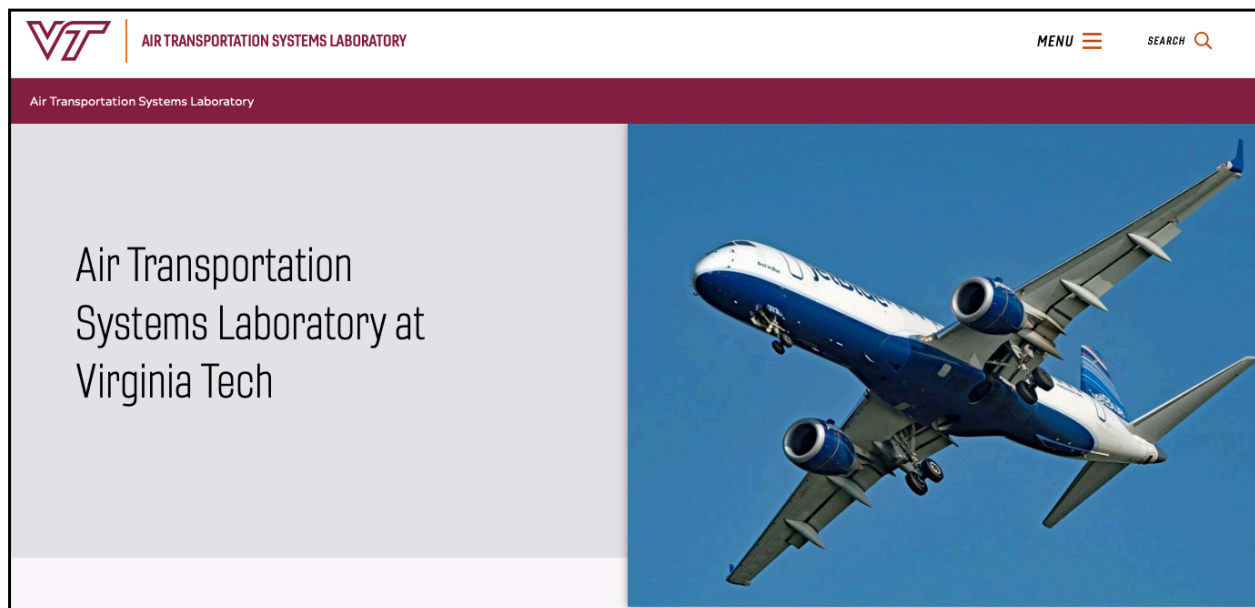
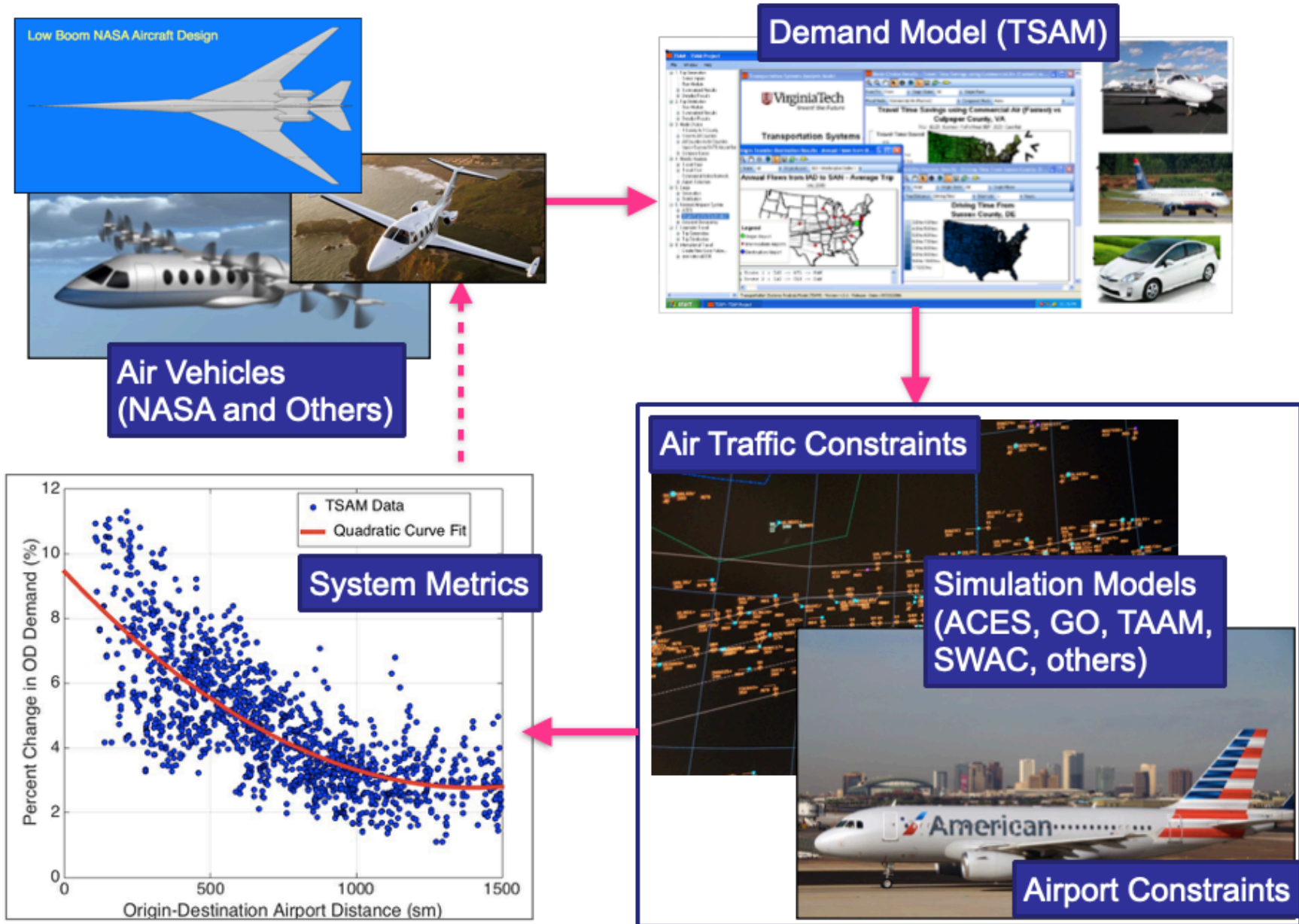


Recent Air Transportation Demand Modeling in the Air Transportation Systems Laboratory



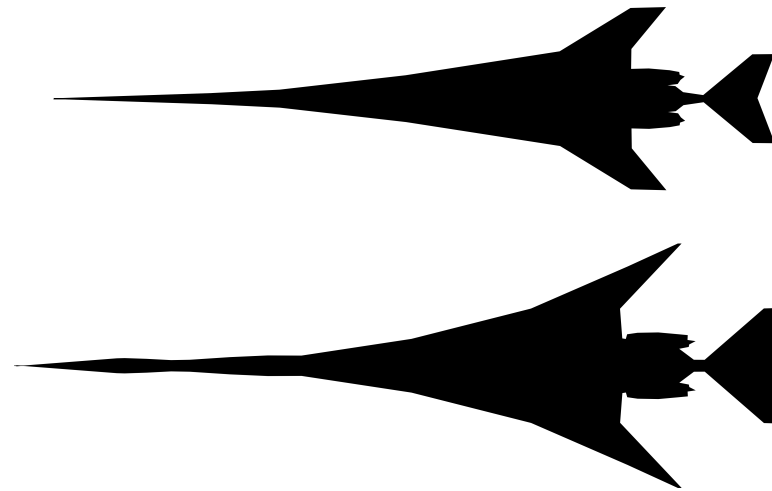
Presented by: A.A. Trani
Air Transportation Systems Laboratory
Virginia Tech
May 2, 2023

Air Transportation Systems Analysis





Supersonic Air Transportation Demand Modeling



Z. Wang, N. Hinze, and A.A. Trani
Air Transportation Systems Laboratory
Virginia Tech
March 15, 2023



Acknowledgements

- Virginia Tech would like to acknowledge the technical and financial support of the following individuals and organizations:
- Ty Marien (NASA Langley Research Center)
- Jonathan Seidel (NASA Glenn Research Center)
- Wu Li (NASA Langley Research Center)
- Karl Geiselhart (NASA Langley Research Center)
- Sam Dollyhigh (Contractor to NASA Langley)
- National Institute of Aerospace (NIA)



Project Objectives

- Estimate worldwide demand of various low-boom and non low-boom supersonic aircraft concepts including worldwide network modeling effects including:
 - Aircraft fleet size
 - Airport curfews
 - Runway length limitations
- Develop models to predict optimized supersonic fleet network utilization
- Integrate the technical outputs of FLOPS into a model that permits NASA engineers to quantify changes in potential markets for various supersonic aircraft concepts
- Model is written in MATLAB TM

MATLAB is a trademark of the Mathworks



Supersonic Aircraft



British/ French Concorde
Mach 2.0 (more than twice the speed of regular subsonic aircraft)
110 passengers
First Flight: 1969

Source: <https://www.baesystems.com/en/heritage/bac-concorde>



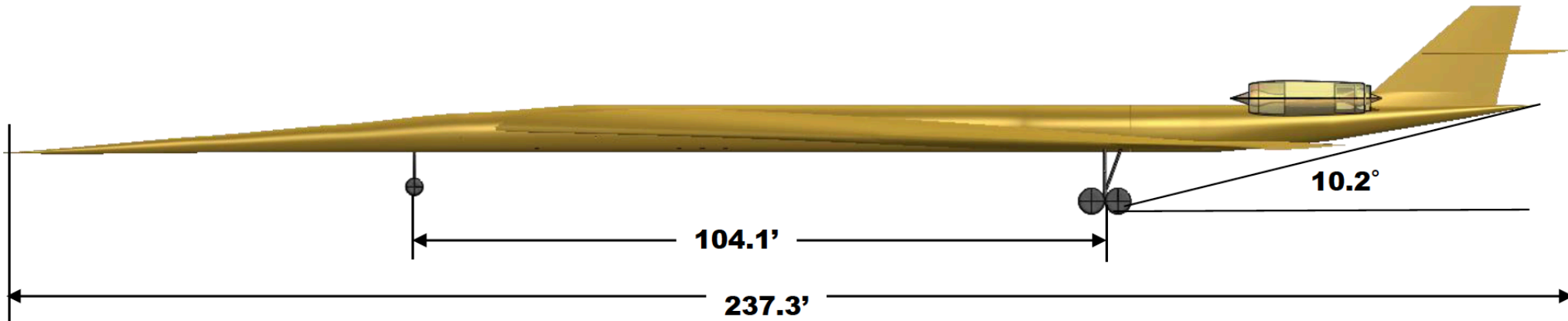
Boom Overture
Mach 1.7
65 passengers
First Flight: 2029
(Estimated)

Source: <https://boomsupersonic.com/overture>

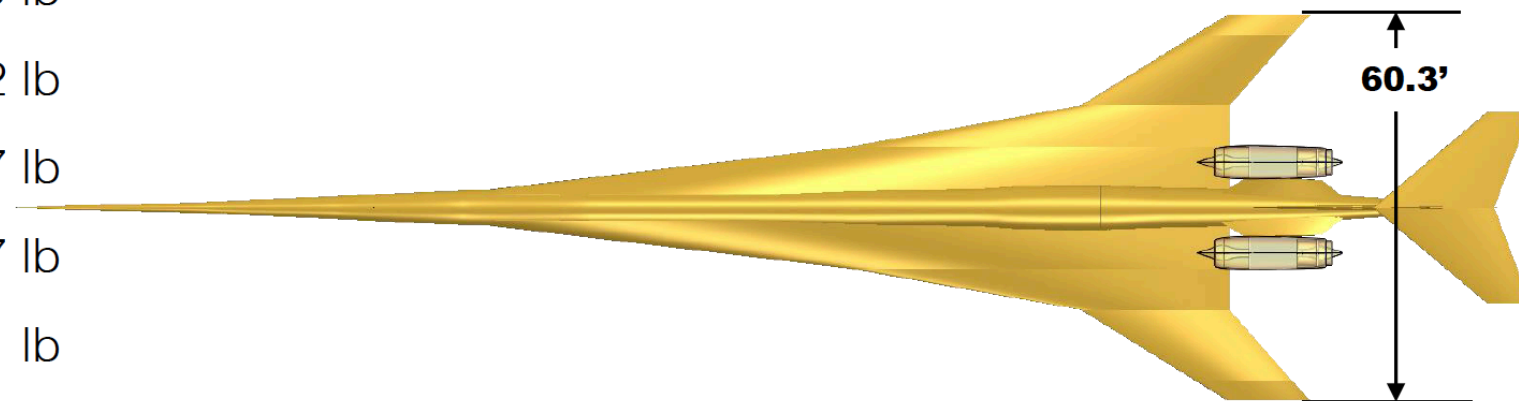
- Concorde and Overture are traditional supersonic designs
- Traditional supersonic aircraft generate strong shock waves that create unacceptable pressures on the ground



NASA 43- Passenger Low-Boom Aircraft

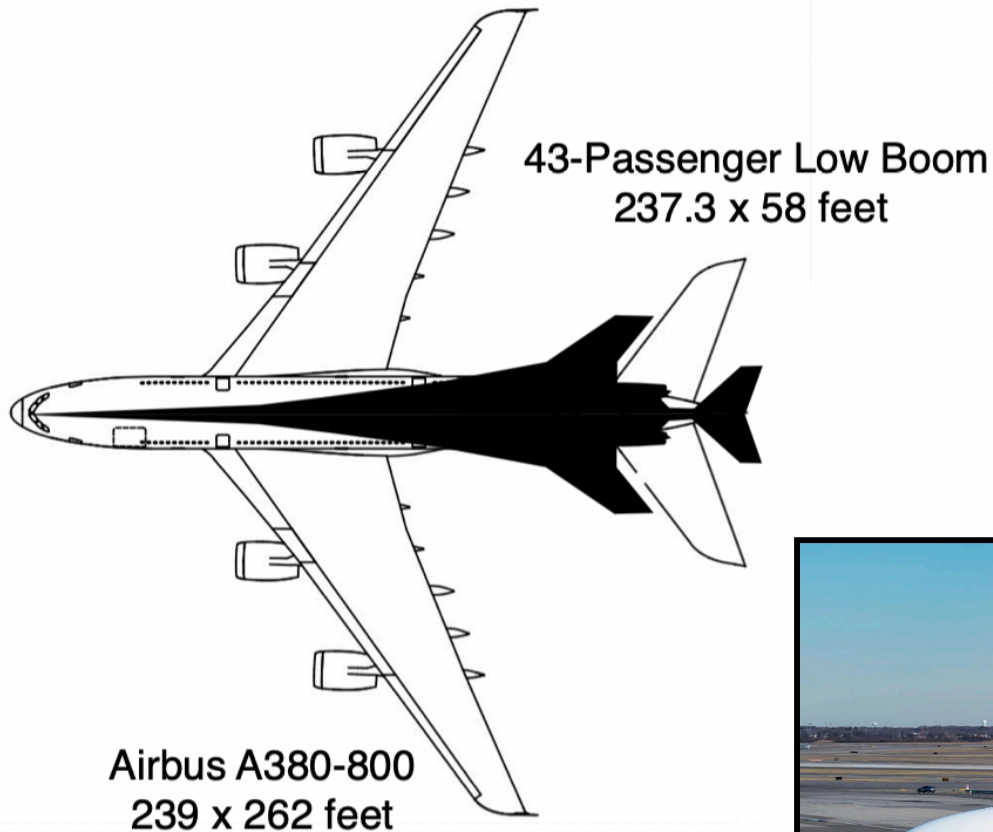


Wing Area	2,917 ft ²
MTOGW	154,510 lb
OEW	69,072 lb
Payload	8,987 lb
Max Fuel	79,887 lb
Block Fuel	70,571 lb
ATA Range	3,000 nmi





The Low-Boom Aircraft is as Long as the Airbus A380



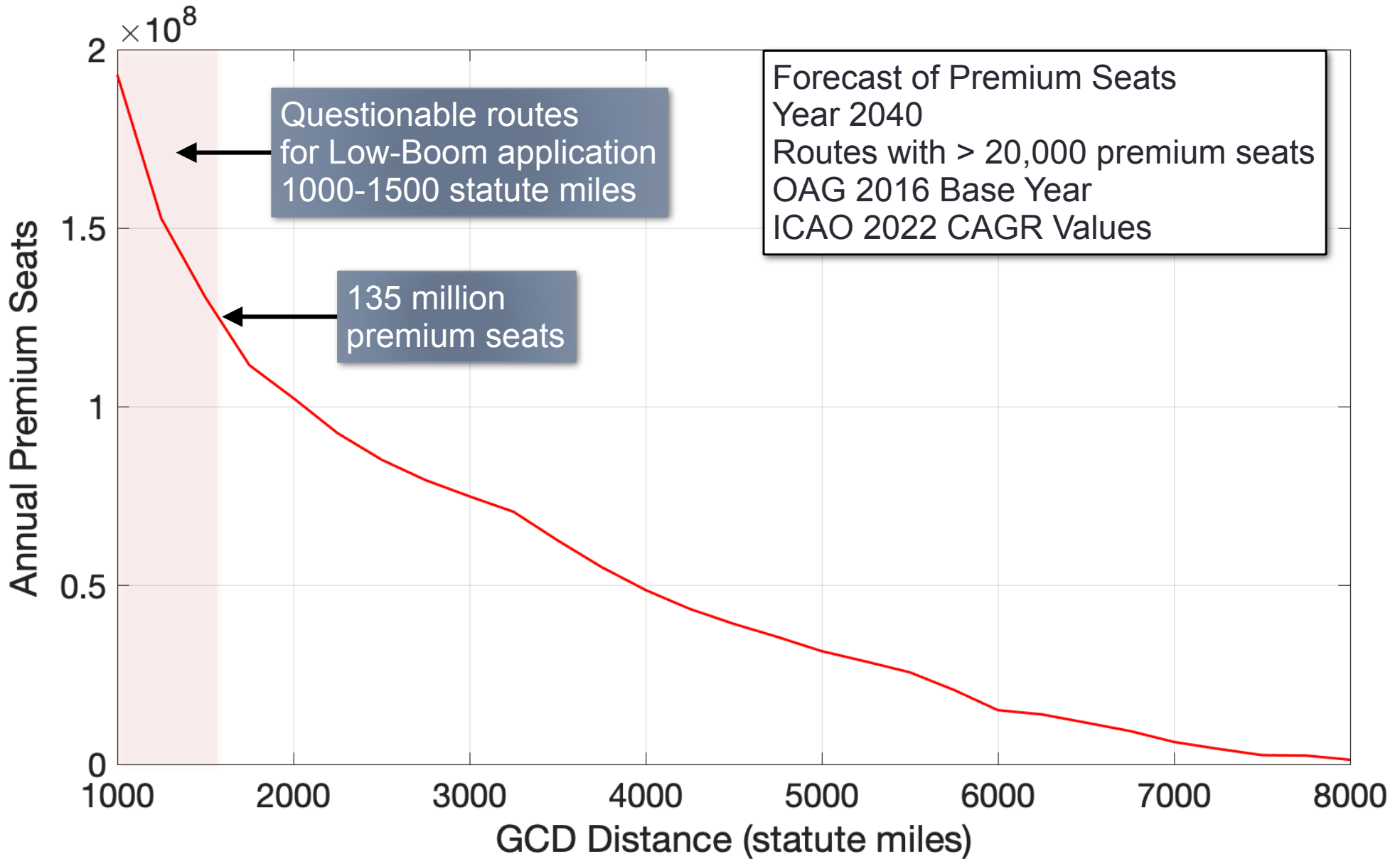
Supersonic flight requires large fuselage lengths and small cross sectional area to reduce drag

Airbus A380-800 (520 passengers typical)



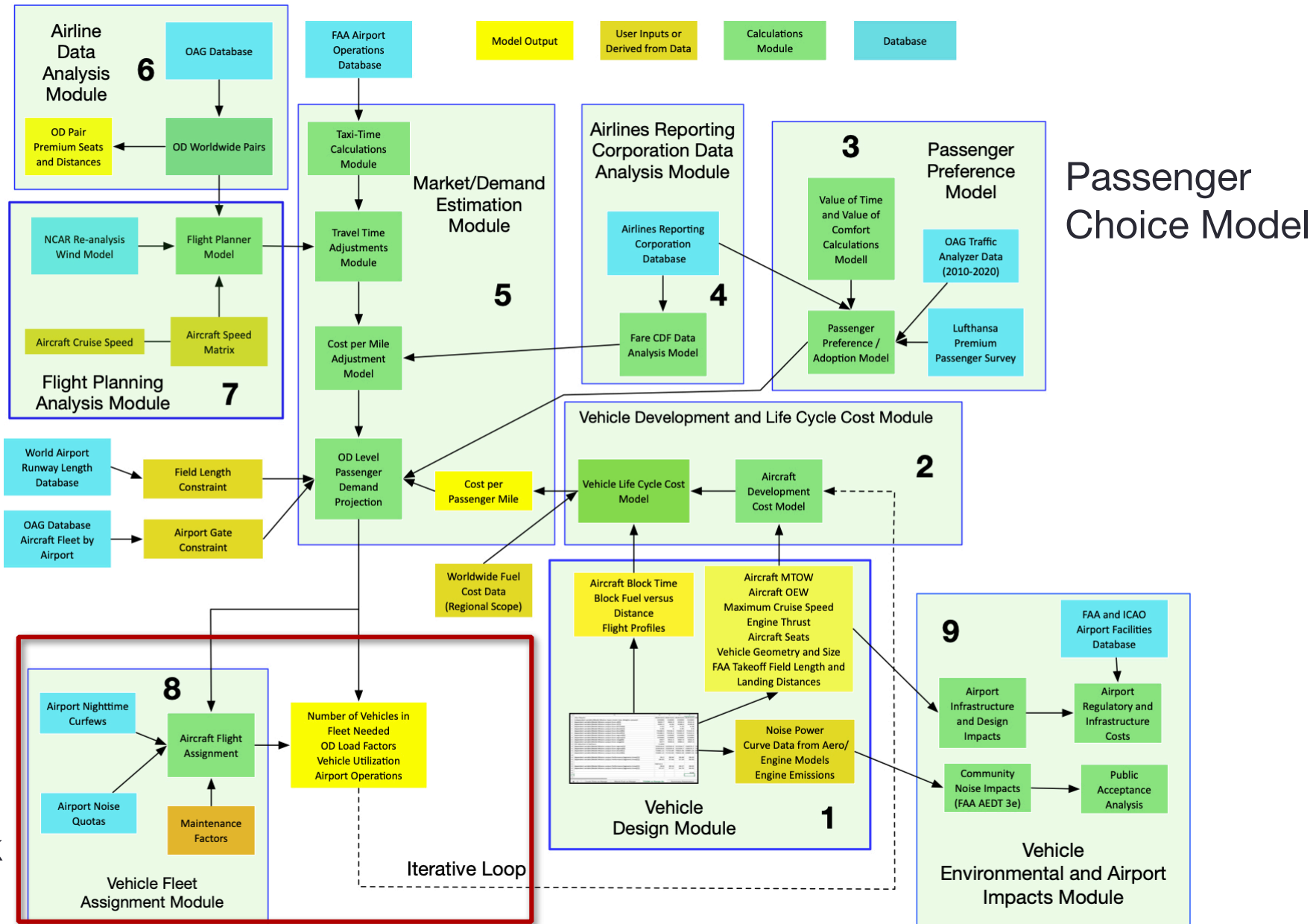


Market of Premium Seats versus Distance





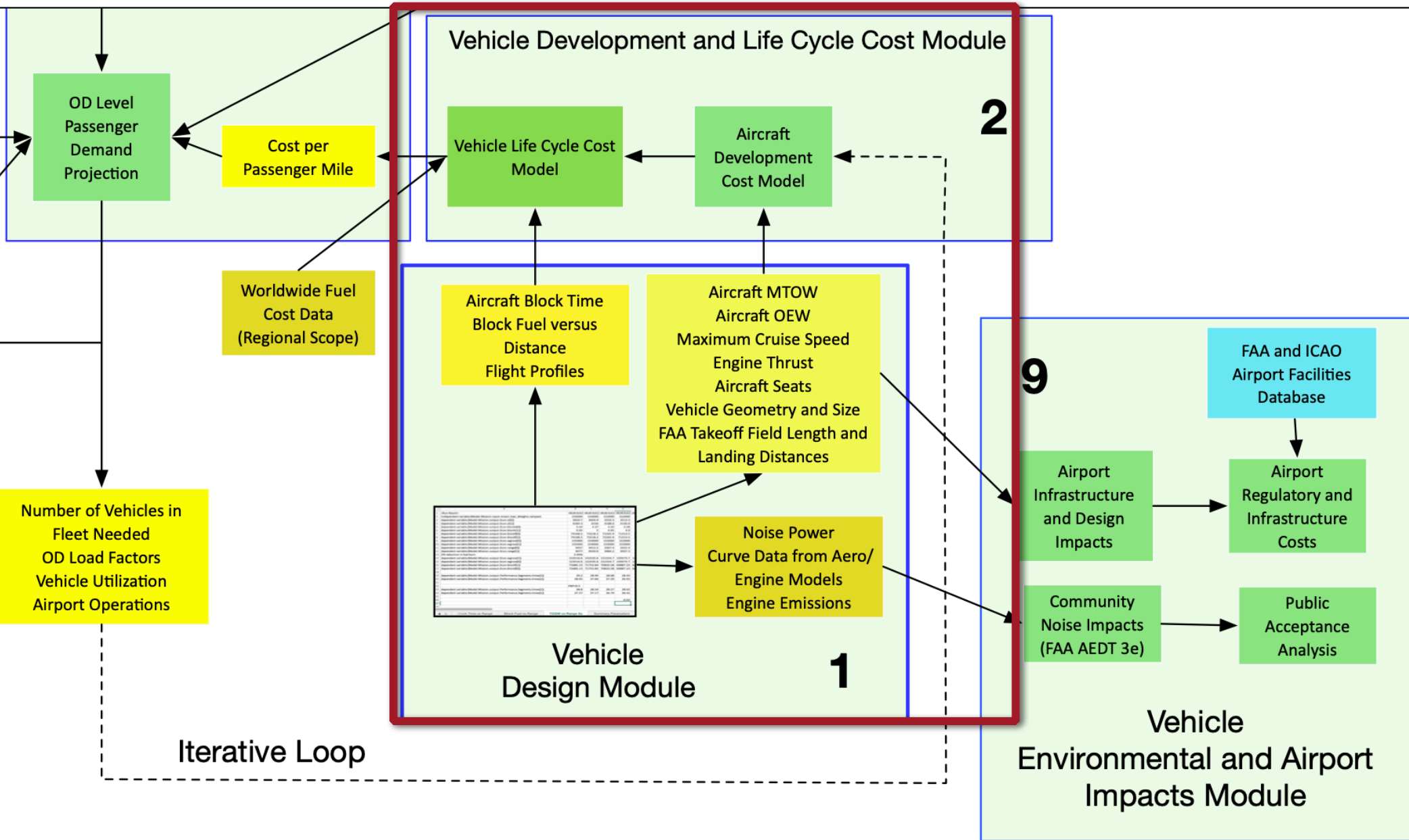
LBSAM2 Model Uses an Iterative Procedure to Estimate Air Transportation Demand



Flight Scheduling Analysis and Network Module



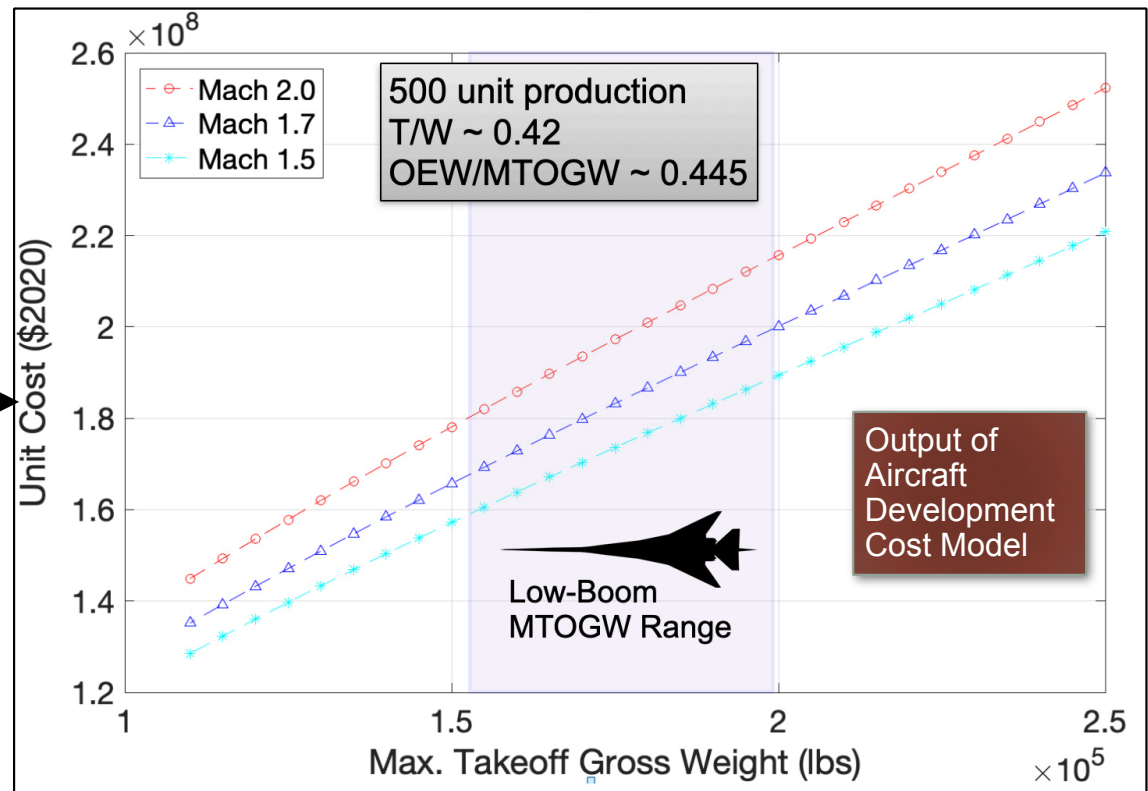
Vehicle Development and Life Cycle Cost Module



Aircraft Development Cost Module

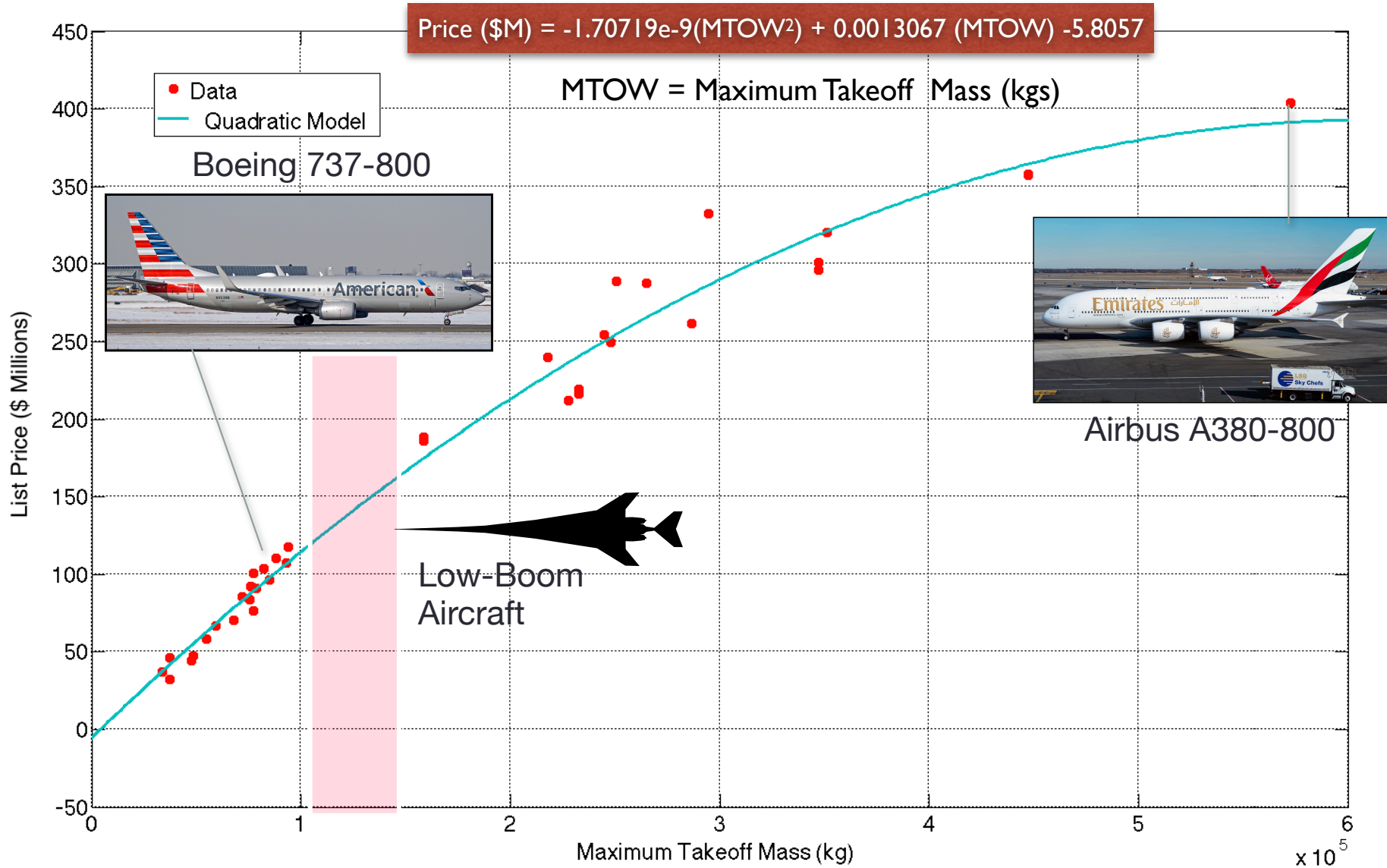
- Aircraft speed, quantity produced, takeoff and empty weights, and other technical parameters produced by FLOPS are used to estimate the vehicle development costs using non-linear regression equations adapted from a RAND cost model
- An operational aircraft life cycle cost model is used to estimate the Cost per Passenger Mile (CPM) based on the initial vehicle cost estimate
- The CPM cost is used by the **Passenger Choice and Market Demand modules**

NASA Design Model FLOPS Model Output		
	178450	177250
Tr	4619.7	4573.8
Pe	4802.8	4756.1
Pe	5.19	5.15
Pe	5.4	5.35
PostFLOPS.Ae.LowBoomMission.output.Econ.blockt[1]	90499.7	89335.1
PostFLOPS.Ae.LowBoomMission.output.Econ.blockf[0]	90499.7	89335.1
PostFLOPS.Ae.LowBoomMission.output.Econ.blockf[1]	178450	177250
PostFLOPS.Ae.LowBoomMission.output.Econ.wgross[0]	178450	177250
PostFLOPS.Ae.LowBoomMission.output.Econ.wgross[1]	4619.7	4573.8
PostFLOPS.Ae.LowBoomMission.output.Econ.range[0]	4802.8	4756.1
PostFLOPS.Ae.LowBoomMission.output.Econ.range[1]	67783	67783
PostFLOPS.Ae.LowBoomMission.input.missin.User_Weights.dowe	1.8	1.8
PostFLOPS.Ae.LowBoomMission.input.missin.Cruise.crmach[0]	1.8	1.8
PostFLOPS.Ae.LowBoomMission.input.rerun0.missin.Cruise.crmach[0]	36000	36000
TopLevelInputs.OtherDV.Thrust	9614	9614
PostFLOPS.Ae.LowBoomMission.input.missin.User_Weights.payload	4620	4620
PostFLOPS.Ae.LowBoomMission.input.confir.Basic.desrng	4802	4802
PostFLOPS.Ae.LowBoomMission.input.rerun0.desrng	70.39	70.33
Signature.sBoom.sBoom_Loudness.Loudness.PLdB		





Aircraft Cost (Reality Check)

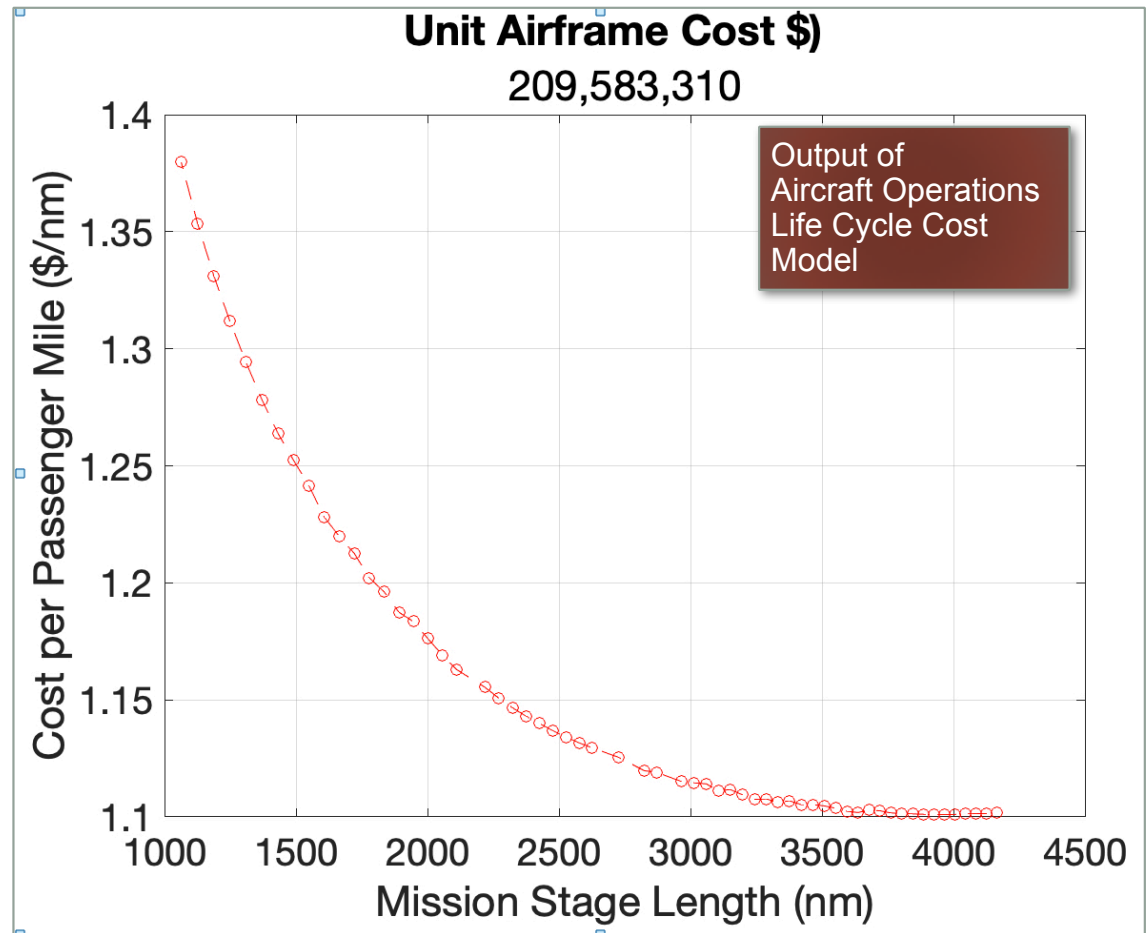




Aircraft Operations Life Cycle Cost Module

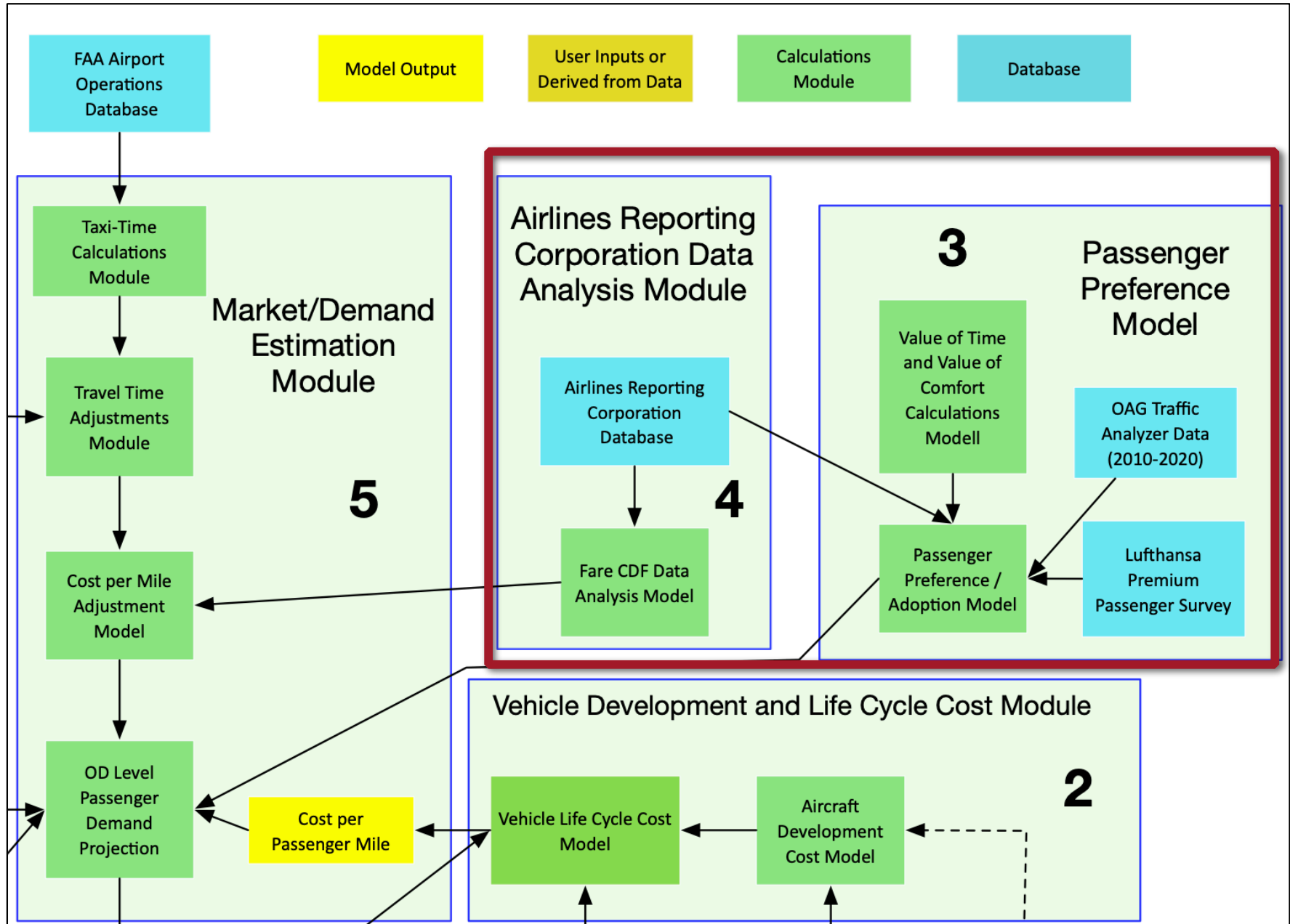
Supersonic aircraft operations life-cycle cost model include the following:

- Vehicle unit cost
- Number of annual operations
- Maintenance hours per flight hour
- Engine overhaul costs
- Time between overhauls
- Landing fee per landing
- Percent of repositioning flights
- Stage length flown
- Fuel consumption and fuel cost
- Hangar cost
- Crew and maintenance personnel
- Avionics and interior refurbishing costs
- Load factor per flight
- Depreciation
- Life-cycle time
- Landing fees and ground handling costs
- Airport emission fees
- Navigation fees
- Insurance costs (liability and hull)
- Taxes airline passenger facility fees





Passenger Preference Module





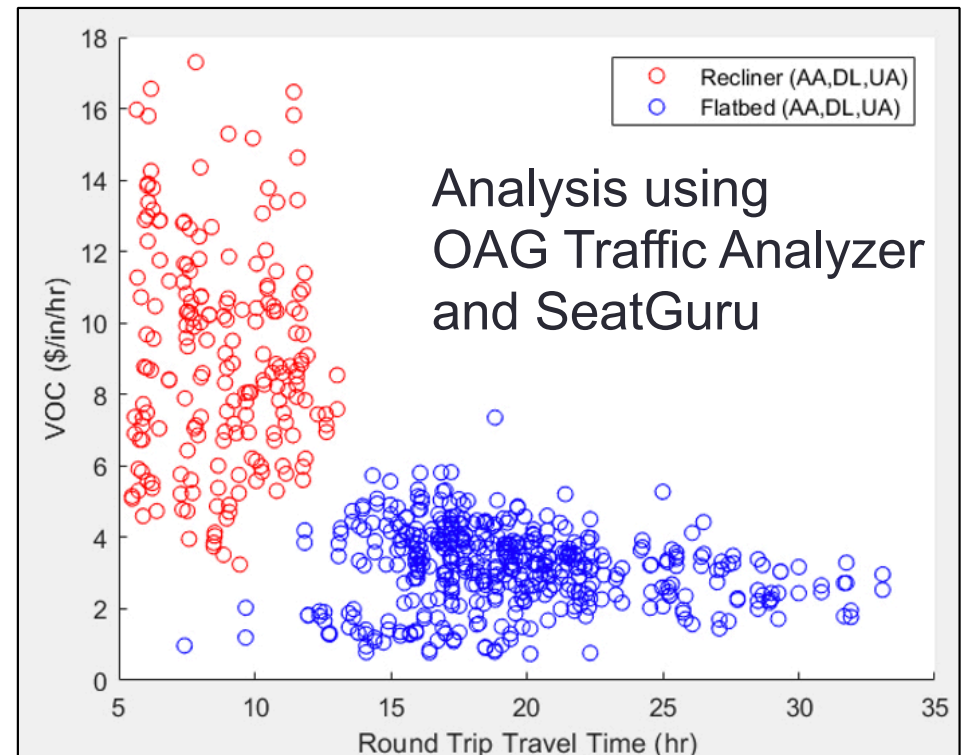
Passenger Preference Module

- Estimates the fraction of passengers willing to switch from subsonic to high-speed commercial services using Value of Time (VOT) and Value of Comfort (VOC)
- Estimates the tradeoffs between the travel time advantages of high-speed travel and the potential disadvantages of traveling in a more confined seat typically found in supersonic vehicles

Estimated Values of Time for premium seats range from \$120-\$240/hr using a Lufthansa passenger survey and OAG Traffic Analyzer airfare analysis



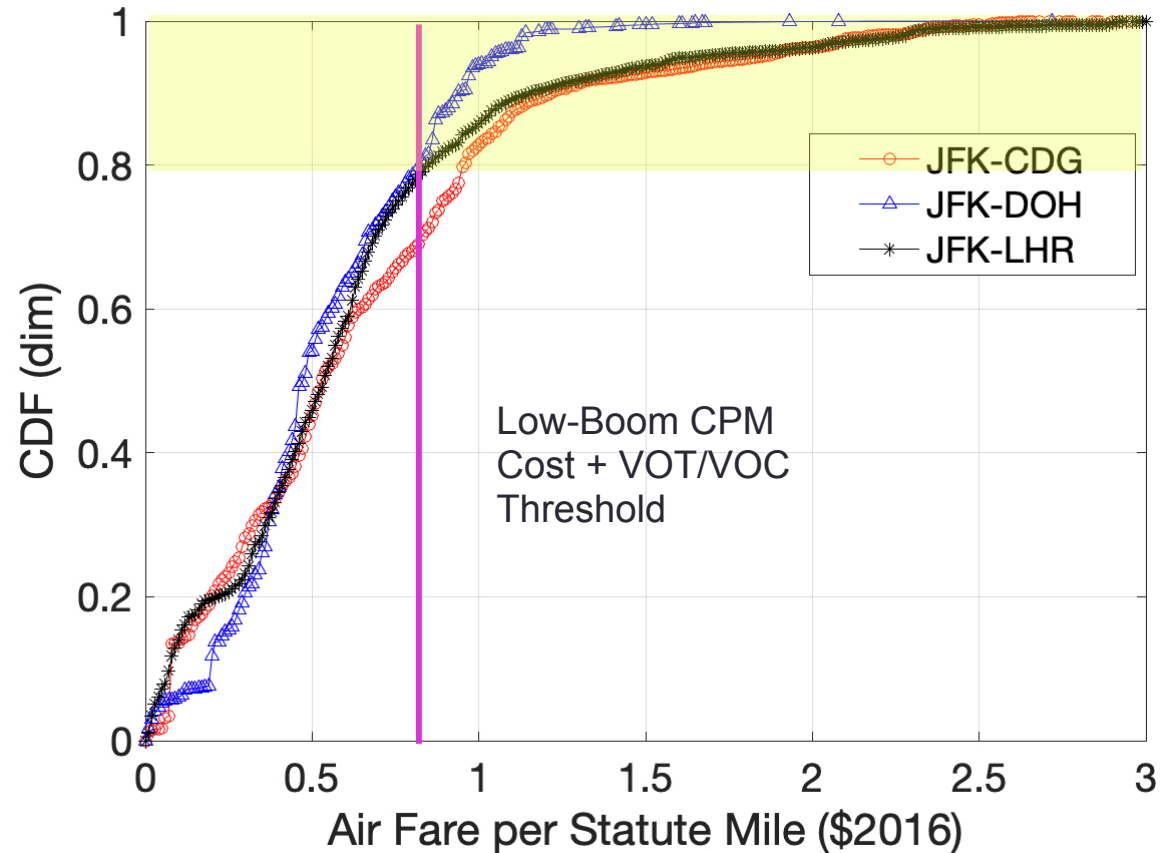
Lufthansa





Market Demand Estimation Module

- Estimates the number of passengers traveling in the high-speed vehicle at the route level.
- Employs the Airline Reporting Corporation (ARC) database with **46 million premium class airline tickets** (first and business class) to estimate the number of passengers switching to high-speed commercial service



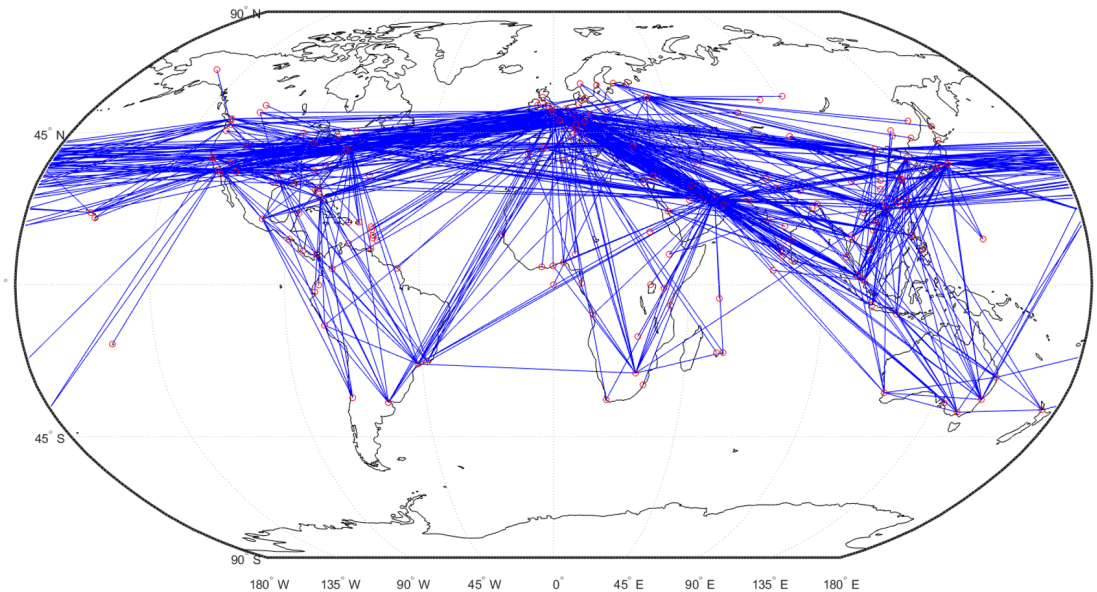
Example: Considering Value of Time and Value of Comfort, 20% of the premium passengers in the JFK-LHR route may be willing to switch to supersonic aircraft

Market	Airports	OD Pairs	Records
US	135	1,535	8.14 million
US-International	327	2,709	9.89 million
International	1,008	12,176	27.19 million

Airline Reporting Corporation (ARC) datasets

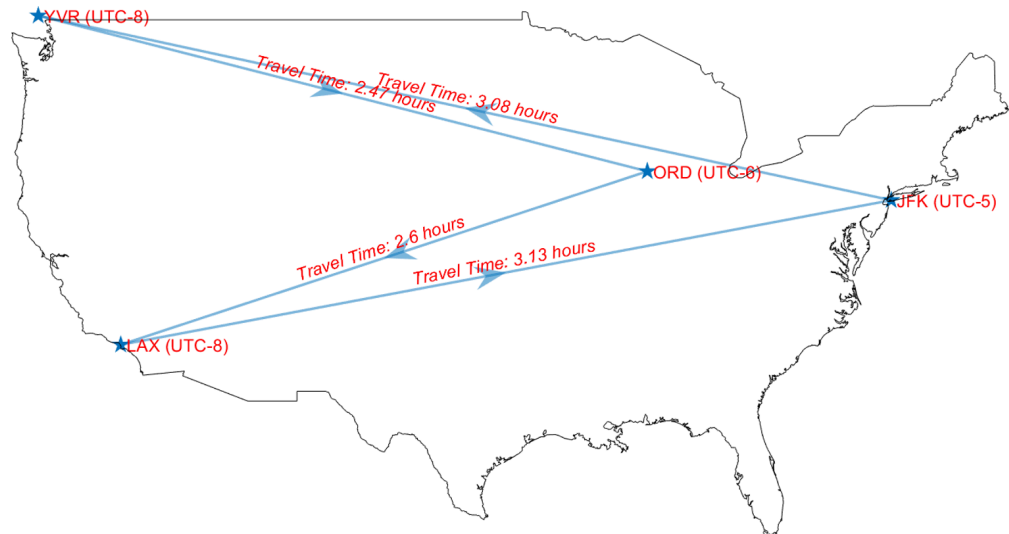
Vehicle Assignment and Network Model

- LBSAM2 includes a mathematical programming module to schedule supersonic flights worldwide
- The LBSAM2 flight scheduling and network model considers the following operational effects:
 - Curfew constraints
 - Maximum daily utilization
 - One and two-day cycles
 - Demand at origin-destination level (determined using the passenger choice model developed in LBSAM2)
 - Maintenance times



Example Network Analysis Metrics Produced in LBSAM2 Flight Scheduling/Network Model

<i>Metric</i>
<i>Weighted Average OD Pair Length</i>
<i>Flights per Day per Vehicle</i>
<i>Passenger Cost per Mile</i>
<i>Load Factor</i>
<i>Daily Vehicle Utilization</i>
<i>Number of Airframes Needed</i>
<i>Passenger Spillover</i>
<i>Origine-Destination Demand</i>
<i>Origin-Destination Seats Offered</i>
<i>Revenue Passenger Kilometers</i>

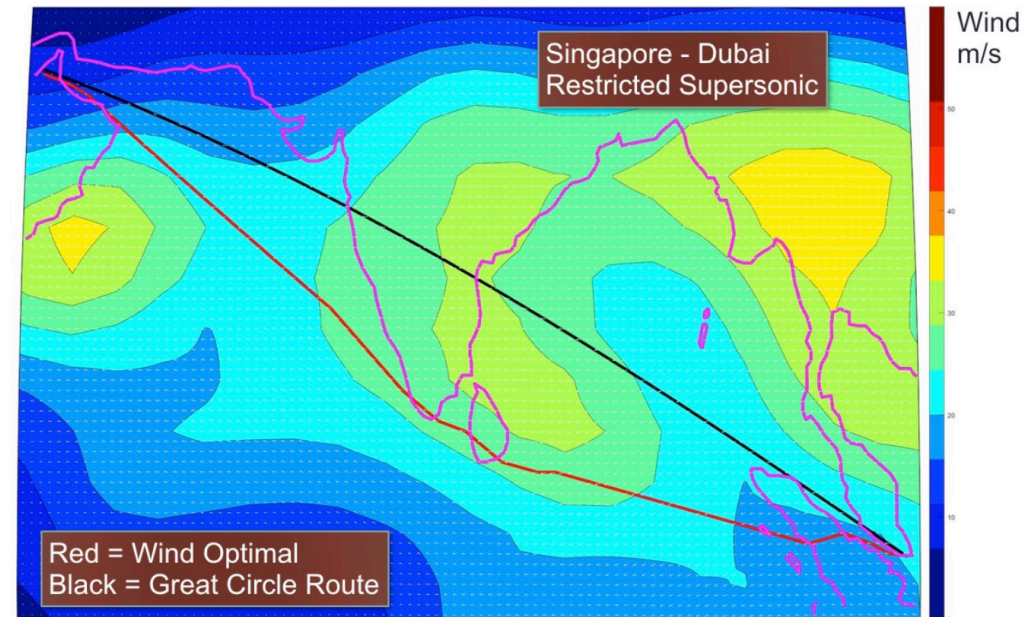
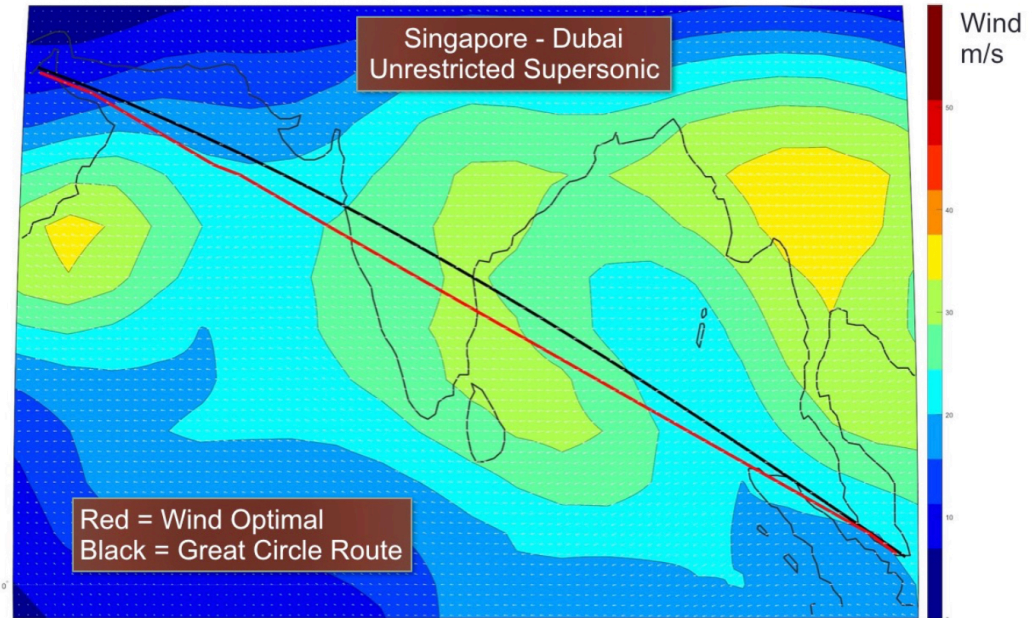
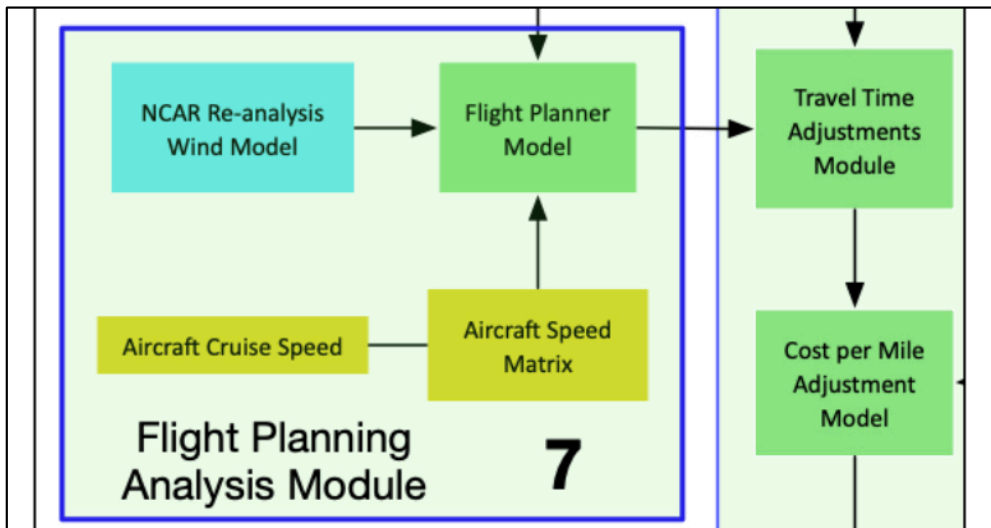


Low-boom supersonic aircraft
one-day cycle



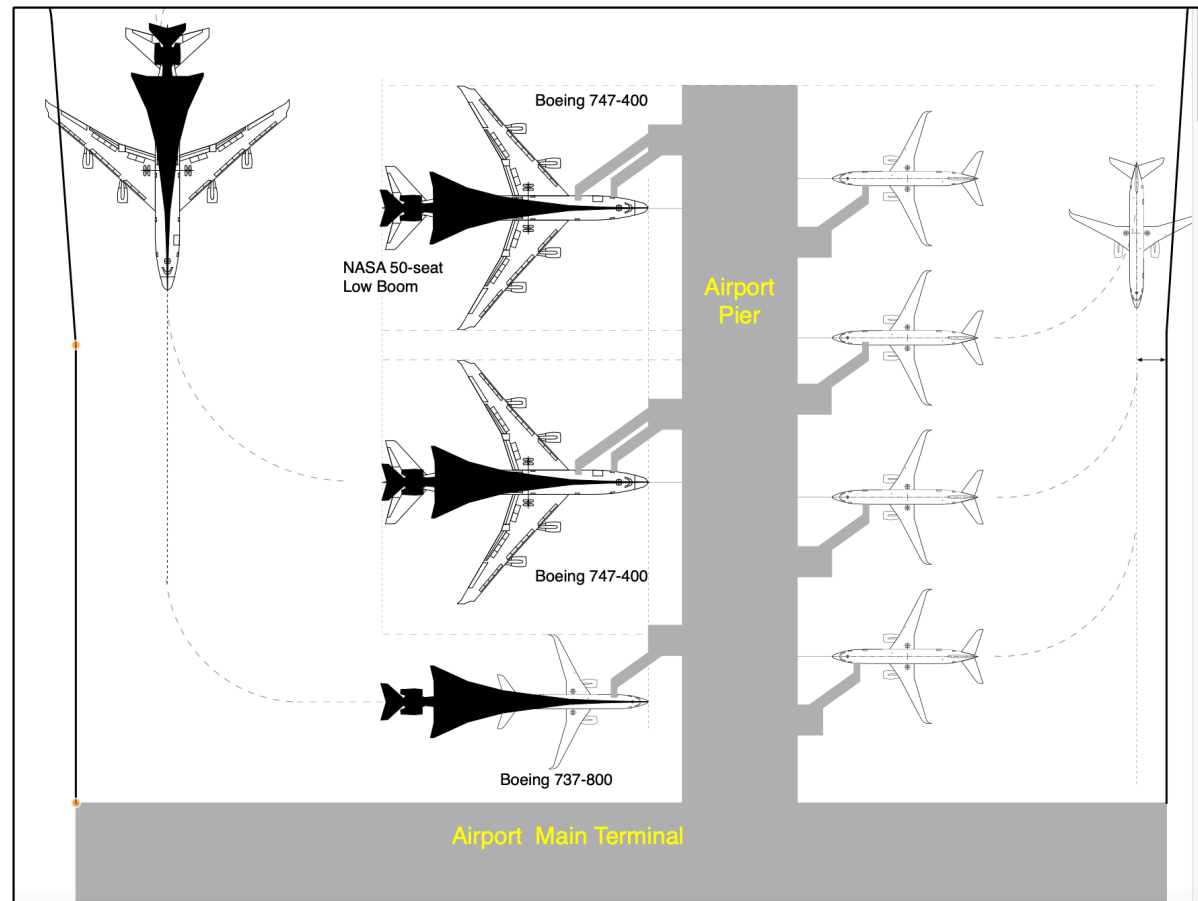
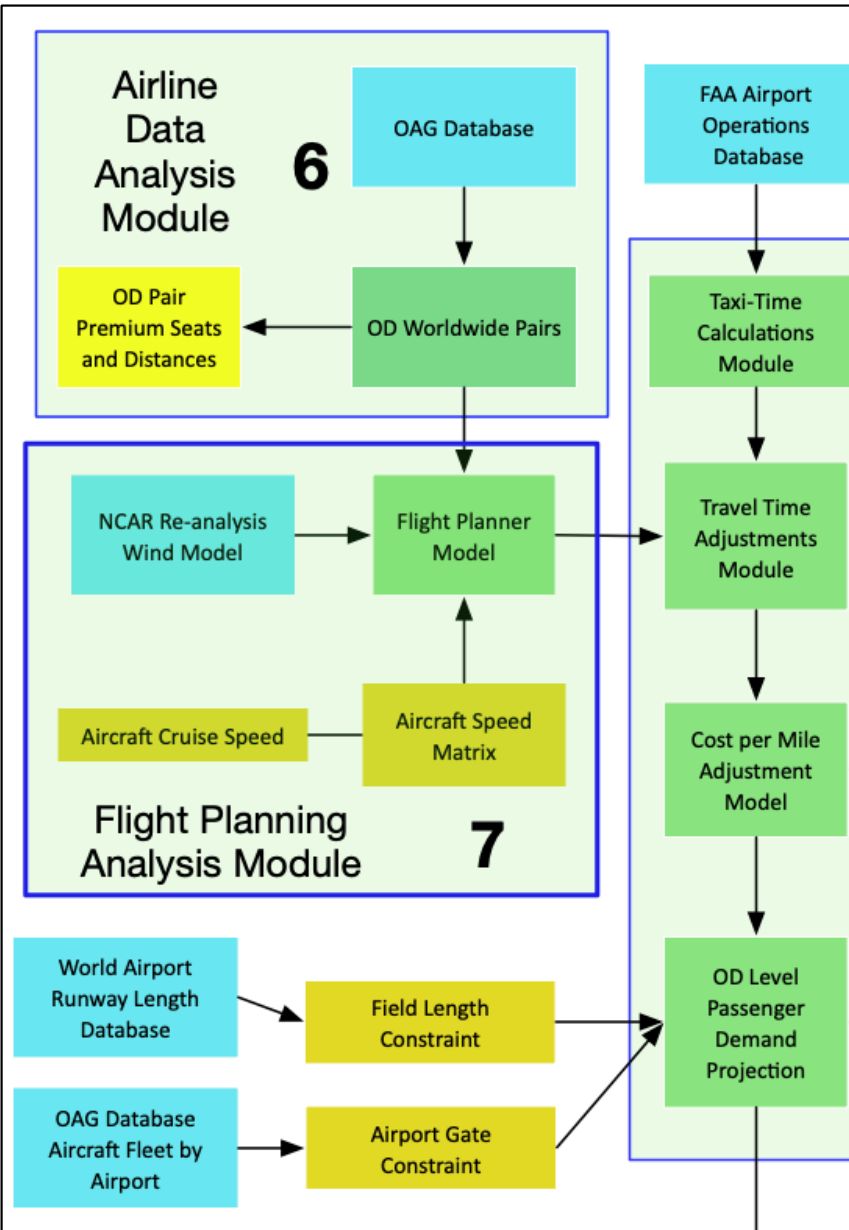
Overland/Overwater Flight Planning

- Estimates flight trajectories for supersonic aircraft considering supersonic overland restrictions (if applicable)
- Flight planner uses NOAA Re-analysis wind data sets
- Runway length and airport gate compatibility analysis are considered in the selection of candidate OD airport pairs



Airport Compatibility Impacts

LBSAM2 checks for runway length and gate size compatibility



Using the LBSAM2 Model to Study NASA Concepts

- Compare Low-Boom (LB) versus non-low-boom (NLB) aircraft designs

Specifications

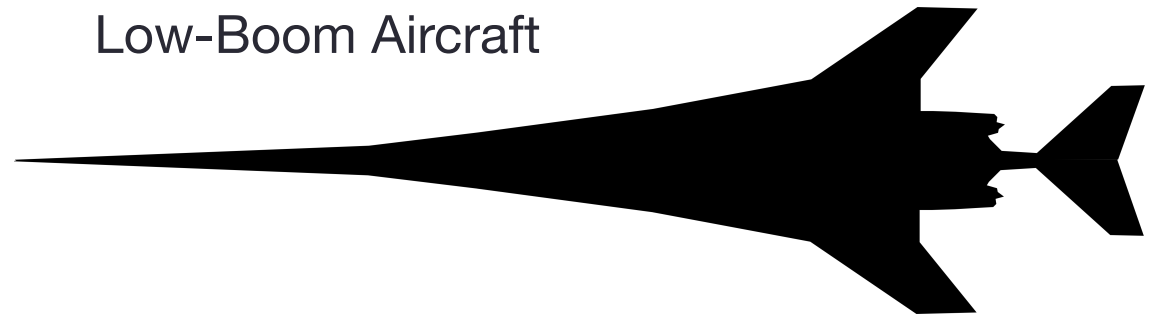
Mach 1.8 overland

Mach 1.8 overwater

43 seats

20% heavier than NLB

Low-Boom Aircraft



Specifications

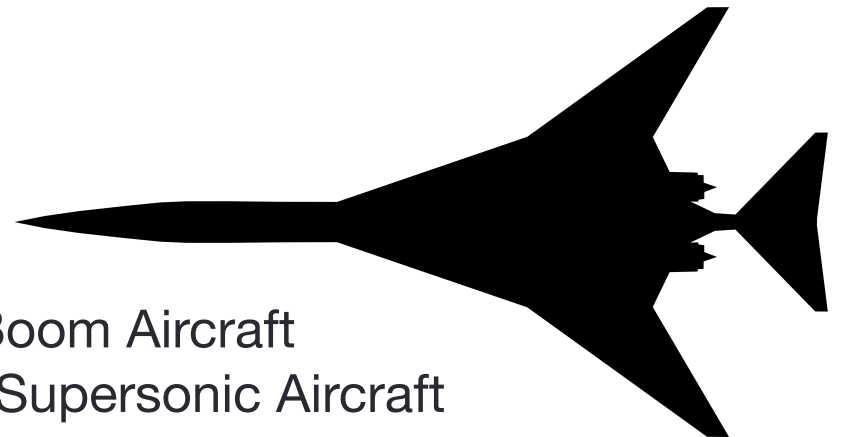
Mach 0.95/1.15 overland

Mach 1.8 overwater

43 seats

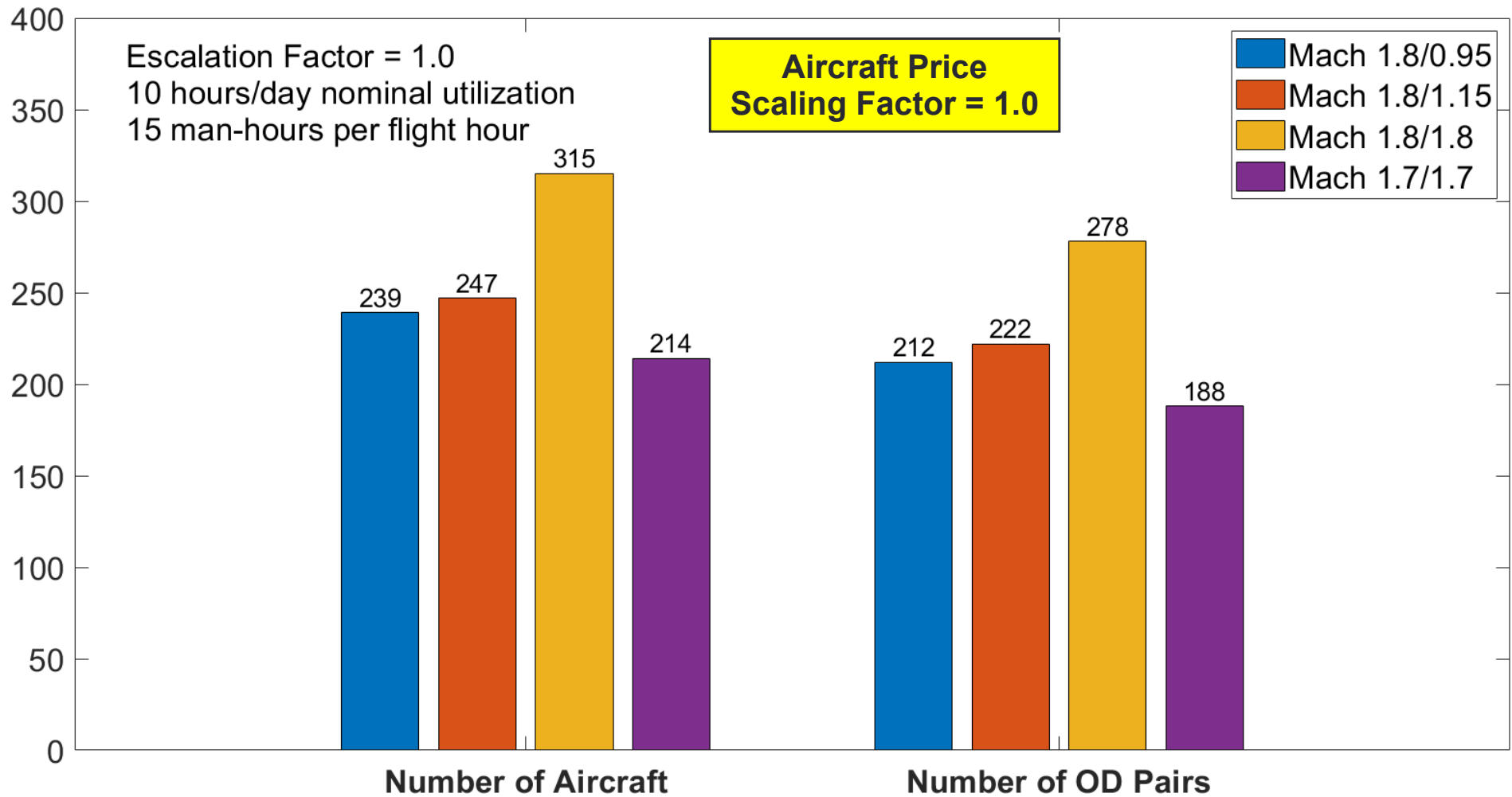
20% lighter than LB

Non Low-Boom Aircraft
Traditional Supersonic Aircraft



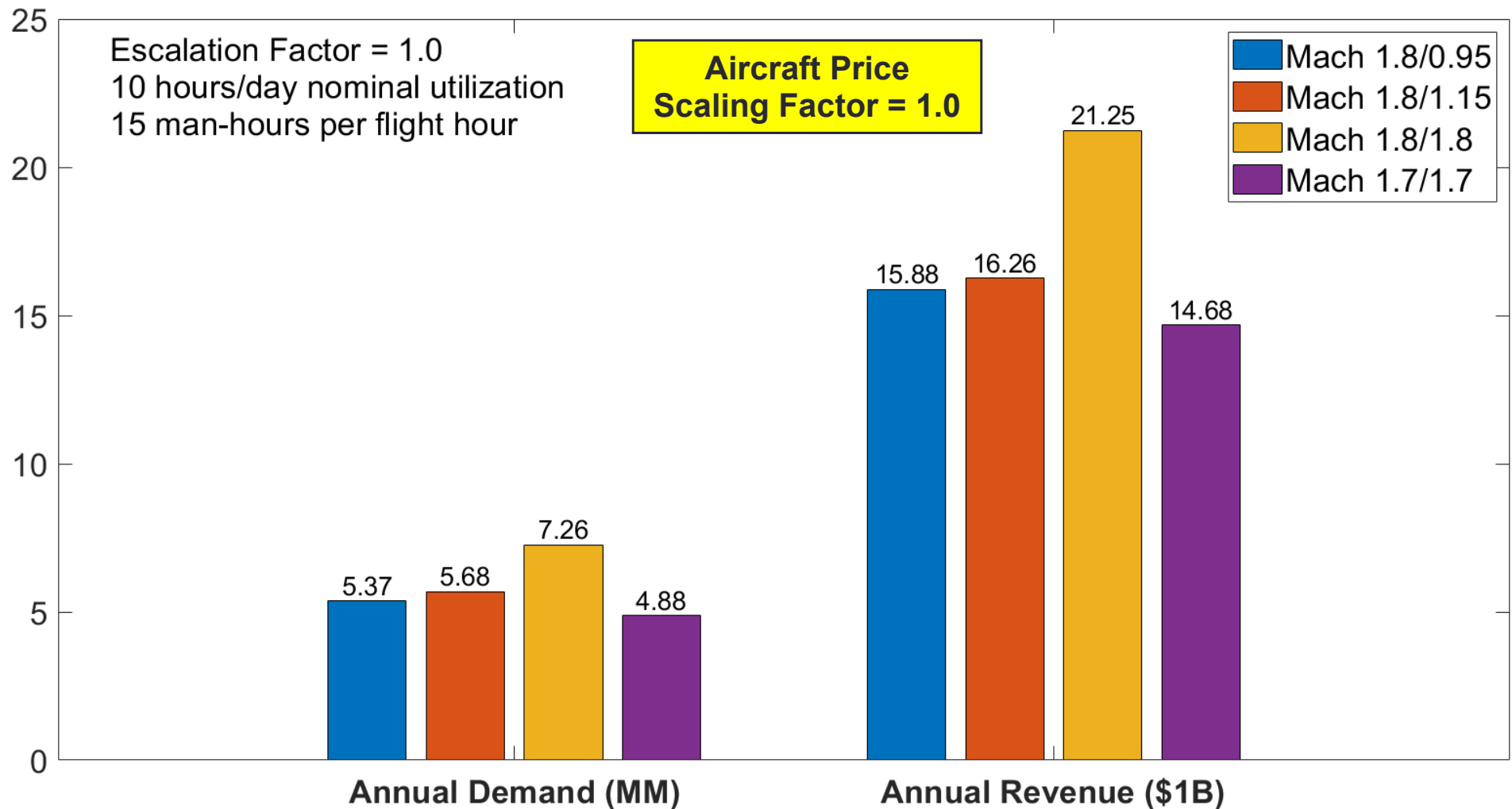


The Mach 1.8 low-boom design is expected to serve more OD pairs compared to a NLB design able to cruise at Mach 1.15 overland





The Mach 1.8 low-boom design has the potential to attract 27% more passengers worldwide compared to a NLB design able to cruise at Mach 1.15 overland





Main Conclusions

- The enhanced LBSAM2 model offers an integrated approach to study worldwide demand for supersonic aircraft concepts
- Model includes network effects and captures the dynamics between fleet size, aircraft unit cost, aircraft economics, and passenger preference
- Model runs converge (demand-supply) in 5-12 iterations
- **Using baseline operational parameters in the model, we estimate between 315-350 low-boom supersonic airframes may be needed in the year 2040**
- **Using baseline operational parameters in the model (i.e., high daily utilization), low-boom supersonic aircraft could transport between 7-8 million passengers annually in 2040**
- Using very optimistic parameters in the model (including \$2.5/gallon fuel prices) we estimate up to 700 low-boom supersonic airframes may be needed in the year 2040
- Producing 350 low-boom aircraft over a life cycle of a program is challenging (costs are high)



Other Studies Using Components of the LBSAM2 Model



LBSAM2 Flight Scheduling and Network Analysis Module to Estimate Regional Air Mobility

- TSAM predicts door-to-door travel behavior (US scope)
- TSAM uses an external life cycle cost model to predict airfares (cost per mile) for user-defined aerospace vehicles (**no network effects modeled directly**)
- Use the LBSAM2 network model to predict realistic network costs for regional air mobility aircraft vehicles
- LBSAM2 network analysis model can solve problems with thousands of OD pairs to assess realistic network costs and predict schedule or on-demand travel



Heart Aerospace



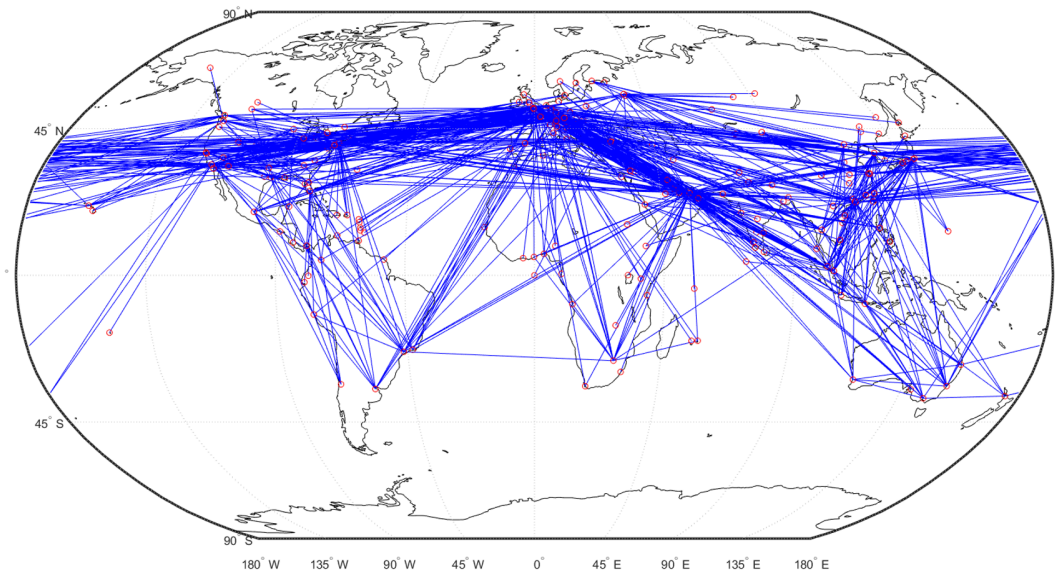
Eviation Alice

Use the LBSAM2 Framework to Predict Advanced Subsonic Demand

- LBSAM2 passenger choice and network analysis models can be used to predict worldwide subsonic aircraft demand using advanced aircraft designs such as the proposed Boeing/NASA VS-1 and VS-2
- The introduction of advanced subsonic aircraft can be studied regionally because the practical range of such aircraft confines them to a region



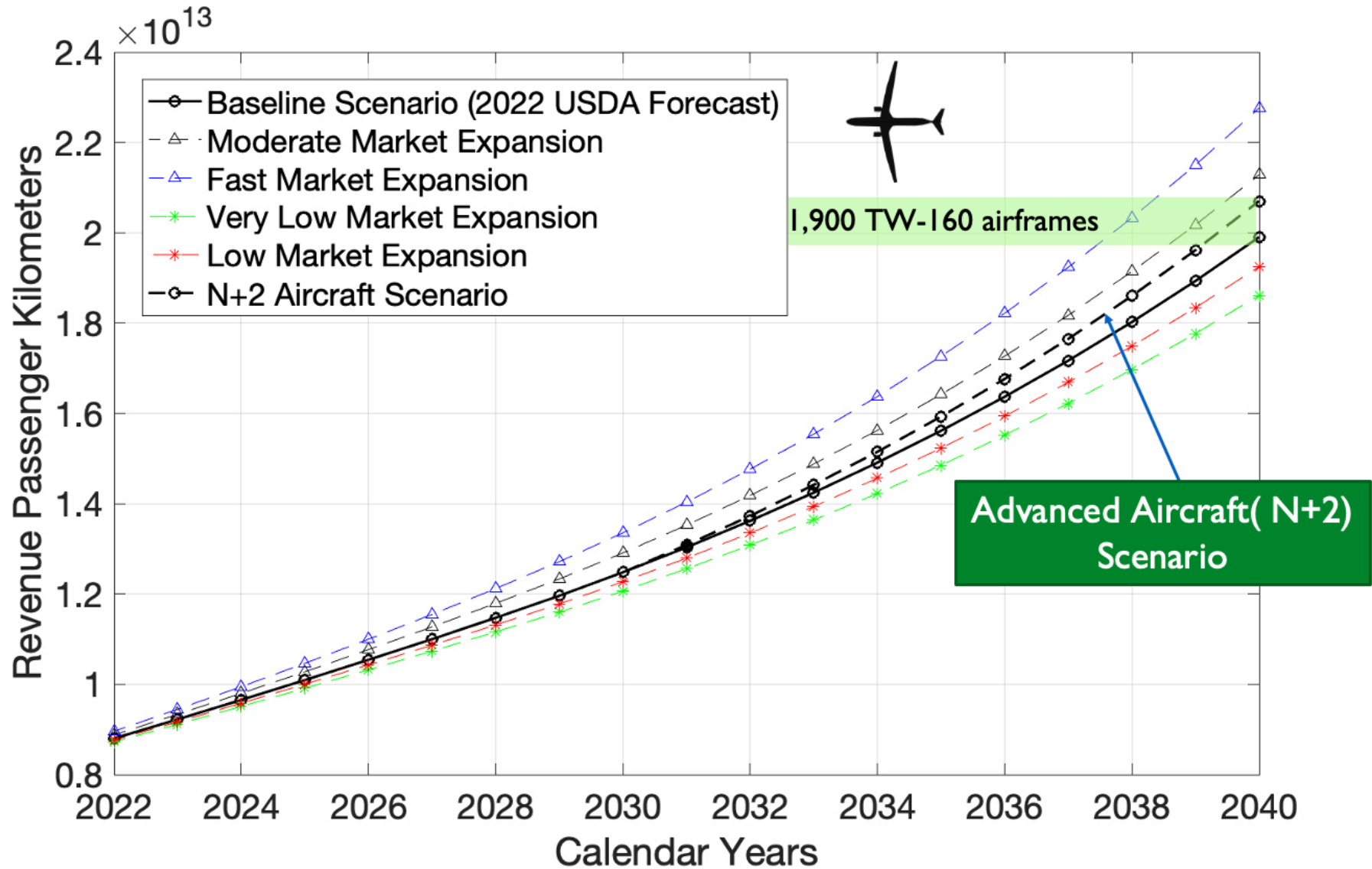
Boeing VS-1 and VS-2 truss-braced subsonic aircraft
(Source: Boeing)



LBSAM2 Worldwide Network
Analysis for Low-Boom Aircraft



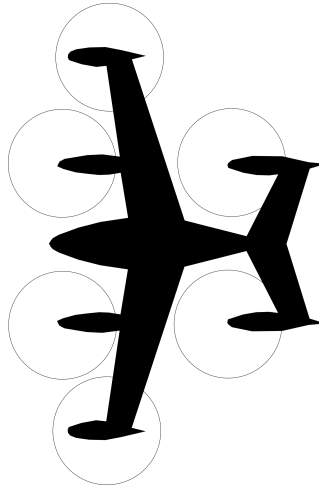
Use the LBSAM2 Framework to Predict Advanced Subsonic Demand



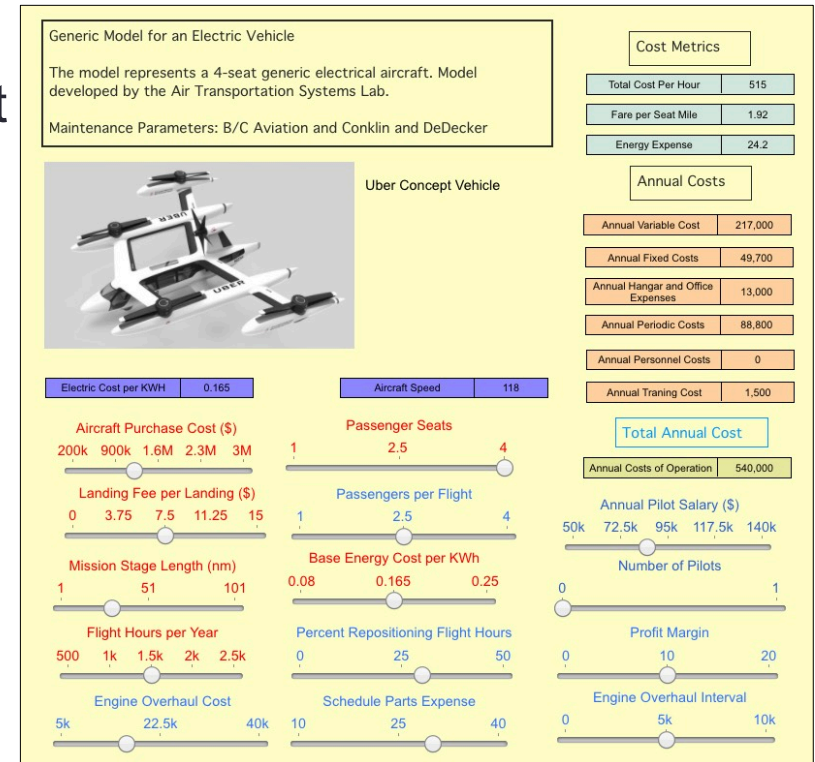


Metropolitan Area eVTOL Demand (NASA Study)

UAM Aircraft Life Cycle Cost Model



UAM Aircraft



Presented by Antonio Trani

Research Team: Dr. M. Rimjha, Dr. S. Hotle, N. Hinze, A. Antonis, A. Olamai, T. Sayantan, and Dr. A. Trani

January 5, 2023



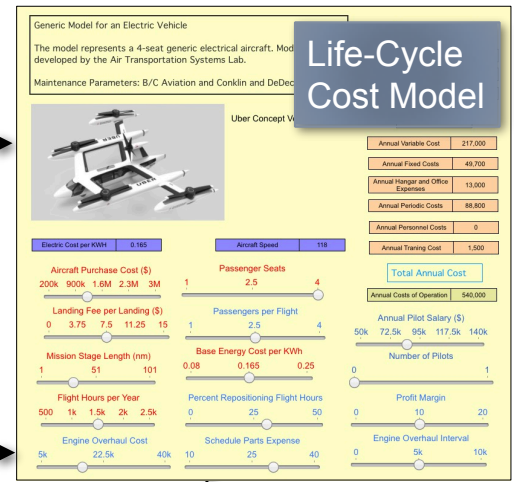
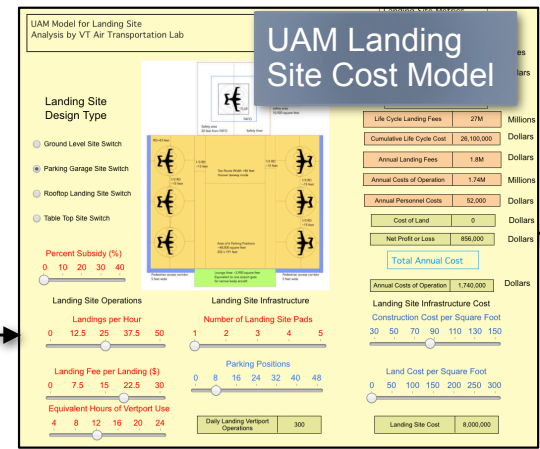
Acknowledgements

- **Jeremy Smith and Ty Marien** at NASA Langley Research Center (Project technical monitors)
- **Sam Dollyhigh** - contractor to NASA Langley Research Center
- **Dr. Laurie Garrow** for sharing data on the stated preference survey
- **NASA Ames** - provided Dallas-Fort Worth airport airspace restrictions
- Los Angeles World Airports, Dallas-Fort Worth International Airport, New York, Texas, and California for providing extended NHTS data

- Work funded under a National Institute of Aerospace Grant Number NNL13AA08B Task Order Number 80LARC18F0120



Integrated UAM Systems Analysis Model



UAM vehicle characteristics:

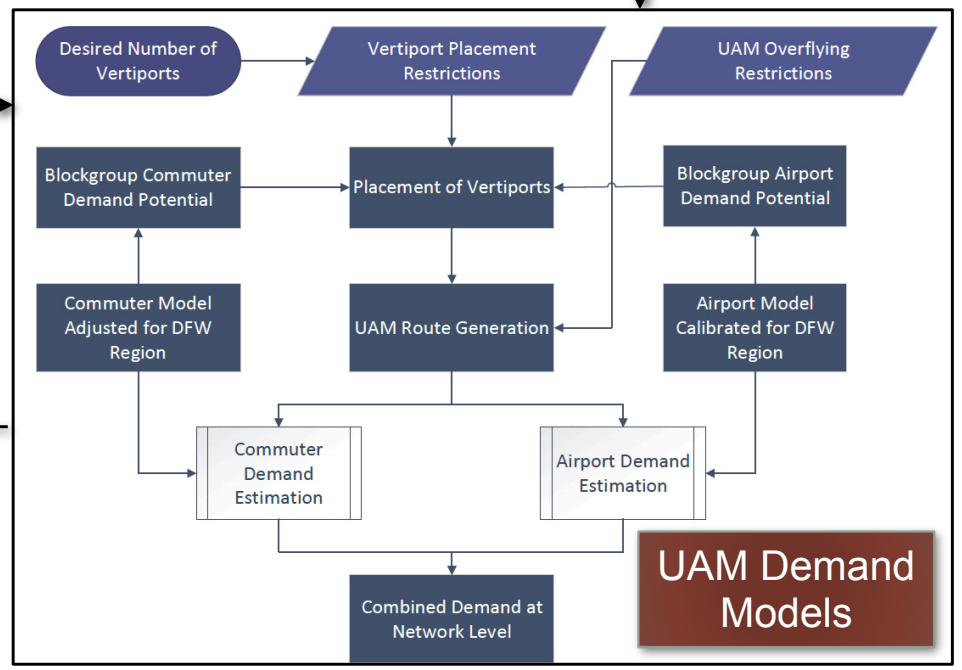
- Aircraft range
- Payload
- Battery life
- Operational speed
- Aircraft size

Aircraft Development Cost Model

UAM Unit Cost

Cost per passenger-mile

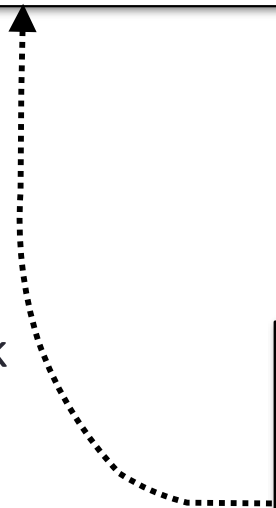
Airspace Restrictions in Urban Areas



Output of Integrated UAM Model

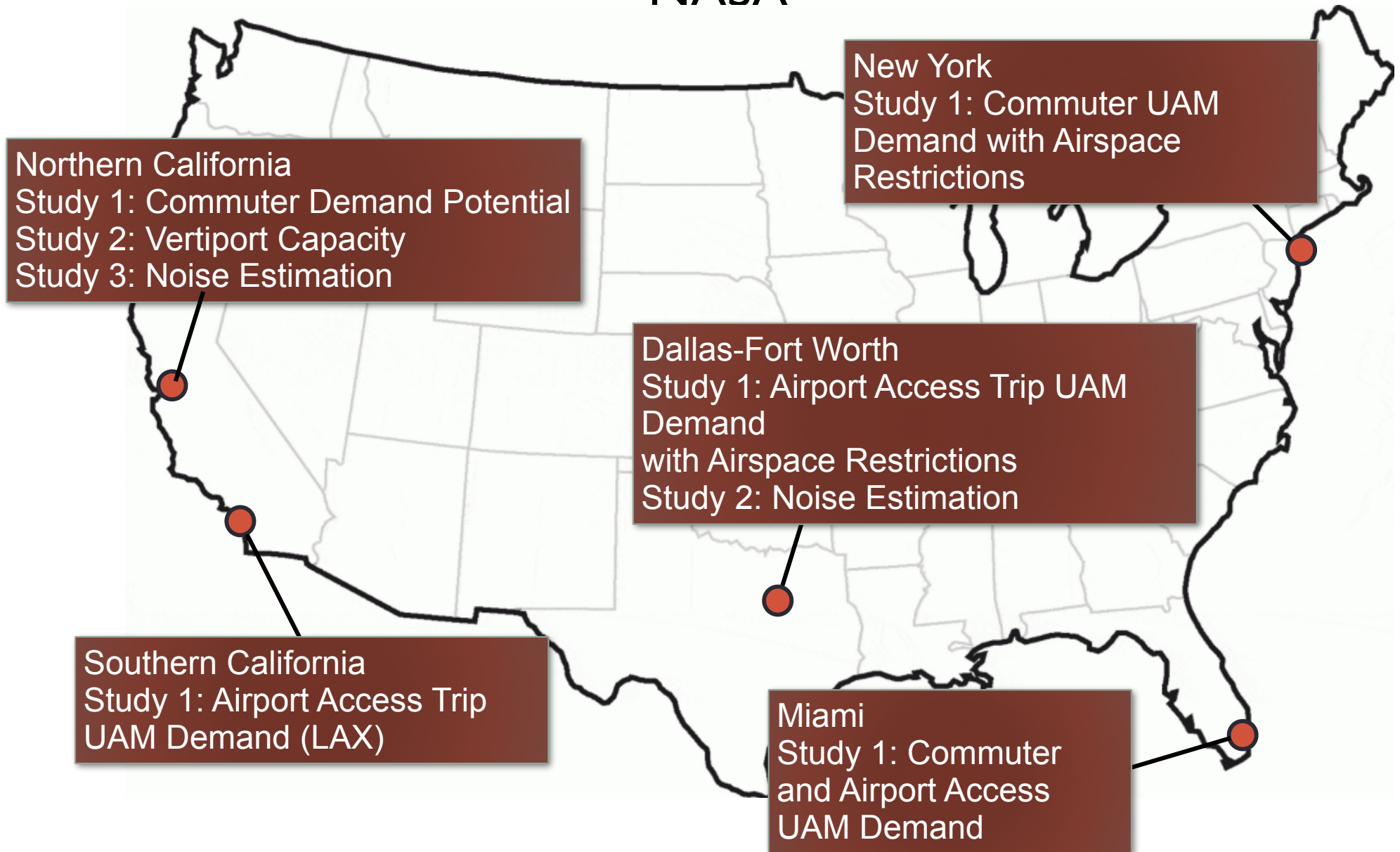
- UAM commuter demand
- UAM airport demand
- UAM cargo demand
- UAM flight routes

Feedback





UAM Areas of Study at Virginia Tech for NASA

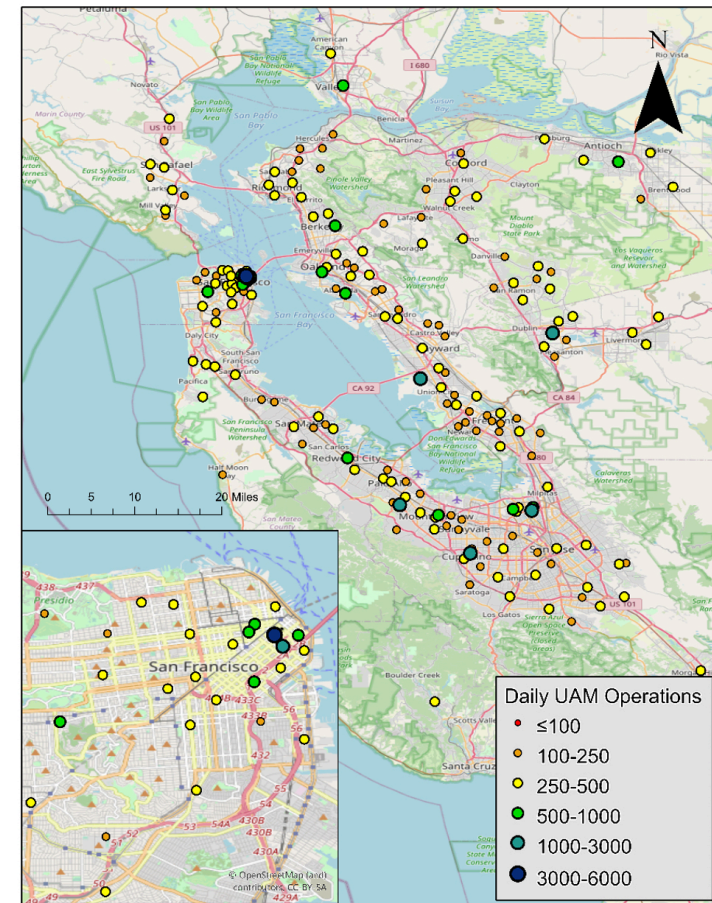
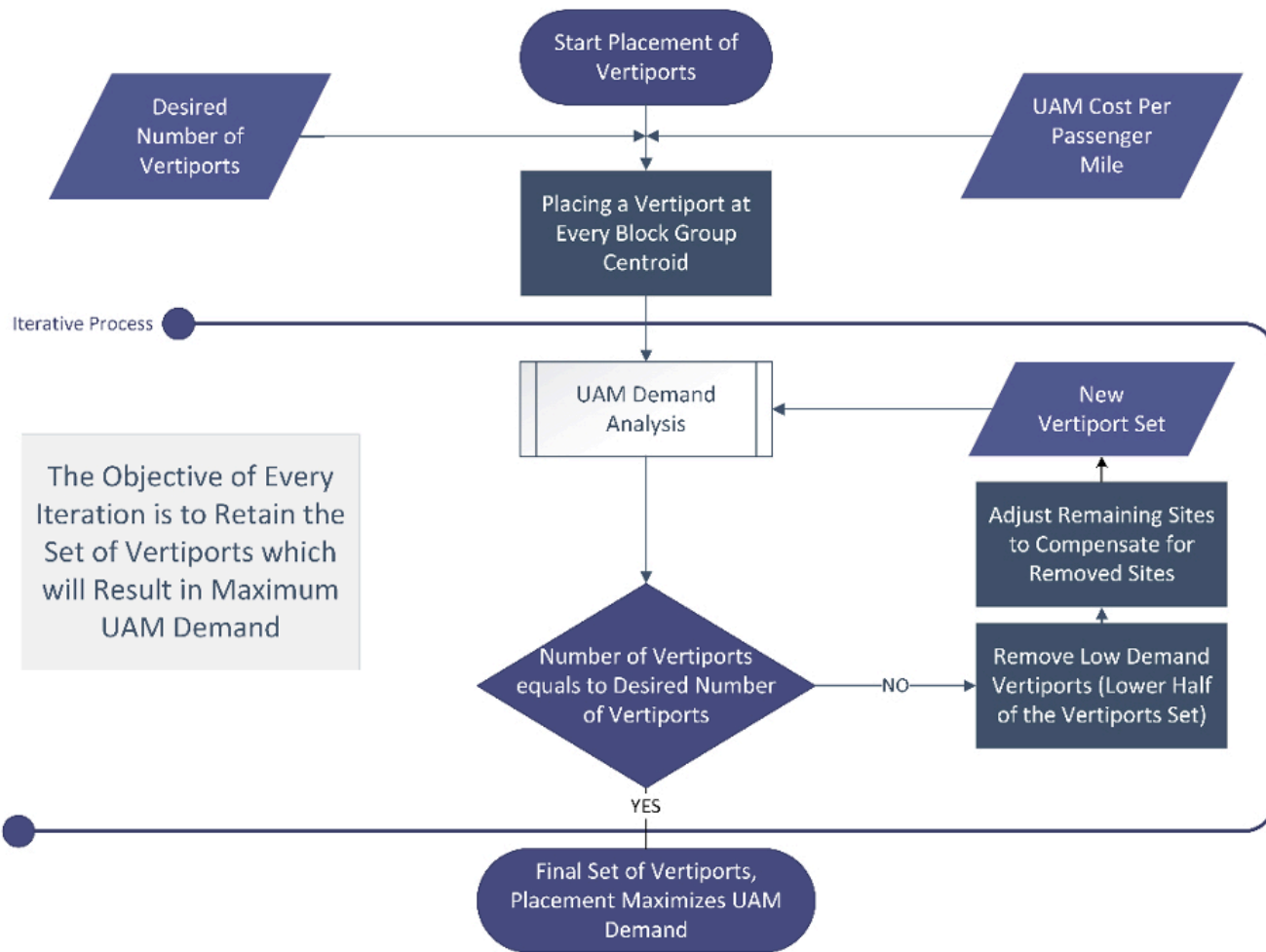




UAM Landing Site Placement Model, Landing Site Space Requirements, and Landing Site Cost Model



Demand-Driven, Iterative UAM Landing Site Vertiport Location Method

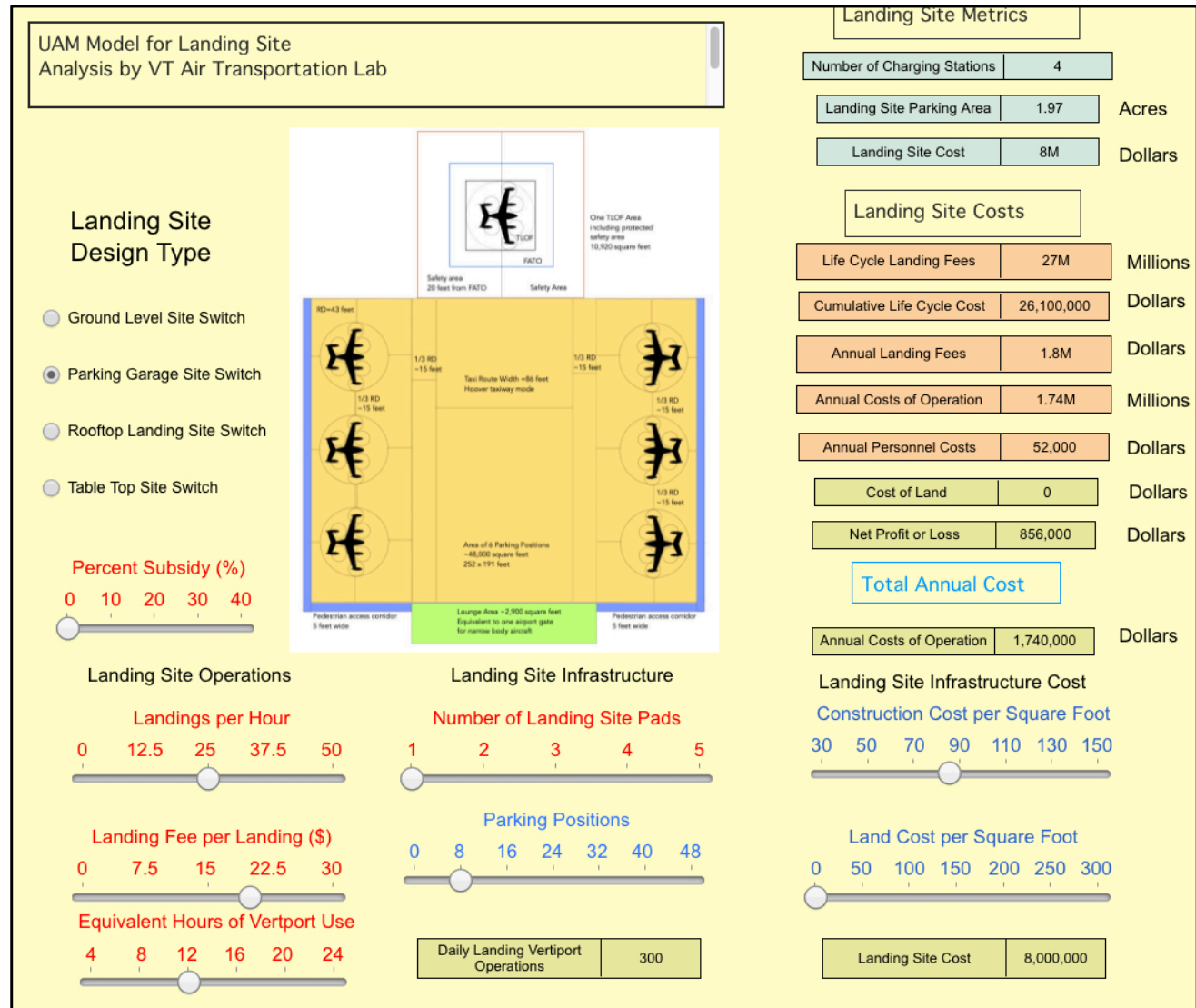




UAM Landing Site Life-Cycle Cost Model

The building blocks of the life-cycle cost model include the following:

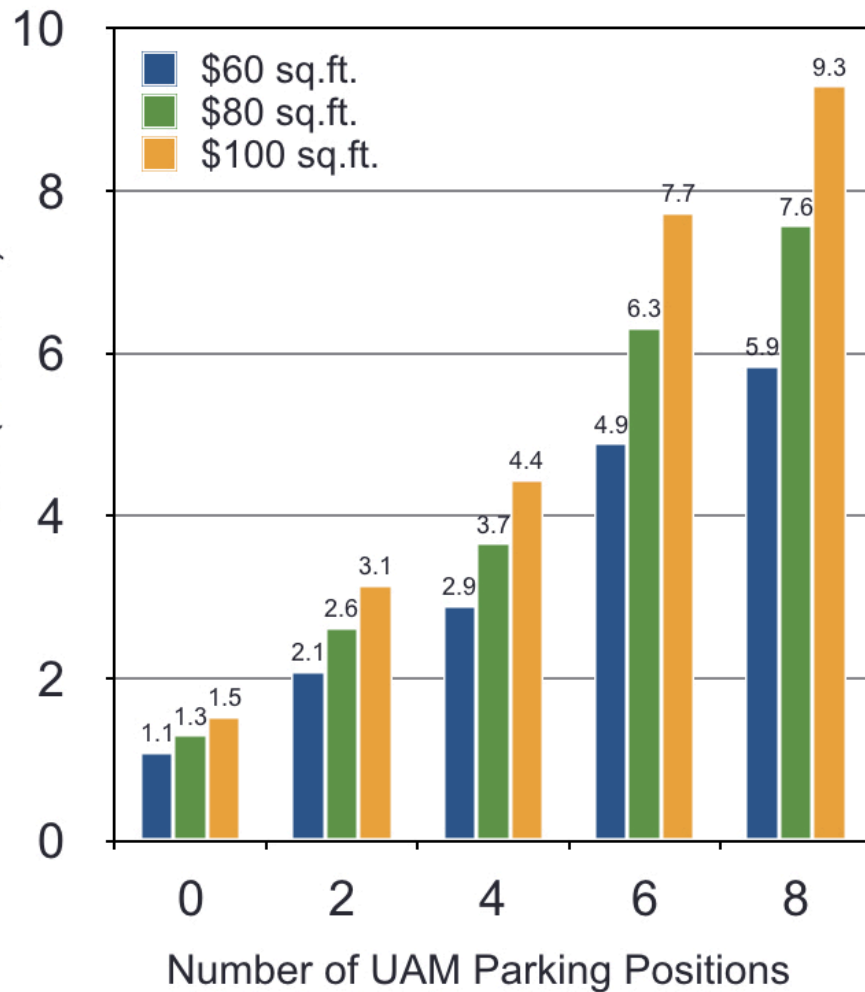
- Landing area type (vacant land, rooftop, parking lot)
- Critical vehicle dimensions
- Number of landing pads
- Number of parking stalls
- Number of charging stations
- Staffing of landing site
- Lounge areas for waiting passengers
- Lighting requirements
- Number of hours of operation per day for the landing site)
- Landing fees
- Percent subsidy to build the landing site



Model developed in STELLA Author

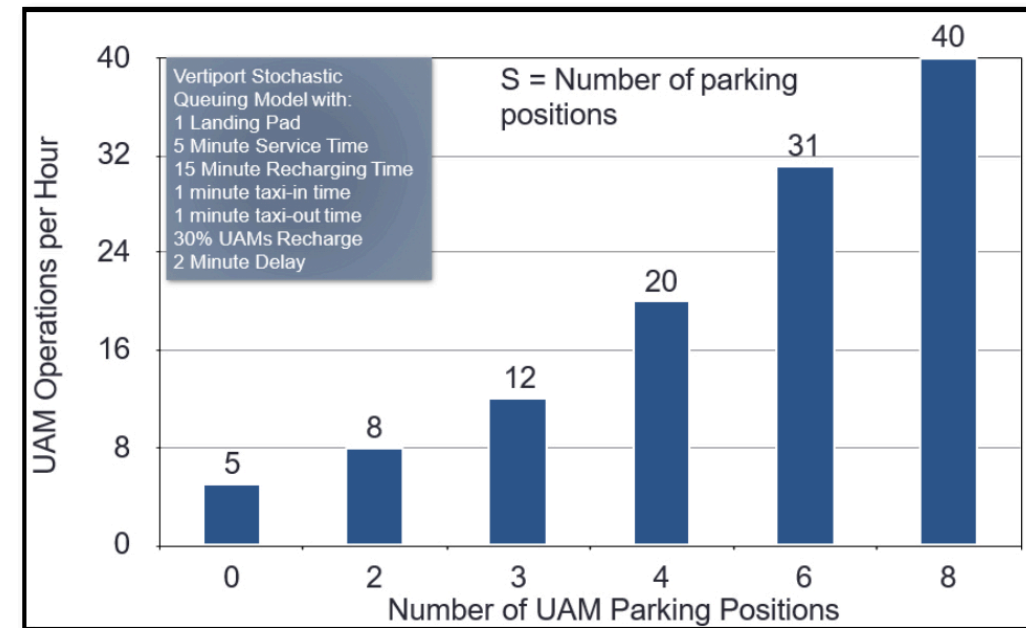
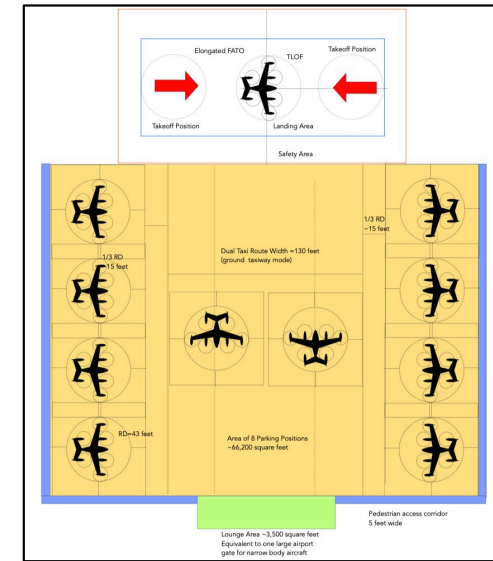


UAM Vertiport Capacity and Cost Analysis



Stochastic Queueing Model with:

- 1 Landing Pad
- 8 Parking Positions
- 5 Minute Service Time
- 15 Minute Recharging Time
- 1 minute taxi-in time
- 1 minute taxi-out time

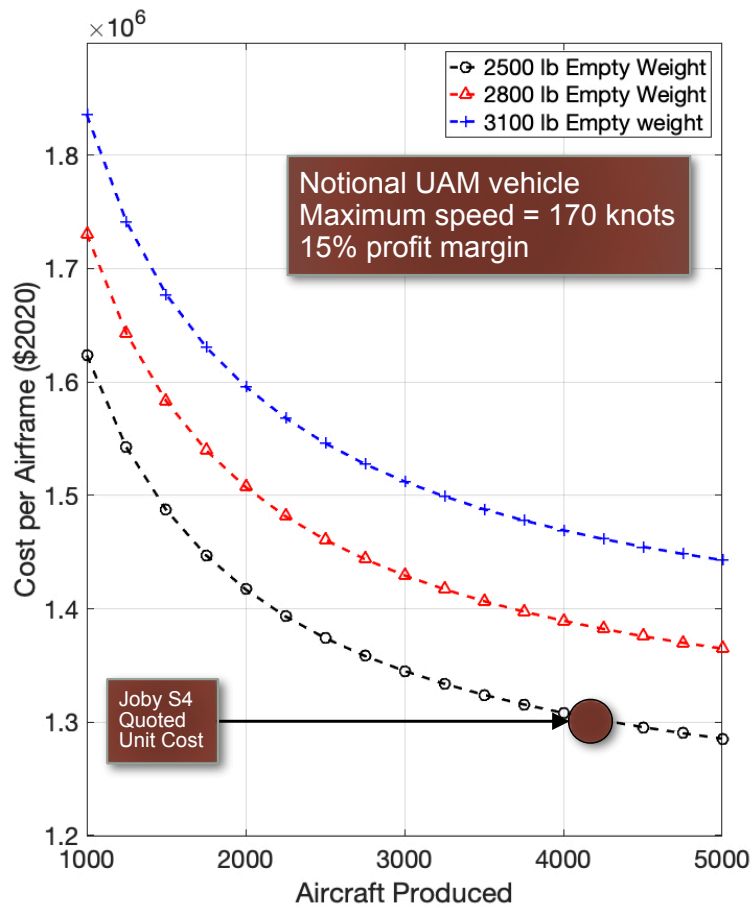




UAM Vehicle Development Cost and Operational Cost Models



UAM Vehicle Development and Operational Life Cycle Cost Models



Aircraft development cost equations adapted from Nicolai and Carichner (2012)

Life-Cycle Cost Model

Generic Model for an Electric Vehicle
 The model represents a 4-seat generic electric vehicle developed by the Air Transportation System
 Maintenance Parameters: B/C Aviation and C

Uber Concept Vehicle

Cost Metrics	
Total Cost Per Hour	515
Fare per Seat Mile	1.92
Energy Expense	24.2

Annual Costs	
Annual Variable Cost	217,000
Annual Fixed Costs	49,700
Annual Hangar and Office Expenses	13,000
Annual Periodic Costs	88,800
Annual Personnel Costs	0
Annual Training Cost	1,500
Total Annual Cost	369,000
Annual Costs of Operation	540,000

Electric Cost per KWh: 0.165 Aircraft Speed: 118

Aircraft Purchase Cost (\$)
 200k 900k 1.6M 2.3M 3M 1

Passenger Seats: 2.5 4

Landing Fee per Landing (\$): 0 3.75 7.5 11.25 15 1 2.5 4

Mission Stage Length (nm): 1 51 101 Base Energy Cost per KWh: 0.08 0.165 0.25

Flight Hours per Year: 500 1k 1.5k 2k 2.5k Percent Repositioning Flight Hours: 0 25 50

Engine Overhaul Cost: 5k 22.5k 40k Schedule Parts Expense: 10 25 40

Annual Pilot Salary (\$): 50k 72.5k 95k 117.5k 140k Number of Pilots: 0 1

Profit Margin: 0 10 20

Engine Overhaul Interval: 0 5k 10k

Maintenance data adapted from Conklin and deDecker (rotorcraft technology)

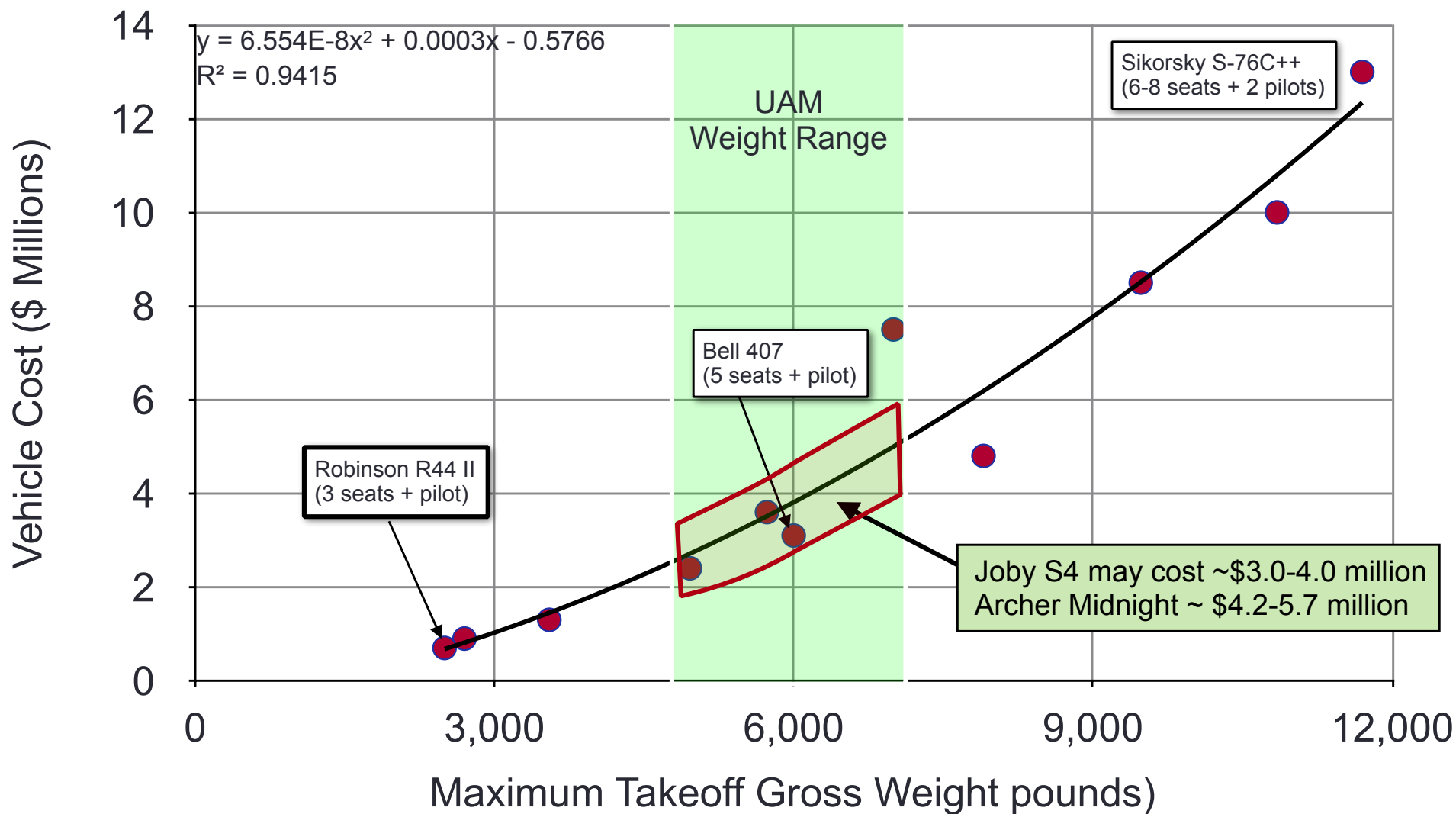
UAM aircraft life-cycle cost model include the following:

- Vehicle unit cost
- Number of annual operations
- Maintenance hours per flight hour
- Engine overhaul costs
- Time between overhauls
- Landing fee per landing
- Percent of repositioning flights
- Energy consumption performance (vs. block speed)
- Energy cost (\$/kW-hr)
- Hangar cost
- Pilot vs no pilot switch
- Avionics and interior refurbishing costs
- Load factor per flight
- Depreciation
- Life-cycle time

Joby's projections are optimistic because they assume Large numbers of aircraft produced



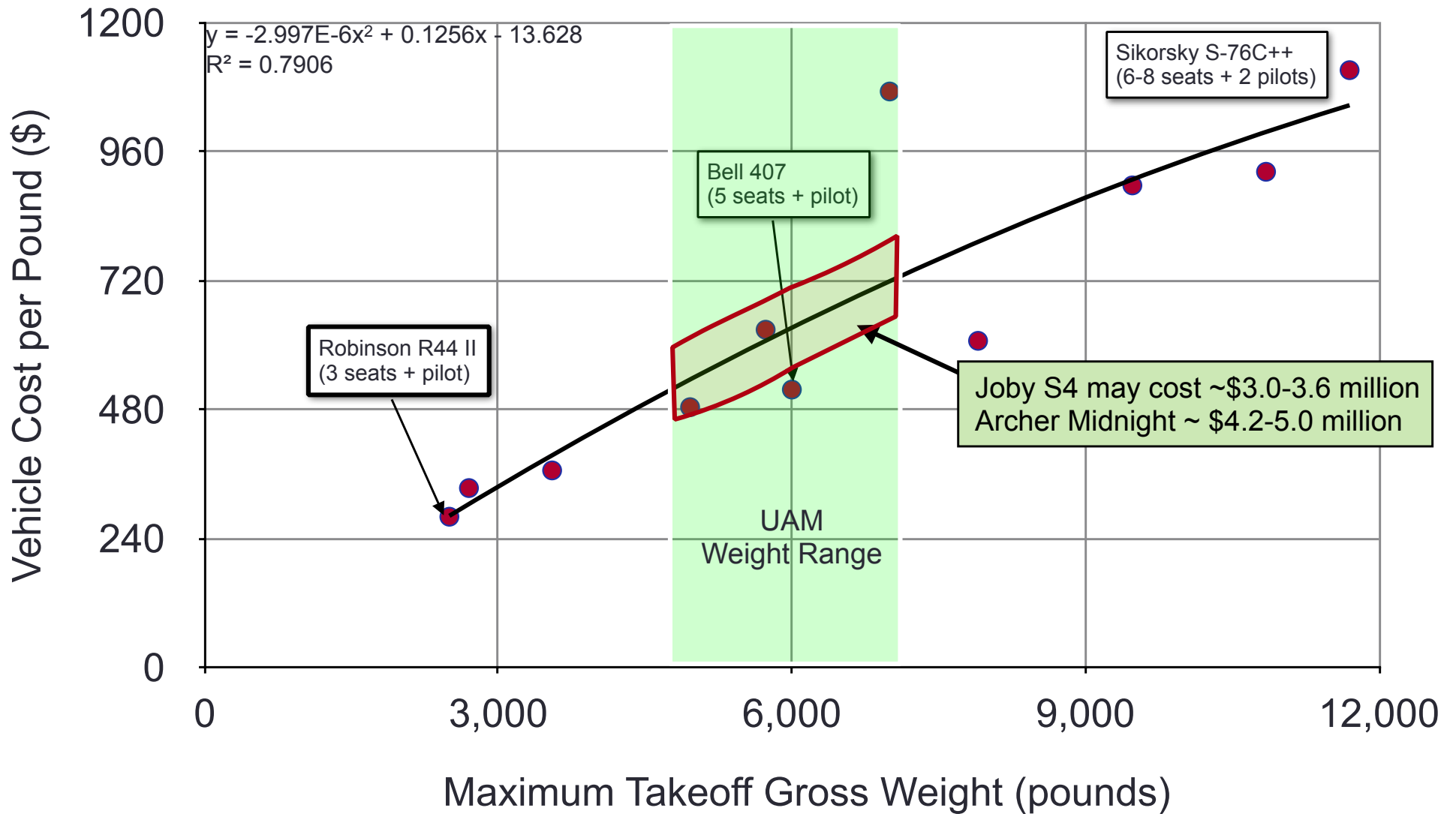
VTOL Technology Cost is Quadratic with MTGOW



Considering battery weight, UAM technology may follow the same weight and cost trends



VTOL Technology Costs per Pound





UAM Vehicle Costs in the Literature

Source		UAM Cost per Passenger Mile (\$)	Trip Purpose
Lilium		\$4.40	Airport
Joby Aviation		\$3.80	Not Specified
<u>Ehang</u>		\$2.28 - \$2.74 Per Available Seat Mile	Not Specified
BAH (5-seat <u>eVTOL</u>)		\$6.25 (near-term) \$2.5 (long-term)	General
Goyal et al. (2021)		~\$2.50 - \$2.85	General
Archer		\$3.0 - \$4.0	Airport
LEK		\$7.68 (2025) \$1.76 (2040)	General
Brown and Harris (2020)	Lift + Cruise	\$4.86	Not Applicable (Systems Study)
	Compound Heli	\$5.12	
	Tilt Wing	\$4.33	
	Tilt Rotor	\$3.80	

Source: Air Traffic Management Exploration (ATM-X) UAM Demand Analysis: Deliverable 1.2



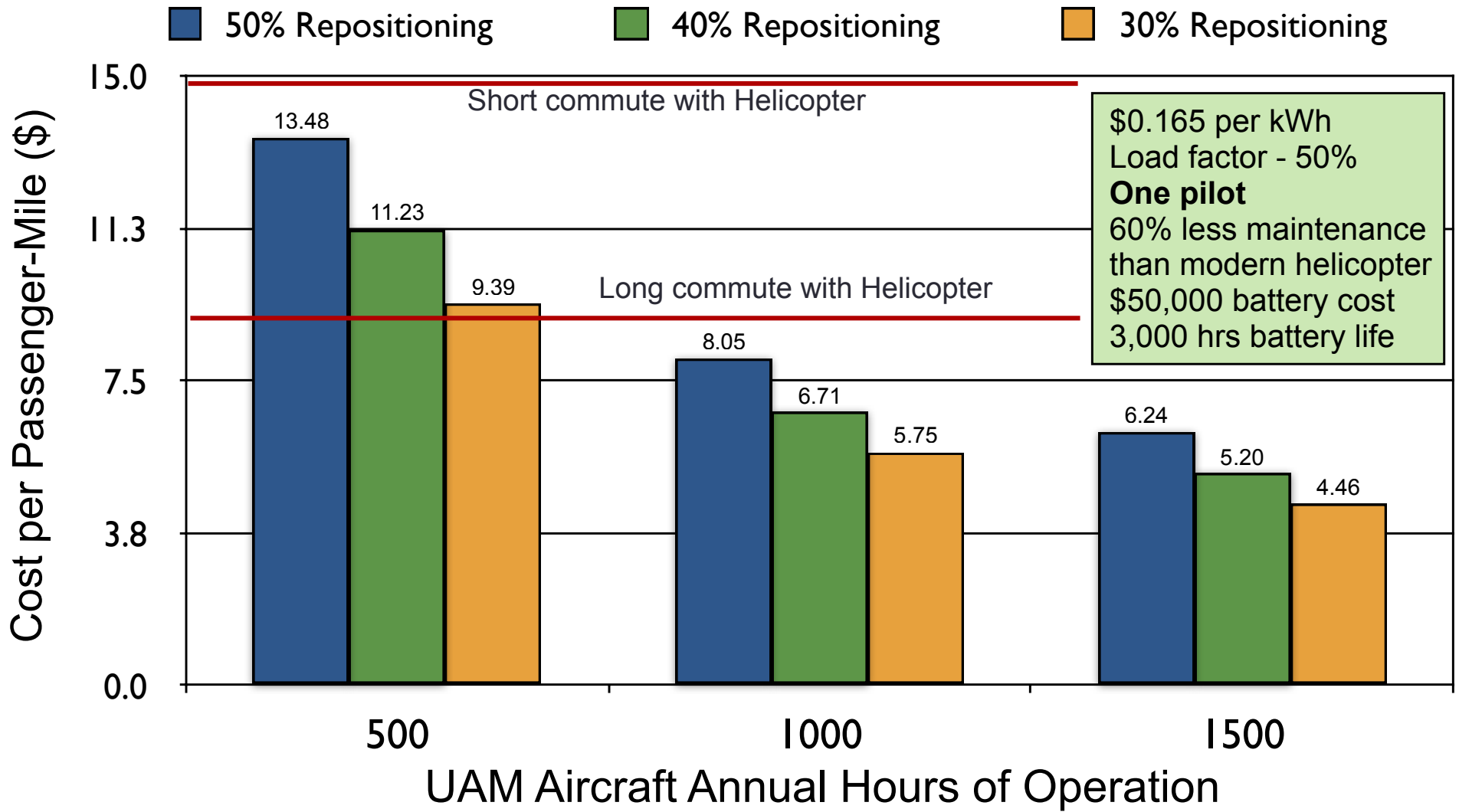
UAM Operational and Cost Uncertainties

1. UAM vehicle production and certification costs
2. Maintenance costs and cycles
 - UAM engines are electric and, in principle, are more reliable
 - UAM aircraft have 6-12 engines that need to be maintained
 - Even with high Mean Time Between Failures (MTBF) for the engines, many engines would require spares and maintenance actions
3. No-pilot option would require additional redundancy in systems for certification (an additional cost)
 - Additional automation cost would be needed for certification under remote pilot operations (assuming a pilot supervises/controls multiple UAM vehicles)
4. Battery life and costs
 - Our analysis uses \$50,000 to replace batteries after 3,000 hrs
5. Design for large number of daily cycles
 - Experience shows that commercial aircraft are designed for 40-60K cycles
 - It is unclear UAM aircraft would be economical if designed for 10-20K cycles
 - Blade helicopters (Bell 407) typically do 8-10 missions a day



Four-Seat UAM (\$3 Million Dollar Unit Cost)

Percent of Flights to Reposition UAM Aircraft



Analysis using the Virginia Tech UAM Life Cycle Cost model

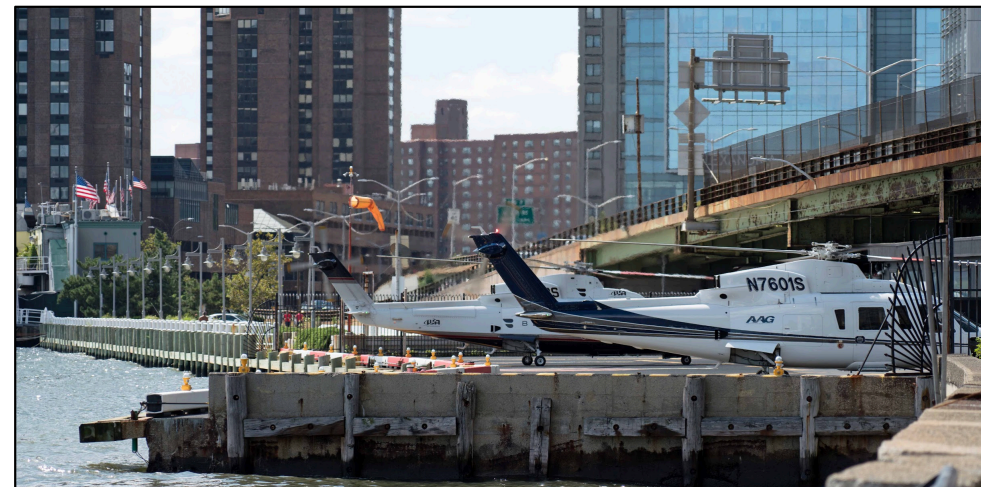


Blade Services to Airports in New York

- **\$195 per seat from Manhattan to JFK airport (\$15/passenger mile)**
- Bell 407 helicopters (single engine) operated under 14 CFR 135
- Five passenger seats (1 pilot + 5 passengers configuration)
- Typical six minute trip from JFK to two Manhattan heliport locations
- Typical daily use of Bell 407 helicopters is 177 minutes (2.95 hrs)
- **12,000 passengers per year (40 passengers per day)**



Bell 407 helicopter
Single Allison 250-C47B engine (813 HP)
6,000 lbs. maximum takeoff weight



Blade Lounge East
East 34th Street with two
Sikorsky S-76C++ helicopters

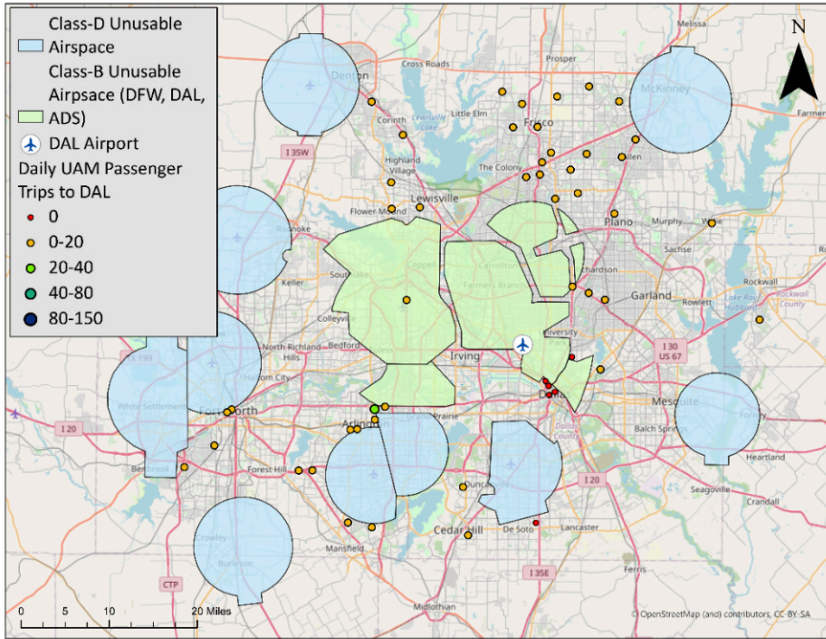


Calibrated UAM Demand Models



Calibrated Logit and Mixed Logit Models to Predict UAM Demand

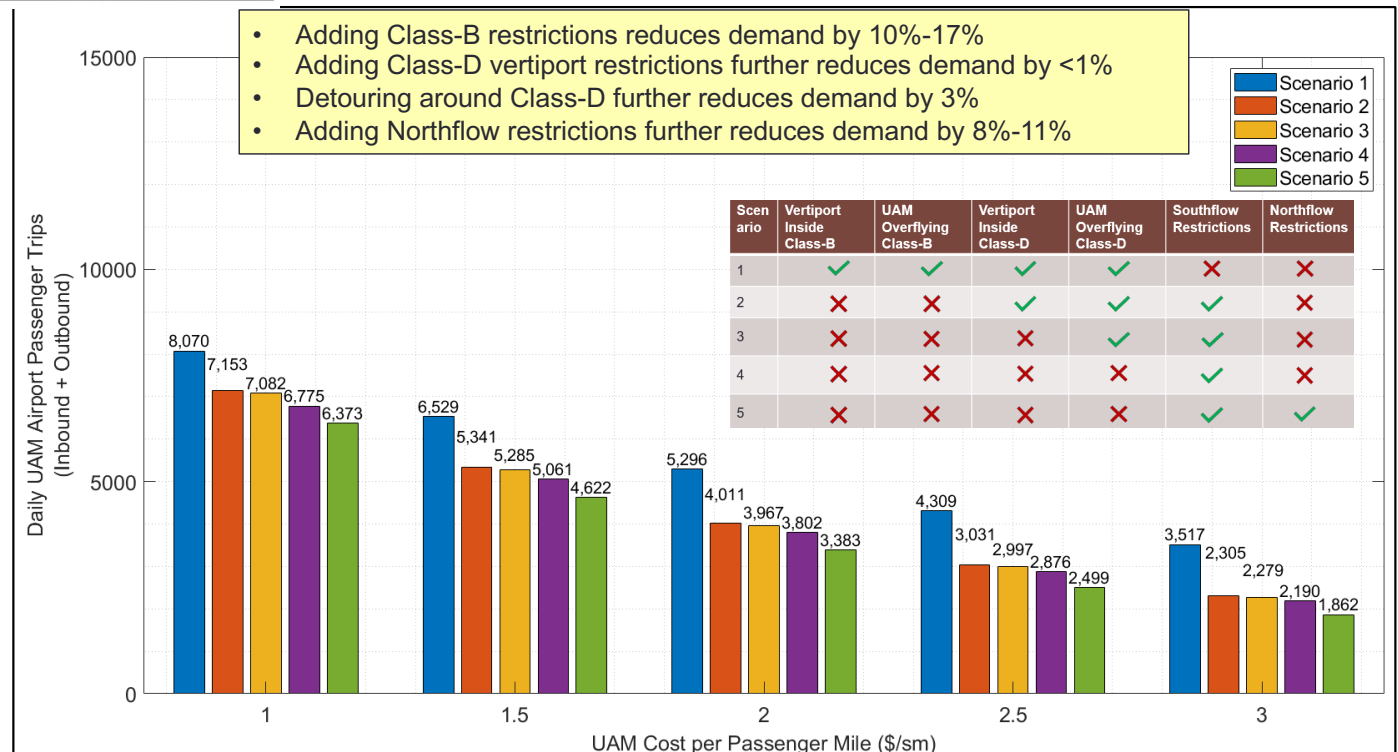
Metropolitan Area	UAM Model	Model Structure	Attributes Considered	Model Scope	Value of Time
Northern California	Commuter trips	Mixed Conditional Logit	In-vehicle travel time, Out-of-vehicle travel time, Number of transfers. Income level (3 categories)	4.3 million commuters 17 counties around San Francisco Bay Area	Out-of-Vehicle VOTs Low Income \$15.7/hr Medium Income \$18.22/hr High Income \$29.30/hr
	Cargo	Parametric Market Share Model	High value goods	High-value air freight Time-sensitive shipments	Not applicable
Southern California	Commuter trips	Mixed Logit Model	Travel time, number of transfers,	9.1 million commuter trips 15 counties	
	Airport trips	Conditional Logit Models	Travel time, Travel cost, Resident, Non-resident, Business, Non-business, submodes constants	99,250 daily airport trips	Business travelers \$52/hr. Non-business travelers \$22/hr.
	Cargo	Parametric - Market Share Model	High value goods	High-value air freight Time-sensitive shipments	Not applicable
Dallas-Forth Worth	Commuter trips	Mixed Logit Model	Travel time, number of transfers	2.9 million commuter trips	
	Airport trips	Conditional Logit Models	Travel time, Travel cost, Resident, Non-resident, Business, Non-business, submodes constants	45,750 daily airport trips	Business travelers \$57/hr. Non-business travelers \$36/hr.
Miami	Commuter trips	Mixed Logit Model calibrated in Northern California	Travel time, number of transfers	2.5 million commuter trips	
	Airport trips	Conditional Logit Models	Travel time, Travel cost, Resident, Non-resident, Business, Non-business,	35,600 daily airport trips	Business travelers \$57/hr. Non-business travelers \$36/hr.



Class B Airspace Restrictions Reduce Airport UAM Trip Demand by 17% in the Dallas Area

- Longer UAM travel times due to airspace class B and D restrictions affect trip cost
- UAM vertiport placement affected by airspace restrictions

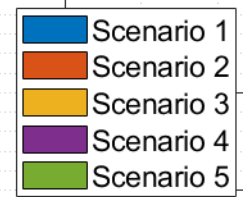
Airspace restrictions developed by NASA Ames Research Center





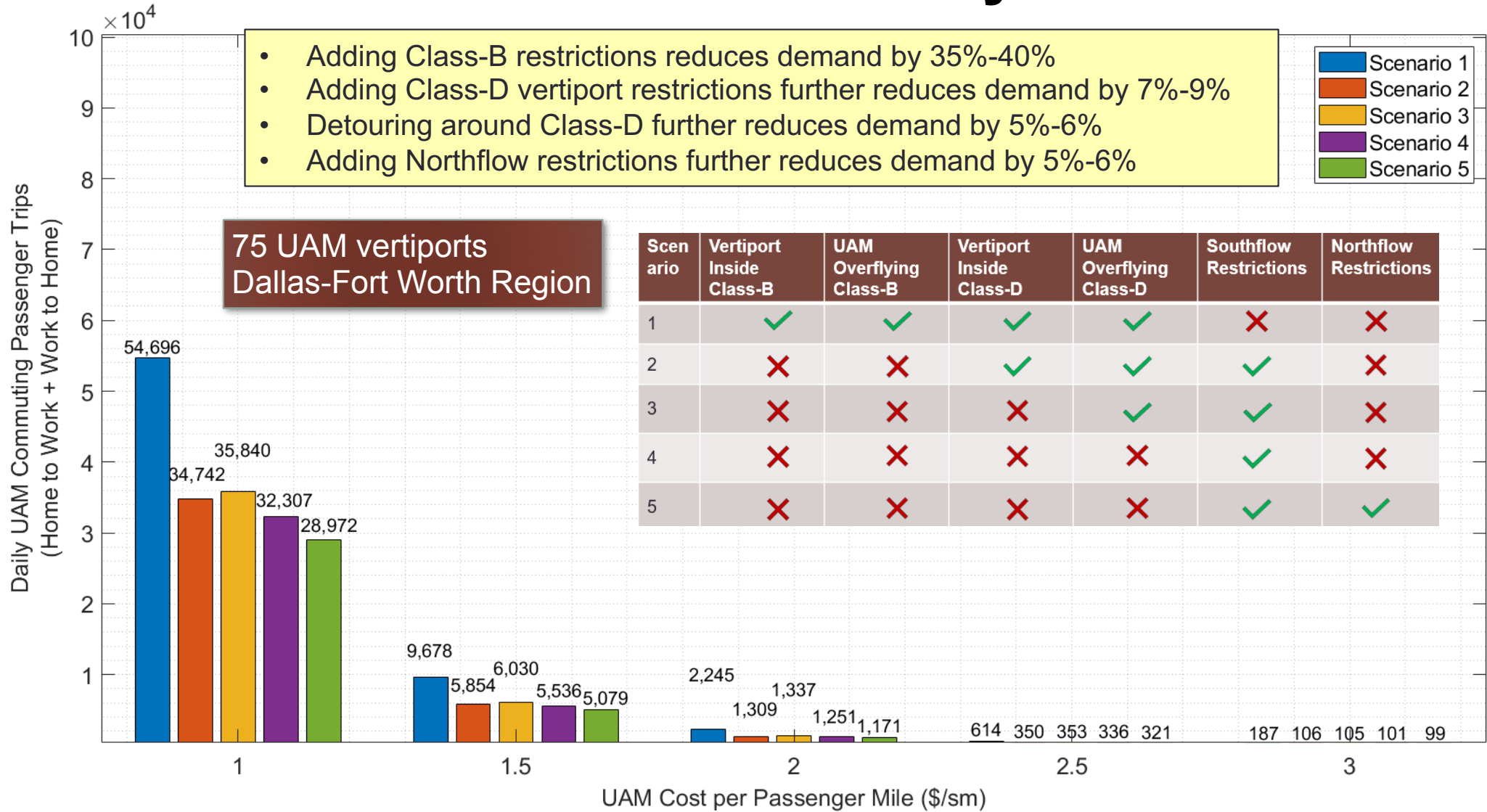
Class B Airspace Restrictions Reduce UAM Commuter Demand by 40%

- Adding Class-B restrictions reduces demand by 35%-40%
- Adding Class-D vertiport restrictions further reduces demand by 7%-9%
- Detouring around Class-D further reduces demand by 5%-6%
- Adding Northflow restrictions further reduces demand by 5%-6%



75 UAM vertiports
Dallas-Fort Worth Region

Scenario	Vertiport Inside Class-B	UAM Overflying Class-B	Vertiport Inside Class-D	UAM Overflying Class-D	Southflow Restrictions	Northflow Restrictions
1	✓	✓	✓	✓	✗	✗
2	✗	✗	✓	✓	✓	✗
3	✗	✗	✗	✓	✓	✗
4	✗	✗	✗	✗	✓	✗
5	✗	✗	✗	✗	✓	✓

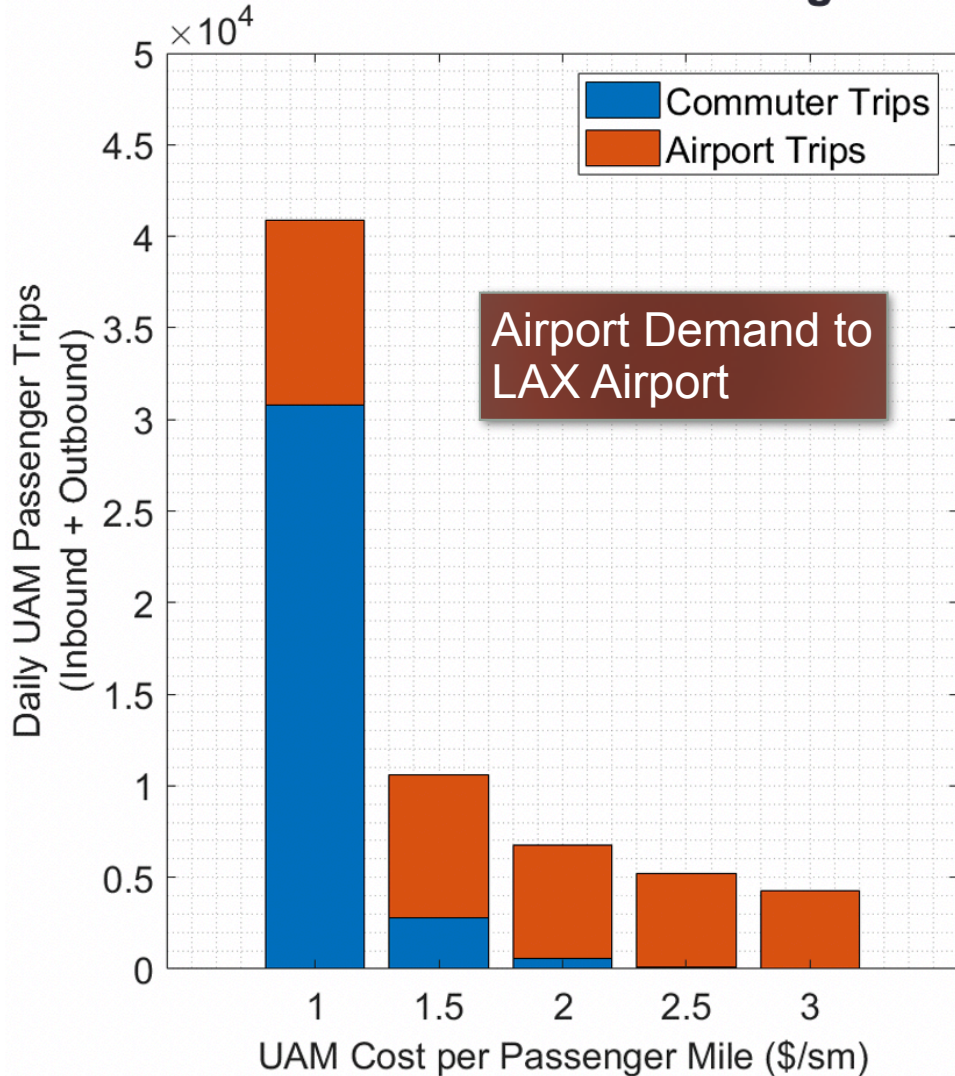




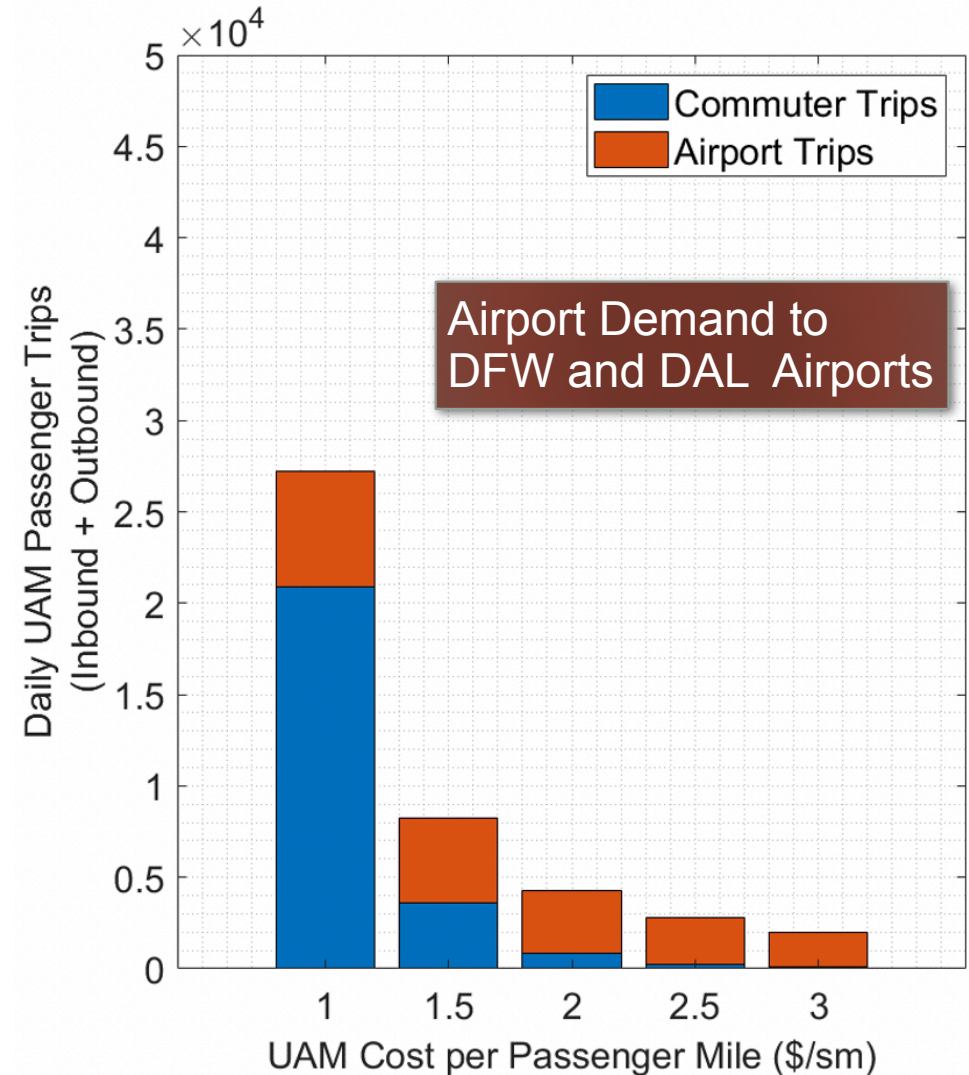
At \$3 per Passenger-Mile and Airspace Restrictions UAM Trips to Airport Remain Feasible

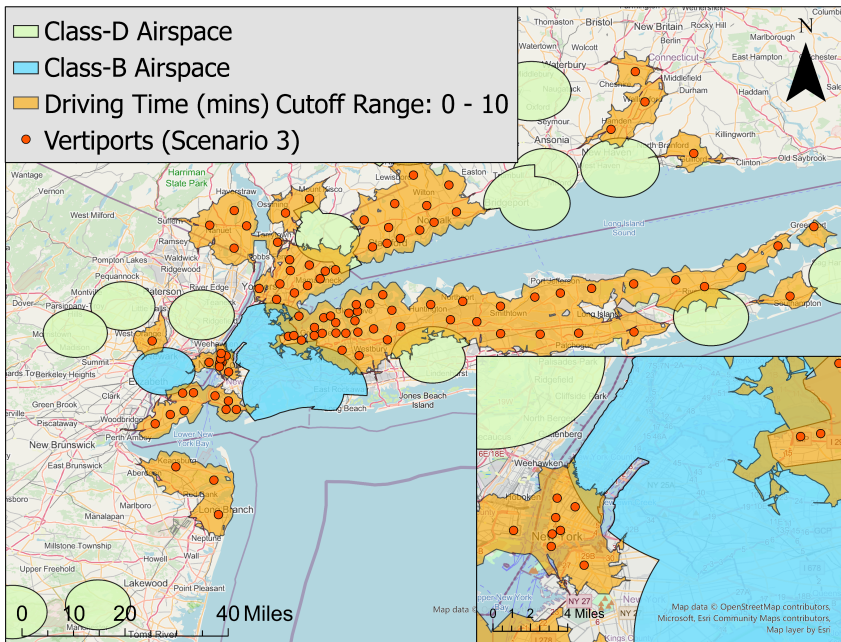
50 UAM vertiports and airspace restrictions

Southern California Region



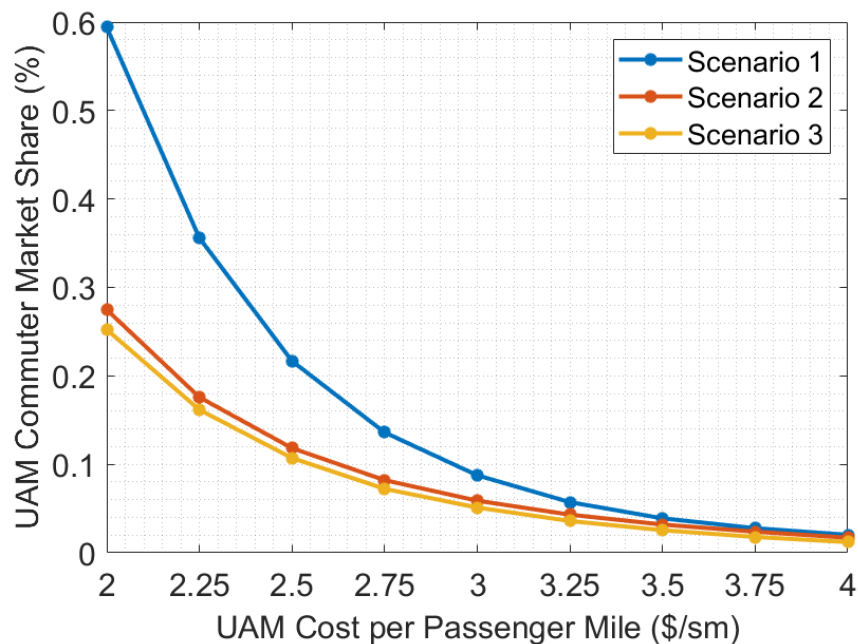
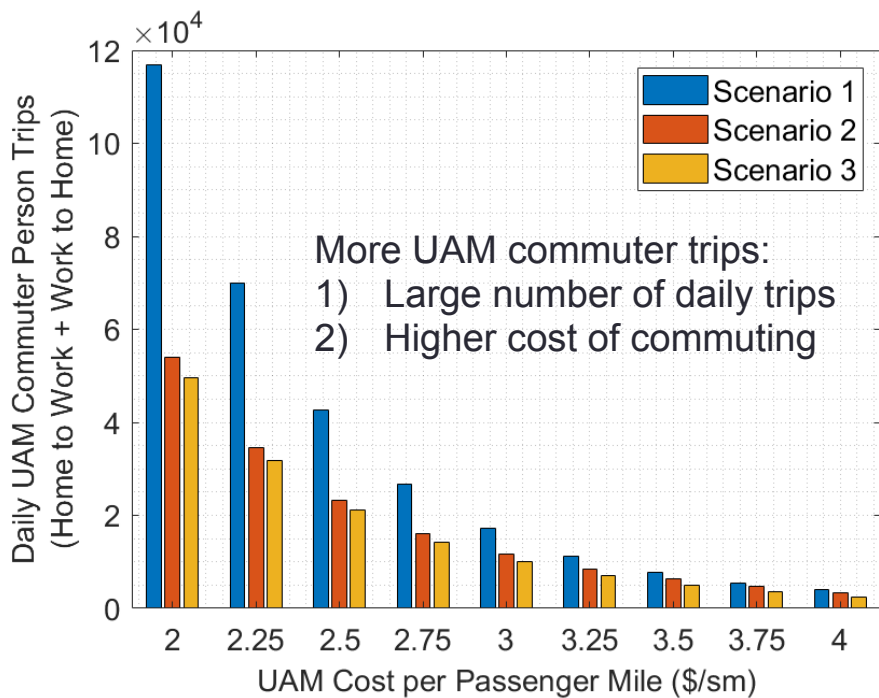
Dallas-Fort Worth Region





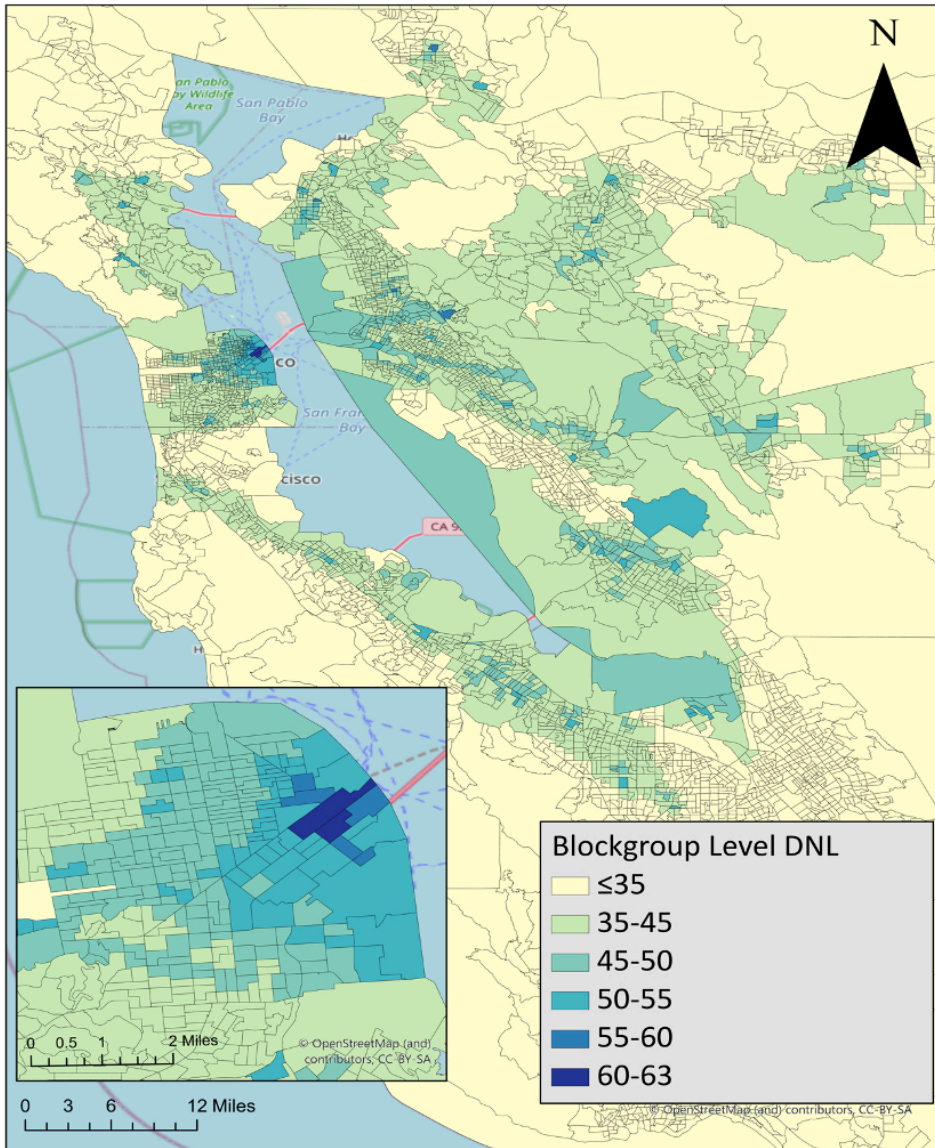
For New York Commuter Demand is Reduced by 55% if Airspace Restrictions are Applied

Scenario	Restrictions	
	Vertiport Placement	UAM Overflying
Scenario 1	None	None
Scenario 2	Only in Class-B Airspace	Only in Class-B Airspace
Scenario 3	In Class-B and Class-D Airspace	In Class-B and Class-D Airspace

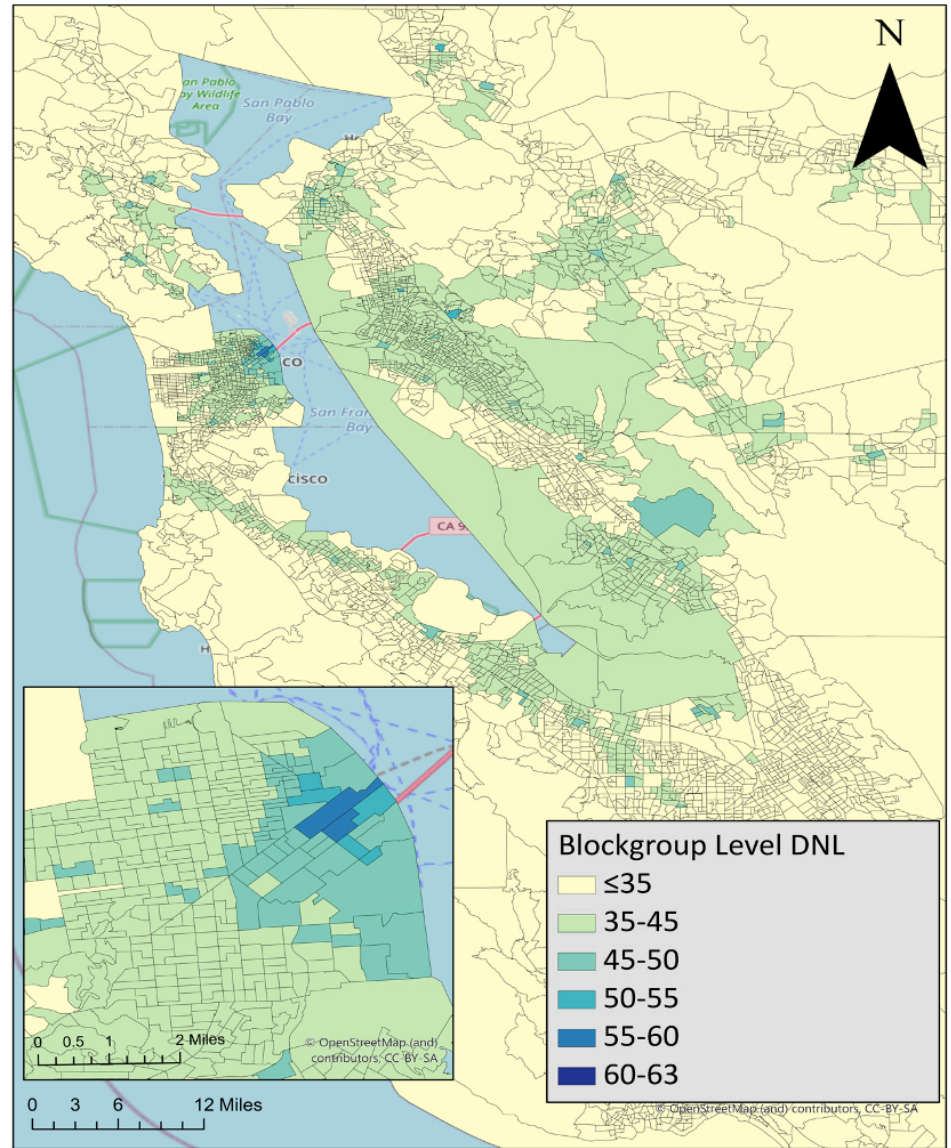




Preliminary Assessment of UAM Noise (Northern California)



10 dBA Reduction compared to R44



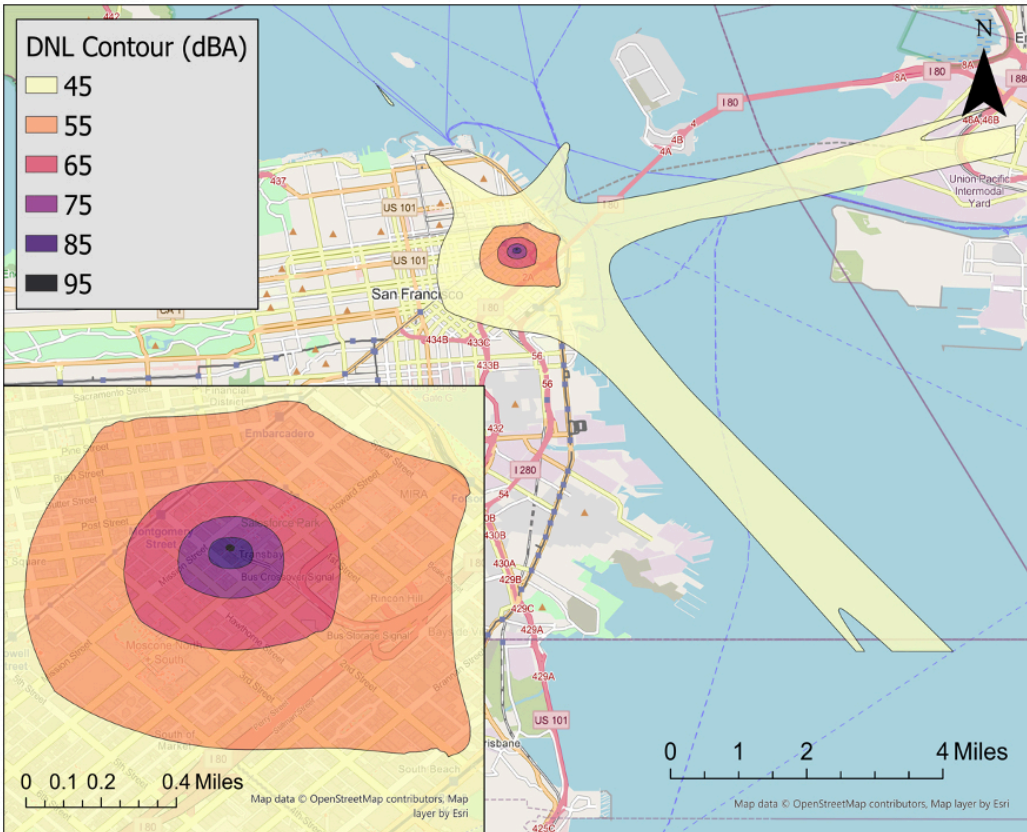
15 dBA Reduction compared to R44



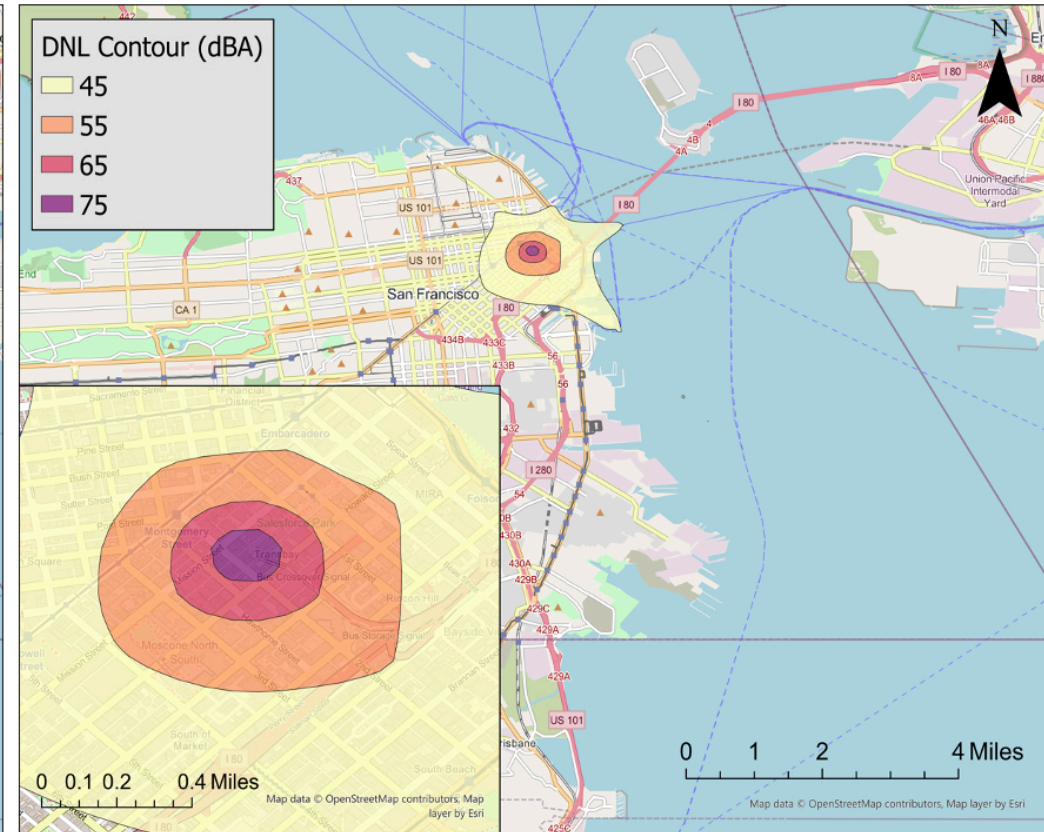
Noise Impacts Using the FAA Aviation Environmental Design Tool Analysis

900 daily UAM operations

DNL	Area under DNL Contour (sq. mi.)		Population under DNL Contour		Highly Annoyed Population	
	10-dBA	15-dBA	10-dBA	15-dBA	10-dBA	15-dBA
45	10.89	1.81	110,811	28,764	21,133	5,485
55	0.70	0.33	11,655	4,213	5,687	2,055
65	0.16	0.08	1,596	677	1,267	537
75	0.03	0.0155	272	93	256	87
85	0.006	-	2	-	2	-
95	0.0002	-	-	-	-	-



15 dBA Reduction compared to R44



10 dBA Reduction compared to R44



Conclusions

- An integrated approach to study UAM operations has been developed
 - Model considers landing site placement, landing site cost and capacity limits
 - UAM demand is estimated using Conditional Logit or Mixed Logit models
- For UAM to be successful, the analysis shows cost per passenger mile needs to be contained at or below \$3 per passenger-mile
- Beyond \$3 per passenger mile, the commuter demand is relatively low
 - New York may see a few hundred person trips of airport demand in the \$5-7 per passenger mile range (high driving cost and high congestion)
- Airspace restrictions result in 20-55% fewer demand trips compared to unrestricted scenarios investigated



Relevant Technical Publications

1. Rimjha, M., A., Trani, and S. Hotle, Urban Air Mobility: Preliminary Noise Analysis of Commuter Operations, AIAA 2021, July 28, 2021, American Institute of Aeronautics and Astronautics, <https://doi.org/ezproxy.lib.vt.edu/10.2514/6.2021-3204>
2. Rimjha, M., Hotle, S., A., Trani, A.A, Hinze, N. and J. Smith, Urban Air Mobility Demand Estimation for Airport Access: A Los Angeles International Airport Case Study, Integrated Communications, Navigation and Surveillance Conference, ICNS, v 2021, April 19-23, 2021, Institute of Electrical and Electronics Engineers Inc.
3. Rimjha, MA. And A.A. Trani, Urban Air Mobility: Factors Affecting Vertiport Capacity, Integrated Communications, Navigation and Surveillance Conference, ICNS, v 2021, April 19-23, 2021, Institute of Electrical and Electronics Engineers, Inc.
4. Rimjha, M., Hotle, S., Trani, A.A, and Hinze, N., Commuter Demand Estimation and Feasibility Assessment for Urban Air Mobility in Northern California, Transportation Research Part A: Policy and Practice, Volume 148, June 2021, Pages 506-524, Elsevier (<https://doi.org/10.1016/j.tra.2021.03.020>).
5. Sayantan, T., Rimjha, M., Hinze, N., Hotle, S. and Trani, A. A. Urban Air Mobility Regional Landing Site Feasibility and Fare Model Analysis in the Greater Northern California Region, Integrated Communications, Navigation and Surveillance Conference, ICNS, v 2019-April, April 2019.
6. Rimjha, M., Tarafdar, S., Hinze, N., Trani, A.A., Swingle, H., Smith, J., Marien, T., and S. Dollyhigh., On-Demand Mobility Cargo Demand Estimation in Northern California Region, Integrated Communications, Navigation and Surveillance Conference, v 2020-September, September 2020, Institute of Electrical and Electronics Engineers, Inc.
7. Syed, N., Rye, M., Ade, M., Trani, A., Hinze, N., Swingle, H., Smith, J., Dollyhigh, S. & Marien, T. (2017). Preliminary Considerations for ODM Air Traffic Management based on Analysis of Commuter Passenger Demand and Travel Patterns for the Silicon Valley Region of California. In 17th AIAA Aviation Technology, Integration, and Operations Conference (p. 3082), <https://doi.org/10.2514/6.2017-3082>



Transportation Systems Analysis Model (TSAM)

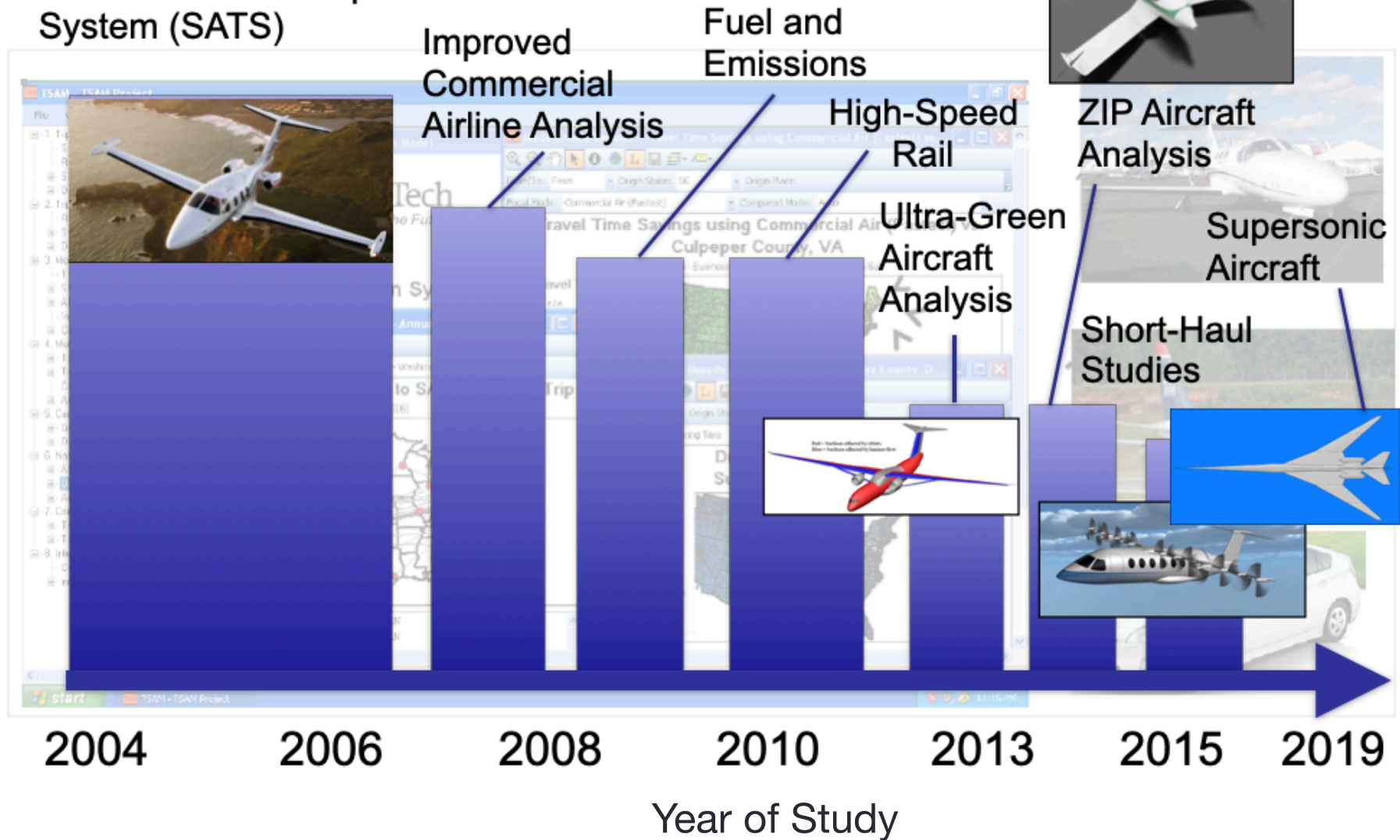


The TSAM Model

- A multi-mode intercity trip demand model that predicts long distance travel (one-way route distance greater than 100 miles) in the continental U.S.
- Employs a multi-step, multi-modal transportation planning framework where trips are: produced, distributed, split into modes, and assigned to routes
- TSAM model can predict intercity travel in the presence of multi-mode alternatives (auto, commercial air, high-speed rail and air taxi modes)
- Mode choice of travelers based on trip characteristics (business and non-business) and traveler demographics (income level)
- Mode choice is sensitive to vehicle performance, level of service and mode cost characteristics
- County-to-county spatial model
- Accepts user-defined airport sets
- Model has airport capacity curves derived using the Enhanced Airfield Capacity

Application of the TSAM Model

TSAM Development
Small Aircraft Transportation
System (SATS)





TSAM is a 64-bit Stand-alone Application

The screenshot shows the TSAM software interface. On the left is a project tree with the following structure:

- 1. Trip Generation
 - Select Inputs
 - Run Module
 - Summarized Results
 - Detailed Results
- 2. Trip Distribution
 - Run Module
 - Summarized Results
 - Detailed Results
- 3. Mode Choice
 - 1 County to 1 County
 - State to All Counties
 - All Counties to All Counties
 - Import Custom Airport Set
 - Compare Cases
- 4. Mobility Analysis
 - Travel Time
 - Airport to Airport Travel Time
 - Station to Station Travel Time
 - County to County Driving Time
 - Tables
 - Maps
 - Travel Cost
 - Commercial Airline Network
 - Road Network
 - Airport Selection
- 5. Cargo
 - All Cargo
 - UAS Cargo
- 6. National Airspace System
 - Air Taxi
 - Flight Generator
 - Airspace Occupancy
 - Legacy General Aviation
 - Commercial Airline
 - Airport Capacity
 - Tables
 - Pareto Diagrams
 - Maps
- 7. Commuter Travel
 - Trip Generation

The main content area features the Virginia Tech logo (with the tagline "Invent the Future") and the NASA logo. The title is "Transportation Systems Analysis Model (TSAM)" with "Version 7.0 - Release - Date : 03/25/2013".

Virginia Tech - Air Transportation Systems Lab

Dr. Antonio Trani (Team Leader)	Nicolas Hinze
Dr. Hojong Baik (Team Co-Leader)	Howard Swingle
Senanu Ashiabor	Anand Seshadri
Nola Shen	Krishna Murthy
Yue Xu	DongHyeok Sohn

NASA Langley Research Center - Project Sponsors

Jeff Viken	Sam Dollyhigh
Systems Integration Lead	Nelson Guerreiro
Systems Analysis Branch	ATK

A red callout box contains the text: "Currently version 7.7".

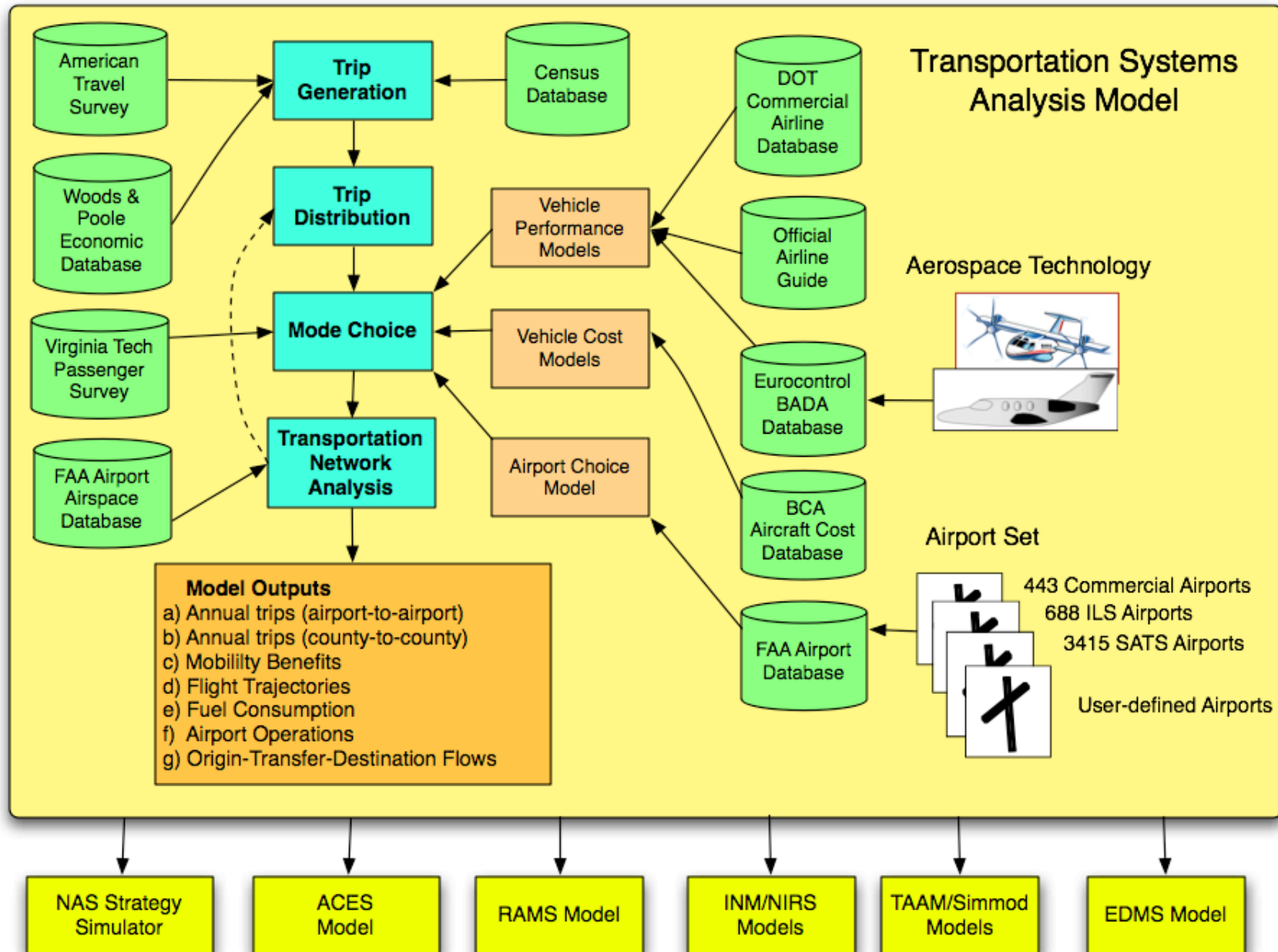
For technical questions about the TSAM please contact Nicolas Hinze (nhinze@vt.edu) directly.

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TSAM Model Flowchart





TSAM Computer Model Application

The screenshot displays the TSAM (Transportation Systems Analysis Model) software interface. The main window is titled "Transportation Systems Analysis Model" and features the Virginia Tech logo with the tagline "Invent the Future". Below the logo, the text "Transportation Systems" is visible.

On the left side, there is a navigation tree with the following categories:

- 1. Trip Generation
 - Select Inputs
 - Run Module
 - Summarized Results
 - Detailed Results
- 2. Trip Distribution
 - Run Module
 - Summarized Results
 - Detailed Results
- 3. Mode Choice
 - 1 County to 1 County
 - State to All Counties
 - All Counties to All Counties
 - Import Custom SATS Airport Set
 - Compare Cases
- 4. Mobility Analysis
 - Travel Time
 - Travel Cost
 - Commercial Airline Network
 - Airport Selection
- 5. Cargo
 - Generation
 - Distribution
- 6. National Airspace System
 - ACES
 - Origin-Transfer-Destination
 - Airspace Occupancy
- 7. Commuter Travel
 - Trip Generation
 - Trip Distribution
- 8. International Travel
 - Create New Case Folder...
 - international2006

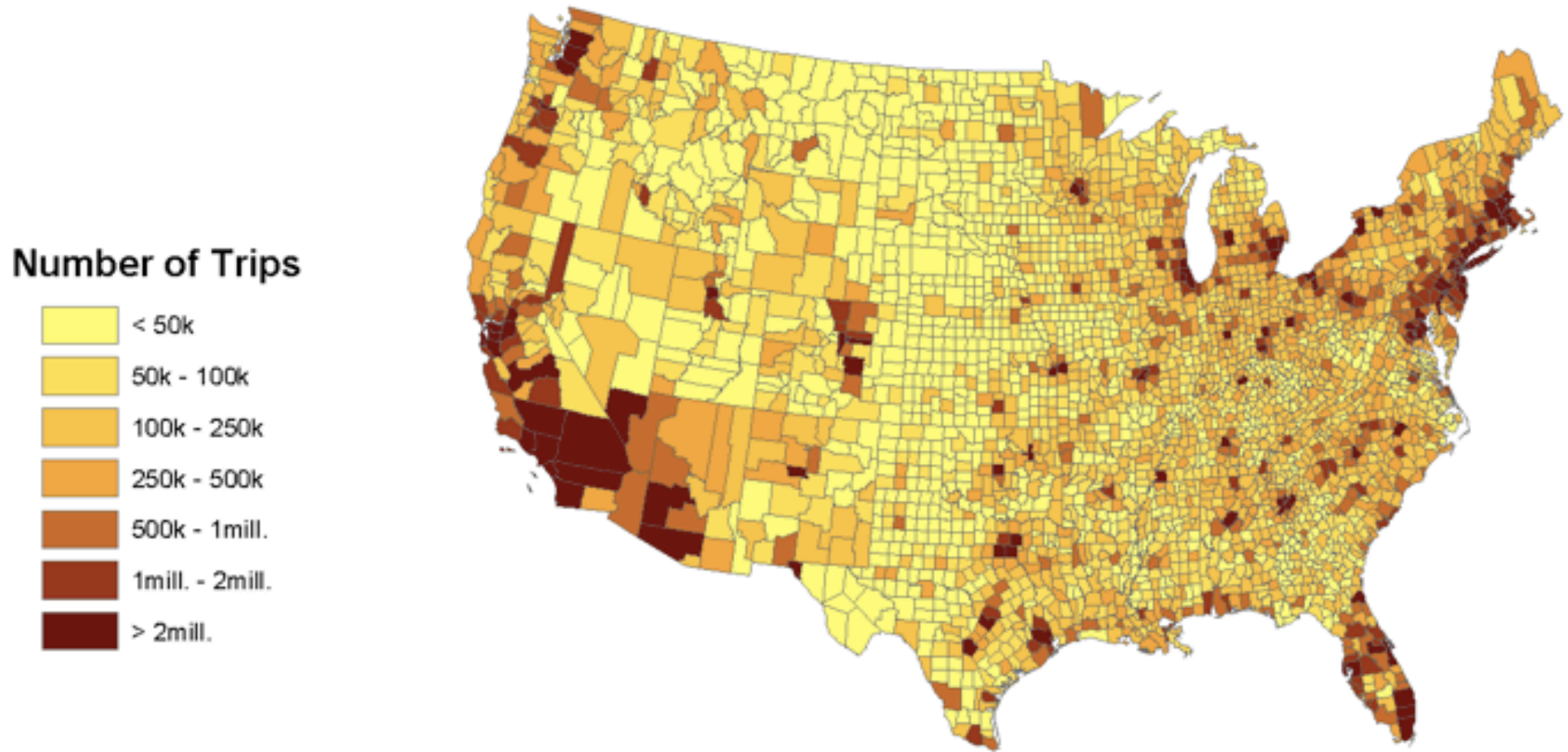
Several analysis windows are open:

- Mode Choice Results - Travel Time Savings using Commercial Air (Fastest) vs... Culpeper County, VA**: Shows a map of Virginia with travel time savings data. Parameters include Origin State: DE, Origin Place: From, Focal Mode: Commercial Air (Fastest), and Compared Mode: Auto. Case details: (VLJ - \$2.25 - Business - Full Without DEP - 2025 - Case 6a).
- Origin-Transfer-Destination Results - Annual Flows from IAD to SAN - Average Trip (otd_2006)**: Displays a map of the United States with flight routes. Legend: Green circle for Origin Airport (IAD), Red circles for Intermediate Airports, and Blue circle for Destination Airport (SAN). Routes listed: Route 1: IAD -> ATL -> SAN; Route 2: IAD -> CLE -> SAN.
- Mobility Analysis Results - Driving Time From Sussex County, D...**: Shows a map of the United States with driving time intervals. Legend: 3.0 to 4.0 hrs, 4.0 to 5.0 hrs, 5.0 to 6.0 hrs, 6.0 to 7.0 hrs, 7.0 to 8.0 hrs, 8.0 to 9.0 hrs, 9.0 to 10.0 hrs, > 10.0 hrs.

The bottom status bar indicates: "Transportation Systems Analysis Model (TSAM) - Version 4.0.1 - Release - Date : 09/19/2006". The Windows taskbar shows the start button, the application name "TSAM - TSAM Project", and the system clock "11:15 PM".



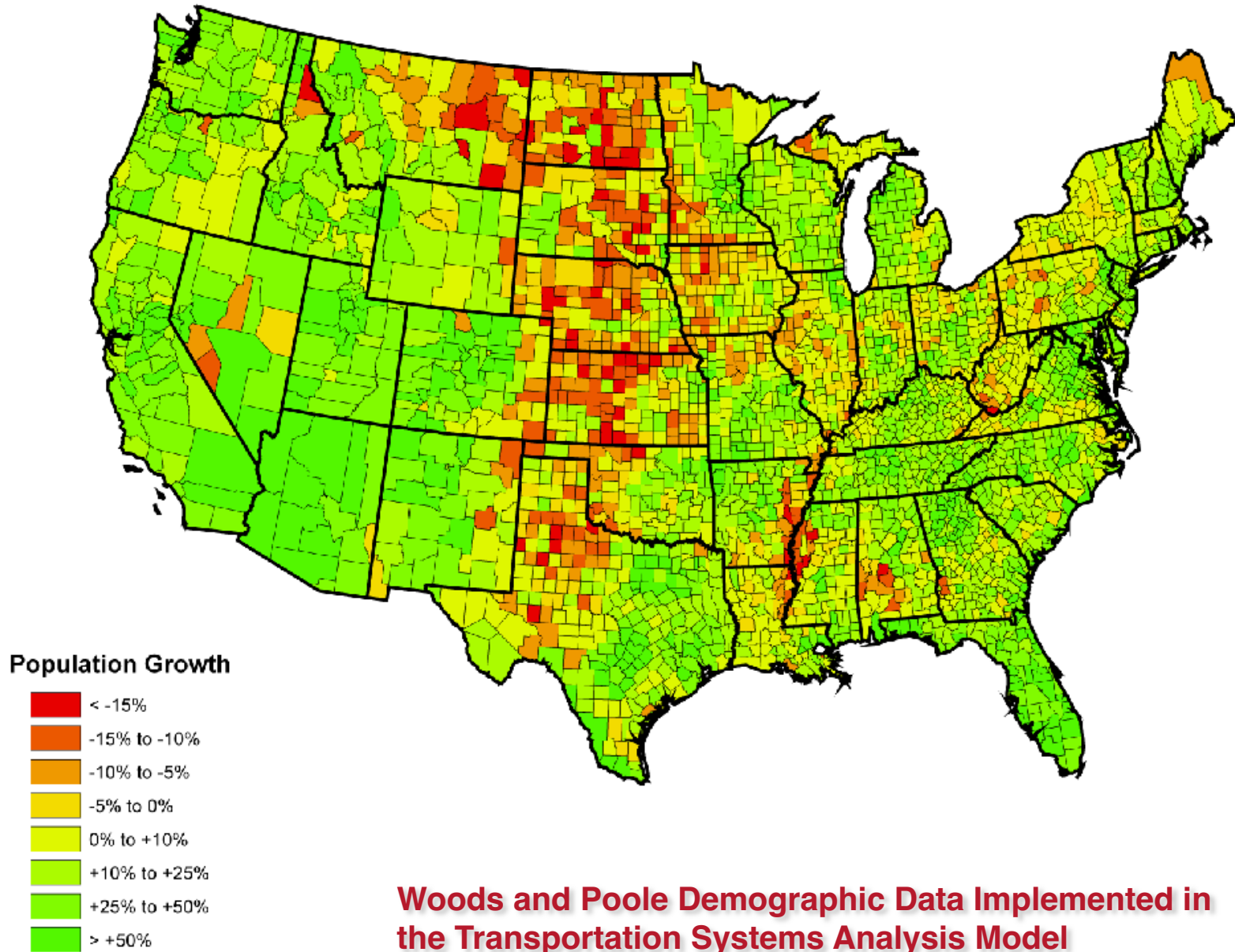
TSAM Trip Generation



**Total Intercity Trips Generated by County
(Business + Non-Business Trips)**



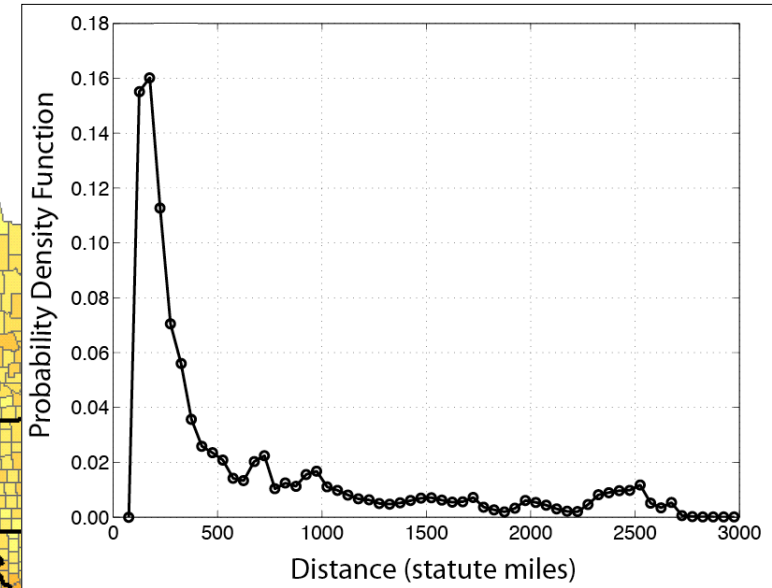
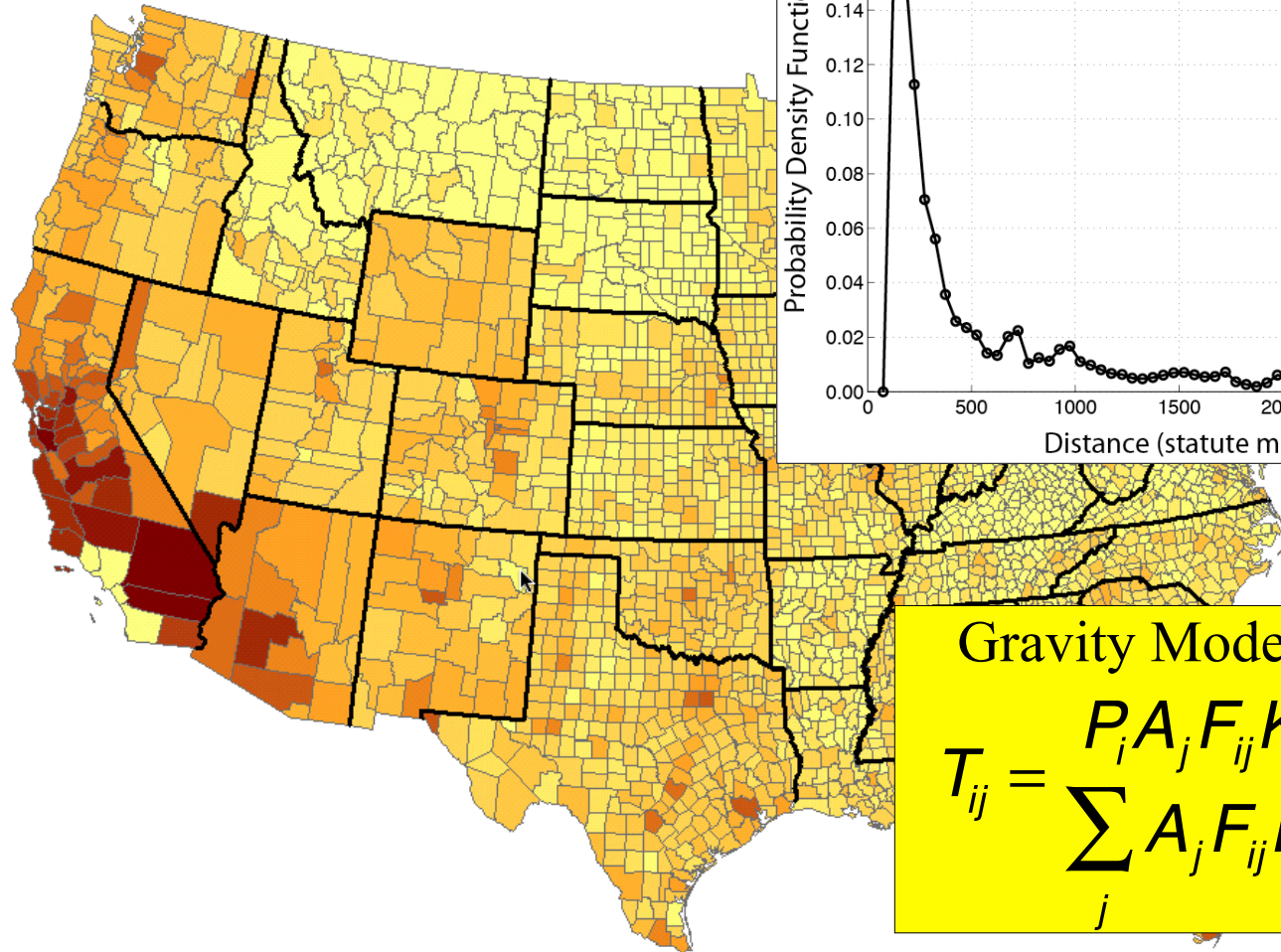
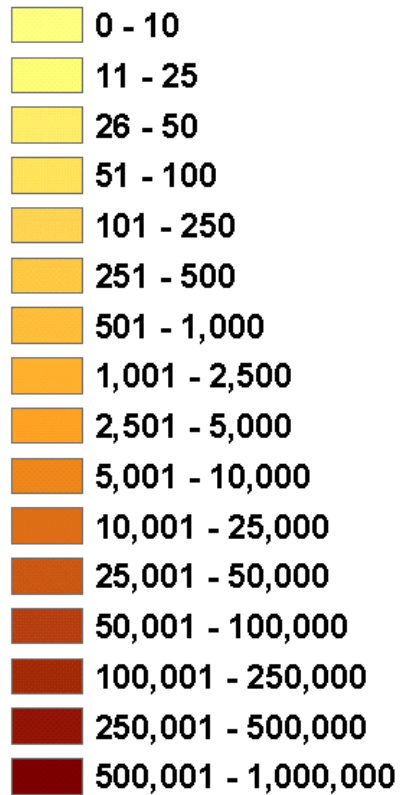
Socio-Economics Behind TSAM



Trip Distribution Step

Virginia Tech

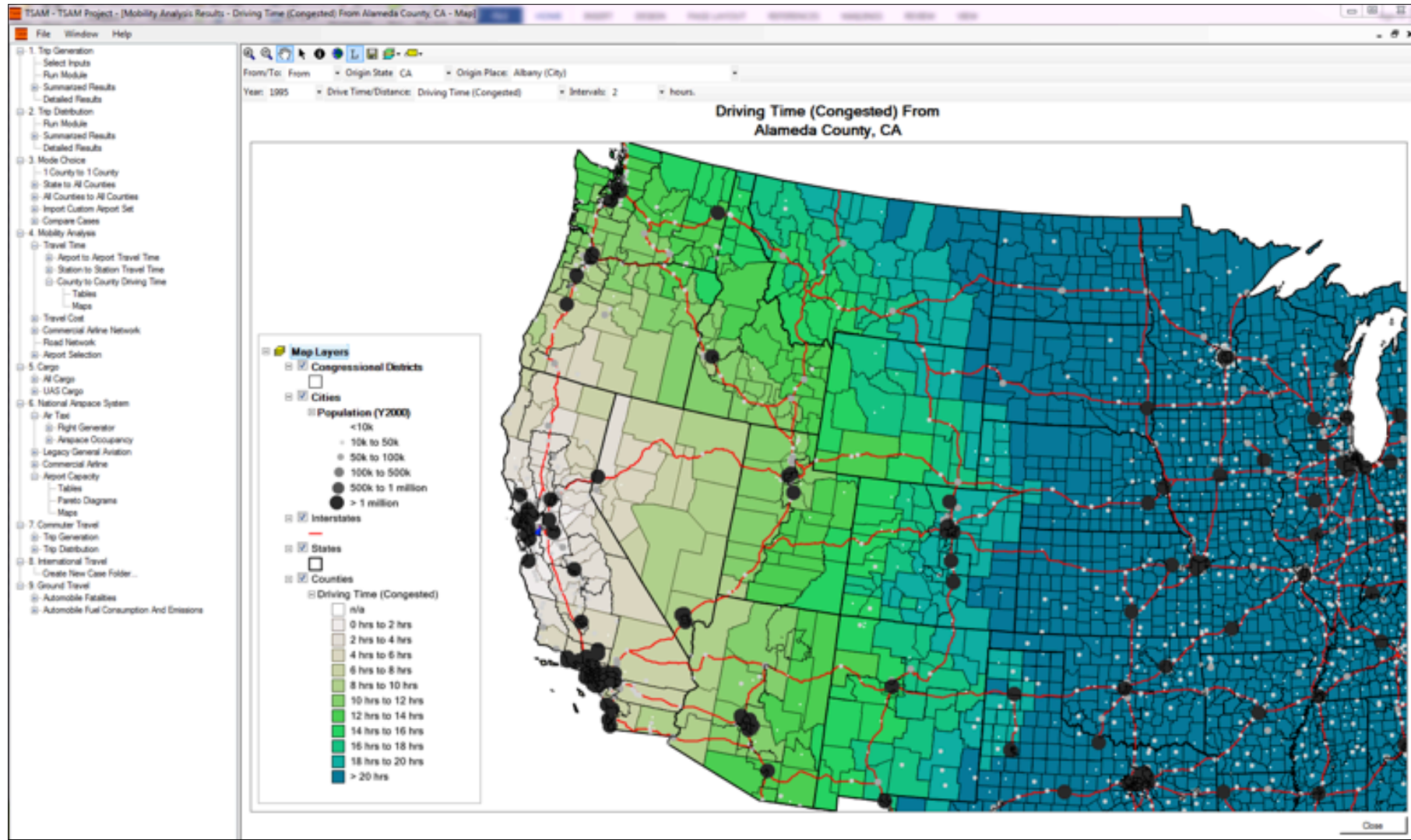
Legend



Gravity Model

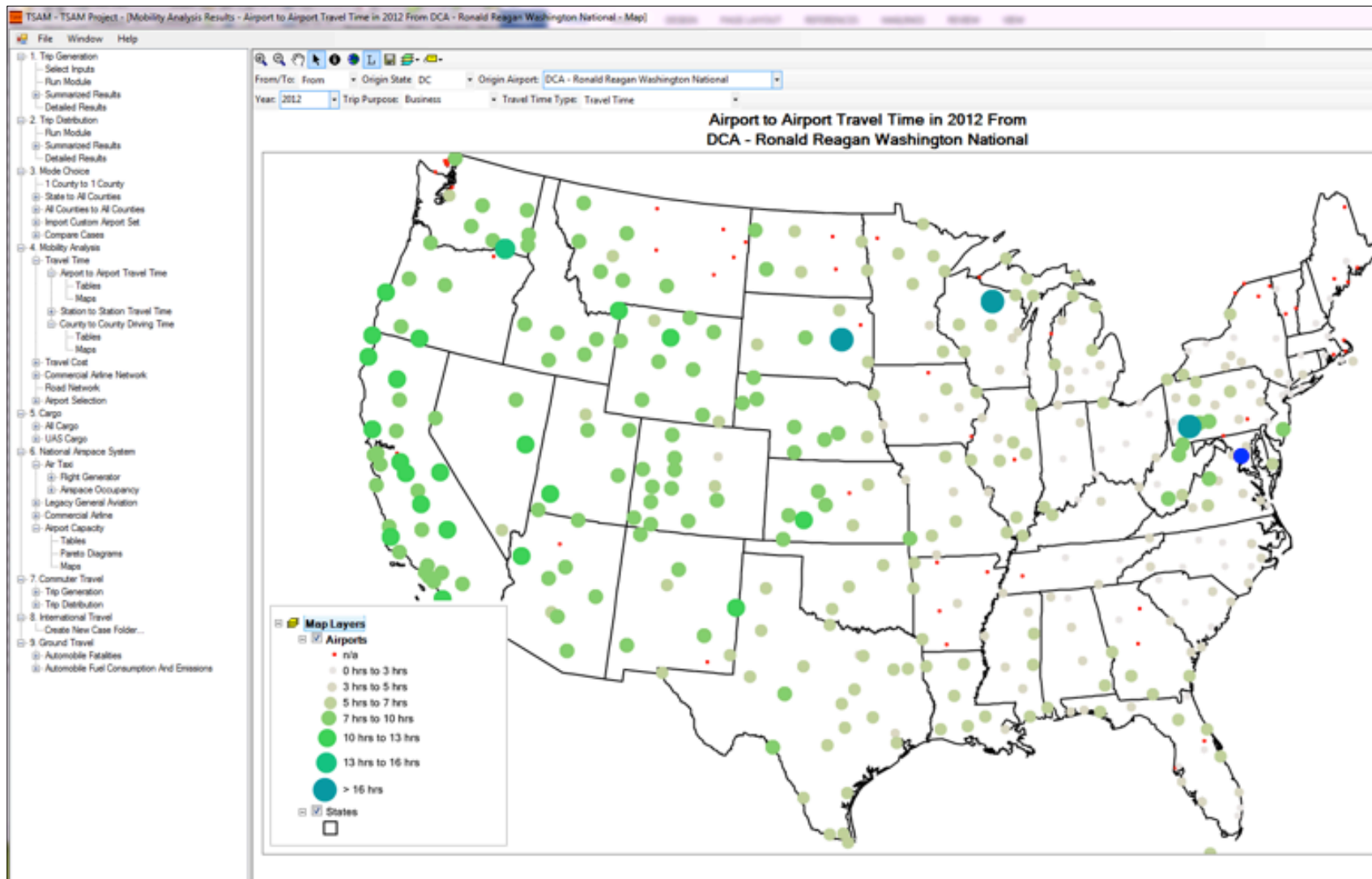
$$T_{ij} = \frac{P_i A_j F_{ij} K_{ij}}{\sum_j A_j F_{ij} K_{ij}}$$

Sample TSAM Map: Auto Driving Time



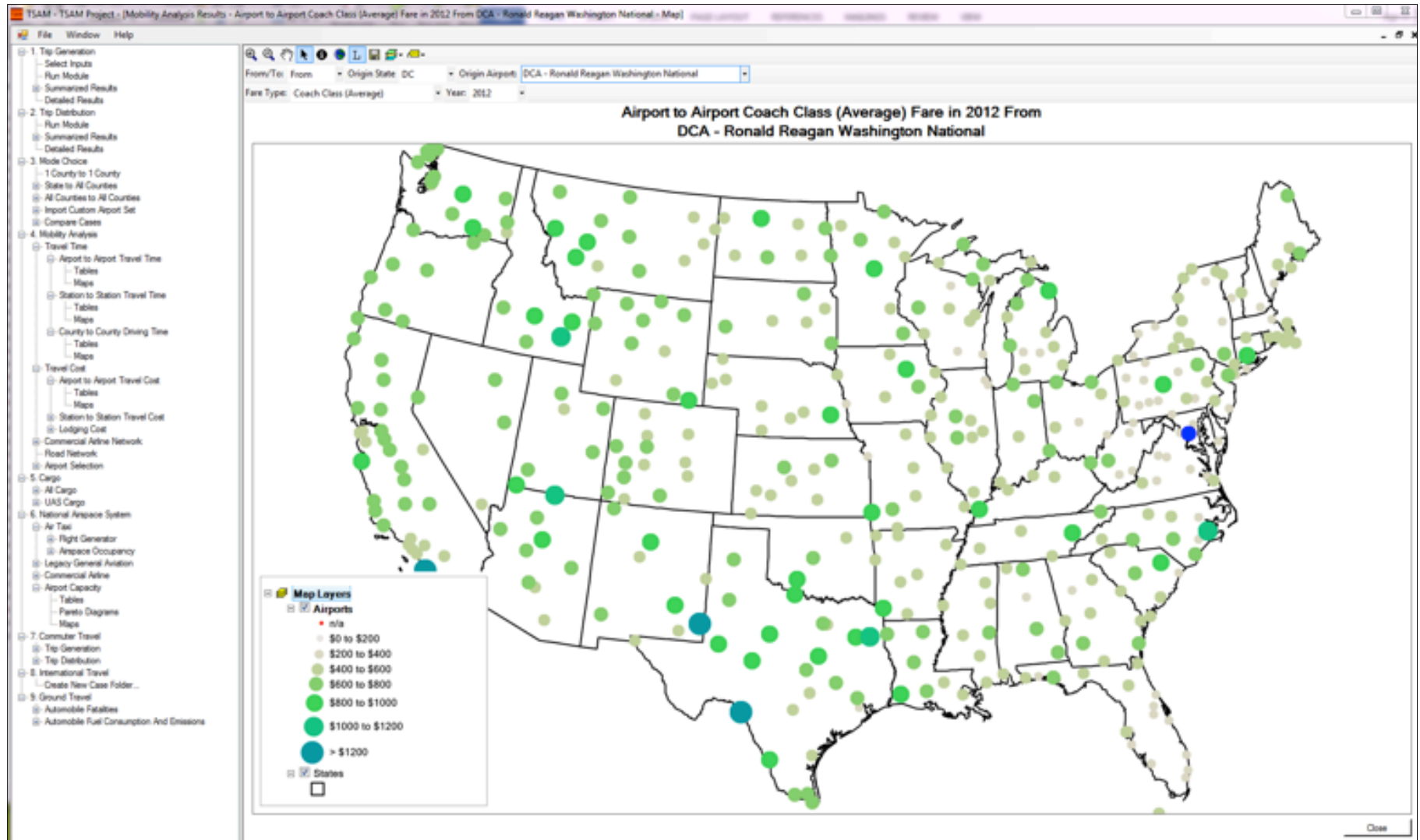


Sample TSAM Map: Airport-to-Airport Travel Time

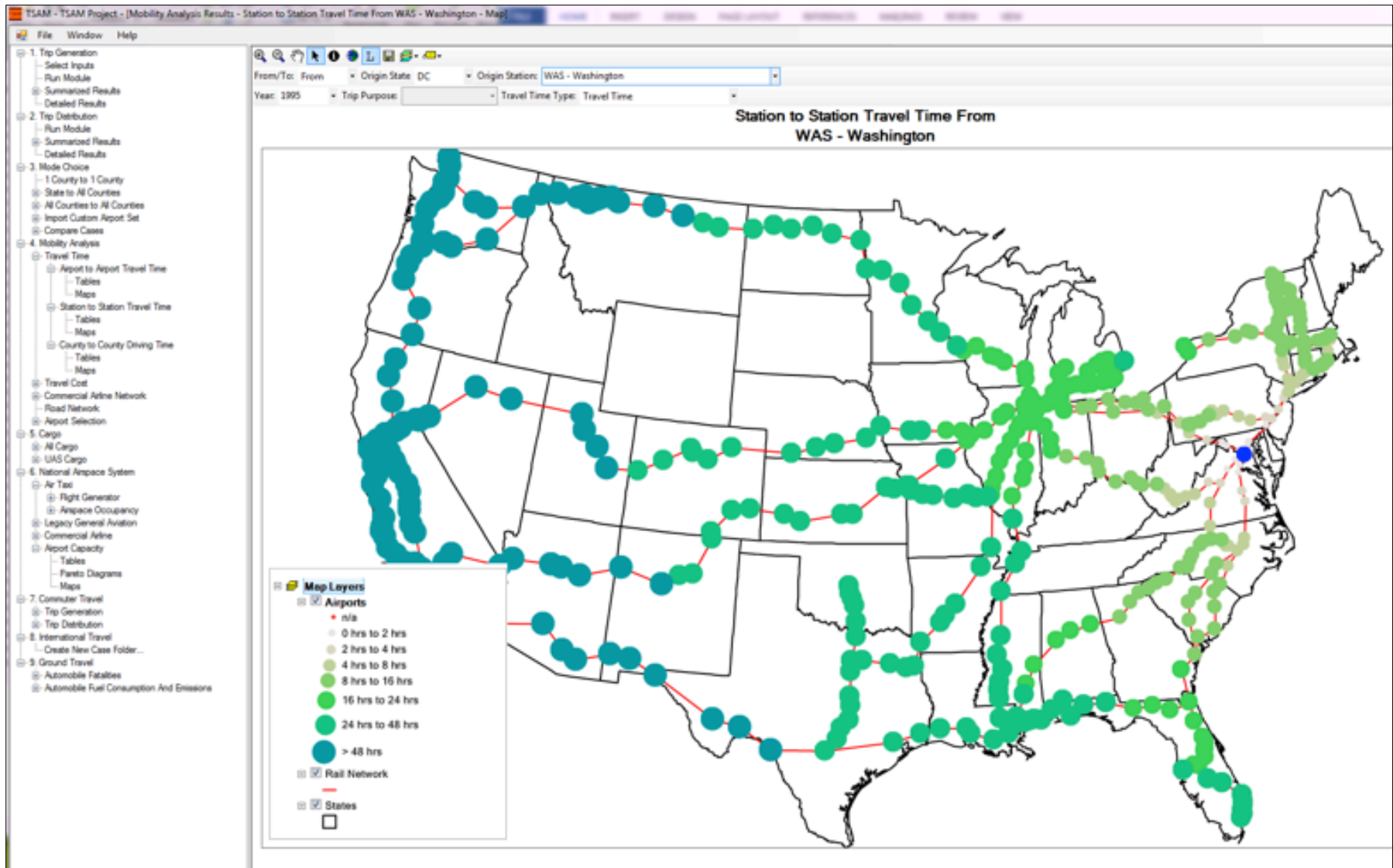




Sample TSAM Map: Airport-to-Airport Average Coach Fares

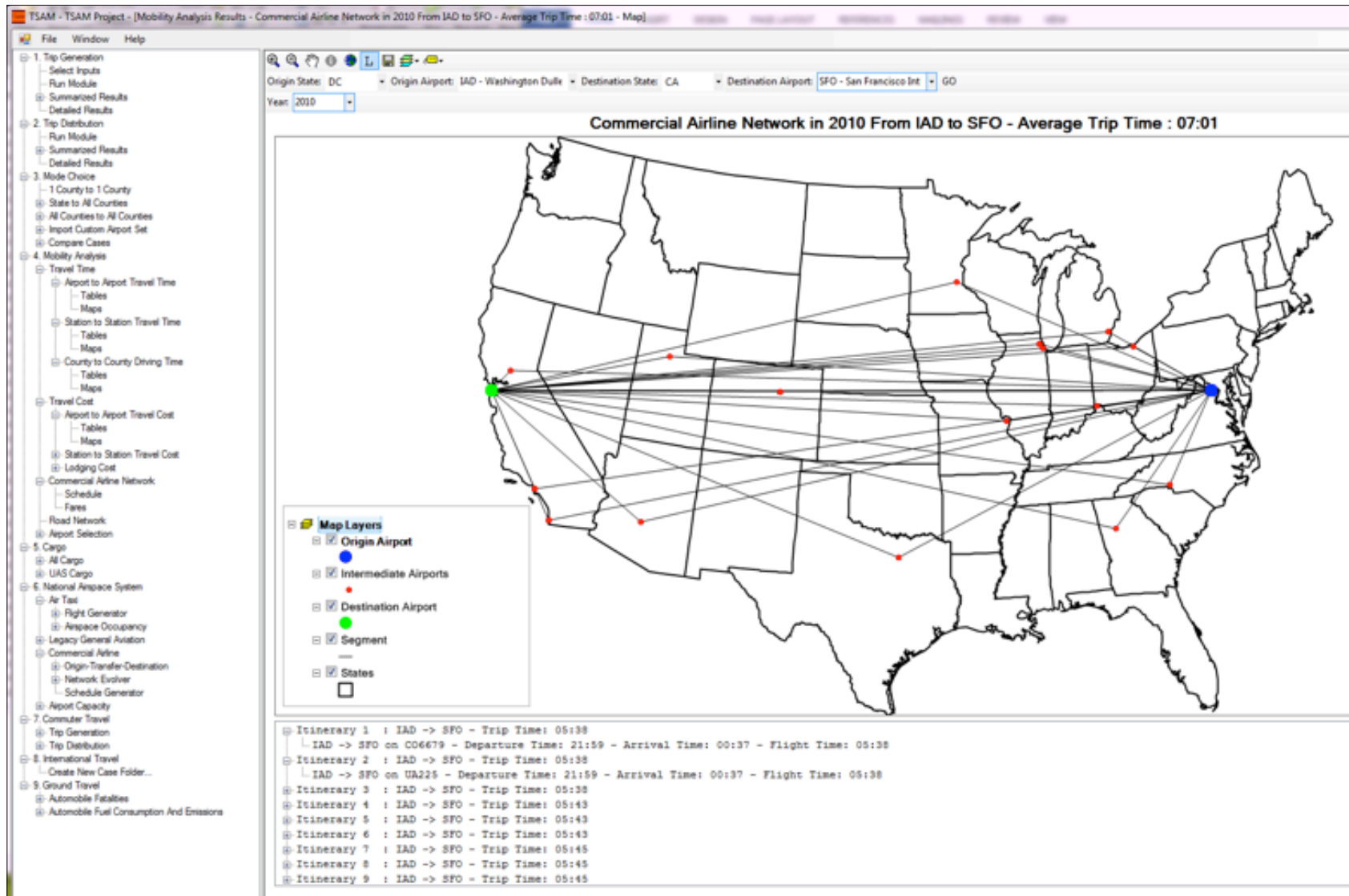


TSAM Map: US Rail System Travel Time



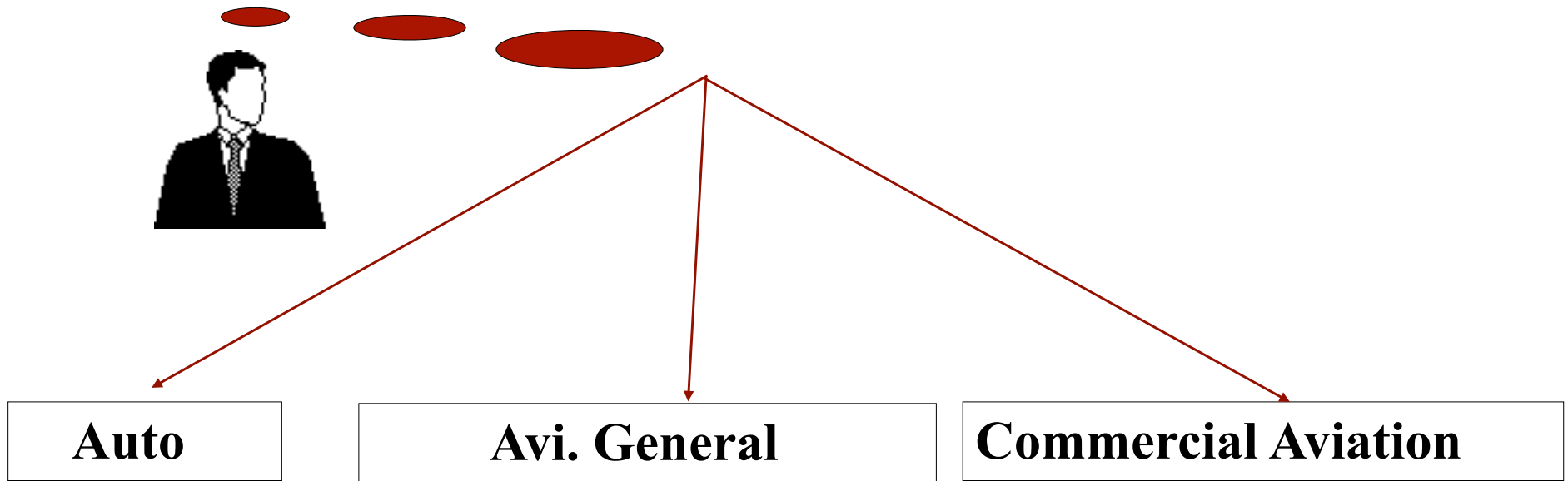


Sample TSAM Map: Commercial Airline Network (IAD-SFO)





Mode Choice Analysis



Factors considered in mode split:

- Travel time
- Travel cost
- Value of time
- Route convenience
- Trip type

Route1 Route2... Route n
Includes Airport Choice

TSAM employs a family of Logit Models (Box-Cox and C-Logit)



Variables Used in Utility Functions

Authors	Variables in the Utility Function
<u>Stopher and Prashker (1976)</u>	Relative time, relative distance, relative cost, relative access-egress distance, departure frequency
Alan Grayson (1982)	Travel time, travel cost, access time, and departure frequency
Morrison and Winston (1985)	Travel time, cost, party size, average time between departures
Koppelman (1990)	Travel time, cost, departure frequency, distance between city pairs, household income



Logit Model in TSAM

- Logit model

$$P_i = \frac{e^{U_i}}{\sum_i e^{U_i}}$$

- Nested logit utility function

$$U_{ij}^{kl} = \alpha_0 \text{Travel Time}_{ij}^k + \alpha_1 \text{Travel Cost}_{ij}^{k1} + \alpha_2 \text{Travel Cost}_{ij}^{k2} + \alpha_3 \text{Travel Cost}_{ij}^{k3} \\ + \alpha_4 \text{Travel Cost}_{ij}^{k4} + \alpha_5 \text{Travel Cost}_{ij}^{k5} + \alpha_6 \text{shortTripDummy}_{ij}^m + \text{regionDummy}_{ij}^k$$

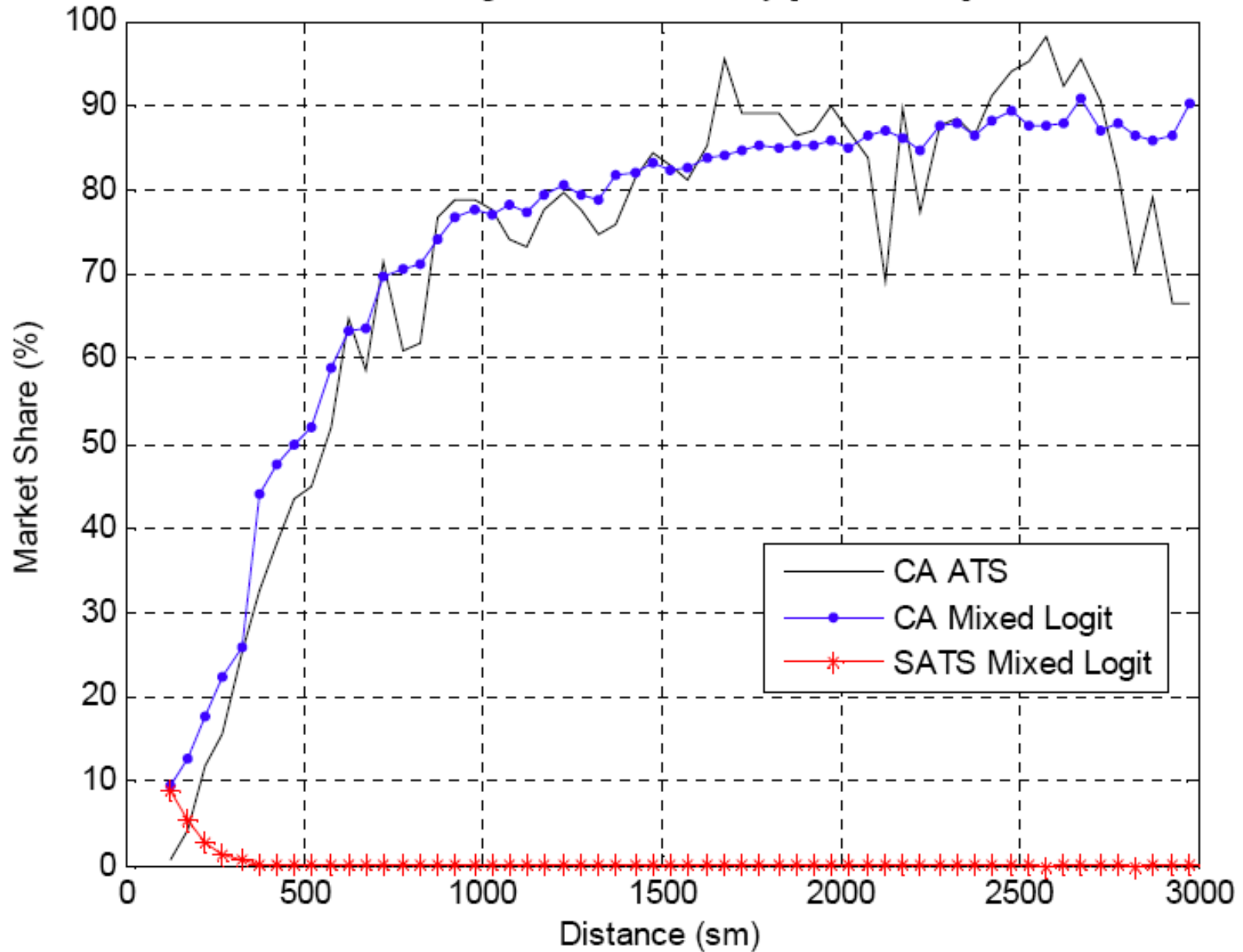
- Mixed logit utility function

$$U_{ij}^{klm} = \alpha_0 \text{Travel Time}_{ij}^k + \alpha'_0 + \alpha_1 \text{Travel Cost}_{ij}^{k1} + \alpha_2 \text{Travel Cost}_{ij}^{k2} + \alpha_3 \text{Travel Cost}_{ij}^{k3} \dots \\ + \alpha_4 \text{Travel Cost}_{ij}^{k4} + \alpha_5 \text{Travel Cost}_{ij}^{k5} + \alpha_6 \text{shortTripDummy}_{ij}^m$$



Initial Model Calibration

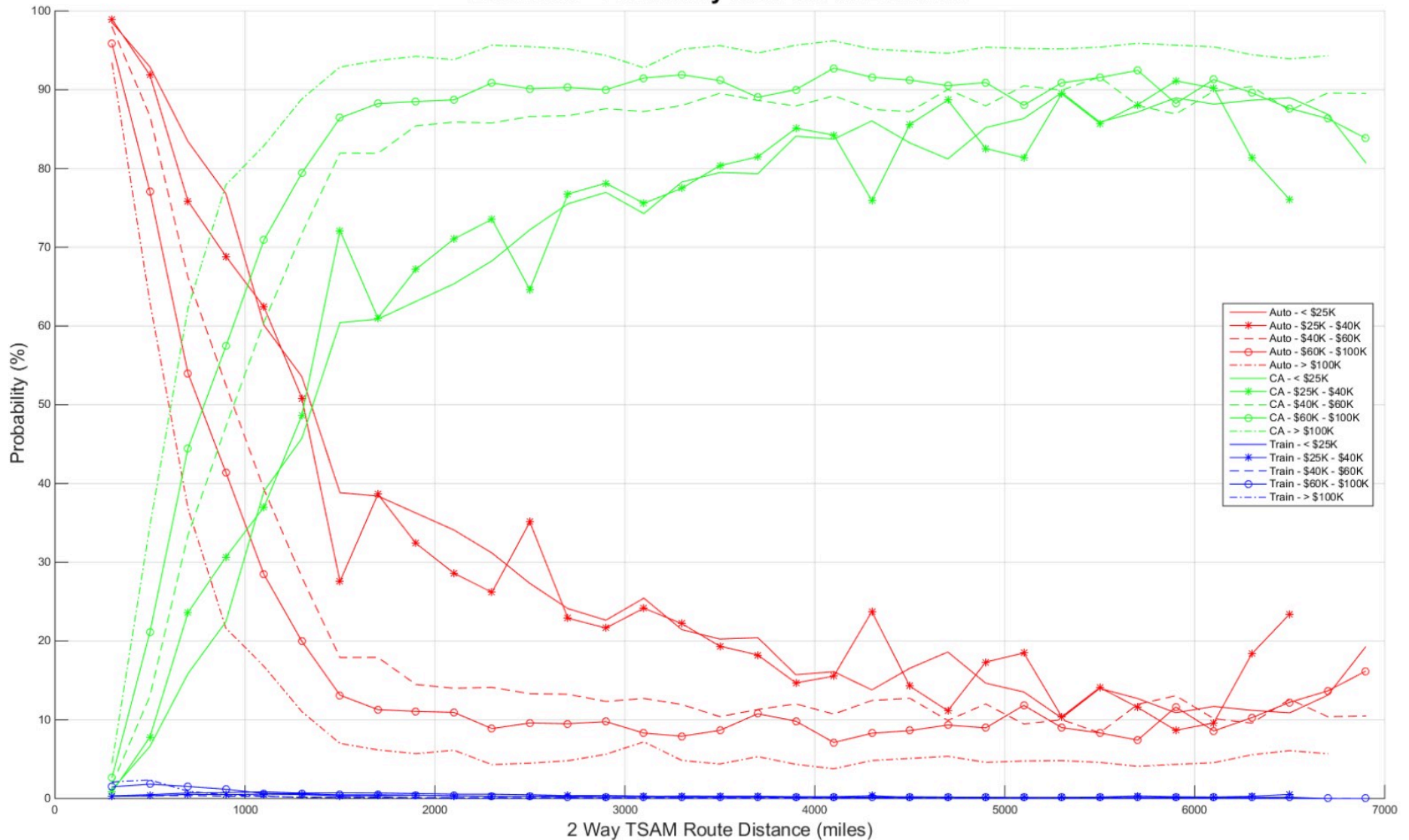
Mixed Logit No SATS Dummy [BUSINESS]





TSAM 7.6 Calibration (Business Travel)

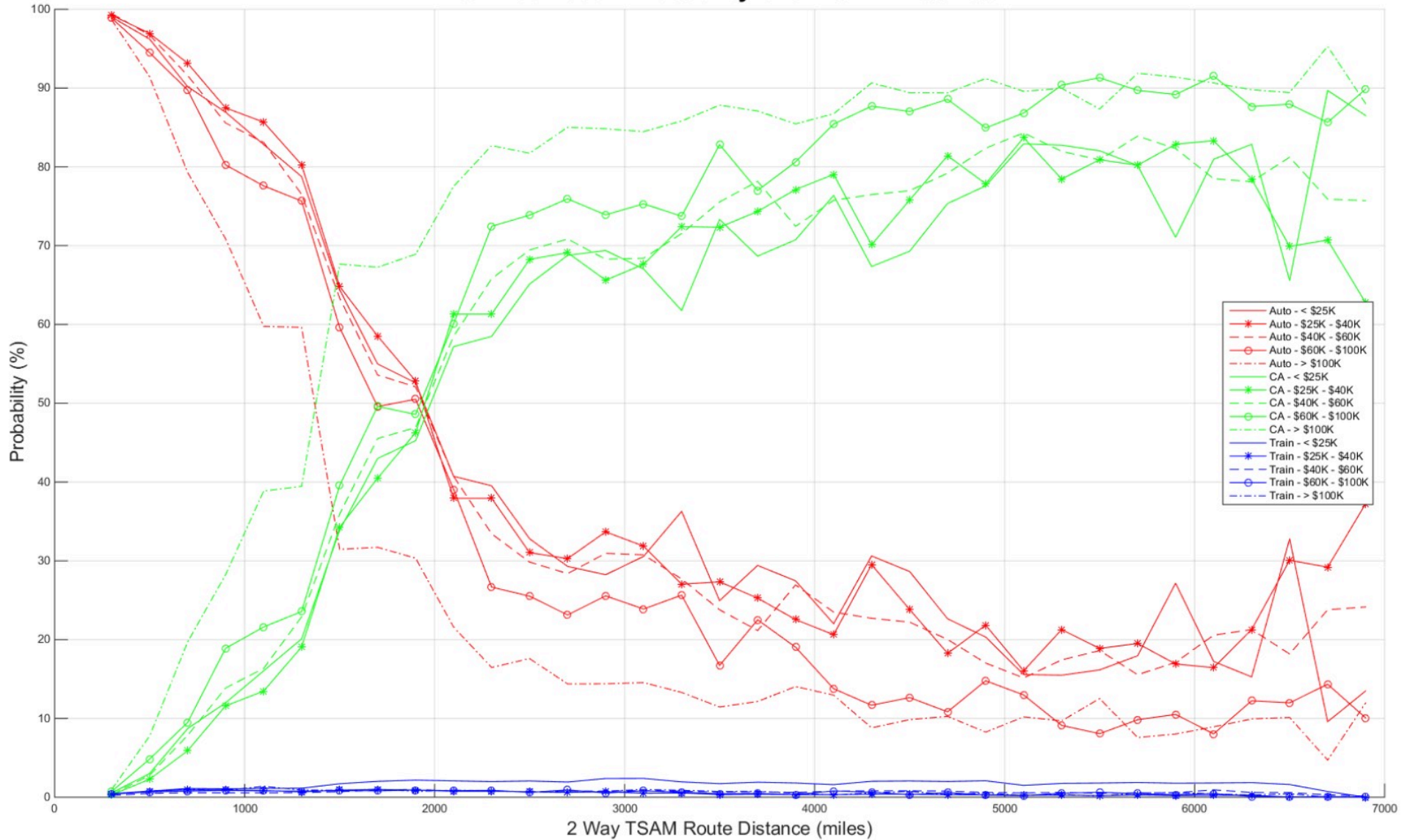
Business - Probability Over TSAM Distance





TSAM 7.6 Calibration (Non-Business Travel)

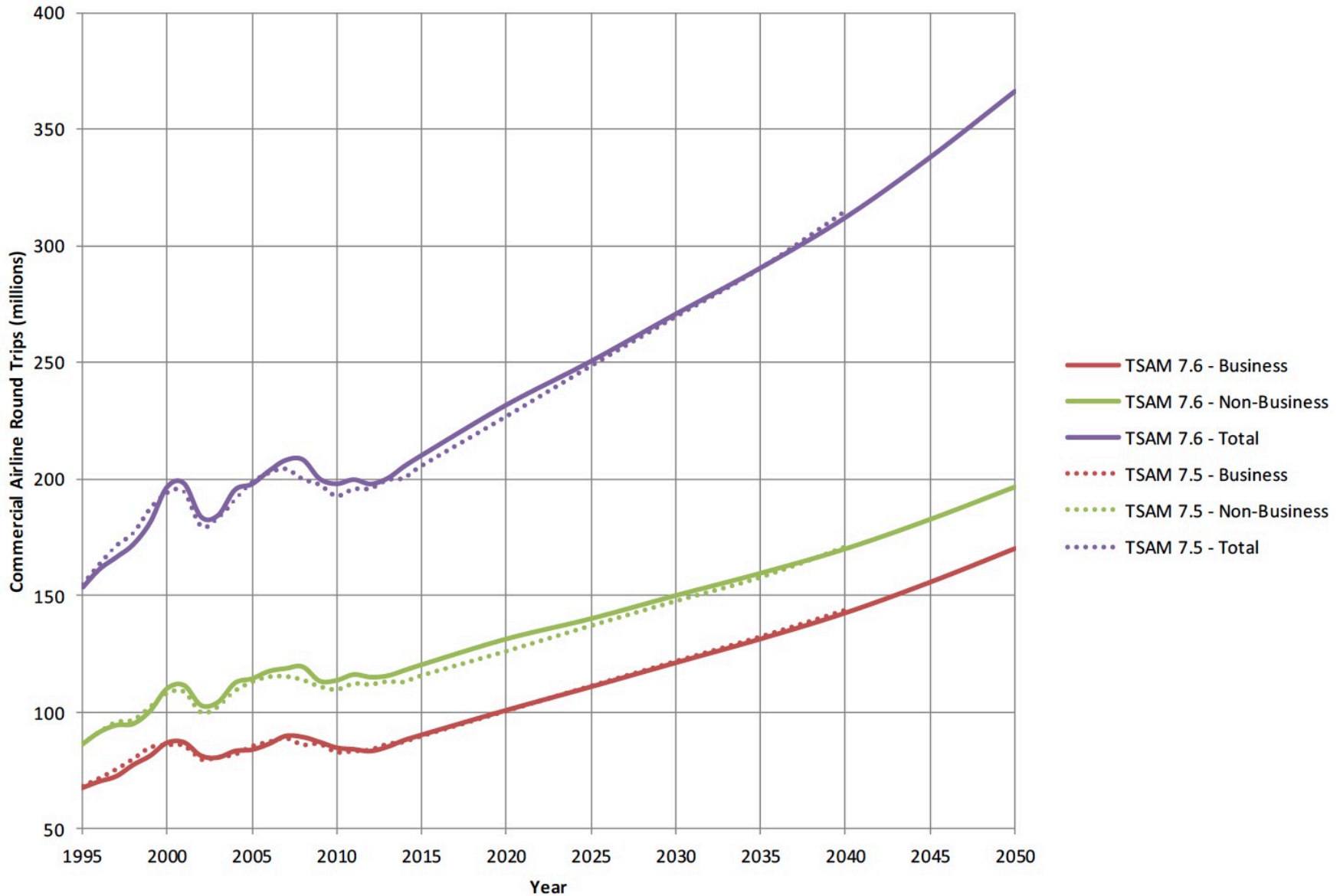
Non-Business - Probability Over TSAM Distance





TSAM 7.6 Calibration (Commercial Trips)

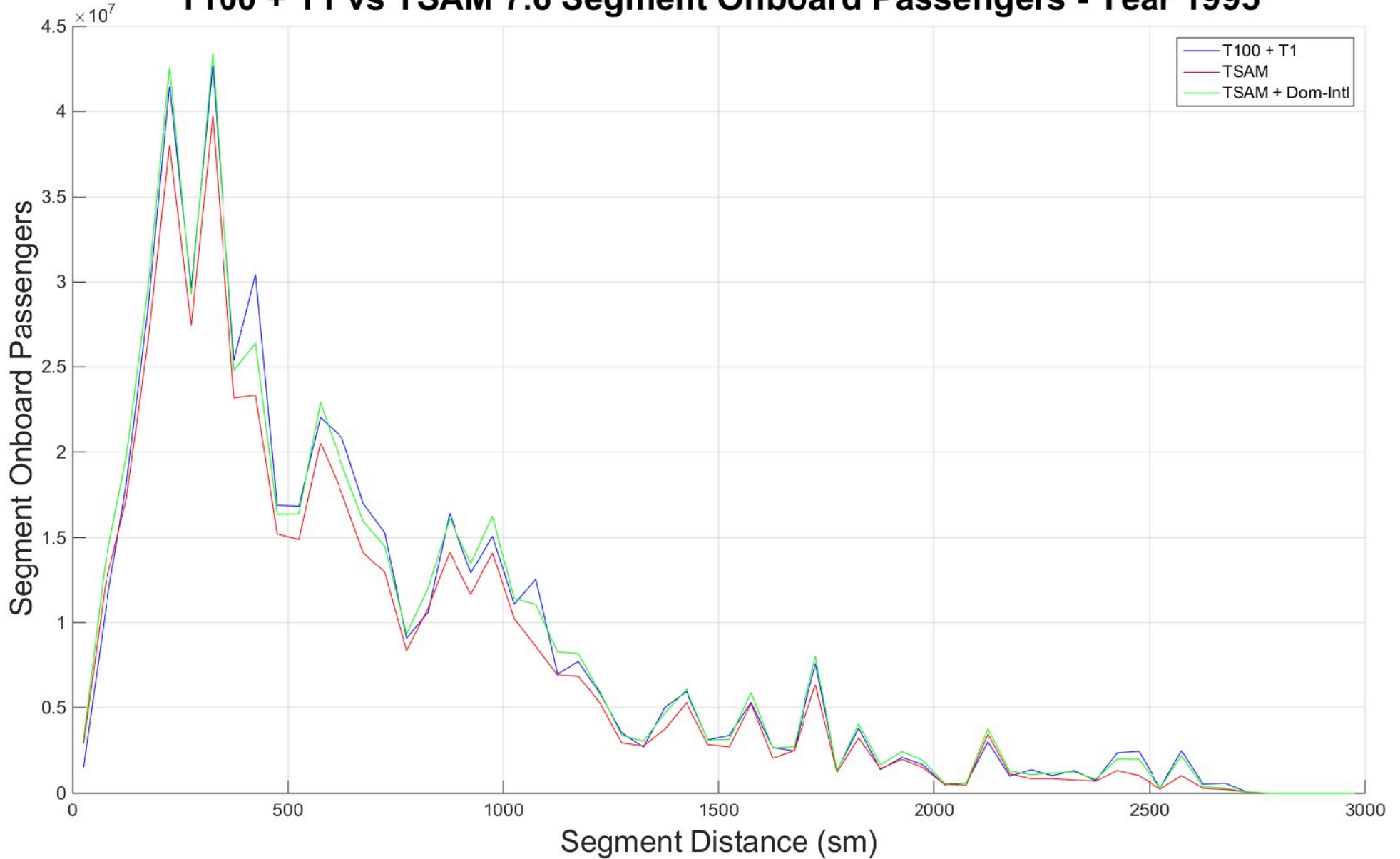
Commercial Airline Round Trips





TSAM 7.6 Calibration (Segment Passengers)

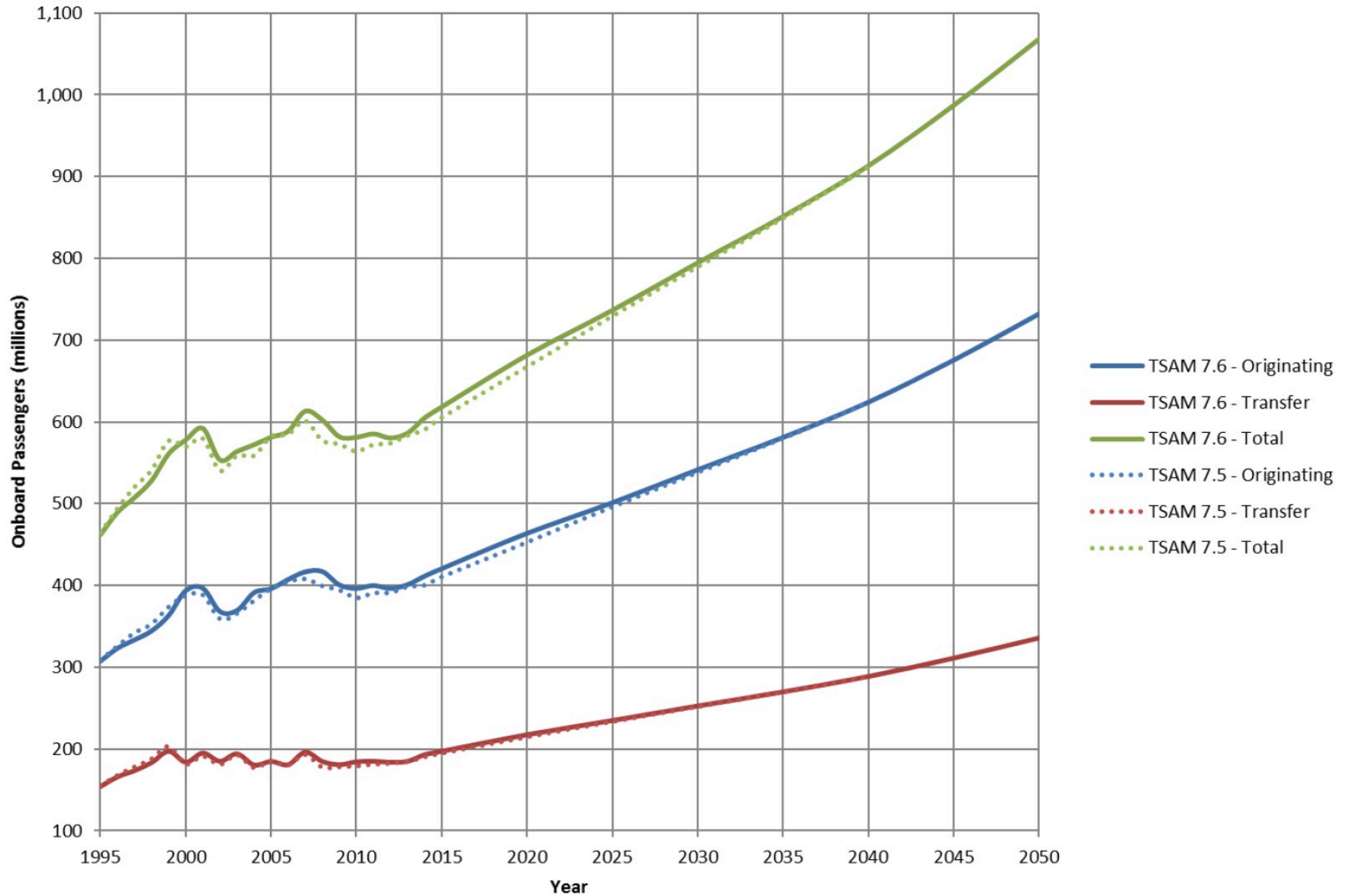
T100 + T1 vs TSAM 7.6 Segment Onboard Passengers - Year 1995





TSAM 7.6 Calibration (Commercial Enplanements)

Commercial Airline Onboard Passengers





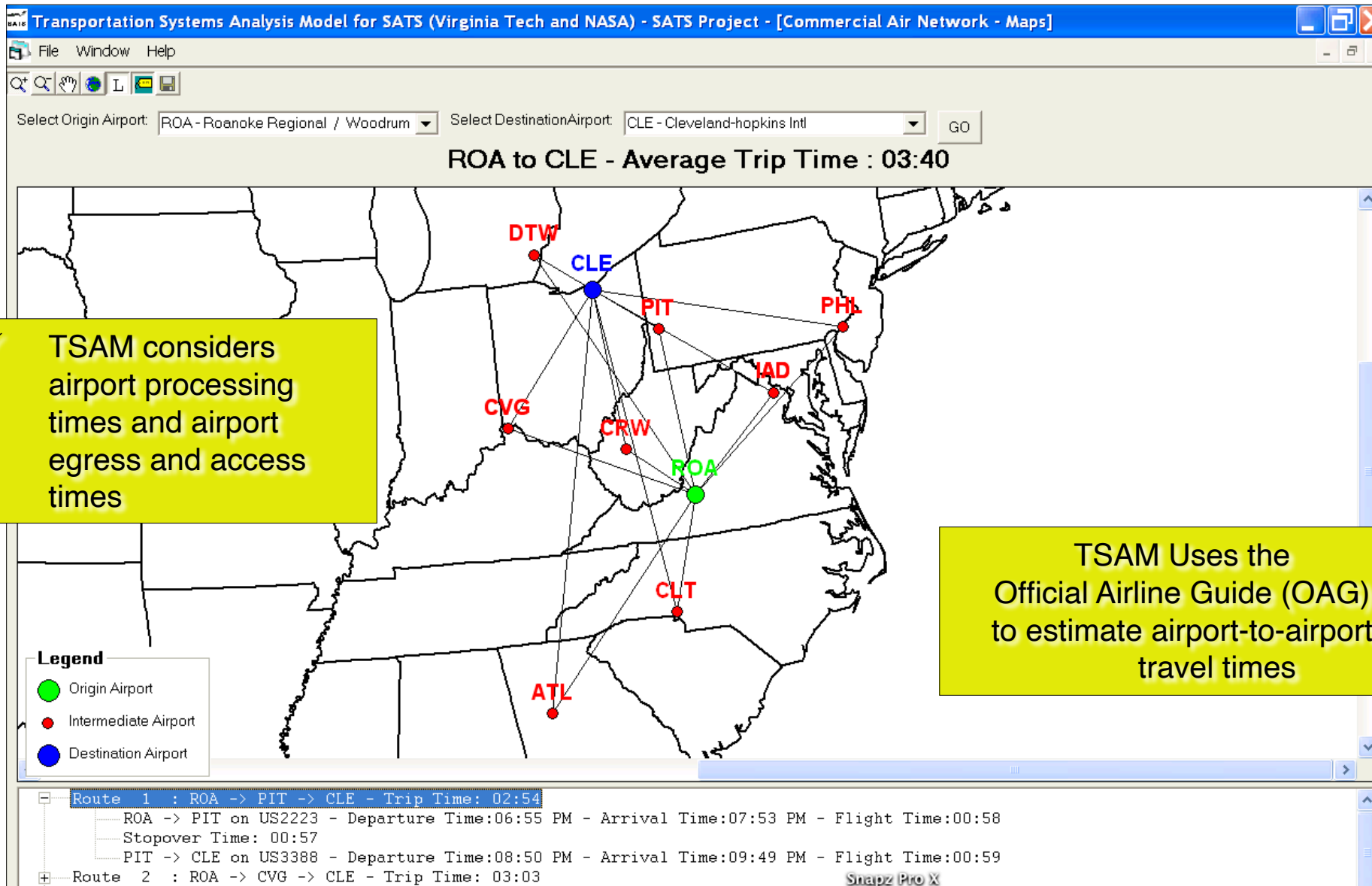
Example Travel Evaluation in TSAM Travel from Blacksburg to Cleveland OH

- Suppose three possible travel alternatives are:
 - Auto
 - Commercial Air
 - On-demand service using VLJ aircraft (future NAS)
- To make a mode selection a user could consider:
 - Travel time
 - Travel cost (including lodging and rentals)
 - Duration of stay



Example Travel Evaluation in TSAM

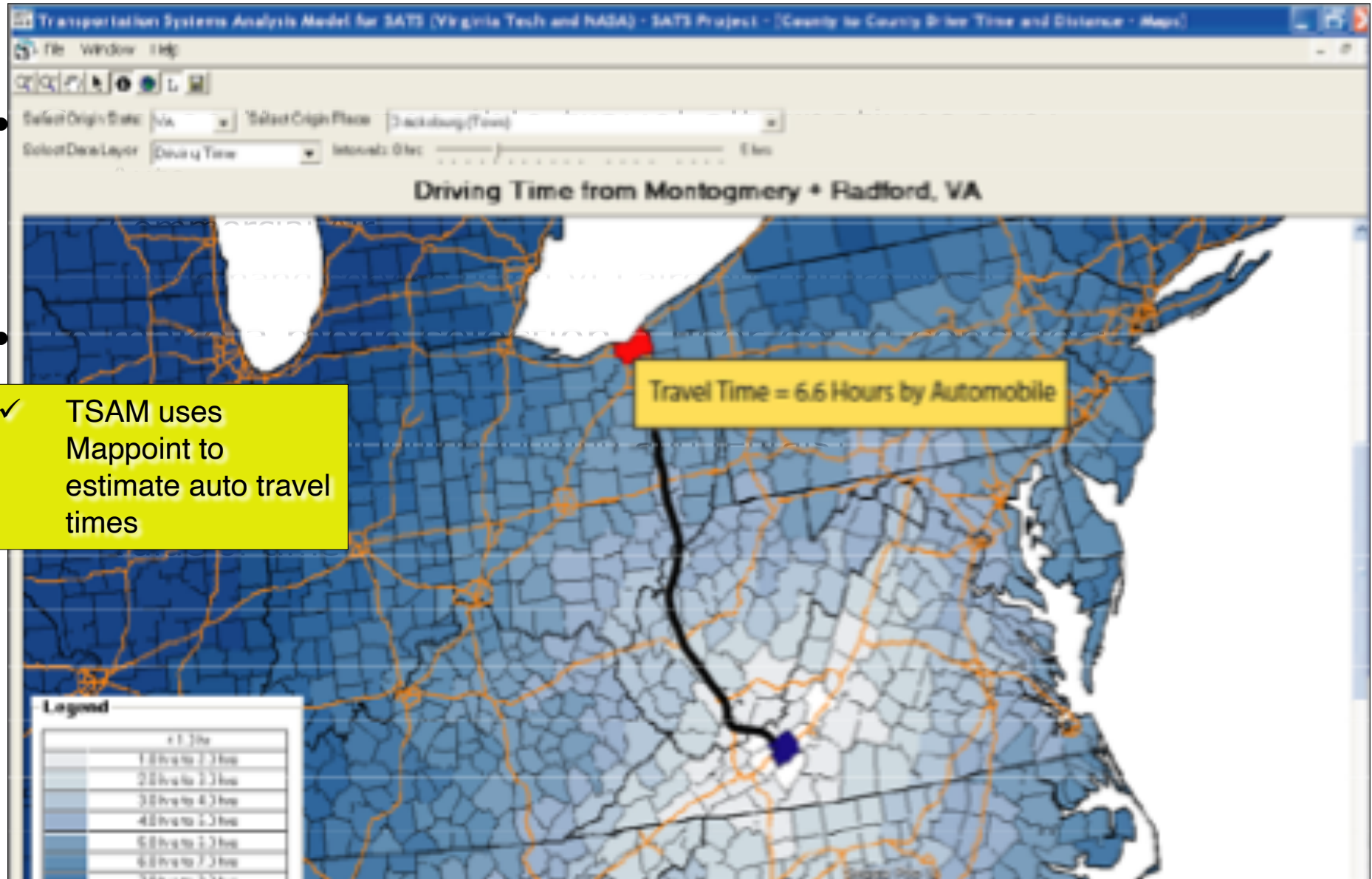
Travel from Blacksburg to Cleveland OH



✓ TSAM considers airport processing times and airport egress and access times

TSAM Uses the Official Airline Guide (OAG) to estimate airport-to-airport travel times

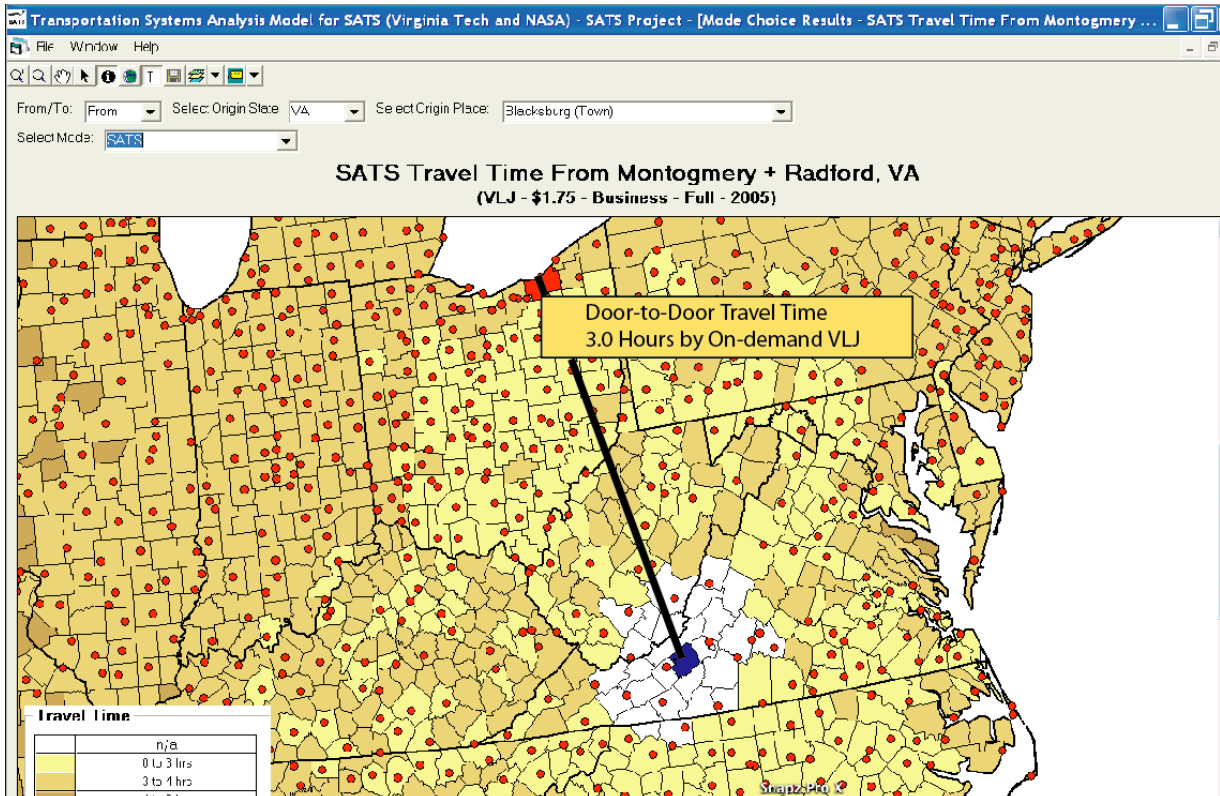
Example Travel Evaluation in TSAM Travel from Blacksburg to Cleveland OH



✓ TSAM uses Mappoint to estimate auto travel times



Example Travel Evaluation in TSAM Travel from Blacksburg to Cleveland OH



- Suppose three possible travel alternatives are:
 - Auto
 - Commercial Air
 - On-demand service using VLJ aircraft (air taxi)
- To make a mode selection a user could consider:
 - Travel time
 - Travel cost (including lodging and rentals)
 - Duration of stay
 - Value of time



Mode Choice Analysis in TSAM

TSAM - TSAM Project - [Mode Choice Model: 1 County to 1 County Trip Analysis]

File Window Help

1. Trip Generation
 - Select Inputs
 - Run Module
 - Summarized Results
 - Detailed Results

2. Trip Distribution
 - Run Module
 - Summarized Results
 - Detailed Results

3. Mode Choice
 - 1 County to 1 County
 - State to All Counties
 - All Counties to All Counties
 - Import Custom Airport Set
 - Compare Cases

4. Mobility Analysis
 - Travel Time
 - Airport to Airport Travel Time
 - Tables
 - Maps
 - Station to Station Travel Time
 - Tables
 - Maps
 - County to County Driving Time
 - Tables
 - Maps
 - Travel Cost
 - Airport to Airport Travel Cost
 - Tables
 - Maps
 - Station to Station Travel Cost
 - Lodging Cost
 - Commercial Airline Network
 - Schedule
 - Fares
 - Road Network
 - Airport Selection

5. Cargo
 - All Cargo
 - UAS Cargo

6. National Airspace System
 - Air Taxi
 - Flight Generator
 - Airspace Occupancy
 - Legacy General Aviation
 - Commercial Airline
 - Origin-Transfer-Destination
 - Network Evolver
 - Schedule Generator
 - Airport Capacity

7. Commuter Travel
 - Trip Generation
 - Trip Distribution

8. International Travel
 - Create New Case Folder...

9. Ground Travel
 - Automobile Fatalities
 - Automobile Fuel Consumption And Emissions

Mode Choice Model: 1 County to 1 County Trip Analysis

1. Select Trip Origin
 State: CA Place: Alhambra (City)

2. Select Trip Destination
 State: AR Place: Alport (Town)

3. Select Trip Purpose
 Business Non-business

4. Additional Modes
 None Air Taxi Train

5. Car Settings
 Cost: \$ 0.4479 /veh-mile

6. Train Settings
 Train Type: Acela 110 mph (2)

7. Air Taxi Settings
 Air Taxi Cost: \$ 1.85 /seat-mile Run Constant Cost Model
 Use Variable Cost Profile: REGIONAL
 Edit Variable Cost Profile
 Air Taxi Airport Set: Full Airport Set (Without OEP)
 Full Airport Set (With OEP)
 ILS Airports Set (Without OEP)
 Custom Airport Set: MCATS_1500
 Air Taxi Schedule Delay: 1.0 hrs
 Maximum Flight Level FL: 400
 Air Taxi Plane: VLJ.PTF
 Air Taxi Plane Range: 1100 statute miles
 Stop Over Time: 45 minutes
 Air Taxi Plane Profile: View Air Taxi Flight Profile

8. Advanced Settings
 Airport/Station Processing Times Maximum Driving Times Scaling Factors

9. Year
 Year: 2012

10. Model Type
 Mode Choice and Commercial Airline Route Choice Model (BoxCox Model) Nested Logit Model (Legacy Model)
 Mode Choice and Commercial Airline Route Choice Model (NASA Model) Conditional Logit Model (Legacy Model) Run Model

11. Model Results
 Airport Selection Detailed Model Results Market Share Display Driving Directions Close

Airport Processing Times

Set the processing times at the origin and destination airports/stations.

Commercial Airports:

Hub Type	Processing time at origin (hrs)	Processing time at destination (hrs)
▶ Large Hub	1.75	0.75
Medium Hub	1.25	0.75
Small Hub	1	0.5
Non Hub	0.75	0.5

Air Taxi Airports:

Airport	Processing time at origin (hrs)	Processing time at destination (hrs)
▶ Airport	0.5	0.25

Train Stations:

Station	Processing time at origin (hrs)	Processing time at destination (hrs)
▶ Station	0.33	0.17

OK Cancel