2021 NASA System Analysis Symposium Introduction

Sharon Monica Jones, PhD
Manager, Systems Analysis and Decision Support
Portfolio Analysis and Management Office (PAMO)
NASA Aeronautics

Systems Analysis Symposium
Objectives

An annual gathering of NASA's system analysis researchers, analysts and their colleagues to exchange results and views about strategic aeronautics related issues

To distribute results of strategic systems analysis studies to the NASA Aeronautics Research Mission Directorate (ARMD)	To obtain peer review about study assumptions and conclusions	To get feedback from the NASA Aeronautics community prior to writing final reports that support ARMD strategic planning activities	To generate ideas for possible future strategic studies needed by ARMD

Symposium Objectives

Aeronautics Research Mission Directorate

Strategic Overview

Strategic Implementation Plan

https://www.nasa.gov/aeroresearch/strategy

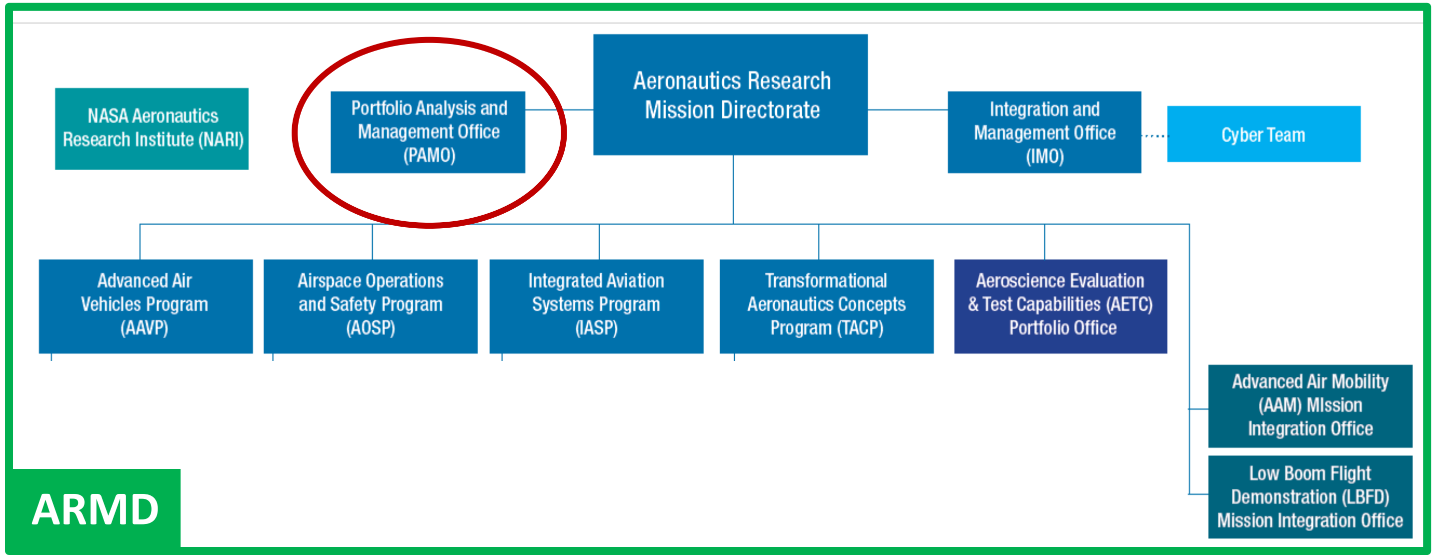
Mega Drivers

Strategic Thrusts

- **Safe, Efficient Growth in Global Operations**
- **Innovation in Commercial Supersonic Aircraft**
- **Ultra-Efficient Subsonic Transports**
- **Safe, Quiet, and Affordable Vertical Lift Air Vehicles**
- **In-Time System-Wide Safety Assurance**
- **Assured Autonomy for Aviation Transformation**

Aeronautics Research Mission Directorate

Where is PAMO in ARMD?



Portfolio Analysis and Management Office (PAMO)
Director
William Harrison

Strategy (PAMO-S)
Team Lead
Naseem Saiyed

Systems Analysis/ Decision Support
Dr. Sharon Monica Jones

Resources (PAMO-R)
Team Lead
Cathy Delaney

Intercenter Systems Analysis Team (ISAT)
Team Lead
Dr. Eric Hendricks (GRC)

ISAT Leadership Group

- Dr. Sharon Monica Jones
- Phil Arcara (LaRC)
- Dr. Susie Go (ARC)
- Xiao-Yen Wang (GRC)
- Dr. Eric Hendricks (GRC)
- Ty Marien (LaRC)
- Mark Guynn (LaRC)
- Jon Seidel (GRC)

Systems Analysis and Decision Support

Strategic Systems Analysis Overview

SYSTEMS ANALYSIS =

OPERATIONS RESEARCH

Strategic Systems Modeling and Analysis
To identify trends that may impact ARMD strategy through the use of systems analysis models and methods

+ POLICY ANALYSIS

Strategic Portfolio Analysis
To use systems and portfolio analysis methods to identify strengths, alternatives and gaps in ARMD's portfolio for strategic decisions

+ DATA ANALYTICS

Strategic Data Analysis
To identify trends that may impact ARMD strategy by analyzing aeronautics technology, business intelligence and/or aviation data

ISAT
Lead, Eric Hendricks

High Level Systems and Data Analysis
Lead, Sharon Monica Jones

Systems Analysis and Decision Support

Team Members

High Level Systems and Data Analysis

Lead, Dr. Sharon Monica Jones

- **Statistical Modeling and Analysis**
- **Top Down Systems Analysis**

Data and Trend Analysis
- Bailey Ethridge (AMA)

High Level Systems Analysis
- Dell Ricks (AMA)

Safety, Multi-Modal and Manufacturing Systems
- Dr. Larry Barr (Volpe)
- Dr. Seamus McGovern (Volpe)

Life Cycle Cost and Policy Analysis
- Jacob Wishart (Volpe)
- David Pace (Volpe)
- Max Litvack-Winkler (Volpe)
- Kendall Mahavier (Volpe)
- Gina Solman (Volpe)

*FTE support **not** provided by PAMO Systems Analysis/ISAT

Intercenter Systems Analysis Team (ISAT)

Lead, Dr. Eric Hendricks and GRC POC

- **Systems Analysis and Conceptual Modeling**
- **Conceptual Level SMEs**

LaRC POC, Fleet Analysis and Advanced Concepts (supersonic/hypersonic)
- Ty Marien

Safety and Autonomy
- Dr. Ersin Ansel*

Acoustics, Propulsion
- Jeff Berton*

ATM/Airspace
- Paul Borchers and Jerry Smith

Certification, MBSE, Electric Aircraft and Advanced Concepts
- Dr. Nick Borer and Nat Blaesser

AAM/UAMs
- Dr. Michael Patterson* and Jerry Smith*

Supersonics/Hypersonics, and Fleet Analysis
- Jon Seidel and Dr. Wu Li

Propulsion, Fuels and Rotary Wing Analysis
- Chris Snyder

Strategic Systems Analysis
Categories of Activities

Mega Drivers

- Strategic systems analyses to support the two-year ARMD Strategic Implementation Plan (SIP) update cycle
- Outputs include trends, scenarios, ideal characteristics and assumptions

What's Next

- Investigates new concepts that yield compelling benefits in a particular focus area
- Goal is to provide some benefit over state-of-the-art to motivate technical challenges and spur new approaches

Just In Time

- Internal capability to answer strategic questions that are necessary for annual strategic planning discussions and other ARMD strategy tasks
- Includes all types of strategic systems analyses

Wednesday, November 10, 2021

TIME	TOPIC	PERSON
10:00 AM – 10:20 AM	**INTRODUCTION**	
10:00 AM – 10:10 AM	Welcome	Steve Clarke, ARMD Deputy Associate Administrator
10:10 AM – 10:20 AM	Objectives/Agenda	Sharon Monica Jones (PAMO), Manager, ARMD System Analysis
10:20 AM – 12:00 PM	**ISAT**	
10:20 AM – 10:30 AM	Intercenter Systems Analysis Team (ISAT)	Eric Hendricks (GRC), ISAT Lead
10:30 AM – 11:00 AM	"What's Next" for • Airworthiness Certification • Regional Mobility	Nick Borer (LaRC)
11:00 AM – 11:30 AM	Strategic Systems Modeling and Analyses • Global Demand Modeling Study • High-Speed Market Studies	Ty Marien (LaRC) Jon Seidel (GRC)
11:30 AM – 12:00 PM	H2 / DeCarbonization Studies: History and Ongoing	Chris Snyder (GRC)
12:00 PM – 12:30 PM	**LUNCH**	

Wednesday, November 10, 2021 (cont'd)

TIME	TOPIC	PERSON
12:30 PM – 2:00 PM	**HIGH LEVEL SYSTEMS ANALYSIS**	
12:30 PM – 1:00 PM	Just-in Time Systems and Market Analyses	Seamus McGovern (Volpe)
1:00 PM – 1:45 PM	COVID-19 Impact on Domestic Commercial Aviation: • Multi-Modal Economic Analysis • Policy Analysis	Max Litvack-Winkler (Volpe) Gina Solman (Volpe)
1:45 PM – 2:00 PM	**BREAK**	
2:00 PM – 3:30 PM	**PROGRAM AND MISSION LEVEL SYSTEMS ANALYSIS**	
2:00 PM – 2:30 PM	Analysis of the Electrical Grid for UAM	David Thipphavong (PAMO)
2:30 PM – 3:00 PM	Exploration of Operations Limits and Emissions For Early UAM Missions	Michael Patterson (LaRC) Dan DeLaurentis (Purdue Univ.)
3:00 PM – 3:30 PM	ARMD Model Based Systems Engineering/Analysis Overview	Eric Hendricks (GRC) Jesse Quinlan (LaRC)
3:30 – 4:00 PM	**WRAP UP**	
3:30 – 4:00 PM	Closing Remarks	Eric Hendricks (GRC) Sharon Monica Jones (PAMO)

Systems Analysis Symposium
Meeting Logistics

- Question and answer sessions
  - Last five to ten minutes of each presentation time slot
  - Questions can be submitted via conference i/o tool:

https://arc.cnf.io/
(select the ARMD System Analysis Symposium session)

- Presenters (MS Teams attendees)
  - Please keep microphones muted
  - Turn off camera when not speaking
  - Use the “raise your hand” feature and wait to be acknowledged by Moderator
  - Agency employees can access symposium slides on the internal ARMD SharePoint

Intercenter Systems Analysis Team (ISAT) Overview

Dr. Eric Hendricks, Glenn Research Center

Presentation to Systems Analysis Symposium

November 10, 2021

Intercenter Systems Analysis Team (ISAT) Overview

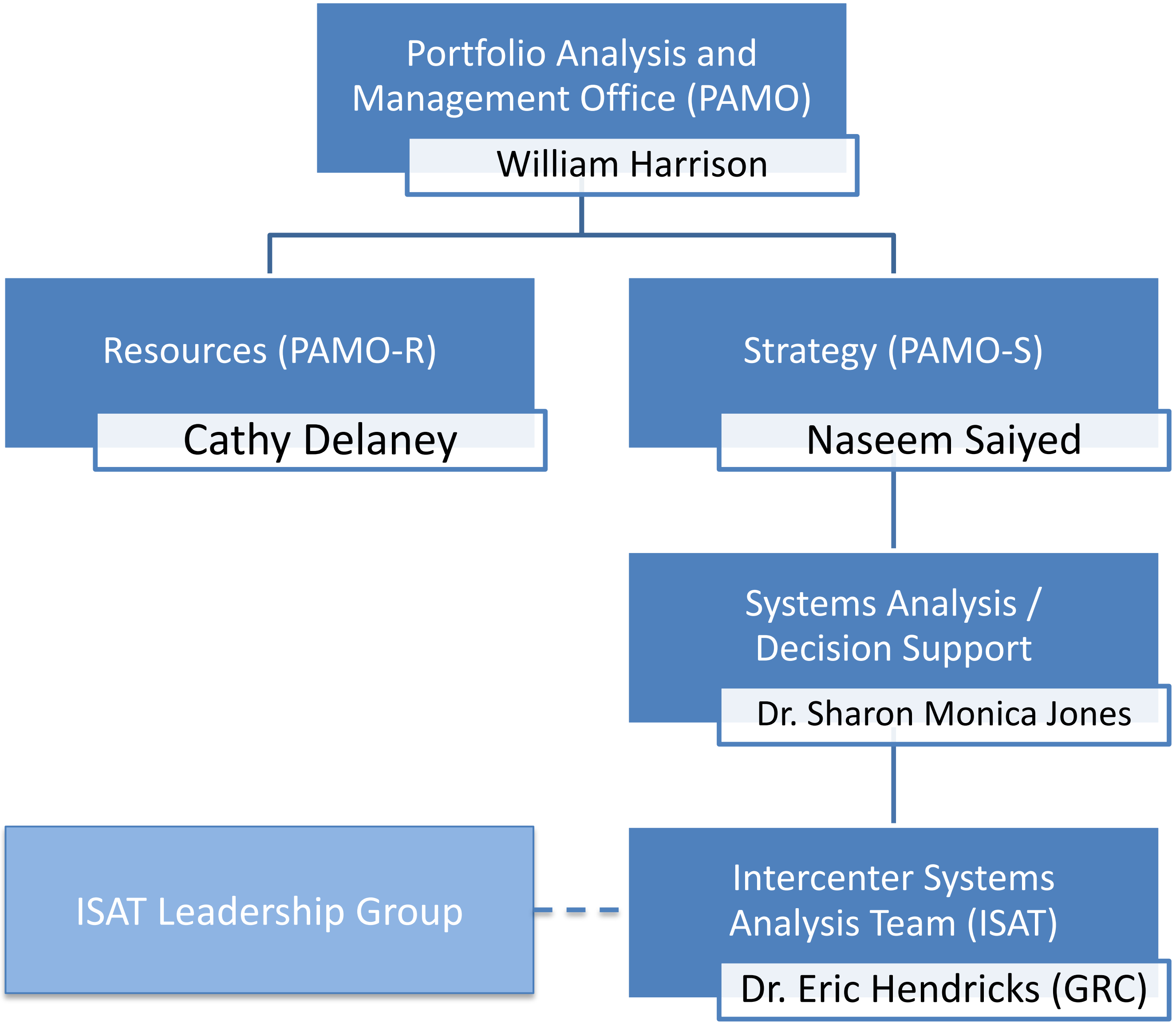
- ISAT was created in 2013 to support ARMD's Strategy, Architecture and Analysis Office under Bob Pearce
  - Initially called the Integrated Systems Analysis & Assessment Capability (ISAAC)
- Team is a diverse, yet integrated, collection of NASA systems analysts that partner with external research organizations for studies as needed
- ISAT has conducted a variety of systems analysis studies that simultaneously consider:
  - Vehicle design
  - Airspace operations
  - Safety
  - Environmental effects
  - Market/economic viability and impacts

ISAT Mission

Provide systems analysis studies and data to support strategic planning and decision making within the Aeronautics Research Mission Directorate (ARMD)

Mega Driver Studies	What's Next Studies	Just In Time Studies

Where ISAT "Sits" within NASA ARMD



ISAT Team Members

- **ISAT Lead –** Eric Hendricks (GRC)
- **Fleet Analysis and Advanced Concepts -** Ty Marien (LaRC)
- **Safety and Autonomy -** Ersin Ansel (LaRC)
- **Acoustics and Propulsion -** Jeff Berton (GRC)
- **ATM/Airspace -** Paul Borchers (ARC), Jerry Smith (LaRC)
- **Certification, MBSE Electric Aircraft and Advanced Concepts -** Nick Borer (LaRC), Nat Blaesser (LaRC)
- **AAM/UAMs -** Michael Patterson (LaRC), Jerry Smith (LaRC)
- **Supersonic/Hypersonic Propulsion and Fleet Analysis -** Jon Seidel (GRC), Wu Li (LaRC)
- **Propulsion, Fuels and Rotary Wing Analysis -** Chris Snyder (GRC)

Current External Partners
Virginia Tech, Georgia Tech, Purdue, NREL, AMA

Sample of Previous ISAT Work

Study Title	Timeframe
Low Carbon Propulsion Options Study	FY14
Projected Global Emissions Due to Commercial Aviation	FY16
Thin Haul Commuter Economics	FY16
Technology Influence on NAS Safety Nets	FY17
Autonomous Cargo Delivery Using Electric Aircraft	FY17
Supersonic Aircraft Demand/Environmental Impact Analysis	FY17
Advanced Technology Certification Gap Analysis (UAM)	FY18
On-Demand Mobility Landing Site Feasibility/Fare Model Analysis	FY18/19
US Demand for a Low-Boom Supersonic Transport Aircraft	FY18/19

Recent and Ongoing ISAT Studies

Study Title	Timeframe
Commercial Hypersonics - Mission Capabilities/Requirements Definition/Economics	FY20
What's Next for Airworthiness Certification: Model-Based Aircraft Certification	FY19/20
What's Next in Regional Mobility: Advanced Regional Air Mobility	FY21/22
Global Demand Modeling	FY21/22
Supersonic Transport Scheduling and Fleet Analysis	FY22
H2 / DeCarbonization: History and Ongoing	FY21
What's Next in Regional Mobility: Electrified Aircraft Regional Airport Impact	FY22/23
Further Exploration of Operations Limits for Advanced Air Mobility Missions	FY22

National Aeronautics and
Space Administration

What's Next (in) …?

Finding the next possible "big ideas" in selected problems

Nick Borer

Aeronautics Systems Analysis Branch

10 November 2021

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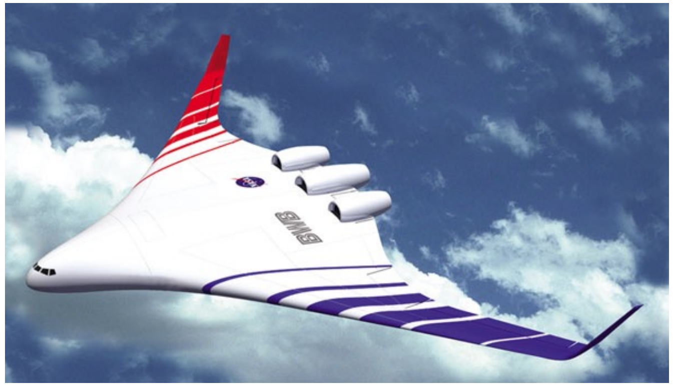
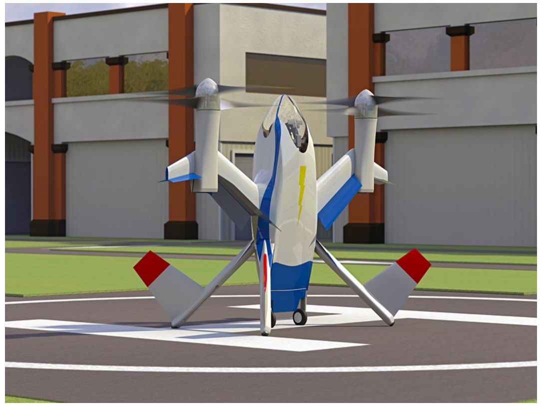
What Is “What’s Next?”

- ISAT’s “What’s Next” studies trace back to a hallway conversation at SciTech 2018
- Typical systems analysis studies consider existing needs and shortcomings, and suggest gaps or otherwise identify approaches to ameliorate them
- Idea behind “What’s Next” is to hypothesize advanced concepts that may either fill gaps or perhaps even address latent, uncharacterized needs, and see how these may drive future NASA investments





NASA images

What’s Happening with “What’s Next”

- Two major themes evaluated to date
- “What’s Next in Airworthiness Certification”
  - Initiated in late 2018
  - Three contracted studies completed – last one ended May 2021
  - Collaborated with the X-57 project
- “What’s Next in Regional Mobility”
  - Initiated in 2020
  - Two contracted studies underway
  - Collaborating with the AAM project, other potential collaborations in work

WHAT'S NEXT IN AIRWORTHINESS CERTIFICATION

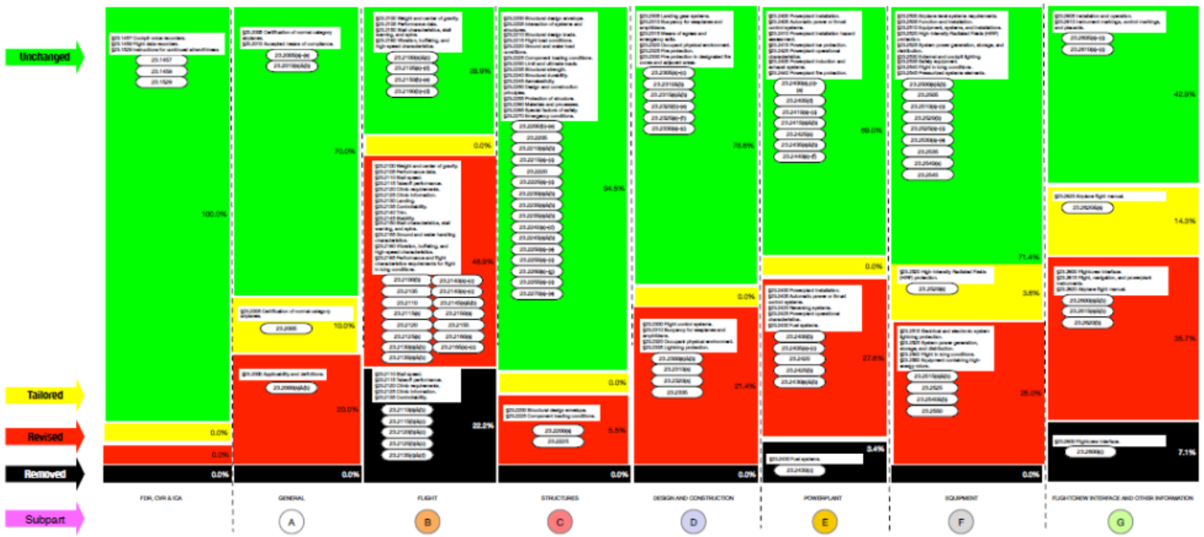
Introduction

- ARMD has embraced emerging markets for Advanced Air Mobility, introducing a challenge and an opportunity
  - 2013 Small Airplane Revitalization Act mandated streamlined airworthiness certification
  - Global movement in small airplane standard development towards adoption of performance-based standards
  - Requires support of industry (both established & emerging) and research community to further develop standards
- Key questions considered for “What’s Next in Airworthiness Certification”
  - KQ1: Can we identify gaps in airworthiness certification today for new and emerging technologies [that are in NASA’s portfolio]?
  - KQ2: Can we identify how certification rules and standards impact the design and development of aircraft with advanced technologies?
  - KQ3: What is NASA’s role to address these gaps/impacts?
- Partnered with FDC/X-57 to serve as “advanced technology surrogate” for this study
  - Detailed, publicly available data on design, design rationale, and performance
  - X-57 is currently going through NASA airworthiness processes
  - Ancillary benefit: led to pivot in X-57 project goals to better align with US research/industry needs

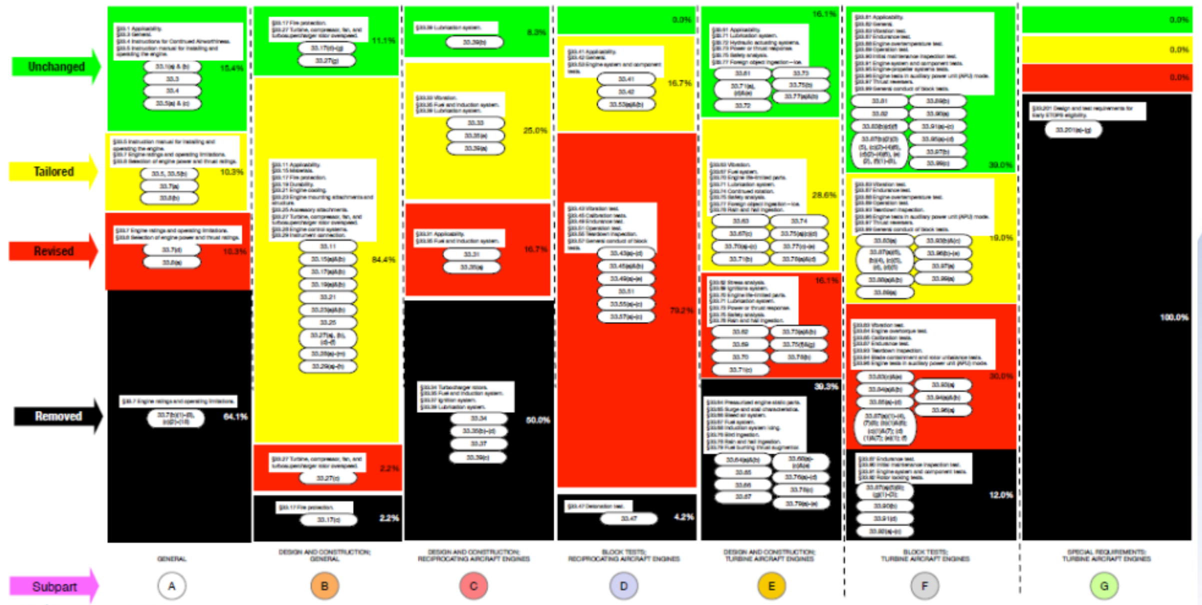
Certification Challenges with New Technologies

- NIA/HS Advanced Concepts, “Initial Assessment of Aircraft Certification Procedures for Emerging Technologies”
  - POP: July 2018-January 2019
  - Compared applicability of current rules and standards to X-57-like platform, as compared to airframe airworthiness (Part 23) and engine airworthiness (Part 33) requirements
  - Delivered Certification Rules and Standards Review (pre-KQ1), Certification Gap Analysis Report (KQ1), Certification Coordination Roadmap (pre-KQ3)

Assessment of Applicability of New Vehicle Concepts to 14 CFR 23, Airworthiness Standards: Normal Category Airplanes



Assessment of Applicability of Electric Propulsion to 14 CFR 33, Airworthiness Standards: Aircraft Engines



Certification Planning

- NIA/HS Advanced Concepts, "Support the X-57 Project Office on Standards Development," April 2019-May 2021*
  - **Leveraged existing task order; new tasks related to ISAT added September 2019*
  - Developed an Airworthiness Validation Plan (KQ2) and Cross-Reference to Certification Checklist (KQ1), included efforts of eight subject matter experts and industry engagement at three events (KQ3)
  - Final report summarized in Final Airworthiness Validation Plan delivered May 2021

Subpart B—Flight	Note
(d) Performance data determined in accordance with paragraph (b) of this section must account for losses due to atmospheric conditions, cooling needs, and other demands on power sources.	Applies to X-57
§23.2110 Stall speed.	Applies to X-57
The applicant must determine the airplane stall speed or the minimum steady flight speed for each flight configuration used in normal operations, including takeoff, climb, cruise, descent, approach, and landing. The stall speed or minimum steady flight speed determination must account for the most adverse conditions for each flight configuration with power set at—	Stall speed determination in all configs required including takeoff and landing engines-propellers and cruise engines-props only. Stall speeds are gathered during stall characteristics investigation used to determine the low-speed fight characteristics score, S_{LSC}. X-57 minimum S_{LSC} is 150.
(a) Idle or zero thrust for propulsion systems that are used primarily for thrust; and NOTE: CM system would be considered the primary thrust producing system. FAA consensus would be required.	CM/HLP use and power settings need to be defined for each config and agreed to by FAA. HLP on/off power off speeds required for approach and landing conditions.
(b) A nominal thrust for propulsion systems that are used for thrust, flight control, and/or high-lift systems. NOTE: Both (a) and (b) subparagraph power settings are required for stall speed determination. It is not either (a) or (b). HLP system would fall into the high-lift system category while the CM system would fall into the thrust producing category for those conditions where a "power-on" stall condition must be considered.	CM/HLP use and power settings need to be defined for TO and Landing configs using both CM/HLP if HLM considered High Lift systems. FAA consensus required.
§23.2115 Takeoff performance.	Applies to X-57
(a) The applicant must determine airplane takeoff performance accounting for—	Applies to X-57
(1) Stall speed safety margins;	
(2) Minimum control speeds; and	
(3) Climb gradients.	
(b) For single engine airplanes and levels 1, 2, and 3 low-speed multiengine airplanes, takeoff performance includes the determination of ground roll and initial climb distance to 50 feet (15 meters) above the takeoff surface.	Applies to X-57
(c) For levels 1, 2, and 3 high-speed multiengine airplanes, and level 4 multiengine airplanes, takeoff performance includes a determination the following distances after a sudden critical loss of thrust—	NA

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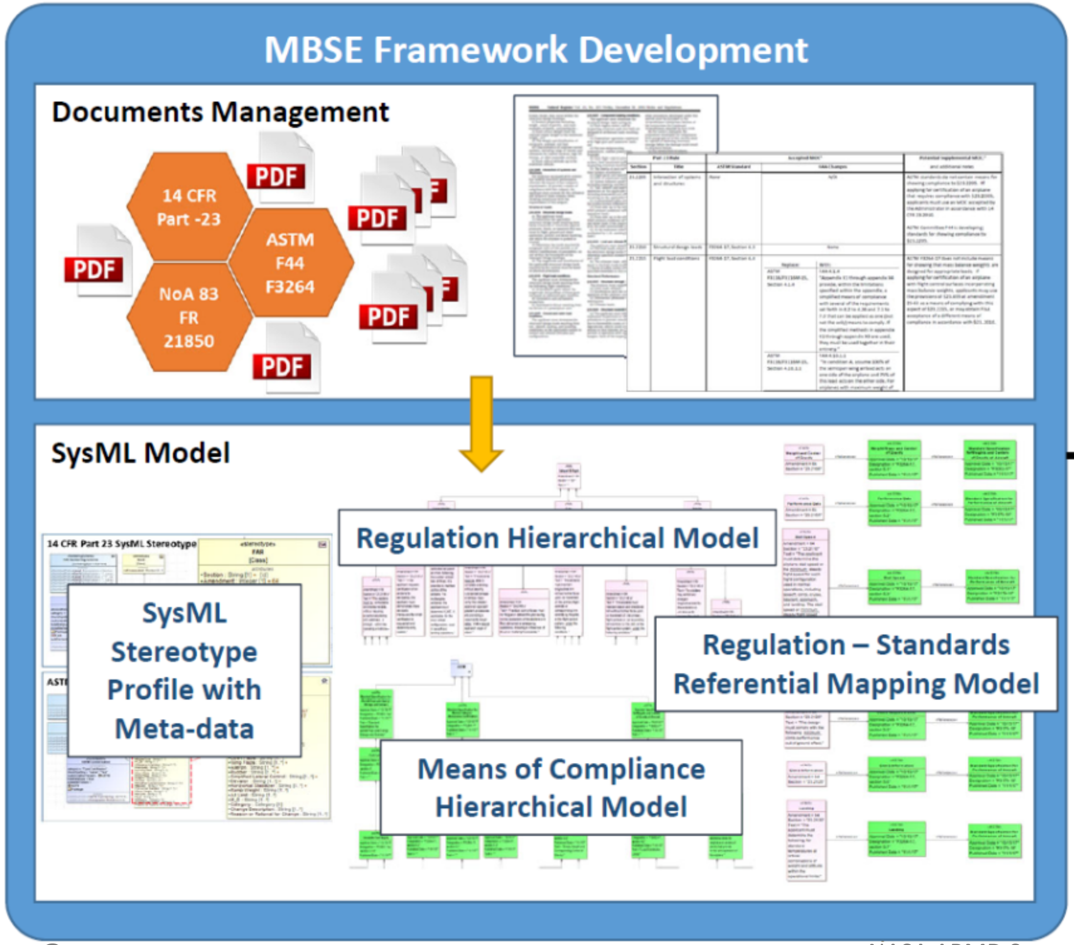
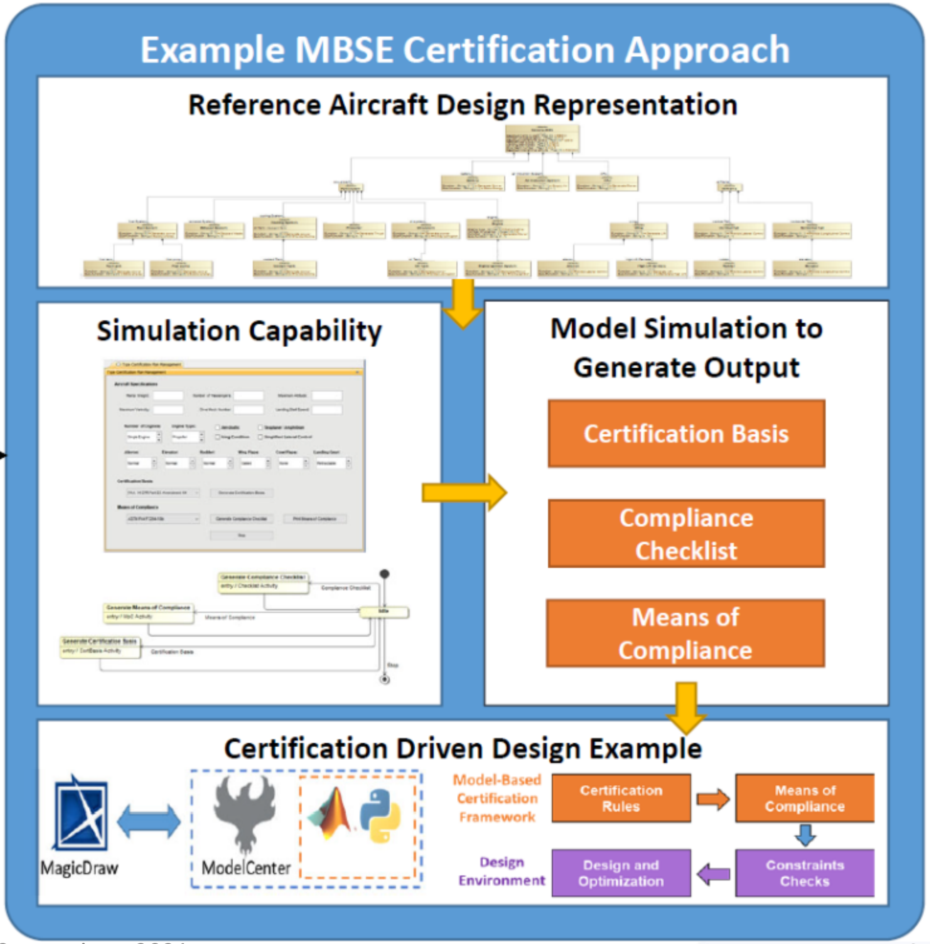
Model-Based Aircraft Certification

- NIA/Georgia Tech, "Model-Based Certification of Aircraft," April-December 2019
  - Developed initial Model-Based Systems Engineering (MBSE) framework for use in assessing advanced technology concepts (pre-KQ2), presented to ASTM F44 (pre-KQ3)





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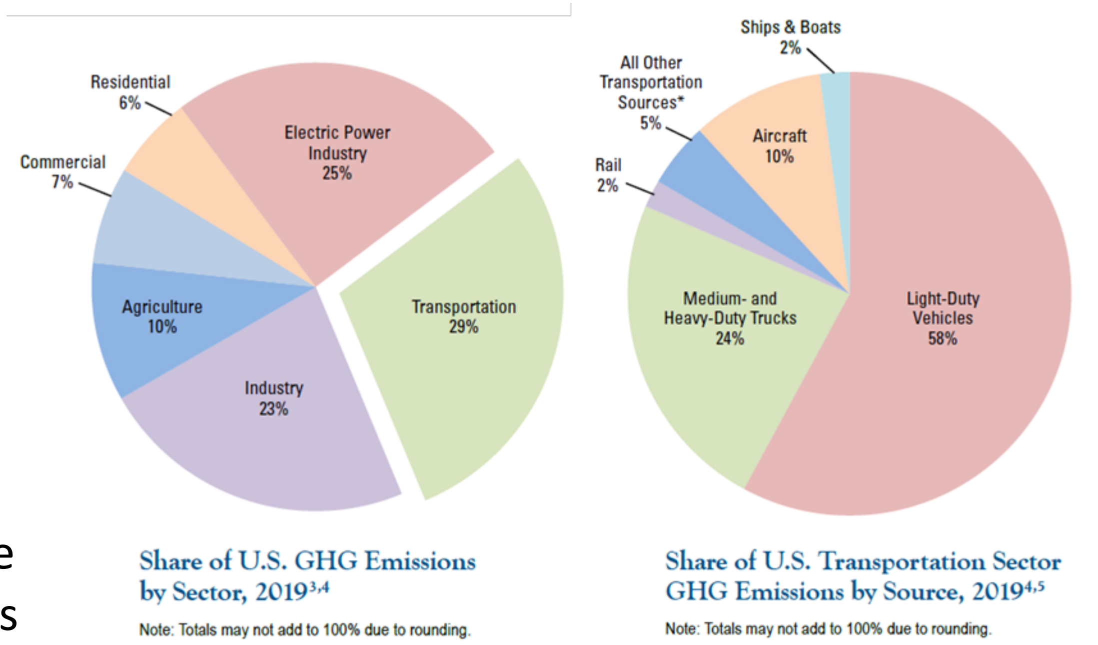
Work Product Summary and Impact

- This effort has helped ARMD identify how NASA can impact development of airworthiness procedures for new technologies
  - Directly influenced FDC/X-57 project objectives, interfacing with other projects (AAM), laid groundwork for others (EPFD)
  - Co-hosted certification workshop in coordination with FAA
- Publicly available reports to date, more to come:
  - NASA/CR-2019-220406, Certification Rules and Standards Review (2019)
  - NASA/CR-2019-220407, Certification Gap Analysis Report (2019)
  - NASA/CR-2019-220408, Certification Coordination Roadmap (2019)
  - AIAA-2019-3344, A Model-Based System Engineering Approach to Normal Category Airplane Airworthiness Certification (2019)
  - AIAA-2020-3096, A Model-Based Aircraft Certification Framework for Normal Category Airplanes (2020)
  - Airworthiness Validation Plan – delivered May 2021, not yet gone through public release process
- Other related research spinoffs
  - AIAA-2019-3576, Development of a Certification Module for Early Aircraft Design (2019)
  - M. Bendarkar, An Integrated Framework to Evaluate Off-Nominal Requirements and Reliability of Novel Aircraft Architectures in Early Design, Ph.D. Dissertation
  - AIAA-2021-1723, “Evaluation of Off-Nominal Performance and Reliability of a Distributed Electric Propulsion Aircraft during Early Design (2021)
- MagicDraw MBSE database for Normal Category Airplanes available for NASA/US Government use
  - Used as example application for Langley-funded project into model-based systems standards (MoSSEC)

WHAT'S NEXT IN REGIONAL (AIR) MOBILITY

Introduction

- Small commuter aircraft will be some of the earliest adopters of electrified aircraft propulsion
- Hypothesized that this trend could squeeze single-aisle transports
  - Original key question: Can small, electrified commuter aircraft combined with system-level improvements in power distribution infrastructure disrupt the current dominance of Single-Aisle class aircraft?
- Focus has shifted to regional cargo and passenger markets either not served (latent demand) or served by ground transportation
  - Leverages 5,000+ public-use airports that already exist in the United states as origin/destination pairs and renewable energy hubs



United States Environmental Protection Agency

NASA: *Regional Air Mobility*

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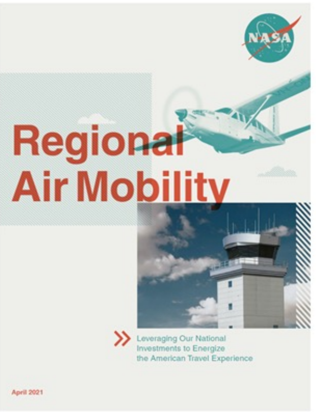
Regional Air Mobility (RAM)

- Increased interest in this transportation segment
  - NASA-led Regional Air Mobility white paper released in April 2021
  - McKinsey commentary on regional aviation
  - Multiple OEMs pursuing electrified regional S/CTOL aircraft
- Opportunities for air cargo, next-day delivery increasing
- Underserved passenger market
  - 90% of the population of the US lives within a 30-minute drive of a regional airport
  - 70% of passenger tours over 50 miles are less than 500 miles
  - Air travel only serves 10% of this market (and virtually none under 250 miles)



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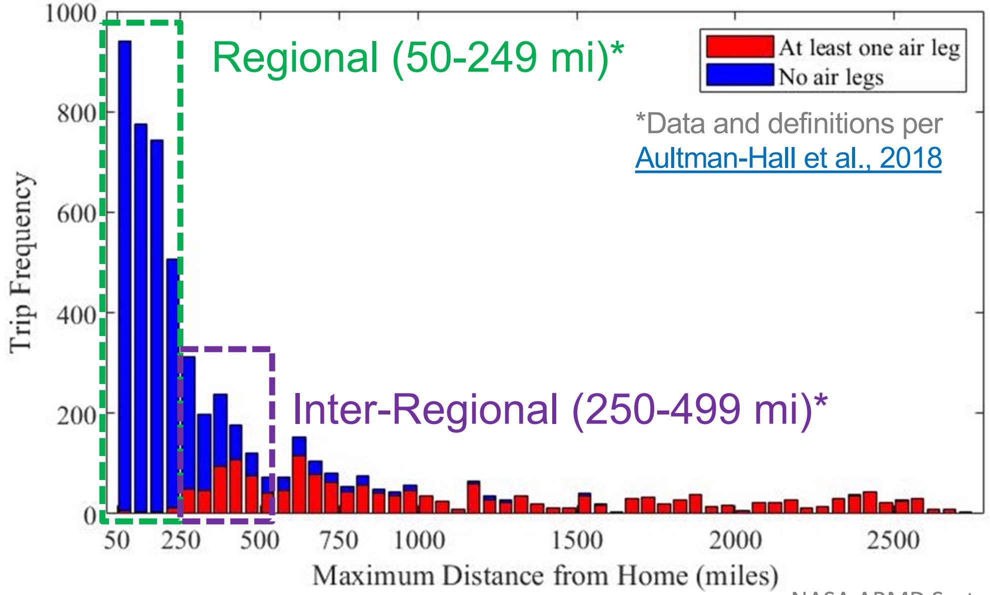
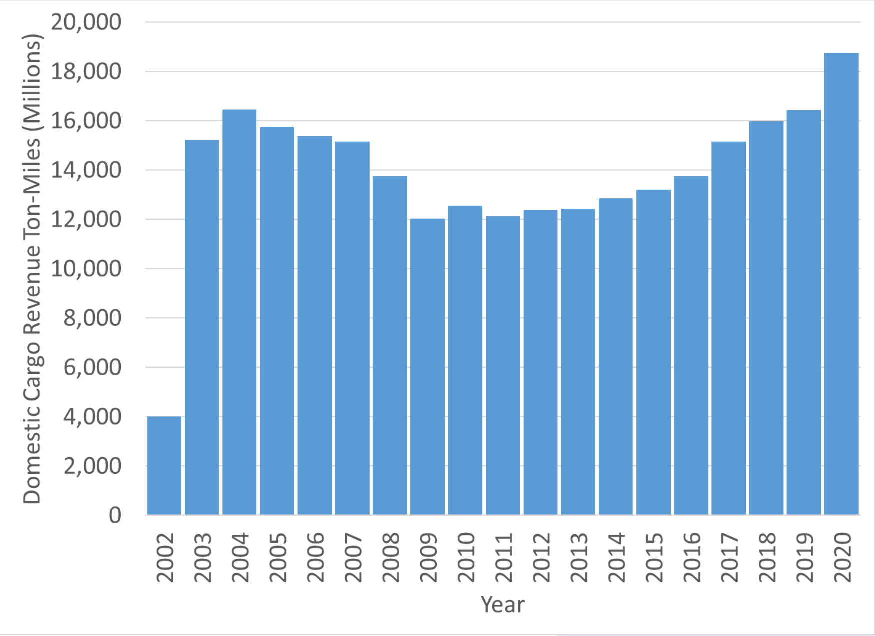
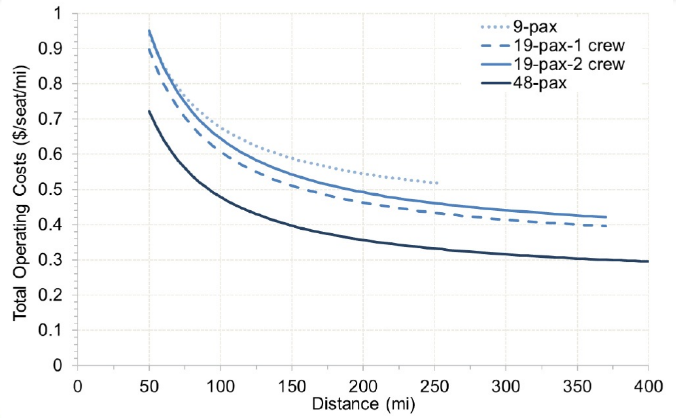


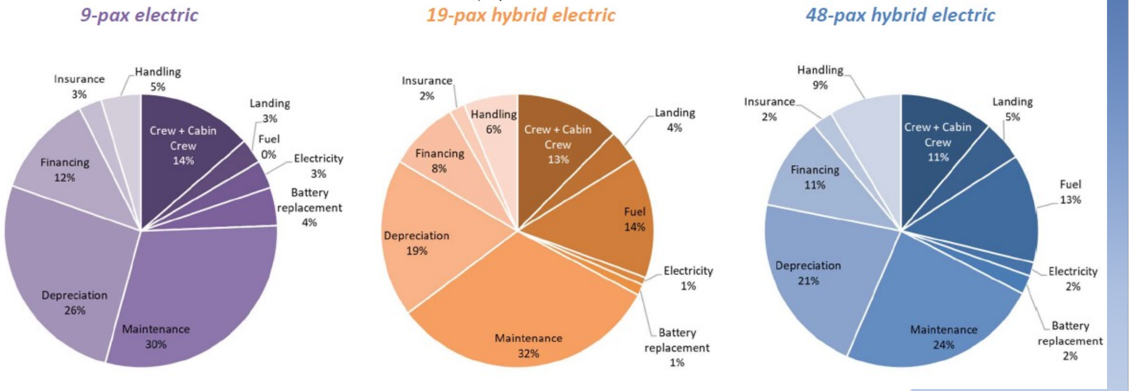


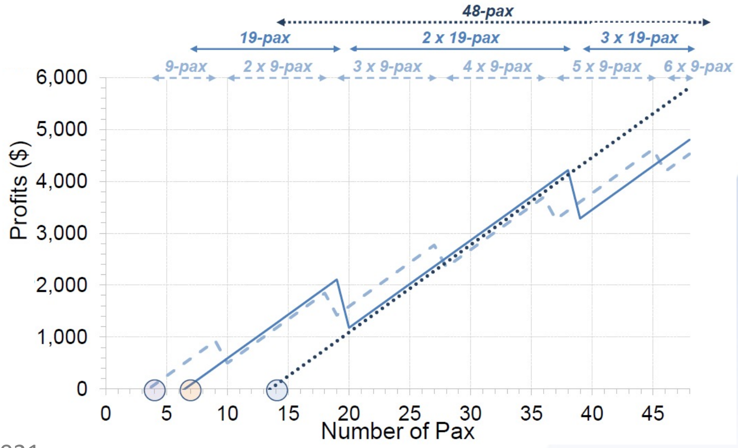
Domestic Cargo Data from Bureau of Transportation Statistics

Advanced Regional Air Mobility Study: Fleet Modeling

- Kicked off study in late 2020 with NIA/Georgia Tech to take a comprehensive look at the regional air mobility market in the mid-Atlantic Region
- Modeling four advanced regional aircraft
  - 5-passenger all-electric (in work)
  - 9-passenger all-electric
  - 19-passenger hybrid-electric
  - 48-passenger hybrid-electric
- Including variety of modeling assumptions, including battery energy density, utilization, simplified vehicle operations (e.g., single-pilot operations for up to 19 pax) and energy costs in various scenarios
- Also tracking fleet metrics – profits, costs, emissions

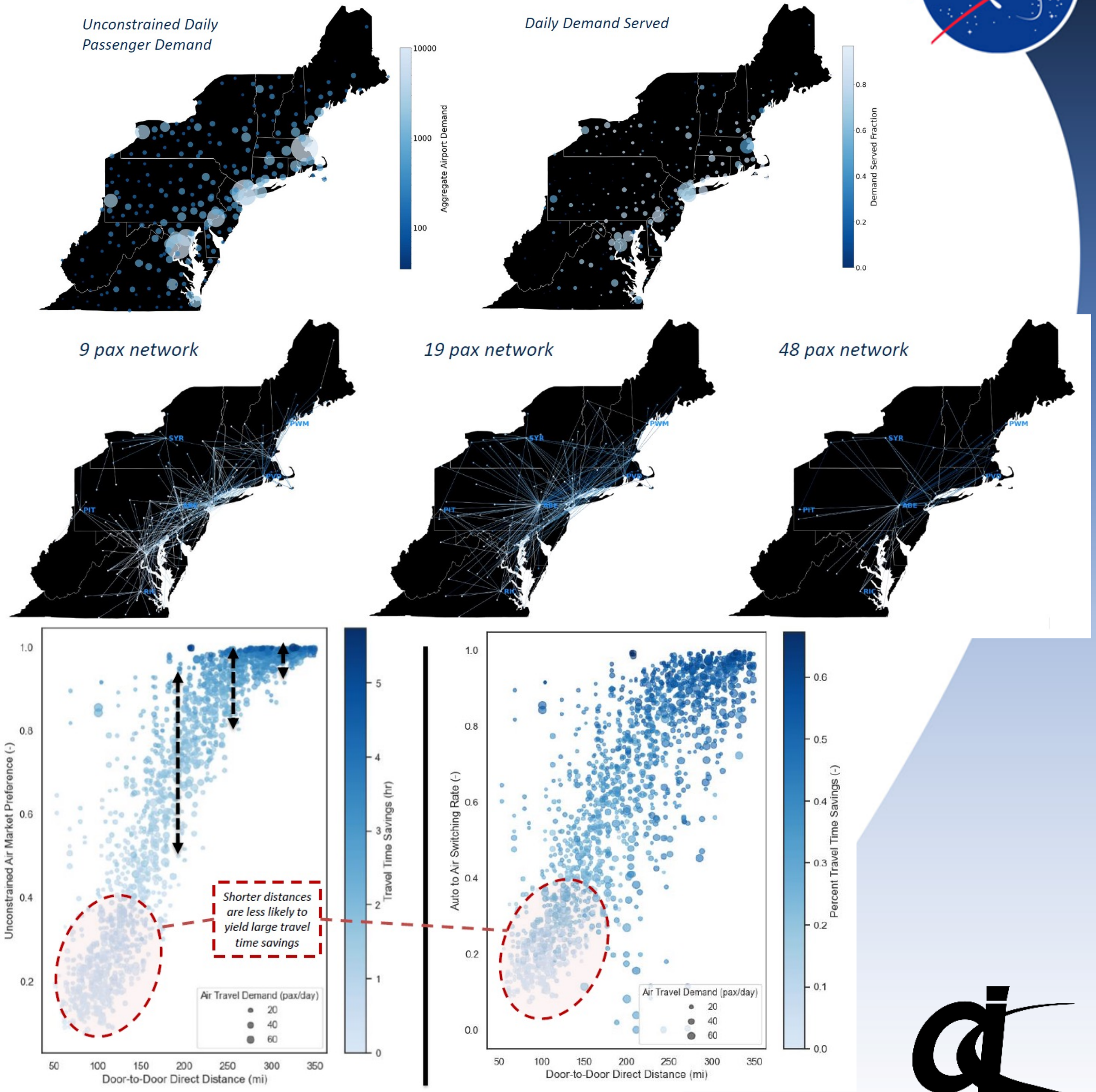






Advanced Regional Air Mobility Study: Passenger Demand

- Modeling operations at ~200 airports in the mid-Atlantic and New England regions of the United States
- Merged demand data from multiple sources to try to estimate both air and ground travel demand
  - Traveler Analysis Framework from the Federal Highway Administration helps to capture ground transportation demand
  - DB1B market database to understand airfares
- “All demand models are wrong, but some are useful”
  - Evaluating multiple scenarios to bound passenger demand and response to changes in pricing



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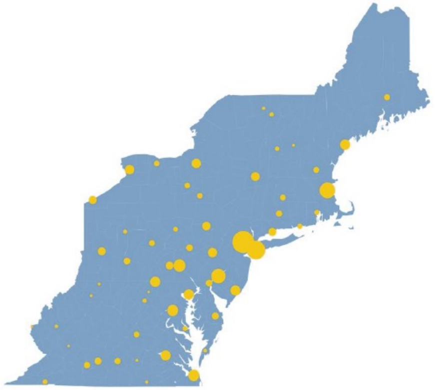
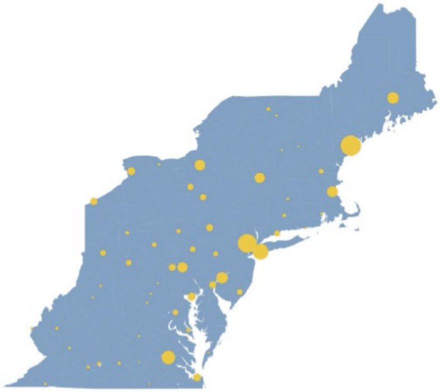
Advanced Regional Air Mobility Study: Cargo Demand

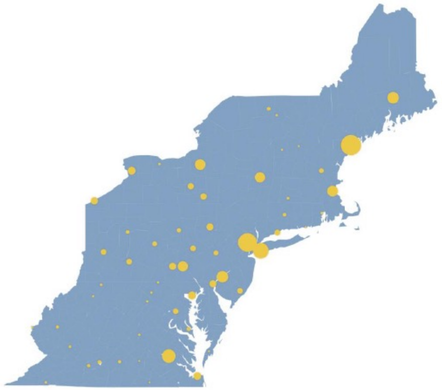
- Introduced cargo demand as means to potentially increase aircraft utilization
- Cargo data much more closely held than passenger data
- Freight Analysis Framework (FAF) zone data used to estimate air cargo demand by filtering likely air cargo commodities
- Multiple scenarios used to generate air cargo demand
- Cargo demand for regional air routes is roughly of same order as passenger demand when defined in terms of mass



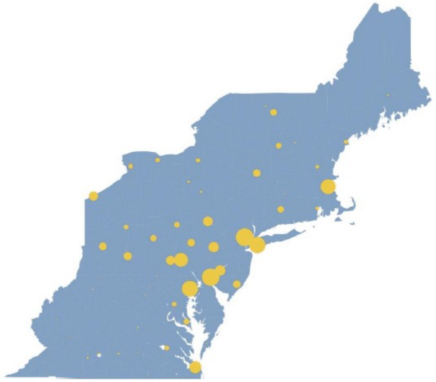
Scenario 1
Cargo Weight Transported (kg): 13,997,115



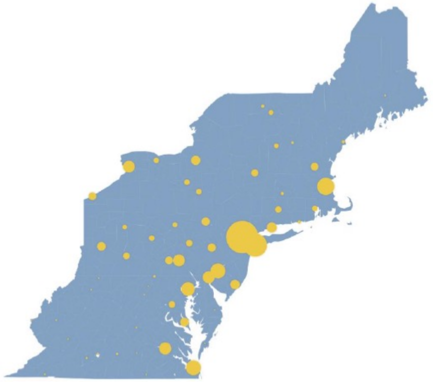
Scenario 2
Cargo Weight Transported (kg): 12,186,063



Scenario 3
Cargo Weight Transported (kg): 13,513,844



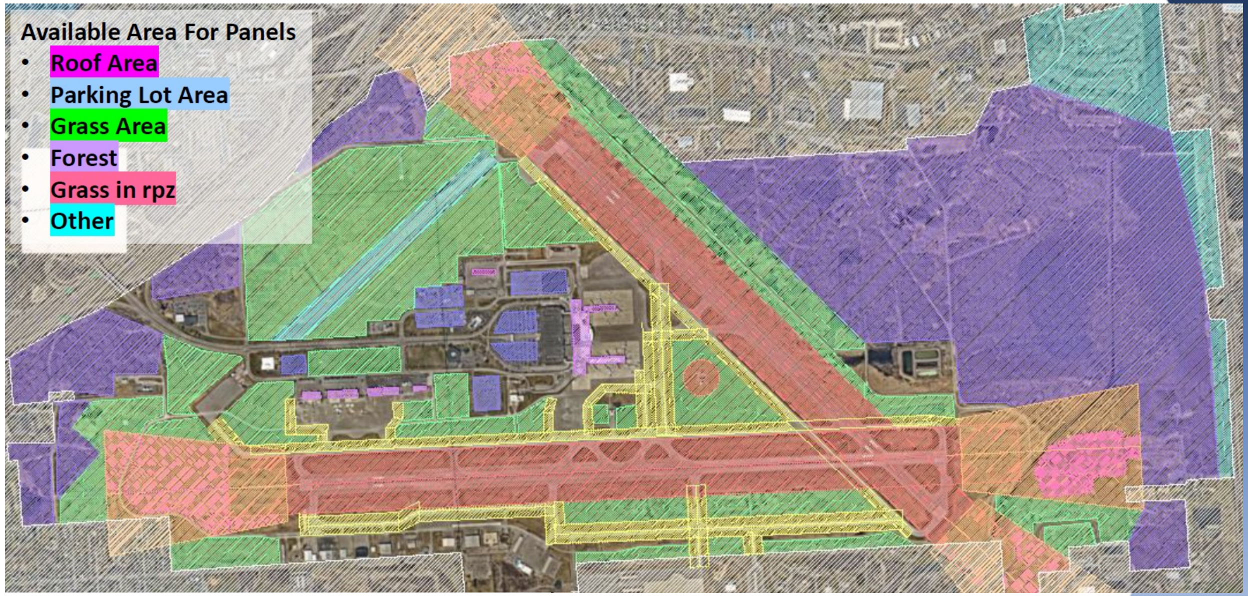
Scenario 4
Cargo Weight Transported (kg): 1,163,645

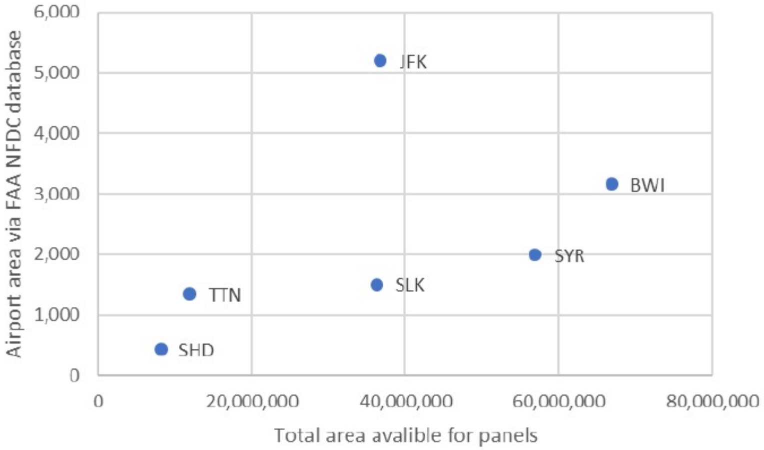


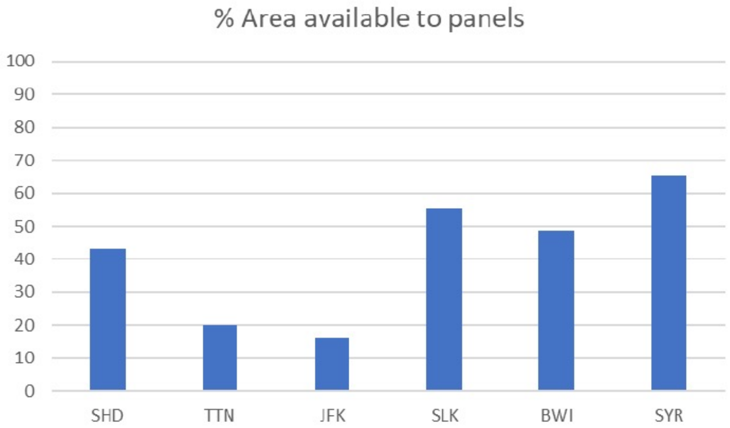
Scenario 5
Cargo Weight Transported (kg): 4,787,260

Advanced Regional Air Mobility Study: Airport Land Use

- Most airports are relatively flat, sparsely developed, public-use land
- Strong potential for increased development for renewable energy harvesting (particularly solar)
  - By mid-2021, [146 airports had begun 225 different renewable energy projects]() – 158 projects/116 airports were developing solar harvesting capabilities
  - ARAMS study includes a look at land available for solar development
- Aircraft can be a strong energy sink for additional demand
  - Renewable projects often limited by ability to move energy off-site







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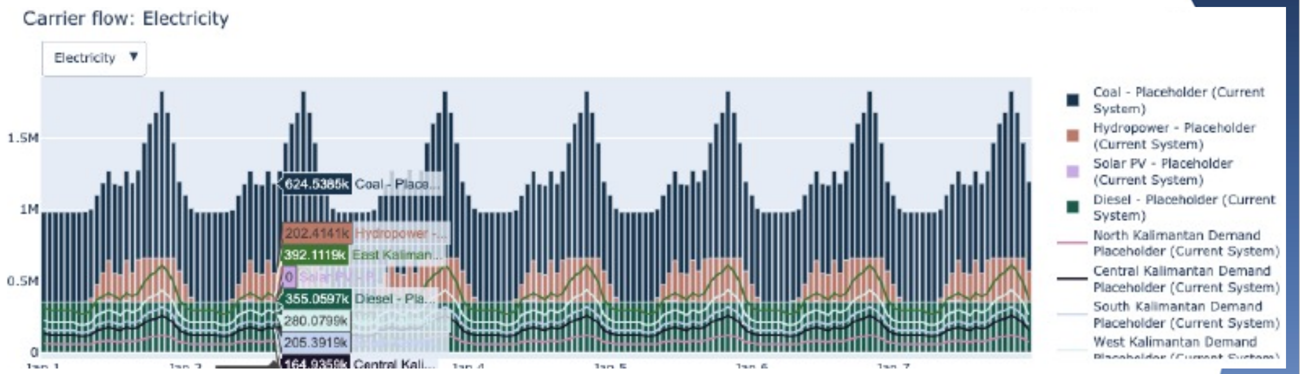
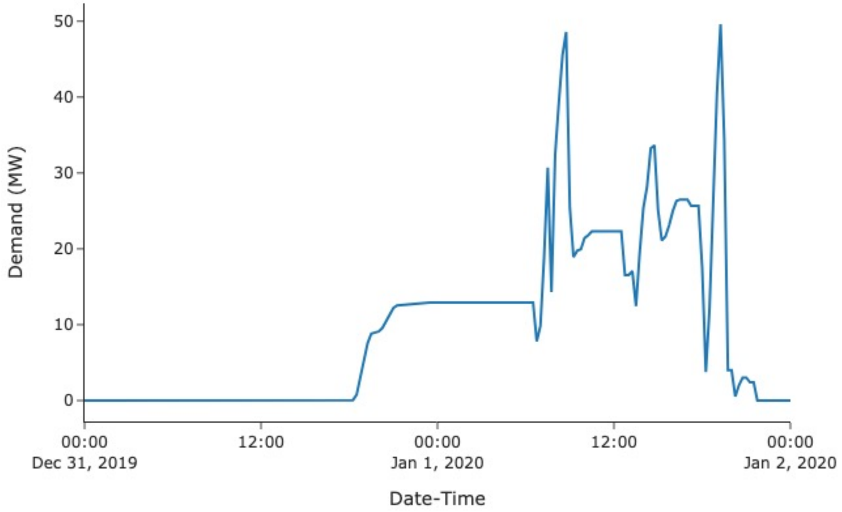


NREL Engage model of electricity flow (representative; analysis from prior study)



Total regional electrified aircraft loads from Advanced Regional Air Mobility Study for a baseline passenger scenario

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National Aeronautics and
Space Administration

What’s Next (in) …?

Finding the next possible “big ideas” in selected problems

Nick Borer

Aeronautics Systems Analysis Branch

10 November 2021

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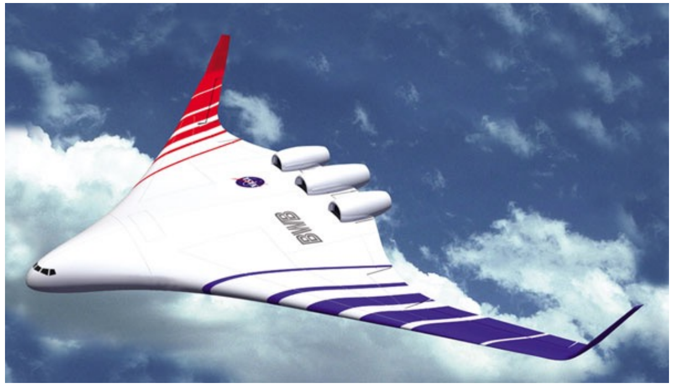
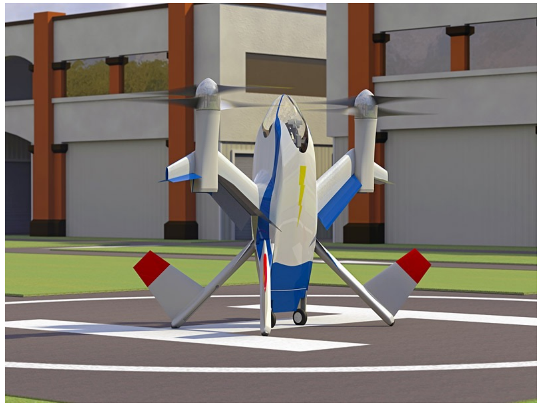
What Is “What’s Next?”

- ISAT’s “What’s Next” studies trace back to a hallway conversation at SciTech 2018
- Typical systems analysis studies consider existing needs and shortcomings, and suggest gaps or otherwise identify approaches to ameliorate them
- Idea behind “What’s Next” is to hypothesize advanced concepts that may either fill gaps or perhaps even address latent, uncharacterized needs, and see how these may drive future NASA investments





NASA images

What’s Happening with “What’s Next”

- Two major themes evaluated to date
- “What’s Next in Airworthiness Certification”
  - Initiated in late 2018
  - Three contracted studies completed – last one ended May 2021
  - Collaborated with the X-57 project
- “What’s Next in Regional Mobility”
  - Initiated in 2020
  - Two contracted studies underway
  - Collaborating with the AAM project, other potential collaborations in work

WHAT'S NEXT IN AIRWORTHINESS CERTIFICATION

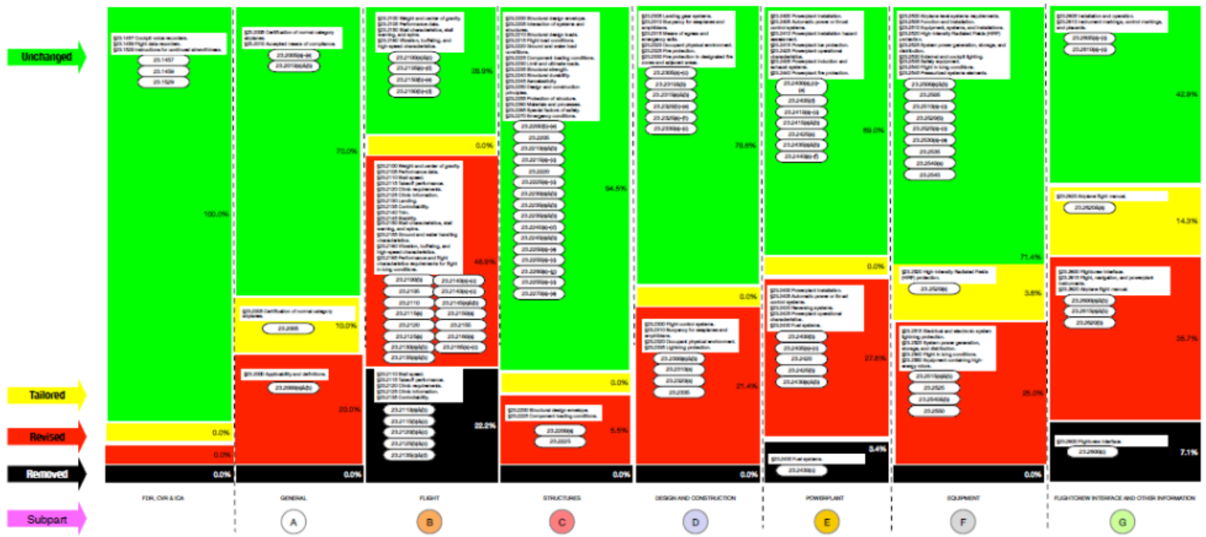
Introduction

- ARMD has embraced emerging markets for Advanced Air Mobility, introducing a challenge and an opportunity
  - 2013 Small Airplane Revitalization Act mandated streamlined airworthiness certification
  - Global movement in small airplane standard development towards adoption of performance-based standards
  - Requires support of industry (both established & emerging) and research community to further develop standards
- Key questions considered for "What's Next in Airworthiness Certification"
  - KQ1: Can we identify gaps in airworthiness certification today for new and emerging technologies [that are in NASA's portfolio]?
  - KQ2: Can we identify how certification rules and standards impact the design and development of aircraft with advanced technologies?
  - KQ3: What is NASA's role to address these gaps/impacts?
- Partnered with FDC/X-57 to serve as "advanced technology surrogate" for this study
  - Detailed, publicly available data on design, design rationale, and performance
  - X-57 is currently going through NASA airworthiness processes
  - Ancillary benefit: led to pivot in X-57 project goals to better align with US research/industry needs

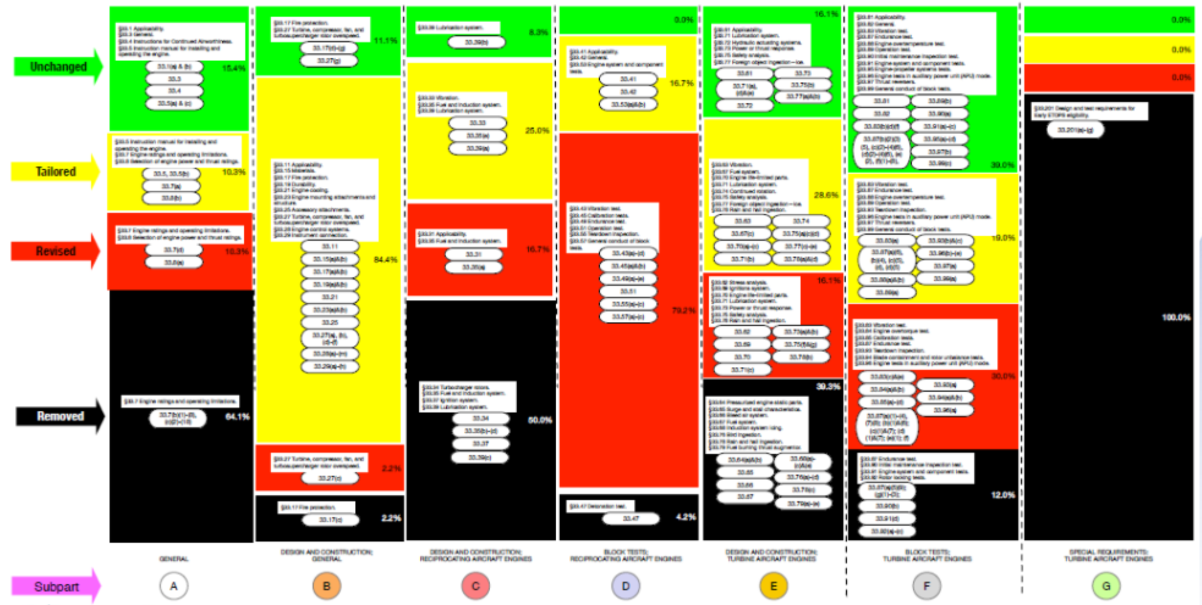
Certification Challenges with New Technologies

- NIA/HS Advanced Concepts, "Initial Assessment of Aircraft Certification Procedures for Emerging Technologies"
  - POP: July 2018-January 2019
  - Compared applicability of current rules and standards to X-57-like platform, as compared to airframe airworthiness (Part 23) and engine airworthiness (Part 33) requirements
  - Delivered Certification Rules and Standards Review (pre-KQ1), Certification Gap Analysis Report (KQ1), Certification Coordination Roadmap (pre-KQ3)

Assessment of Applicability of New Vehicle Concepts to 14 CFR 23, Airworthiness Standards: Normal Category Airplanes



Assessment of Applicability of Electric Propulsion to 14 CFR 33, Airworthiness Standards: Aircraft Engines



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Certification Planning

- NIA/HS Advanced Concepts, "Support the X-57 Project Office on Standards Development," April 2019-May 2021*
  - **Leveraged existing task order; new tasks related to ISAT added September 2019*
  - Developed an Airworthiness Validation Plan (KQ2) and Cross-Reference to Certification Checklist (KQ1), included efforts of eight subject matter experts and industry engagement at three events (KQ3)
  - Final report summarized in Final Airworthiness Validation Plan delivered May 2021

Subpart B—Flight	**Note**
(d) Performance data determined in accordance with paragraph (b) of this section must account for losses due to atmospheric conditions, cooling needs, and other demands on power sources.	Applies to X-57
§23.2110 Stall speed.	Applies to X-57
The applicant must determine the airplane stall speed or the minimum steady flight speed for each flight configuration used in normal operations, including takeoff, climb, cruise, descent, approach, and landing. The stall speed or minimum steady flight speed determination must account for the most adverse conditions for each flight configuration with power set at—	Stall speed determination in all configs required including takeoff and landing engines-propellers and cruise engines-props only. Stall speeds are gathered during stall characteristics investigation used to determine the low-speed fight characteristics score, S_{LSC}. X-57 minimum S_{LSC} is 150.
(a) Idle or zero thrust for propulsion systems that are used primarily for thrust; and NOTE: CM system would be considered the primary thrust producing system. FAA consensus would be required.	CM/HLP use and power settings need to be defined for each config and agreed to by FAA. HLP on/off power off speeds required for approach and landing conditions.
(b) A nominal thrust for propulsion systems that are used for thrust, flight control, and/or high-lift systems. NOTE: Both (a) and (b) subparagraph power settings are required for stall speed determination. It is not either (a) or (b). HLP system would fall into the high-lift system category while the CM system would fall into the thrust producing category for those conditions where a "power-on" stall condition must be considered.	CM/HLP use and power settings need to be defined for TO and Landing configs using both CM/HLP if HLM considered High Lift systems. FAA consensus required.
§23.2115 Takeoff performance.	Applies to X-57
(a) The applicant must determine airplane takeoff performance accounting for—	Applies to X-57
(1) Stall speed safety margins;	
(2) Minimum control speeds; and	
(3) Climb gradients.	
(b) For single engine airplanes and levels 1, 2, and 3 low-speed multiengine airplanes, takeoff performance includes the determination of ground roll and initial climb distance to 50 feet (15 meters) above the takeoff surface.	Applies to X-57
(c) For levels 1, 2, and 3 high-speed multiengine airplanes, and level 4 multiengine airplanes, takeoff performance includes a determination the following distances after a sudden critical loss of thrust—	NA

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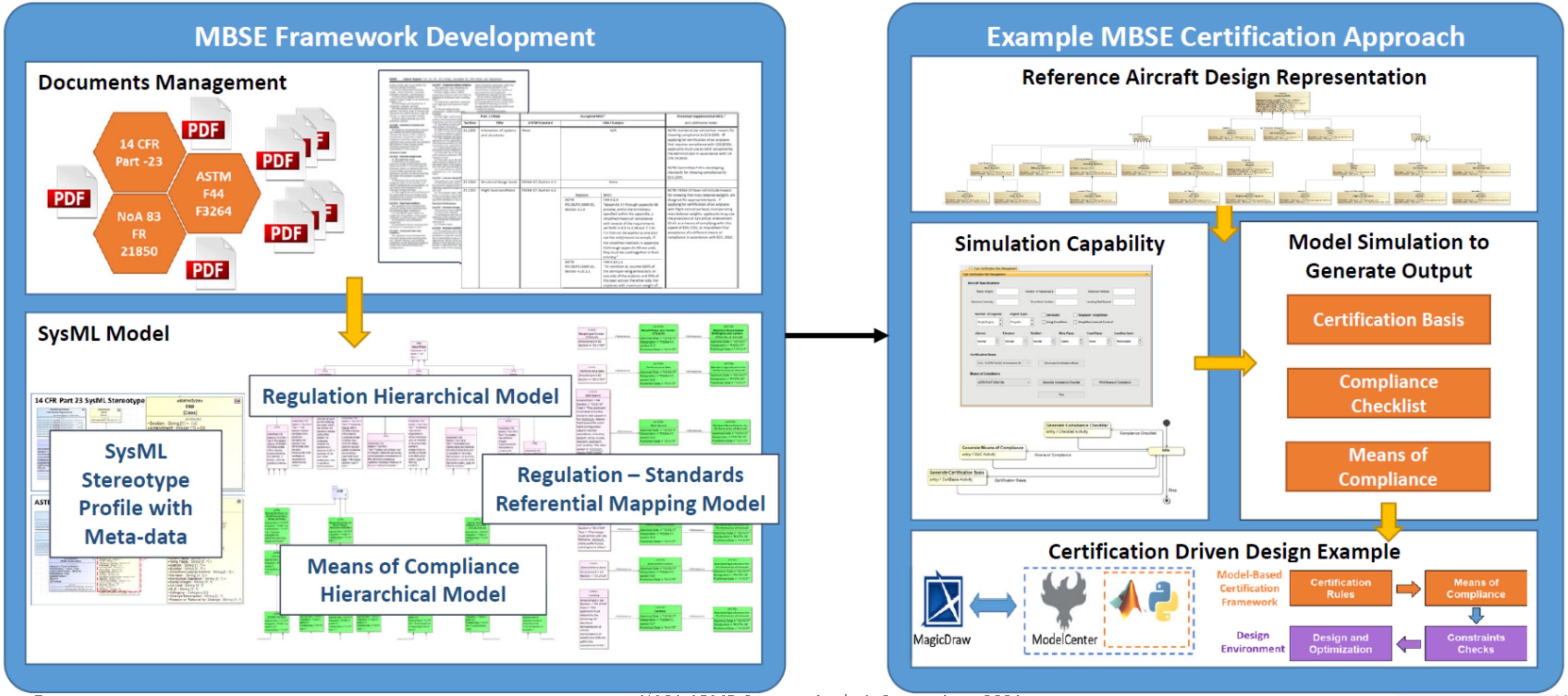
Model-Based Aircraft Certification

- NIA/Georgia Tech, "Model-Based Certification of Aircraft," April-December 2019
  - Developed initial Model-Based Systems Engineering (MBSE) framework for use in assessing advanced technology concepts (pre-KQ2), presented to ASTM F44 (pre-KQ3)



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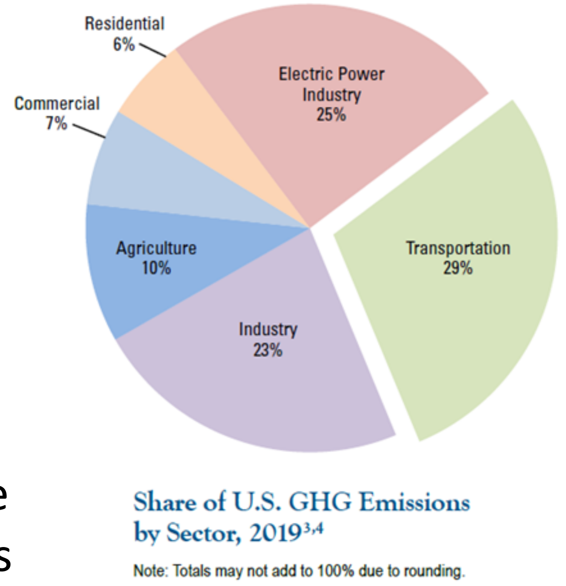
Work Product Summary and Impact

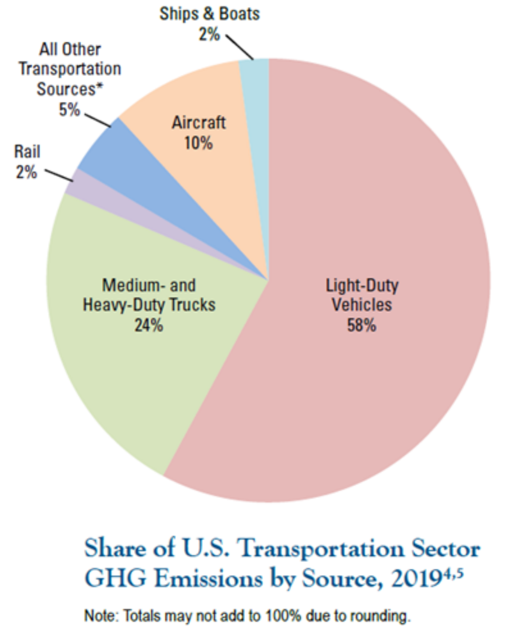
- This effort has helped ARMD identify how NASA can impact development of airworthiness procedures for new technologies
  - Directly influenced FDC/X-57 project objectives, interfacing with other projects (AAM), laid groundwork for others (EPFD)
  - Co-hosted certification workshop in coordination with FAA
- Publicly available reports to date, more to come:
  - NASA/CR-2019-220406, Certification Rules and Standards Review (2019)
  - NASA/CR-2019-220407, Certification Gap Analysis Report (2019)
  - NASA/CR-2019-220408, Certification Coordination Roadmap (2019)
  - AIAA-2019-3344, A Model-Based System Engineering Approach to Normal Category Airplane Airworthiness Certification (2019)
  - AIAA-2020-3096, A Model-Based Aircraft Certification Framework for Normal Category Airplanes (2020)
  - Airworthiness Validation Plan – delivered May 2021, not yet gone through public release process
- Other related research spinoffs
  - AIAA-2019-3576, Development of a Certification Module for Early Aircraft Design (2019)
  - M. Bendarkar, An Integrated Framework to Evaluate Off-Nominal Requirements and Reliability of Novel Aircraft Architectures in Early Design, Ph.D. Dissertation
  - AIAA-2021-1723, "Evaluation of Off-Nominal Performance and Reliability of a Distributed Electric Propulsion Aircraft during Early Design (2021)
- MagicDraw MBSE database for Normal Category Airplanes available for NASA/US Government use
  - Used as example application for Langley-funded project into model-based systems standards (MoSSEC)

WHAT’S NEXT IN REGIONAL (AIR) MOBILITY

Introduction

- Small commuter aircraft will be some of the earliest adopters of electrified aircraft propulsion
- Hypothesized that this trend could squeeze single-aisle transports
  - Original key question: Can small, electrified commuter aircraft combined with system-level improvements in power distribution infrastructure disrupt the current dominance of Single-Aisle class aircraft?
- Focus has shifted to regional cargo and passenger markets either not served (latent demand) or served by ground transportation
  - Leverages 5,000+ public-use airports that already exist in the United states as origin/destination pairs and renewable energy hubs



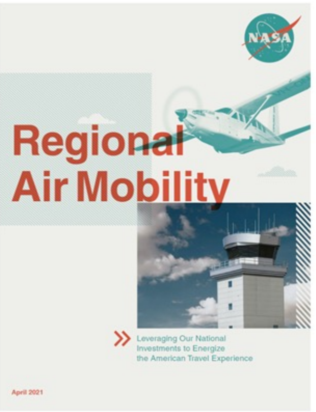


United States Environmental Protection Agency

NASA: *Regional Air Mobility*

Regional Air Mobility (RAM)

- Increased interest in this transportation segment
  - NASA-led [Regional Air Mobility white paper] released in April 2021
  - McKinsey [commentary] on regional aviation
  - Multiple OEMs pursuing electrified regional S/CTOL aircraft
- Opportunities for air cargo, next-day delivery increasing
- Underserved passenger market
  - 90% of the population of the US lives within a 30-minute drive of a regional airport
  - 70% of passenger tours over 50 miles are less than 500 miles
  - Air travel only serves 10% of this market (and virtually none under 250 miles)



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Xwing	Southern Airways Express
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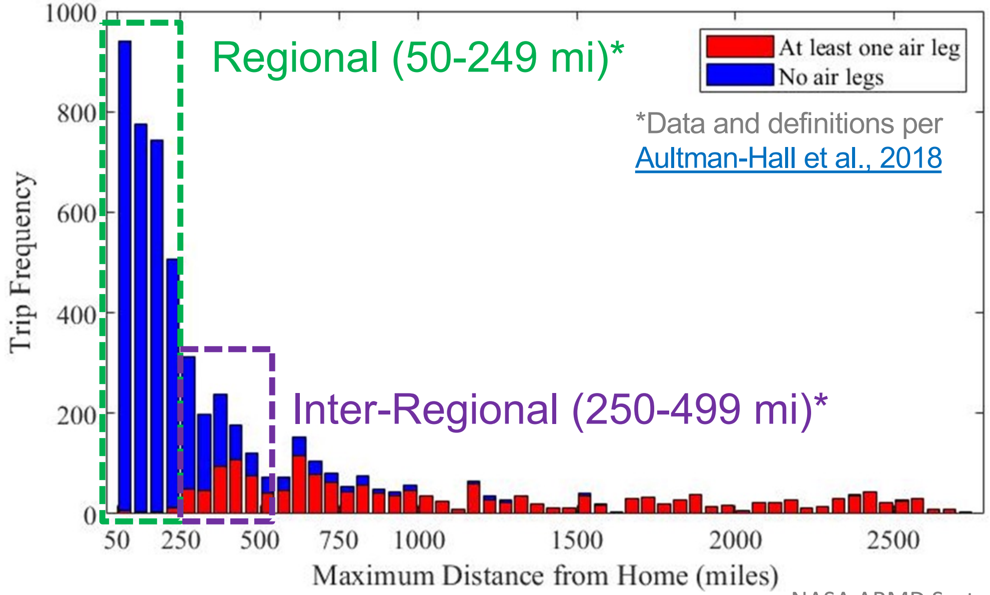
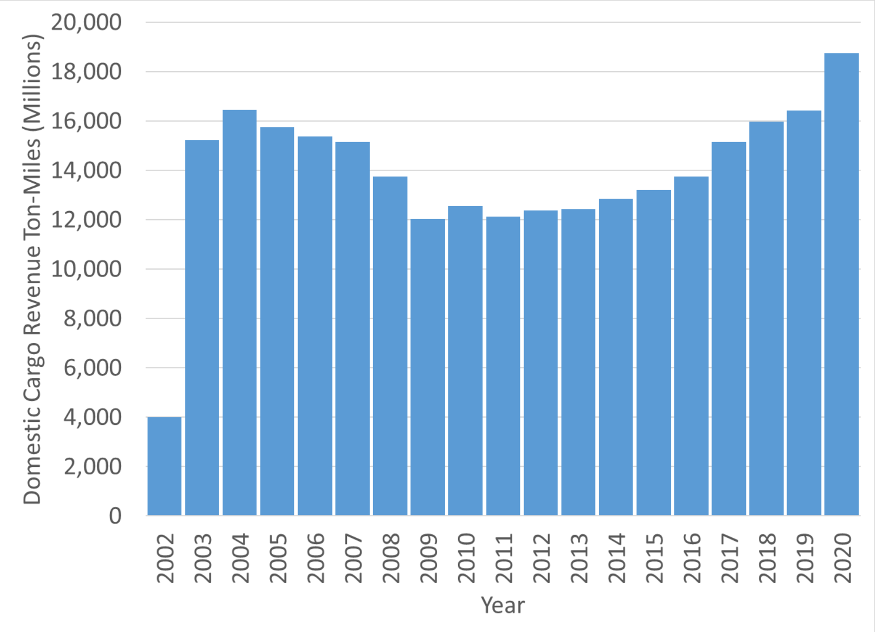
Electra.Aero	Holmes Consulting LLC
Georgia Tech	Radius Capital
Explorer Aircraft	UP Partners | Airmap
FLOAT Shuttle	Curated Innovation

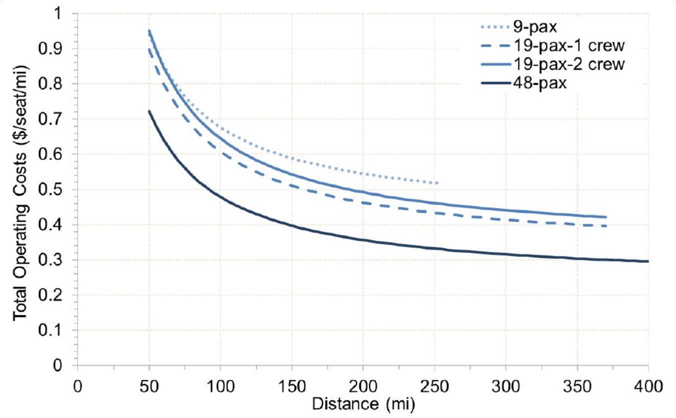


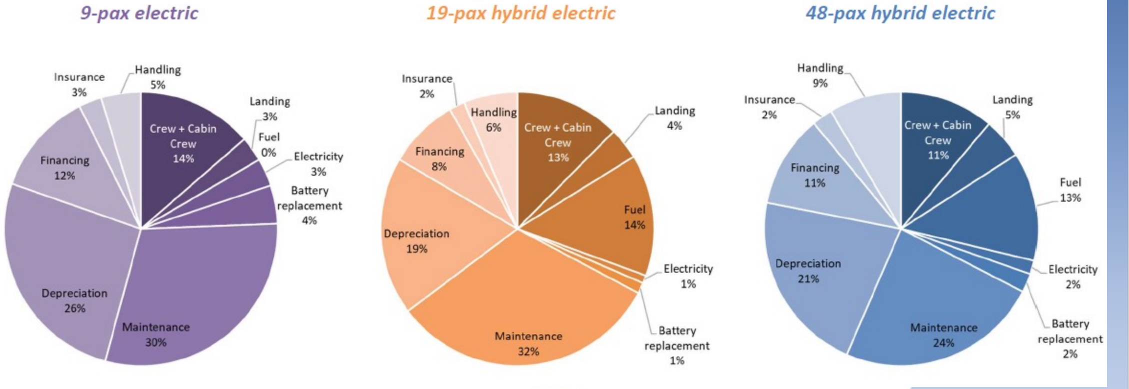


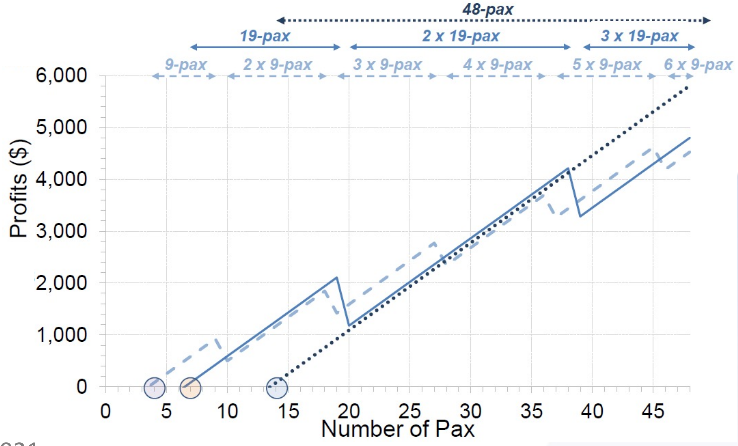
Domestic Cargo Data from [Bureau of Transportation Statistics]

Advanced Regional Air Mobility Study: Fleet Modeling

- Kicked off study in late 2020 with NIA/Georgia Tech to take a comprehensive look at the regional air mobility market in the mid-Atlantic Region
- Modeling four advanced regional aircraft
  - 5-passenger all-electric (in work)
  - 9-passenger all-electric
  - 19-passenger hybrid-electric
  - 48-passenger hybrid-electric
- Including variety of modeling assumptions, including battery energy density, utilization, simplified vehicle operations (e.g., single-pilot operations for up to 19 pax) and energy costs in various scenarios
- Also tracking fleet metrics – profits, costs, emissions







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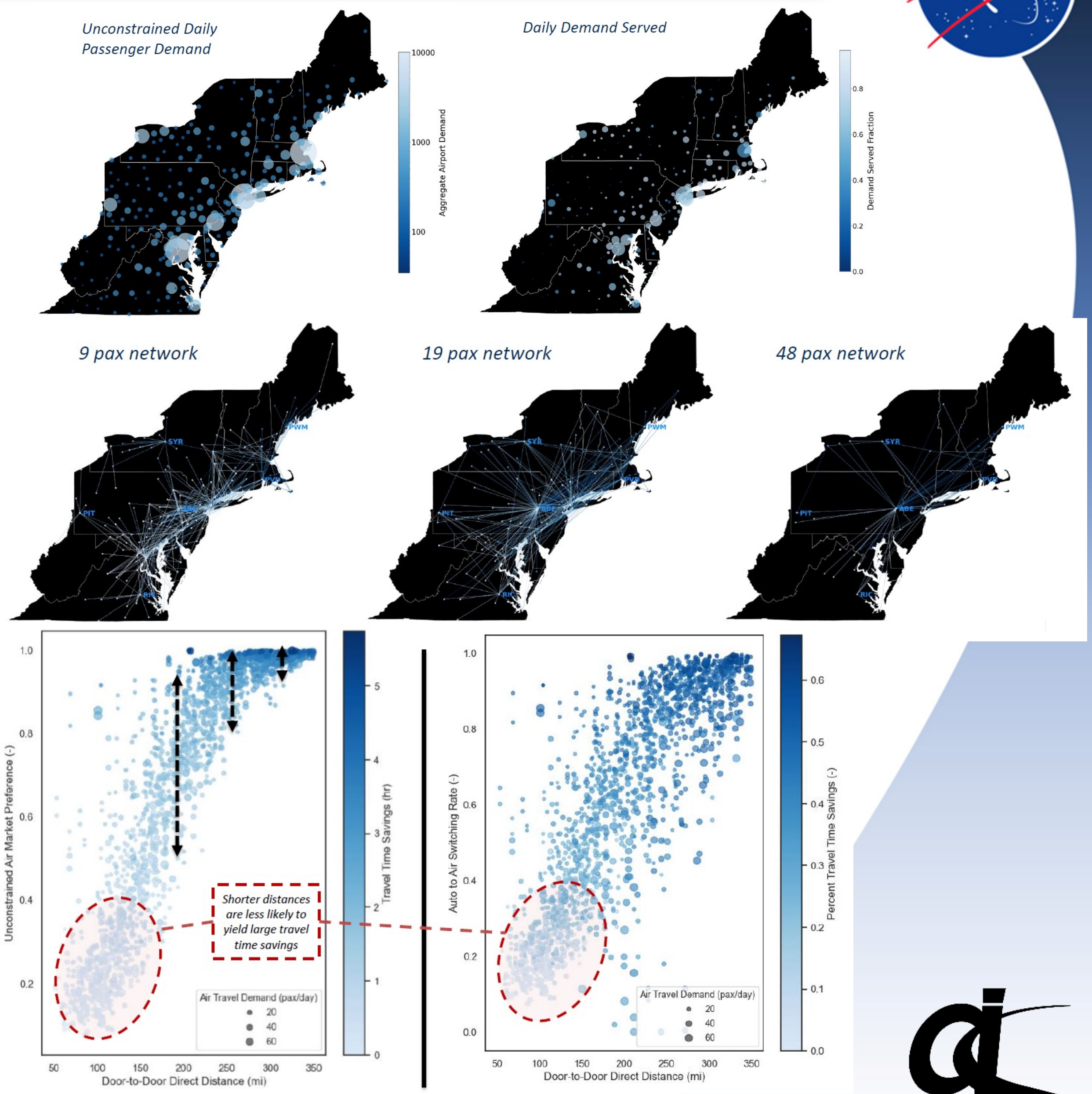
Advanced Regional Air Mobility Study: Passenger Demand

- Modeling operations at ~200 airports in the mid-Atlantic and New England regions of the United States
- Merged demand data from multiple sources to try to estimate both air and ground travel demand
  - Traveler Analysis Framework from the Federal Highway Administration helps to capture ground transportation demand
  - DB1B market database to understand airfares
- "All demand models are wrong, but some are useful"
  - Evaluating multiple scenarios to bound passenger demand and response to changes in pricing



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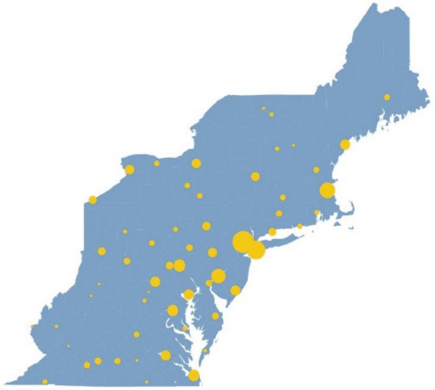
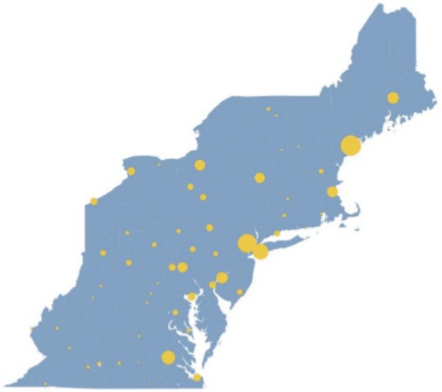
Advanced Regional Air Mobility Study: Cargo Demand

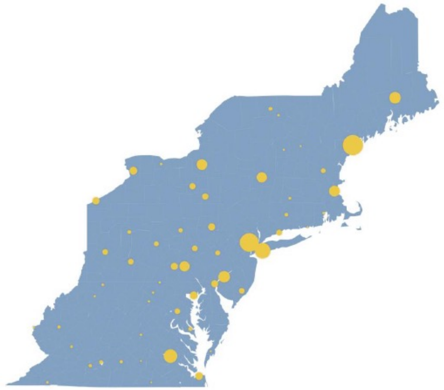
- Introduced cargo demand as means to potentially increase aircraft utilization
- Cargo data much more closely held than passenger data
- Freight Analysis Framework (FAF) zone data used to estimate air cargo demand by filtering likely air cargo commodities
- Multiple scenarios used to generate air cargo demand
- Cargo demand for regional air routes is roughly of same order as passenger demand when defined in terms of mass



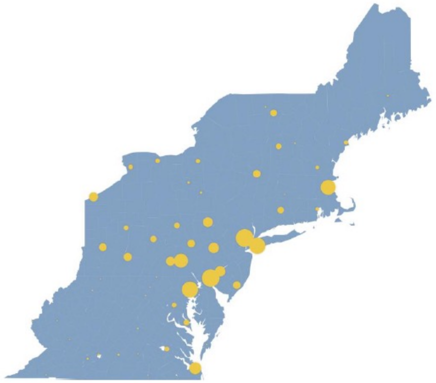
Scenario 1
Cargo Weight Transported (kg): 13,997,115



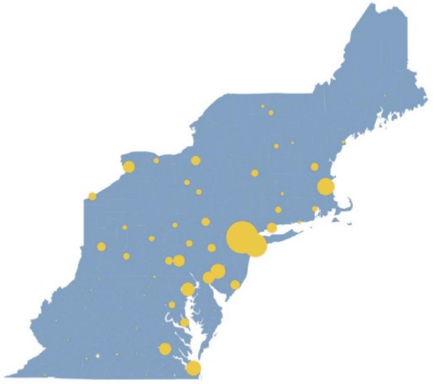
Scenario 2
Cargo Weight Transported (kg): 12,186,063



Scenario 3
Cargo Weight Transported (kg): 13,513,844



Scenario 4
Cargo Weight Transported (kg): 1,163,645



Scenario 5
Cargo Weight Transported (kg): 4,787,260

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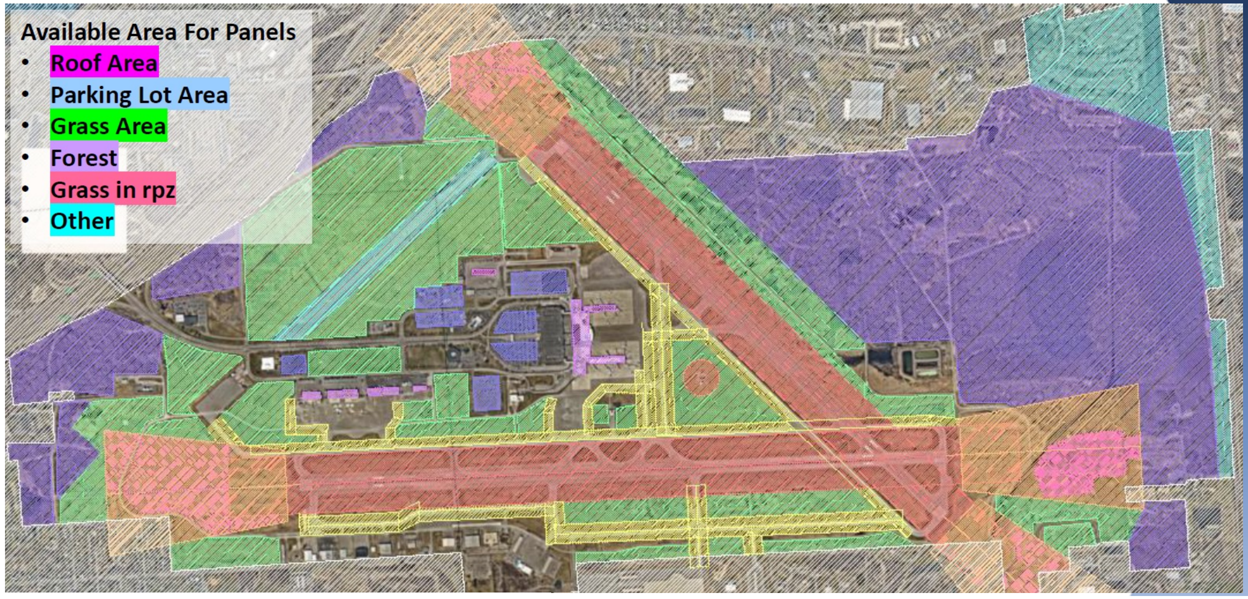
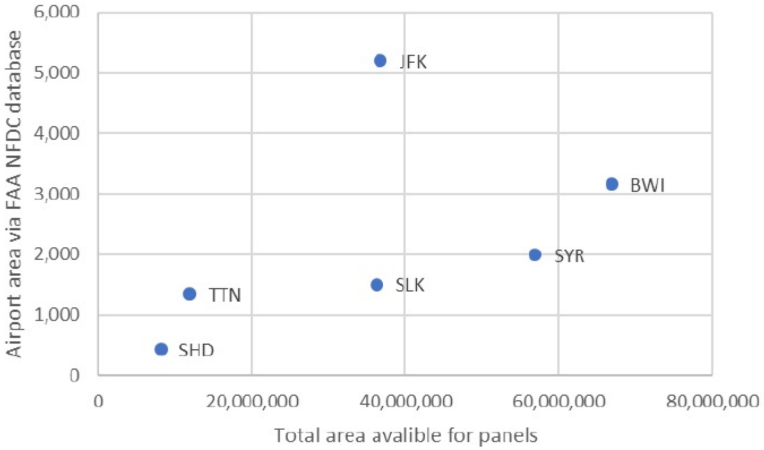
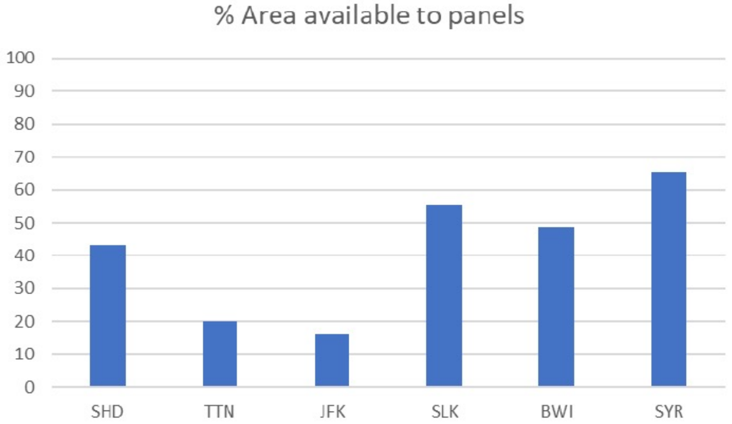
Advanced Regional Air Mobility Study: Airport Land Use

- Most airports are relatively flat, sparsely developed, public-use land
- Strong potential for increased development for renewable energy harvesting (particularly solar)
  - By mid-2021, 146 airports had begun 225 different renewable energy projects – 158 projects/116 airports were developing solar harvesting capabilities
  - ARAMS study includes a look at land available for solar development
- Aircraft can be a strong energy sink for additional demand
  - Renewable projects often limited by ability to move energy off-site







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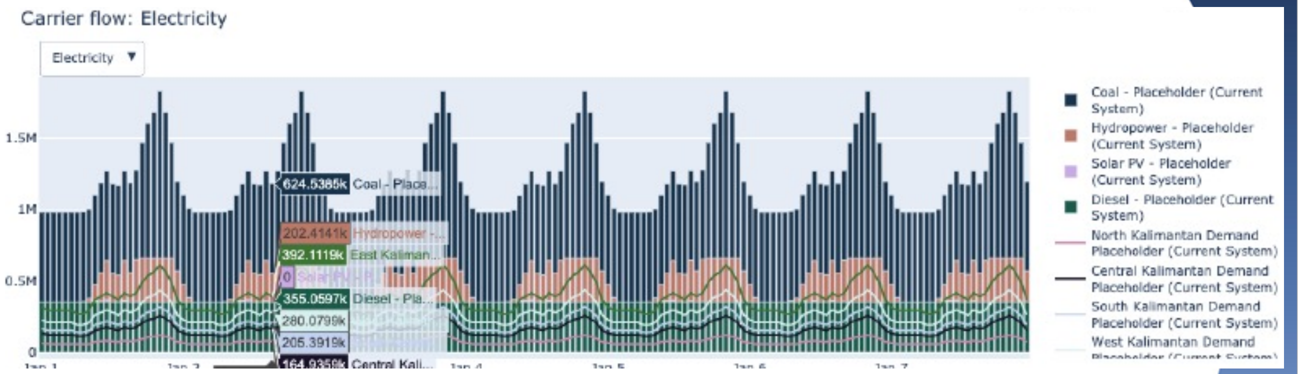

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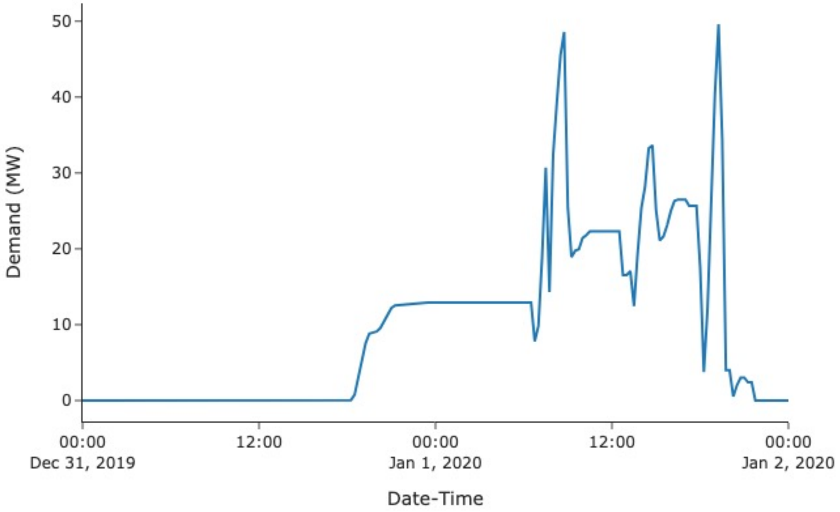

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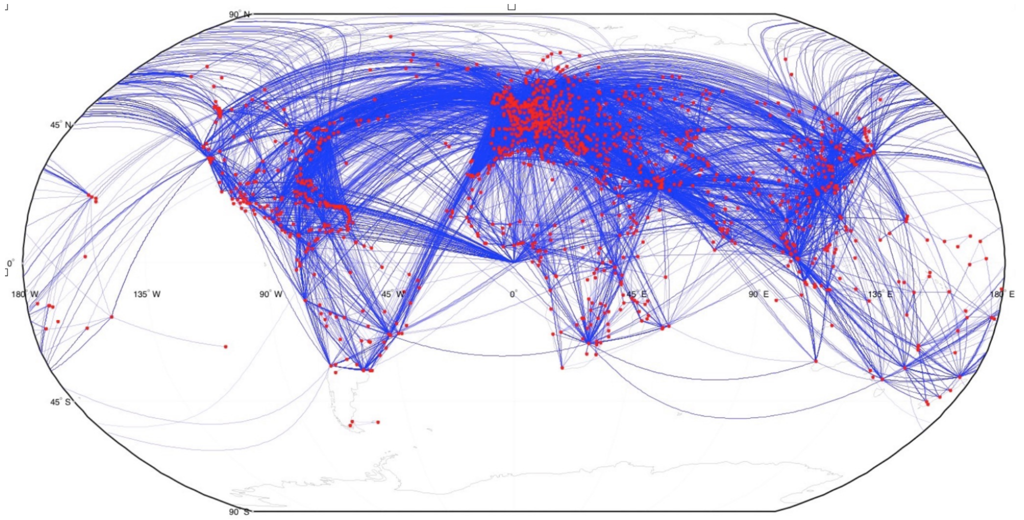
Global Demand Modeling Study



Ty V. Marien
Aeronautics Systems Analysis Branch
NASA Langley Research Center

ISAT Systems Analysis Symposium, 10 November 2021

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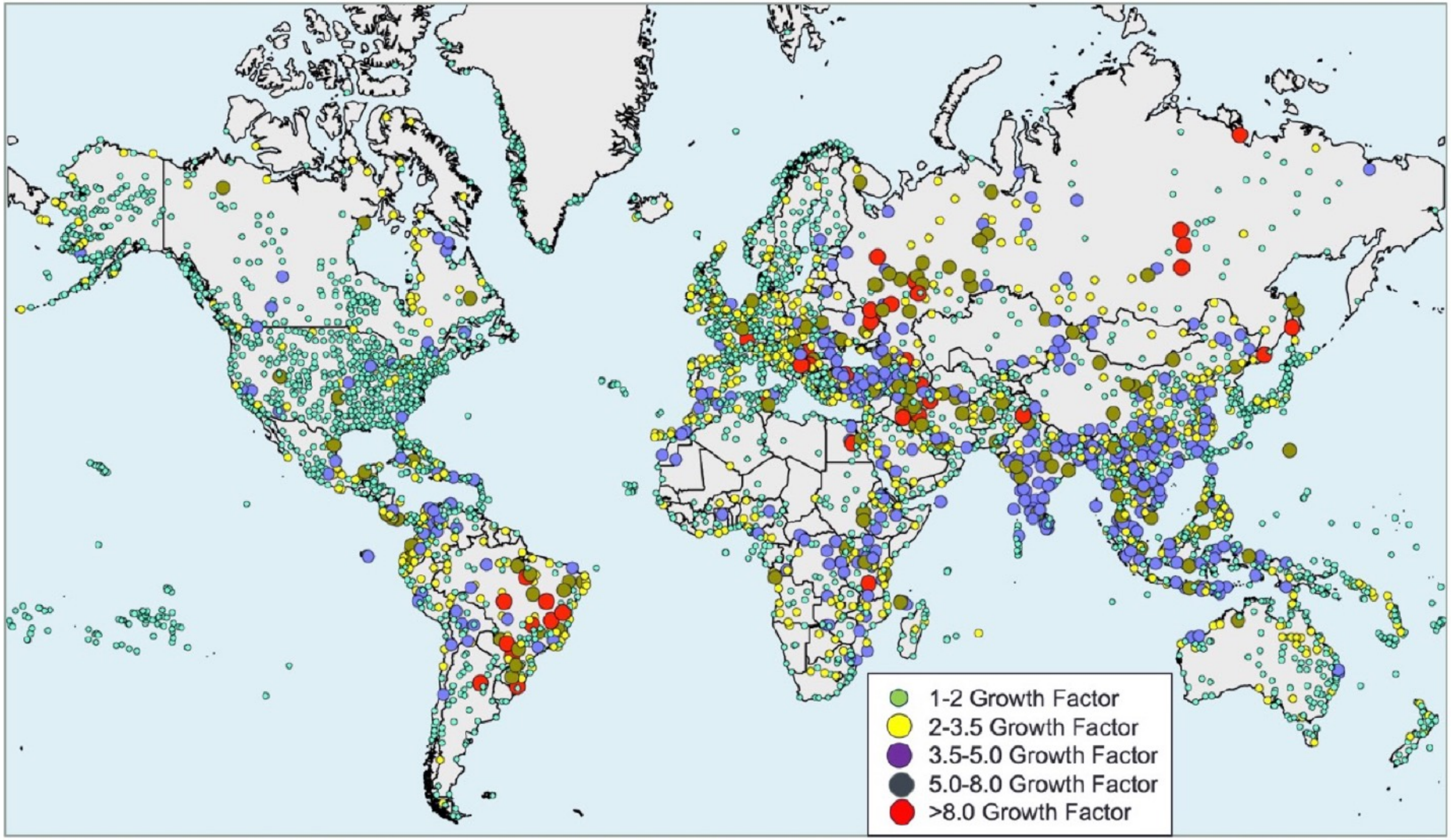
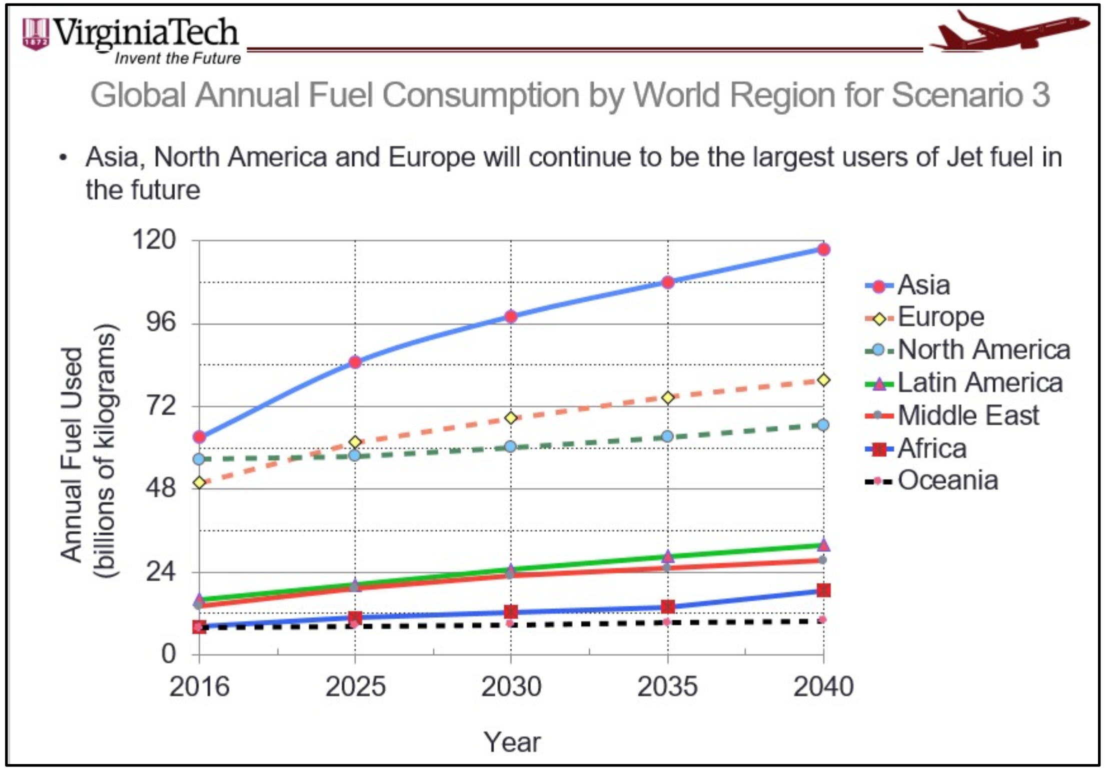
Study Background

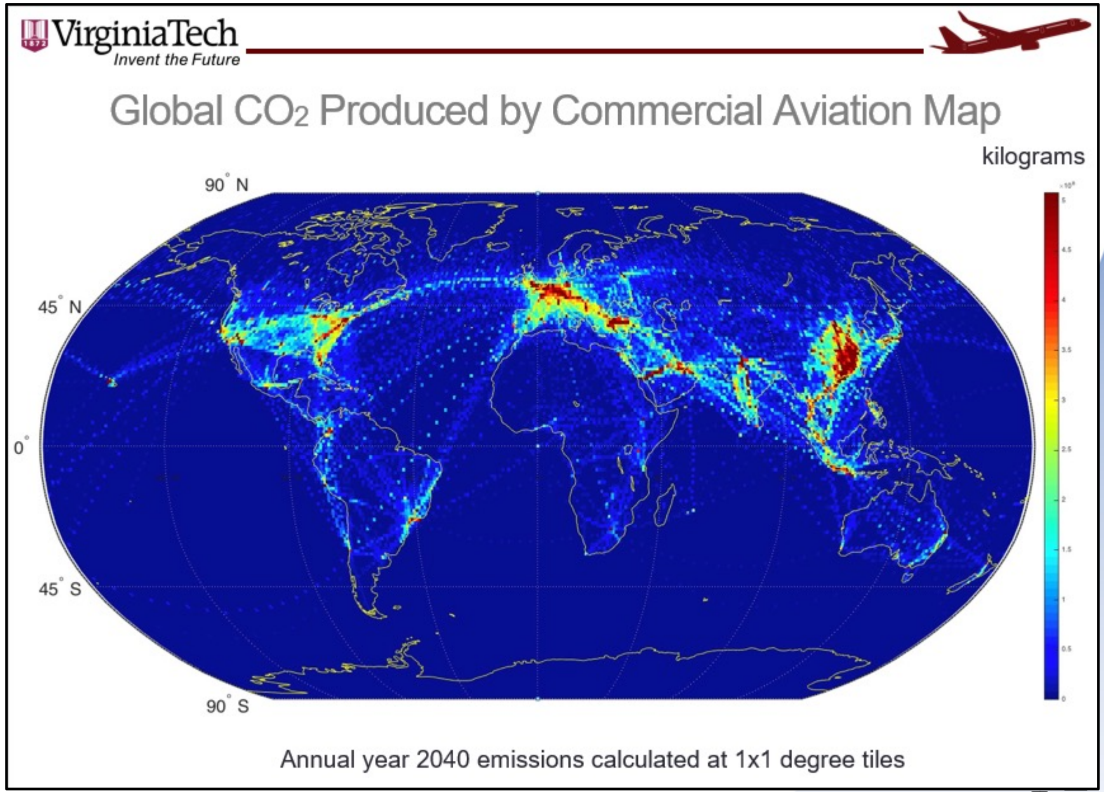
- ISAT (previously ISAAC) funded development of the Global Demand Model (GDM) by Virginia Tech in 2015
  - Initial prototype of GDM model projected the number of seats offered at airports worldwide out to the year 2040 and the number of trips between origin/destination pairs.
  - In 2017, a fleet evolution and operations model was added. GDM was used to forecast the fuel burn and emissions for the worldwide commercial fleet out to 2040.
- *ISAT Mega-Drivers Modeling:* Revisit the socioeconomic & environmental Mega-Drivers embodied in the *ARMD Strategic Implementation Plan*, exploring a next level of analysis across the global aviation landscape.
- The recent Mega-Drivers focus prompted us to take another look at the GDM to see if it could help us evaluate potential drivers in global aviation.
- In August 2020, we initiated a new task order with NIA / Virginia Tech to update and improve the GDM.

GDM Airports



Sample GDM Outputs

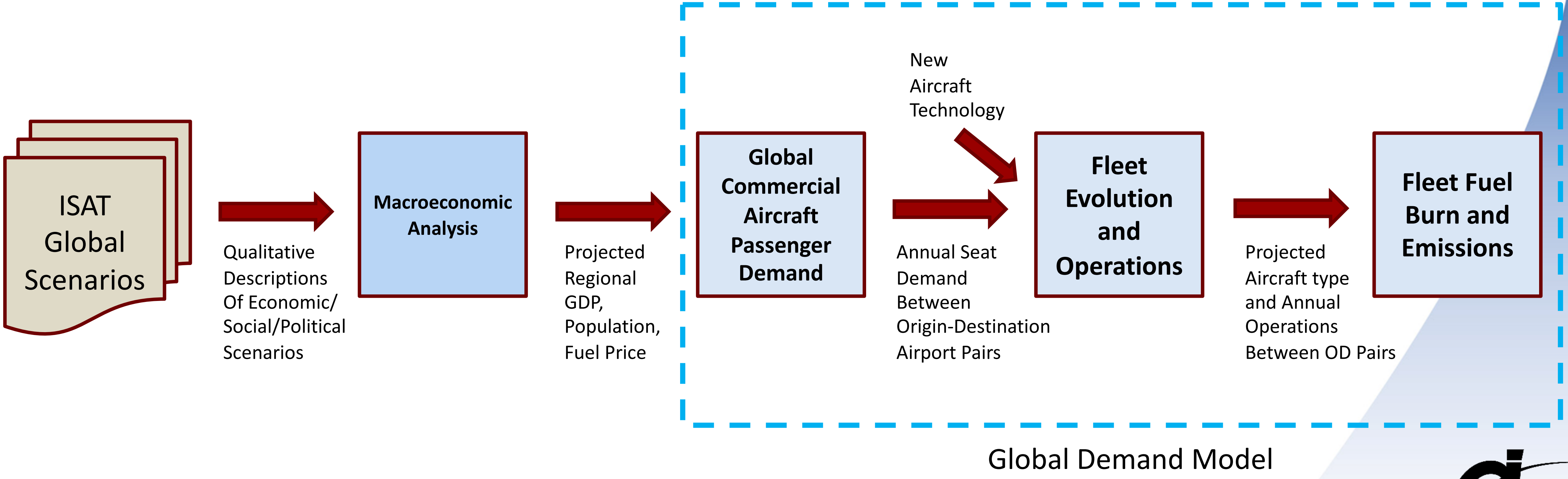




GDM forecasts global passenger demand for commercial aviation. More importantly, GDM forecasts commercial aircraft fleet fuel burn and emissions between OD pairs, which can be aggregated in various ways.

Mega-Drivers Modeling

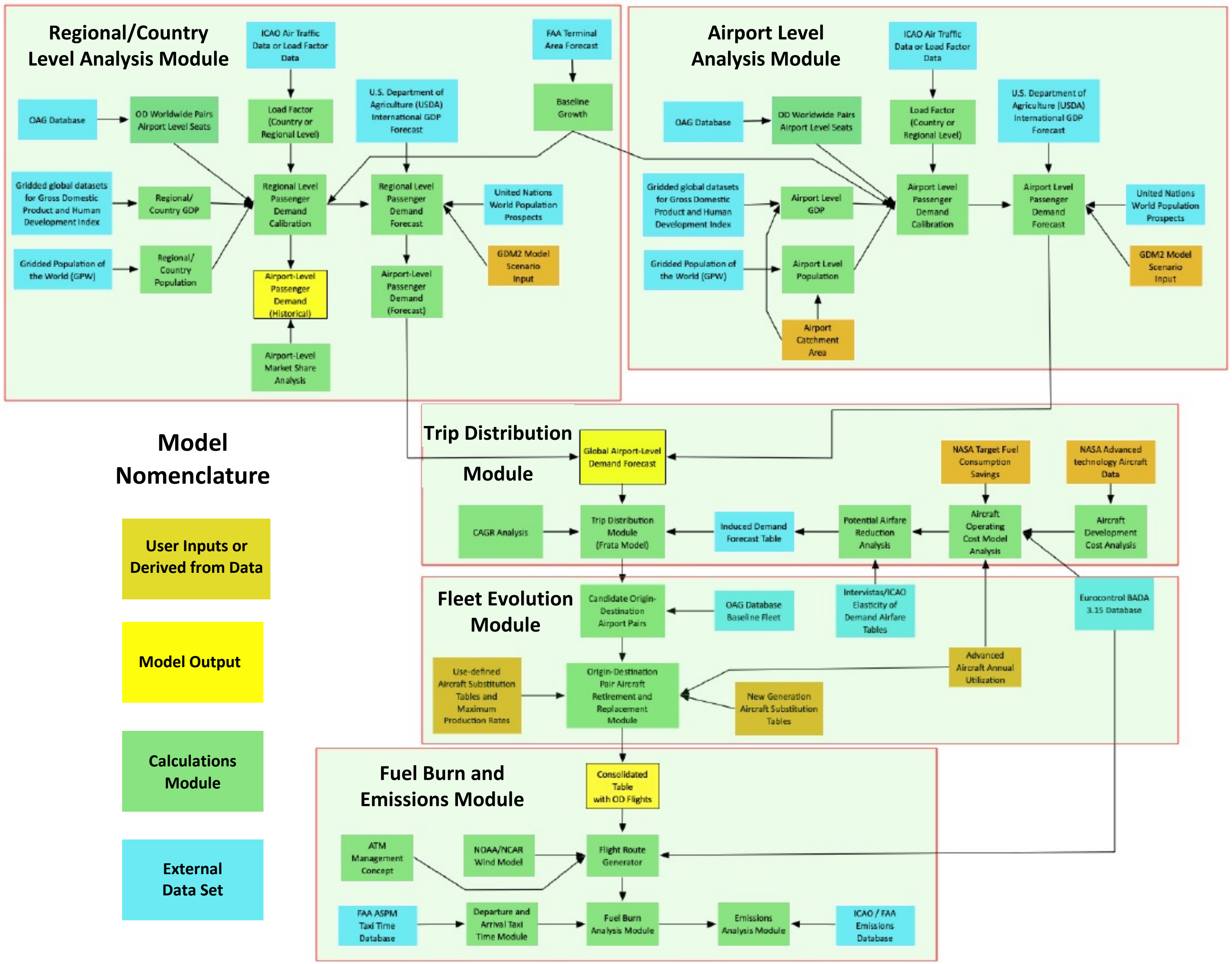
The Global Demand Model fits into the larger goal of translating the ISAT global scenarios into quantitative impacts on global passenger demand, aircraft fleet operations, fuel burn, & emissions



FY21 Study Tasks

- Explore the connections between the ISAT scenarios and inputs into the GDM, including possible shocks to the transportation system.
- Implement an airfare elasticity of demand model
- Work to improve the demand prediction models
- Update GDM with latest databases & recalibrate the model to the new data
- Update the aircraft fleet evolution model the latest information and projections

GDM Description



GDM is composed of 5 modules:

1) Regional/Country Level Analysis
2) Airport Level Analysis
3) Trip Distribution
4) Fleet Evolution
5) Fuel Burn and Emissions

GDM Databases

GDM uses historical databases containing airline operations, GDP, and population to create regression models for passenger demand.

Databases containing projections for GDP and population are used to forecast future demand and aircraft operations.

These databases were updated to the most recent available versions.

Dataset	Relevance of Data	GDM Data
Official Airline Guide	Provides seats, frequencies and aircraft types worldwide	1996 – 2019
Gridded global datasets for Gross Domestic Product and Human Development Index	GDP PPP data available worldwide at 30-second resolution.	1990, 2000, 2015 Version 3
U.S. Department of Agriculture (USDA) International GDP Forecast	Provides world country forecasts of GDP	1980 - 2031 Version 01/2020
Gridded Population of the World (GPW)	Population reported at 30-second resolution	2000, 2005, 2010, 2015, 2020 Version 4.11
United Nations World Population Prospects	World population estimates	1950 – 2100 Version 2019
Terminal Area Forecast (TAF)	FAA forecasts for US airports	2019

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Airfare Elasticity Modeling

Price elasticity of demand is a measure of the change in the quantity purchased of a product in relation to a change in its price.

Airfare price elasticity values were found in an ICAO report for a number of world regions.

Values are a ratio of % change in amount demanded to the % change in its price.

For example, a 10% reduction in airfare for the domestic North America market should result in an 8% increase in demand.

Price Elasticity Table

	Africa	Asia	Europe	Latin America	Middle East	North America	Southwest Pacific
Africa	**0.48**	0.48	0.48	0.48	0.48	0.48	0.48
Asia	0.76	**0.76**	**0.72**	0.76	0.76	**0.48**	0.76
Europe	1.10	**0.72**	**1.12**	1.10	1.10	**0.96**	1.10
Latin America	1.00	1.00	1.00	**1.00**	1.00	1.00	1.00
Middle East	0.48	0.76	1.10	1.00	0.86	0.80	0.86
North America	0.80	**0.48**	**0.96**	0.80	0.80	**0.80**	0.80
Southwest Pacific	0.48	0.76	1.10	1.00	0.86	0.80	0.78

- Weighted average values were calculated from combining OAG 2019 region to region distribution and ICAO available price elasticity values.

Exogenous effects

In order to better model global future scenarios, we asked Virginia Tech to look at adding exogenous shocks to the air transportation system. They focused on the following historical events to allow similar shocks to be inserted into the demand forecast:

- 9/11
- COVID-19 pandemic
- Impact of low-cost carriers in Europe
- Introduction of the B787 into the fleet

Dummy variables were used in the regression analyses to correct the seat demand due to exogenous events.

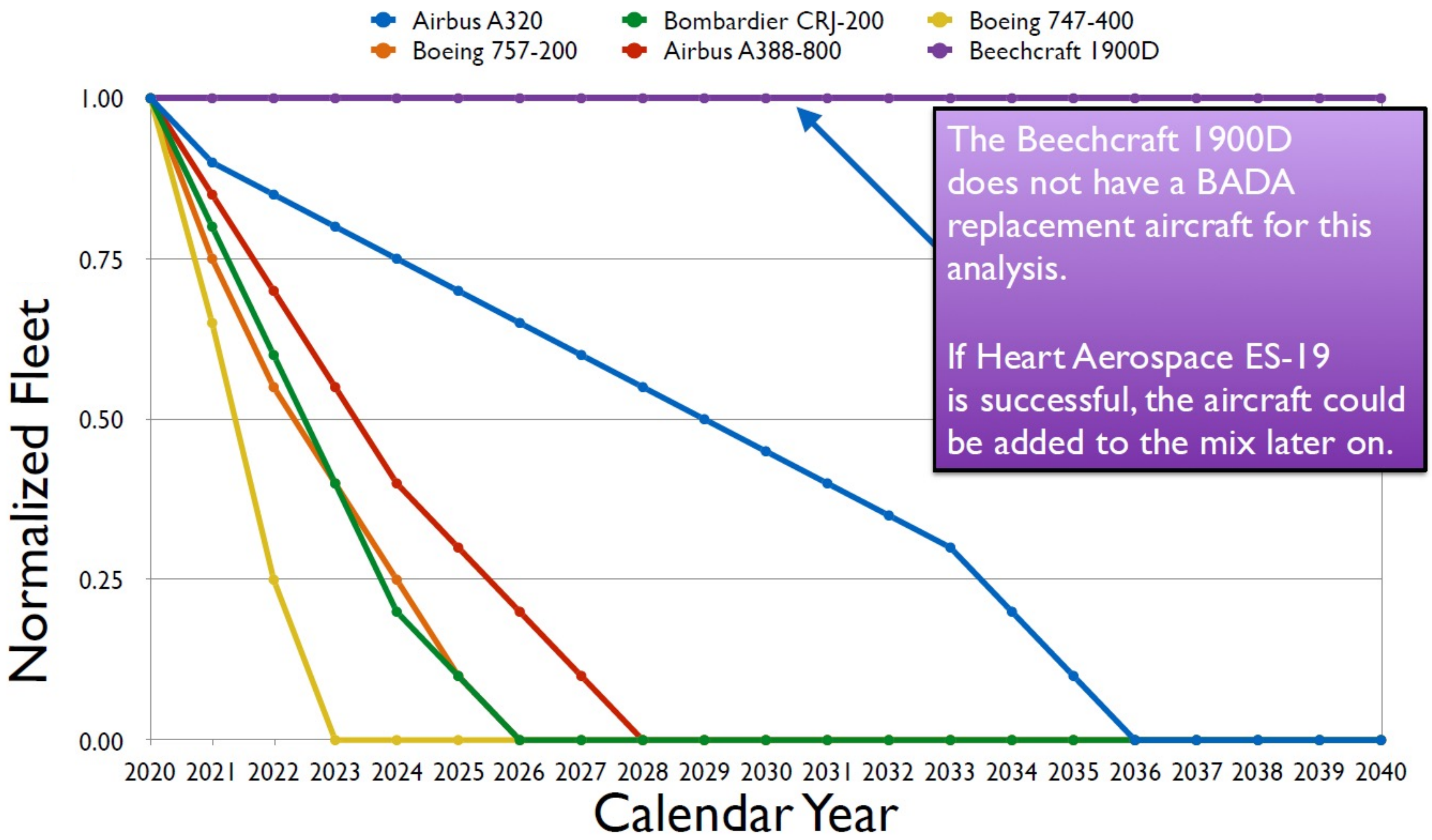
Fleet Evolution and Aircraft Replacement

Based on historical OAG data, GDM forecasts the aircraft models and annual operations between OD pairs.

The Fleet Evolution module retires and replaces existing aircraft with N+1 (e.g., B737-Max 7, A321neo) and N+2 aircraft. The N+2 aircraft are based on performance models from the Environmentally Responsible Aviation (ERA) project.

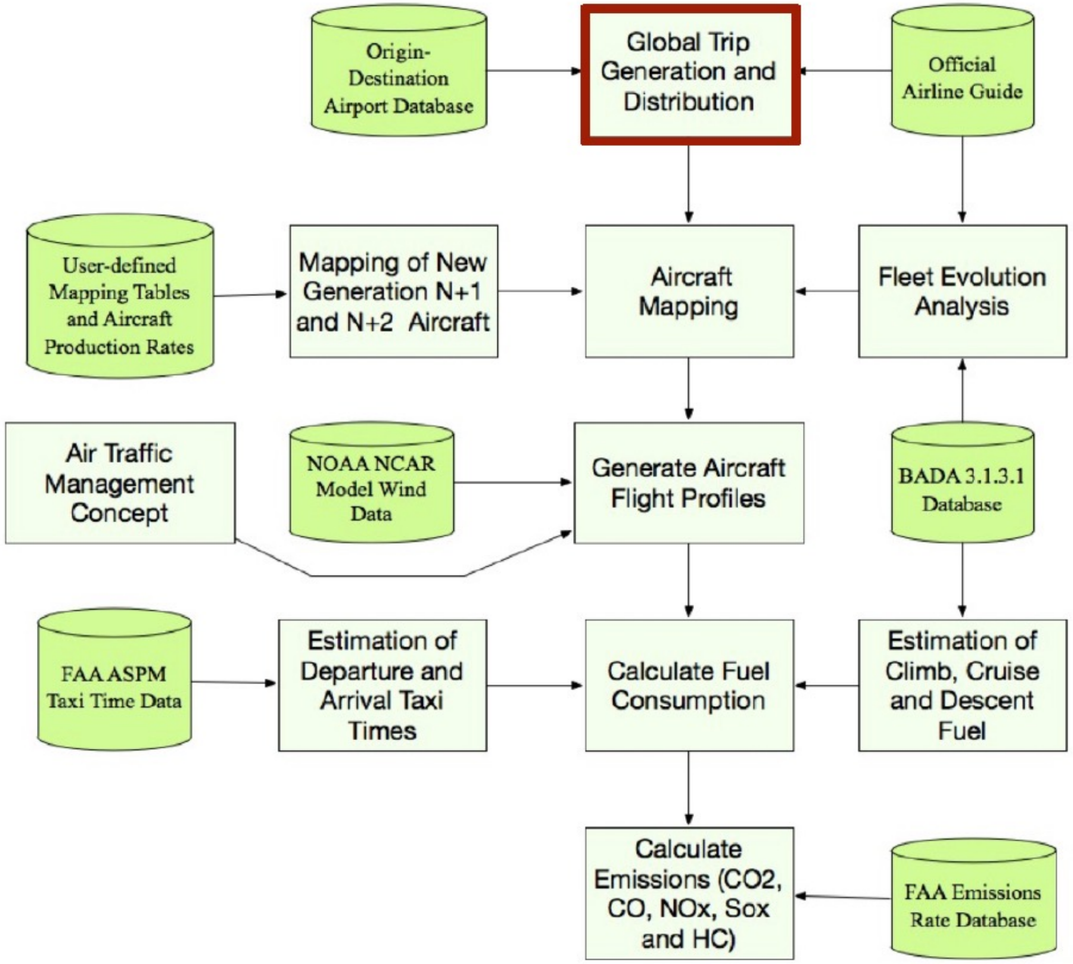
Retiring Aircraft	Replacement Aircraft	Updated Year of Full Retirement	Remarks
Airbus 310	Airbus 330-900	2022	Few A310 left in passenger service (only operations in Iran and Afghanistan with 23 daily flights)
Airbus 340-600	Airbus 350 Boeing 777-300	2024	56 daily flights in 2019
Boeing 717-200	Embraer E2 190	2028	977 daily flights worldwide in 2019
Boeing 737-300	Boeing 737-7Max	2026	440 daily flights worldwide in 2019
Boeing 737-500	Boeing 737-7Max	2026	470 flights worldwide in 2019
Boeing 747-400	Boeing 777-300 Airbus 350X	2022	151 daily flights worldwide in 2019
Boeing 757-200	Boeing 787-8 Airbus 330-900	2026	614 daily flights worldwide in 2019
Boeing 767-200	Boeing 787-8	2026	193 daily flights worldwide in 2019
Boeing 767-300	Boeing 787-8 Airbus A330-900	2026	436 daily flights worldwide in 2019
Bombardier Regional Jet CRJ-200	Bombardier (Mitsubishi) Regional Jet CRJ-700 Embraer E170	2026	Large fleet retirements due to economics of 50 seat aircraft
Embraer E135	Bombardier (Mitsubishi) Regional Jet CRJ-700 Embraer Embraer E170	2026	Large fleet retirements due to economics of 50 seat aircraft
McDonnell Douglas MD-82	Boeing 737-8Max	2025	914 daily flights flights worldwide in 2019
Airbus 380-800	Boeing 777X and Airbus 350X	2028	After Covid-19 most A 380s will retire (340 daily flights worldwide in 2019)

Fleet Evolution and Aircraft Replacement



The amount of time required to replace an aircraft model is a function of the number existing aircraft in the fleet and the assumed production rates of the replacement aircraft.

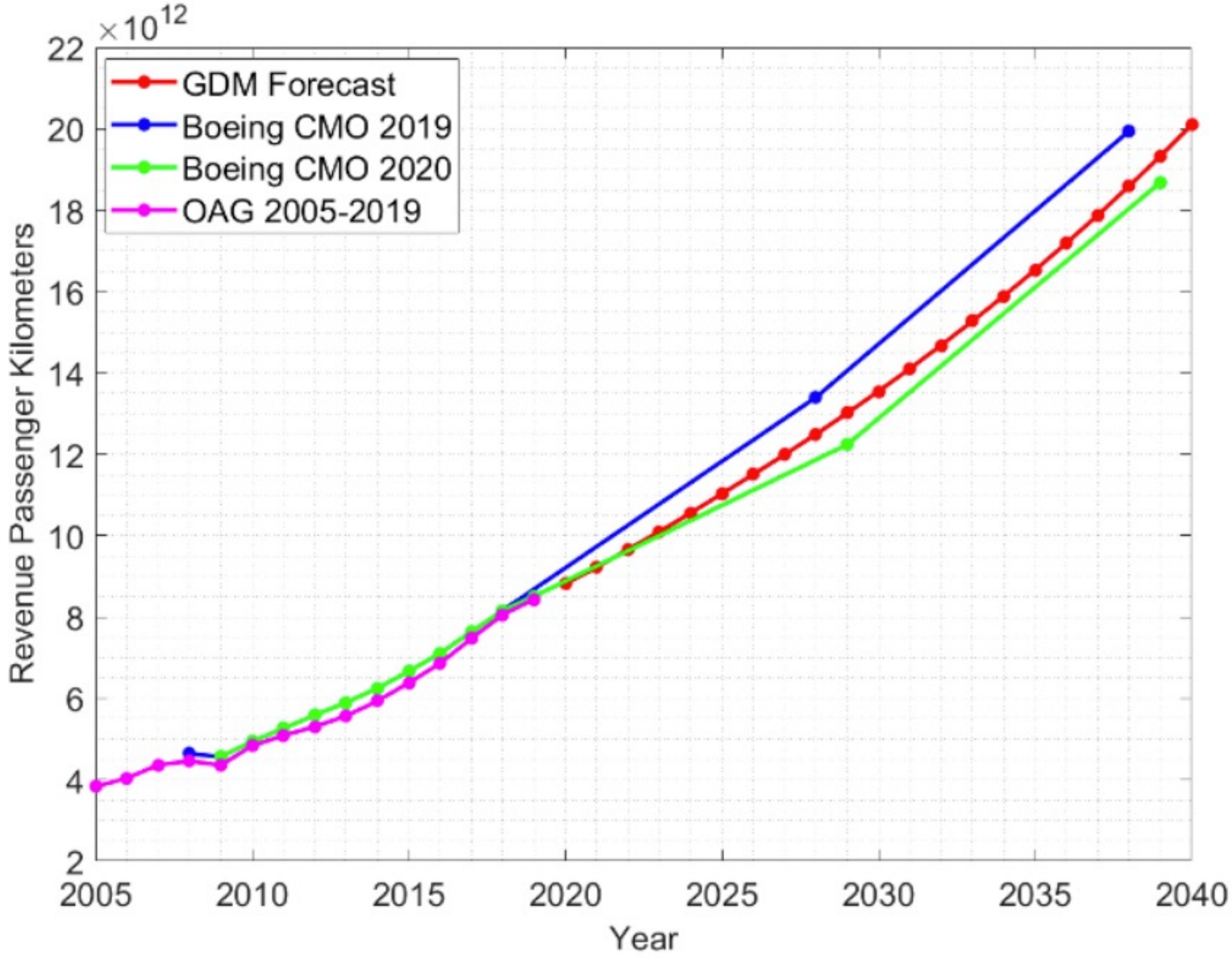
Fleet Fuel Consumption and Emissions



Fleet evolves
via external tables
to the model

Changes in fleet
affect air transportation
cost which affects
demand (via demand
elasticity tables)

GDM Compared to the Boeing Commercial Market Outlook



GDM = Global Demand Model
CMO = Commercial Market Outlook
OAG = Official Airline Guide

Boeing CMO 2020 includes COVID-19 corrections

ISAT Scenarios

Scenario	Description of Scenario	Modeling Approach
Baseline Case (business as usual after Covid-19 recovery)	• Covid-19 travel restrictions by region according to IATA May 2021 forecasts (some regions extend to first quarter of 2024) • Air travel demand recovers according to IATA May 2021 forecasts • USDA GDP data (county level)	• Uses USDA GDP forecasts available in January 2021 • Model Covid 19 with dummy variables similar to 9/11 effects (dummy variables active between 2020 and 2024 with end dates changing by region according to IATA May 2021 forecasts) • Population forecast (existing in GDM model) - no adjustments for Covid-19 • Enhanced GDM model with new segment/regional analysis modules and external ties to air fare elasticity
Market Expansion	• Baseline scenario to handle Covid-19 conditions (2020-2023/2024) • Faster economic growth • New technology developments in aviation (NASA advanced aircraft introduced) •	• Model Covid 19 with dummy variables similar to 9/11 effects (dummy variables active between 2020 and 2024 with end dates changing by region according to IATA May 2021 forecasts) • USDA GDP forecasts (available in January 2021) + Growth Factor • Introduce new NASA subsonic efficient aircraft designs in 2030-time frame (from N+3 and commercial transport vehicle studies) • Develop module to predict new air fare structures • Enhanced GDM model with new segment/regional analysis modules and external ties to air fare elasticity • GDP estimates are modified from baseline USDA to reflect faster economic growth

Instead of projecting a single worldwide aviation forecast, we intend to generate several forecasts in order to support the “Mega-Drivers” research goals.

Different forecast may demonstrate common requirements in terms of aviation technology needs.

ISAT has developed a set of future world scenario descriptions that can be used as a starting point for this type of analysis.

ISAT Scenarios

Scenario	Description of Scenario	Modeling Approach
Terrorism	• Baseline scenario to handle Covid-19 conditions (2020-2024 per IATA regional projections) • Demonstrates a terrorism attack in 2030 time-frame • Depressed aviation growth • Increased cost of business	• Model Covid 19 with dummy variables similar to 9/11 effects (dummy variables active between 2020 and 2024 with end dates changing by region according to IATA May 2021 forecasts) • USDA GDP forecasts (available in January 2021) - Growth Factor (negative growth) • Uses newly developed develop to predict new air fare structures (increased cost causality) • Enhanced GDM model with new segment/regional analysis modules and external ties to air fare elasticity • GDP estimates are modified from baseline USDA to reflect slower economic growth
Energy and Environment	• Baseline scenario to handle Covid-19 conditions (2020-2022) • More strict environmental policies • New technology developments in aviation • Emphasis on mitigation of climate change	• Model Covid 19 with dummy variables similar to 9/11 effects (dummy variables active between 2020 and 2022) • USDA GDP forecasts (available in January 2021) - Growth Factor (also run with neutral FDP impact) • Introduce new NASA subsonic efficient aircraft designs in 2030-time frame (from N+3 and commercial transport vehicle studies) • Use new module to predict new air fare structures based on fuel/energy prices • Enhanced GDM model with new segment/regional analysis modules and external ties to air fare elasticity • GDP estimates are modified from baseline USDA to reflect environmental policies in GDP

Virginia Tech took four of the existing ISAT scenario descriptions and is working on a simplified modeling approach to demonstrate the impact of the scenarios on worldwide passenger demand and aircraft operations.

Study Accomplishments

- Literature review of global market forecasts, macroeconomic models, air transportation demand elasticities, airline load factors
- Passenger demand models updated/improved
- Fuel price added as an independent variable in the model
- Effect of exogenous shocks incorporated to demand forecasts
- Airfare elasticity of demand model created
- GDM databases updated
- Fleet evolution aircraft/assumptions updated
- Simple global scenario cases currently being explored

Follow-on Tasks

- Evaluate the results of this study with Volpe Center. Determine if updates to the GDM are consistent with the vision/requirements for the Mega-Drivers modeling. If not, replan. If we choose to go forward, then:
  - Define the scenarios needed for our Mega-Drivers analysis (including new aircraft technologies introduced).
  - Conduct a macroeconomic analysis that translates qualitative future scenario descriptions into quantitative socioeconomic parameters that can be used by the GDM (i.e., global GDPs, population, fuel price, exogenous shocks).
  - Run the toolset for the defined scenarios to produce forecast passenger demand and global fleet fuel burn/emissions.
  - Analyze the results to draw conclusions about NASA technology investments for aeronautics.

Questions?

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High Speed Point-to-Point Market Analysis
Quick Review

Jon Seidel
NASA Glenn Research Center

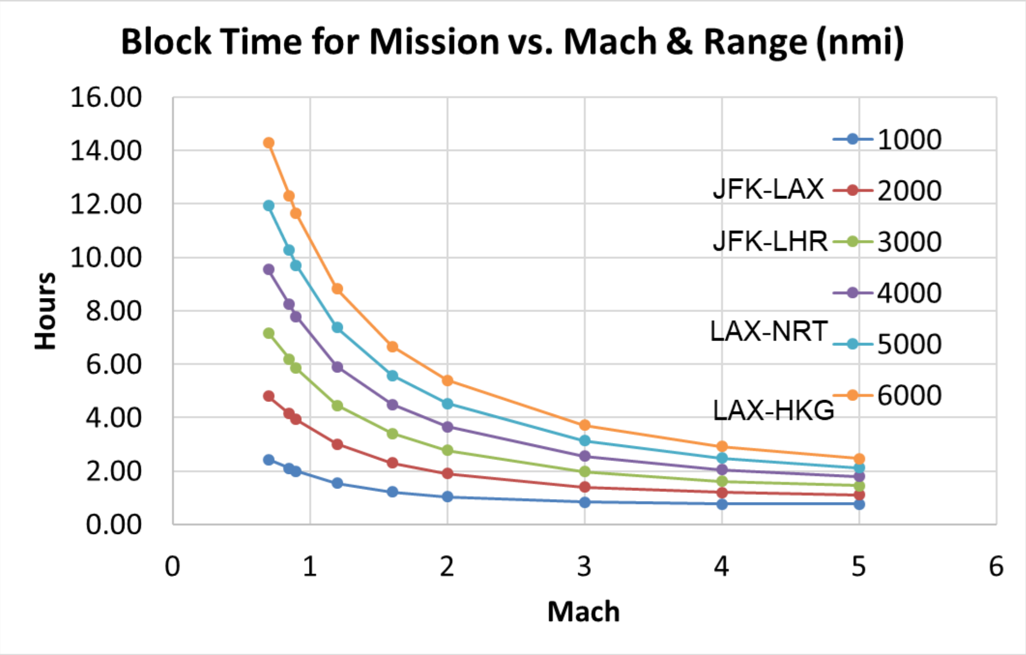
Systems Analysis Symposium
November 10, 2021

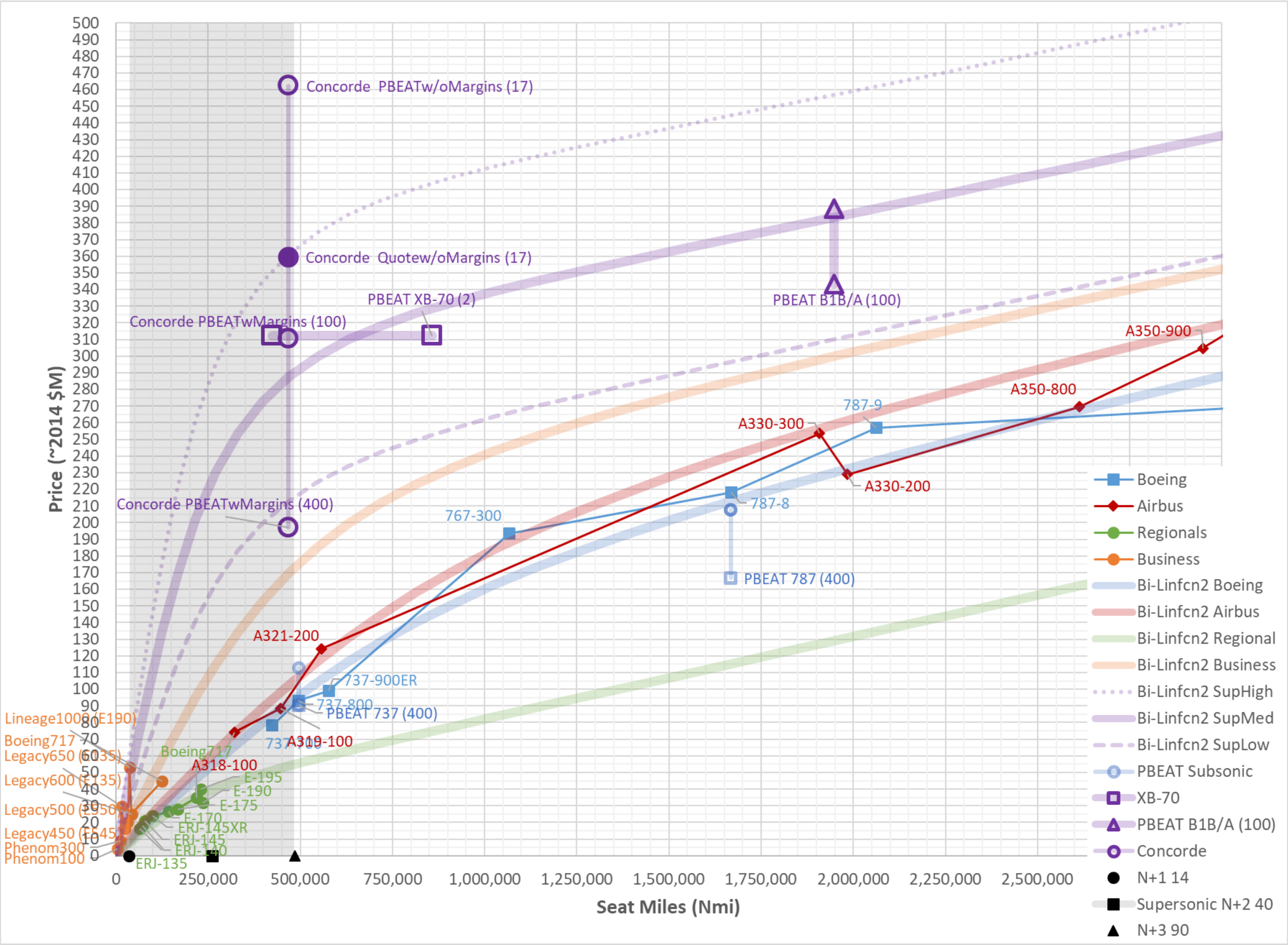
Recent NASA-Sponsored Market Studies at a glance

1. 2018 PAMO Supersonic Mach 1.8 (public report): Market & value-of-time studies complementing CST vehicle study of passenger class (PAX=18, 40, 60)
2. 2020 PAMO Hypersonic P2P study (unpublished): Market studies *premium seat traffic & city pair demand* leveraging PAMO-supersonics; 2013 gross 0th-order sizing.
   - Helped guide HTP studies to examine continuum, with Mach=2.0 lower bound for consistent grounding & applicability to both Hypersonic and Supersonic
3. 2021 HTP SAIC/Bryce (public report): Market studies & *stakeholder surveys of high-end users*, qualitative barriers examination.
4. 2021 HTP Deloitte/SpaceWorks (public report): Market studies & *vehicle concept tradespace; 1st-order MDO propulsion & airframe sizing & costs, ~quantitative look at barriers*
5. 2022 PAMO Supersonic Mach 1.6, 1.8, 2.0: Networking city-pairs & time savings

2020 PAMO Hypersonic P2P Speed vs. Range & Cost

- Diminishing time savings above Mach=2.0
- High cost sensitivity & uncertainties above Mach=1.0 (DDT&E and O&S cost)





HTP Sponsored Studies

Favorable High-Speed Market Characteristics

	SAIC (with Bryce Space & Technology)	Deloitte (with SpaceWorks & NIA)
Mach	3	2 to 4
Range	4500 nmi	4000 nmi to 4500 nmi
Number of routes	300	90 (1)
Aircraft Size (# PAX)	10 GA or 50 Commercial	20 to 50
Aircraft Cost	$200M - $300M	$131M - $228M (2)

SAIC Final Report: https://ntrs.nasa.gov/citations/20210015471
Deloitte Final Report: https://ntrs.nasa.gov/citations/20210014711

(1) Deloitte only considers over water routes
(2) Mach 3 at 4500 nmi

Summary Comments

- Weight & performance sensitivities indicate Mach~2 can support the largest commercial market of scheduled traffic; Mach~3 and 4+ could be viable in unscheduled bizjet market
- Passenger ticket price is high & sensitive due to high DDT&E and fuel-burn; vehicle size limits (due to airport integration) & limited premium traffic prohibit ability to defray with increased PAX count, results in reduced load factors
- Environmental (LTO & high altitude cruise emissions) are paramount concerns; dependence on SAFs could have net positive impact by bearing costs for fleet; barriers (emissions, noise, boom, NAS integ., etc.) should be CST/HTP synergies

- *Studies highlighted the need for <u>objective</u> market forecasting and cost/economics capabilities to help guide NASA technology investments*

H2 / DeCarbonization studies: history and ongoing

November 10, 2021

Christopher A. Snyder

NASA Glenn

Study Objectives

Identify potential NASA Hydrogen (H2) studies to support Decarbonization of Aviation

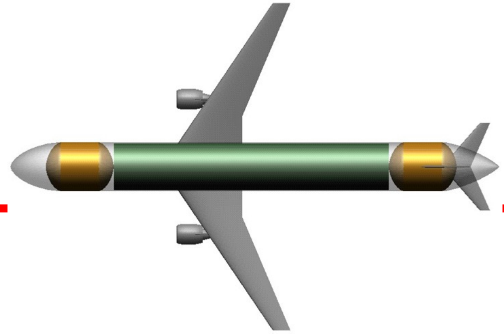
- Find and review previous NASA H2 and low/zero carbon aircraft studies
- International H2 research/system studies (limited search)
- Related US efforts
- Emissions (on-going, preliminary)

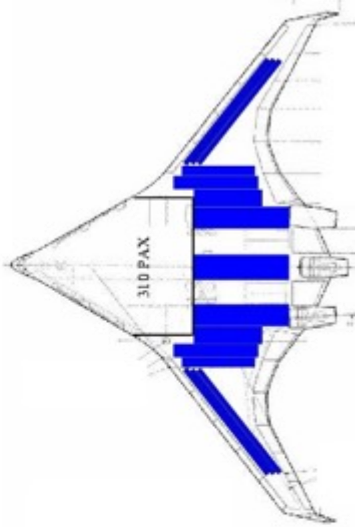
Summarize for further insight/ potential research areas.

(backup slides include fuller bibliography & information)

Note: Originally, focus was efficiency/CO2 (or zero, net CO2); but now there are additional considerations (CO2, NOx, contrails, etc.)

NASA H2 Studies (1998-2011)





Alternate Fuel Aircraft (A/C) Bibliography

- Compiled by Mark Guynn, NASA Langley, March 2005
- 26 studies & presentations, mostly NASA (1998-2005). Includes Cryoplane (2004), Boeing Fuel Cell Demonstrator (2003)
- More detailed “Introduction and observations” in backup slides

Post 2006: NASA focus transitioned to N+x studies (generally hydrocarbon, explore advanced propulsion and airframe technologies) - but two additional, relevant efforts

- 2009 Propulsion Investigation for Zero and Near-Zero Emissions Aircraft
- 2011 First-Order Altitude Effects on the Cruise Efficiency of Subsonic Transport Aircraft

NASA H2 Studies (1998-2011): Major observations

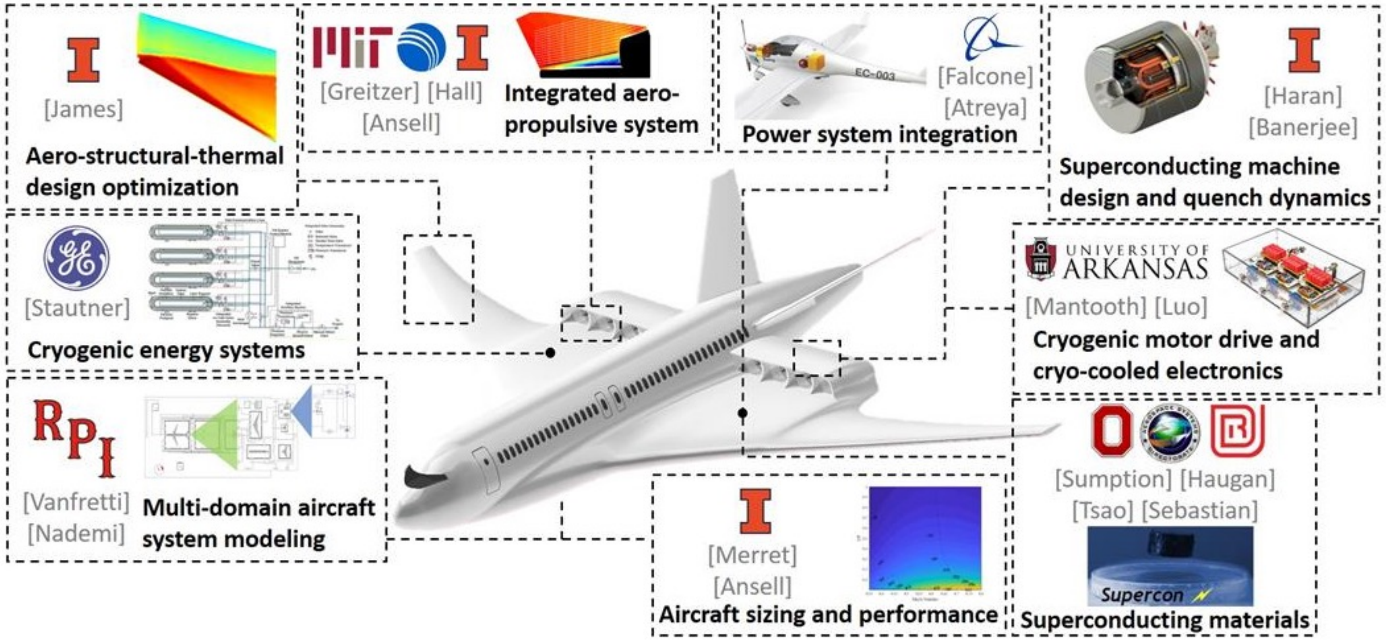
- H2 combustion in gas turbine most promising approach to eliminate CO_2 in transport aircraft (and enable significant NO_X reductions, >80%).
- H2 fuel cell (HFC) could potentially eliminate CO_2 and NO_X, but need to significantly improve fuel cell and electric propulsion system weights, as well as airframe improvements. (Reduce propulsion system requirements.)
  - SOA: 0.5 kW/kg, potential near-term to replace piston engines in general aviation class aircraft.
  - 10x improvement required for small commuter
  - 20x improvement for commercial (e.g. Boeing 737-200, *circa 2000*)
- Batteries about only "zero emissions" solution; but only UAV, limited range.
- Alternate cruise altitudes (contrail avoidance) can result in fuel penalties under 1%, generally less than 2%, but worse cases could reach 10%.

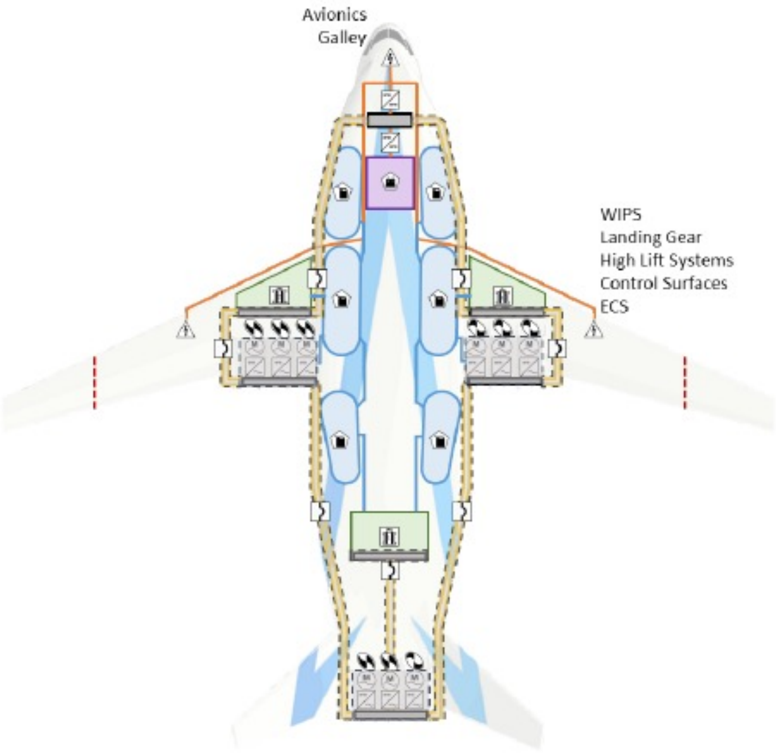
NASA H2 Studies (present, in-house)

- N+x, Distributed Electric Propulsion (DEP) and Electrified Aircraft Propulsion (EAP) efforts opened up the design space. Revisiting LH2 and new/ advanced technologies requiring the development of next generation of propulsion and airframe methodologies and tools.
  - Not just reduced CO2, but climate (CO2, NOx, contrails, etc.)
  - Improved power/weight and efficiency of more electric systems, not just gas turbine engines anymore (hybrid solutions).
  - New airframe technologies and designs (aerodynamic efficiency and weight improvements).
- NASA sponsoring university / industry collaborations to continue exploration of LH2 aircraft and train next generation of engineers *(next slide)*

NASA H2 Studies (present, “outside NASA”)

- Present H2 aircraft studies under University Leadership Institute (ULI) https://nari.arc.nasa.gov/uli
- Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) https://cheeta.illinois.edu/





International H2 research/system studies

Europe (and others) also had limited efforts after 2005 until recently

- International Forum for Aviation Research (IFAR https://ifarlink.aero/)
  - Various N.&S. American, European, Asian, and Middle Eastern countries
  - Working Group goals (Report on Inspirational Projects, March 31st, 2020)
    - “Continuing to develop aircraft and engine design and technology in a relentless pursuit of improvements in fuel efficiency and reduced CO2 emissions”
    - “Supporting the commercialization of sustainable, alternate aviation fuels . . .”
    - “Developing radically new aircraft and propulsion technology and accelerating technologies that will enable the ‘third generation’ of aviation”
  - Includes joint US (NASA) / Canada contrail studies *(presently sustainable aviation fuels [SAF], but wonder about Liquid H2 [LH2])*
  - European efforts noted includes hardware development and smaller-scale demonstrators to gain practical, operational experience (e.g. LH2 and fuel cells).

International H2 research/system studies (2)

- ACI-ATI: (Airports Council International – Aerospace Technology Institute)
  - Looking at sustainable aviation fuels (SAF) upgrades (near term)
  - Liquid H2 (LH2) Airport considerations (far term, similar to some US FAA and DOE efforts, FAA is member of ACI)
- Hydrogen and Fuel Cell Joint Undertaking (JU), under Clean Sky 2:
  - "Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050" (by McKinsey & Company), May 2020.
  - Executive summary is brief, but informative (pages 5-7). Used simplifying, consensus assumptions to perform preliminary analyses. Main body of report includes MANY illustrative charts (very readable)
  - Strong proponents for Hydrogen and fuel cells (although it WAS commissioned by Hydrogen and Fuel Cell groups, not necessarily wrong, maybe *a little bias*)

International H2 research/system studies (3)

- Articles by BBC & Kleinman Center for Energy Policy (U.Penn)
  - Looking at sustainable aviation fuels (SAF), specifically cost.
  - Future SAF estimated to cost about 2X of present fuels (and will continue to be cheaper, without “carbon tax”), resulting in only about 10% increase in average ticket cost for transatlantic flight. Fuel cost shouldn’t be show-stopper; although it is a matter of will. (Need to watch out for unintended consequences.)

Observations on International

- International efforts similar to US, but
- More hardware and demonstrator work underway (more $ than NASA)

But if only looking at NASA, not getting the whole US portfolio

Additional US studies (not NASA-led, ones included so far)

Federal Aviation Authority (FAA) (more detail in backup slides)

- ASCENT: Aviation Sustainability CENTer – FAA Center of Excellence for Alternative Jet Fuels and Environment. (fuels, emissions and modeling, more on later slide)
- CAAFI : Commercial Aviation Alternative Fuels Initiative
- CLEEN: Continuous Lower Energy, Emissions and Noise

Department of Energy (DOE) https://www.energy.gov/

- DOE has a broad portfolio of energy programs. Comprehensive web presence (maybe a little daunting, there is a lot there).
- DOE Hydrogen Program: https://www.hydrogen.energy.gov/
- Office of energy efficiency and renewable energy (EERE)
  https://www.energy.gov/eere/office-energy-efficiency-renewable-energy
  Searchable library: https://www1.eere.energy.gov/library/default.aspx

(But wait, there's more)

Additional US studies (2)

DOE (continued)

- DOE Hydrogen and Fuel Cell Technologies Office https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office
- DOE H2@Airports Workshop https://www.energy.gov/eere/fuelcells/h2airports-workshop

- Advanced Research Projects Agency – Energy (ARPA-E https://arpa-e.energy.gov/, noting only two programs among others)
  - Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH) https://arpae.energy.gov/technologies/programs/reeach
  - Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives(ASCEND) https://arpa-e.energy.gov/technologies/programs/ascend-0

Funding (FY21): DOE: $7B, EERE: $2.8B, ARPA-E: $427M

Additional US studies (3)

Observations

- There are substantial US efforts on Hydrogen (H2), sustainable aviation fuels (SAF) and aviation technologies that are complementary to NASA efforts.
- DOE and FAA efforts include fuel, proof of concept, pilot plant and infrastructure efforts directly applicable to aviation and NASA.
- FAA CLEEN, and DOE’s REEACH & ASCEND are directly applicable to aviation propulsion and power.
- Some study references note NASA participation/collaboration (although often not clear who, so we need to build on those connections).

Emissions (preliminary)

Various groups doing emissions work:

- FAA ASCENT: Aviation Sustainability CENTer – FAA Center of Excellence for Alternative Jet Fuels and Environment. (fuels, emissions and modeling). https://ascent.aero/ (non FAA site) + various links can be found at participating universities (search by researcher, MIT or University of Washington)
- IFAR report notes contrail work in Canada, some collaboration with US.

Still gathering information. New research is updating impact effects (climate and air quality impacts, older assumptions versus newer estimates, level of confidence in data). Important to understand true environmental costs for using traditional aviation (jet) fuels, SAF and LH2.

Summary

- Studies from NASA and other organizations on H2 and related studies are being gathered and reviewed to help guide future, NASA DeCarbonization of Aviation efforts.
- Earlier studies assumed simplifying assumptions with LH2 fuel, but often did not include overall energy and environmental considerations.
- New analysis tools enable higher fidelity studies, including advanced technologies and exploring new designs and operations.
- The various considerations (energy, feedstocks, etc.) for SAF and LH2 production are better understood. But further information still needed to understand and assess their environmental impacts in future aviation studies.
- Present NASA study database is dated. Other US and non-US entities are also studying this area. Prudent to leverage best expertise to update studies.

Potential future efforts

Various individual technologies/ systems are improved and better understood today.
Methodologies and tools exist to capture these effects in more comprehensive studies.
Time for new studies to better understand the cost / benefits for various future systems.

- Fuels and their emission impacts (overall system view and methodologies) are becoming more standardized/consistent. Common baseline for next generation studies.
  - Traditional hydrocarbon (HC) fuels and SAF (also LH2, any “new” fuels?).
    - Is LH2 a better option for far term? what about near term? (and probably not using Helium)
    - Does SAF + carbon capture and sequester (CCS) makes more sense?
  - Liquid H2 tankage: Many previous studies used 35% tank/fuel weight (large aircraft). Some recent studies are using gravimetric index [GI: weight H2 / (weight H2 + tank)] with values from 0.15 to 0.35. 0.15 to 0.35 GI may be valid for smaller vehicles, but even 0.35 is non-starter for single-aisle and larger aircraft. (35% tank/fuel weight = 0.74 GI)
  - Emissions modeling of costs for CO2, H2O (water), NOx, soot, etc.

Potential future efforts (2)

- Propulsion and airframe technologies have advanced, need to assess “best” future options, find complementary combinations. Tools and methodologies exist to
  - More and all-electric systems have improved weights and efficiencies – how might they be best used to meet modern needs for safety, cost, emissions, etc.
  - Revisit gas turbine versus fuel cell.
  - Aircraft designs: beyond “tube and wing”, hybrid wing-body, trussed-braced wing, etc.
- Operational changes that can impact aircraft design and efficiency
  - Revisit effects of reduced cruise altitude to mitigate water and contrails effects
  - Reduced cruise speed and altitude (revisit past studies)
    - Reducing speed can improve energy efficiency of flight
    - Even more efficiency improvements through additional propulsion and airframe optimization for slower cruise speeds. (use advanced turboprop, unswept wing, etc.)
    - Reduced cruise speed can result in reduced number of flights/day/plane (longer ranges)
    - Reduced cruise altitudes can reduce number of aircraft or reduced clearance.

Thanks for your attention.

Questions?

Backup charts

Backup charts (summaries & bibliographies): table of contents

March ’05 Alternate Fuel A/C Bibliography (excerpt)

Mark Guynn, NASA Langley, March 2005

Comments

- Numerous concepts for alternate fuel, zero CO_2, zero CO_2 & NO_X, and truly zero emissions aircraft have been studied by NASA GRC and LaRC over the past several years – most focused on transport aircraft
- This bibliography identifies the various activities and related events over that timeframe (filenames)
- A limited number of non-NASA studies and activities are included in this bibliography
- Initial GRC/LaRC studies (circa 1998-1999) were high-level feasibility studies using simplified propulsion models (efficiency, wt.) combined with existing airframe models
- Second generation studies added propulsion modeling (e.g. new cycles for H_2 fuel turbofans, component build-up of fuel cell system) and airframe modifications to accommodate propulsion system characteristics

Alternate Fuel A/C Bibliography Comments (cont.)

- Given the increase in fidelity, the more recent studies should be deemed more valid; however past results are included for completeness and traceability
- Recent GRC/LaRC studies still include simplifying assumptions, particularly in fuel system, which have not be validated with more detailed modeling
- Note that rapid advances in technology can make “state-of-the-art” assumptions of past studies out-dated
- Some of the material covered may seem repetitive, especially since the history is reviewed in a number of the presentations; however often the results given are updates to previous work
- General observations/conclusions are provided at the end of this package

Alternate Fuel A/C Observations (1)

- Although specific results vary due to different assumptions, increased knowledge, more fidelity, etc. some general conclusions are supported throughout
- Combustion of H_2 in gas turbines is the most promising approach to eliminating CO_2 emissions from transport aircraft
  - Resulting aircraft tends to have lighter TOGW, but heavier empty weight and lower aerodynamic efficiency
  - Varied opinions on potential for NO_X reduction with H_2 combustion
- Some H_2 fuel cells systems offer the potential to eliminate both CO_2 and NO_X
  - NO_X is potential emission whenever air is subjected to high pressures and temperatures
  - Current technology H_2 fuel cell and electric propulsion systems are too heavy for use in transport size aircraft
  - A more near term potential exist for replacing piston engines in light GA class
  - A combination of advances in airframe and propulsion technology is best approach to realizing H_2 fuel cell aircraft (a lighter, more efficient airframe relaxes propulsion system requirements)

Alternate Fuel A/C Observations (2)

- Current state-of-the-art for fuel cell power density is 0.5 kW/kg
  - Need 2x increase for PAV systems (e.g., Piper Warrior II)
  - Need 10x increase for small commuter a/c (e.g., Fairchild SA 227AL)
  - Need 20x increase for Commercial a/c (e.g., Boeing 737-200)
- Solid Oxide Fuel Cell/Gas Turbine hybrid systems have been the focus of several recent studies
  - System-level performance of SOFC/GT hybrid systems (APU application)
    - » 45% efficient for sea-level full power
    - » 72% efficient for cruise (part-power). Cruise efficiency is high due to utilizing the cabin air (with no cost)
  - SOFC/GT hybrid system weight ~ 0.23 kW/kg
    - » 78% of weight of hybrid system due to Fuel Cells, 65% of Fuel Cell weight due to interconnects

Alternate Fuel A/C Observations (3)

- Truly "zero emissions" entails significant additional penalties
  - With no emissions, the aircraft weight stays constant or grows during the flight; reducing cruise efficiency and increasing structural weight
  - Specific power and energy of current energy storage devices (e.g. batteries) makes them unsuitable for anything but small UAVs
  - Trapping products of fuel+air reactions (combustion or electrochemical) requires a complex system and results in aircraft weight growth throughout the mission
  - Revolutionary concepts for high specific power, high specific energy, zero emission power sources exist at TRL 0
- "Zero *harmful* emissions" is more realistic goal for alternate fueled aircraft than "zero emissions", but requires understanding of the potential impacts of emitted substances throughout the flight envelope

H2-studies(NASA_2008+) ***Introduction***

- Only 2 additional NASA studies after the 2006 Mark Guynn summary, as there was essentially limited or no requests for further work. NASA GRC and LaRC studies focused on transport aircraft. Summary and report or presentation filenames included
- Recent GRC/LaRC studies still include simplifying assumptions, particularly in fuel system, which have not been validated with more detailed modeling.
- Studies did not note climate impact from revised vehicles and operations, except in most general terms for fuel, CO_2 and NO_x levels
- Note that rapid advances in technology can make “state-of-the-art” assumptions of past studies out-dated
- General observations/conclusions are provided at the end of this package

H2-studies(NASA_2008+) ***Bibliography/Summary***

- "Propulsion Investigation for Zero and Near-Zero Emissions Aircraft" *"TM-2009-215487-ZEA(ZeroEmissionsAircraft).pdf"*
  - 1st order (overall) study by NASA GRC, LaRC and US ARL (Cleveland).
  - Review of some previous studies, effort focused on 70 and 100 pax Aircraft (AC)
  - Kerosene (gas turbine) or Liquid Hydrogen (LH2) fuel [gas turbine, Hydrogen Fuel Cell (HFC) with PEM or SOFC tech (electric) & gas turbine – HFC combined]
  - More detailed HFC and LH2 tankage system weights performed and discussed
  - Gas turbine with LH2 advanced combustors can reduce NOx emissions by 95% (in addition to 70% reduction from advanced kerosene combustor from SOA)
  - HFC (electric) propulsion weight is so high that AC design will not converge. HFC integrated into gas turbine converges, but HFC weights result in heavier AC and higher fuel usage.
- "Subsonic Transport cruise altitude study" *"NASA-TM-2011-217173_Altitude_MGuynn.pdf"*
  - August 2011 NASA Technical memorandum by Mark Guynn (LaRC)
  - 1st order analysis of cruise altitude effects on B737-800 and B777-200LR class AC (NPSS, FLOPS engine / AC models)
  - Use various climb/cruise scenarios, from optimum climb/cruise speed/altitude to set cruise altitude and optimum cruise velocity determined
  - < 1% fuel consumption penalty if altitude maintained within 4,000 ft of optimum, but increases for fixed altitude and can be as high as 10% for altitudes significantly offset from optimum for entire mission

H2-studies(NASA_2008+) ***Observations***

- Combustion of H_2 in gas turbines is the most promising approach to eliminating CO_2 emissions from transport aircraft
  - Resulting aircraft tends to have lighter TOGW, but heavier empty weight and lower aerodynamic efficiency
  - ***Lower liquid H2 tankage weight assumptions seem highly suspect with more modern efforts and assumptions. Would cause significant impact on aircraft weight and LH2 aircraft viability for larger pax/range designs.***
  - Significant potential for NO_X reduction with H_2 combustion
- Some H_2 fuel cells systems offer the potential to eliminate both CO_2 and NO_X
  - NO_X is potential emission whenever air is subjected to high pressures and temperatures.
  - Current (2008) technology H_2 fuel cell and electric propulsion systems deemed too heavy for use in transport size aircraft. Significant improvement required in fuel cell and ancillary systems (i.e., thermal management)
  - A more near-term potential exist for replacing piston engines in light GA class

H2-studies(NASA_2008+) ***Observations (2)***

- Some H_2 fuel cells systems offer the potential to eliminate both CO_2 and NO_X (cont.)

  A combination of advances in airframe and propulsion technology is best approach to realizing H_2 fuel cell aircraft (a lighter, more efficient airframe relaxes propulsion system requirements)

- Variation in cruise altitude (such as flying at lower than optimum altitude for potentially, reduced climate impact) has small impact on fuel usage (1-4%) for small excursions. But reducing cruise altitude can reduce available altitude range for number of flight operations. (Unsure impact on overall aviation traffic flow.)

NASA ULI: CHEETA bibliography

Primary sources of dissemination

- AIAA Aviation/SciTech + AIAA/IEEE EATS
- Cryogenic Engineering Conference and International Cryogenic Materials

Conference (CEC-ICMC)

- IEEE Aerospace Conference
- ASME Turbo Expo
- Places to start:

Aircraft configuration: https://arc.aiaa.org/doi/10.2514/6.2021-2409

MDO methods: https://arc.aiaa.org/doi/10.2514/6.2021-3281

Propulsor design: https://arc.aiaa.org/doi/10.2514/6.2021-3287

Superconducting Machine: https://iopscience.iop.org/article/10.1088/1757-899X/756/1/012030

Power transmission system: https://arc.aiaa.org/doi/abs/10.2514/6.2021-3310

Electronics components:

https://ieeexplore.ieee.org/abstract/document/9479307

Inverter design: https://ieeexplore.ieee.org/abstract/document/9235140

Hydrogen tanks: IOP publishing, pending

Multi-domain modeling: https://arc.aiaa.org/doi/10.2514/6.2020-3580 Some H_2 fuel cells

NASA ULI: CHEETA bibliography (2)

2019

- Ansell. P.J., "Foundation of the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA), a NASA University Leadership Initiative Study," AIAA/IEEE Electric Aircraft Technologies Symposium, 2019.

2020

- Balachandran, T., Lee, D., Salk, N., and Haran, K. S., "A fully superconducting air-core machine for aircraft propulsion," In IOP Conference Series: Materials Science and Engineering, Vol. 756, No. 1, March 2020, p. 012030. https://iopscience.iop.org/article/10.1088/1757-899X/756/1/012030
- Balachandran, T., Reband J.D., Xiao, J., Sirimmana, S., Dhilon, R., Haran, K.S., "Co-design of an Integrated Direct-drive Electric Motor and Ducted Propeller for Aircraft Propulsion," AIAA Paper 2020-3560, AIAA-IEEE Electric Aircraft Technologies Symposium (EATS), 2020. https://arc.aiaa.org/doi/abs/10.2514/6.2020-3560; https://ieeexplore.ieee.org/abstract/document/9235149
- Hossain, M.M., Rashid, A.U., Sweeting, R., Wei, Y., Mhiesan, H., Mantooth, H.A. and Woldegiorgis, D., "Cryogenic Characterization and Modeling of Silicon Superjunction MOSFET for Power Loss Estimation," AIAA Paper 2020-3660, AIAA Propulsion and Energy Forum, 2020. https://arc.aiaa.org/doi/abs/10.2514/6.2020-3660
- Haugan, T. J., Sebastian, M. A., Sumption, M. D., and Tsao, B., "Update on Cryogenic/Superconducting Technology for Electric Aircraft Drivetrains," AIAA-IEEE Electric Aircraft Technologies Symposium (EATS), #EATS-08-05, 26-Aug-2020 (Oral).
- Haugan, T. J., Sebastian, M. A., Sumption, M. D., and Tsao, B., "Electric Power Distribution Technologies for Electric Aircraft Drivetrains," Raytheon RTX Electrification Workshop, #2.1.3.1, Virtual Online, 2-Sept-2020 (Invited).

NASA ULI: CHEETA bibliography (3)

2020 (cont.)

- Haugan, T. J., Sebastian, M. A., Sumption, M. D., and Tsao, B., "Design of a 20MW Drivetrain Microgrid for Electric Aircraft Propulsion Powered by Liquid H2 Fuel Cells," Applied Superconductivity Conference 2020, Virtual Online, Wk2LOr4D, 5 Nov 2020, (Oral).
- Kovacs, C.J. and Haugan, T. J., "Metal Composite HTS T-Junction Terminals for Aerospace Power Distribution," International Symposium on Superconductivity (ISS) 2020, METI Japan host Virtual Online, AP8-1, 3 Dec 2020 (Oral).
- Lauer, M. and Ansell, P.J., "Experimental Investigation of Transonic Aero-Propulsive Interactions for a Distributed Overwing Ducted Fan," AIAA-IEEE Electric Aircraft Technologies Symposium (EATS), 2020, (Oral).
- Mhiesan, H., Hossain, M. M., Rashid, A. U., Wei, Y., and Mantooth, A., "Survey of Cryogenic Power Electronics for Hybrid Electric Aircraft Applications," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1-7. https://ieeexplore.ieee.org/abstract/document/9172807
- Podlaski, M., Vanfretti, L., Nademi, H., and Chang, H., "UAV Dynamics and Electric Power System Modeling and Visualization using Modelica and FMI," Proceedings of the 76th Vertical Flight Society Annual Forum, Virginia Beach, Virginia, October 6–8, 2020. https://move.rpi.edu/sites/default/files/publication-documents/VFS76_Vanfretti.pdf
- Podlaski, M., Vanfretti, L., Nademi, H., Ansell, P.J., Haran, K.S., and Balachandran, T., "Initial Steps in Modeling of CHEETA Hybrid Propulsion Aircraft Vehicle Power Systems using Modelica," AIAA Paper 2020-3580, AIAA/IEEE Electric Aircraft Technologies Symposium, 2020, pp. 1-16. https://arc.aiaa.org/doi/abs/10.2514/6.2020-3580; https://ieeexplore.ieee.org/abstract/document/9235182

NASA ULI: CHEETA bibliography (4)

2020 (cont.)

- Ranjan, P., Zheng, W., and James, K.A., "Mission-Adaptive Lifting System Design using Integrated Multidisciplinary Topology Optimization," AIAA Paper 2020-3143, AIAA Aviation Forum, 2020. https://arc.aiaa.org/doi/abs/10.2514/6.2020-3143
- Sebastian, M. A., Haugan, T., Sumption, M. D., Tsao, B., and Kovacs, C. J., "Cryogenic/Superconducting Technology for Electric Aircraft Drivetrains," International Symposium on Superconductivity (ISS) 2020, METI Japan host Virtual Online, AP5-1, 2 Dec 2020 (Oral)
- Sebastian, M. A., Haugan, T., Sumption, M. D., Tsao, B., and Kovacs, C. J., "Cryogenic / Superconducting Technology for Electric Aircraft Drivetrains," Electronic Materials and Applications (EMA) 2021, ACerS Virtual Online, S7 Symposia, 20-22 Jan 2021 (Oral)

H2-studies(EU+_2010+) ***Introduction***

- European Union (Clean Sky II) study and related article from BBC. Also U. of Pennsylvania position paper on SAF. Finally, Aircraft Council International (ACI)/ Aerospace Technology Institute (ATI - UK company) study (H2 at airports)
- EU efforts mention some more-detailed aircraft and subsystems modeling, still appears to use lower-order (preliminary) modeling of vehicles, subsystems and climate impact. Study include annexes with more detailed assumption discussion.
- Many seem written with less-technical audience in mind (especially BBC article). U of Penn. is more financially-based analysis.
- General observations/conclusions are provided at the end of this package

H2-studies(EU+_2010+) ***Bibliography/Summary***

- "Decarbonizing Aviation Is Not As Hard As We Think - Kleinman Center for Energy Policy" *"Kleinman-Energy(Serpell)_08-2019.pdf"*
  - Position paper by Oscar Serpell at Kleinman Center for Energy Policy (https://kleinmanenergy.upenn.edu/) advocating SAF for long-range aircraft
  - Includes assumed values for cost estimates, but only considering aviation net CO_2, not other effects from aviation emissions on climate.
  - Although all-electric is feasible for many sectors to decarbonize, not practical for long-range aircraft. Synthetic aviation fuel (SAF) estimated to cost double of present fuels and require significant energy to produce (depending on process; such as water electrolysis for H_2 and direct air CO_2 capture).
  - ***However, "***doubling of fuel cost should only increase ticket cost by 8.5% based on transatlantic ticket price" *(fuel only ≈10% of ticket price for that market).*
- "The hydrogen revolution in the skies – BBC Future" *"2021-04-09_The hydrogen revolution in the skies - BBC Future.pdf" (2 versions, page spacing cut some, different text from each)*
  - Future Planet article discussing the potential and pitfalls for liquid hydrogen and SAF fueled airplanes. Written for the less-technical audience than pure engineers.
  - Recognizes the damage cost from present fuels needs to assessed to help justify the use of alternatives such as SAF, biofuels, or liquid hydrogen. Aviation efficiency improving, but growth rate overwhelms efficiency improvements (= rising aviation CO_2 production). .
  - UK government funding work to accelerate zero-emissions aircraft design and SAF production. SAF for near term (decarbonize present fleet), *Maybe* H_2 for long term (probably gas turbines?). H_2 will be significantly costlier (maybe *ONLY* 2x) versus fossil fuels for next few decades.
  - Industry prefers SAF, expect to achieve zero CO_2 emissions by **2060** (w/SAF, a little H_2), because of reduced cost and infrastructure changes. Aviation is "small enough" that SAF production required seems quite possible in desired timeframes.

H2-studies(EU+_2010+) ***Bibliography/Summary***

- "Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050"
  "20200720_Hydrogen Powered Aviation report_FINAL web(CleanSky2).pdf "
  - Study by McKinsey & Company for the Clean Sky 2 Joint Undertakings (JU) and Fuel Cells and Hydrogen 2 JU. Input from 24 EU companies and organizations, May 2020
  - Executive summary is brief, but informative (pages 5-7). Appears to have used simplifying, consensus assumptions to perform preliminary analyses. **Main body of report includes MANY illustrative charts to help make "story"** *(very readable)*
  - Report layout (chapters):
    - 1. Introduction: The challenge of decarbonizing aviation
    - 2. Aircraft design: Feasibility and cost of H2 propulsion
    - 3. Infrastructure: Liquid hydrogen supply and refueling challenges
    - 4. Roadmap: Key findings and decarbonization scenarios
    - **5. Recommendations: Advancing H2-powered aviation**
    - Annex 1: Approach and metrics to assess climate impact of aviation
  - "The report's overall conclusion is that hydrogen propulsion has the potential to be a major part of the future propulsion technology mix. As a disruptive innovation it will require significant research and development, investments, and accompanying regulation to ensure safe, economic H2 aircraft and infrastructure mastering climate impact." Also strong proponent for fuel cells *(although study jointed funded by Fuel Cells and Hydrogen 2 JU)*.
  - Synthetic Aviation Fuels (SAF) can achieve significant "Net CO2 reduction" for aviation, but not a good long-term solution considering aviation's contribution to climate change. Present aviation emissions include CO2, NOx, soot and water vapor (contrails/cirrus clouds) which have significant adverse climate effects versus only accounting for CO2 emissions levels. H2 best addresses issues (2-3 more effective than SAF reducing aviation's adverse climate effects).

(continued on next slide)

H2-studies(EU+_2010+) ***Bibliography/Summary***

- "Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050" *(continued)*
  - LH2 challenges include production, handling, tankage, refueling, infrastructure, costs, and accompanying technology innovation. Significant energy requirement for LH2 production, but significantly less than "Zero net CO2" SAF. Near-term LH2 usage is low enough for local supply chains until 2040.
  - Liquid H2 tankage assumed to be at 15-20% gravimetric efficiency (gravimetric efficiency defined as: LH2 fuel weight/(fuel + tank). Gravimetric efficiency needed
  - Even with aggressive program support, will not achieve 2050 aviation CO2 goals (probably abo
  - Includes more detailed breakdown of various fuel and propulsion options and cost increases across AC classes (higher costs for larger AC, longer ranges). Notes significant time to certify (10 years) and time to replace fleet (>10 years).
- "Integration of Hydrogen Aircraft into the Air Transport System: An Airport Operations and Infrastructure Review" *"aci-ati-hydrogen-report(20210101).pdf"*
  - Aircraft Council International (ACI)/ Aerospace Technology Institute (ATI - UK company) study, released early 2021. (www.aci.aero)
    - » *To increase the awareness and understanding amongst airports regarding implications and challenges of hydrogen powered aircraft with respect to infrastructure, operations, and safety.*
    - » *To highlight some of the knowledge gaps in order to focus resources into closing such gaps.*
    - » *To provide useful references to airports and other aviation stakeholders where additional information can be found.*
    - » *To highlight some of the stakeholders involved in present and historic initiatives for hydrogen-powered aviation.*

    (bullets copied from report)
  - Includes significant number of references to help share knowledge of other study efforts.
  - Further work planned on assessing costing for various hydrogen options to help inform future direction

H2-studies(EU+_2010+) ***Observations***

- All papers recognize the need for environmental cost added to fossil fuels to help facilitate net zero CO_2 aviation conversion.
  - Varied solution space (SAF versus LH2) – no clear winner.
  - SAF “easier” to achieve net zero CO_2. But doesn’t address “bad” aviation emissions (NOx, soot, contrails/ clouds, etc.). Can be implemented sooner than LH2, requires less infrastructure investment and aviation changes. SAF will have higher, long-term energy usage than LH2. Favored by industry and finance.
  - LH2 more directly addresses climate issues from aviation emissions (not just CO_2, but also NOx, soot, contrails/ clouds, etc.). Significant changes to aircraft and infrastructure, but lower fuel energy costs. More “pure” solution for climate issues. Favored by technologists and researchers (maybe government agencies too).
  - Have to start ASAP and aggressive programs to achieve 2050 goals if using LH2 pathway. SAF or graduated SAF to LH2 pathway has higher probability to achieve 2050 goals. Industry suggesting 2050+10years more likely/ achievable goal.
  - Much more costing work needed to better understand financial implications
- Aerospace Daily & Defense Report: April 30, 2021 – Fuel Tankering (if don’t get everyone onboard). Buying non-SAF outside EU because it’s cheaper, fly airplanes heavy to not buy higher-prices EU fuel (SAF blend). By 2035, 100 million tonnes additional CO_2 produced by aviation.

FAA CAAFI overview

- CAAFI: **C**ommercial **A**viation **A**lternative **F**uels **I**nitiative
- Website: https://www.caafi.org/ *(includes a lot of information, well-organized)*
- "Mission statement" : (from brochure)
  "Since 2006, the Commercial Aviation Alternative Fuels Initiative (CAAFI) has sought to enhance energy security and environmental sustainability for aviation through the use of alternative jet fuels. CAAFI is a coalition of airlines, aircraft and engine manufacturers, energy producers, researchers, international participants and U.S. government agencies. Together these stakeholders are leading the development and deployment of sustainable aviation fuels (SAF) for commercial aviation.
  CAAFI's goal is to promote the development of SAF options that offer equivalent safety and favorable costs compared with petroleum based jet fuel, while offering environmental improvement and energy supply security for aviation."
- Sponsors include: (1 government agency, 3 aviation trade associations)
  - Federal Aviation Administration (FAA)
  - Aerospace Industries Assoc. (AIA)
  - Airlines for America® (A4A)
  - Airports Council International - North America (ACI-NA)

FAA CAAFI additional files / information

- "CAAFI_Brochure_2020-03.pdf" *(1-pager overview of CAAFI – fairly comprehensive. Retrieved 2021-07-15 from https://www.caafi.org/about/pdf/CAAFI_Brochure.pdf)*
- *"2021_Goals_and_Priorities-2021-01.pdf" (10 page details 2021 priorities and 2020 highlights, includes links for additional information. Retrieved 2021-07-15 from https://www.caafi.org/files/2021_Goals_and_Priorities.pdf)*
- *"beto-sust-aviation-fuel-sep-2020.pdf" (The U.S. Department of Energy's Bioenergy Technologies Office (DOE BETO) published this report describing potential pathways for producing sustainable aviation fuel. Retrieved 2021-07-15 from https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf)*
- *CAAFI FAQs https://www.caafi.org/resources/faq.html*

FAA ASCENT overview

- ASCENT: **A**viation **S**ustainability **CENT**er - FAA Center of Excellence for Alternative Jet Fuels and Environment.
- Website: https://ascent.aero/ (non FAA site) + *various links can be found are participating universities (search by researcher)*
- James Hileman, FAA Program Manager.
- Cooperative aviation research organization co-led by Washington State University and the Massachusetts Institute of Technology.
- Focus Areas (AJF = Alternate Jet Fuels)
  - AJF: supply chain analyses, fuel performance testing, aircraft component performance
  - Environment: noise & emissions, impacts, technology assessment
- In 2021:
  - Annual Budget $10+ million
  - Funding 54 Research Projects
  - Producing 119 Publications, Reports, Presentations
  - Educating 112 Students
  - With 70 Industrial Partners

FAA ASCENT additional files / information

- “2.2_ASCENT_Overview_12_2018.pdf” *(ASCENT overview)*
- “03_Hileman_20210127 (FAA-Hileman) Briefing for ARPA-E Event.pdf” *(Title: “Some Perspectives on the Environmental Impacts of Aviation and Alternative Fuels.” Includes additional website links for further information.)*

FAA CLEEN overview

- CLEEN: **C**ontinuous **L**ower **E**nergy, **E**missions and **N**oise
- Website: *(includes links to Phase I & II consortium meetings and reports)* https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/
- 2010 start (5 year phases), industry tasks, cost-sharing required, Phase I & II subsonic civil transports only
- Phase I (2010-2015)
  Boeing, General Electric (GE), Honeywell, Pratt & Whitney (P&W), and Rolls-Royce
  ≈ $125 Million (government) investment
- Phase II (2015-2020)
  Aurora Flight Sciences, Boeing, Collins Aerospace, Delta Tech Ops/MDS Coating Technologies, General Electric, Honeywell, Pratt & Whitney, and Rolls-Royce
  ≈ $100 Million (government) investment

Goal Area	CLEEN I Goals (2010-2015)	CLEEN II Goals (2015-2020)
Noise (cumulative below Stage 4)	-32 decibels (dB)	-32 decibels (dB)
LTO NO_X Emissions (Below CAEP/6)	-60 percent	-75 percent (-70 percent re: CAEP/8)
Aircraft Fuel Burn	-33 percent	-40 percent

FAA CLEEN overview (2)

- Program goals: *(Phase III revision, retrieved on 2021-07-15 from* https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/#pg
- Phase III tightens original goals, adds community noise and particulate matter goals, and includes supersonic aircraft,

Quantitative goals for subsonic fuel burn, emissions, and noise reductions under CLEEN Phases I, II and III			
Goal Area	CLEEN Phase I	CLEEN Phase II	CLEEN Phase III
Noise Reduction Goal	25 dB cumulative noise reduction cumulative to Stage 5		25 dB cumulative noise reduction relative to Stage 5 and/or reduces community noise exposure
Fuel Burn Goal	33% reduction (relative to year 2000 best-in-class in-service aircraft)	40% reduction (relative to year 2000 best-in-class in-service aircraft)	20% below CAEP/10 CO_2 standard
NOx Emissions Reduction Goal	60% margin to CAEP/6 landing/take-off NOx emissions standard	70% margin to CAEP/8 landing/take-off NOx emissions standard	
Particulate Matter Emissions Reduction Goal	-	-	Reduction relative to CAEP/11 standard
Entry into Service Target	2018	2026	2031

FAA CLEEN additional files / information

- “CLEENI_CLEENII_Projects_2020-02.pdf” *(Phase I & II companies and tasks. Retrieved 2021-07-15 from https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/media/CLEENI_CLEENII_Projects.pdf)*

DOE Hydrogen additional files / information

- "hfto-h2-airports-workshop-2020-soloveichik.pdf" *(DOE Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH) overview, (17-pages), virtual H2@Airports Workshop on November 4–6, 2020, some references not specific enough to trace)*
- "REEACH_Project Descriptions_FINAL.pdf" *(REEACH—Range Extenders for Electric Aviation with Low Carbon and High Efficiency, 2020-08 listing of various ASCEND-funded projects: (3-pages), entity, project title, $, short summary)*
- "ASCEND_Project_Descriptions_FINAL.pdf" *(ASCEND—Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives, 2020-10 listing of various ASCEND-funded projects: (3-pages), entity, project title, $, short summary)*

Personal opinion: DOE doing a great job (many programs, various options to find information). Specific to Hydrogen: DOE is focusing more on overall energy, emissions and infrastructure (like H2@airport workshops), with maybe less focus on airplane (or aircraft propulsion-specific efforts). *(Although their portfolio does include some aviation propulsion-related efforts.)* DOE is also a good information source to support aviation studies by NASA and industry.

Just-in Time Systems and Market Analyses

NASA ARMD Systems Analysis Symposium

Seamus McGovern

U.S. DOT Volpe National Transportation Systems Center

10 November 2021

U.S. DOT Volpe National Transportation Systems Center

- Federal laboratory in Cambridge, Massachusetts
- 500 civil servants with additional contractor support
- Staff includes engineers, policy analysts, scientists, economists, environmental protection specialists, operations research analysts, and safety specialists
- Multiple transportation modes

U.S. DOT. (2020). Retrieved from https://www.volpe.dot.gov/work-with-us/small-business-innovation-research/contact-sbir

FY22 Overview

1. Advanced air mobility (AAM) and unoccupied aircraft systems (UAS) related:
   - m:N business case analysis (BCA) and return on investment (ROI) planning

2. Transport category aircraft related:
   - Convergent Aeronautics Solutions (CAS) X1 desirability analysis

m:N

Business Case Analysis (BCA) and Return on Investment (ROI) Planning

Supporting

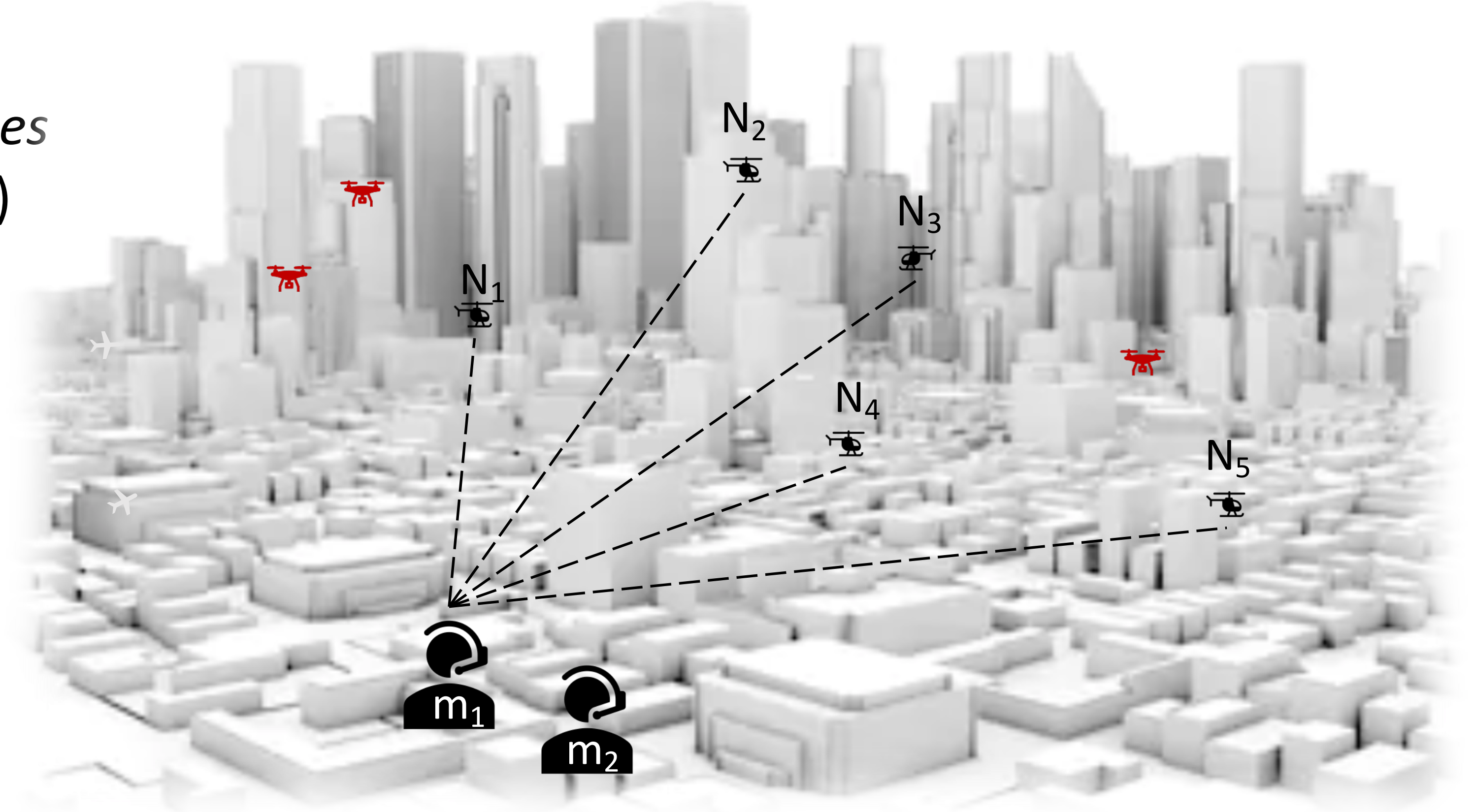
Vanessa Aubuchon and Kelley Hashemi
Transformational Tools and Technologies (TTT) Project
NASA Transformative Aeronautics Concepts Program (TACP)

Hashemi, K. (2021). *Multi-Vehicle Control Working Group*. Retrieved from https://nari.arc.nasa.gov/sites/default/files/attachments/Day%201%20KelleyHashemi%20Slides.pdf

m:N Operations

Multi-vehicle control = m:N

- Shrinking group of humans (m) *manages* many highly automated air vehicles (N)
- Not vehicle flight control



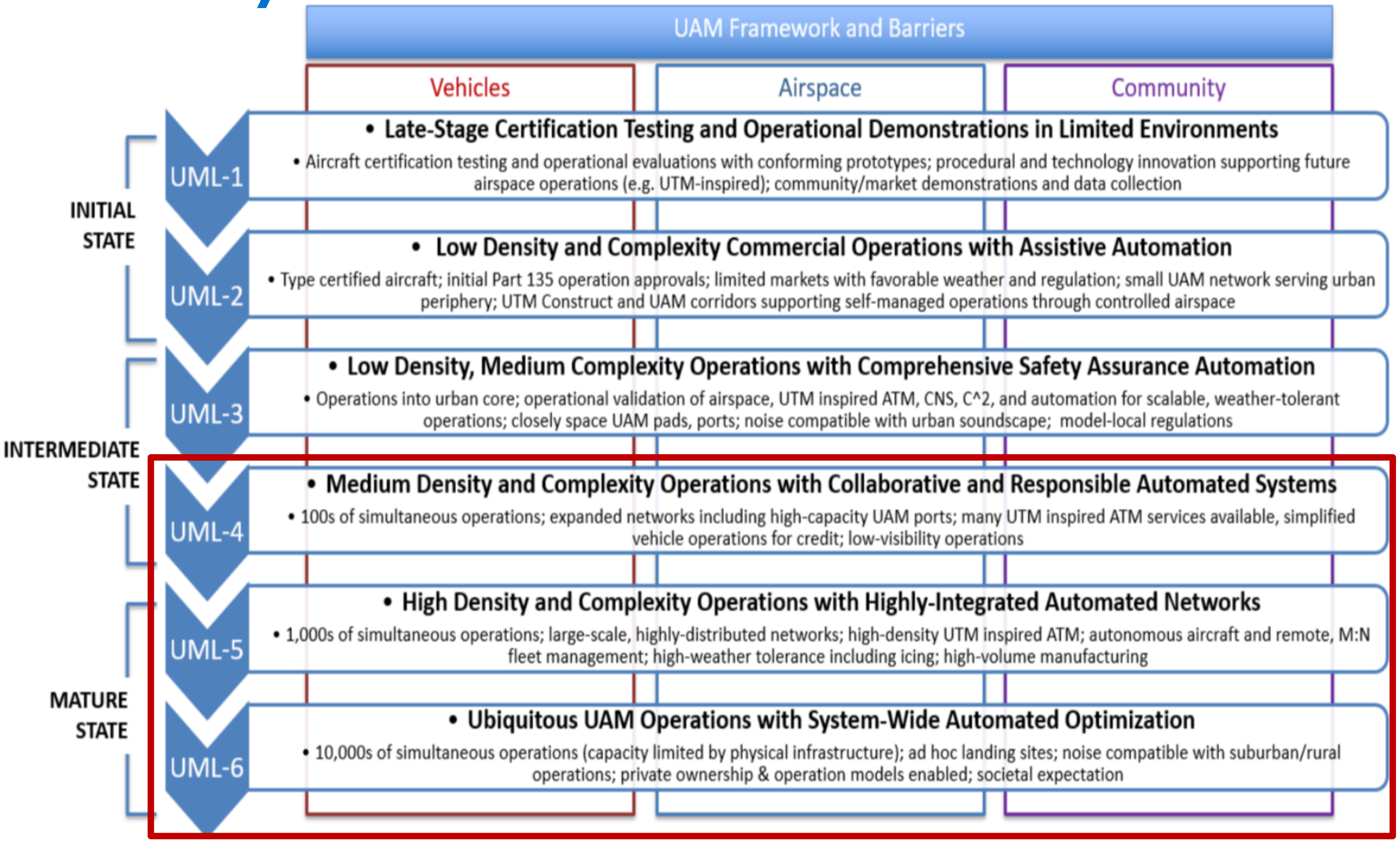
Hashemi, K. (2021). *Multi-Vehicle Control Working Group*. Retrieved from https://nari.arc.nasa.gov/sites/default/files/attachments/Day%201%20KelleyHashemi%20Slides.pdf

Enables desired future state

- Operations scalability
- Increasingly autonomous vehicles

Applicable to range of use cases supporting advanced air mobility vision

UAM Maturity Levels



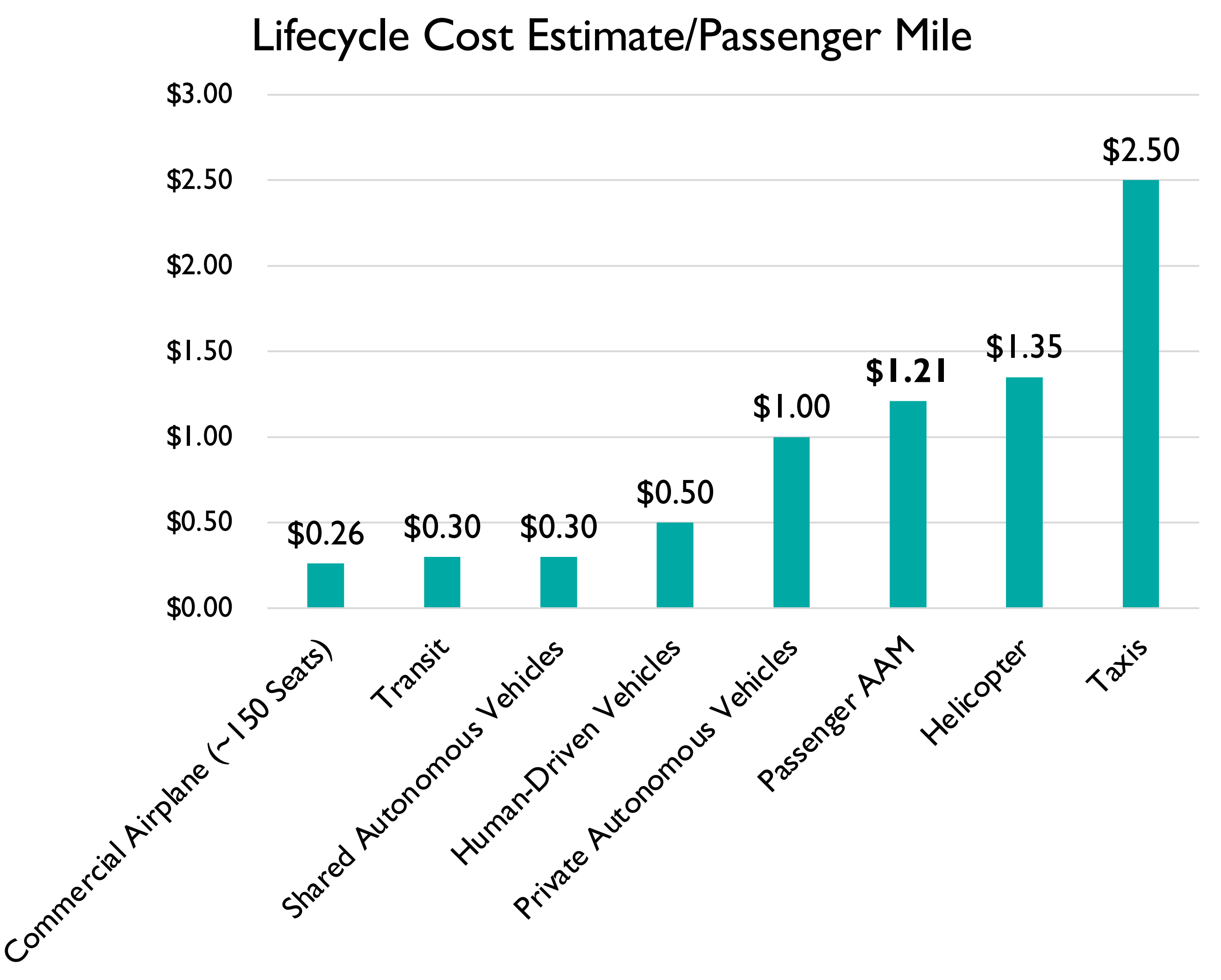
NASA. (2020). *UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4*. Retrieved from https://ntrs.nasa.gov/citations/20205011091

Volpe m:N Efforts

- Study costs associated with UML-5 (high-density, highly automated AAM and UAS) operations
  - Drawing parallels to helicopter ops (using contemporary, high-volume ops as a baseline)
  - Assess costs and opportunities where autonomy may improve the ROI for m operators managing N vehicles
- Provide clarity on business case and ROI when going from one or more operators controlling one aircraft to one operator controlling multiple, automated aircraft (AAMs and UASs) using 2+ use cases
- Goal: Development of a model having inputs and outputs for m:N

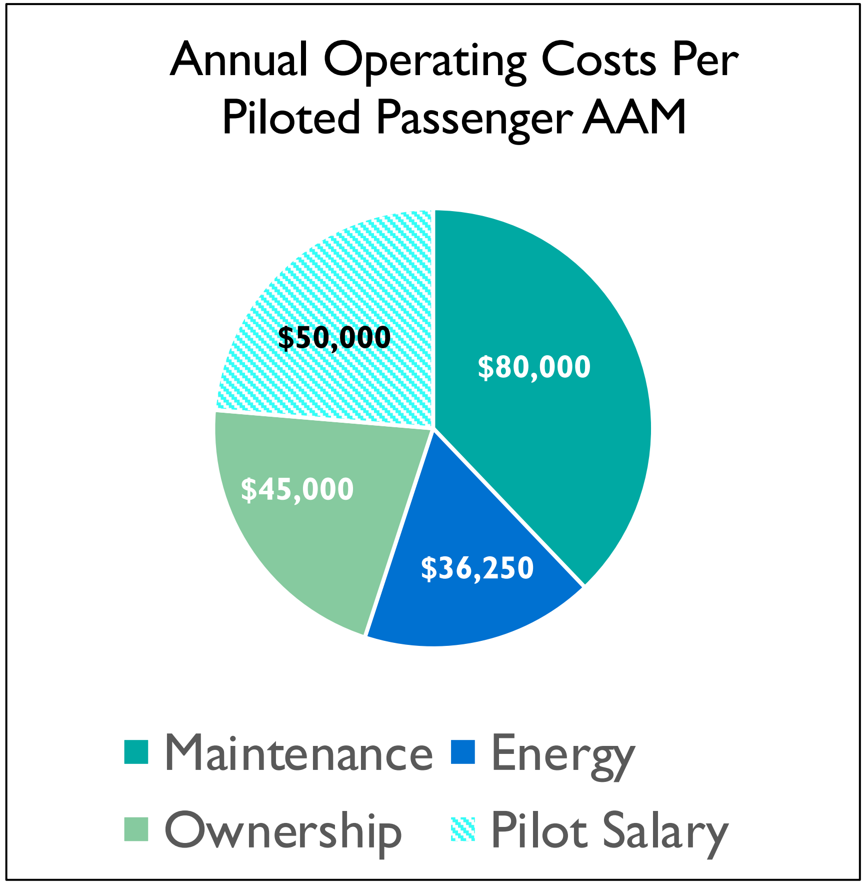
AAM Passenger Use: Initial Cost Input Research

- AAM expected to be more expensive than other modes but competitive, especially with travel-time benefits
- May choose to isolate manufacturing costs and operating costs separately in analysis

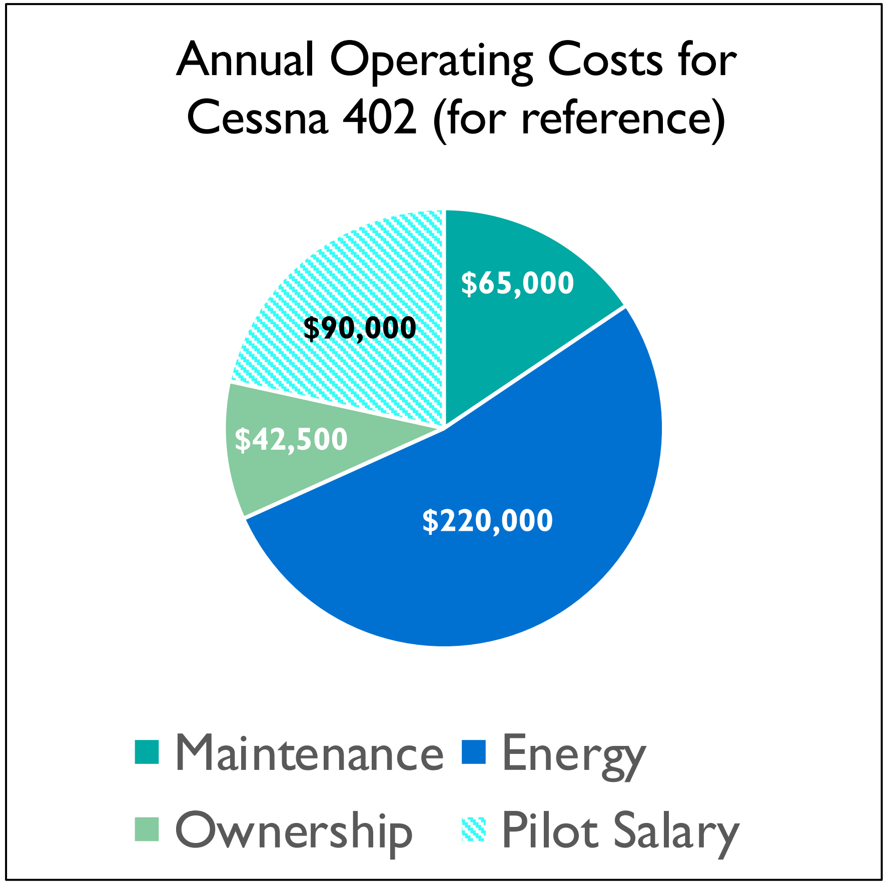


Lifecycle Inputs per Aircraft:
- Annual Miles: 400,000
- Annual Hours Flown: 1,750
- Useful Life: 15 Years

AAM Passenger Use-Case: Piloted vs. Autonomous



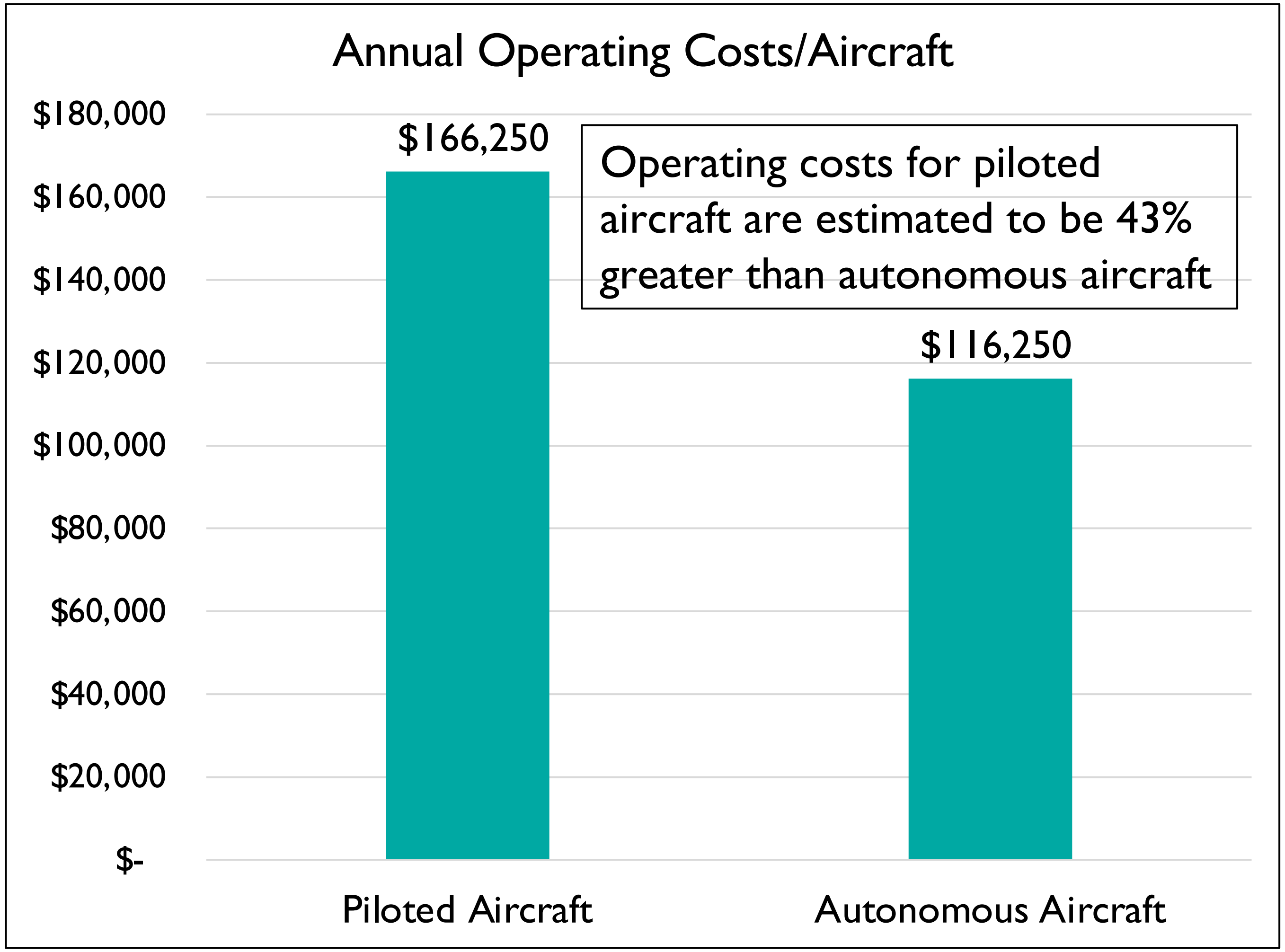
Total Annual Operating Costs: $211,250



Total Annual Operating Costs: $417,500

- In addition to saving $50,000 annually in operating costs, automation may allow for a 25% increase in capacity / payload (operators could save on energy costs or use the extra space for another passenger)

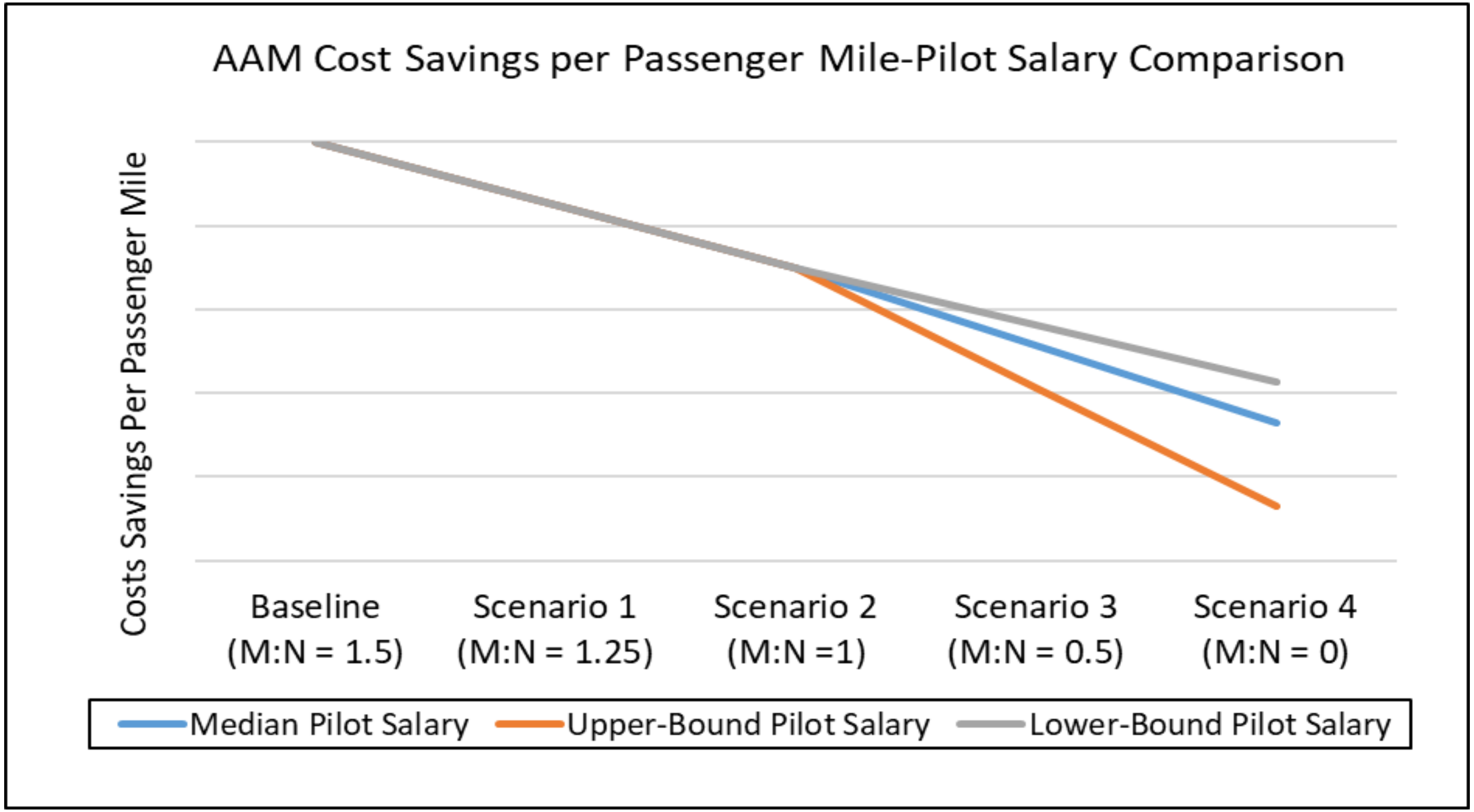
AAM Passenger Use-Case: Piloted vs. Autonomous



- Initial research indicates that paying pilot salary expenses (including benefits, such as healthcare) would make the AAM market economically unfeasible long-term

- m:N scale may be more of a step function than a line or curve (may also change significantly based on key technological advances)

Spreadsheet-Based Parametric Model: Illustrative Pilot/Operator Example



Possible ROI-/BCA-Supporting m:N Efforts

- Calculation of N upper bound (currently assume 1:2 for AAM and 1:100 for UAS) using
  - operations research (i.e., quantitative probabilistic queueing model) and
  - human factors (i.e., frequency & duration distributions for events requiring intervention)

- Automation vs. remote access (per Meaconing, Intrusion, Jamming & Interference—MIJI—concerns) using AAM formation 1:N as interim

- Other ROI/BCA supporting requirements & considerations:
  - Latency (e.g., general delays, time-of-flight position due to lags, etc.)
  - Flying public (e.g., 3-7% have clinical phobia to flying; 7-10% affected by claustrophobia; 40% report fear of flying)
  - Comm, nav, and surveillance (CNS) errors, algorithms, and limitations

Convergent Aeronautics Solutions (CAS) XI

"Desirability" Analysis

Supporting

Wes Ryan and Ralph Jansen
Convergent Aeronautics Solutions (CAS) Project
NASA Transformative Aeronautics Concepts Program (TACP)

NASA. (2021). Retrieved from https://www.nasa.gov/sites/default/files/thumbnails/image/tacp-news-release3.jpg

Volpe CAS X1 Support

- NASA's single-aisle future transport aircraft concept is an X1 activity within NASA's Convergent Aeronautical Solutions (CAS) Project

- X1 effort has designated three areas of study:
  - Desirability
  - Viability
  - Feasibility

- Volpe is supporting the Desirability area

Data Review and Definitions – Network, Operations, Fleet

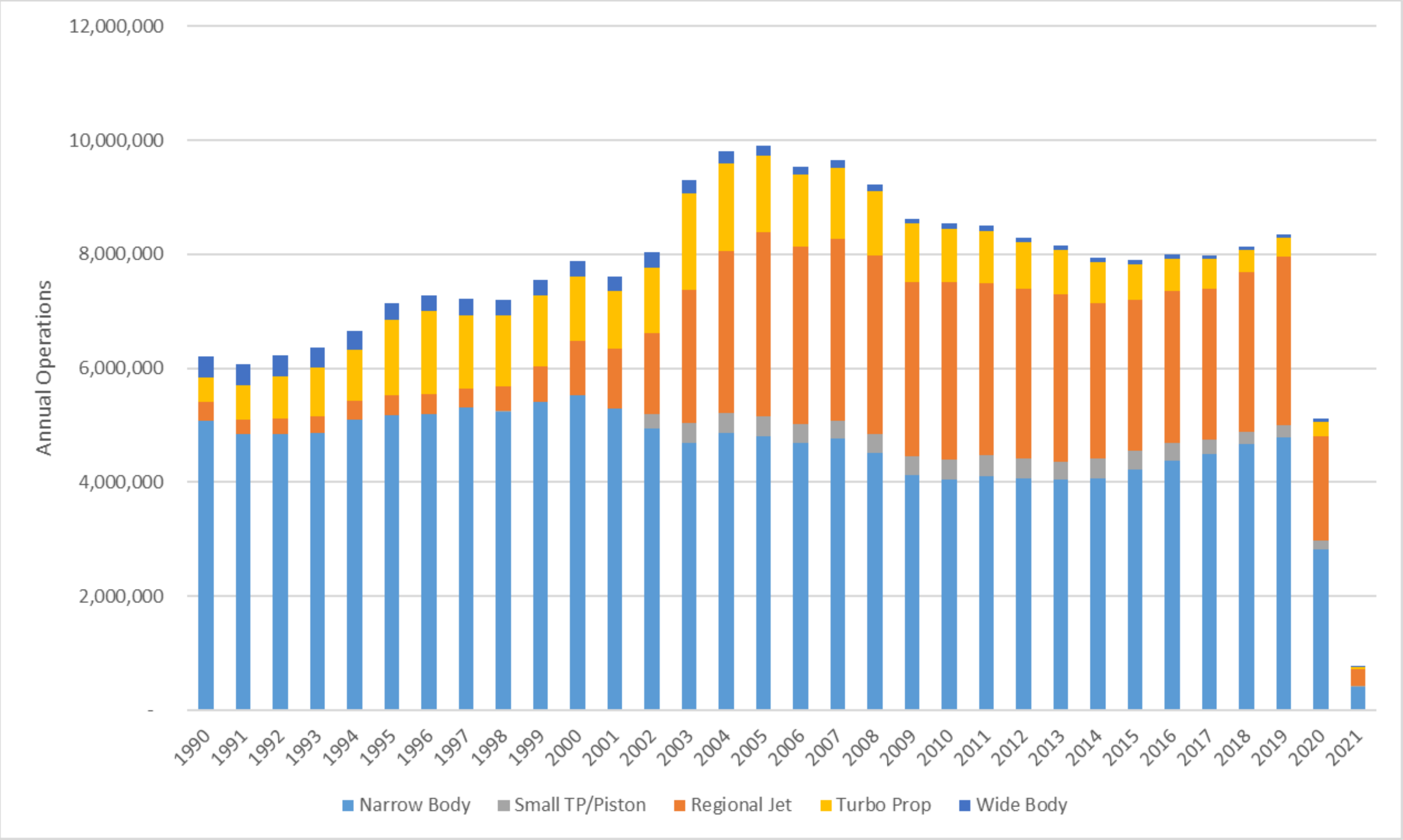
Database	Network	Operational Metrics	Fleet Characteristics	Notes
Common Operations Database (COD)	Global Origin-Destination (OD) pairs • Great Circle Distance (GCD) • Country Pairs • ICAO Route Groups	• Available Seat Miles (ASM) • Operations • Available Ton Miles (ATM)	• Aircraft name and engine equipment code • In-service commercial Passenger, Freighter and Business Jet markets • Seats and Seat Class • Age • Payload	• Combination of several data sources • Base year: 2018 • PAX market ~36 million rows • Well defined operations/fleet data for commercial markets; less certainty with <19 seat P/TP market • Proprietary database
BTS T-100 Domestic Segment	Domestic OD pairs	• ASMs/ATMs • Operations	• Aircraft name and engine type • Usage type (PAX, freighter, combo)	• Year range: 1990-2021 • Data quality mixed, but reasonable at more aggregate (market) levels • Public database
Cirium Fleet Analyzer	N/A	N/A	• Serial coded aircraft detail • In-service history (order, delivery, in-service, retirement) • Airline/Carrier information • Seats • Age	• Panel data (individual aircraft by year): 1970-2021 • Proprietary database
Official Airline Guide (OAG)	Global Origin-Destination (OD) pairs	• ASMs/ATMs • Operations	• Aircraft name • Airline/Carrier • Seats/payload	• Year range: 2000-2020 • Proprietary database

North America Domestic Commercial Passenger Markets (COD 2018)

							Percent NA Domestic to Global		
Market	Seat Range	Operations	Available Seat Miles (in millions)	In-Service Fleet	Avg. Seats	Avg. Distance	Operations	Available Seat Miles (in millions)	In-Service Fleet
Small TP/Piston	<19	881,363	2,846	-	13	248	59%	66%	-
TP	20-100	642,786	9,177	397	57	248	18%	21%	27%
RJ	20-100	3,067,534	87,201	1,728	68	418	61%	59%	53%
NB	101-210 (single aisle)	4,885,740	630,782	3,682	156	809	21%	23%	21%
WB	>210 (twin aisle)	234,961	77,480	213	263	1,252	6%	3%	4%
Total		9,712,384	807,486	12,739	137	609	26%	14%	33%

Note: Data internal to U.S. DOT Volpe Center

Domestic U.S. Commercial PAX Market – No. Operations (BTS)



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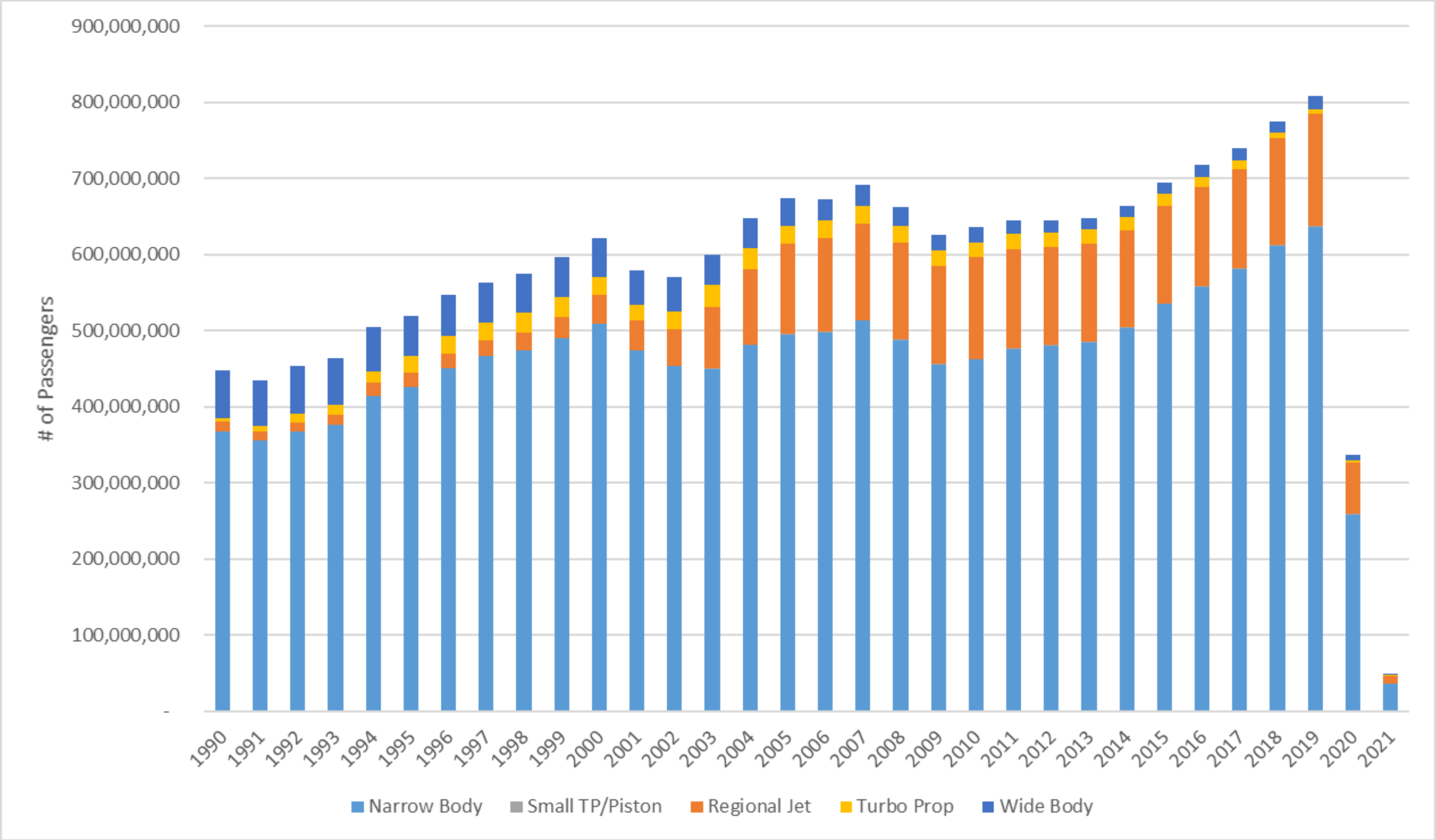
Domestic U.S. Commercial PAX Market – No. Passengers (BTS)



U.S. Department of Transportation
Volpe Center

FY21 Internal Project Support

- Primary:
  - Max Litvack-Winkler, Jacob Wishart, David Pace, Gina Solman, and Kendall Mahavier
- Multi-modal and multi-disciplinary SMEs:
  - Gary Baker, Scott Gilman, Eli Machek, Hannah Rakoff, Jingsi Shaw, and Scott Smith

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Multi-Modal Economic Analysis of the COVID-19 Pandemic Exogenous Shock

ARMD Systems Analysis Symposium

Max Litvack-Winkler

Economist, Economic Analysis Division, Volpe Center

November 10, 2021

Background and Introduction

- Volpe Center is conducting a COVID-19 Impact Study in support of NASA's Aeronautics Research Mission Directorate
  - Analyze COVID-19's effect on various modes of transport and economic indicators, including insights on modal resiliency
- This presentation illustrates results of passenger and freight multimodal trends in relation to economic indicators before and during the COVID-19 pandemic through Q1 2021
  - Focus on the aviation market

Agenda

- Relationship between economic indicators and transportation activity
- Overview of transportation activity in the 21st century prior to COVID-19
- Impact of COVID-19 on transportation activity
- Economic indicator/transportation activity analysis
- Resiliency

Transportation is a Derived Demand

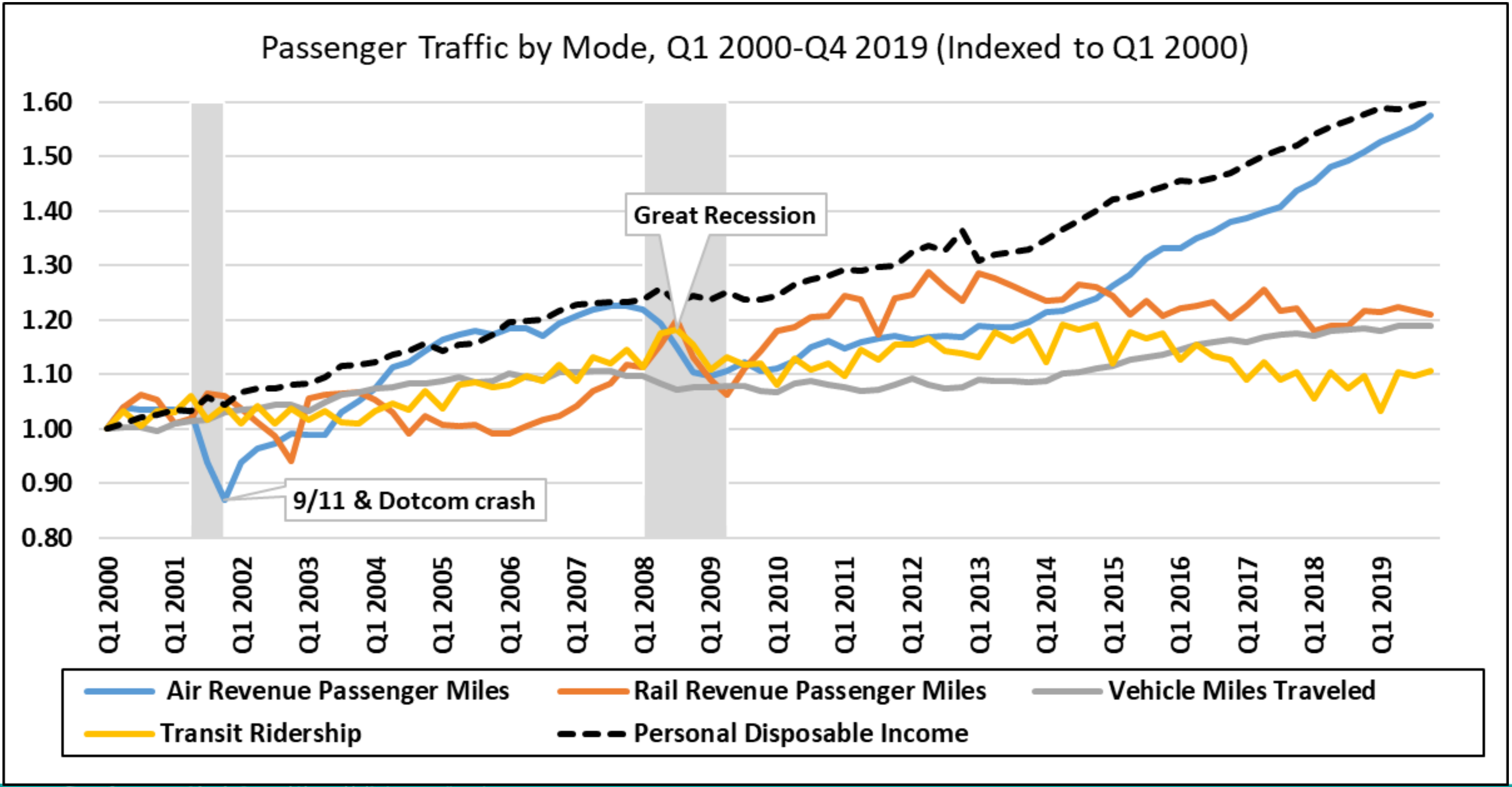
Growth in Disposable Income and Employment → Increased Household Travel Demand → Higher Levels of Passenger Travel

Growth in GDP and Industrial Production → Increased Demand for Freight → Higher Levels of Freight Activity

Modal Data Dictionary

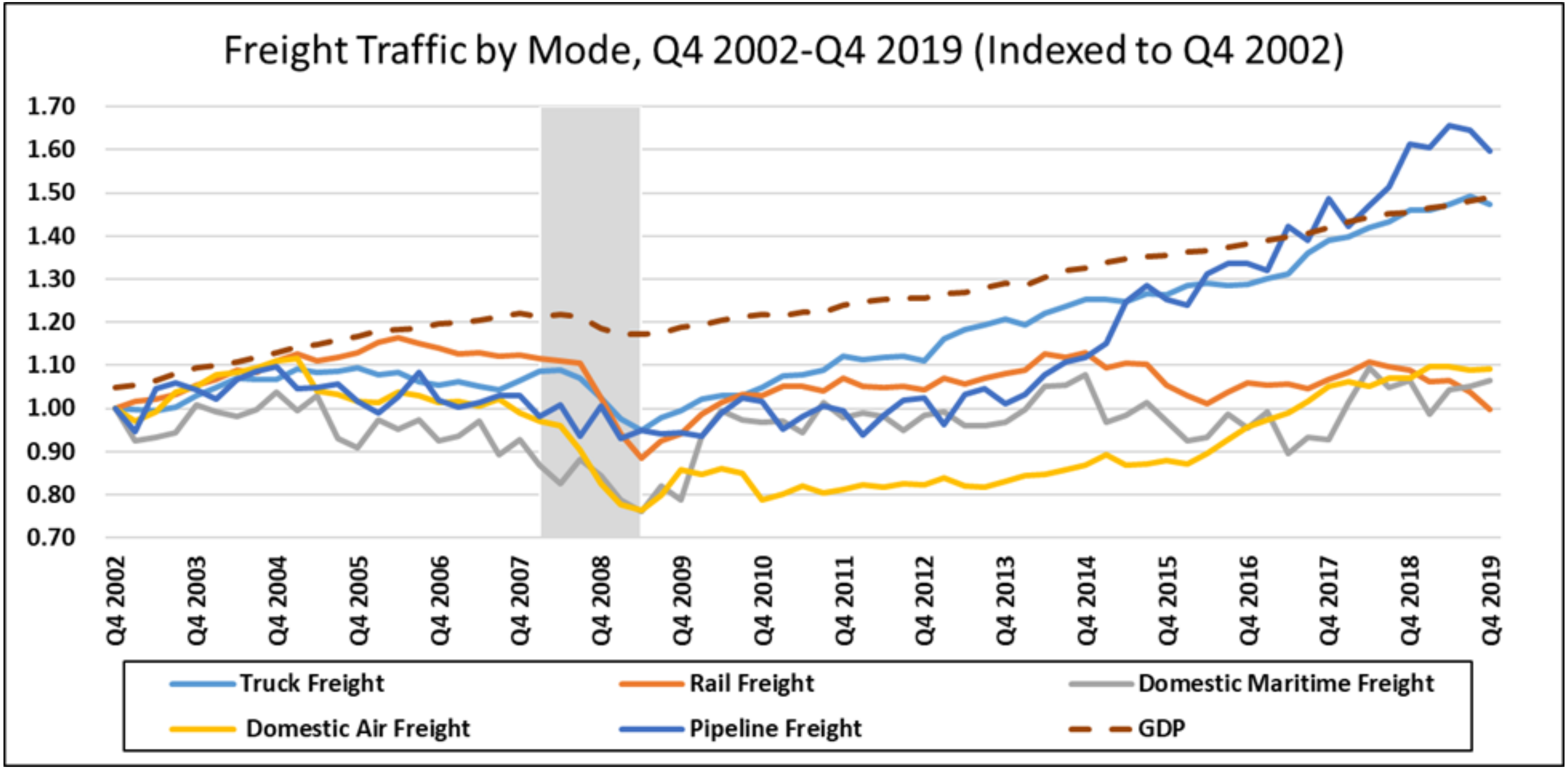
Mode	Freight/Passenger	Data Metric	Source
Aviation	Passenger	Aviation Revenue Passenger Miles	Bureau of Transportation Statistics
Highway	Passenger	Vehicle Miles Traveled	Bureau of Transportation Statistics
Transit	Passenger	Estimated Unlinked Passenger Trips	American Public Transportation Association
Rail	Passenger	Rail Revenue Passenger Miles	Bureau of Transportation Statistics
Aviation	Freight	Air Revenue Ton Miles of Freight and Mail	Bureau of Transportation Statistics
Truck	Freight	Truck Tonnage Index	Bureau of Transportation Statistics
Rail	Freight	Rail Carloads and Intermodals	Bureau of Transportation Statistics
Maritime	Freight	Monthly Tonnage Indicator	Bureau of Transportation Statistics
Pipeline	Freight	Pipeline Movement	Energy Information Administration

Modal Passenger Activity: Pre-COVID-19

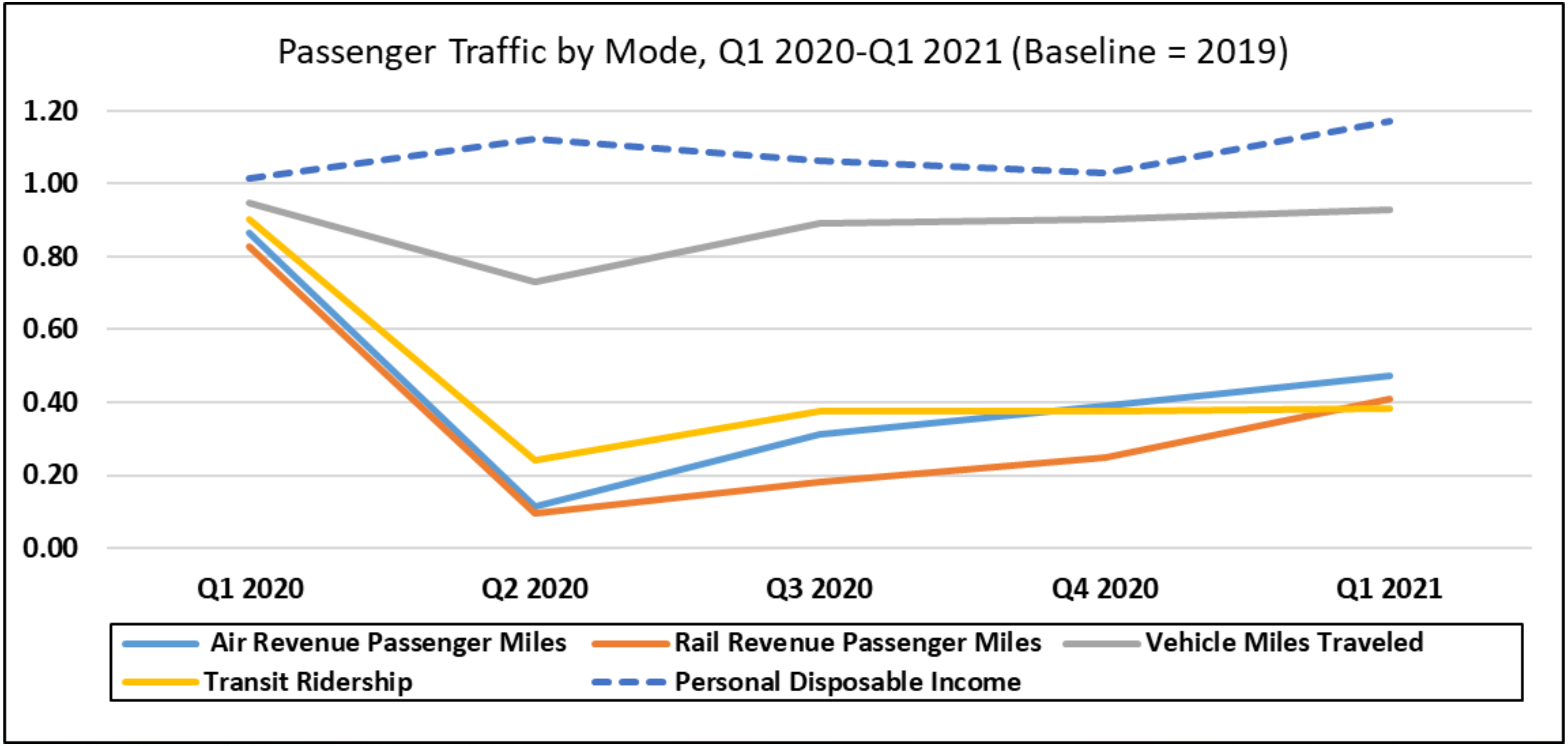


Grey Bars Indicate Recessionary Periods

Modal Freight Activity: Pre-COVID-19



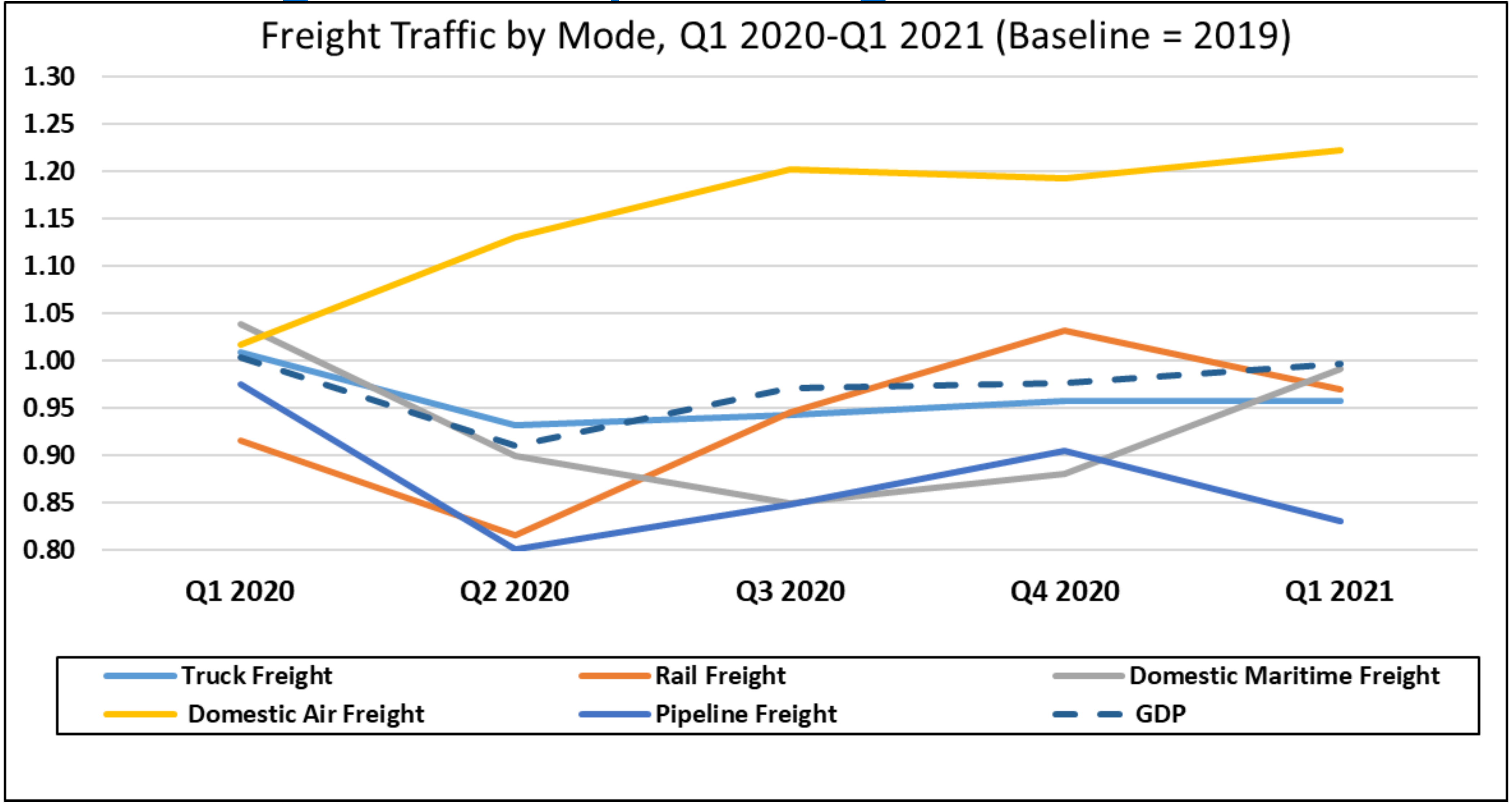
Modal Passenger Activity During COVID-19



Decrease in Modal Passenger Travel During U.S. Recessions

Recessionary Period	Air	Rail	Vehicle	Transit
COVID-19 Pandemic	-89%	-90%	-27%	-76%
Great Recession	-11%	-5%	-3%	-3%
9/11 & Dotcom Crash	-16%	-4%	1%	-2%

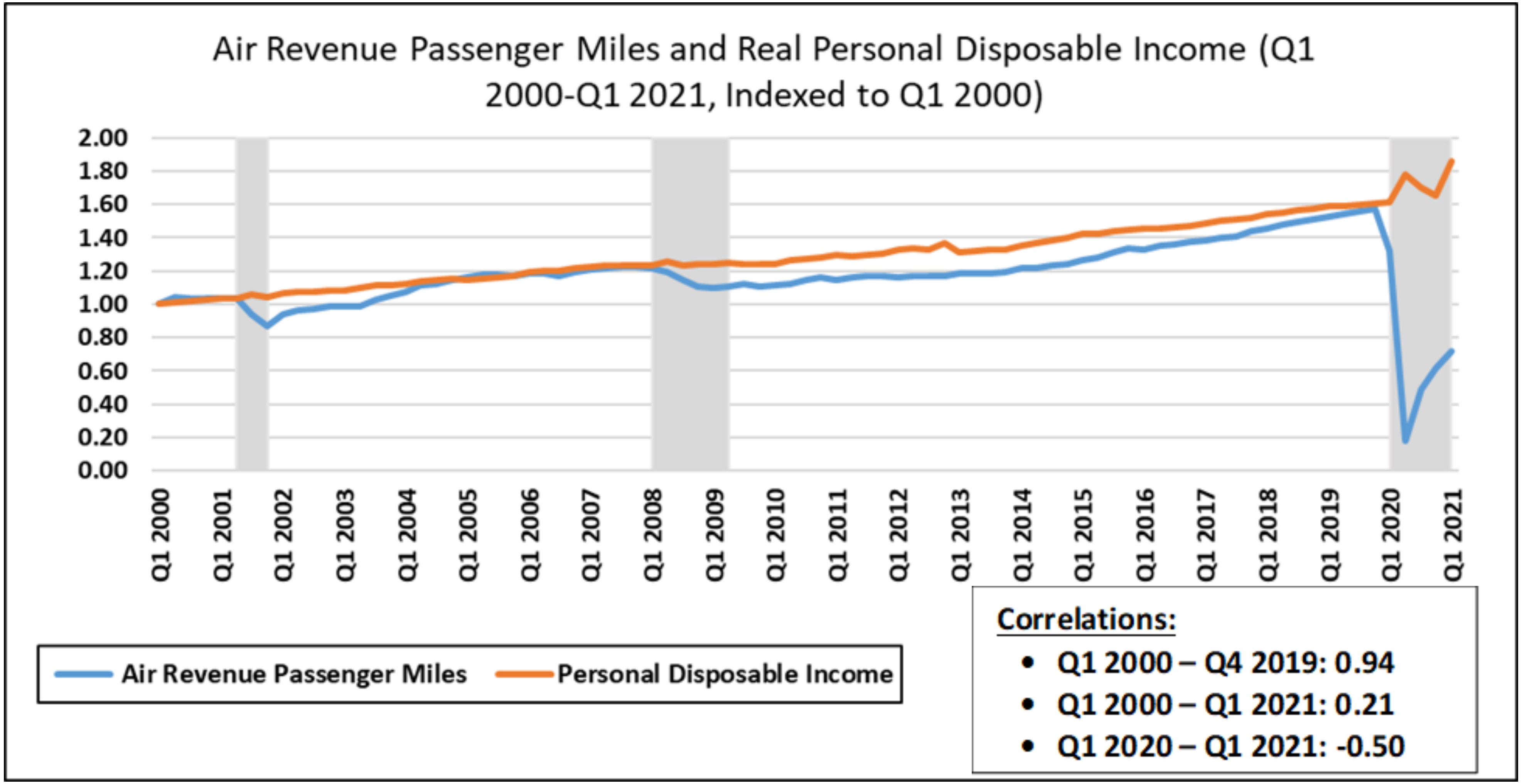
Modal Freight Activity During COVID-19



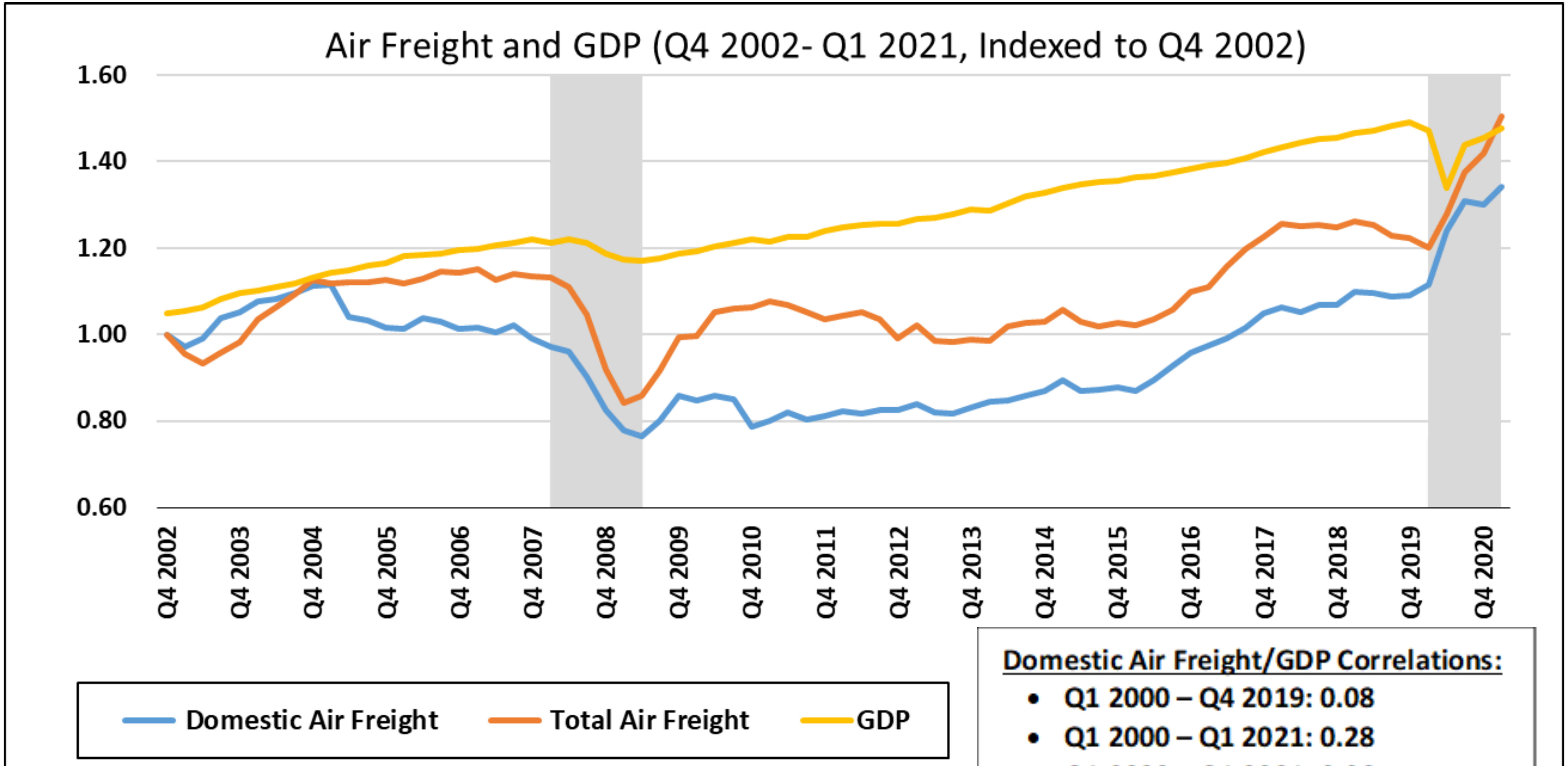
Decrease in Modal Freight Travel During U.S. Recessions

Recessionary Period	Air	Rail	Truck	Maritime	Pipeline
COVID-19 Pandemic	2%	-8%	-18%	-16%	-20%
Great Recession	-25%	-11%	-22%	-22%	-10%
9/11 & Dotcom Crash	N/A	0%	-3%	-7%	-4%

Passenger Air Travel and Real Disposable Income



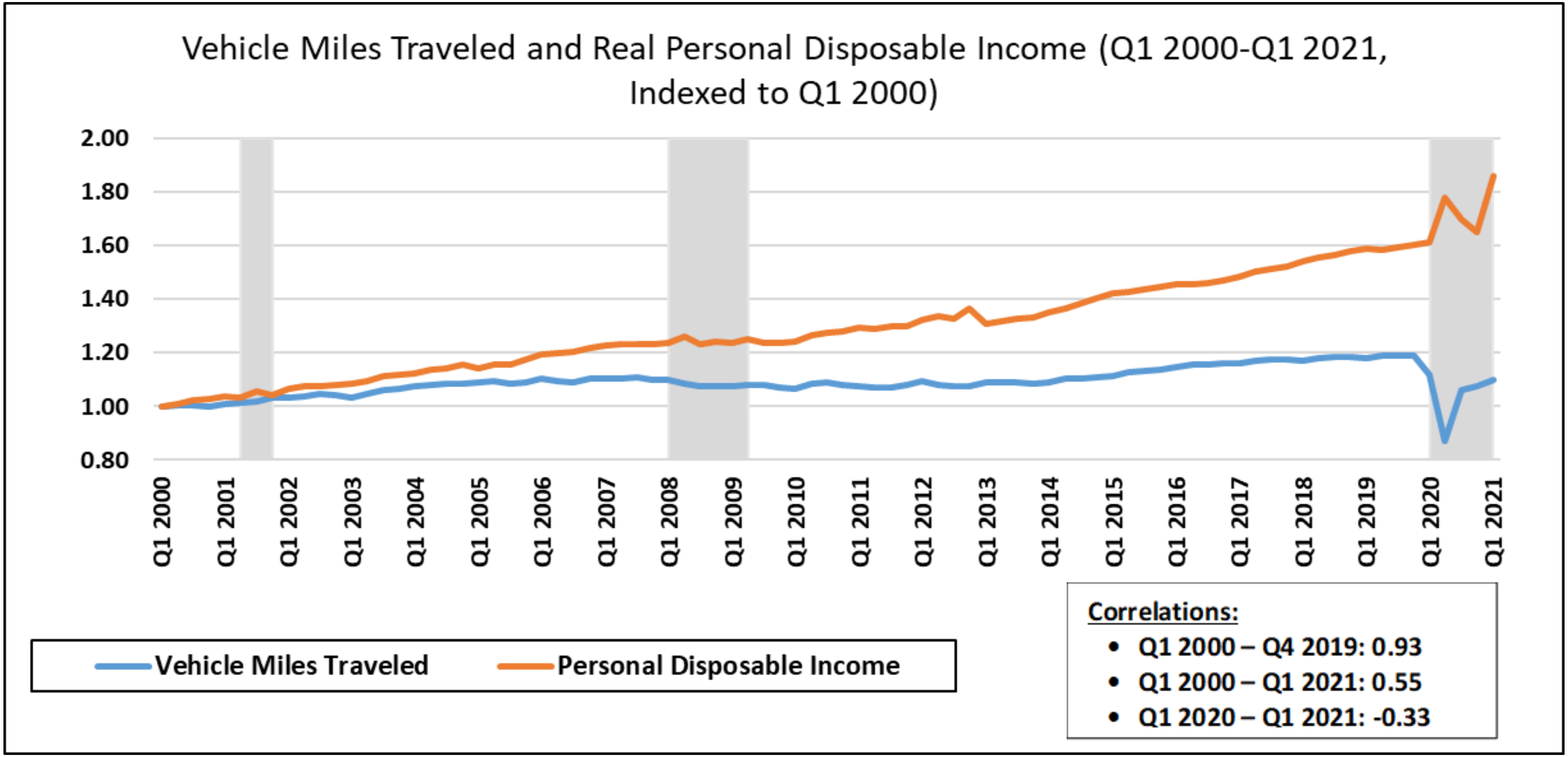
Air Freight and GDP



Domestic Air Freight/GDP Correlations:

- Q1 2000 – Q4 2019: 0.08
- Q1 2000 – Q1 2021: 0.28
- Q1 2020 – Q1 2021: 0.06

Vehicle Miles Traveled and Real Disposable Income



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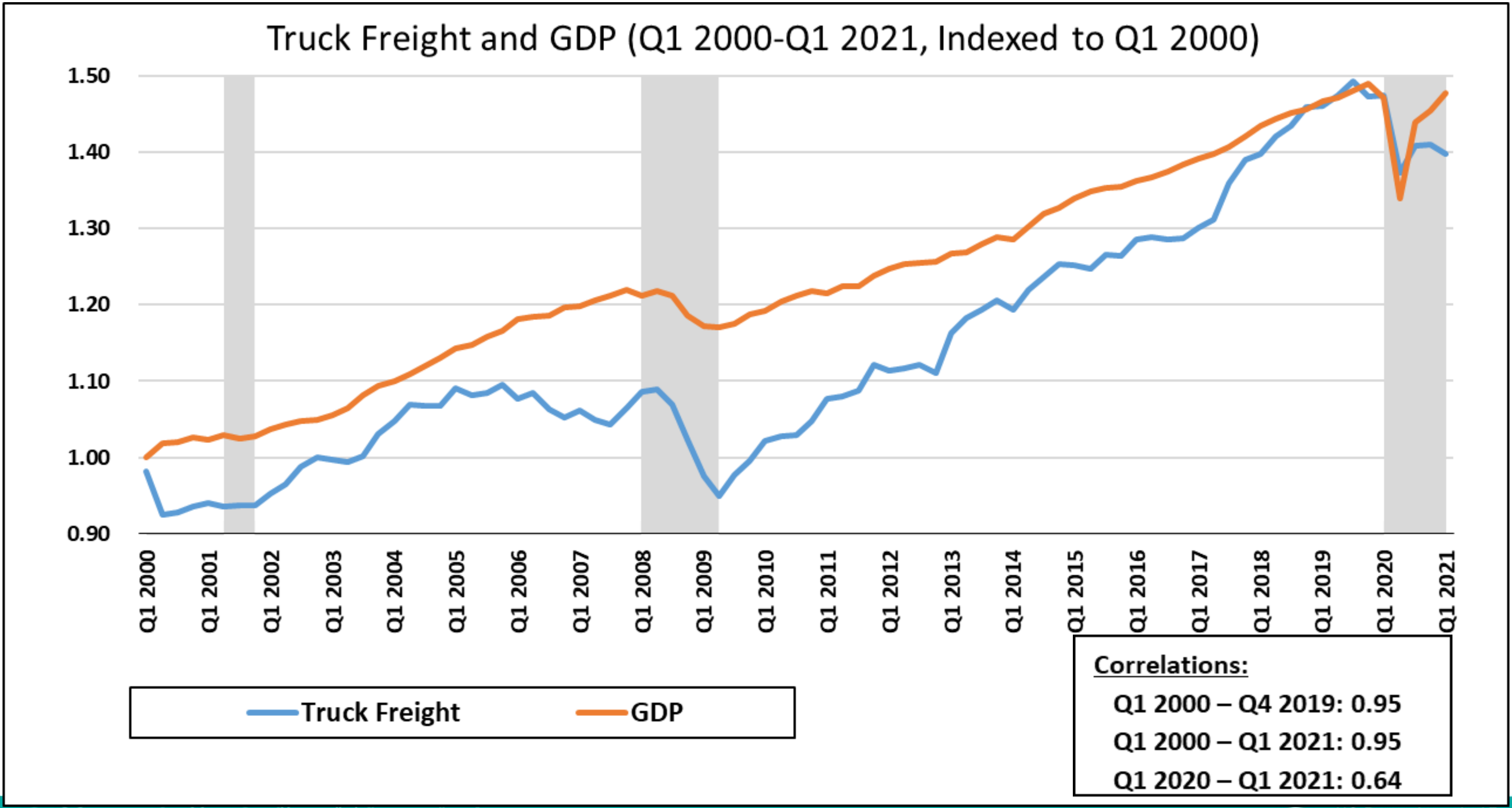
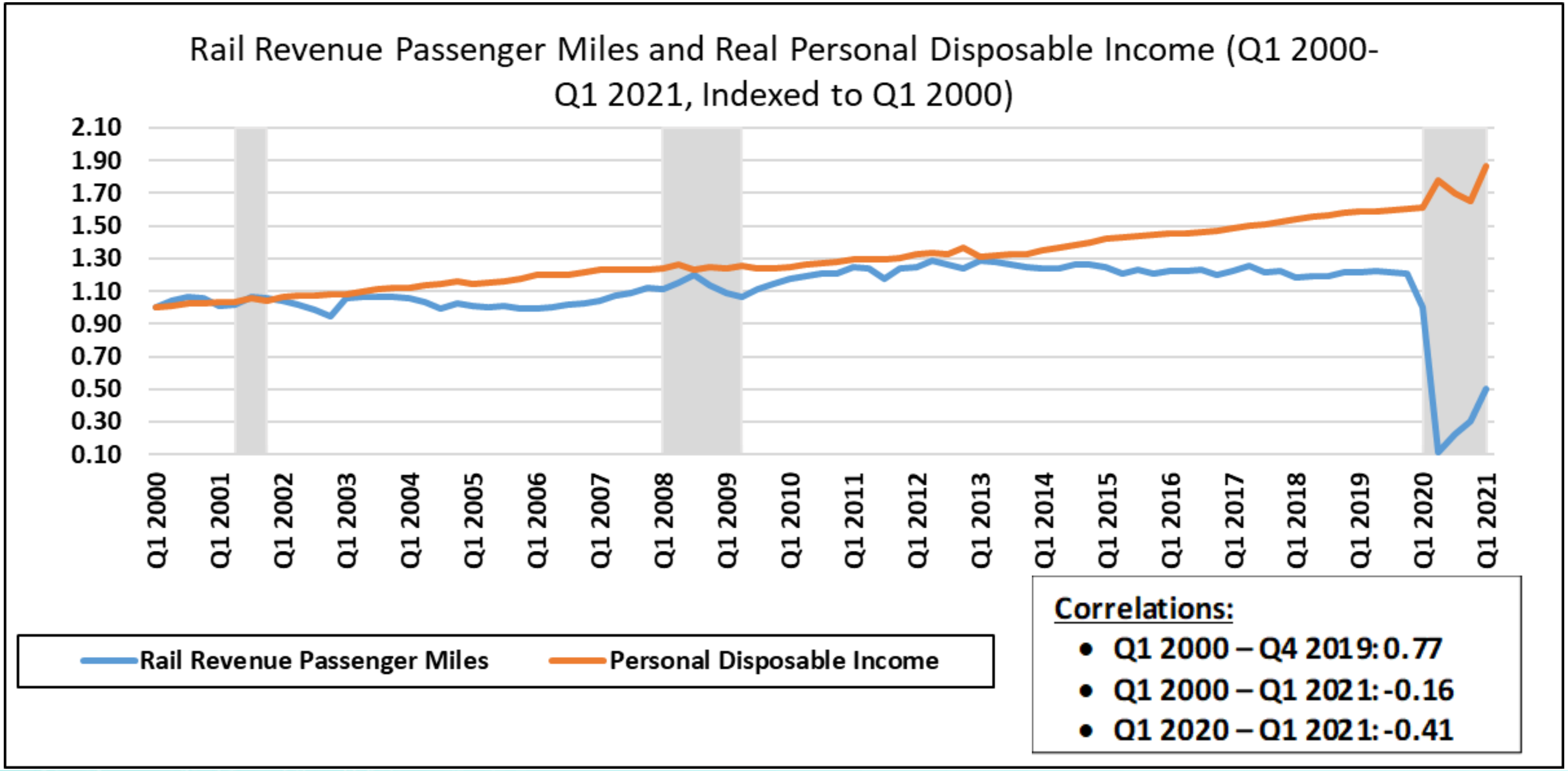
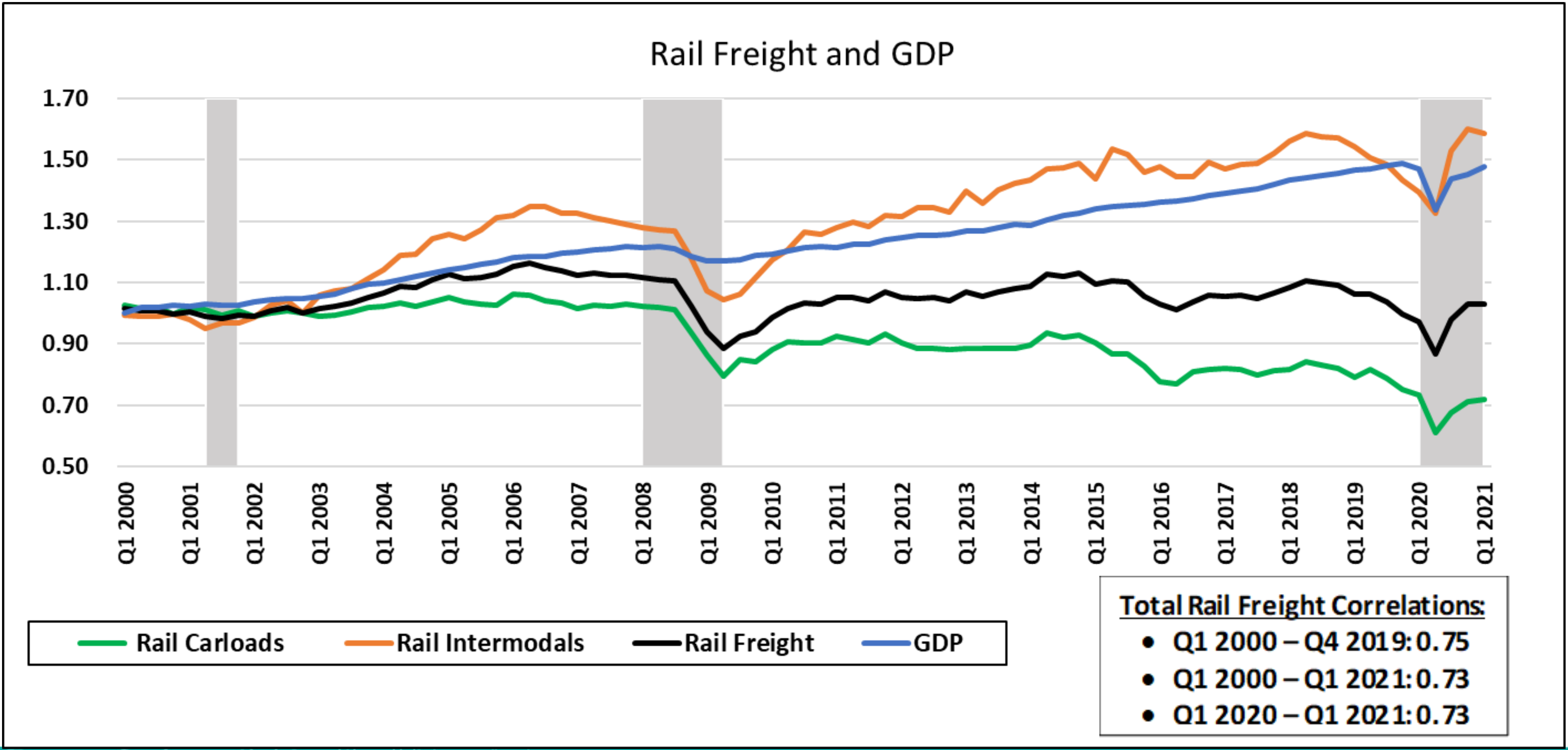
Truck Freight and GDP



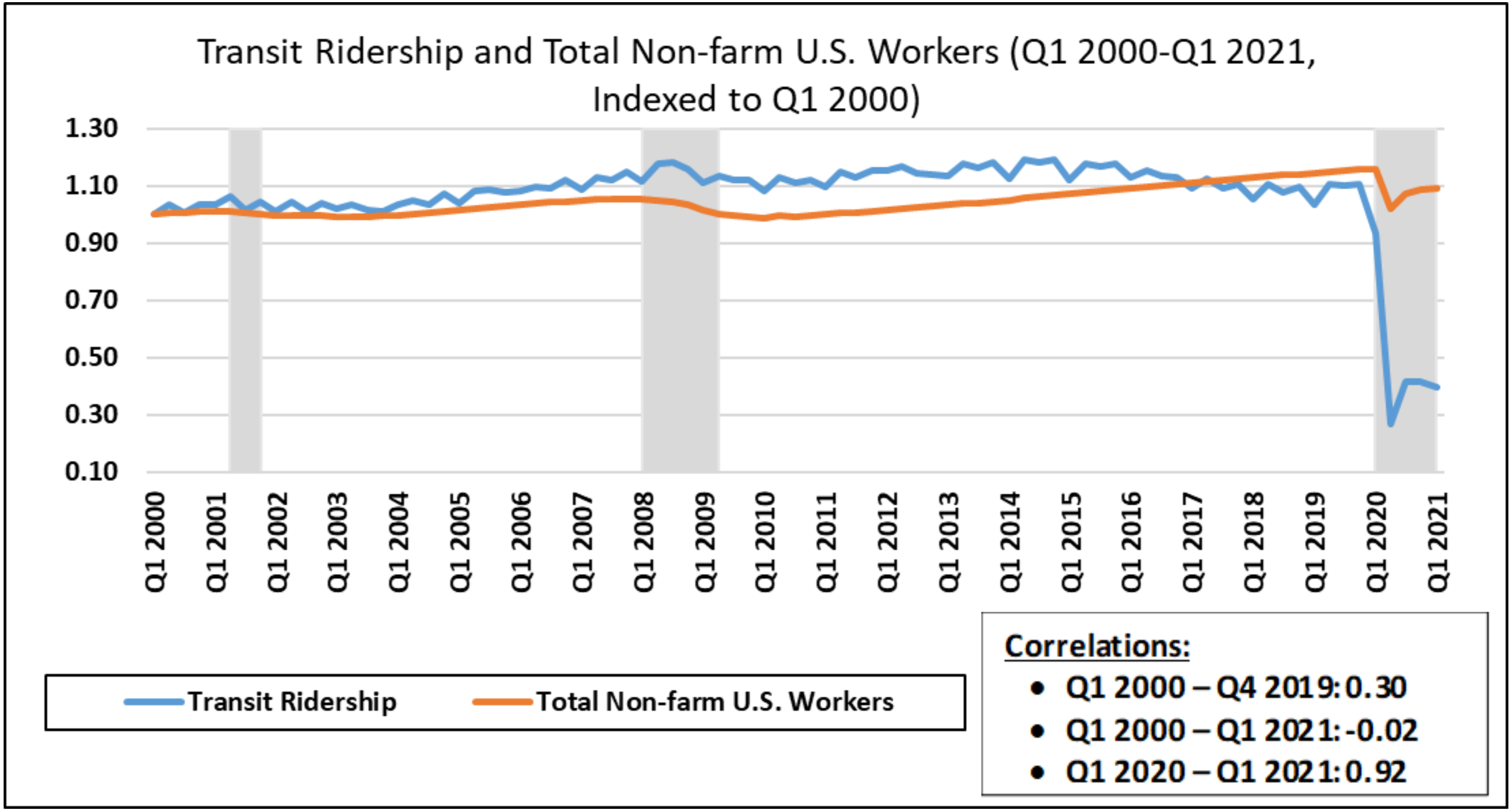
Passenger Rail Travel and Real Disposable Income



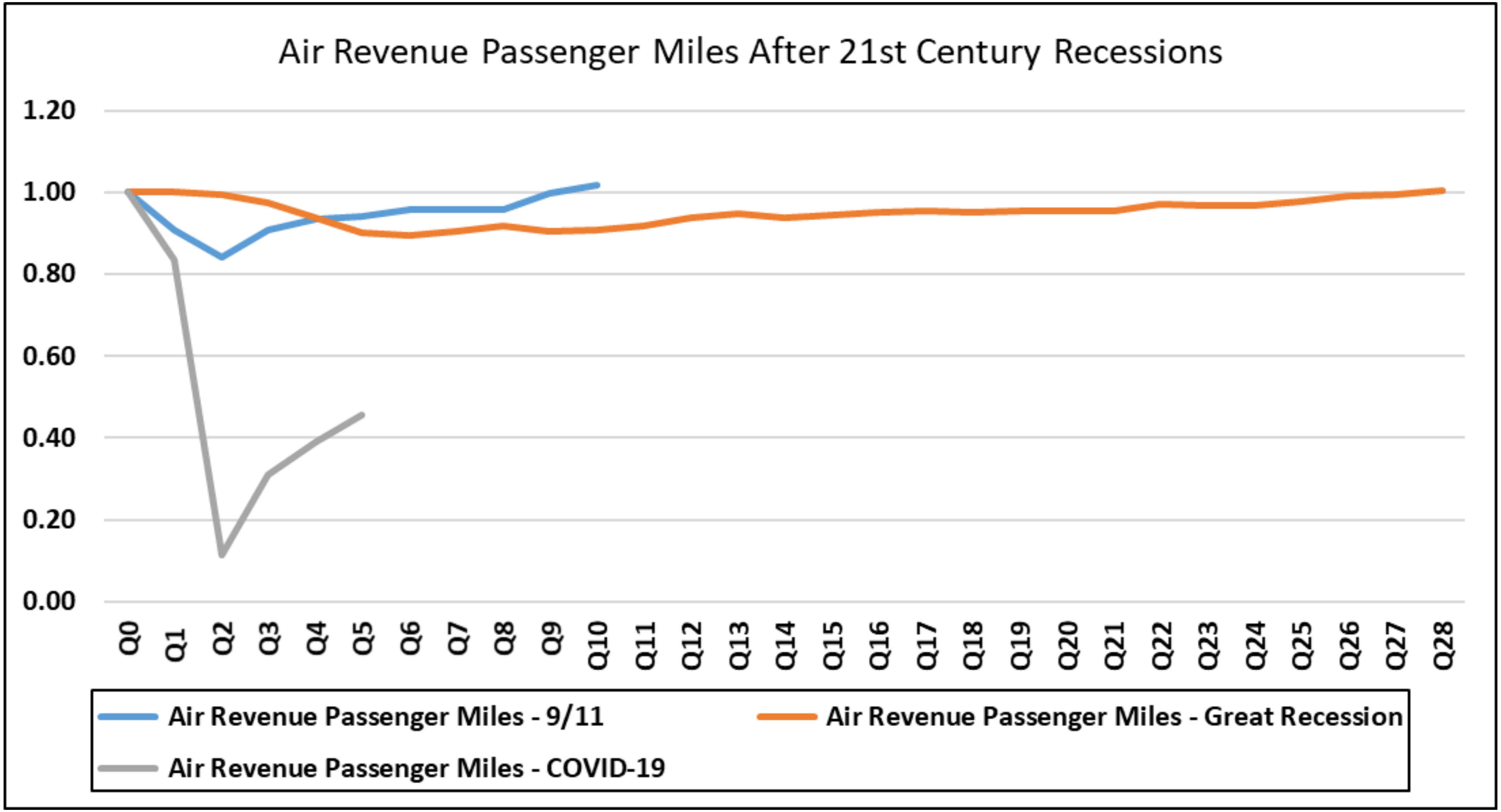
Rail Freight and GDP



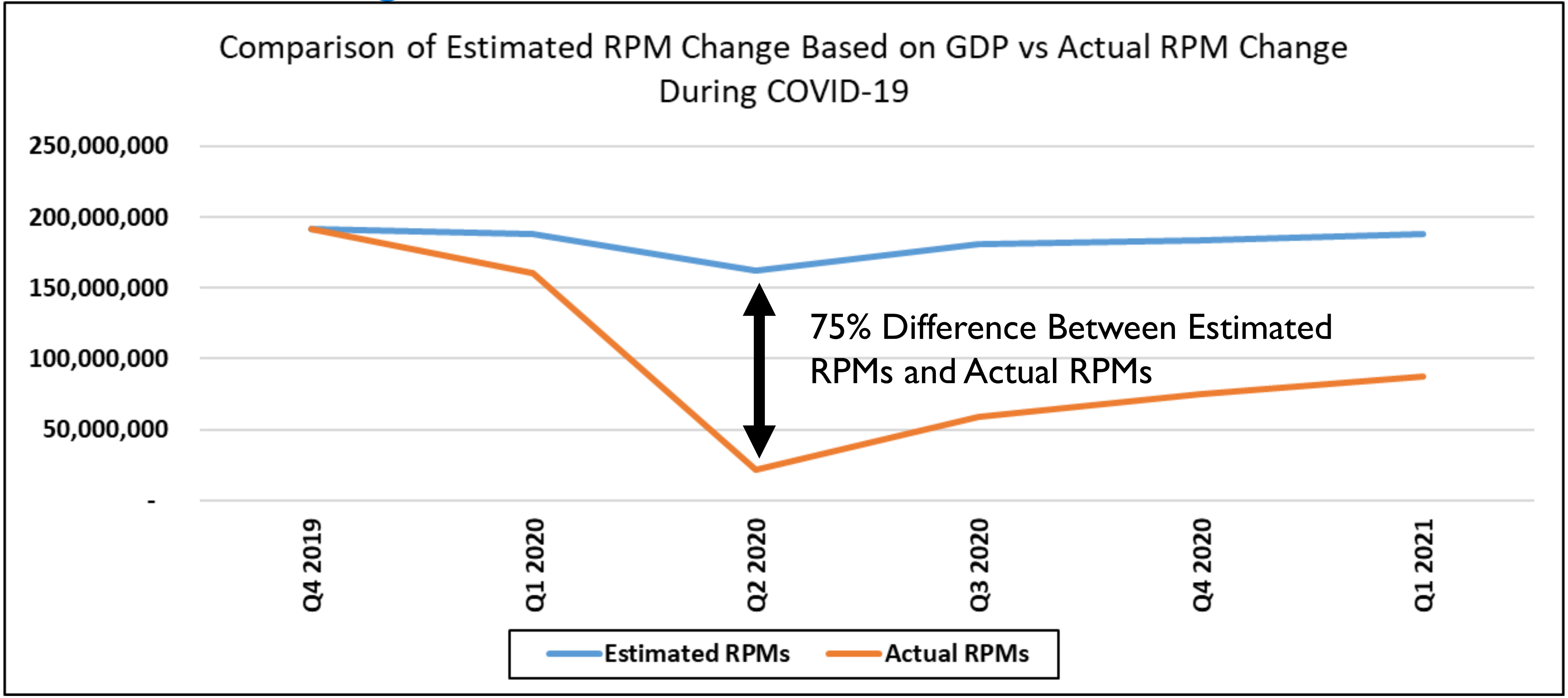
Transit Ridership and Employment



Resiliency: Air Travel Comparison After Recessions



Resiliency: Estimated Air Travel vs Actual Air Travel Based on GDP Change



Summary of Correlations Between Economic Indicators and Passenger Transportation Before and During COVID-19

Relationship	Pre-COVID-19 Pandemic Correlation	COVID-19 Pandemic Correlation
Passenger Air Travel-Disposable Income	0.94	-0.50
Vehicle Travel-Disposable Income	0.93	-0.33
Passenger Rail Travel-Disposable Income	0.77	-0.41
Passenger Air Travel-Employment	0.94	0.99
Vehicle Travel-Employment	0.90	0.87
Passenger Rail Travel-Employment	0.50	0.93
Transit Ridership-Employment	0.30	0.92

Summary of Correlations Between Economic Indicators and Freight Transportation Before and During COVID-19

Relationship	Pre-COVID-19 Pandemic Correlation	COVID-19 Pandemic Correlation
Air Freight-Gross Domestic Product	0.08	0.06
Truck Freight-Gross Domestic Product	0.95	0.64
Pipeline Freight-Gross Domestic Product	0.78	0.50
Rail Freight-Gross Domestic Product	0.28	0.91
Maritime Freight and Industrial Production	0.36	0.47

Key Takeaways

- COVID-19 caused a breakdown in the passenger travel-economic indicator relationship
  - Freight fared significantly better, and domestic air freight increased during COVID-19.
- Both passenger and freight relationships weakened
- High degree of uncertainty regarding modal recovery
  - Pandemic is still ongoing

Future Research

- Future analysis could be conducted following the conclusion of the pandemic and include:
  - A full time series dataset
  - Modal trends based on vaccination rates and virus outbreaks
  - Complete analysis of recovery paths
  - Long-term modal changes due to the COVID-19 pandemic (e.g. reduction in business travel, impact on transit ridership, etc.).
- Additional research areas include:
  - Break down transportation trends by region or State within the U.S.
  - Study the pandemic's effect on international travel.
  - Examine transportation metrics within counties based on virus rates, vaccination rates, and economic activity.

Q+A Session

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COVID-19 Federal Policy Effects on the Aviation Industry

ARMD Systems Analysis Symposium

Gina Solman

Environmental Protection Specialist

Policy Analysis & Strategic Planning Division

Volpe Center

November 10, 2021

Background and Introduction

- Literature review and policy analysis of U.S. Government actions that affected the aviation industry during the COVID-19 pandemic
  - Part of the Volpe Center's COVID-19 Impact Study in support of NASA's Aeronautics Research Mission Directorate
- Types of policies covered:
  - Restrictions on passenger air travel
  - Regulatory flexibilities to support industry and supply chain resilience
  - Financial support

Change in Passenger Demand and Capacity

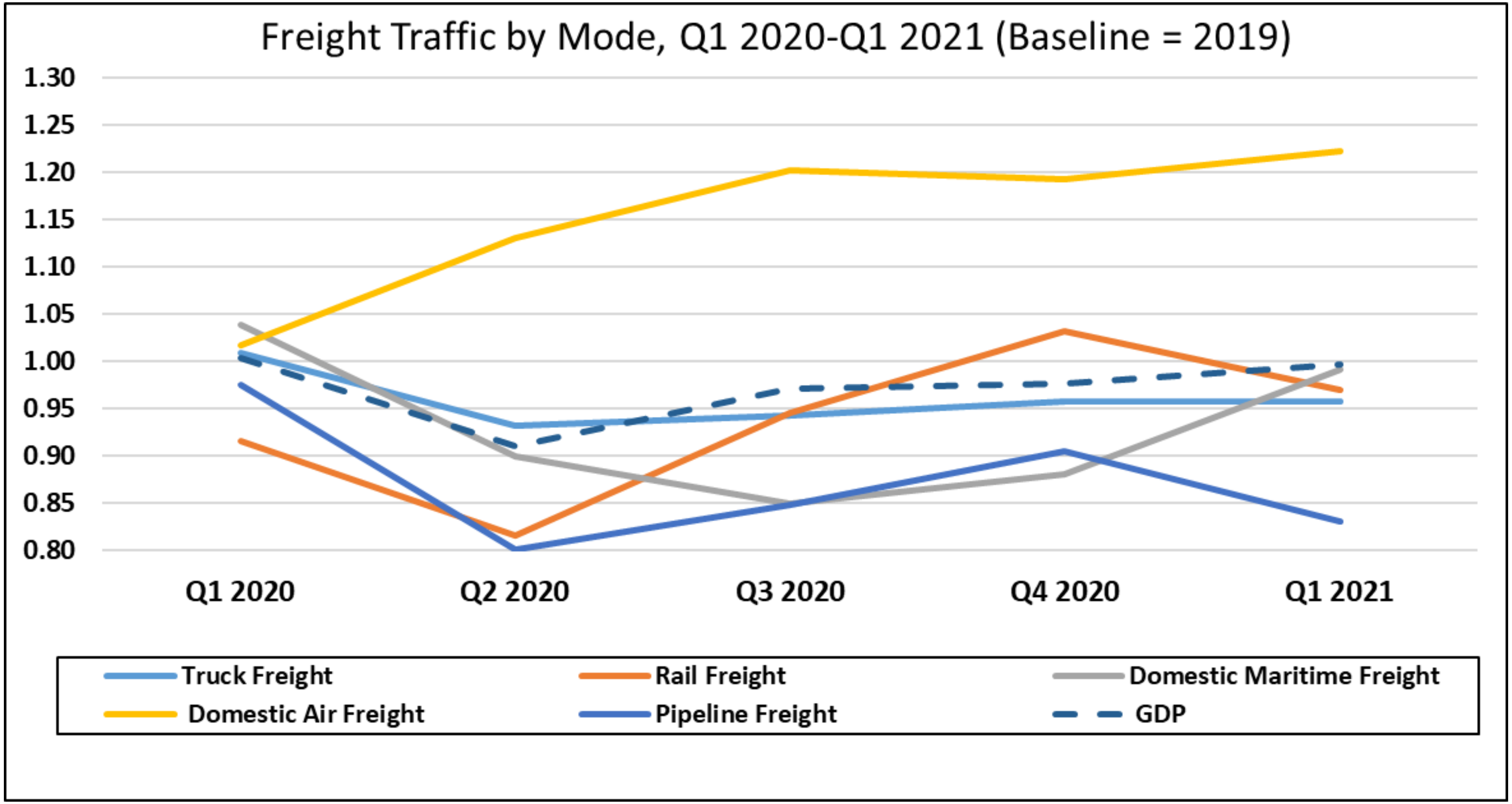
2020 CALENDAR YEAR	DEMAND Revenue Passenger Kilometers (RPK) change from 2019	CAPACITY Available Seat Kilometers (ASK) change from 2019	Passenger Load Factor (PLF) change from 2019	Passenger Load Factor (PLF Level)
Total Market	-65.90%	-56.50%	-17.80%	64.80%
North America Total	-65.20%	-50.20%	-25.60%	59.20%
North America International	-75.40%	-65.50%	-23.90%	60.10%
U.S. Domestic	-59.60%	-41.40%	-26.40%	58.80%

Source: IATA

Passenger air travel

- Policies that limited supply
  - Presidential proclamations to suspend or limit entry to the U.S.
- Policies that may have limited demand
  - State-level stay-at-home orders
  - CDC requirements
    - proof of negative COVID-19 test result or recovery
    - wearing mask on planes and other forms of transportation
  - CDC risk-based recommendations for travel destinations

Change in Freight Traffic by Mode



Regulatory Flexibilities – FAA Actions

- Cargo transport exemptions
- Airport Slot Use Temporary Waivers
- Employee Reliefs

Financial Support to the Aviation Industry

- $121 billion total support to the aviation industry

	Payroll Support	Grant Funding	Loans & Loan Guarantees
CARES Act	$32 billion 89% utilization 611 participants	$10 billion 3,000 airports	$46 billion allocated $38.3 billion sought (83%) $21.9 billion executed (57% of sought)
Consolidated Appropriations Act, 2021	$16 billion 98% utilization 518 participants	$2 billion	
American Rescue Plan Act of 2021	$15 billion 98% utilization 480 participants		

Stipulations to Ensure Effective Policies

- Employee retention policies
- Targeted assistance
- Access to air transportation

Considerations for Future Policies

- Provide evaluation and support of new technologies, designs, and processes to make flying safer
  - Contactless biometrics
  - Automated sanitation of baggage, kiosks, bathrooms, water fountains, high use areas
  - Testing and modeling of air flow, virus movement, and mask use onboard aircraft
- Invest in research and development to support competitiveness and sustainability of the aviation industry
- Attract and retain specialized workforce
- Target assistance to sectors that have the greatest need
- Ensure access to the national airspace system – small community service
- Develop national aviation preparedness plan for communicable diseases

Key Takeaways

- Government intervention supported recovery
  - Provided substantial financial assistance to maintain operations
  - Adjusted to changes in demand for passenger vs. cargo
  - Safeguarded specialized workforce

- Possible future work
  - Expand assessment to other shocks
  - Seek to understand impact of government intervention vs. industry actions

Q+A Session

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Analysis of the Electrical Grid for UAM

Systems Analysis Symposium
November 10, 2021
David Thipphavong

Presentation Roadmap

- Bottom Line Up Front
- Introduction
- Strategic Analyses

	Without ground EVs	With ground EVs
Analysis by electrical interconnection (grid) • Electricity can be shared between metro areas • Best case	1 599,818 UAM charging (today max)	2 475,177 UAM charging (2050 max)
Analysis by metro area • Electricity cannot be shared between metro areas • Worst case	3 159,429 UAM charging (today max)	4 94,541 UAM charging (2050 max)

= Order of presentation

- Bottom Line and Recommendations

Bottom Line Up Front

- Many technology, infrastructure, regulatory, and acceptance challenges to conduct UAM operations with eVTOLs profitably at scale while also meeting demand
  - Morgan Stanley's recent projection of the UAM Total Addressable Market worldwide through 2040 is 1/3 smaller than their 2018 projection due to these challenges

- Success of UAM depends upon the availability of electricity

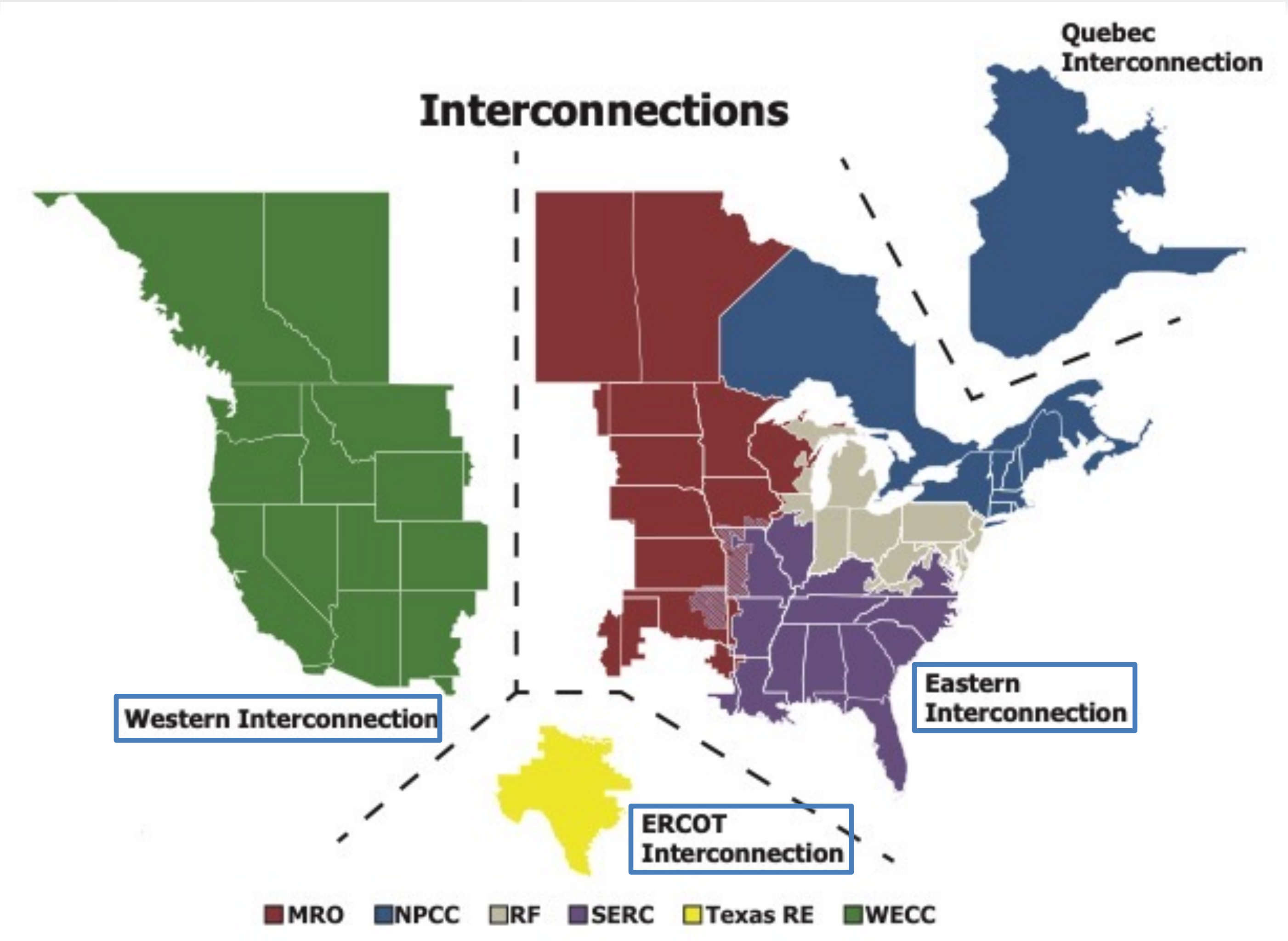
No electricity → No powered flight → No business case

  - UAM eVTOLs may not be able to charge at scale large enough for business case
    - Lack of available electrical grid capacity may constrain UAM operations below UML-5 in many U.S. metro areas before 2050
    - Ground EVs will proliferate and consume more and more electrical grid capacity over time

Available electrical grid capacity may be a formidable constraint for UAM, in addition to regulatory/policy hurdles and public support

Introduction

Electrical Grids (aka Interconnections) in North America



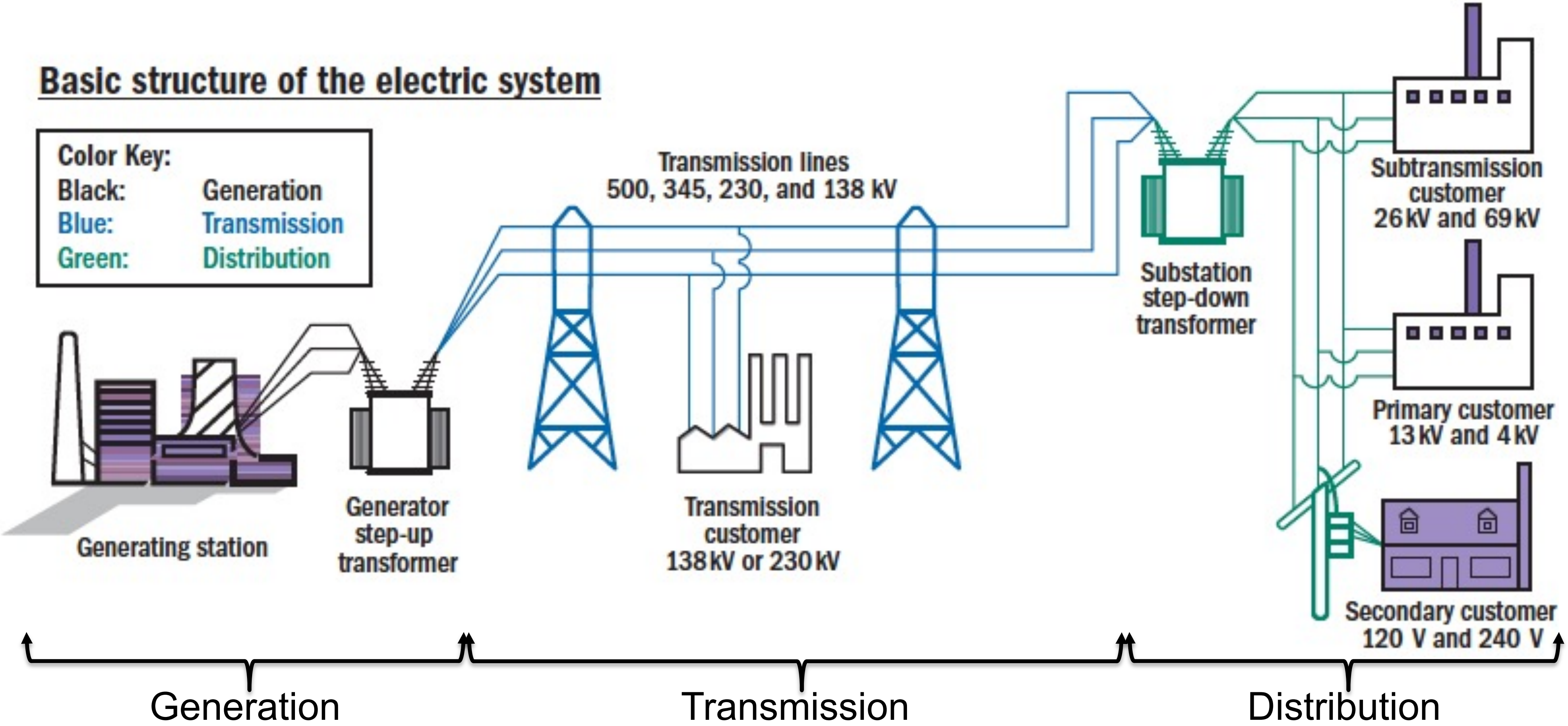
The U.S. is part of three major electrical grids

- Western Interconnection
- Eastern Interconnection
- ERCOT (Electricity Reliability Council of Texas) Interconnection

Today's analysis is for the continental U.S. (does not include Alaska, Hawaii, or Canada)

Source: North American Electricity Reliability Corporation (NERC)
https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/NERC%20Interconnections.pdf

Electrical Grid Structure



Interconnections can share some regional generation and transmission capacity, but not local distribution capacity

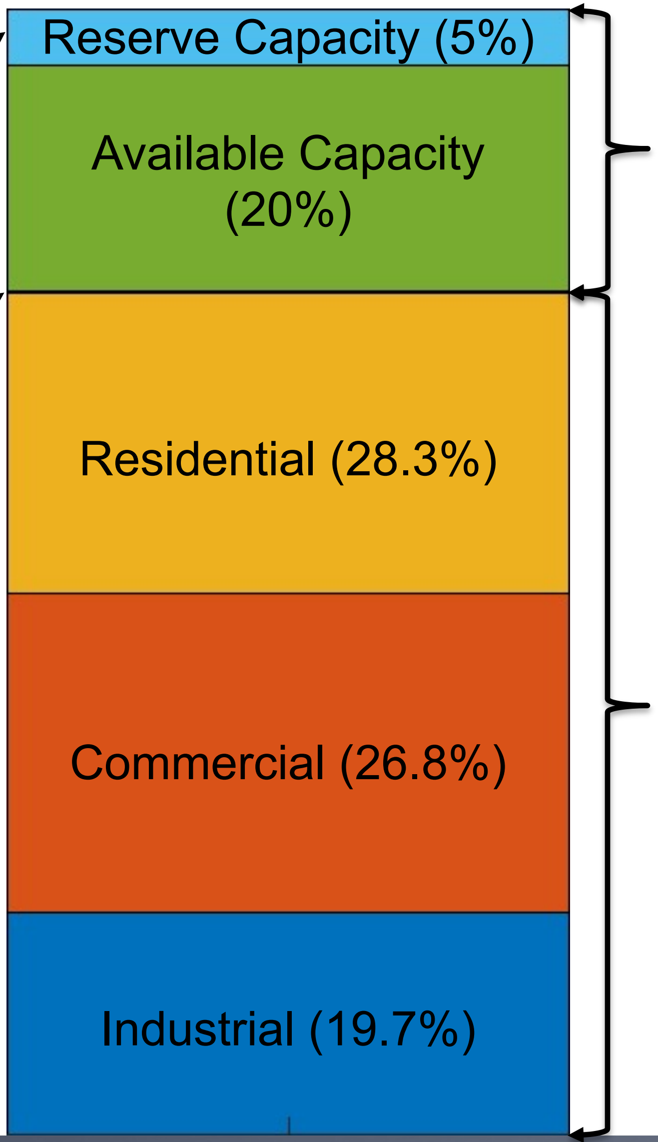
Source: https://www.nae.edu/19579/19582/21020/183082/183133/The-US-Electric-Power-System-Infrastructure-and-Its-Vulnerabilities

U.S. Electrical Grid Utilization (2019)

- Assume for maintenance, contingencies, etc.
- Based on historical high electrical grid utilization of ~95% (~1970 and 2000)

Transportation (0.15%)
- Expected to grow to 11.9% by the year 2050
- Projection only includes ground transportation

- Peak ground EV electricity usage occurs in early evening
- UAM trips and charging also expected to have a peak during this time



2019 unutilized capacity: 25%

This analysis is on the sufficiency of available electrical grid capacity for UAM

2019 utilized capacity: 75%

Source (electrical grid utilization): Federal Reserve Bank of St. Louis https://fred.stlouisfed.org/series/CAPUTLG2211S#0

Source (electricity usage): U.S. Energy Information Administration https://www.eia.gov/electricity/annual/html/epa_02_02.html

Source (electricity usage projection): National Renewable Energy Laboratory: https://www.nrel.gov/docs/fy18osti/71500.pdf https://data.nrel.gov/submissions/90

Source (peak ground EV electricity usage): https://www.energy.gov/sites/prod/files/2019/12/f69/GITT%20ISATT%20EVs%20at%20Scale%20Grid%20Summary%20Report%20FINAL%20Nov2019.pdf

Variables Modeled and their Ranges

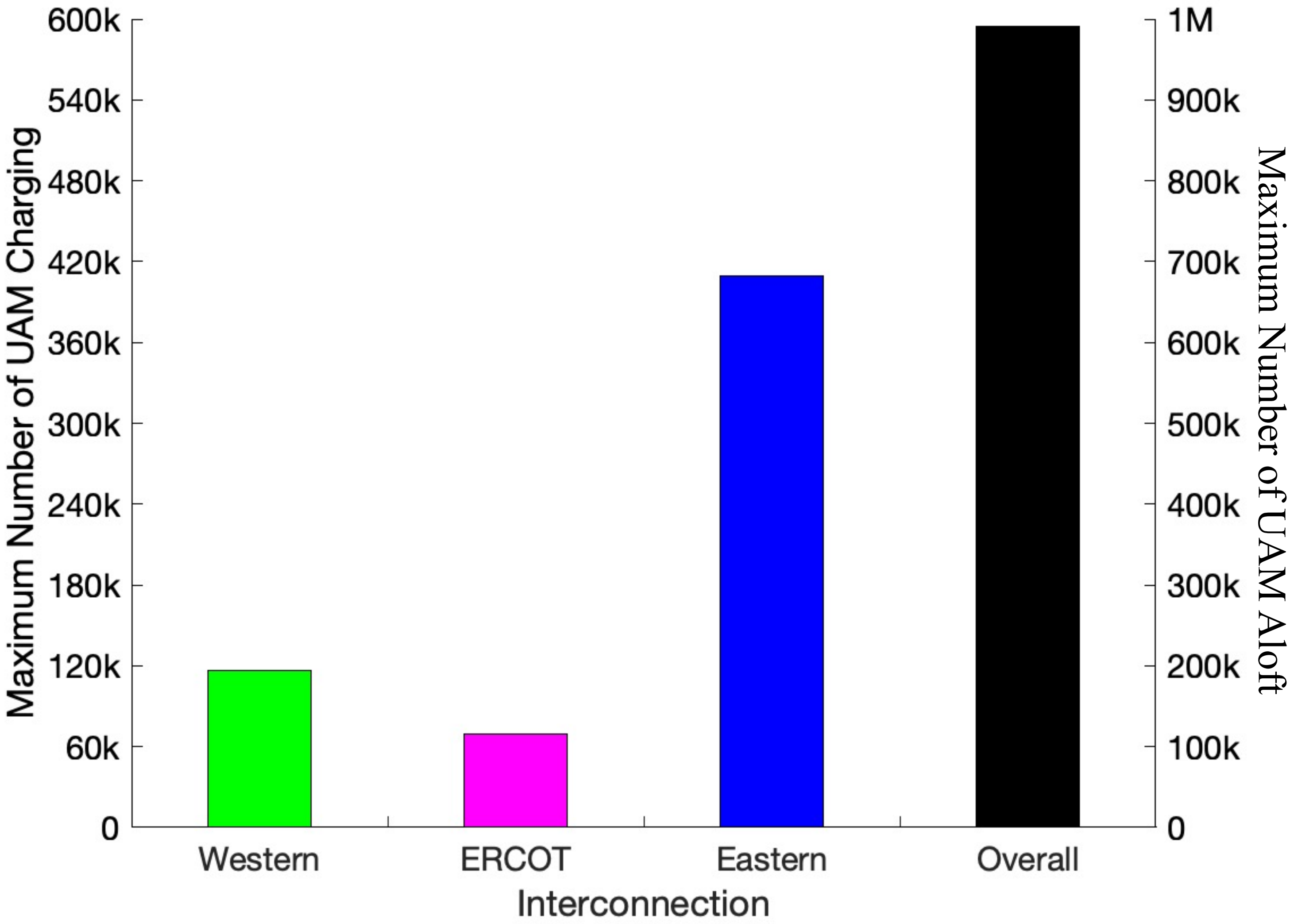
Variable	Baseline Value	Range of Values in Sensitivity Analysis	Data Source(s)
Available electrical grid capacity	20%	0%-50%	Federal Reserve Bank of St. Louis; eia U.S. Energy Information Administration
Electricity generation capacity growth rate	1.54% (per annum; base scenario)	1.25%-2%	eia U.S. Energy Information Administration
Population growth rate	0.52% (per annum; main series)	0.35%-0.75%	United States Census Bureau
Ground EV ownership	40% (low among cluster of estimates)	5-50%	U.S. Department of Energy; Bloomberg New Energy Finance; IHS Markit
Ground EV charging power	7.2 kW (common Level-2 charging)	4.8-9.6 kW	U.S. Department of Energy
Ground EV peak charging	20%	5-25%	U.S. Department of Energy; USDRIVE
UAM charging power	400 kW; RVLT quadrotor eVTOL; 7-min recharge after 20-nmi flight at 130 kts	200 kW-600 kW	Black & Veatch; 

Values from industry and government sources
Conducted sensitivity analysis on each variable

Analysis by Electrical Interconnection (Grid)

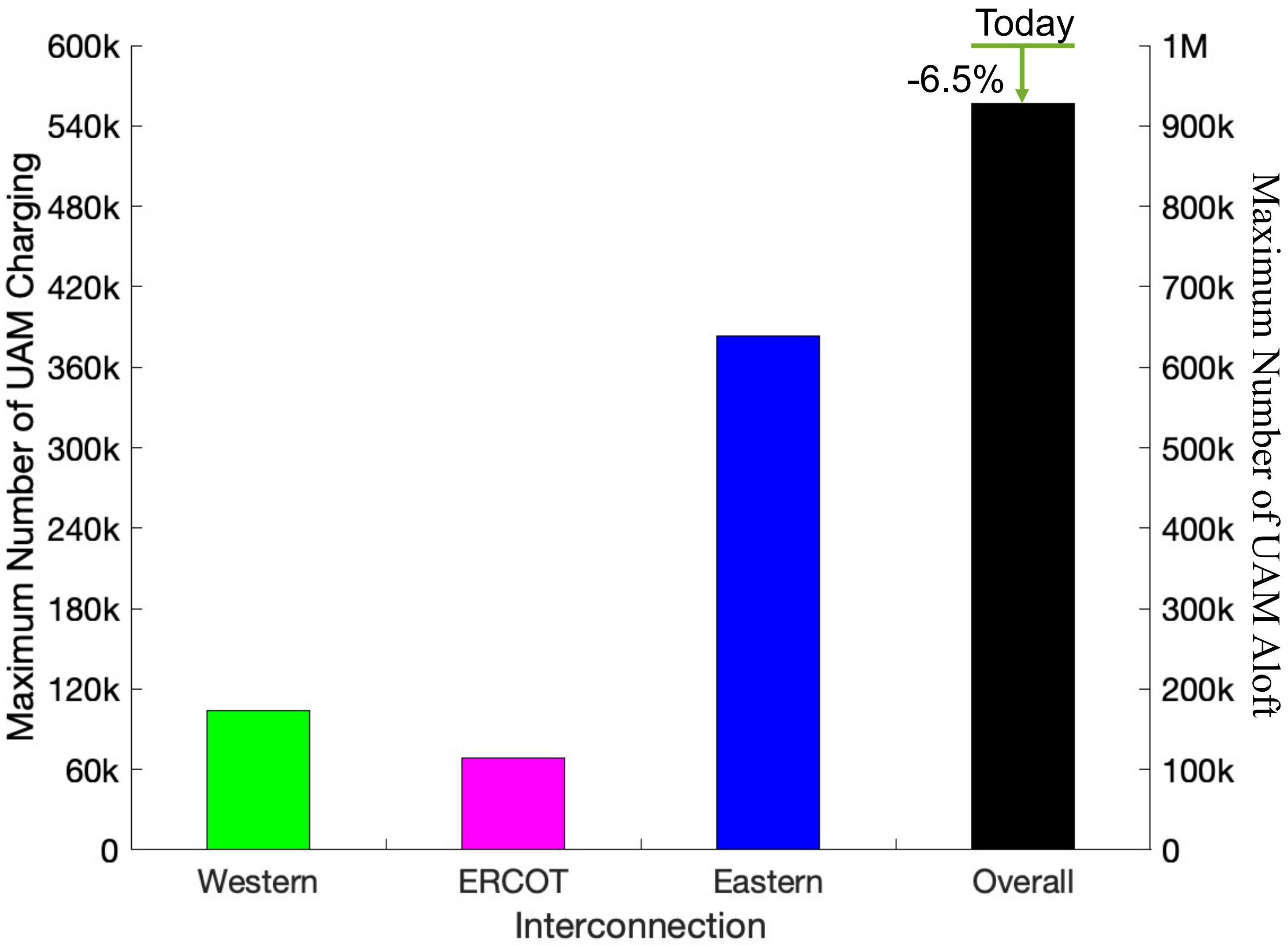
	Without ground EVs	With ground EVs
Analysis by electrical interconnection (grid) • Electricity can be shared between metro areas • Best case	1 599,818 UAM charging (today max)	2 475,177 UAM charging (2050 max)
Analysis by metro area (top 15; extending to top 40) • Electricity cannot be shared between metro areas • Worst case	3 159,429 UAM charging (today max)	4 94,541 UAM charging (2050 max)

Estimated Maximum Number of UAM Operations Possible—Today



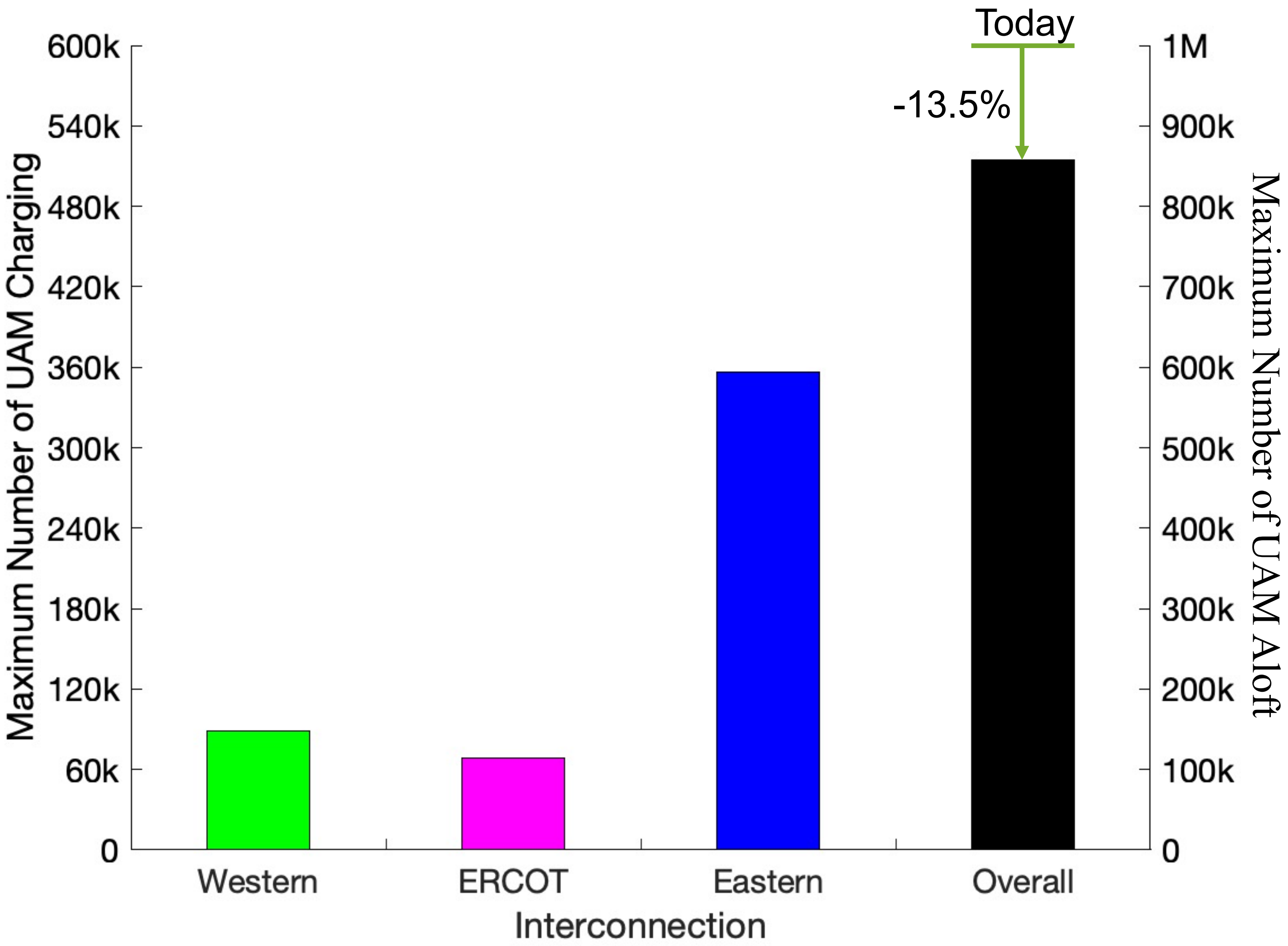
- The analysis here only has a ground EV fleet of 0.5%
- The impact of ground EVs on the maximum number of UAM operations possible today is small
- Of all the UAM in an interconnection
  - 50% are aloft
  - 30% are recharging at vertiport
  - 20% are parked at vertiport
- For example, in the CONUS today, there is available electrical grid capacity for 600k UAM to be charging simultaneously and 1M UAM to be aloft at the same time

Estimated Maximum Number of UAM Operations Possible—2030



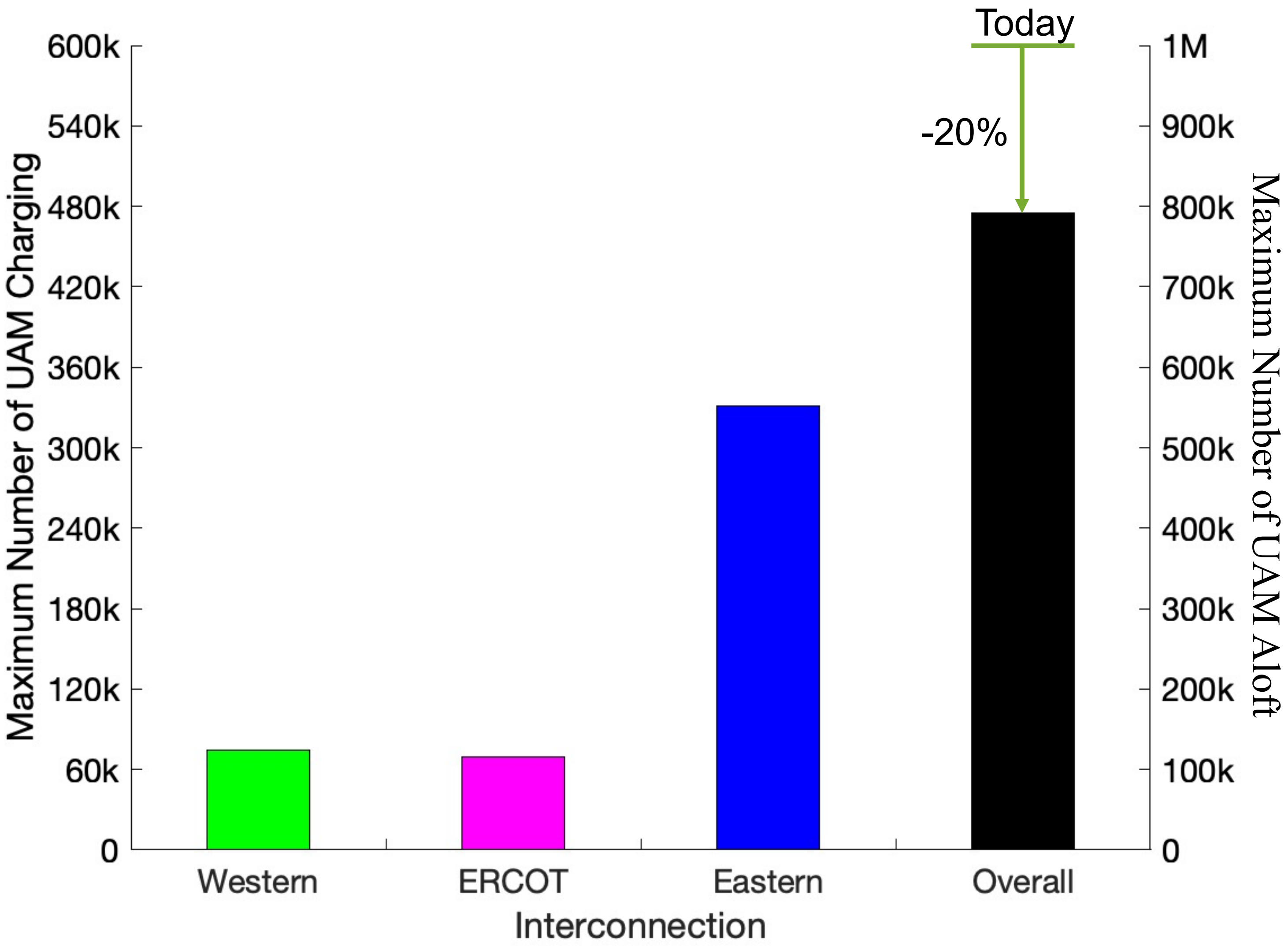
- The analysis here has a <u>ground EV fleet of 12.8%</u>
- Proliferation of ground EVs will consume more of the available electrical grid capacity

Estimated Maximum Number of UAM Operations Possible—2040



- The analysis here has a ground EV fleet of 26.4%
- Proliferation of ground EVs will consume even more of the available electrical grid capacity

Estimated Maximum Number of UAM Operations Possible—2050

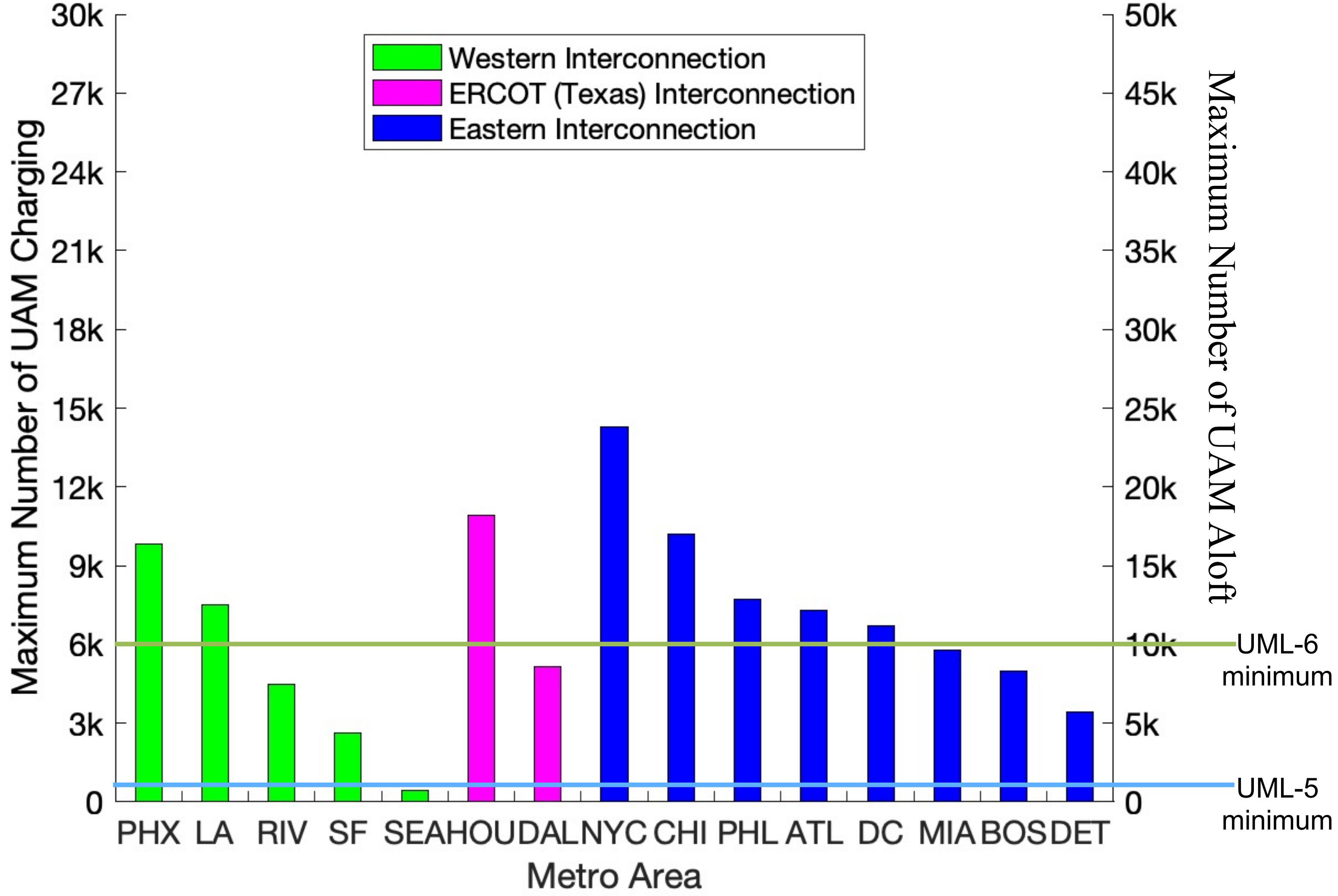


- The analysis here has a <u>ground EV fleet of 40%</u>
- Proliferation of ground EVs is estimated to reduce the maximum number of UAM operations possible in 2050 by 21%
- This is a best-case scenario in which electricity <u>can</u> be transmitted and distributed within each interconnection as needed
- This may require as much as
  - $1.7T investments to remove power distribution constraints
  - $0.7T to increase transmission capacity

Analysis by Metro Area

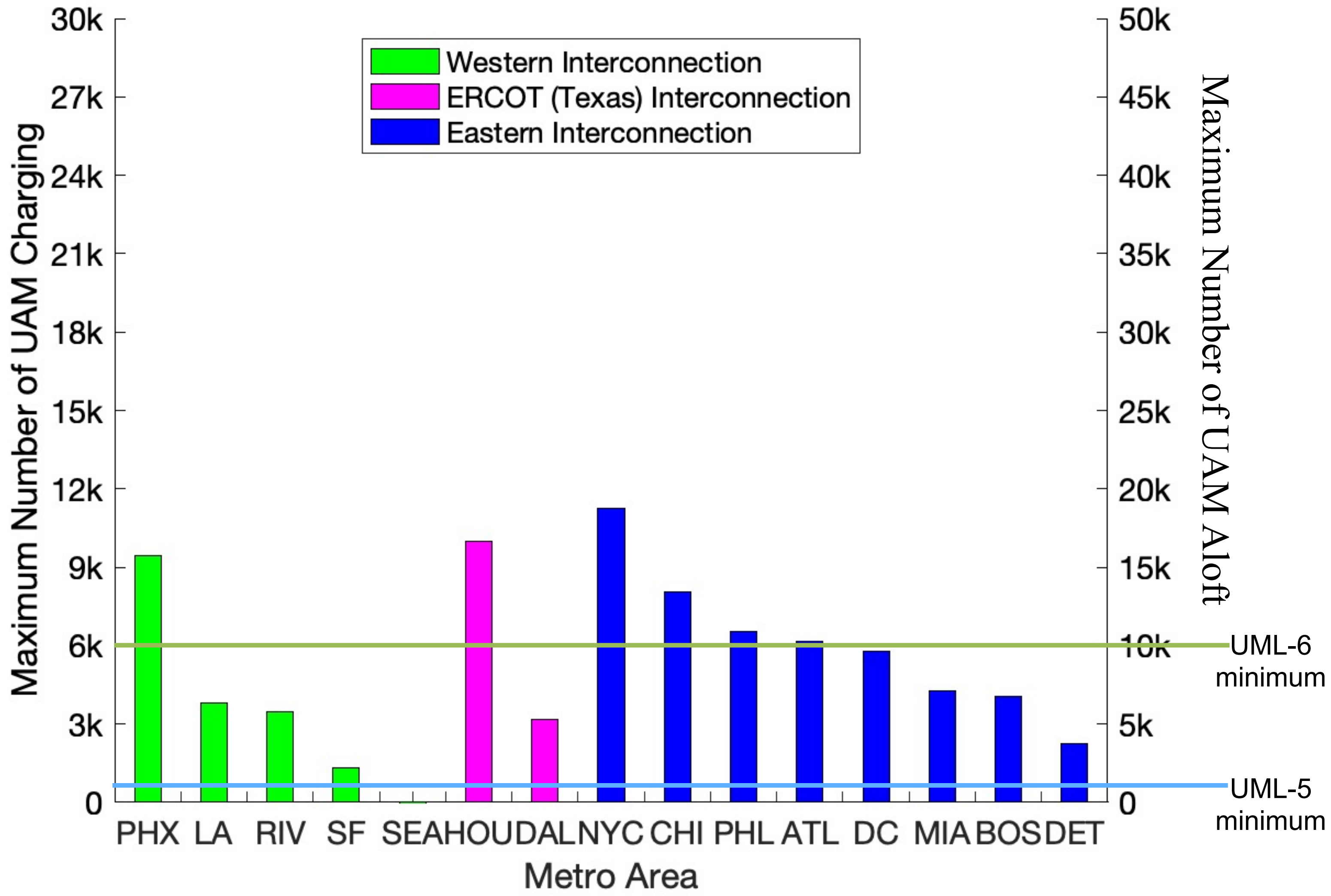
	Without ground EVs	With ground EVs
Analysis by electrical interconnection (grid) • Electricity can be shared between metro areas • Best case	1 599,818 UAM charging (today max)	2 475,177 UAM charging (2050 max)
Analysis by metro area • Electricity cannot be shared between metro areas • Worst case	3 159,429 UAM charging (today max)	4 94,541 UAM charging (2050 max)

Estimated Maximum Number of UAM Operations Possible—Today



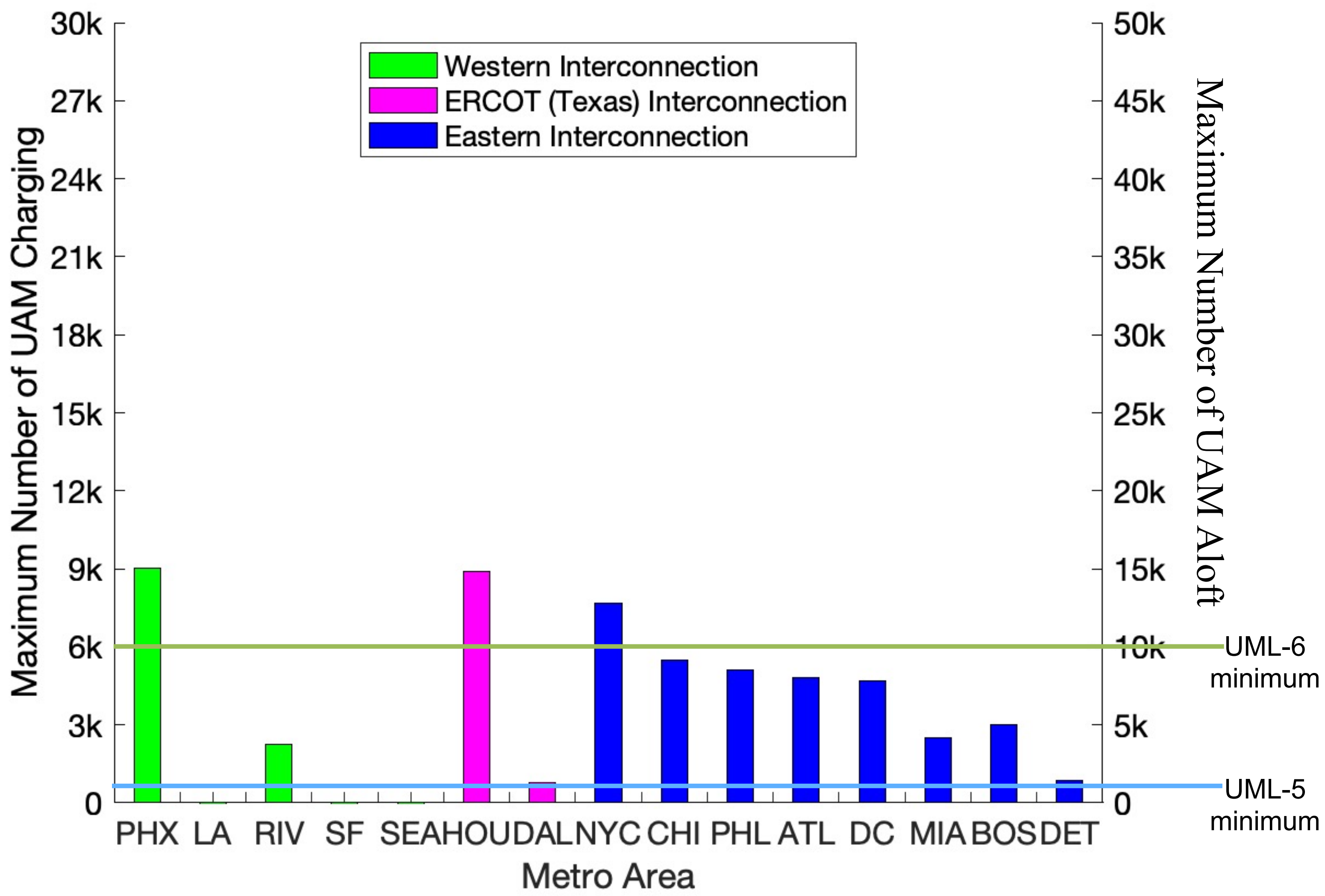
- The analysis here only has a ground EV fleet of 0.5%
- The impact of ground EVs on the maximum number of UAM operations possible today is small
- There may only be available electrical grid capacity for UML-6 operations in eight U.S. metro areas today **if** electricity cannot be transmitted and distributed within each interconnection as needed

Estimated Maximum Number of UAM Operations Possible—2030



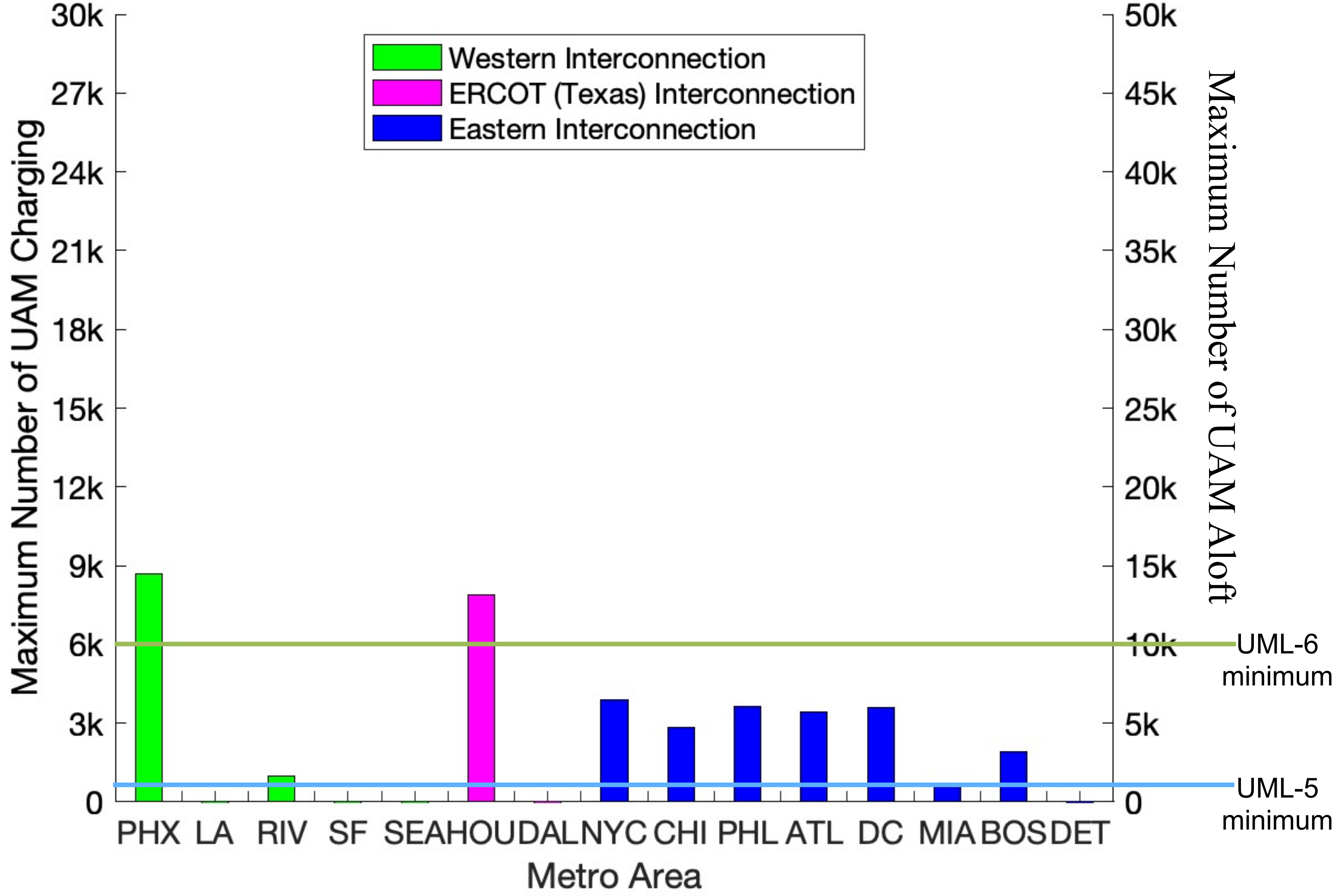
- The analysis here has a <u>ground EV fleet of 12.8%</u>
- Proliferation of ground EVs will consume more of the available electrical grid capacity
- Due to lack of power, additional metro areas may no longer be able to conduct UML-6 operations
- Some metro areas may not have available electrical grid capacity to conduct any UAM operations

Estimated Maximum Number of UAM Operations Possible—2040



- The analysis here has a ground EV fleet of 26.4%
- Proliferation of ground EVs will consume even more of the available electrical grid capacity
- Due to lack of power, most metro areas may not be able to conduct UML-6 operations
- Additional metro areas may not have available electrical grid capacity to conduct any UAM operations

Estimated Maximum Number of UAM Operations Possible—2050



- The analysis here has a <u>ground EV fleet of 40%</u>
- Proliferation of ground EVs will consume even more of the available electrical grid capacity
- Due to lack of power, nearly all metro areas may not be able to conduct UML-6 operations
- Even more metro areas may not be able to conduct any UAM operations
- This is a worst-case scenario in which electricity <u>cannot</u> be transmitted and distributed within each interconnection as needed

Trends Suggested from Sensitivity Analyses

Variable (in order from most sensitive to least)	Why the Maximum # of UAM Operations Possible may be Lower than Estimated in the Analyses	Areas/Sources of Variation
Available electrical grid capacity	Available power can be lower than national average of 20% (e.g., during periods of high demand, if electrification in general is broader and/or faster than expected)	Interconnections, metro areas, seasons, time of day, extreme weather conditions and events
UAM charging power	UAM aircraft and operations may require charging faster than the nominal 400 kW value used in this analysis	UAM vehicle type, missions, operating/environmental conditions
Ground EV peak charging	More ground EVs may need to charge to a greater extent during less-than-ideal conditions	Seasons, time of day
Ground EV ownership	Ground EV prices decrease faster than expected	Interconnections, metro areas
Ground EV charging power	Some current ground EVs and additional future ground EVs are capable of charging faster than the nominal 7.2 kW value used in this analysis	Ground EV makes and models
Electricity generation capacity growth rate	Cost of renewable electricity generation technologies decrease less than expected, overall economic growth is lower than expected	Renewable generation technology costs, economic growth
Population growth rate	Greater than expected population growth can increase the number and impact of ground EVs	Fertility, mortality, migration rates

Bottom Line and Recommendations

Bottom Line

- Many technology, infrastructure, regulatory, and acceptance challenges to conduct UAM operations with eVTOLs profitably at scale while also meeting demand

- Success of UAM depends upon the availability of electricity

  No electricity → No powered flight → No business case

- UAM eVTOLs may not be able to charge at scale large enough for business case
  - Lack of available electrical grid capacity may constrain UAM operations below UML-5 in many U.S. metro areas before 2050
  - Ground EVs will proliferate and consume more and more electrical grid capacity over time

Available electrical grid capacity may be a formidable constraint for UAM, in addition to regulatory/policy hurdles and public support

Recommendations

- Develop comprehensive estimates of UAM energy needs under expected range of
  - Missions (e.g., speed, distance, load)
  - Operating conditions (e.g., wind)
  - Requirements (e.g., maximum charging/turnaround time)

- Reduce or eliminate the need to recharge during early evening peak, such as by
  - Reducing structural mass
  - Increasing battery energy density

- Incorporate UAM requirements into metro area and utility company plans at least several years in advance (if additional infrastructure is needed)

OPERATIONS LIMITS FOR PASSENGER-CARRYING URBAN AIR MOBILITY MISSIONS

Systems Analysis Symposium | November 10, 2021

Presenter: Prof. Daniel DeLaurentis

(Team: Sai Mudumba, Hsun Chao, Apoorv Maheshwari, Brandon Sells, Nick Gunady, Prof. William Crossley)

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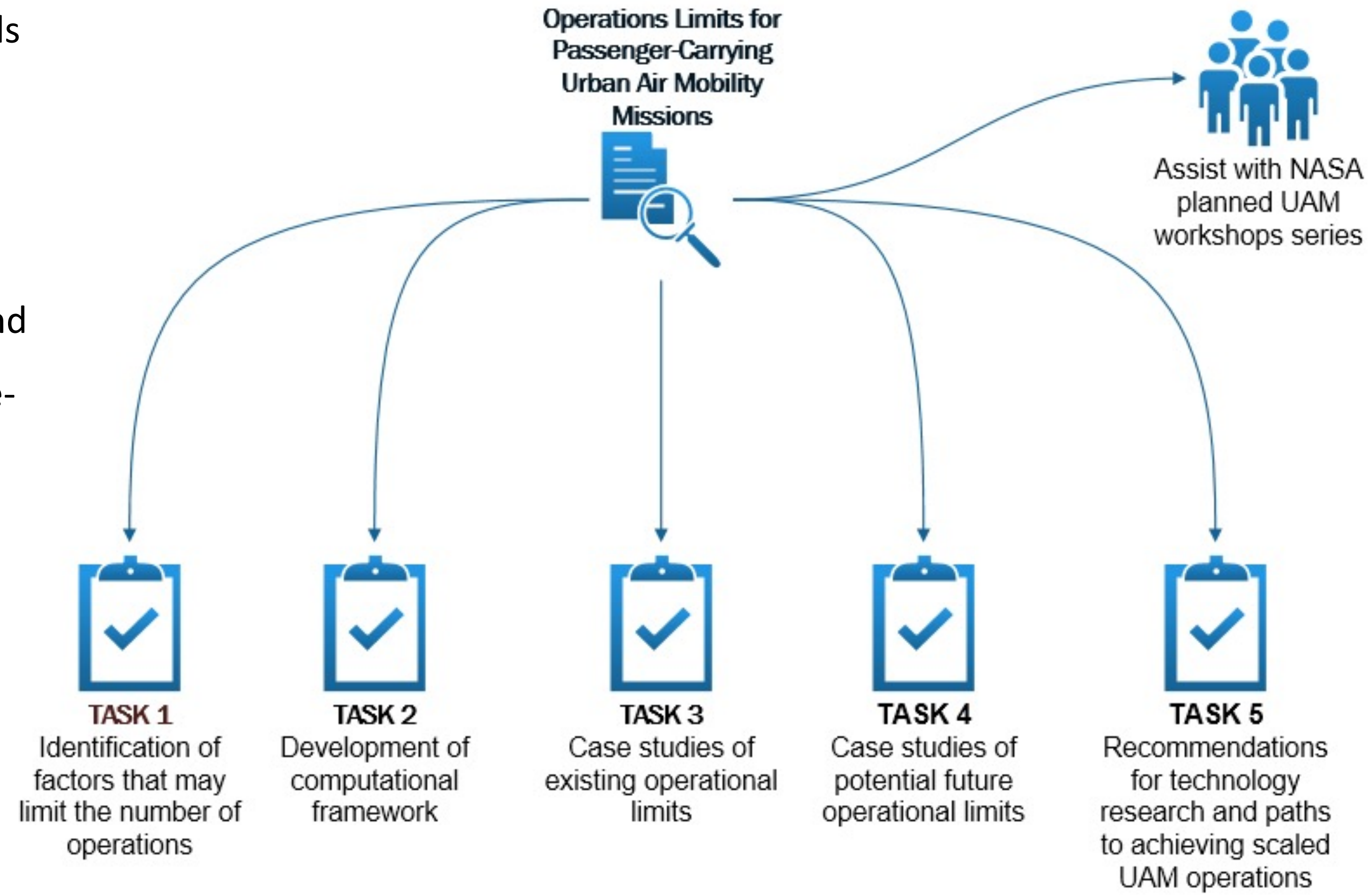
Study Motivation and Overview

Motivation

- Convergence of new technologies and new business models leading to emergence of new aviation markets, e.g., passenger-carrying ***Urban Air Mobility (UAM)***
- Important to assess the evolution of technology, infrastructure, societal acceptance, airspace integration, and many other factors to take us from the current state-of-the-art to the envisioned large-scale operations
- For near-term applications of passenger-carrying UAM and which issues will be the key "bottlenecks" limiting the scalability of early UAM operations ("Op Limits")
- Create computer model, driven by appropriate data & scenarios, to analyze significance of key Op Limits

*Overview**



*Two Metro-Areas Studied: Chicago and Dallas

Identify and Organize Potential Op Limits via "ROPE" Table

Challenge: There are many Op Limit factors, we want to organize them in a fashion that is comprehensible and that eases import to computational model.

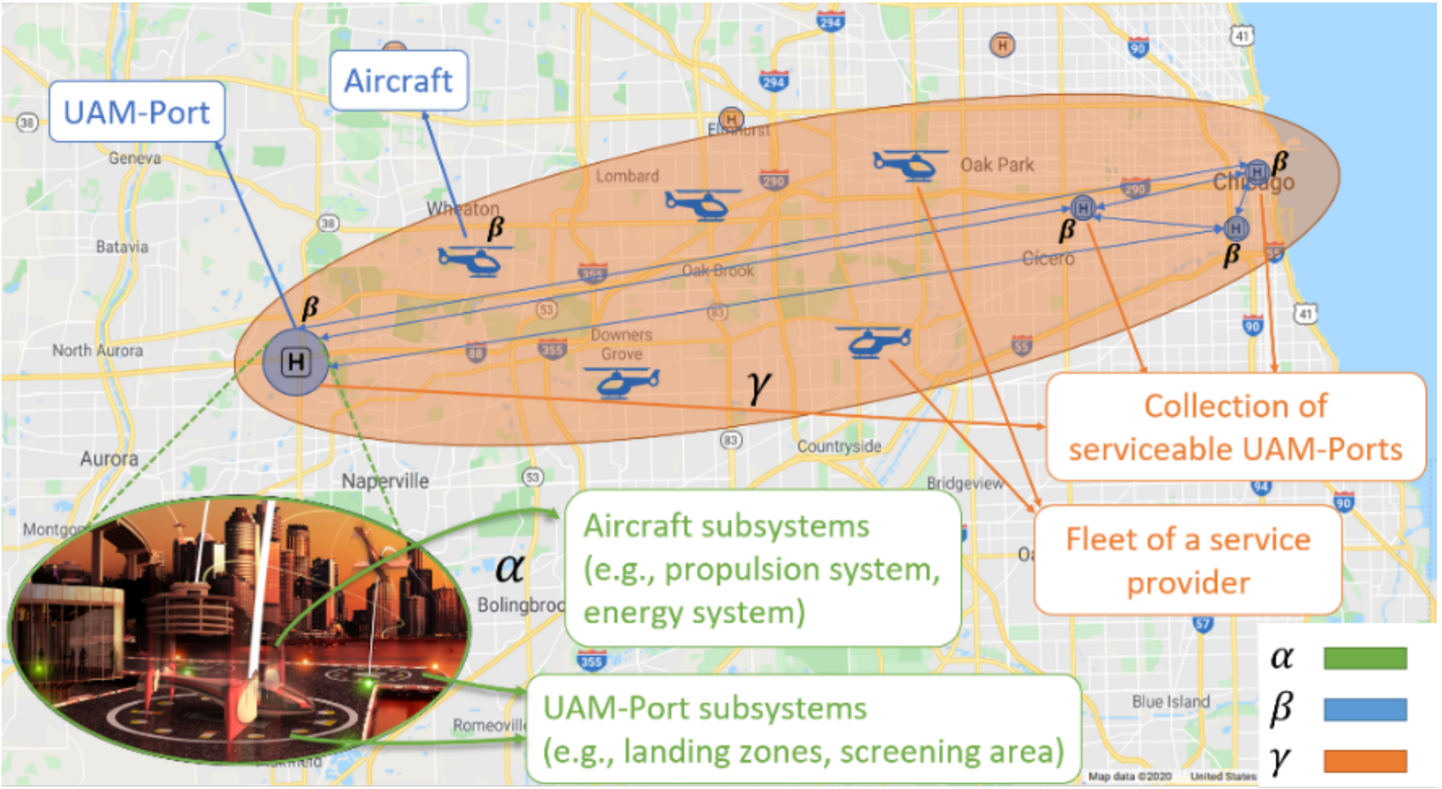
Approach: Build upon ROPE Table Methodology, a decomposition method, to examine any System-of-systems (SoS) problem

Product: Each identified Op Limit is classified based upon the category of the related system, identified as follows:

Categories	Descriptions
Resources	The entities (systems) that give physical manifestation to the system-of-systems
Operations	The application of intent to direct the activity of resources
Policies	The external constraints that impact the operations and influence intent
Economics	The behaviors and incentives of stakeholders that give intent to the SoS operation

Hierarchical Breakdown of ROPE Table Elements

- ROPE table enables view on key dimension of categorization: hierarchy level of an entity in SoS
- Identifying appropriate hierarchy level is essential to problem scoping, identification of interdependencies, and making reasonable assumptions for modeling



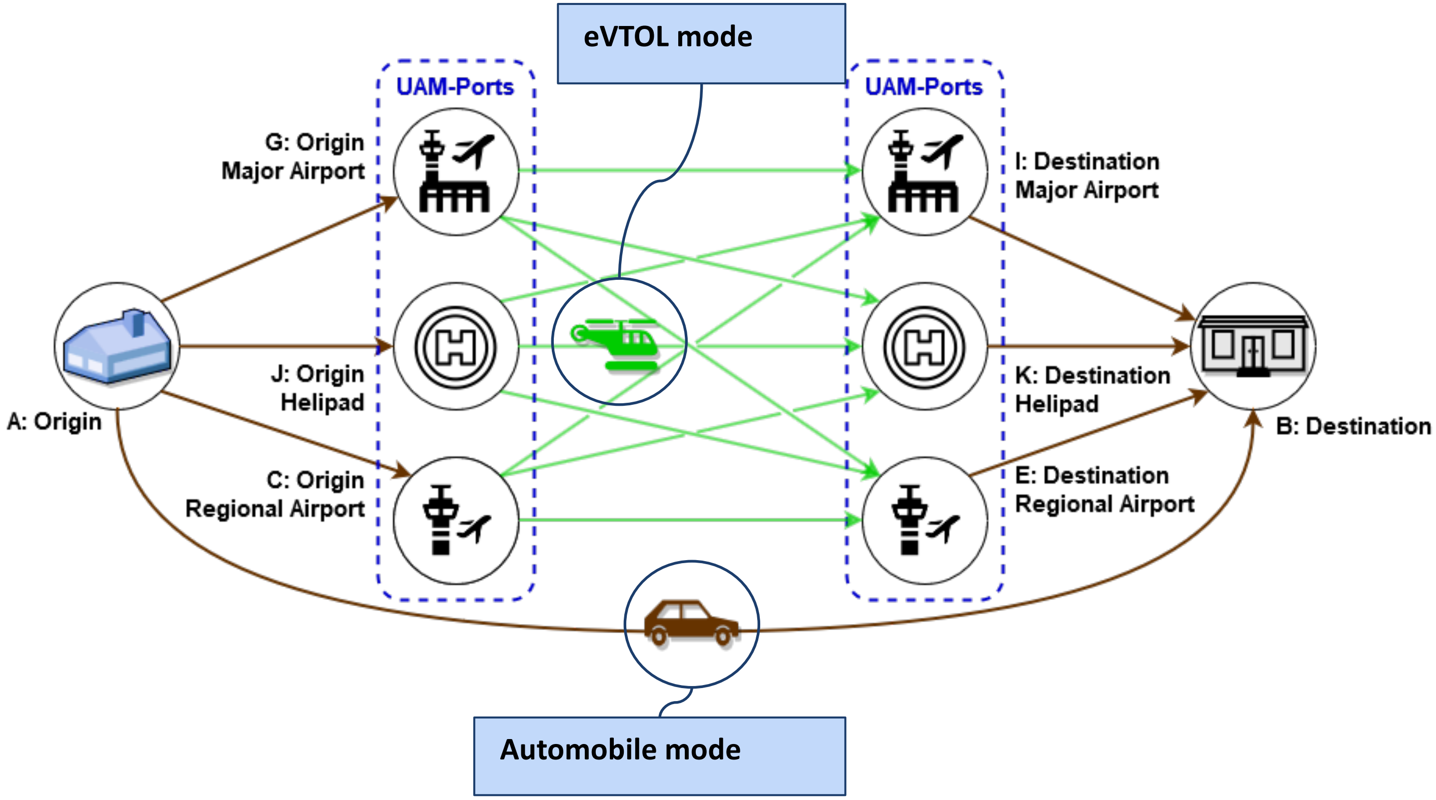
Background Map data © 2020 Google

ROPE table citation: Maheshwari, A., Mudumba, S., Sells, B., Chao, H., DeLaurentis, D., Crossley, W. (2020). Urban Air Mobility ROPE Table: A Decomposition Tool to Identify and Organize Potential Operational Limits. Purdue University Research Repository. doi:10.4231/81N6-EV29 https://purr.purdue.edu/publications/3465/1

Unit of Analyses- the Urban Trip

Transportation network model composes of electric vertical takeoff and landing (eVTOL) and automobile modes

- **Green edges** are trips made by eVTOL vehicles
- **Brown edges** are trips made by automobiles
- UAM trips consist of both automobile and eVTOL modes (e.g., branch: AJKB)
- Automobile trips are conventional, ground-based trips (e.g., branch: AB)



Note: *UAM-Ports include only existing, publicly-owned infrastructures (i.e., major, regional airports, and heliports) in a metropolitan area*

Effective Cost Metric Identifies UAM-preferred Trips

Effective Cost Metric Definition and UAM-preferred Trips Estimation

- Effective cost metric definition:
  - $Cost_{eff,i} = Cost_{oper,i} + Cost_{time,i}$
  - $Cost_{time,i} = time_{trip,i} * value_{time}$

$Cost_{eff,i}$: effective cost of mode i $\left[\frac{\$}{hr}\right]$

$Cost_{oper,i}$: $operating\ cost\ of\ mode\ i\ \left[\frac{\$}{hr}\right]$

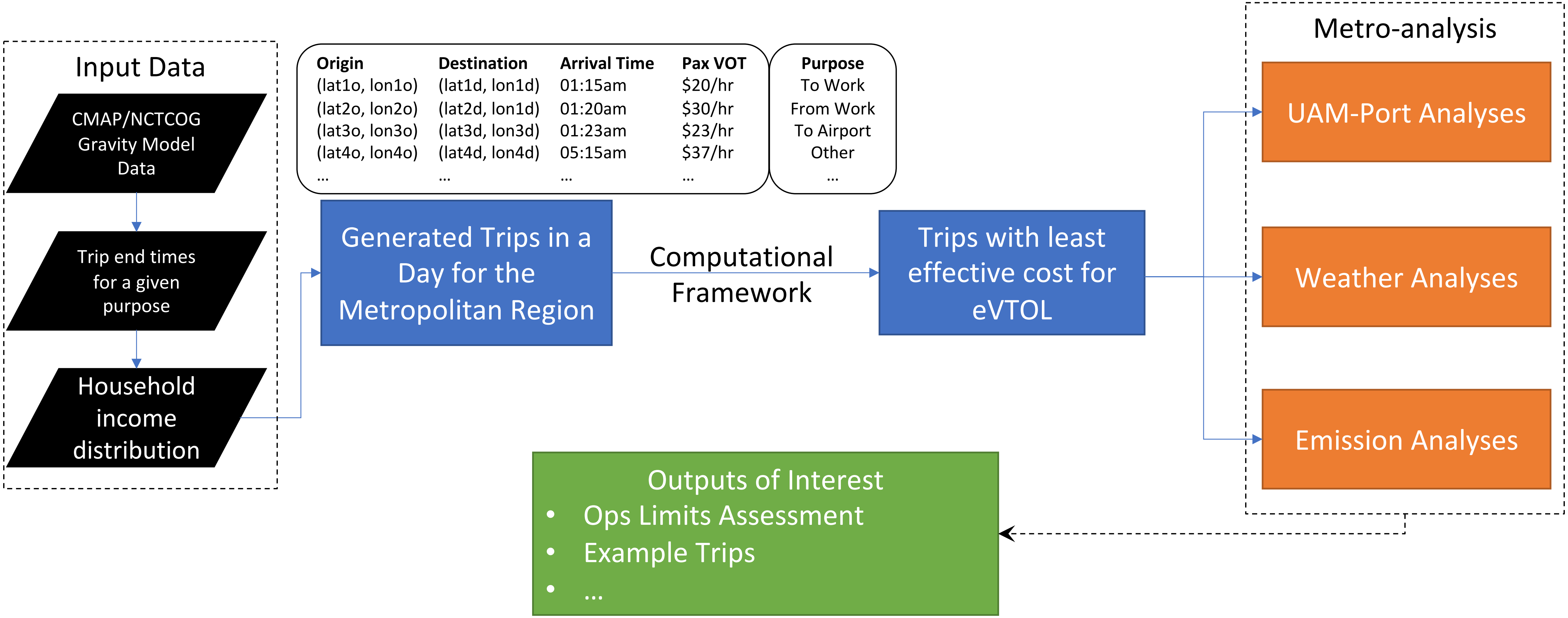
$Cost_{time,i}$: $time\ cost\ of\ mode\ i\ \left[\frac{\$}{hr}\right]$

$time_{trip,i}$: $trip\ time\ of\ mode\ i\ [hr]$

$value_{time}$: $individual's\ value\ of\ time\ [\frac{\$}{hr}]$

- Effective cost metric is used to determine the mode of travel with the least effective cost
- A trip is called UAM-preferred when the UAM trip has a lower effective cost than the equivalent automobile trip

Computational Framework Analyzes Op Limits



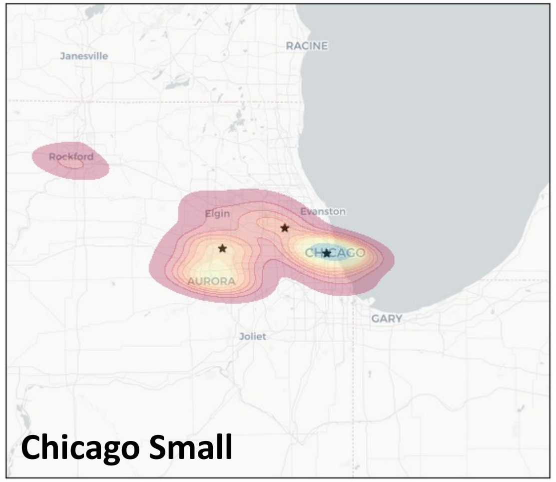
Chicago Metropolitan Agency for Planning (CMAP)
North Central Texas Council of Governments (NCTCOG)

UAM Preferred Trips For Different Network Sizes (Launch)

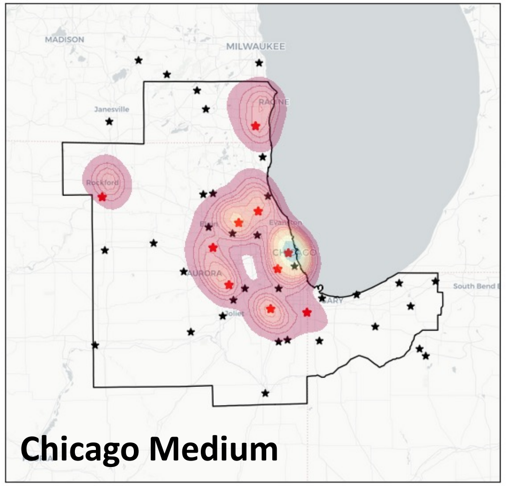
Chicago Commute Trips: 6,221,968

Dallas Commute Trips: 5,306,336

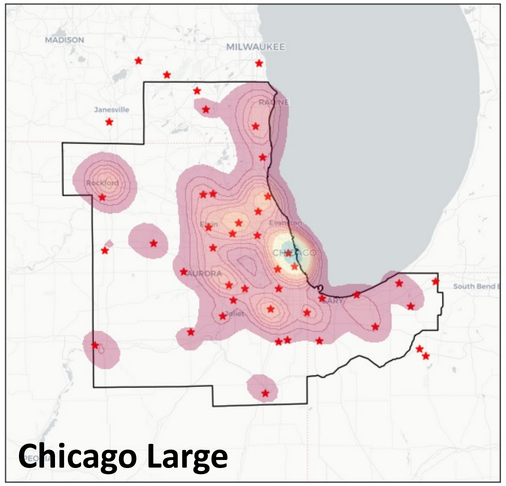
	Small (3 Vertiports)	Medium (10 Vertiports)	Large (All existing infra)
Chicago	397	3504	6305
Dallas	853	2330	6928



Chicago Small

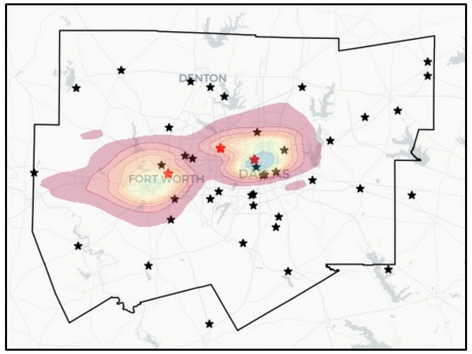


Chicago Medium

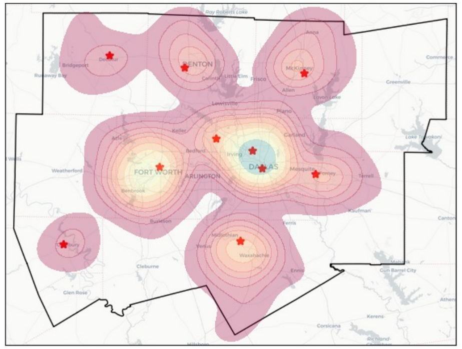


Chicago Large

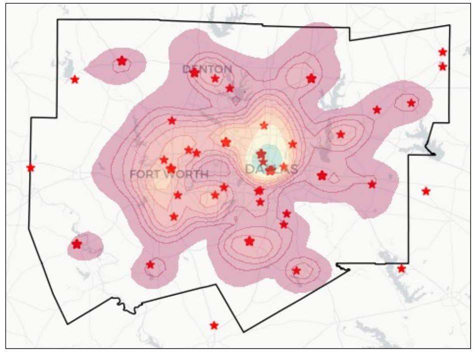
Dallas Small



Dallas Medium



Dallas Large



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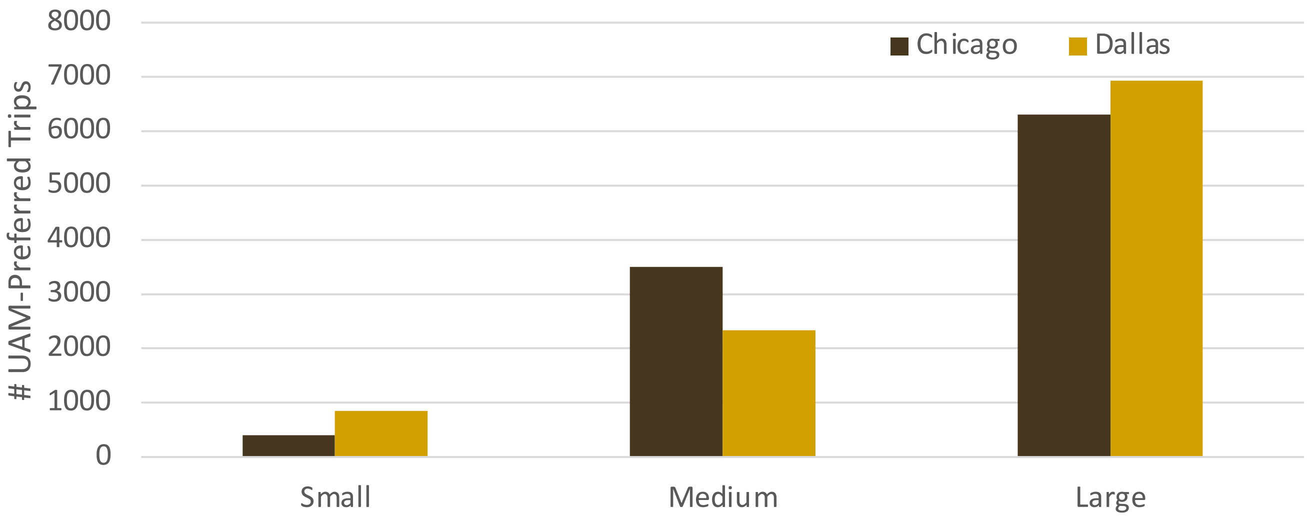
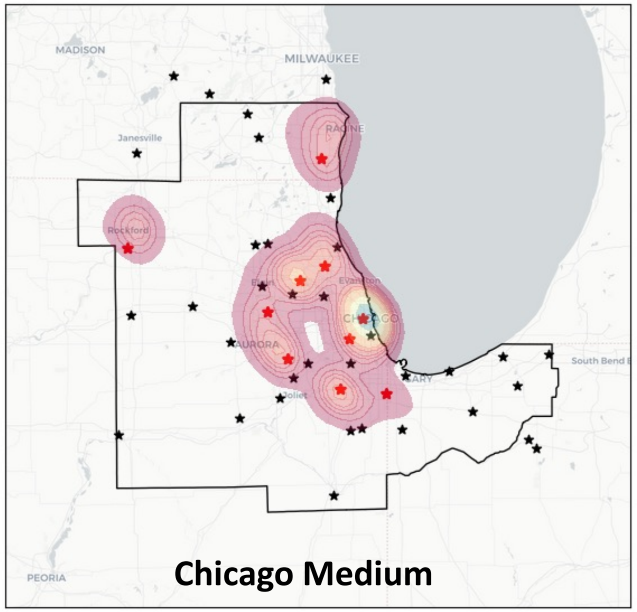
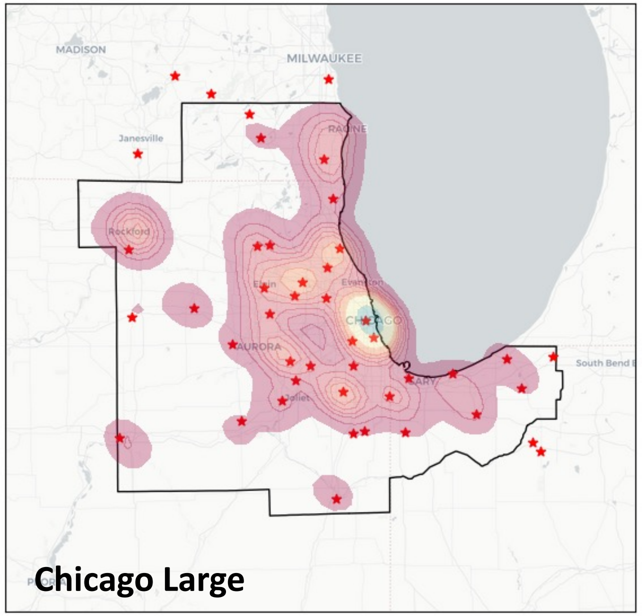
Note: Launch Scenario UAM Operation Cost $605/hr + 1pax

Key Observations from # UAM Preferred Trips

- #Trips increase with the number of vertiports; seems to follow a non-linear relationship
- Vertiport siting plays a significant role
  - Most trips concentrated around the vertiport locations
  - A few vertiports had quite high concentration of trips, even with high-cost launch scenario
  - Implications for congestion management







Background map data for all figures © OpenStreetMap contributors

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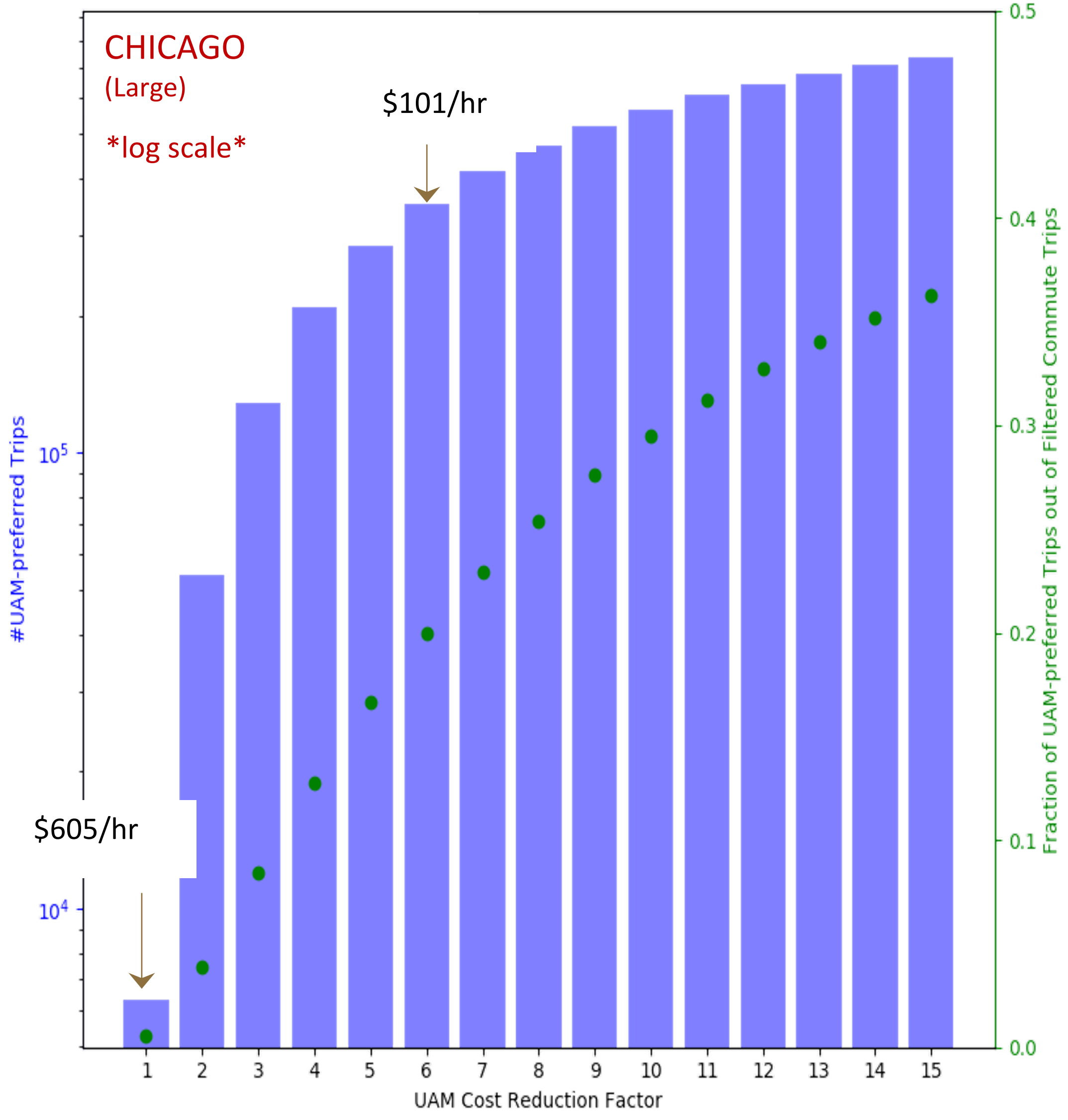
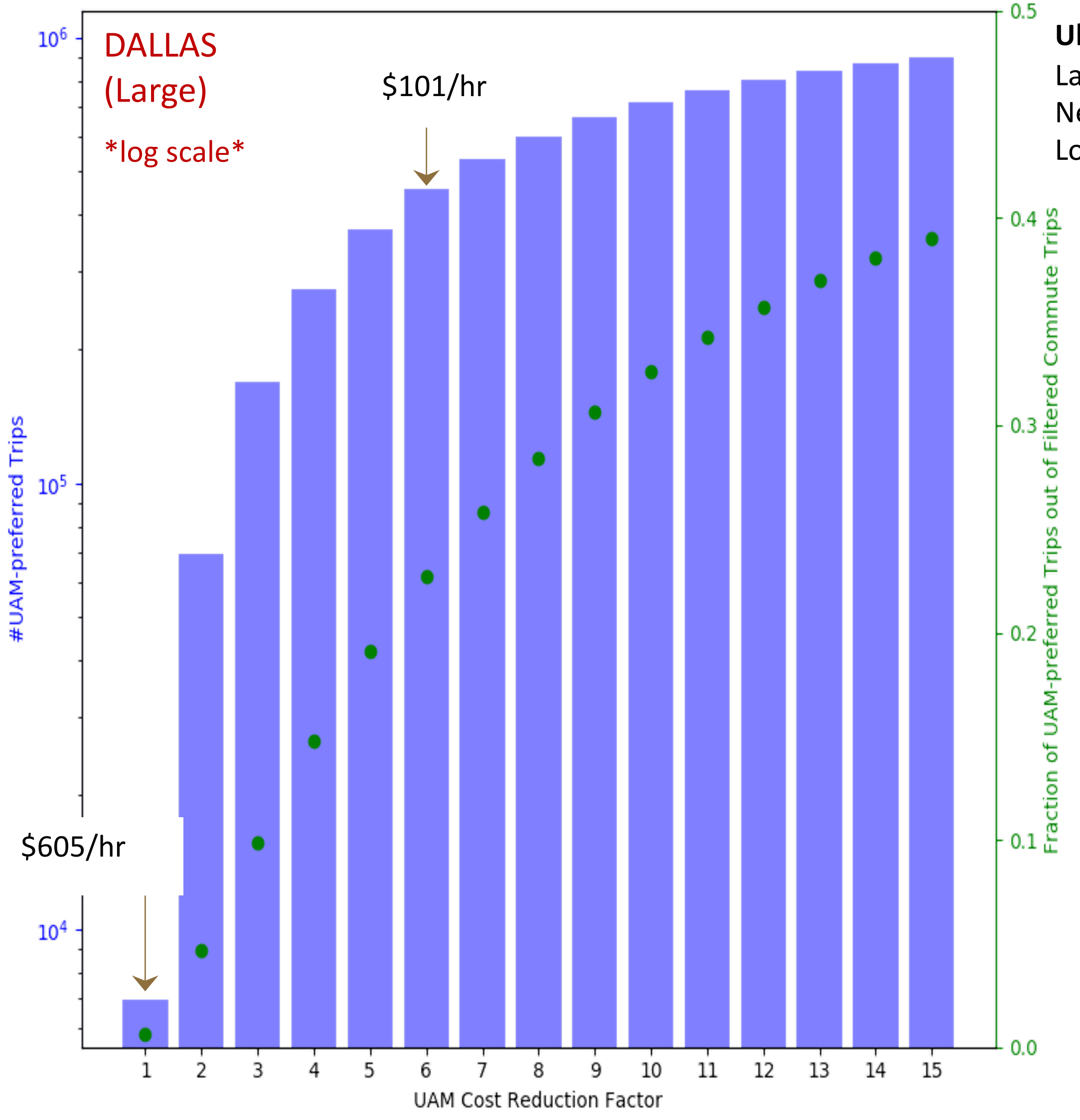
Sensitivity Studies w/ Trip Cost and Related Factors

Impact of UAM Cost Reduction on # of UAM-preferred Trips



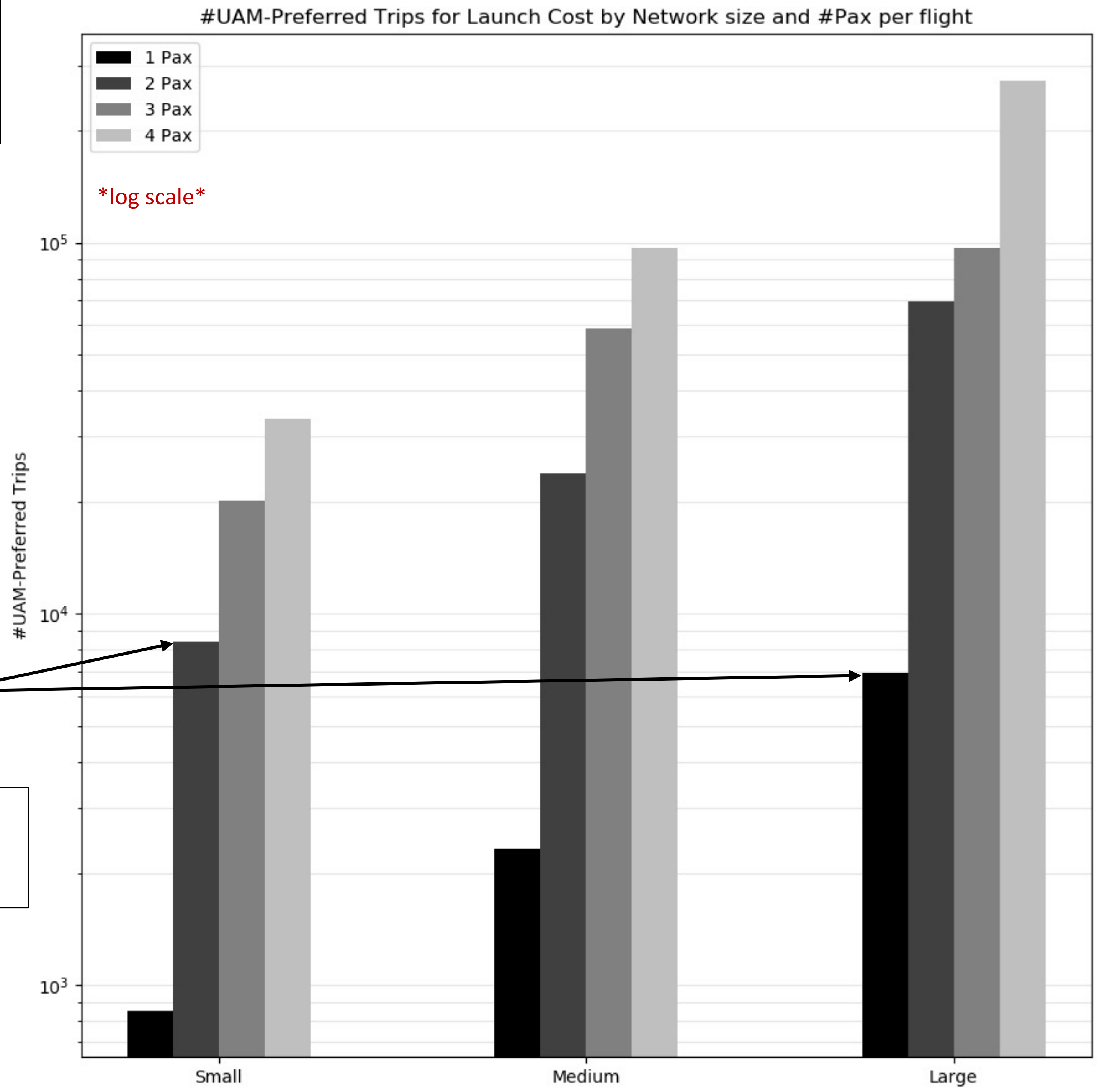


Uber Elevate Scenarios
Launch: $605/hr + 1pax
Near: $583/hr + 3pax
Long: $186/hr + 4pax

Filtered Trips
Trips with different UAM-ports closest to the origin and destination

Impact of Ridesharing (DALLAS)

- Assuming the direct impact to the operating cost due to ride-sharing, #UAM-preferred trips are calculated
- For example, operating cost for
  - 1 pax → $605/hr
  - 2 pax → $303/hr (=605/2)
- Surprisingly, increasing the #pax per flight to 2 produces a larger impact as compared to operating at all available infrastructure locations with ridesharing not enabled!



Enabling ride sharing will be key to lowering UAM operating cost to make it a real market

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WEATHER ANALYSIS

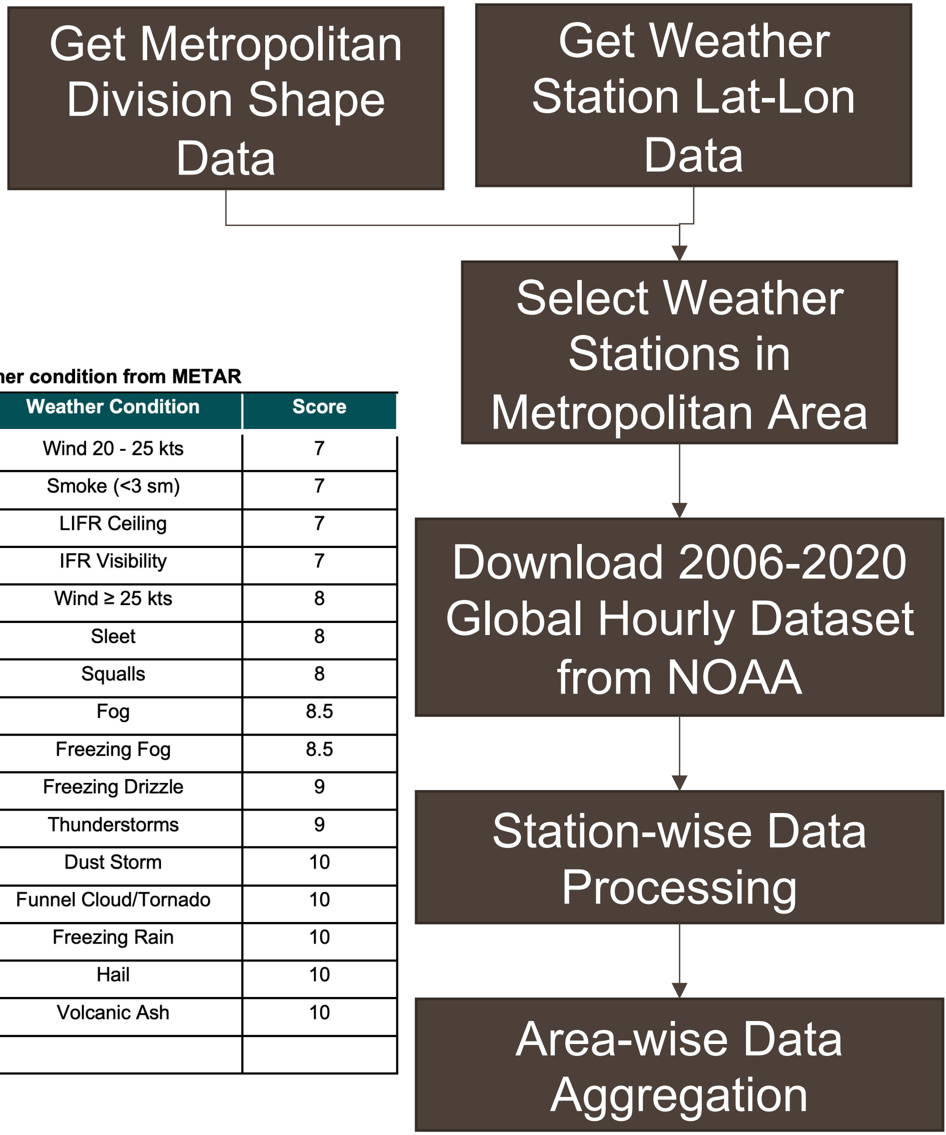
Overview and Results Snapshot

Quantifying Weather Impact

- **Weather data source:**
  - National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD)
  - NOAA ISD contains worldwide hourly ground weather data
- **UAM weather impact scoring:**
  - Based on UAM Market Study Report* impact score table
    - 33 unique weather conditions
    - Score from 1 (good) to 10 (bad)
  - Impact Score (IS) is used to assess the level of UAM operational impact by weather phenomena

Table 10: Impact Scores for each weather condition from METAR

Weather Condition	Score	Weather Condition	Score
Drizzle	1	Wind 20 - 25 kts	7
Rain	1	Smoke (<3 sm)	7
MVFR Ceiling	1	LIFR Ceiling	7
Haze	1	IFR Visibility	7
Ice Crystals	1	Wind ≥ 25 kts	8
Sand Whirls	1	Sleet	8
Sand	2	Squalls	8
Snow Grains	2	Fog	8.5
Temp ≤ 32°F	3	Freezing Fog	8.5
Temp ≥ 100°F	3	Freezing Drizzle	9
IFR Ceiling	4	Thunderstorms	9
Dust	5	Dust Storm	10
Snow	5	Funnel Cloud/Tornado	10
Sandstorm	5	Freezing Rain	10
Wind 15 - 20 kts	5	Hail	10
Mist (vis >= 5/8 sm)	6	Volcanic Ash	10
Snow Pellets	6		



Booz Allen Hamilton. (2018). *Final Report Urban Air Mobility (UAM) Market Study*. Retrieved from https://ntrs.nasa.gov/api/citations/20190001472/downloads/20190001472.pdf

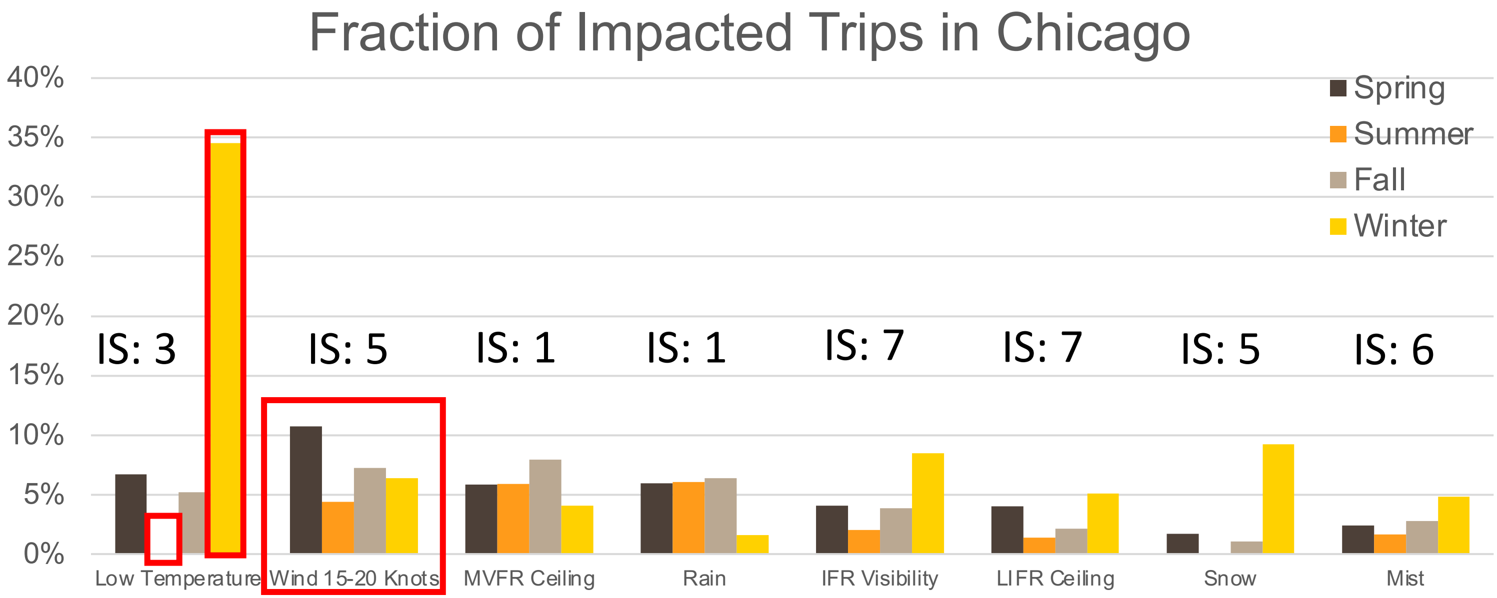
Weather Condition Ranking - Results

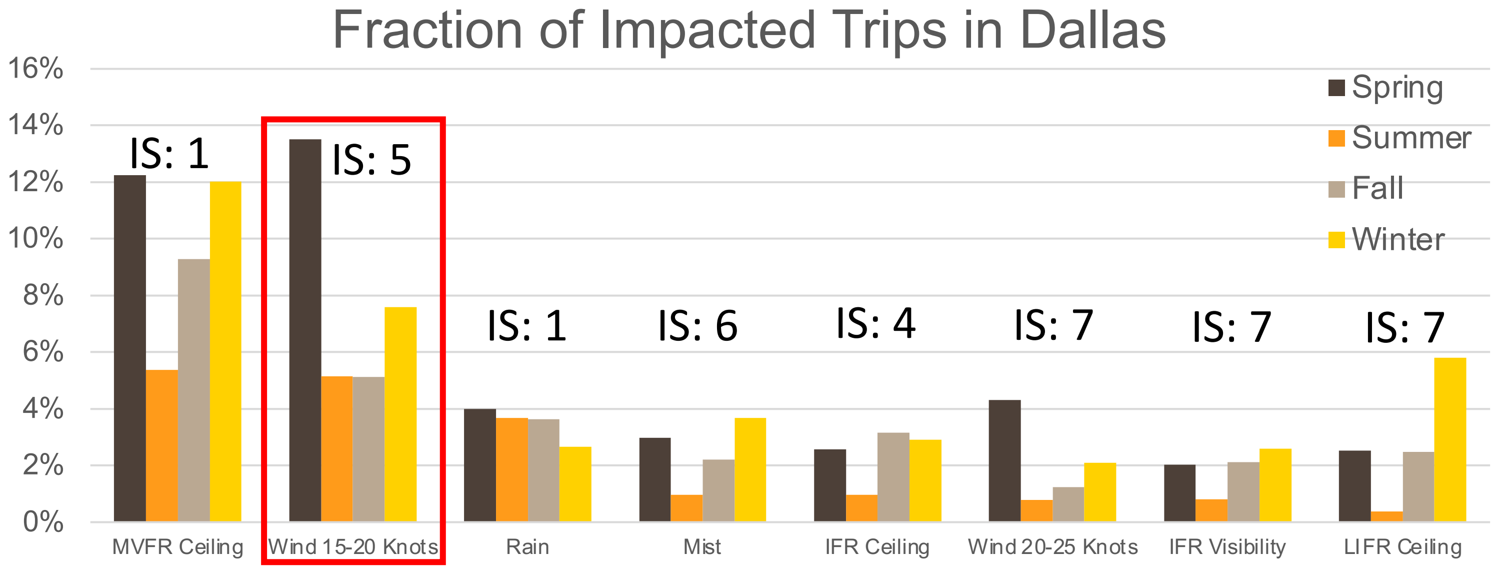
Wind 15-20 knots is the most frequently occurring weather condition in both cities

- Implies technology solution should be integrated onboard the vehicle

Low temperatures in Winter is important for Chicago

- Higher number of trips impacted in winter; 0 impacted in summer
- Modular technology solution might be suitable for this weather condition





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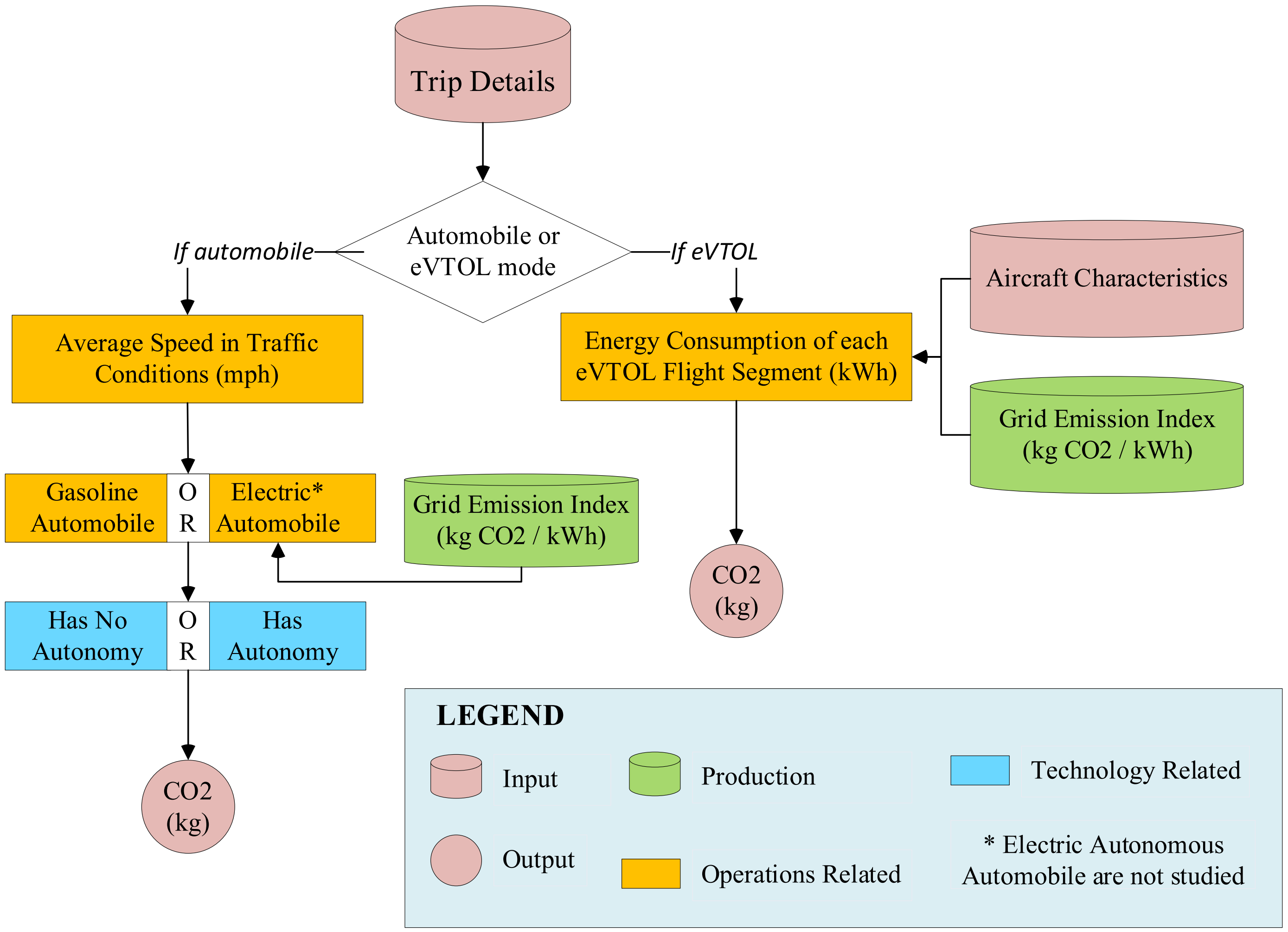
EMISSIONS ANALYSIS

Overview and Results Snapshot

CO_2 Emissions Framework for Urban Trips

- A framework for estimating CO_2 emissions for any UAM trip and similar automobile-based trips considering current and emerging technologies
- **Use Cases:**
  - eVTOL + Gasoline Cars without autonomy
  - eVTOL + Gasoline Cars with autonomy
  - eVTOL + Electric Autos without autonomy



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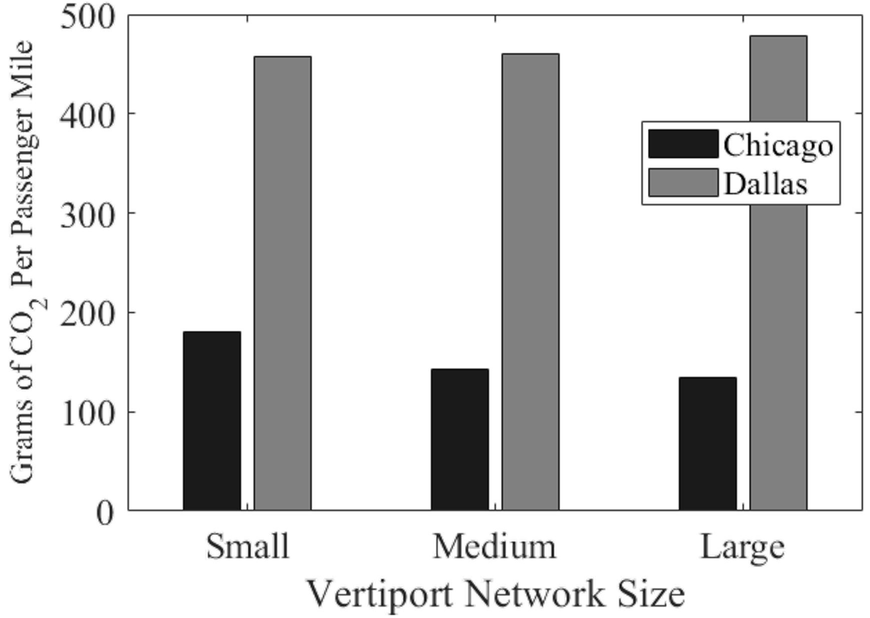
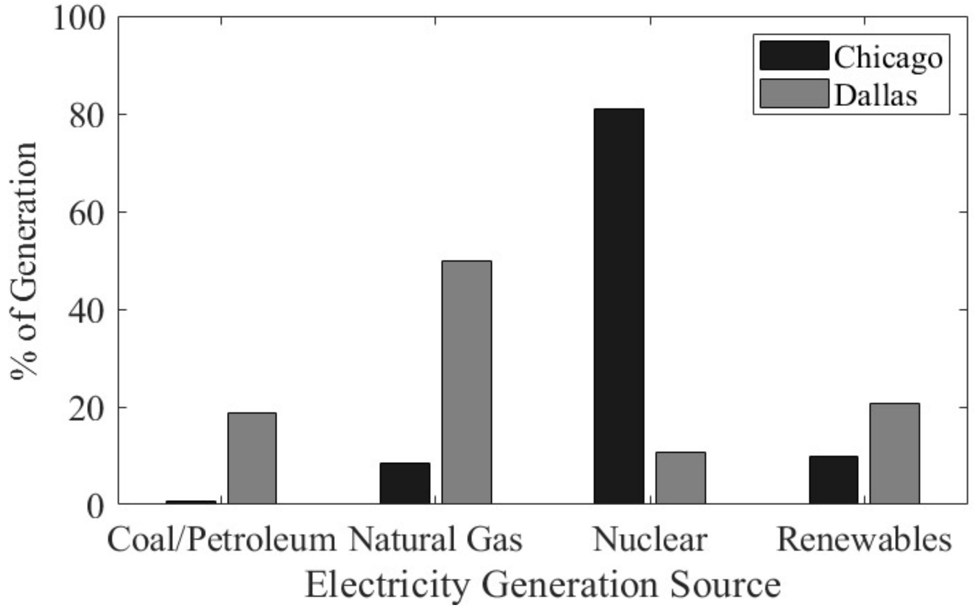
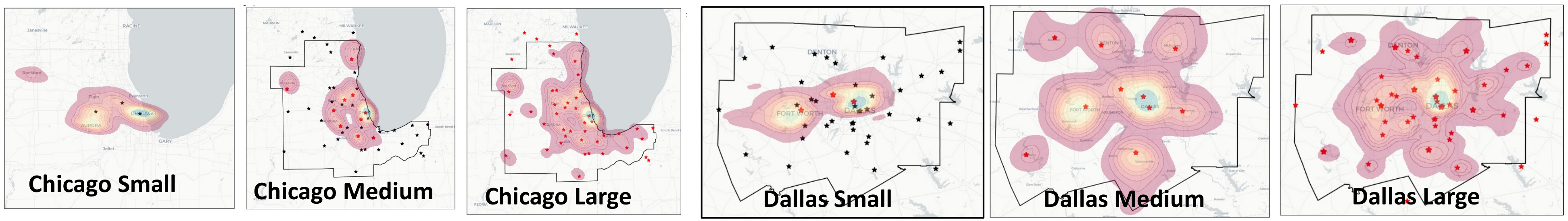
Estimates of CO2 Emissions in Dallas and Chicago

- Electricity grid makeup drives emissions from UAM operations with eVTOL + Gasoline Cars without autonomy







Overview of New Study Effort (Commenced Oct. 2021)

Further exploration of operations limits for Advanced Air Mobility (AAM) missions

- Identify further factors that may limit the number of AAM (e.g., Emergency medical, sUAS package delivery, etc.) operations and potential interdependencies with already identified UAM limits
- Perform case studies on additional Metro areas considering existing and potential future operational limits
- Compare and contrast results across the various Metro areas/case studies
- Recommend technology research most promising for paths to achieving scaled AAM operations

BACKUP SLIDES

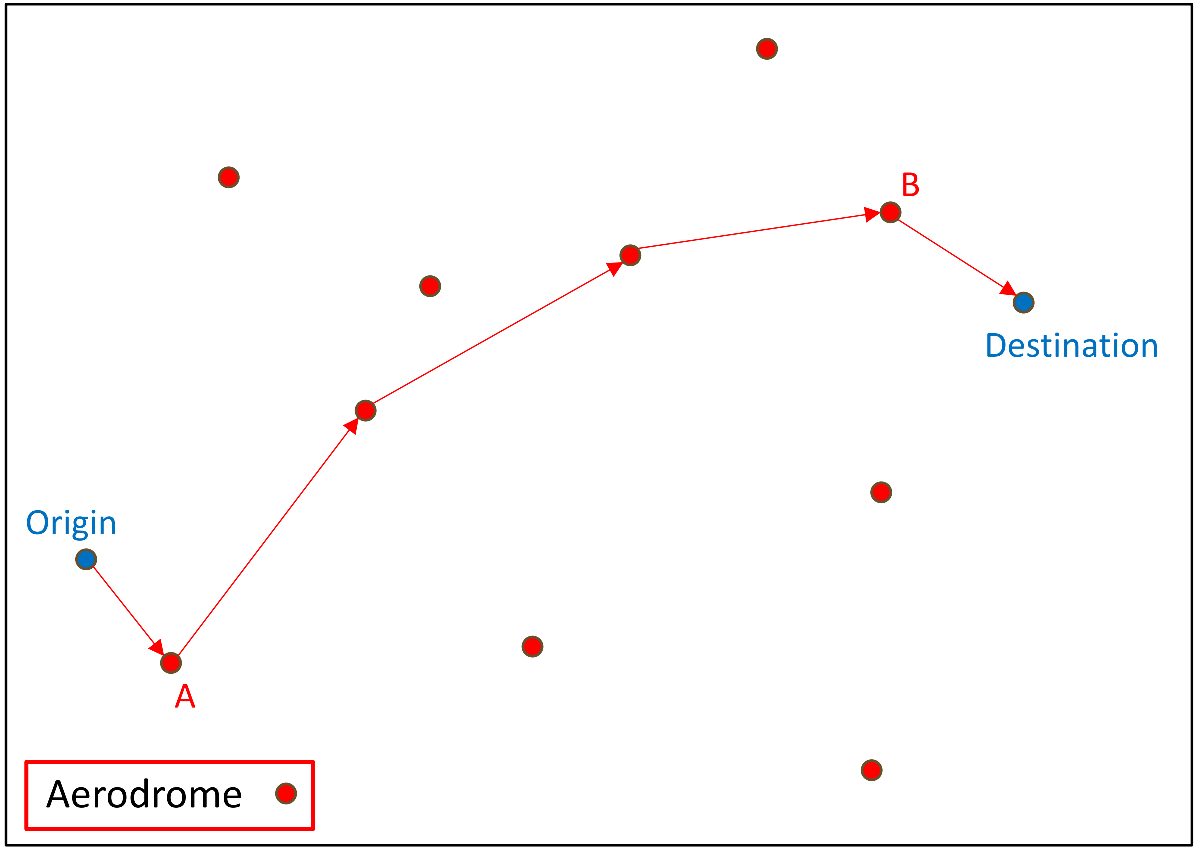
COMPUTATIONAL FRAMEWORK

Detailed Slides

COMPUTATIONAL FRAMEWORK

3 Distinct Problems:

- Distance Between Points
  - Foundation for all other problems
  - Lots of Formulations: Haversine, Ellipsoidal Distance, Google Maps API, etc.
- Nearest Aerodrome Determination
  - Find Aerodromes A and B efficiently at scale
- Flight Routing
  - How to fly from Aerodrome A to Aerodrome B minimizing travel time



COMPUTATIONAL FRAMEWORK ARCHITECHTURE

Primary output of the computational framework is an effective cost measure designed to effectively capture two elements of a trip: operating cost and travel time

$$Cost_{eff,i} = Cost_{oper,i} + Cost_{time,i}$$
$$Cost_{time,i} = time_{trip,i} * value_{timee}$$

where,

$Cost_{eff,i}$: Effective cost for the mode i

$Cost_{oper,i}$: Operating cost of mode i

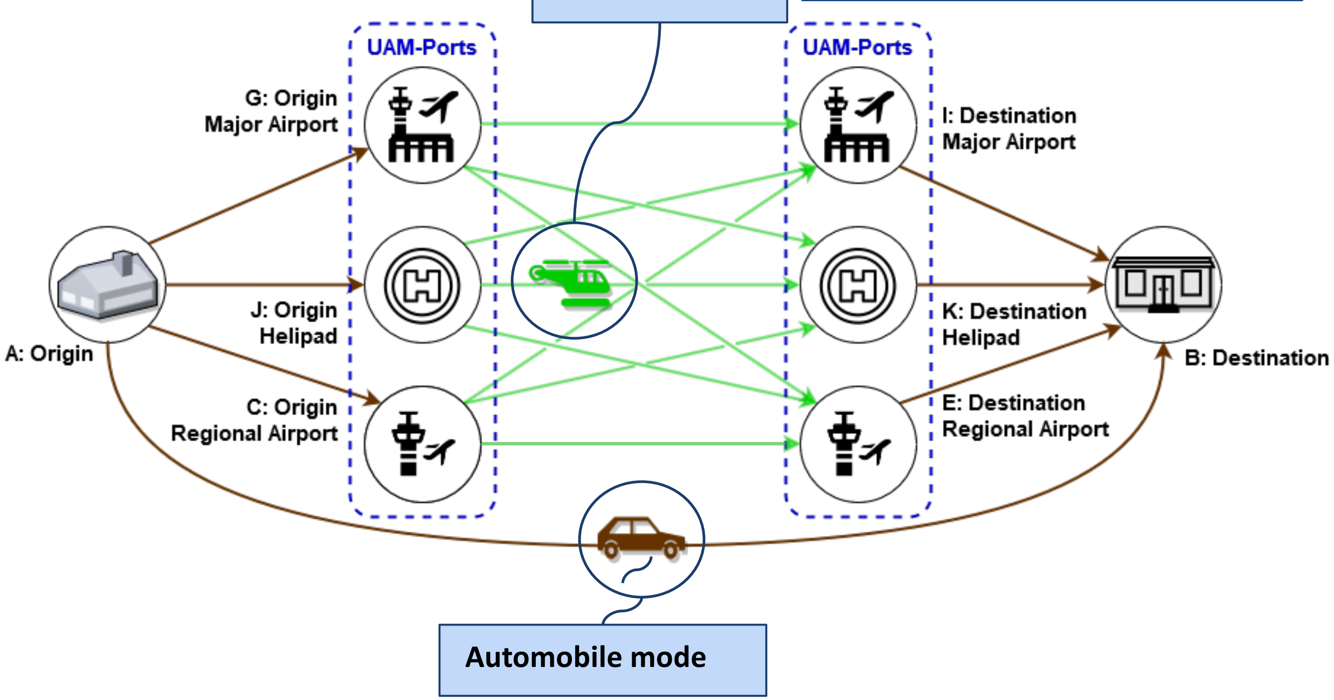
$Cost_{time,i}$: Cost due to the travel time on mode i

$time_{trip,i}$: Total door-to-door trip time for mode i

$value_{time}$: Value of time of the passenger

Our framework assumes that the traveler always picks the mode with the least effective cost

Network Model of the Modular Computational Analysis Framework*



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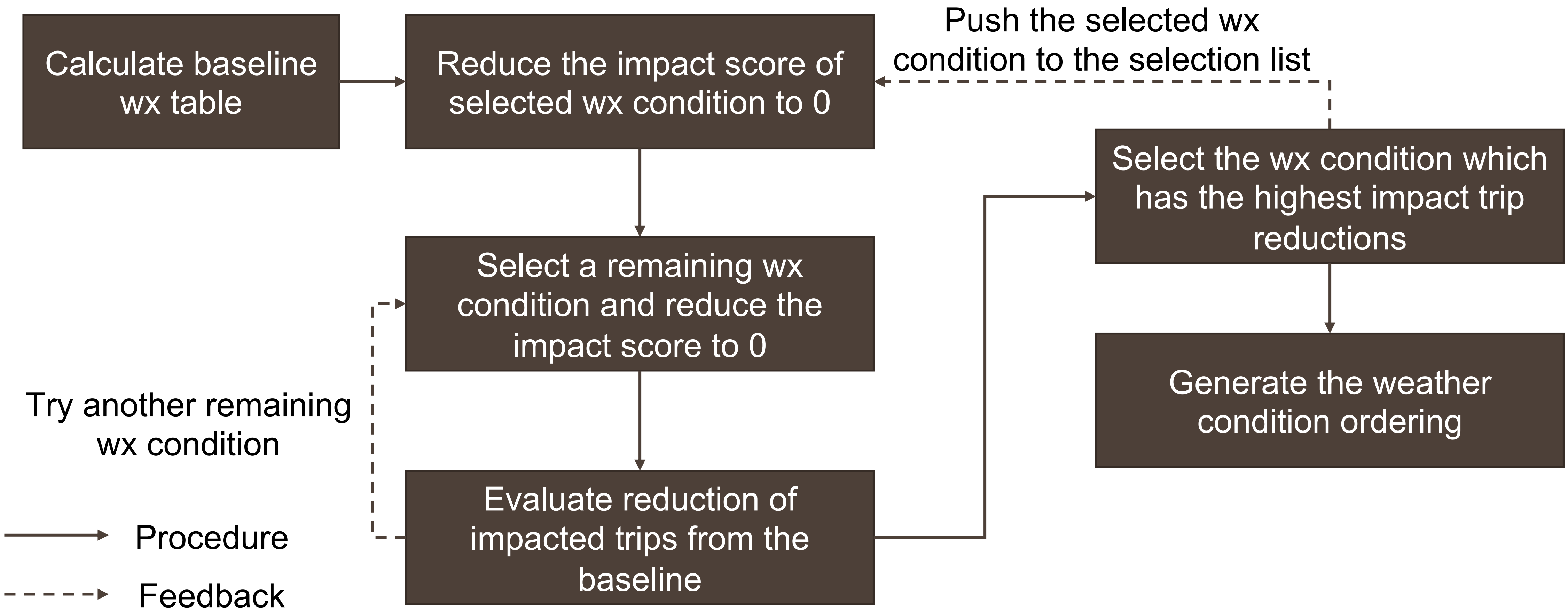
GREEDY ALGORITHM FOR WEATHER CONDITION RANKING

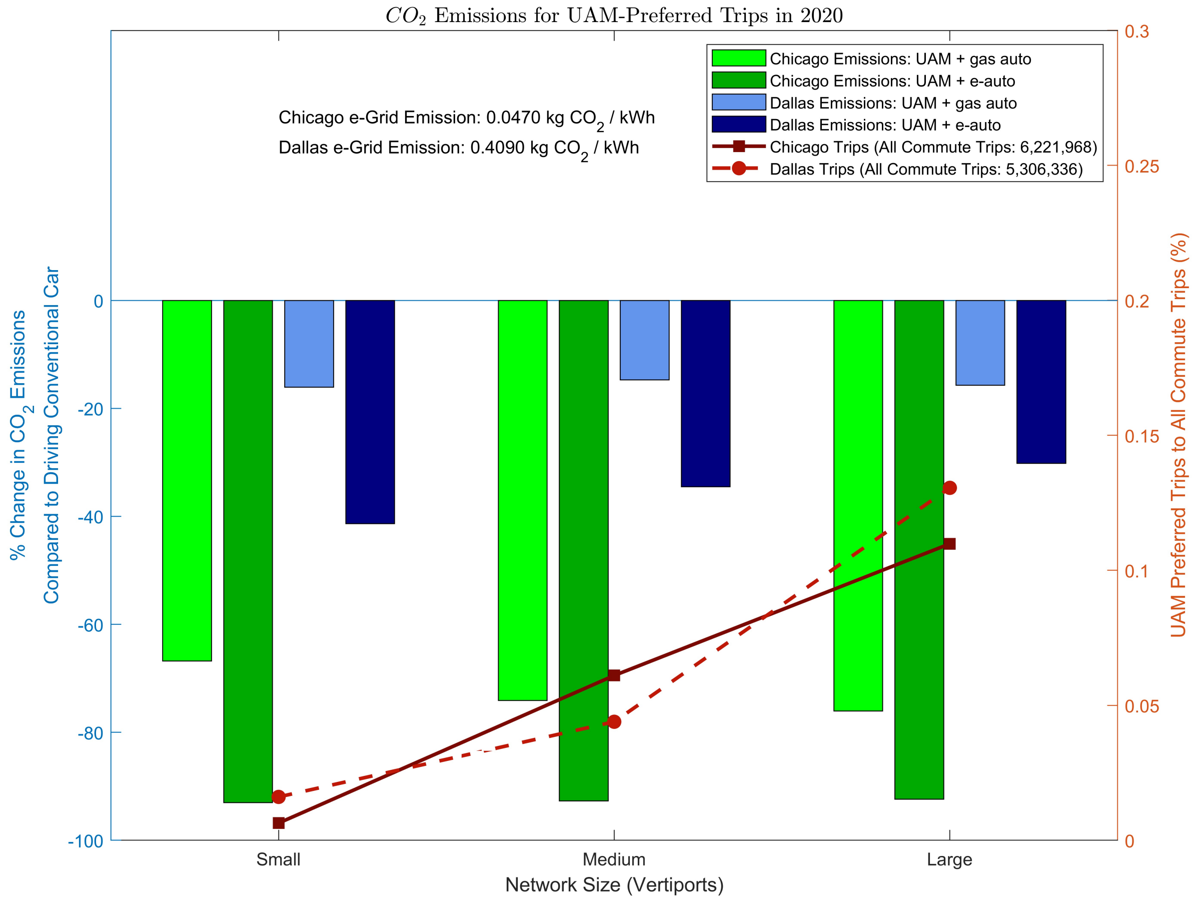


EMISSIONS RESULTS – OP LIMITS 1

Percentage of UAM Preferred trips and % Decrease in CO_2 emissions compared to driving conventional cars

- Bar graphs show % decrease in CO2 emissions of UAM trips + gasoline auto and UAM trips + electric auto compared to conventional gas autos for Chicago and Dallas, respectively
- X-axis shows the network size of vertiports, for both Chicago and Dallas metros.
- UAM-preferred trips percentage (%) is shown in red lines for small, medium, and large networks. These are % of UAM-preferred trips from the total commute trips in Chicago and Dallas regions. The total number of commute trips for Chicago and Dallas are 6,221,698 and 5,306,336 respectively.

Grid CO_2 Emissions Rate for Chicago:
[2020, 2030, 2040] = [0.0470, 0.1000, 0.1274] kg CO_2/kWh of electricity generated
Grid CO_2 Emissions Rate for Dallas:
[2020, 2030, 2040] = [0.4090, 0.3334, 0.3073] kg CO_2/kWh of electricity generated



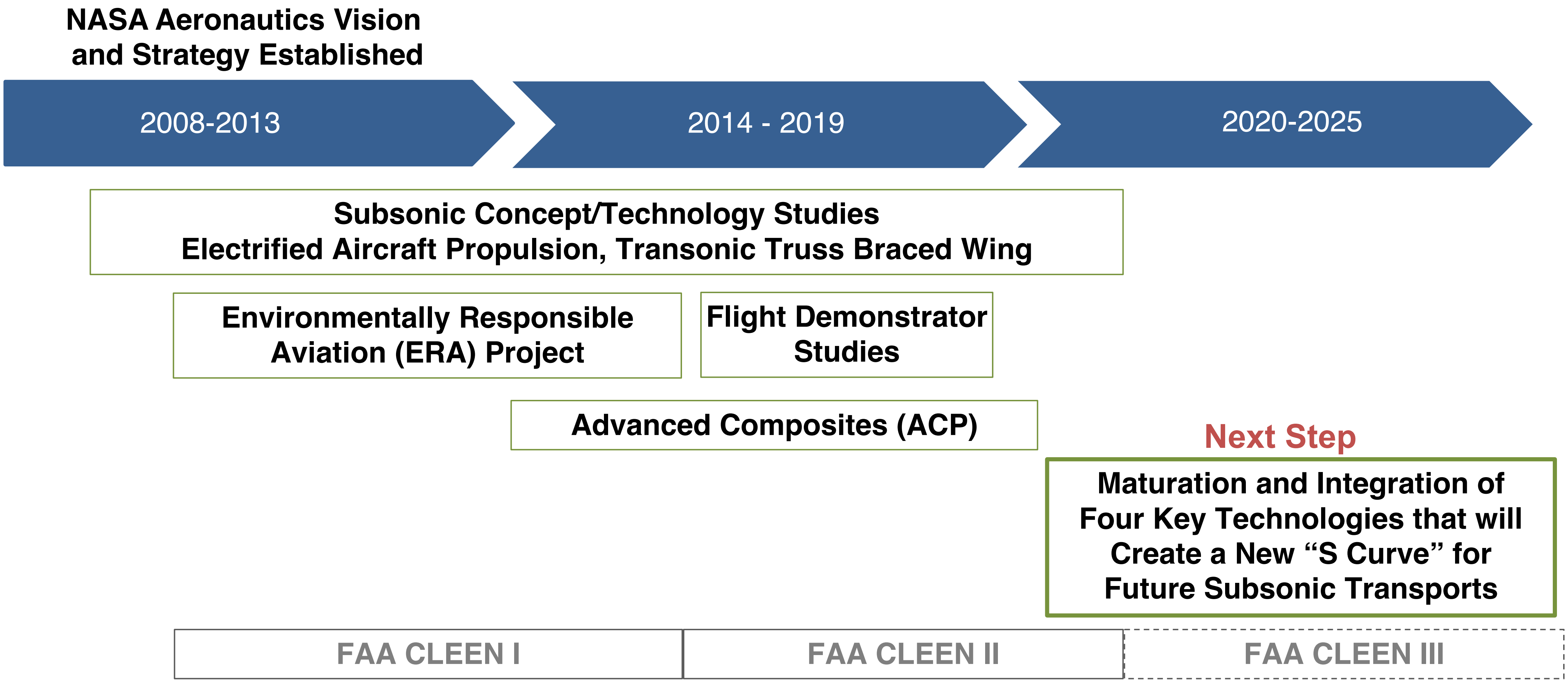
Model Based Systems Analysis and Engineering (MBSA&E) Overview

Eric Hendricks & Jesse Quinlan, NASA

Systems Analysis Symposium

November 10, 2021

Subsonic Transport Technology Prioritization

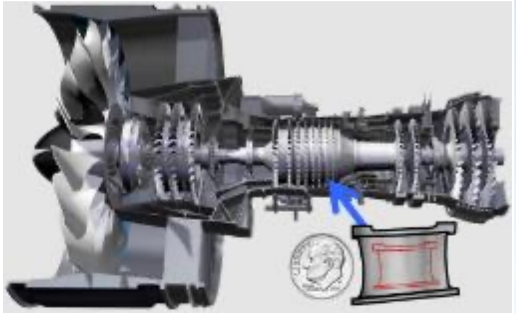


ARMD Subsonic Transport Strategy Based on over a Decade of Research, Concept and Technology Development, and NASA-Industry Partnership

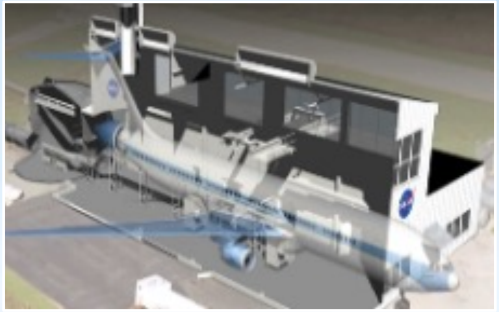
Subsonic Transport Technologies

Ensure U.S. industry is the first to establish the new “S Curve” for the next 50 years of transports

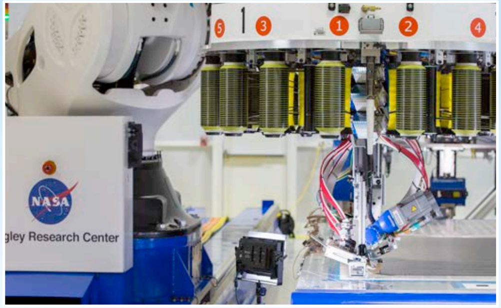
Transonic Truss-Braced Wing
5-10% fuel burn benefit



Small Core Gas Turbine
5-10% fuel burn benefit

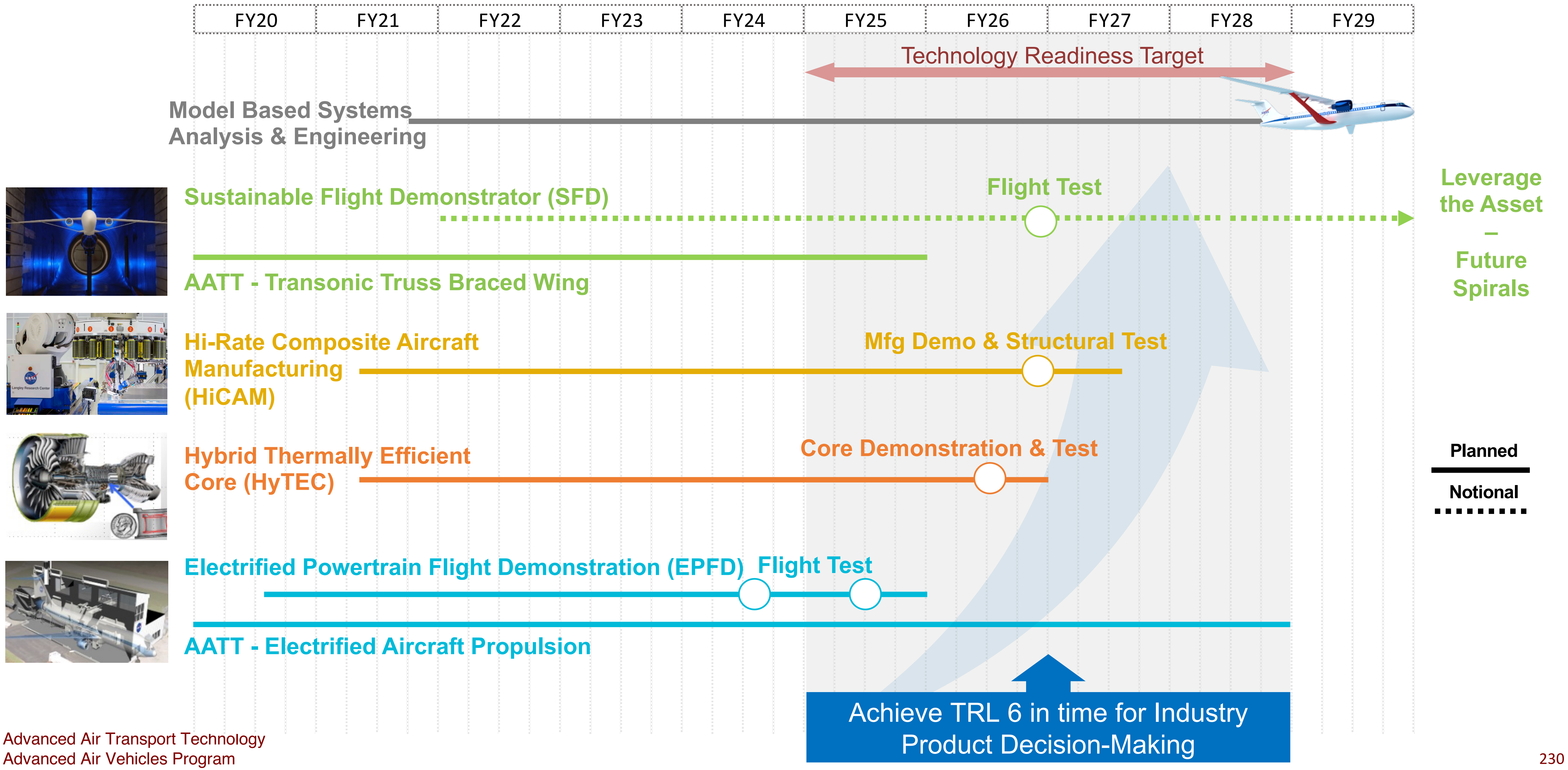


Electrified Aircraft Propulsion
~5% fuel burn and maintenance benefit



High-Rate Composite Manufacturing
4x-6x manufacturing rate increase

Sustainable Flight National Partnership (SFNP)

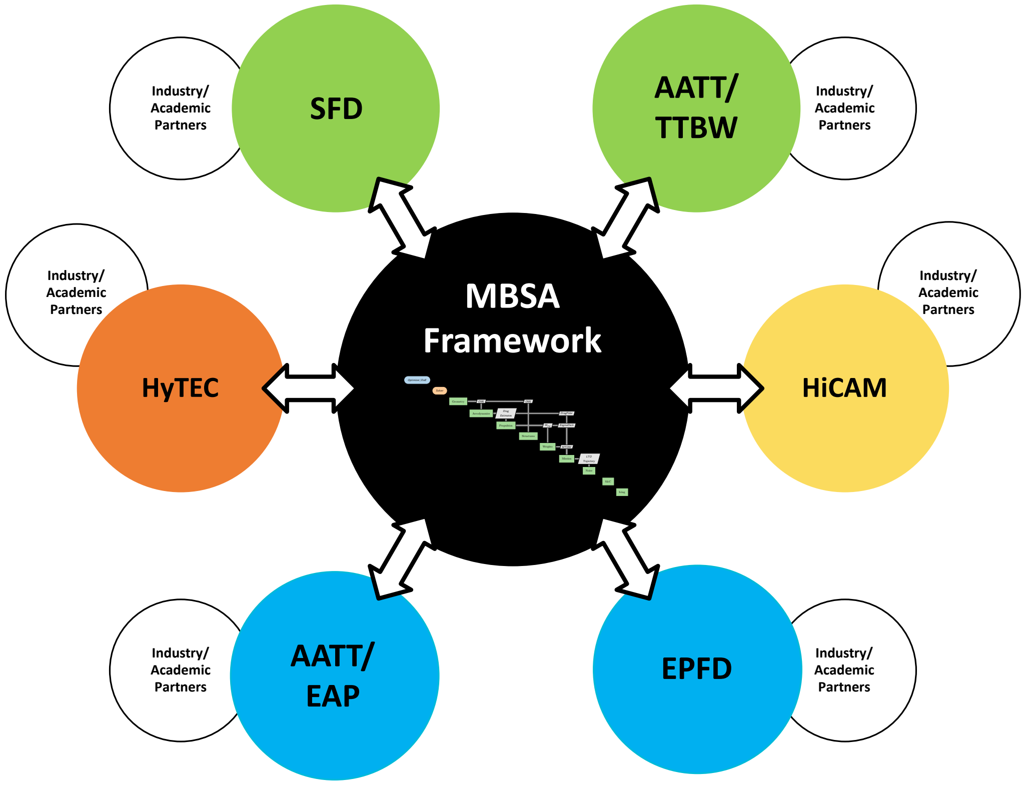


The Vision

A systems-level, digital integration across SFNP projects

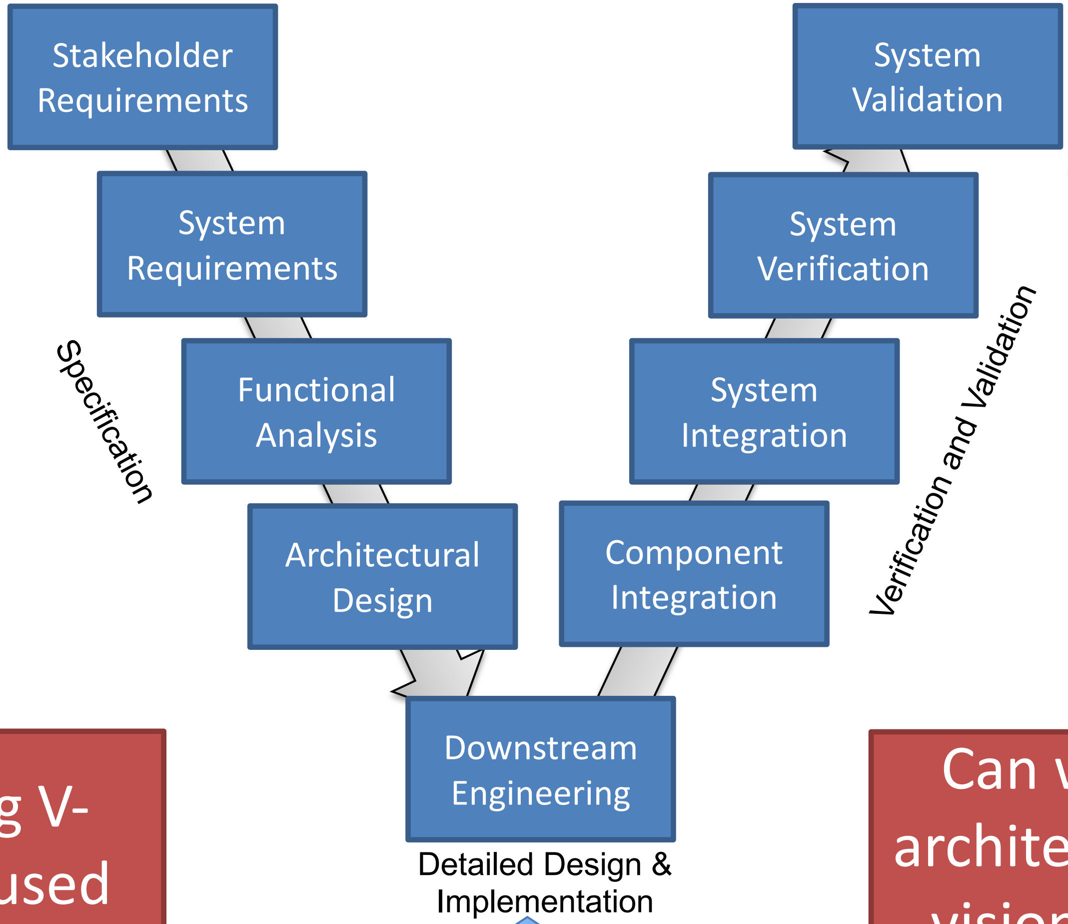
- Open, cross-project/program/external-capable MBSA ecosystem building off ARMD investments and capabilities across AAVP/IASP/TACP in support of the SFNP

- Coordinated, integrated systems analysis studies in support of SFNP
  - Common, open, reference vehicle models
  - Common, open, vision vehicle models
  - Technology benefit assessments and sensitivity studies informed by the SFNP demos



Classic Systems Engineering V-Model

Left Side:
specification of the system properties (requirements, architecture, interfaces, etc.)



Right Side:
verification of the system against the specifications

The Systems Engineering V-Model is conventionally used for product development

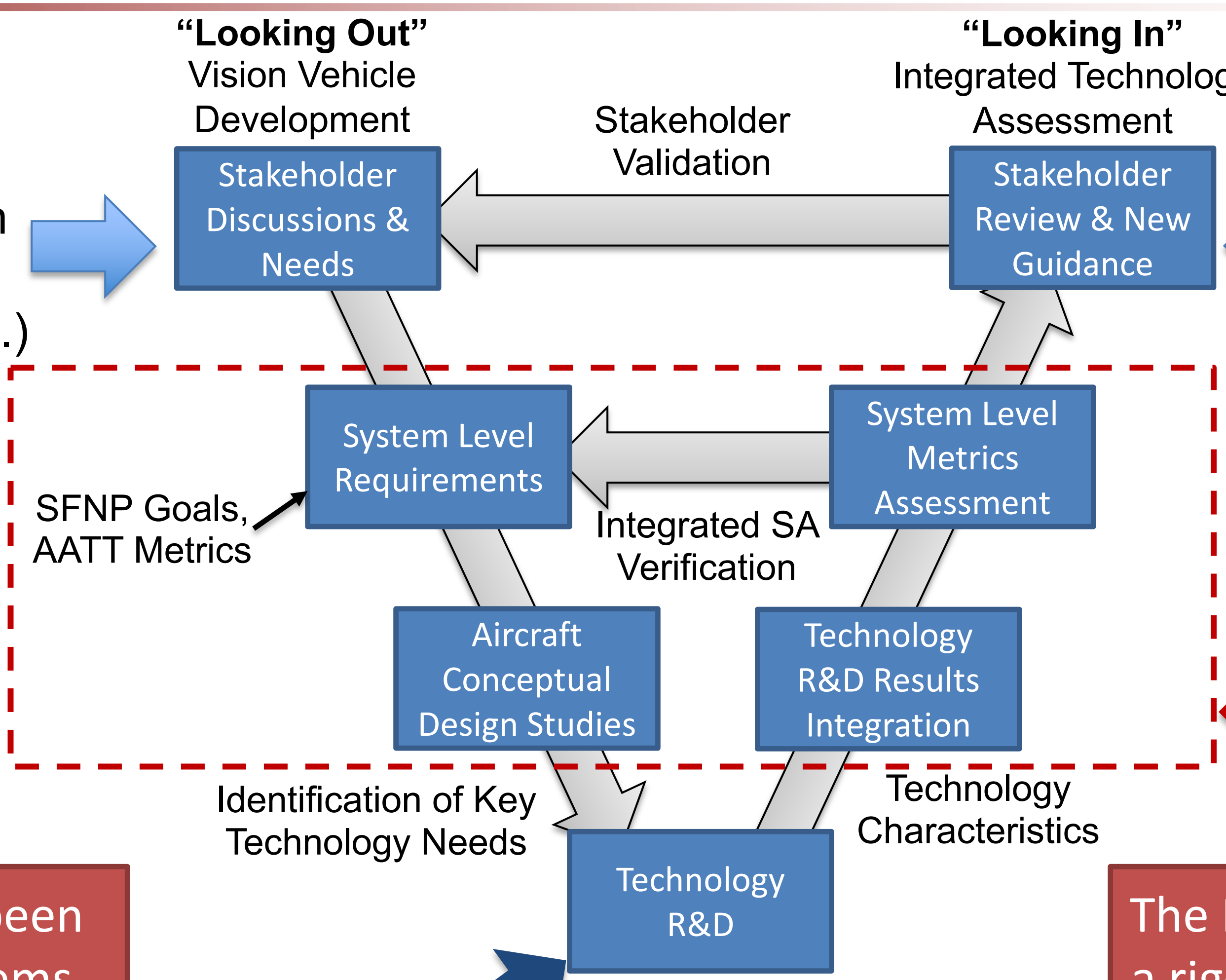
Bottom:
discipline-specific engineering and design work

Can we adapt this model to architect a similar construct for vision concept development and systems analysis for SFNP?

*Based on **Agile Model-Based Systems Engineering Cookbook** by Bruce Powel Douglass

SFNP Systems Analysis and Engineering V-Model

Left Side:
specification of the system properties (requirements, architecture, interfaces, etc.)



Right Side:
verification of the system against the specifications

New MBSA&E Framework

Both legs of this V have been done historically by systems analysis teams but generally in an ad-hoc manner

SFNP Project Engagement

Bottom:
discipline-specific engineering and design work

The MBSA Framework will provide a rigorous and traceable approach with improved interfaces with internal/external tech R&D efforts

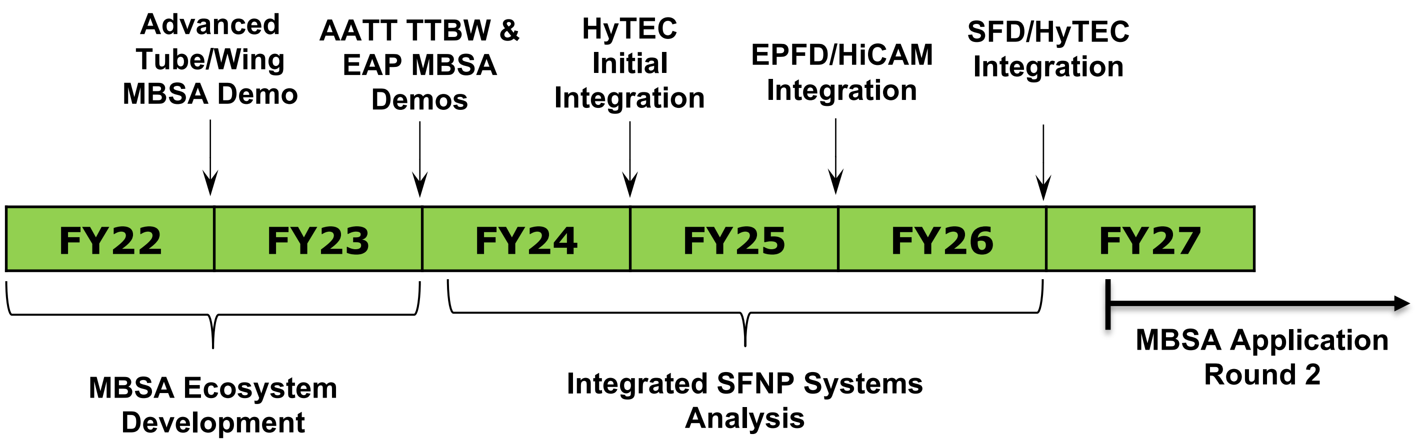
Phased MBSA&E - Key Points of Progress

Phase I - Develop common MBSA&E Framework/Ecosystem

- Create building blocks needed for key disciplinary analyses where lacking
- Integrate building blocks to form coupled MBSA&E framework – leveraging cross-project collaboration (e.g. TTT)
- Evaluate and test the MBSA&E framework with several use cases (conventional aircraft, TTBW, EAP)

Phase II - Coordinate cross-project integrated model development and systems analysis studies

- Development of open, common SFNP reference and vision vehicle concepts and models
- Regular, frequent tech interchange meetings across SFNP systems analysis teams, including external project partners
- Integrated systems analysis studies to incrementally 'roll-up' SFNP findings into a consolidated understanding of vision vehicle benefits and trades

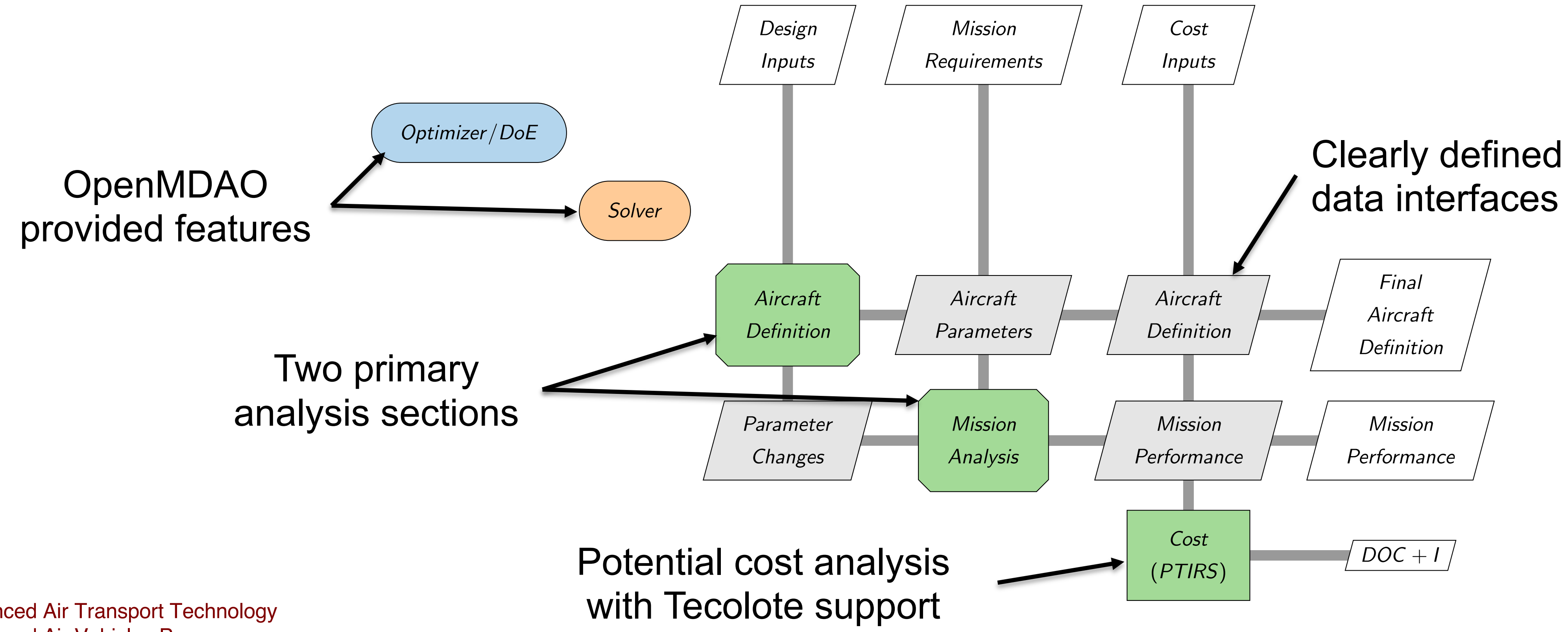


MBSA&E: Phase I

MBSA Framework – Top Level

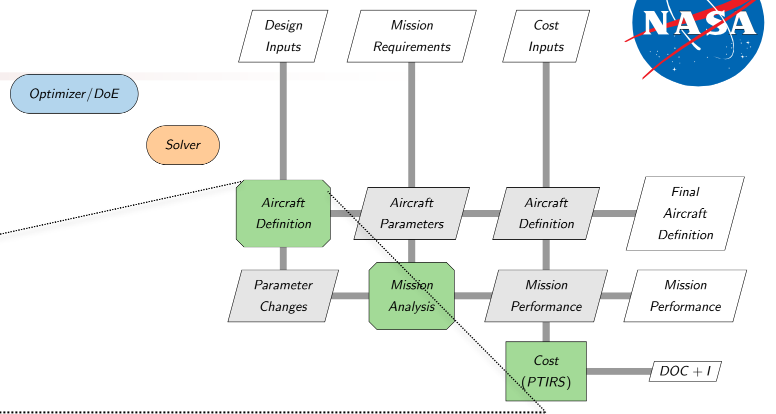
- Provides a rigorous and traceable systems analysis approach with improved interfaces with internal/external tech R&D efforts

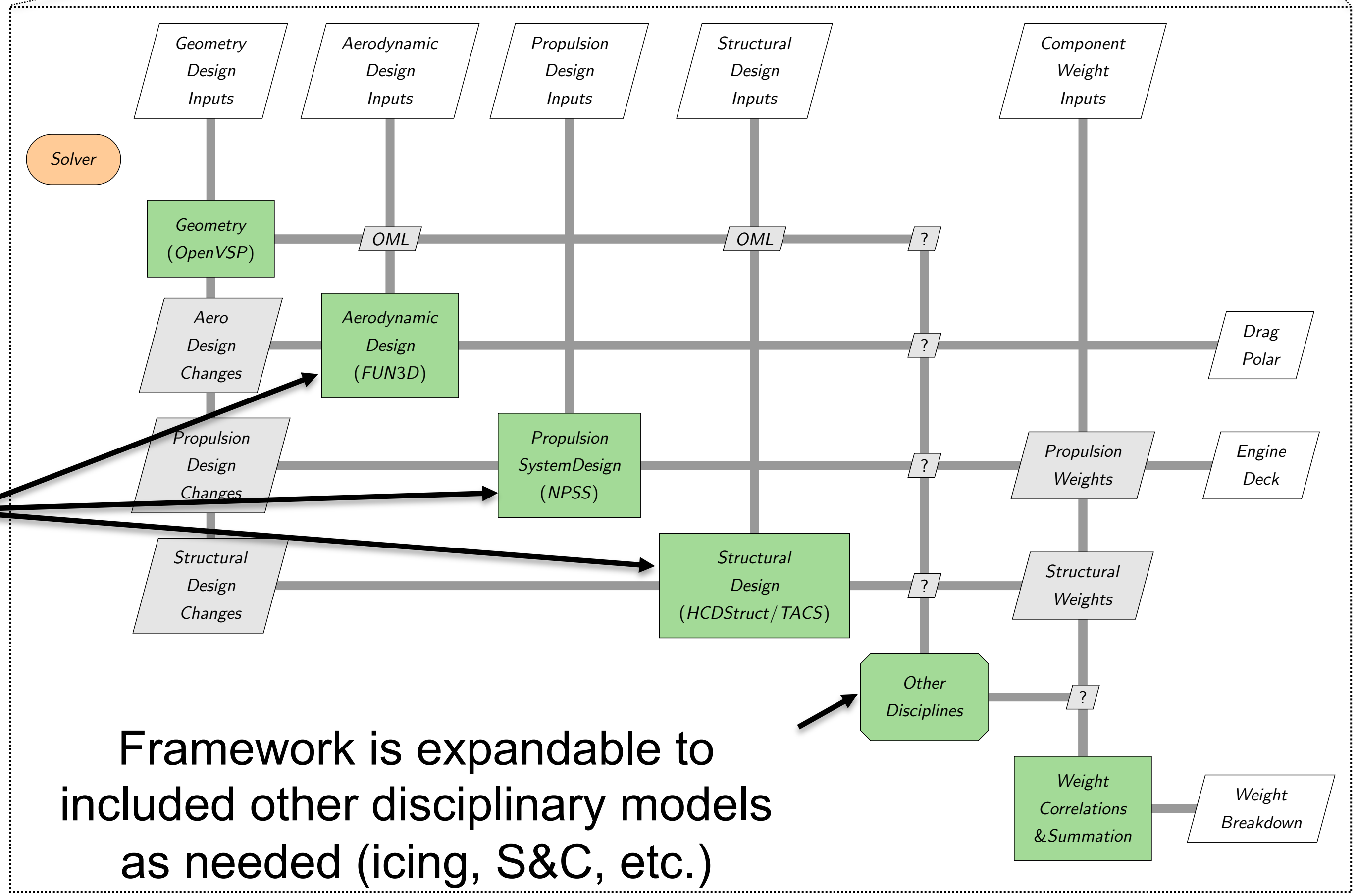
- Framework will be created in OpenMDAO (TTT leading development) which will provide advanced capabilities for coupling existing tools and producing optimized, converged solutions



MBSA Framework – Aircraft Definition Section

- Analysis section focuses on defining the aircraft configuration and size in a single integrated model
- Develops the aerodynamic, propulsion system, structural and other disciplinary designs





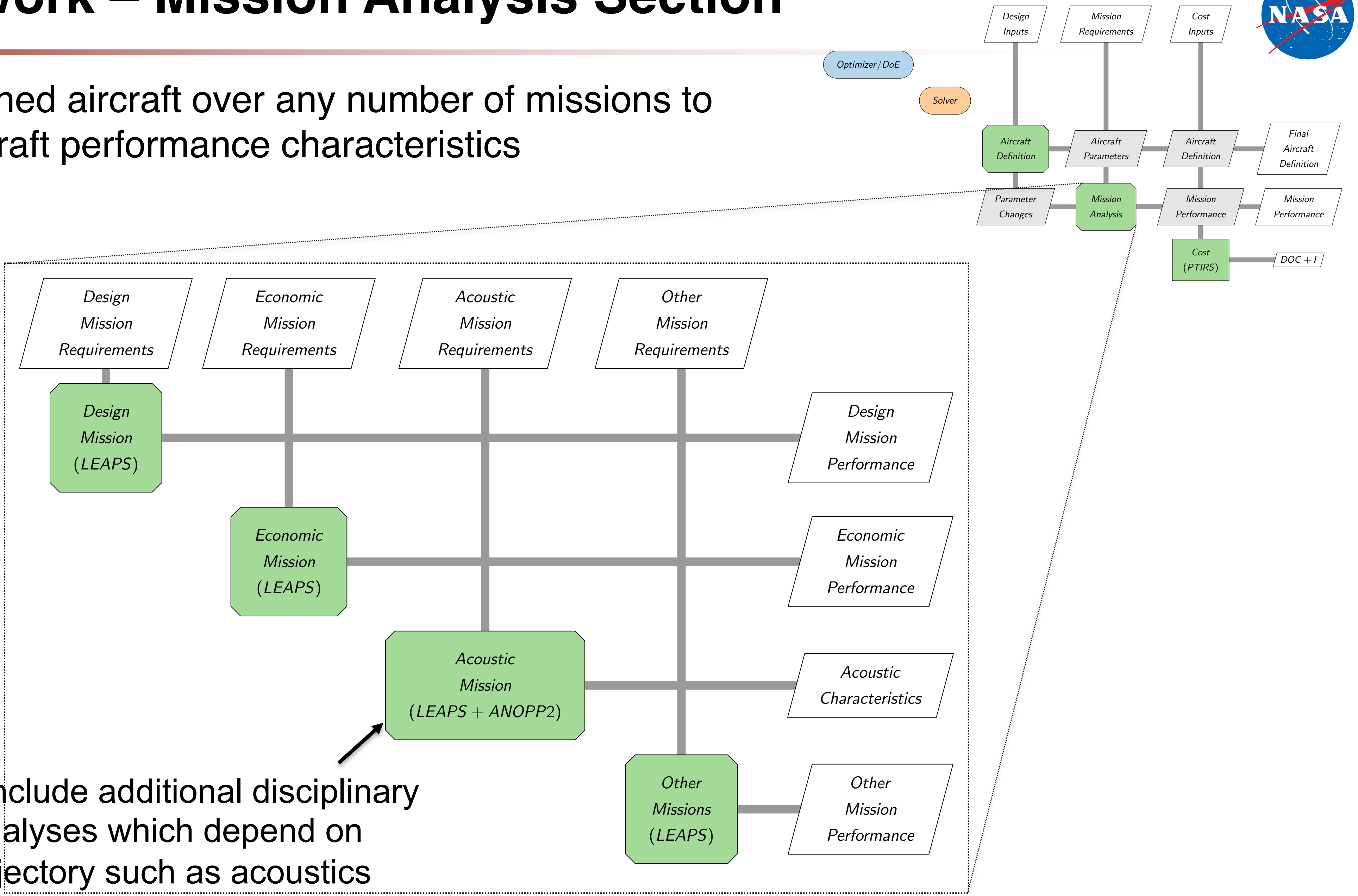
Disciplinary models are points of engagement with internal/ external tech R&D efforts:

- Modifying inputs and assumptions to traditional systems analysis tools
- Integrating high fidelity models

Framework is expandable to included other disciplinary models as needed (icing, S&C, etc.)

MBSA Framework – Mission Analysis Section

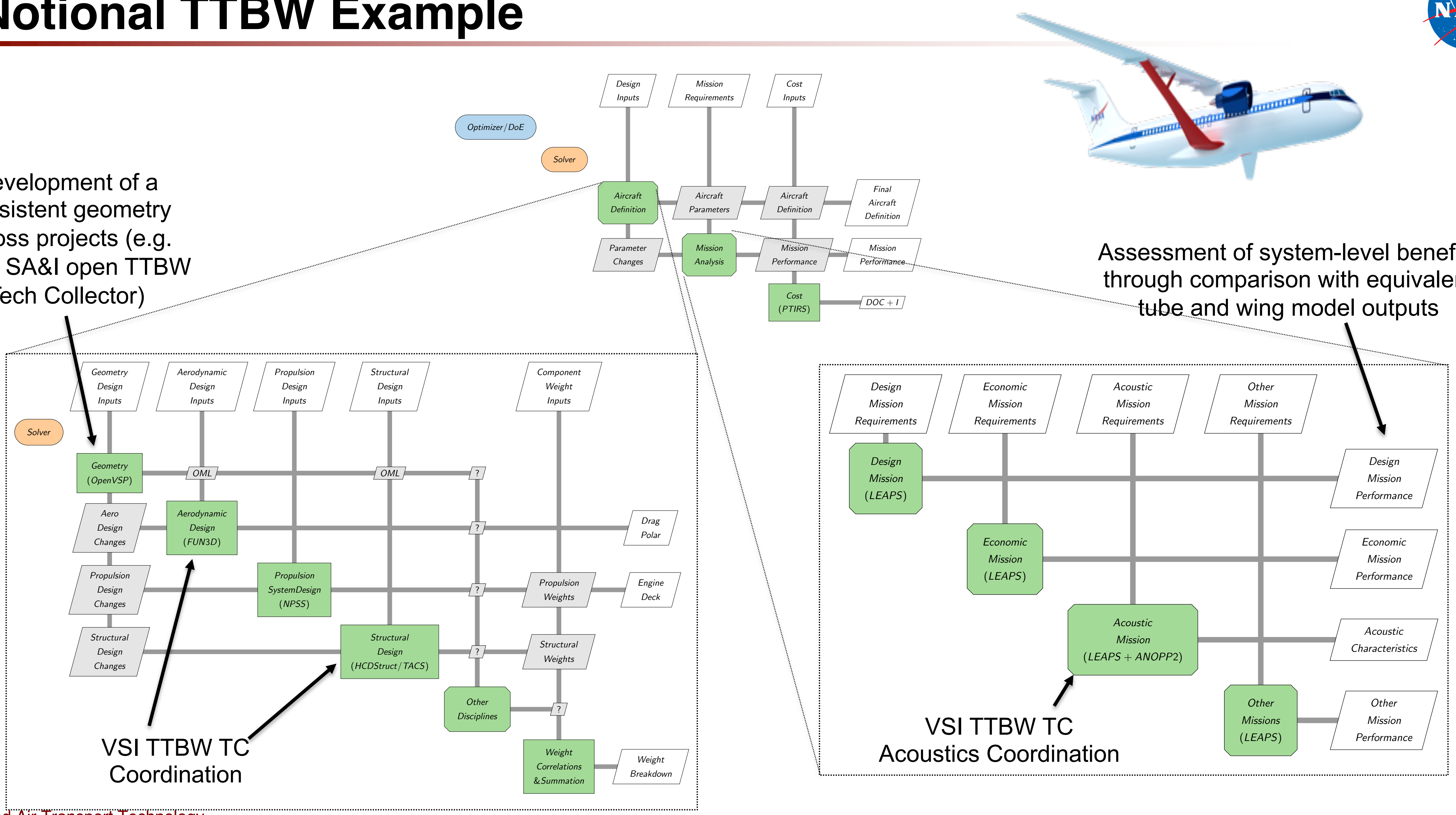
- Evaluates the defined aircraft over any number of missions to determine the aircraft performance characteristics



May include additional disciplinary analyses which depend on trajectory such as acoustics

Notional TTBW Example

Development of a consistent geometry across projects (e.g. AATT SA&I open TTBW Tech Collector)

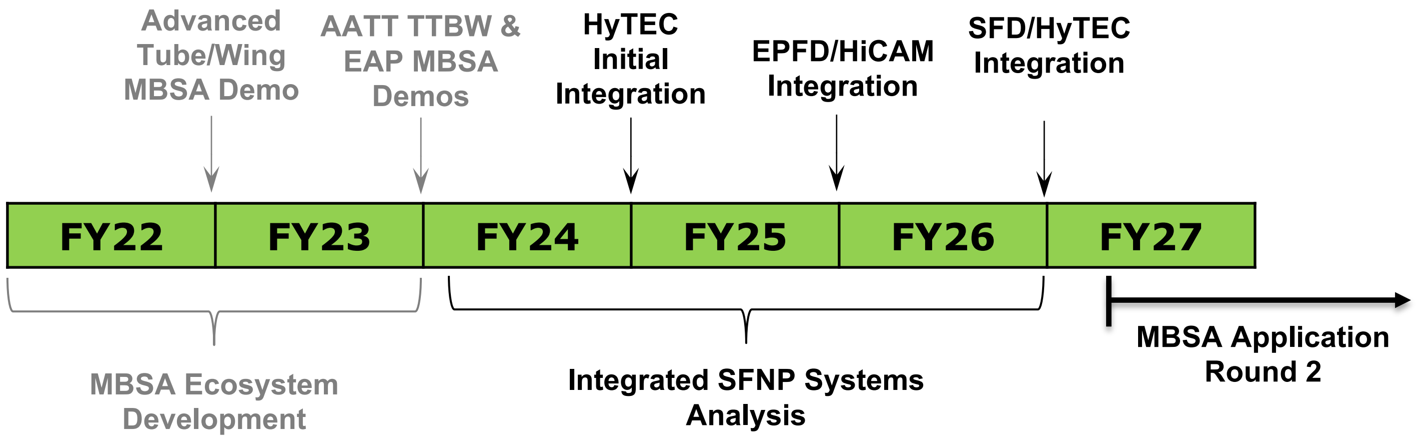


Assessment of system-level benefits through comparison with equivalent tube and wing model outputs

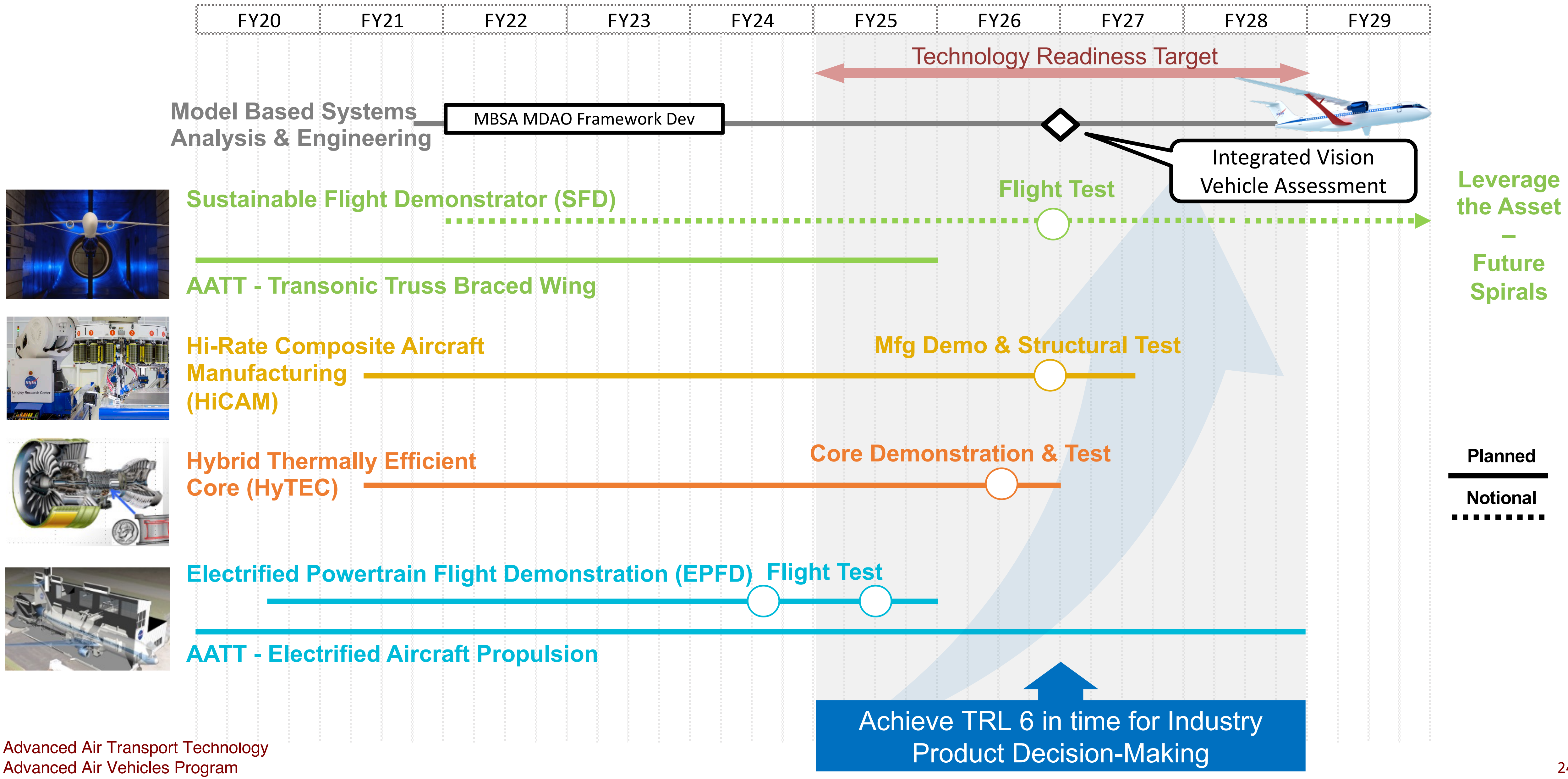
MBSA&E: Phase II

Overview of Phase II

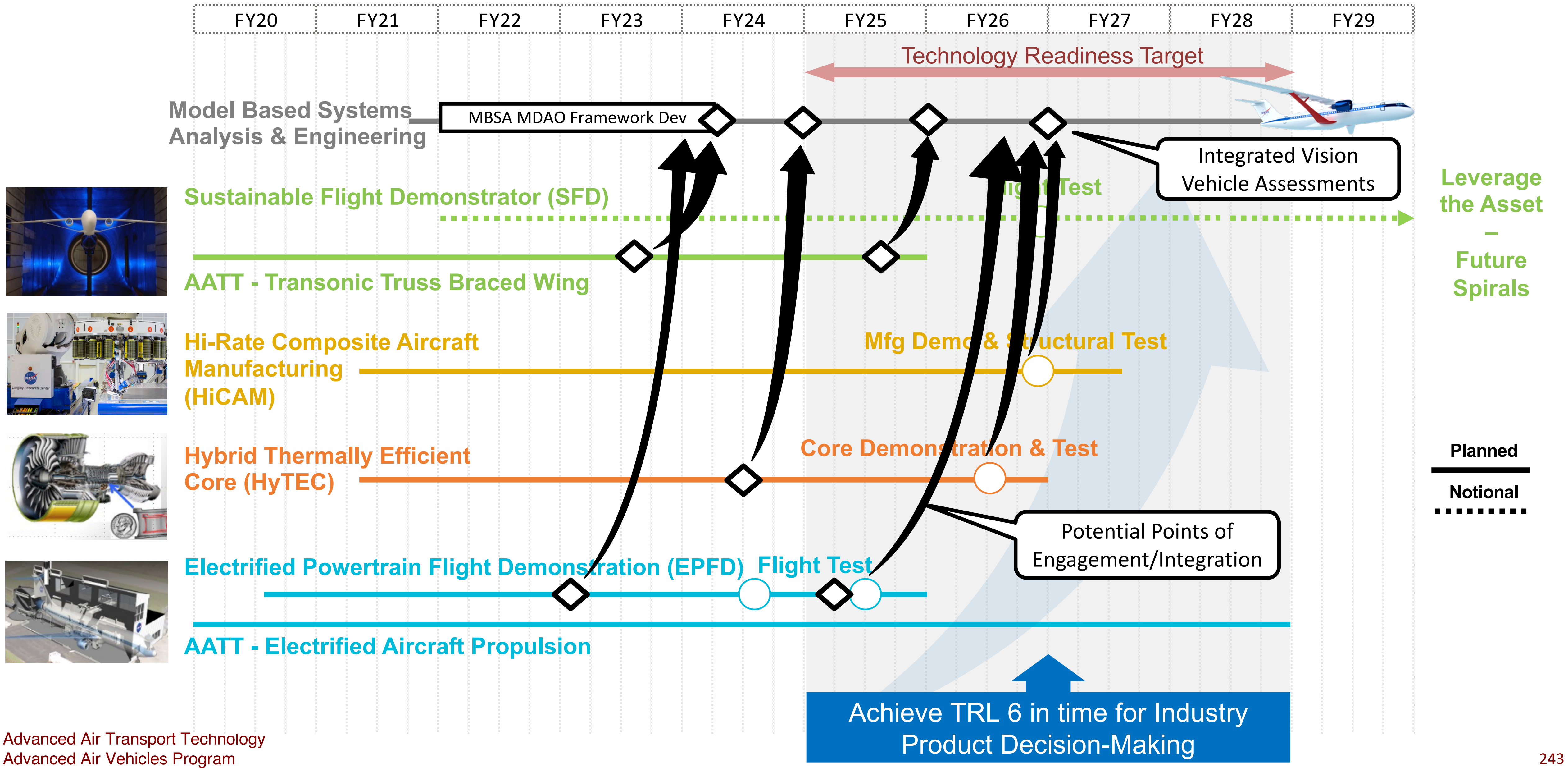
- Phase II will focus on the coordination of integrated systems analysis studies for the broader SFNP
- Key elements of Phase II will include:
  - Formulation of integrated systems analysis needs for the SFNP with an emphasis on development and assessment of vision vehicle concepts associated with the flight demo concepts
  - Project-specific technical interchange activities informed by the key project decision points and deliverables
  - Integration of experimental data, flight test data, and SME input into the integrated vision vehicle models for the purposes of technology benefit assessments for the SFNP
  - Regular cross-project reviews of the integrated, system-level vehicle models and associated systems analysis results to inform project plans and objectives early and frequently
  - Close coordination with the contract partners involved with each of the SFNP projects



MBSA&E – Phase II – FY24-26



MBSA&E – Phase II – FY24-26 :: Notional Integration



Final SFNP MBSA&E ‘Deliverables’

- Common, open, MBSA&E framework/ecosystem
  - Built in OpenMDAO with support for core SFNP systems analysis and vehicle modeling tools
  - Framework architecture and component data interfaces informed by cross-project systems analysis teams and external SFNP partners
  - Library of open NASA plug-ins and SFNP data
  - MBSE attributes where possible (requirements tracking, common interfaces, etc)
- Common, open, systems-level SFNP reference vehicle models
- Common, open, systems-level SFNP vision vehicle models
- Integrated system-level benefit assessments of the SFNP vision vehicle concepts informed by SME elicitation and ground/flight demos across the SFNP

A systems-level, digital integration across SFNP projects