Aircraft Technology Modeling and Assessment

Project 10

FAA Project Manager: Sandy Liu

Georgia Tech (Lead University): Dimitri Mavris (PI), Jimmy Tai (Co-PI)

REs: Brennan Stewart, Jai Ahuja, Christian Perron, Holger Pfaender

GRA Leads: Edan Baltman, Joao De Azevedo, Zayne Roohi, Srikanth Tindivanam

Purdue: William Crossley (PI), Dan DeLaurentis (co-PI), Muharrem Mane (Research Scientist)

GRAs : Tien-Yueh Fung, Katelin Zichittella

October 25 - 27, 2022
Alexandria, VA

This research was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 10 through FAA Award Number 13-C-AJFE-GIT under the supervision of Rangasayi Halthore and Laszlo Windhoffer. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA.

ASCENT
AVIATION SUSTAINABILITY CENTER

ASCENT Project 10

Aircraft Technology Modeling & Assessment

Georgia Institute of Technology &
Purdue University

PI: Dimitri Mavris, GT

PM: Sandy Liu
Laszlo Windhoffer

Cost Share Partner: Boom Supersonics, Georgia Institute of Technology

Objective: Model and assess potential evolution of commercial airline fleet due to the introduction of future supersonic aircraft and how technology development could affect the environmental impacts of aviation (e.g., fleet-level fuel burn, emissions and noise). The effort will examine ***SST vehicle modeling; fleet route simulation; fleet simulation, and AEDT supersonic modeling.***

Project Benefits: Provide an understanding of how introduction of new supersonic transports that could enter into commercial airline service and private use will affect fleet-wide fuel burn, noise and emissions.

Research Approach:

SST Vehicle Modeling:

- RANS CFD based aero shaping
- Multi-fidelity and parametric drag polar generation
- RANS CFD for LTO drag estimation
- Propulsion cycle modeled with NPSS using parametric loss models and multi-design point sizing
- Propulsion power management utilizes variable nozzle throat and fuel flow to optimize fuel efficiency or noise
- Propulsion flowpath and weight modeled with WATE++
- Mission analysis using FLOPS sizes vehicle for 65pax, Mach 1.7, 4250 nmi
- LTO trajectory modeled using FLOPS detailed takeoff and noise modeled using ANOPP
- Vehicle design space is parametrically explored to determine impact on noise and fuel burn
- Developing modeling methods for supersonic full-flight capabilities in AEDT

Major Accomplishments (to date):

SST Vehicle Modeling: Successfully implemented new RANS CFD based active subspace aero optimization; Implemented parametric drag polar into mission analysis; implemented VRNS optimization; used generic GT 65pax M1.7 SST for Greensboro Airport

Fleet Route Simulation: Developed flexible route optimization tool; Completed future SST demand study where demand depends on vehicle capabilities; Supported CAEP E-Study; Developed inventory of estimated future global SST emissions

AEDT SST Full-Flight Modeling: Developing implementation plan for SST models in AEDT; Decided on OD pairs for initial SST mission type implementations in AEDT

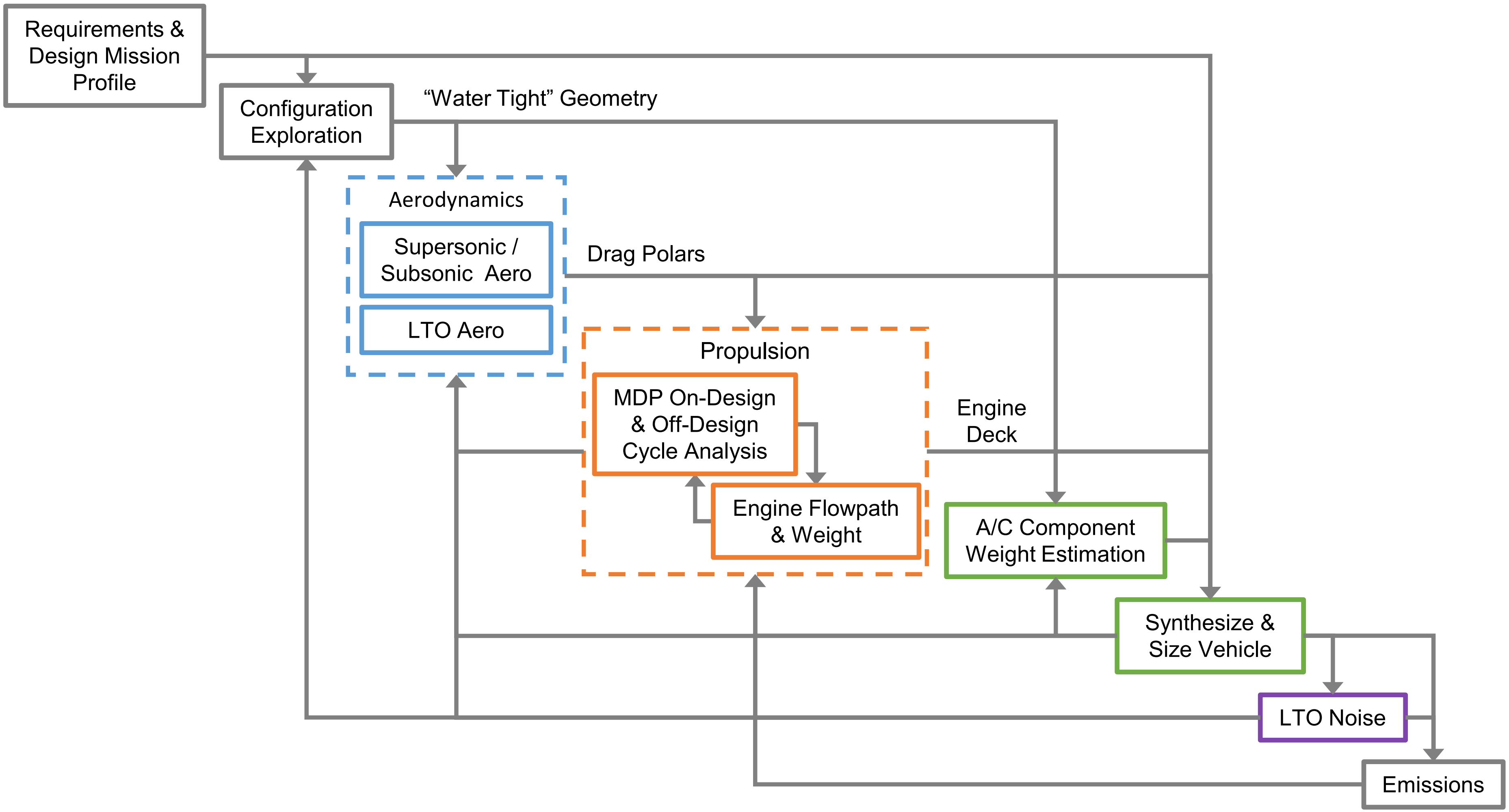
Future Work/Schedule remainder of PoP:

Complete new 65-passenger, M1.7 and M2.0 SST; Perform validation on off-design missions for all SSTs for AEDT; Develop and validate models using newly obtained OEM data for AEDT; Develop and support AEDT implementation activity for one SST concept

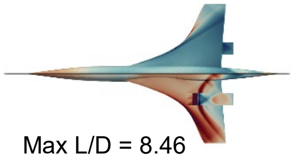
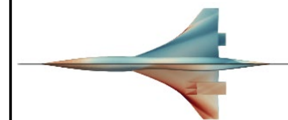
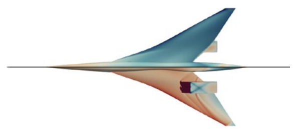
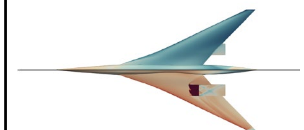
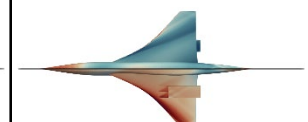
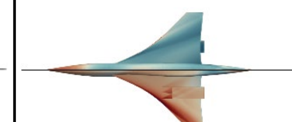
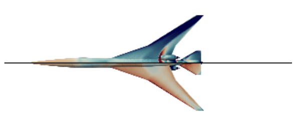
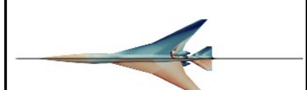
This research was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 10 through FAA Award Number 13-C-AJFE-GIT-006 under the supervision of Rangasayi Halthore, Maryalice Locke, and Laszlo Windhoffer. Any opinions, findings, conclusions or recommendations expressed in this this material are those of the authors and do not necessarily reflect the views of the FAA.

Framework for Advanced Supersonic Transport (FASST)

Purpose: Modeling and simulation (M&S) environment to design commercial supersonic transports with capability to examine fuel burn and LTO noise interdependencies and with direct linkage to fleet analysis



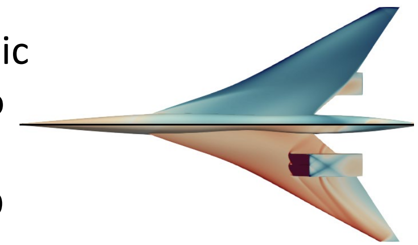
Matrix of SST Airframe Designs

	$M_\infty = 1.4$	$M_\infty = 1.6$	$M_\infty = 1.7$	$M_\infty = 1.8$	$M_\infty = 2.0$	$M_\infty = 2.2$
100 PAX	“Large SST”	 Max L/D = 8.46		 Max L/D = 8.39	 Max L/D = 8.09	
75 PAX						 Max L/D = 7.13
65 PAX			 Max L/D = 10.34		 Max L/D = 9.68	
55 PAX	“Medium SST”			 Max L/D = 7.51	 Max L/D = 7.26	 Max L/D = 7.07
25 PAX	 Max L/D = 7.73					
SSBJ	 Max L/D = 9.41	 Max L/D = 8.72		 Max L/D = 8.29		“SSBJ”

Supersonic Aero Optimization & Polar Generation

AERO DESIGN VARIABLES
Sweep (inboard and outboard)
Twist at 5 wing stations
Taper ratio (inboard and outboard)
Aspect Ratio
Dihedral (inboard and outboard)
Wing break location
Airfoil camber at 5 wing stations

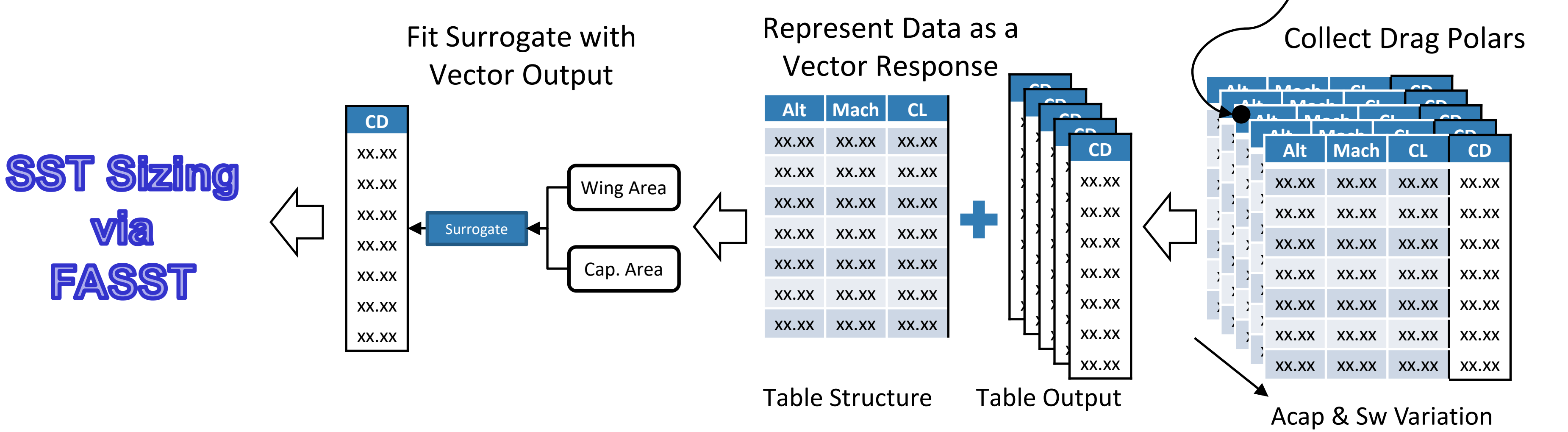
Aerodynamic shaping to **maximize cruise L/D**



Freeze Configuration Except Engine Capture Area (Acap) and Wing Area (Sw)

Active subspaces for dimensionality reduction
Adaptive sampling for RANS based design optimization

Multi-fidelity (inviscid + RANS CFD) Drag Polar Generation

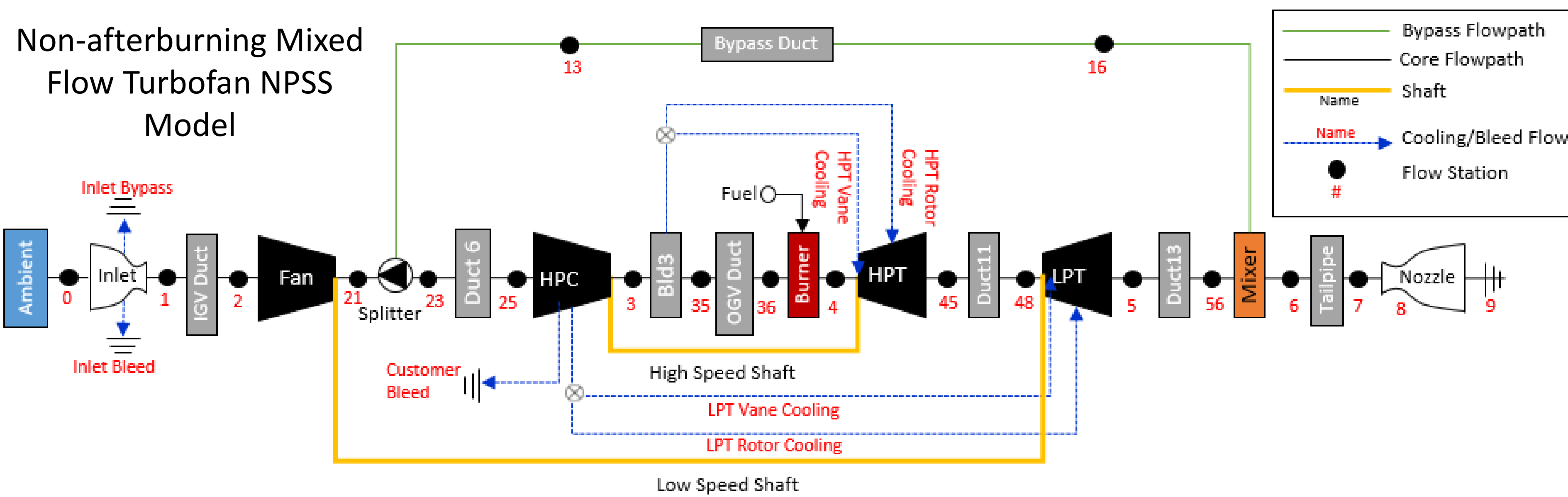


Supersonic Engine Modeling

- On-Design
  - Simultaneous multi-design point sizing
- Off-Design
  - Engine has 2 controls:
    1. fuel flow
    2. nozzle throat
  - For mission analysis:
    1. fuel flow controls thrust
    2. nozzle throat targets peak fan efficiency
  - For LTO noise analysis:
    1. Fuel flow still controls thrust
    2. At high power: nozzle throat used to keep airflow high and reduce jet speed and noise
    3. At low power: nozzle throat is used to reduce fan speed and fan noise

Engine Design Parameters
Fan Pressure Ratio
Overall Pressure Ratio
Design Turbine Rotor Inlet Temperature
Bypass Ratio
Max Turbine Rotor Inlet Temperature

Non-afterburning Mixed Flow Turbofan NPSS Model



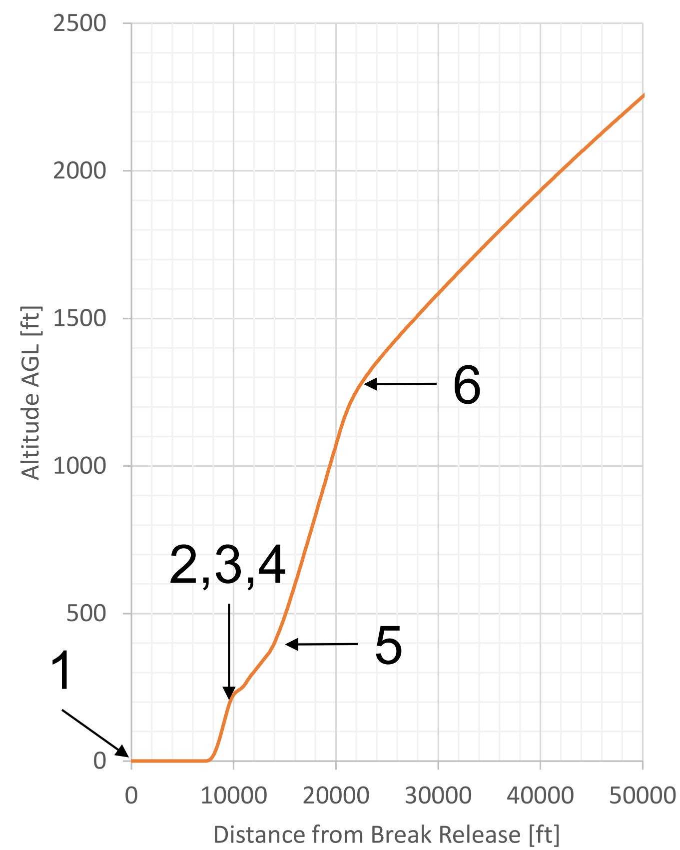
Variable Noise Reduction System (VRNS) Modeling

Programmed High Lift Devices

Generate Take-off & Landing Drag Polars (with multiple high lift device settings)

Trajectory Variables

1. Takeoff De-rate – initial reduction in thrust for takeoff
2. Programmed Lapse Rate – automatic reduction in thrust engaged after the obstacle
3. Target Flight Path Angle – reduced flight path to gain speed
4. Transition to Constant Thrust and Speed – maintain speed and gain altitude
5. Pilot Initiated Cutback

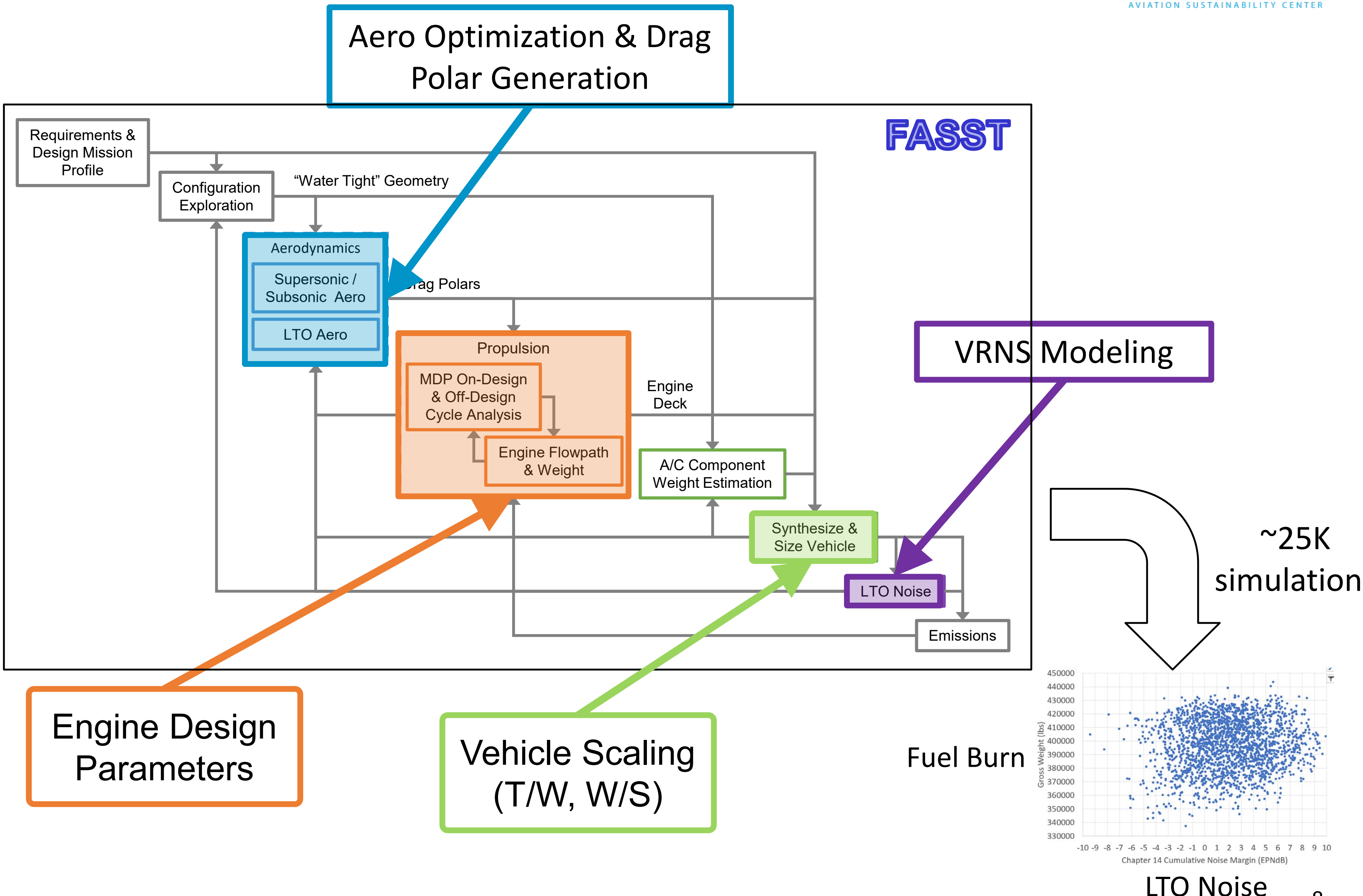


NASA FLOPS Detailed Take-off & Landing Analysis

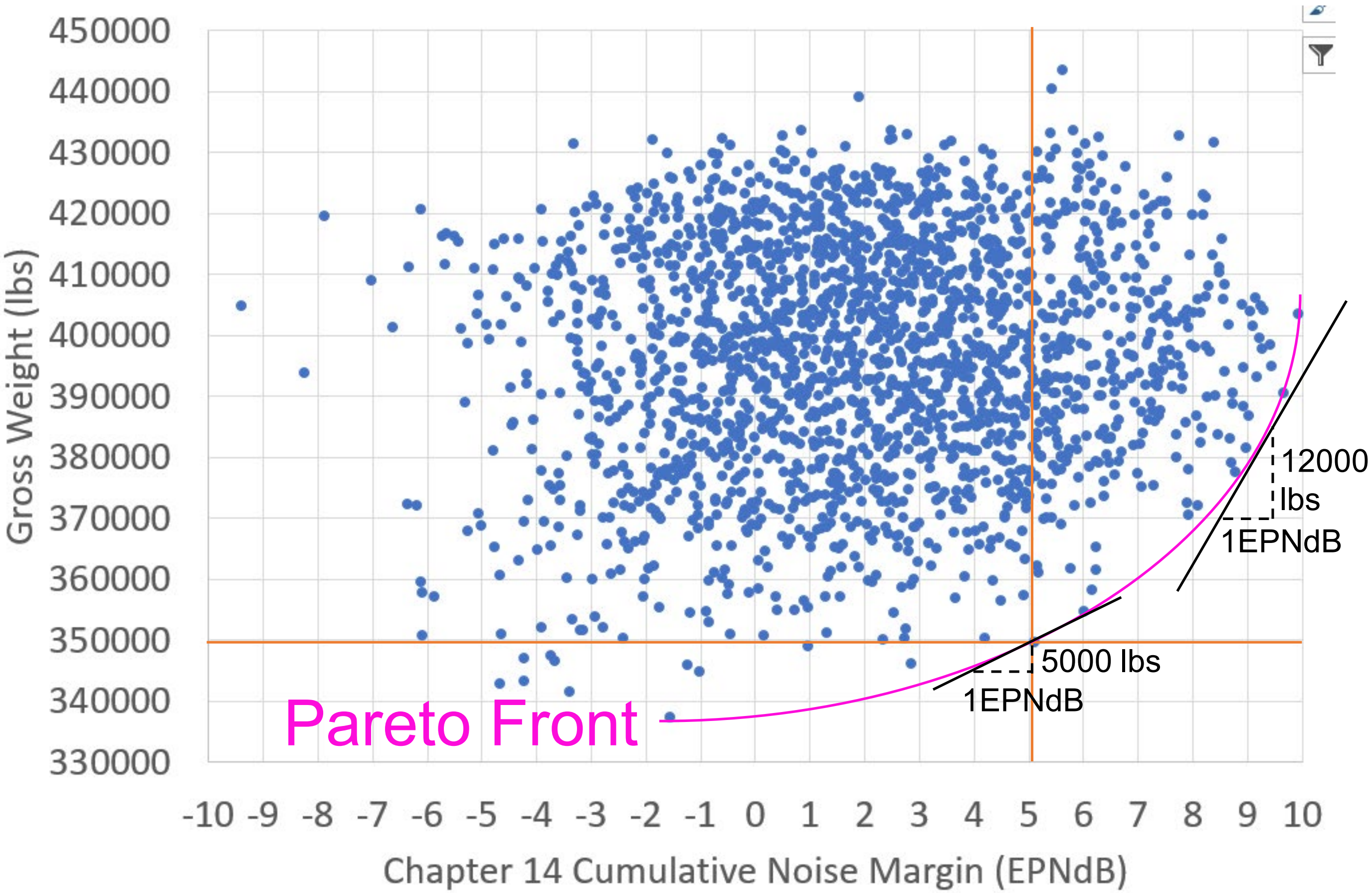
Take-off & Landing Trajectories

NASA ANOPP

Pareto Front Generation



65pax Mach 1.7 Pareto Front



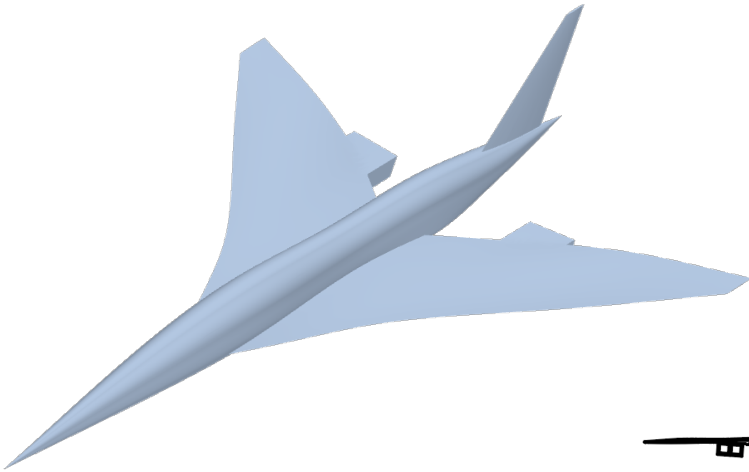
Highlighted Point Design Variables

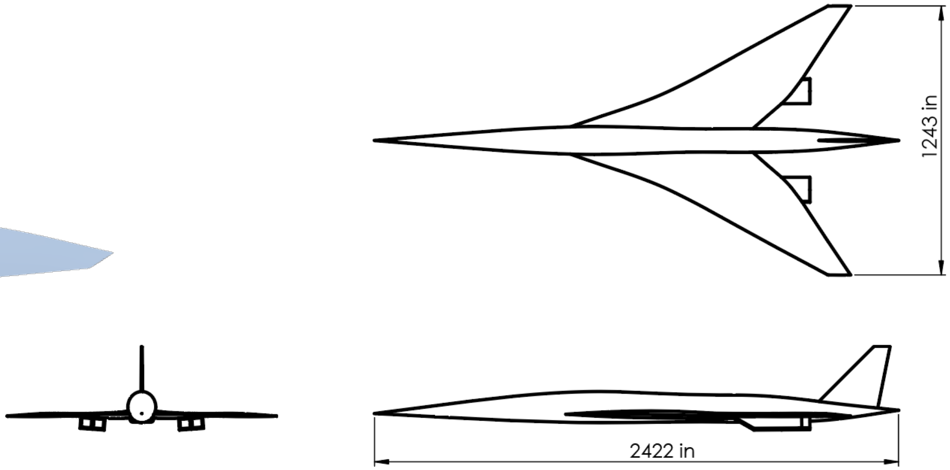
FPR = 2.09
OPR = 25
PNT2Nc=0.952
TOC_EXTR=1.03
TWR = 0.338
WSR = 82
VARTH = 0.93
PLR = 0.82
GFIX = 6
HSTOP1 = 370
HSTOP2 = 1150
HPT_desBladeTemp=1972
LPT_desBladeTemp = 2100
Fan_RSspacing=1.26

Preliminary Results – Do Not Quote

Highlighted design point predicts just over 5db of margin
The gross weight penalty needed to gain 1db of margin increases with margin

Current 65 Passenger M1.7 Design





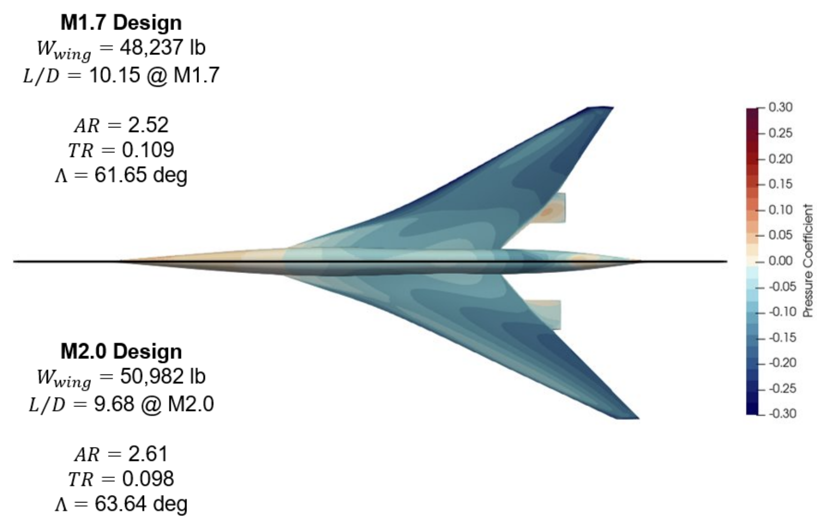
Preliminary Results – Do Not Quote

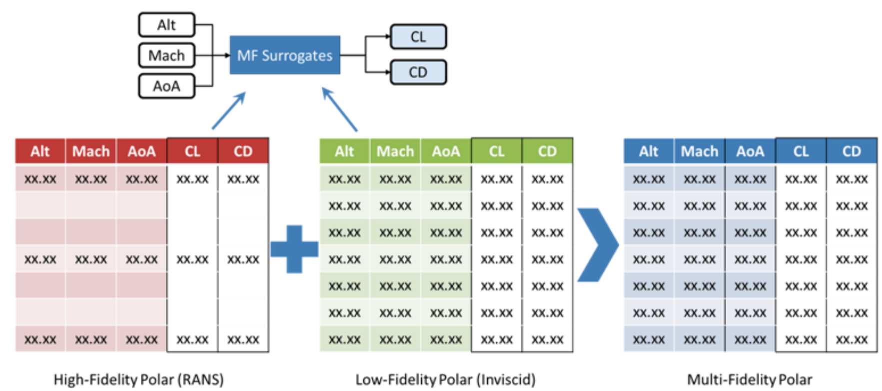
Metrics	Value
Ramp Weight (lb)	349,640
Block Fuel (lb)	132,740
Design Range (nmi)	4,250
Design Payload (no. of passengers)	65
Cumulative Noise / Ch.14 Margin (EPNdB)	281.4 / 5.1
Balanced Take-off Field Length (ft)	9,586
Landing Field Length (ft)	10,461
Approach Speed (kts)	164

Component	Weight (lb)
Wing	61,716
Vertical Tail	1,346
Fuselage	27,056
Landing Gear	13,385
Propulsion	41,560
Systems & Equipment	30,253
Empty Weight	**175,316**

Progress on 65 Pax Mach 2.0 Vehicle Development

- Define design variables and bounds
- Reduce dimensionality through gradient free active subspace techniques
- Improve L/D through RANS CFD based adaptive sampling
- Develop baseline multi-fidelity drag polar using numerous Euler cases and a strategic handful of RANS case
- Develop parametric multi-fidelity drag polar capturing impacts of changing planform area and capture area on performance
- Integrate multi-fidelity polars into FASST for vehicle mission analysis and engine cycle optimization





Summary Remarks

- Showcased following capabilities …
  - Aero shaped optimization process
    - Utilizing active subspace technique
  - Supersonic propulsion system modeling
  - Multi-fidelity and parametric drag polar generation process
  - VRNS modeling process
- Interdependencies between fuel burn and LTO noise (Ch.14 margin)
  - Varies along the Pareto Front
- Full flight modeling of SSTs in AEDT
  - Arrived at consensus on AEDT implementation requirements to address specific differences between SSTs and subsonic aircraft
  - Developed a plan for generating data packages for enabling full-flight SST modeling in AEDT
  - Generating data for NASA 55t STCA on a set of 4 high demand OD pairs for enabling first cut implementation of SSTs in AEDT
  - Developing Requirements and Scoping documents to lay out specifics of implementation plan for SMEs

Project 10

Aircraft Technology Modeling and Assessment

Georgia Institute of Technology &

Purdue University

PI: William Crossley, Daniel DeLaurentis (Purdue)

PM: Sandy Liu

Cost Share Partner(s): Purdue University, OAG

Objective: Model and assess potential evolution of commercial airline fleet due to the introduction of future supersonic aircraft and how technology development could affect the environmental impacts of aviation (e.g., fleet-level fuel burn, emissions and noise). *The effort will examine **SST vehicle modeling; fleet route simulation; fleet simulation, and AEDT supersonic modeling.***

Project Benefits: Provide an understanding of how introduction of new supersonic transports that could enter into commercial airline service and private use will affect fleet-wide fuel burn, noise and emissions.

Research Approach:

- Use Fleet-Level Environmental Evaluation Tool (FLEET) to model airline operations and predict evolution of fleet utilization along with environmental impacts
- Purdue's three major tasks for current effort:
  - Expanding FLEET's US-touching route network to a global network
  - Assess impact of introducing SST into airline fleet for a variety of demand evolution scenarios
  - Develop prototype business jet analog to FLEET to analyze the fleet-level impacts of supersonic business jet aircraft

Major Accomplishments (to date):

- Development of alternate aircraft cost estimation models to replace FLOPS capabilities
- Update of historical airline operations from 2005 to 2011 baseline
- Expansion of FLEET airline model from US-touching network to worldwide
- Preliminary model of business-jet operations

Future Work / Schedule:

- Conduct FLEET simulations based on a global route network
- Continue development of business jet analog to FLEET

This research was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 10 through FAA Award Number 13-C-AJFE-PU under the supervision of Sandy Liu. Any opinions, findings, conclusions or recommendations expressed in this this material are those of the authors and do not necessarily reflect the views of the FAA.

Fleet-Level Environmental Evaluation Tool (FLEET) and Supersonic Demand Prediction – Purdue

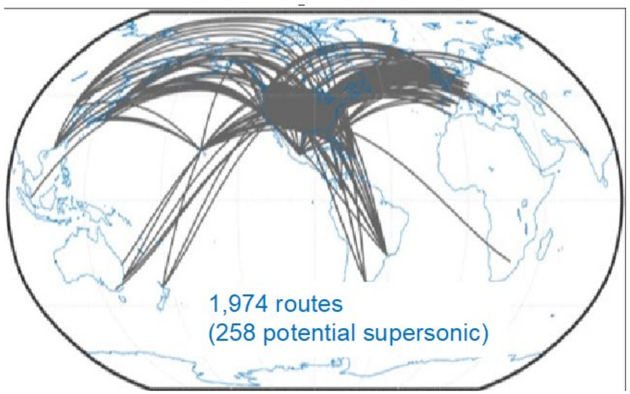
- FLEET is a system dynamics-inspired simulation tool to evolve airline fleet, passenger demand, and environmental impacts over time
  - Maximize profit while allocating aircraft on routes to meet passenger demand
  - Introduce technologically advanced aircraft and retire aircraft from the fleet
  - Explore environmental and operational impacts of demand and fleet evolution
- ASCENT Project 10:
  - Introduce supersonic aircraft to FLEET
    - Assume 5% of passengers on a route are business class or above travelers, based on data for historic domestic flights – these are potential passengers
    - Identify potential routes for supersonic operations
    - Consider an A10 Notional Medium SST (55-seat) provided by Georgia Tech colleagues, with performance and block time and fuel coefficients from FLOPS, ground path of route flown from GT's algorithm
    - Expand analysis to worldwide airline network of operations and update historical travel from 2005 to 2011 baseline
  - Expand FLEET to model business jet operations

Supersonic demand includes both passenger demand and routes

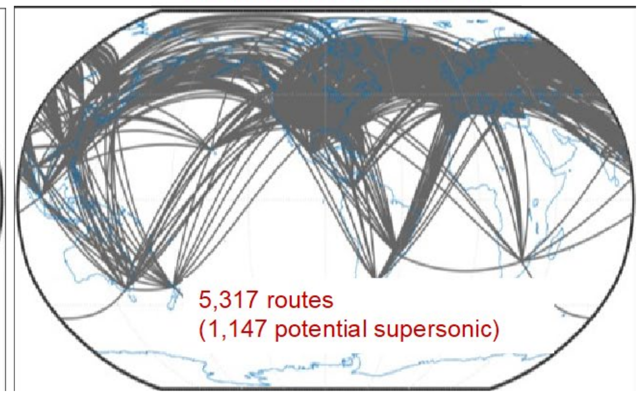
FLEET Route Network Update

- Utilize OAG data to expand airline network from US-touching to Worldwide
  - Move analysis baseline from 2005 to 2011; estimate fleet size and mix for worldwide airline operations
  - Update historical demand to 2019 and model COVID impact and recovery on travel demand
- Estimate fleet evolution and projected emissions

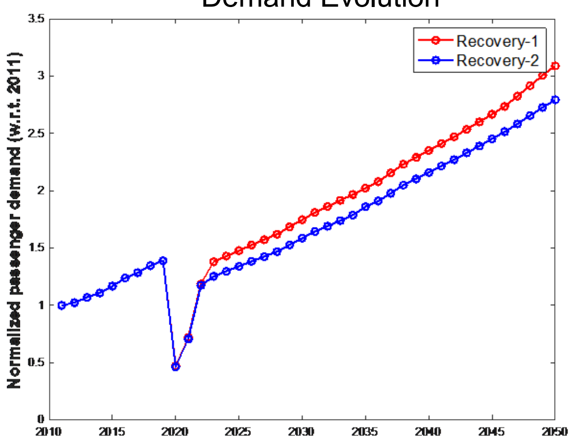
"US-touching" route network



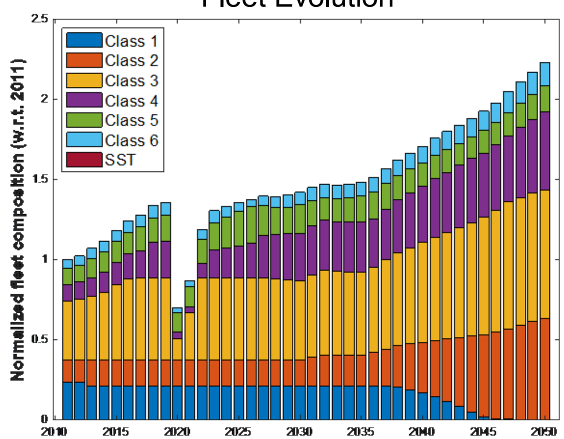
Worldwide route network



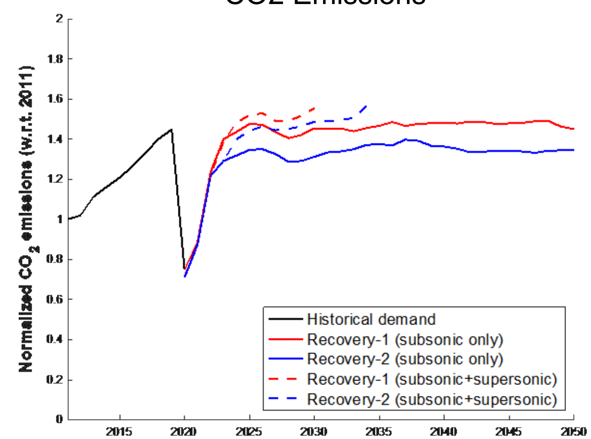
Demand Evolution



Fleet Evolution

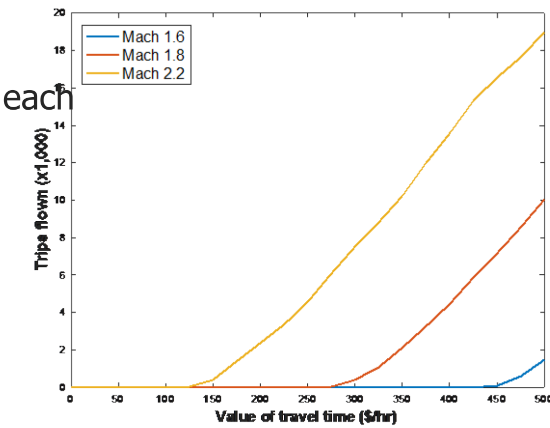


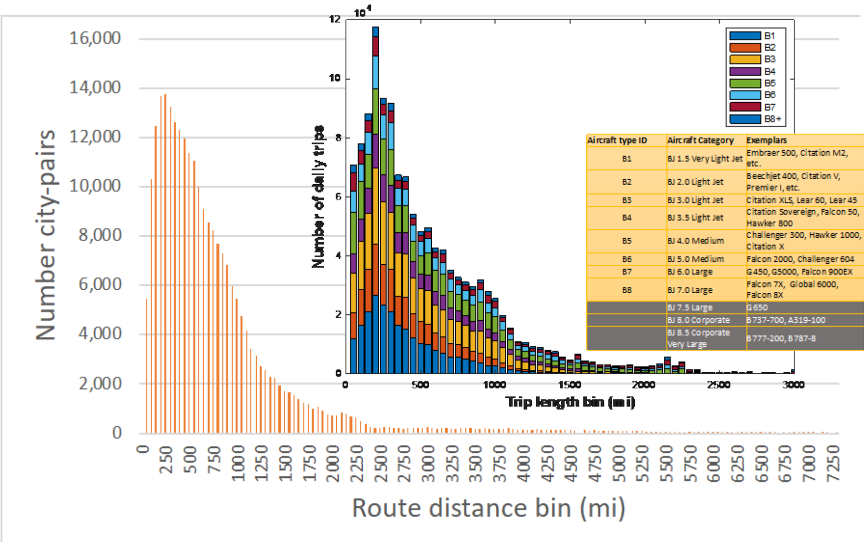
CO2 Emissions



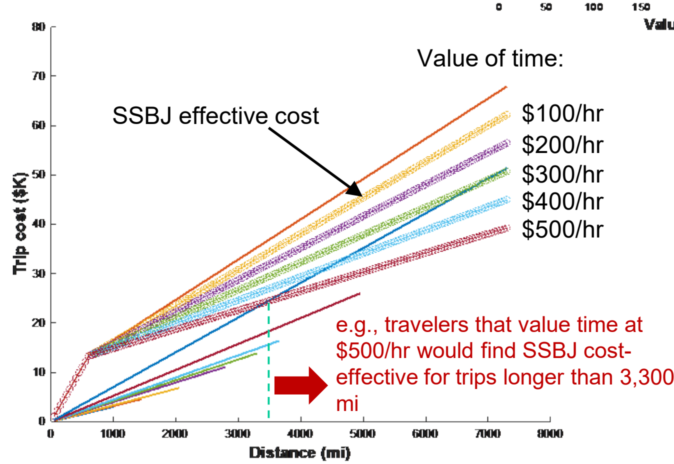
FLEET Model of Business Jet Operations

- Model activity of 217 companies that provide provide 50% of service (more than 4 trips per day): **4,417 airports; 167,488 city-pairs; 1,302,639 trips**
- Group city-pairs into ”route bins” simplifies modeling
- Model different types of operators, e.g.
  - Fractional operators must provide service (meet demand) with specific aircraft types and high trip frequency
  - Corporate operators must meet demand with the aircraft that they own and can have infrequent flights
- Identify SSBJ fleet size and utilization based on value of travel time savings for each operator





Aircraft type ID	Aircraft Category	Exemplars
B1	BJ 1.5 Very Light Jet	Embraer 500, Citation M2, etc.
B2	BJ 2.0 Light Jet	Beechjet 400, Citation V, Premier I, etc.
B3	BJ 3.0 Light Jet	Citation XLS, Lear 60, Lear 45
B4	BJ 3.5 Light Jet	Citation Sovereign, Falcon 50, Hawker 800
B5	BJ 4.0 Medium	Challenger 300, Hawker 1000, Citation X
B6	BJ 5.0 Medium	Falcon 2000, Challenger 604
B7	BJ 6.0 Large	G450, G5000, Falcon 900EX
B8	BJ 7.0 Large	Falcon 7X, Global 6000, Falcon 8X
	BJ 7.5 Large	G650
	BJ 8.0 Corporate	B737-700, A319-100
	BJ 8.5 Corporate Very Large	B777-200, B787-8

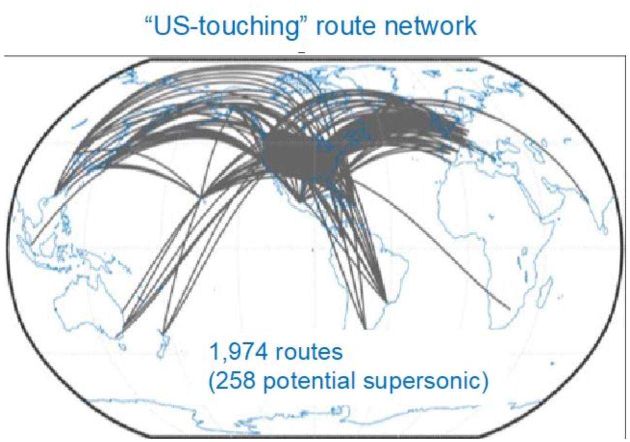


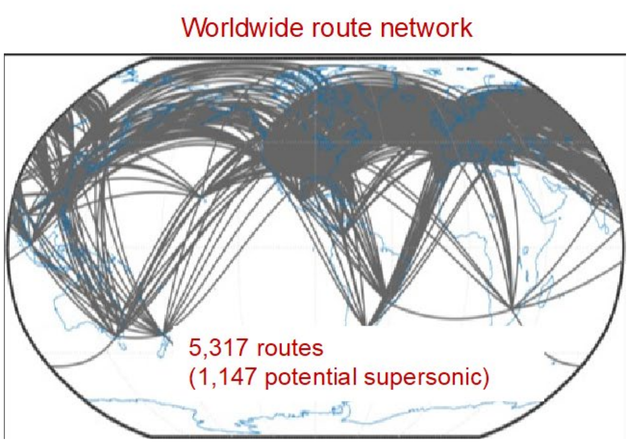
MORE DETAILS (NEXT SLIDES)…

17

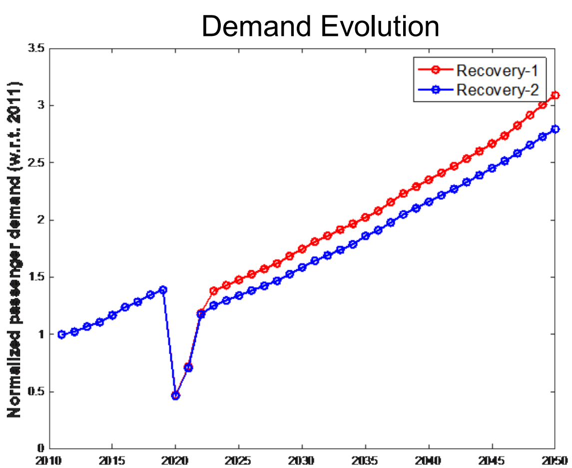
FLEET Route Network Update

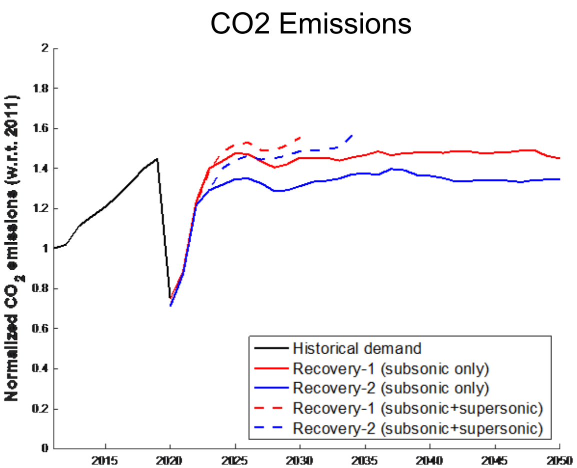
- Utilize OAG data to expand airline network from US-touching to Worldwide
  - Move analysis baseline from 2005 to 2011; estimate fleet size and mix for worldwide airline operations
  - Update historical demand to 2019 and model COVID impact and recovery on travel demand
- Estimate fleet evolution and projected emissions

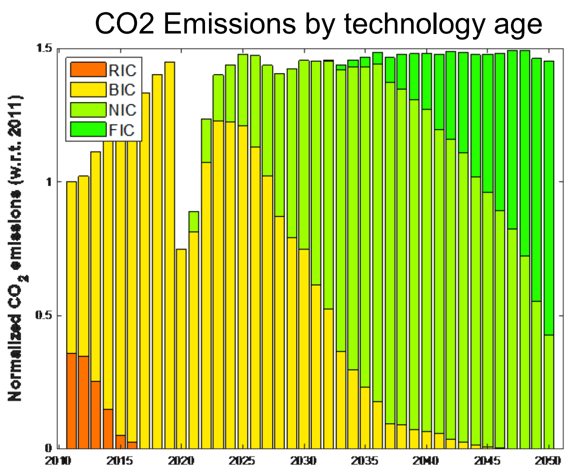




RIC: representative in class
BIC: best in class
NIC: new in class
FIC: future in class

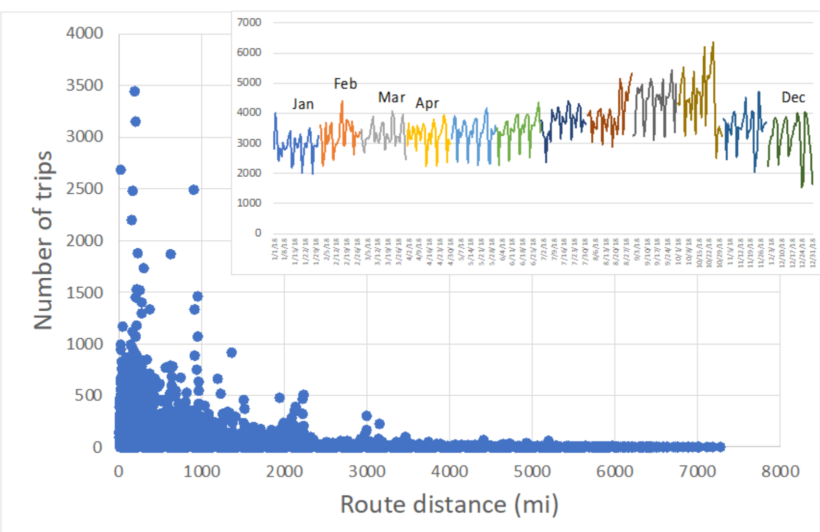




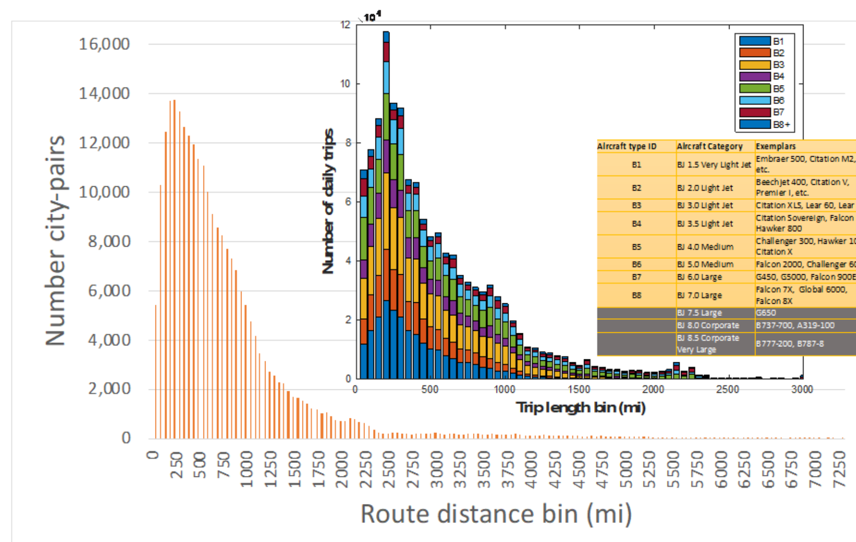


Identify Level of Abstraction Necessary to Model Business Jet Operations

- Model activity of 217 companies that provide provide 50% of service (more than 4 trips per day): **4,417 airports; 167,488 city-pairs; 1,302,639 trips**
- Group city-pairs into "route bins" simplifies modeling
- Model different types of operators, e.g.
  - Fractional operators must provide service (meet demand) with specific aircraft types and high trip frequency
  - Corporate operators must meet demand with the aircraft that they own and can have infrequent flights
- Identify SSBJ fleet size and utilization based on value of travel time savings for each operator



Binned routes

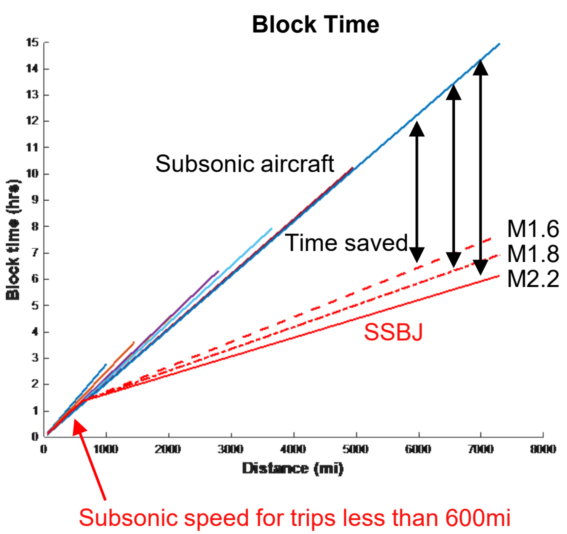


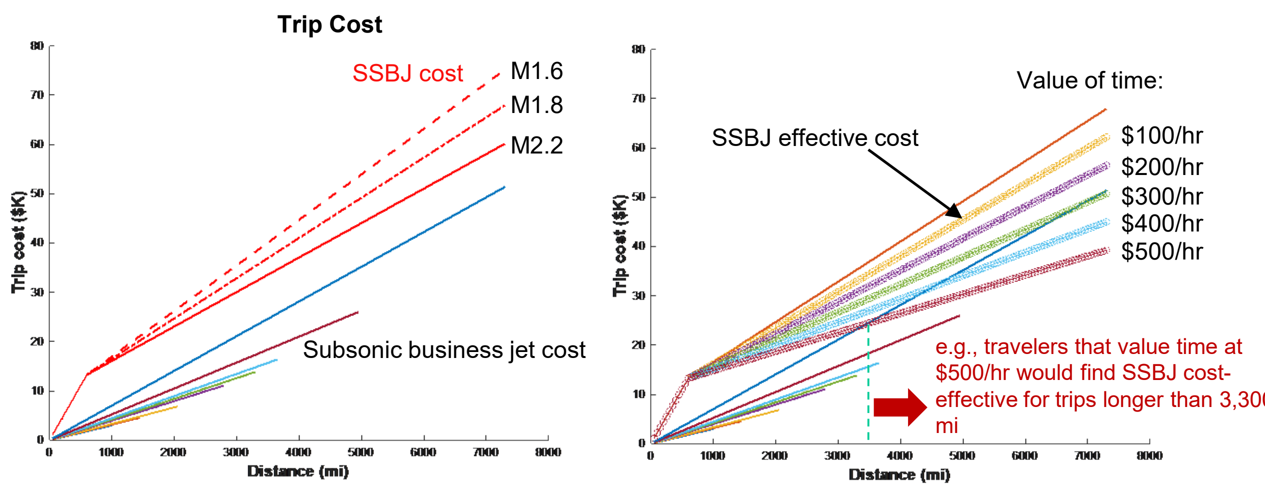
Aircraft type ID	Aircraft Category	Exemplars
B1	BJ 1.5 Very Light Jet	Embraer 500, Citation M2, etc.
B2	BJ 2.0 Light Jet	Beechjet 400, Citation V, Premier I, etc.
B3	BJ 3.0 Light Jet	Citation XLS, Lear 60, Lear 45
B4	BJ 3.5 Light Jet	Citation Sovereign, Falcon 50, Hawker 800
B5	BJ 4.0 Medium	Challenger 300, Hawker 1000, Citation X
B6	BJ 5.0 Medium	Falcon 2000, Challenger 604
B7	BJ 6.0 Large	G450, G5000, Falcon 900EX
B8	BJ 7.0 Large	Falcon 7X, Global 6000, Falcon 8X
	BJ 7.5 Large	G650
	BJ 8.0 Corporate	B737-700, A319-100
	BJ 8.5 Corporate Very Large	B777-200, B787-8

Use Value of Travel Time as Differentiator Between Subsonic and Supersonic Service

- SSBJ provides time savings w.r.t. subsonic aircraft
  - We've assumed that aircraft would fly supersonic only if distance is greater than 600 mi here (to be refined later on)
- Cost to operate SSBJ is higher than cost to operate subsonic aircraft
  - We've made assumptions about SSBJ cost (to be refined later)
- Time savings of flying the faster SSBJ can be considered cost savings, depending on the value of travel time
- Consider different values of travel time and the effective cost of SSBJ
  - Effective cost = Cost – travel time savings

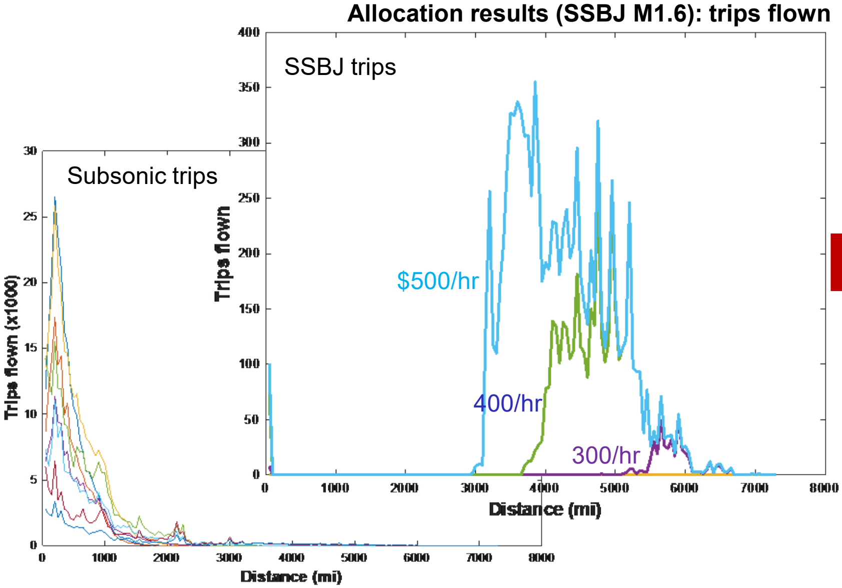
$$savings_{c,j} = \left[(tt_{sub})_{c,j} - \left(tt_{sup}\right)_{c,j}\right] \times (value\ of\ time)_c$$

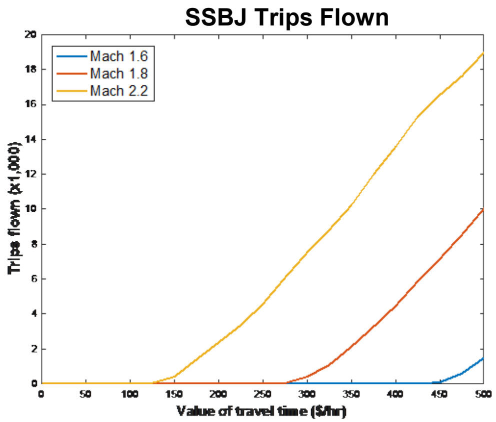


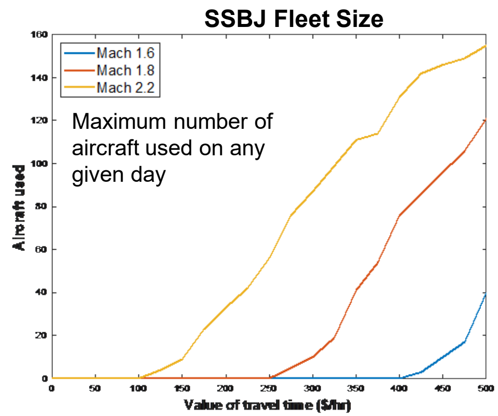


Capability Demonstration Using SSBJ and Identifying Cost-Effective Routes / Service

- Let allocation problem determine which routes to serve with SSBJ
  - Make allocation decisions based on effective trip cost
- Allocation problem can identify cost-effective routes and estimate fleet size used to satisfy demand

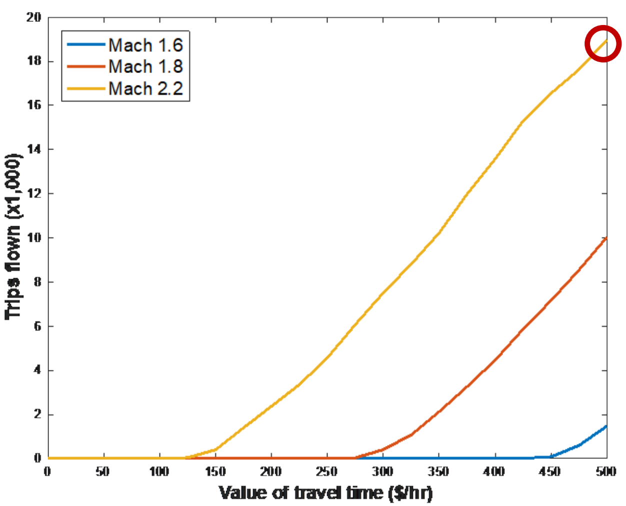


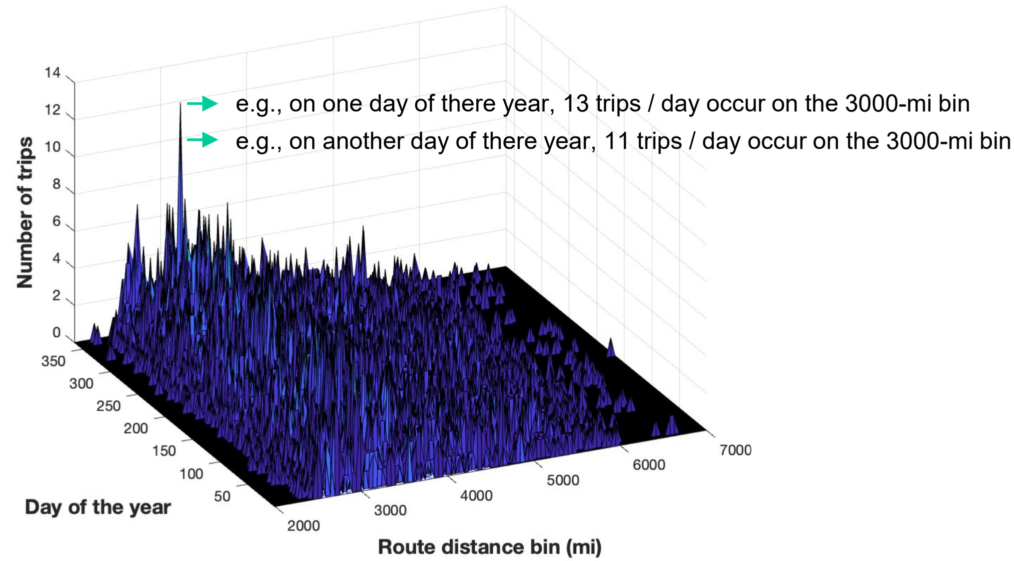




Preliminary Assessment of Noise Impact

- Analyze the number of trips on each route distance-bin (city-pair)
  - Identify city-pairs and airports that could be origin and destinations
- Identify upper bound on the expected number of SSBJ operations and potential airports affected
  - Surrogate for potential noise impact





- At most 13 trips (landings and takeoffs) occur between city-pairs that are 3,000 mi apart
- 156 city-pairs fall in this route distance-bin (from OAG data)
- 152 unique airports make up these 156 city-pairs
  → At most 152 airports would see a maximum of 13 SSBJ takeoff and landings