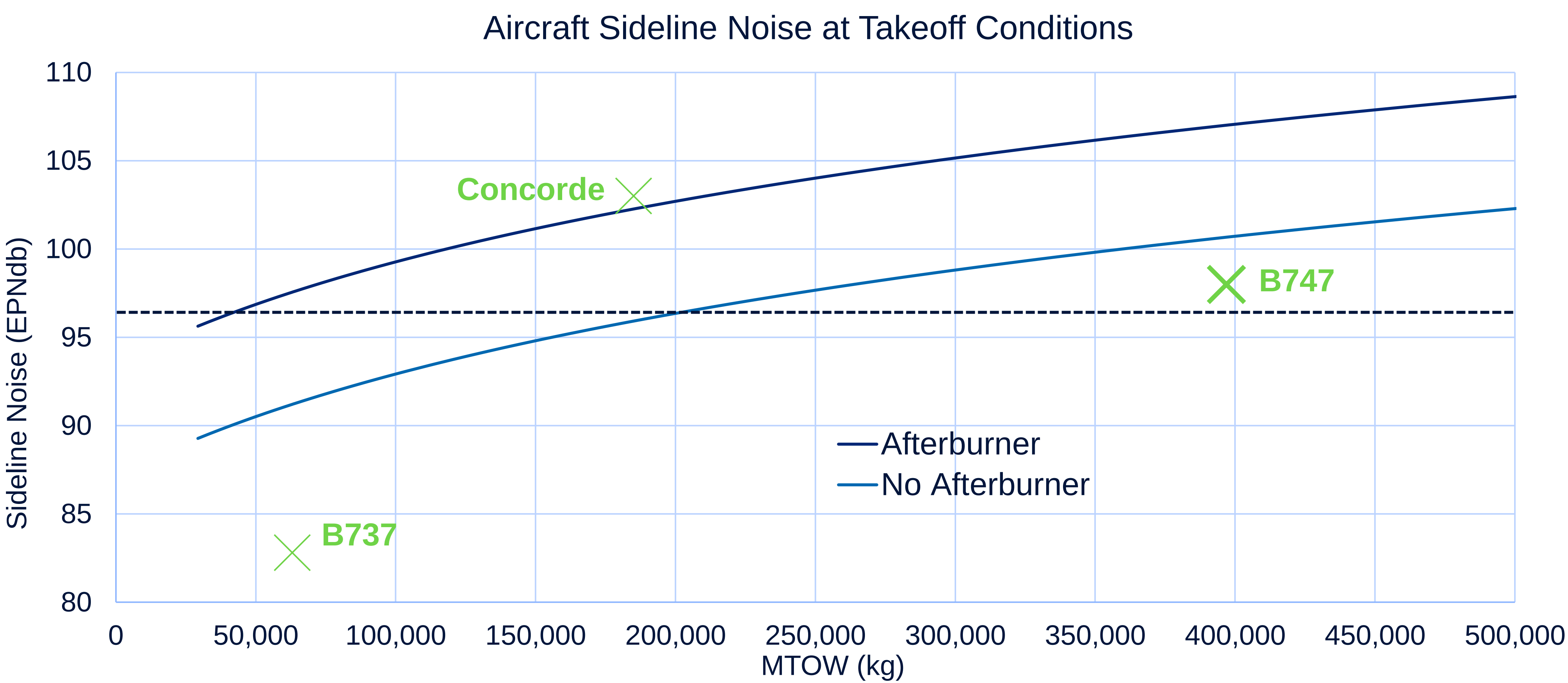
Emissions	Jet-A Mach 2 50 pax 4,000 nmi	SAF Mach 2 50 pax 4,000 nmi	LNG Mach 2 50 pax 4,000 nmi	LH2 Mach 2 50 pax 4,000 nmi	B777-200 LR 291 Pax 4,970 nmi	B787-8 243 Pax 4,650 nmi	Concorde 128 Pax 3,900 nmi	Gulfstream G550 19 Pax 6,750 nmi
Total Fuel (kg)	37,900	36,500	37,200	18,700				
CO_2e (kg/km/pax)	**0.33**	**0.32**	**0.29**	**0.0008**	**0.08**	**0.05**	**0.31**	**0.02**
MTOW (kg)	76,200	73,900	79,400	67,100	347,500	227,900	177,000	41,300
MEW (kg)	31,300	30,800	35,200	41,500				

Alternative Fuel Supply

- **LNG already has established production to supply multiple industries**
  - However, this fuel is still a hydrocarbon producing emissions similar to Jet-A, just with a cleaner burn
  - This offers some potential benefits but doesn’t provide a novel solution to emissions
- **SAF offers a “net-zero” carbon solution through production methods but challenges remain**
  - Emissions are similar to Jet-A
  - SAF production forecasted to reach 3 billion gallons per year by 2030
    - However, the global aviation industry used 95 billion gallons of aviation fuel in 2019
    - 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
- **Hydrogen production is even farther behind, especially for “green” hydrogen production**
  - Like LNG, it requires cryogenic storage and currently has expensive means of production

Takeoff Noise

- **Many aircraft have takeoff noises in the low 90s EPNdB with limits around 96 EPNdB in compliance with Annex 16, Volume I, Chapter 14**

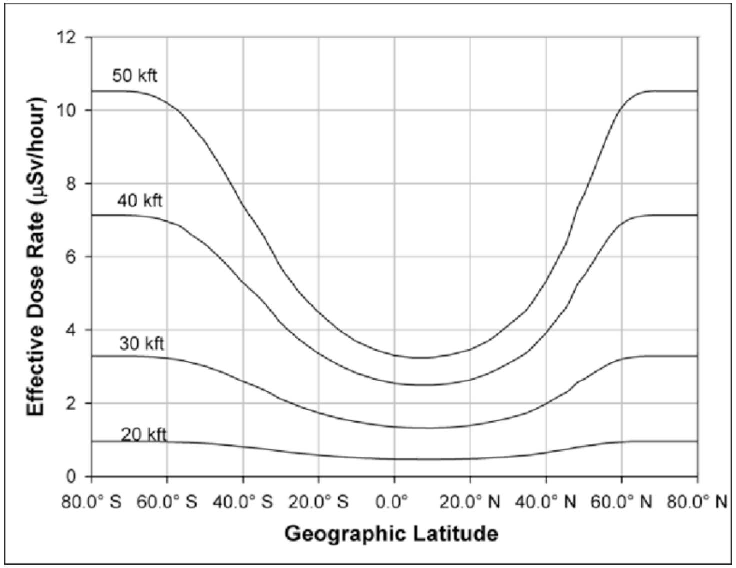


Radiation Exposure Update

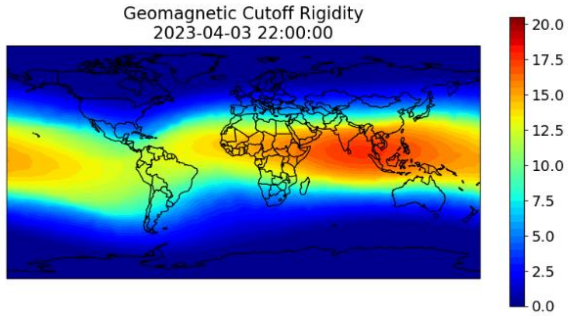
- **The radiation curves provide rough estimates based on average exposure rates**
  - 11-year solar cycles create fluctuations in exposure rates
  - Routes have unique exposure rates based on latitudes and to a lesser extent, longitudes

- **Radiation calculations above 60,000 ft**
  - Radiation dose rates appear to peak around 60,000 ft (Pfotzer maximum)
  - After that, exposure decreases to roughly 80% of the peak at 100,000 ft

- **Geomagnetic Cutoff Rigidity indicates the geomagnetic shielding provided by Earth’s magnetic field against charged cosmic ray particles**
  - In chart on right, red indicates region of greatest protection (or the least radiation exposure)



Effective dose rate from GCR, as related to geographic latitude at selected altitudes at 20° E longitude. Dose rates are for the mean solar activity from January 1958 through December 2008



Radiation Exposure Compared to Subsonic

- **For reference, a member of the public should not exceed 1 mSv (~40 flights if effective dose is 25 μSv per flight) per year while the occupational dose limit should not exceed 20 mSv per year**
  - Both values are recommended averages over a 5-year period
  - The max occupational dose limit for a single year is 50 mSv

Route	Distance (nmi)	Average Latitude	Mach	Cruise Altitude (ft)	Time at Cruise (hr)	Effective Dose Rate (μSv/hr)	Total Effective Dose (μSv)
JFK – LHR	3,000	51 º N	0.8	32,600	6.30	3.84	24.2
JFK – LHR	3,000	51 º N	2	56,300	2.57	8.98	23.1
JFK – LHR	3,000	51 º N	4	80,400	1.23	14.2	**17.5**
LAX – NRT	4,737	47 º N	0.8	32,600	10.0	3.52	35.3
LAX – NRT	4,737	47 º N	2	56,300	4.08	7.80	31.8
LAX – NRT	4,737	47 º N	4	80,400	1.97	12.1	**23.9**
LAX – SYD	6,507	0 º	0.8	32,600	13.8	1.94	26.9
LAX – SYD	6,507	0 º	2	56,300	5.63	3.72	21.0
LAX - SYD	6,507	0 º	4	80,400	2.73	5.53	**15.1**

Recommendations

Key Findings | Overall

- **Economic metrics resulted in ticket price premiums of 2 to 2.5 times over business class tickets in order to capture ~10% of the market currently serviced by hundreds of subsonic aircraft.**

- **Given our key findings with respect to market demand, aircraft technical specifications/capabilities, financial considerations, and various environment factors:**

  - ***We believe there is a high-speed PTP market, but it is relatively small for the foreseeable future due to a combination of challenging factors***

  - ***The environmental issues must be solved without significantly impacting the design and capabilities of the aircraft in order for this market to be realized***

  - ***Small improvements in the aircraft (i.e., engine TSFC, structural mass reductions, etc.) can have a significant positive impact on financial viability due to impacts on $/RPM***

Recommendations

1. **NASA and FAA should continue their efforts to enable and permit overland supersonic flight**
   - Potential to drastically increase market size by six-fold and increase access to providers
   - Provides more robust business cases for supersonic / hypersonic developers and operators

2. **In the meantime, enact a two-phased “leader-follower” strategy to allow markets and technology to mature**
   - First-to-market transoceanic “leader” aircraft in Mach 1.5-2 range aimed at addressing high demand routes
   - “Follower” aircraft designed to address growing and/or newly emerging markets via further technology improvements (longer range, higher speeds, etc.)
   - Allows for initial regulatory requirements and certification processes to be established and matured for lower speed systems (Mach 1.5 to 2) before attempting higher speeds (Mach 3+)

3. **Continue investments in supersonic and hypersonic aircraft technologies, particularly in the areas of:**
   - Engine fuel efficiency and emissions
   - Takeoff noise
   - Aircraft and engine structures/materials

4. **Continue 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

Future Work

Economic Model Improvements (for MIDAS)

- Permit more refined route-based ticket pricing
- Permit dynamic ticket pricing in competitive environments
- Incorporate more ground operations details for pre-flight/post-flight maintenance and/or overhaul

Environmental Impact Factors

- Enable technology modeling for noise reduction, sonic boom mitigation, and improved emissions to be implemented into the aircraft design & sizing process/model
- Evaluate high-fidelity HSCEV reference vehicles that are more explicitly addressing these challenges and benchmark against vehicle sizing models used to date

Additional Scenario Studies

- Evaluate PTP scenarios with staggered aircraft retirement rates that would more easily enable block upgrades
- Perform more refined analysis of the "leader-follower" scenarios
  - Consider more synergies between manufacturers
  - Combine trade/sensitivity studies to evaluate multiple scenarios
- Reduce trade space to focus on specific aircraft
  - Target more company-specific economic metrics and include more risk factors for each operator and manufacturer
- Conduct further analysis into the airport operations that would make the most sense for high-speed aircraft and the expected passenger class that would be served

Market Ideation

- Continue to investigate and characterize the market and public interest

Closing Thoughts

SPACEWORKS.AERO

info@spaceworks.aero | 1050 Crown Pointe Parkway
Suite 1400 | Atlanta, GA 30338 USA | 770.379.8000

NASA SBIR/STTR Contract #80NSSC22C0008

Original Baseball Cards

- **For reference against Updated Baseball Cards presented**

AIRCRAFT X-1

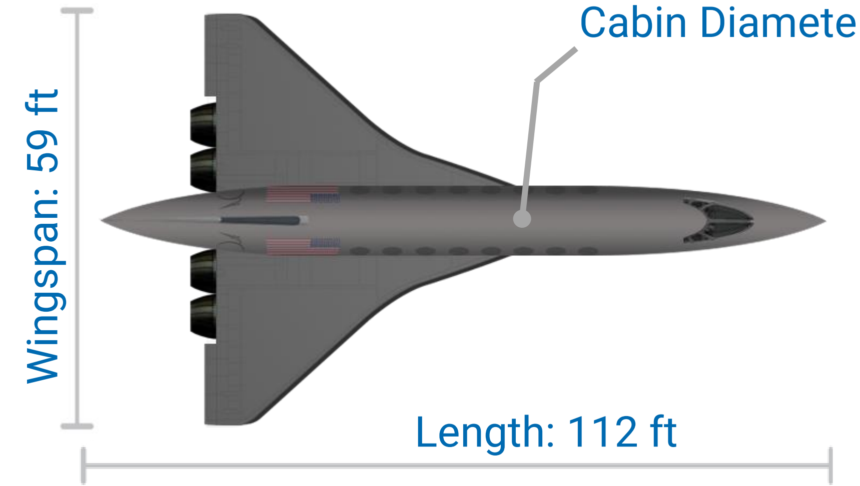
ID: JTA.M2.P50.R4000

Mach 2
Cruise Speed

4,000 nmi
Max Range

50
Passenger Count

JetA
Fuel Type



167,000 lbm	69,000 lbm	4 x 15,700 lbf
MTOW	MEW	Engine Thrust SLS
4.4 hours	**56,300 ft**	**6,600 ft**
Gate-to-Gate Time at Max Range	Cruise Altitude	Bal. Field Length SL

COST METRICS (FY21 USD)

DDT&E		TFU	
$3.7B	**$2.1B**	**$95M**	**$11M**
Airframe	Engine	Airframe	Engine

ENVIRONMENTAL METRICS

91 EPNdB
Lateral Takeoff Noise

0.33 kg/km/pax
Emissions (CO2e)

104 PNLdB
Sonic Boom

0.1 kg/km/pax
Fuel Consumption Rate

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

NASA SBIR Contract #80NSSC22C0008

AIRCRAFT X-1

SpaceWorks NASA

ID: JTA.M2.P50.R4000

Key Inputs

Mach 2
Cruise Speed

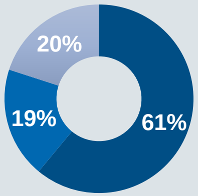
4,000 nmi
Range

50
Passenger Count

JetA
Fuel Type

OPERATOR METRICS

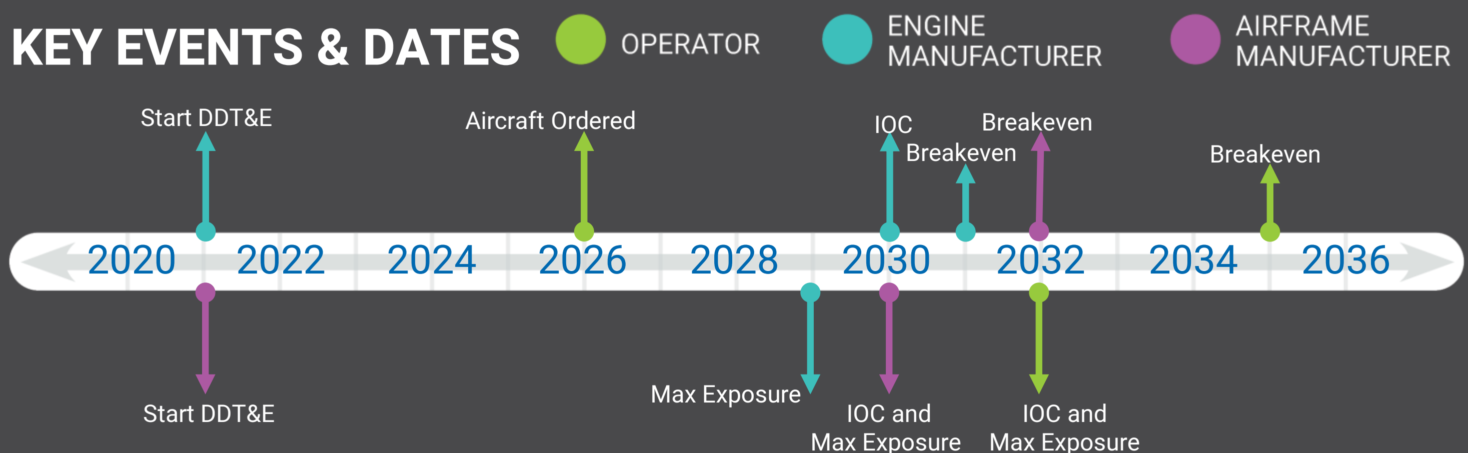
$4,300-$4,800	1.6M	22
Ticket Price	Pax/Year	Routes Captured



MANUFACTURER METRICS

$350M	$239M	$28M x4	143
Aircraft Price	Airframe Price	Engine Price	Aircraft Sold

KEY EVENTS & DATES



Business Results

OPERATOR

25%	$2.4B	$5.0B
IRR	NPV	Max Exposure

ENGINE MANUFACTURER

25%	$1.0B	$1.4B
IRR	NPV	Max Exposure

AIRFRAME MANUFACTURER

25%	$2.2B	$3.3B
IRR	NPV	Max Exposure

BUSINESS CASE ANALYSIS

This aircraft is capturing 22 of 37 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.

NASA SBIR Contract #80NSSC22C0008

AIRCRAFT X-2

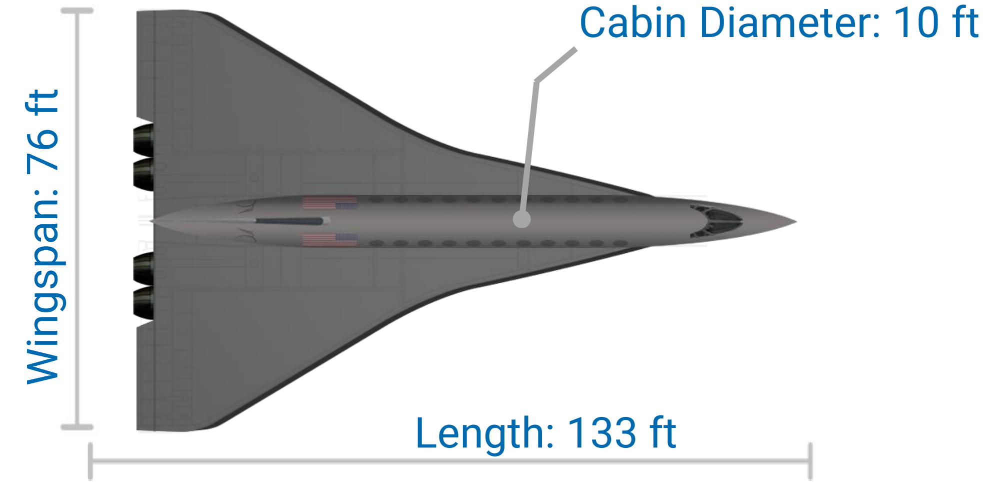
ID: JTA.M3.P50.R5700

Mach 3
Cruise Speed

5,700 nmi
Max Range

50
Passenger Count

JetA
Fuel Type



COST METRICS (FY21 USD)

DDT&E		TFU	
$7.3B	$3.8B	$220M	$49M
Airframe	Engine	Airframe	Engine

ENVIRONMENTAL METRICS

97 EPNdB
Lateral Takeoff Noise

1.02 kg/km/pax
Emissions (CO2e)

106 PNLdB
Sonic Boom

0.32 kg/km/pax
Fuel Consumption Rate

545,000 lbm
MTOW

163,500 lbm
MEW

4 x 51,100 lbf
Engine Thrust SLS

4.1 hours
Gate-to-Gate Time
at Max Range

73,300 ft
Cruise Altitude

7,800 ft
Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 6.4
- Supersonic cruise condition Isp = 2000 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

NASA SBIR Contract #80NSSC22C0008

AIRCRAFT X-2

SpaceWorks® NASA

ID: JTA.M3.P50.R5700

Key Inputs

Mach 3
Cruise Speed

5,700 nmi
Range

50
Passenger Count

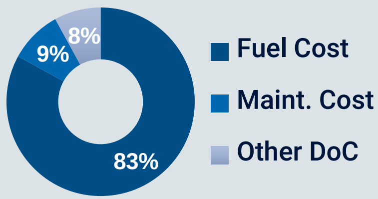
JetA
Fuel Type

OPERATOR METRICS

$11,600-$14,800
Ticket Price

0.8M
Pax/Year

24
Routes Captured



MANUFACTURER METRICS

$848M
Aircraft Price

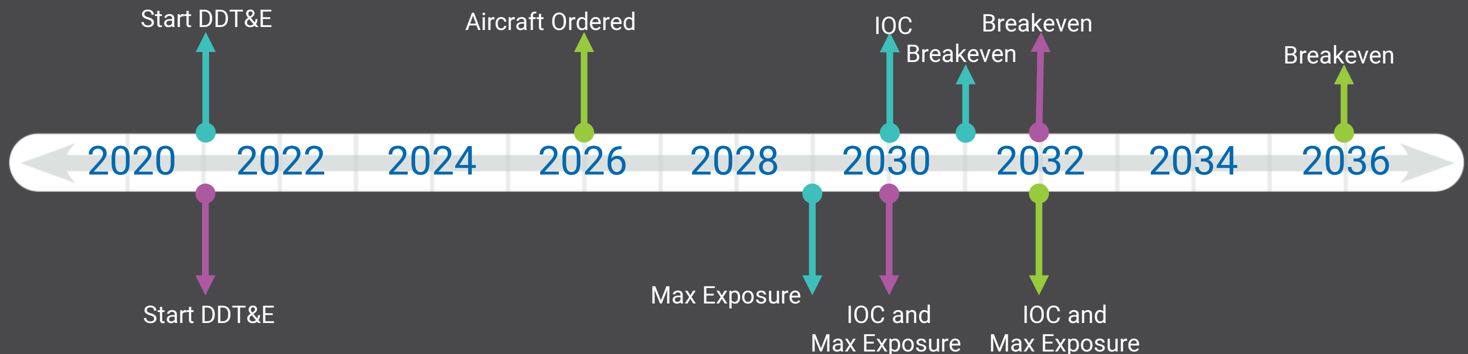
$539M
Airframe Price

$77M x4
Engine Price

81
Aircraft Sold

KEY EVENTS & DATES

OPERATOR ENGINE MANUFACTURER AIRFRAME MANUFACTURER



Business Results

OPERATOR

21%	**$1.9B**	**$7.4B**
IRR	NPV	Max Exposure

ENGINE MANUFACTURER

21%	**$1.2B**	**$3.1B**
IRR	NPV	Max Exposure

AIRFRAME MANUFACTURER

21%	**$2.6B**	**$7.5B**
IRR	NPV	Max Exposure

BUSINESS CASE ANALYSIS

This aircraft is capturing 24 of 78 addressable routes that are within its design range which are a mix of Atlantic & Pacific Ocean routes. High ticket prices can’t compensate for excessive aircraft prices, fuel costs, and max exposures which results in IRRs less than 25%

NASA SBIR Contract #80NSSC22C0008