FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

Overview of CLEEN Assessment Work and Plans for the Future

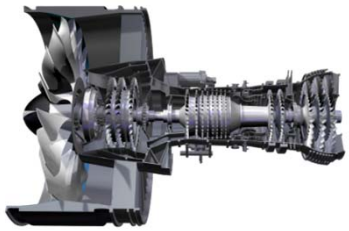
Project managers: Levent Ileri, Arthur Orton (FAA)
Lead investigator: Dimitri Mavris (PI), Jimmy Tai (Co-PI),
Christopher Perullo (Co-PI)

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

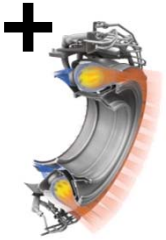
ASCENT
AVIATION SUSTAINABILITY CENTER

Objectives

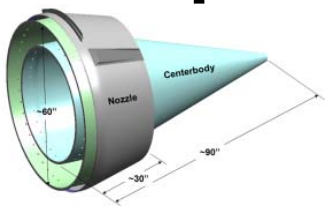
- **GA Tech integrates NASA design & analysis tools**
- **Assess technology combinations**
- **Identify synergistic technologies**
- **Compare to company estimate**

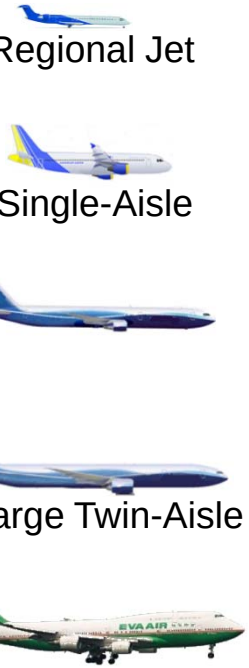


+



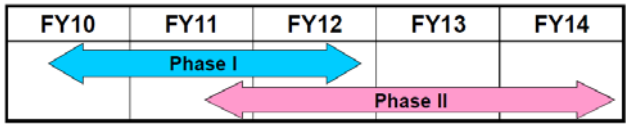
+





Subsystem Technology Impacts → **Technology Effects on Vehicle** → **Fleet Level Implications**

EDS Assessment of CLEEN Technologies



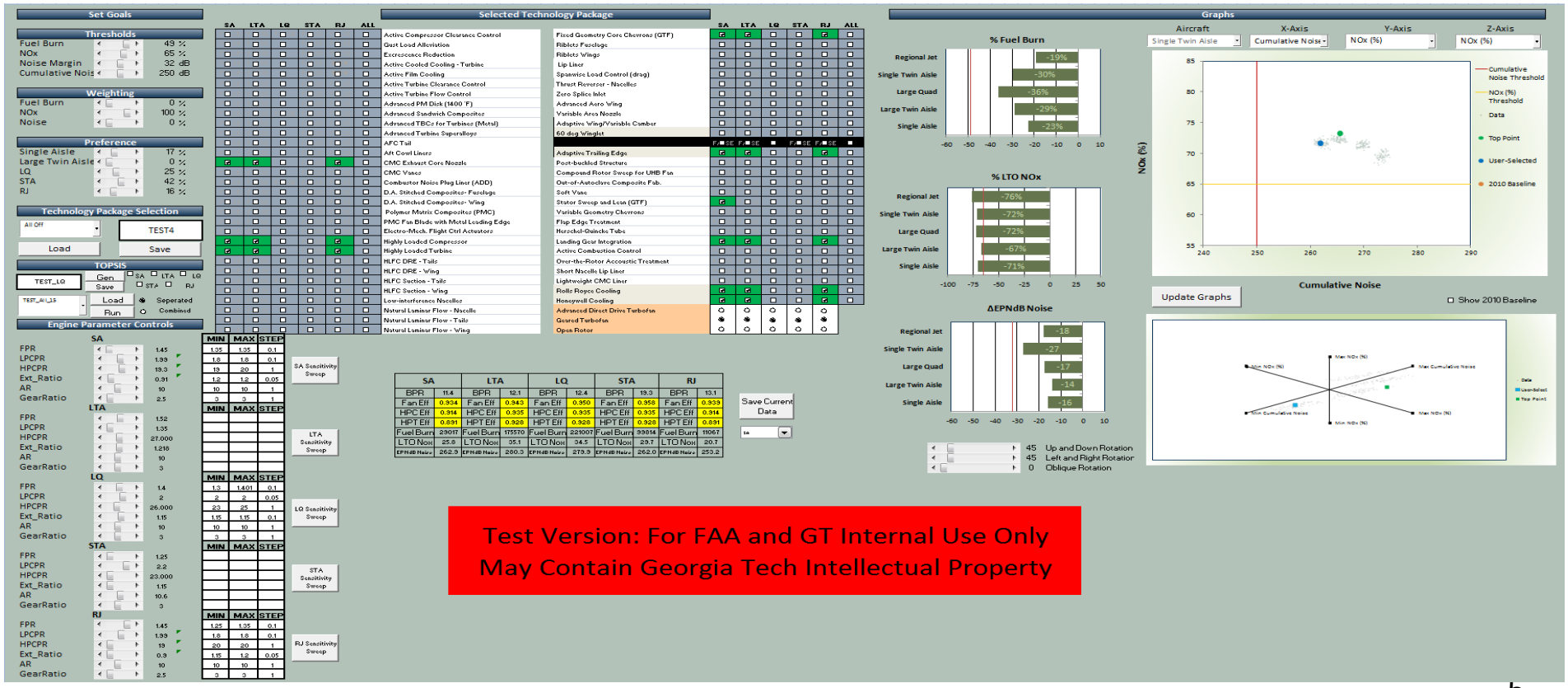
- 2 phase approach
  - Phase 1: GT worked with FAA CLEEN Program personnel to define similar, public-domain technologies in order to assess potential benefit
  - Phase 2 (Ongoing)
    - Incorporating proprietary data and models into the assessment
    - Developed parametric spreadsheet based technology calculator
- Assessment was performed by leveraging the EDS baseline and generic vehicles developed in previous years
- Results included vehicle and fleet level results of fuel burn, emissions, and noise (vehicle only)
  - Vehicle results are proprietary
- Many of the technology models developed last year(s) directly support ongoing assessments

Continuing Support of CLEEN (ASCENT and PARTNER CoE)

- PARTNER has since been replaced with the ASCENT CoE
- Current work focuses on including additional industry data in EDS vehicle models
- EDS used for *independent assessment* of CLEEN technologies and their environmental benefit (i.e., fleet results) using detailed industry data
- Constructed a technology tradeoff calculator
  - Spreadsheet based tool that encompasses EDS analysis
  - End goal is to provide integrated platform for FAA to perform internal assessments
  - Leverages CLEEN Phase I and Phase II and NASA technology programs
- Focuses on refining *Non-Proprietary* EDS with proprietary data → resulting modeling environment is CLEEN-EDS
  - This allows the fundamental modeling enhancements funded by CLEEN to be leveraged for other technology modeling work
  - If necessary modeling enhancements will be proprietary
- Assessment process will be ongoing and updated on an annual basis

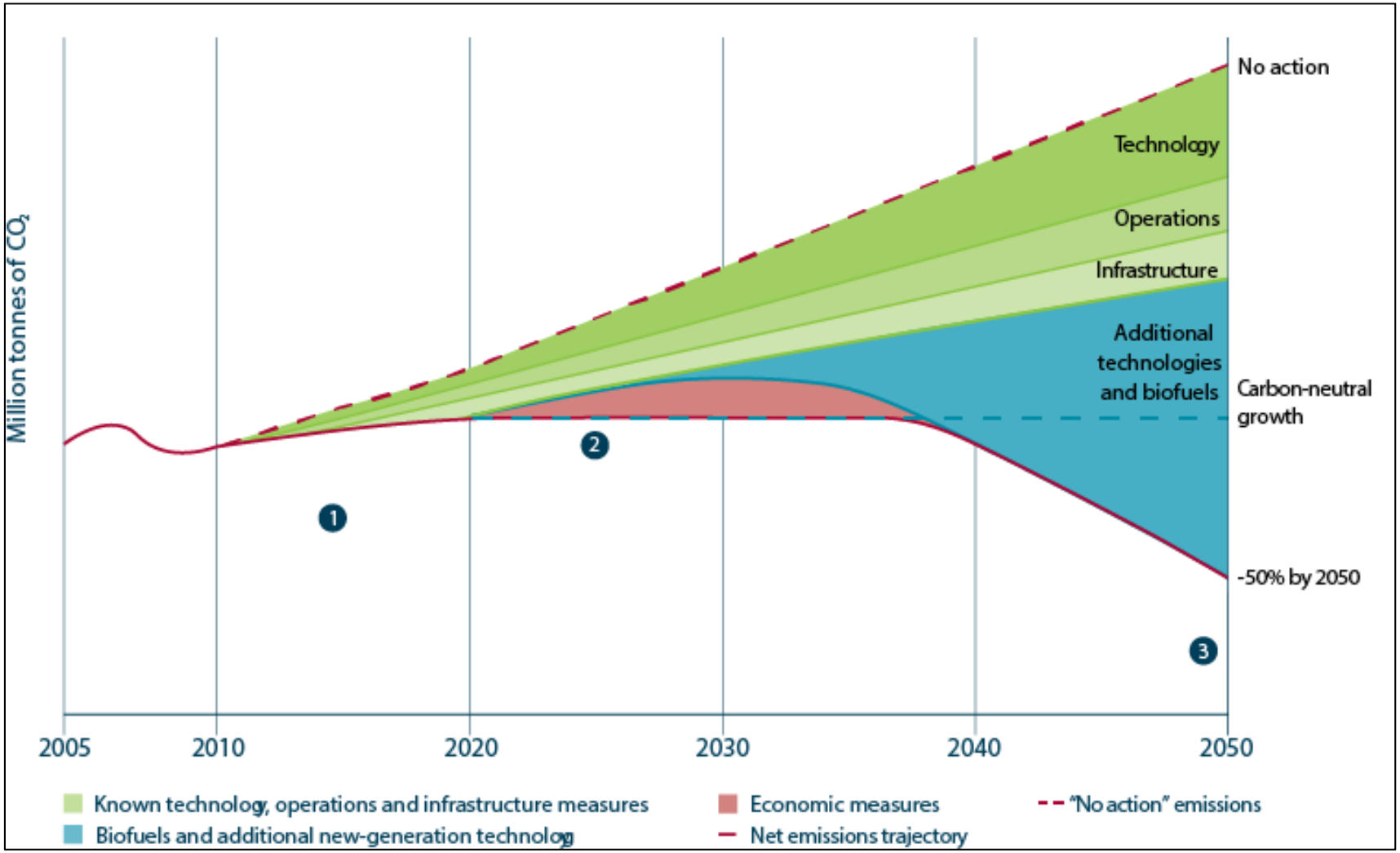
Technology Dashboard Development

- Goal is to embed EDS capabilities within excel-based analysis
- Developed fleet-wide assessment capability using response surface modeling
  - Used artificial neural networks to train multiple output responses as a function of more than 100 input parameters



2014 FLEET ASSESSMENTS

Goal of Fleet Assessment



Technology Scenario Definitions

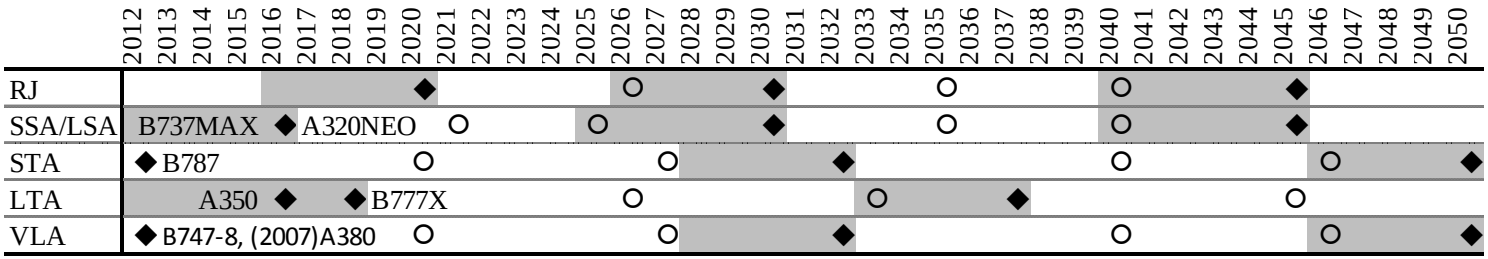
- Before defining specific technology packages GT & FAA developed three scenarios
- Each scenario subdivided into N+1 and N+2
- Aggressive w/o CLEEN can be compared to Aggressive to identify CLEEN contribution

Scenario	Description
Evolutionary	'Normal' technology evolution TAPS II only CLEEN technology included in N+1
Aggressive	Represents higher rate of technology development Includes all CLEEN Techs in N+1
Aggressive w/o CLEEN	Identical to aggressive with all CLEEN technologies removed and GTF cycle constrained to current technology level

Fleet Replacement Assumptions

- Used ‘projected’ vehicle introduction dates and historical trends of upgrades / performance improvement packages to define CLEEN fleet replacements

FOUNDATIONAL MODEL



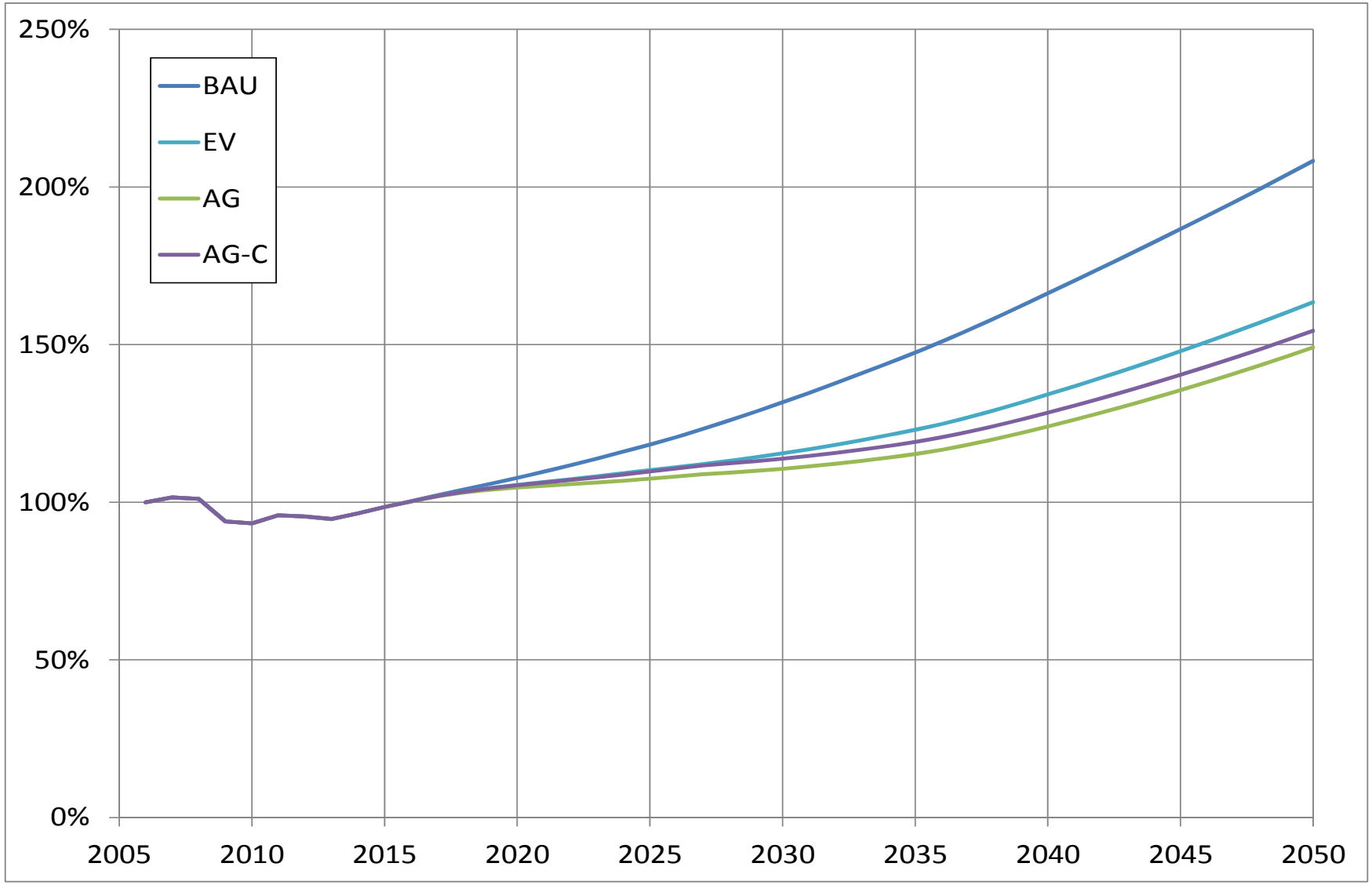
*Pfaender AIAA-2013-4284

◆ Major Technology Upgrade
O Incremental Technology Upgrade
Program launch to entry into service

CLEEN Replacement Schedule

Vehicle	Timefram	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
RJ	N+1	0	0	0	25	50	75	100	100	100	100	100	100	100	75	50	25	0	0	0	0	0
RJ	N+2	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100
SA	N+1	0	25	50	75	100	100	100	100	100	100	75	50	25	0	0	0	0	0	0	0	0
SA	N+2	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100	100	100	100
STA	N+1	0	0	0	25	50	75	100	100	100	75	50	25	0	0	0	0	0	0	0	0	0
STA	N+2	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100	100	100	100	100
LTA	N+1	0	0	0	25	50	75	100	100	100	100	100	100	100	100	100	75	50	25	0	0	0
LTA	N+2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100
VLA	N+1	0	0	0	0	0	25	50	75	100	100	100	100	75	50	25	0	0	0	0	0	0
VLA	N+2	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100	100	100	100

2014 CLEEN Fleet FB Results

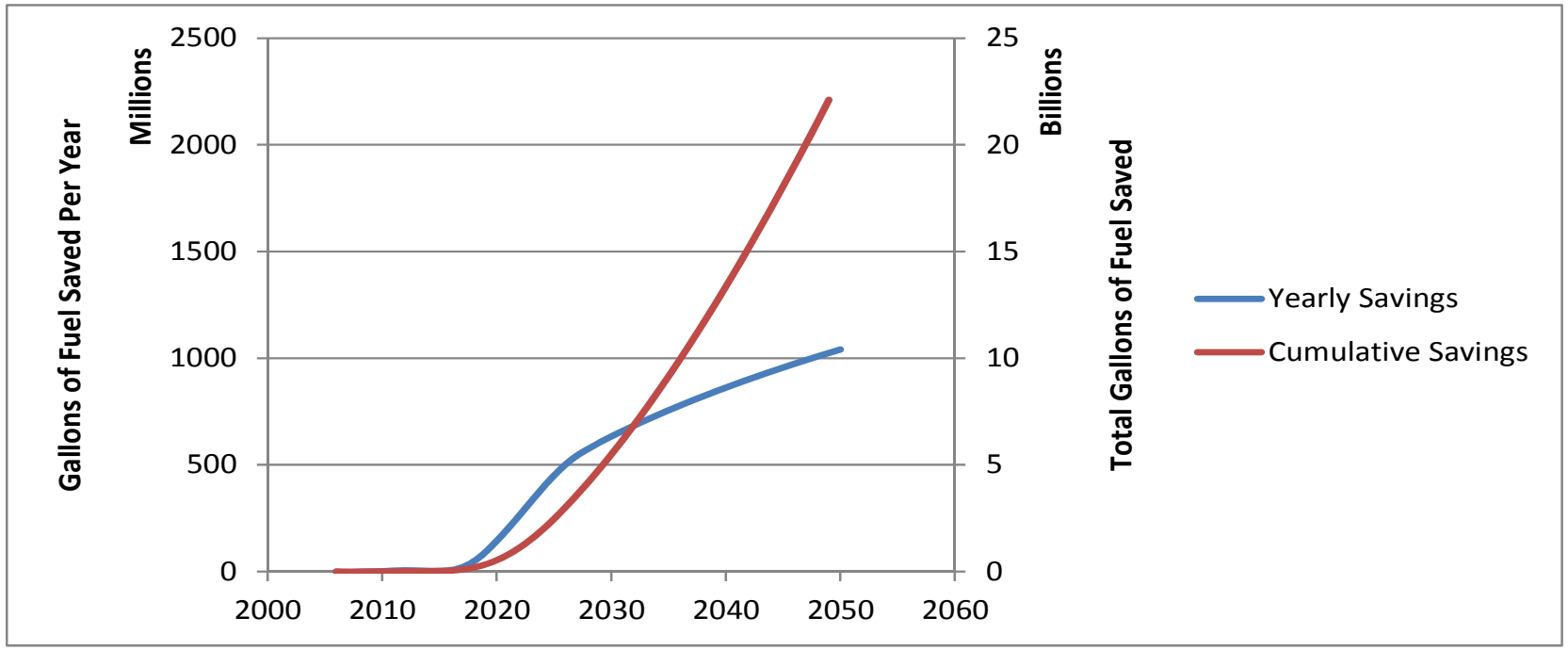


***Preliminary, do not cite or quote**

Detailed Breakout of Impacts

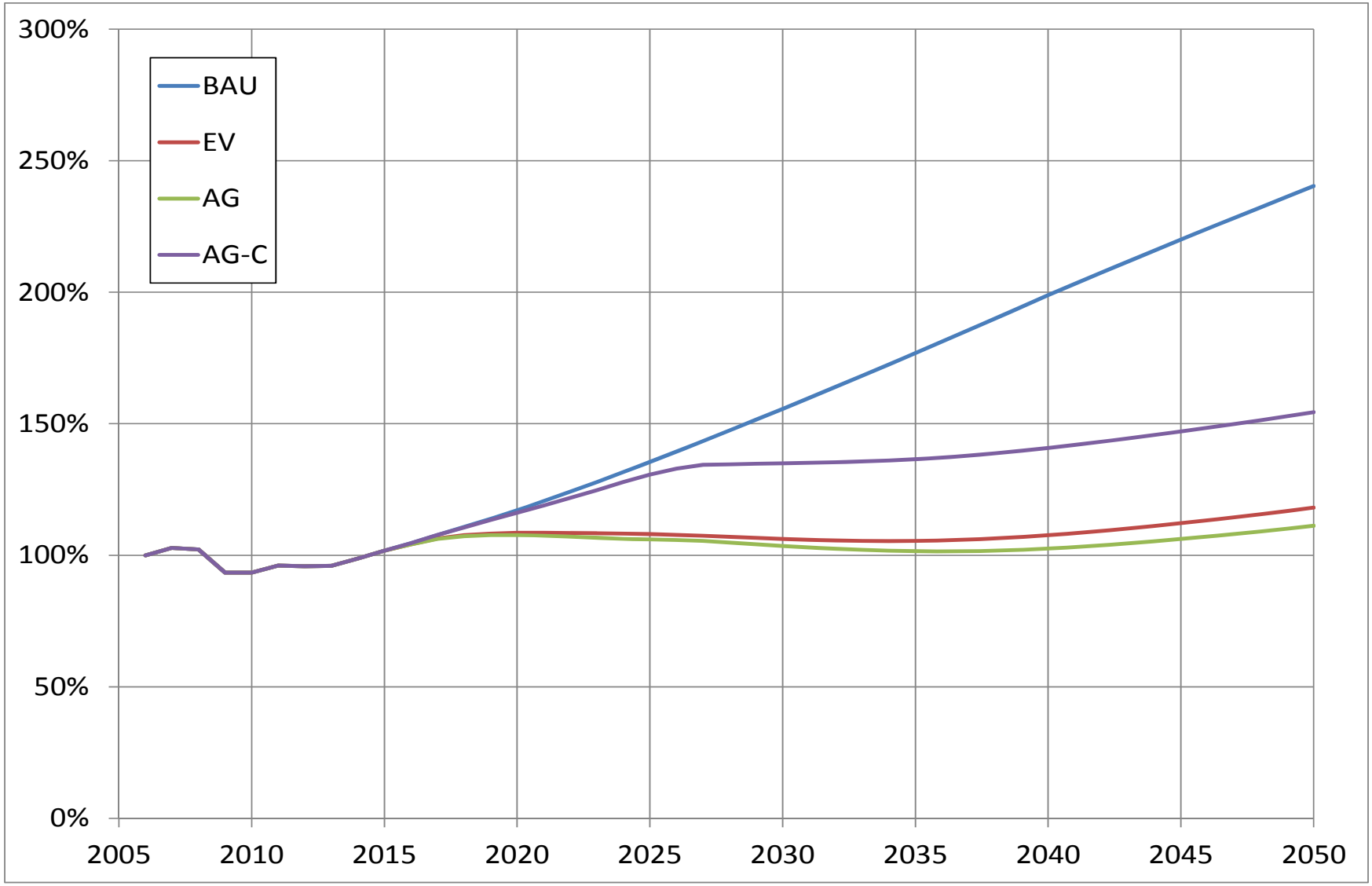
Scenario	2014 EV	2014 AG	2014 AG-C
2020	2%	3%	3%
2025	7%	8%	7%
2030	12%	16%	14%
2050	21%	28%	26%

- Chart to the left shows percent fuel burn savings relative to BAU scenario
- When translated to gallons of fuel saved impacts are significant
- Operational and alternative fuels technology can provide additional savings



***Preliminary, do not cite or quote**

2014 CLEEN Fleet NOx Results



***Preliminary, do not cite or quote**

Final Outcomes Under PARNTER

- Modeled a set of non-proprietary N+1 technologies representative of and/or complementary to CLEEN
- Modeled CLEEN technologies:
  - Boeing adaptive trailing edge, CMC acoustic exhaust nozzle
  - GE TAPS II combustor benefits captured with non-proprietary model – 60% NOx margin to CAEP/6
  - Honeywell turbine cooling
  - Pratt & Whitney ultra high bypass geared turbofan
  - Rolls-Royce dual wall turbine cooling, CMC blade tracks
- Technology model sets provide an excellent basis to be leveraged for ASCENT project 10. Their usefulness does not stop with the end of this project!
- Vehicle level assessments across 5 classes with EDS provided CLEEN with insight into CLEEN, other N+1, N+2 technology fuel burn, NOx, noise benefits
- Fleet level assessments with GREAT provided CLEEN with views of possible futures with different levels of technology, an idea of CLEEN's impact on these futures
- Provided FAA with in-house analysis capability (Excel dashboard delivered) for examining impact of a large list of technologies on 5 vehicle classes, with some control of key engine and aircraft parameters
- Documented in reports to FAA

Transition from PARTNER to ASCENT

- Georgia Tech's work to-date was completed under the FAA PARTNER center of excellence
- PARTNER has since been replaced with the ASCENT CoE
- New project under ASCENT expands modeling work, but focus still on technology modeling
  - CLEEN Assessments
  - Definition of fleet assessment scenarios
  - Vehicle mission change specifications
- Under the new effort two additional universities have been added to the team, led by Georgia Tech (PI: Dimitri Mavris)
  - Stanford: Vehicle design expertise (PI: Juan J. Alonso)
  - Purdue: Fleet system modeling expertise (PI: William Crossley)
- Georgia Tech still responsible for CLEEN industry technology modeling
  - Modeling stays proprietary
  - Continue to use existing NDA/PIA agreements

Overview

Objective: Develop and use technology, vehicle, and fleet models for assessments of an array of future aircraft performance scenarios at the vehicle and fleet level

- Provide modeling and assessment mechanism for CLEEN / CLEEN II
- Evaluate broader future scenarios out to 2050
- Support NextGen Goals Analysis and CAEP trends assessment

Approach:

1. Developing a set of harmonized fleet assumptions for use in future fleet assessments
   - Workshop/consensus approach with academia, government, industry experts invited
2. Modeling advanced aircraft technologies and advanced vehicles expected to enter the fleet through 2050
   - Leveraging previous modeling work in CLEEN, NASA programs heavily – filling gaps as necessary for scenarios developed in (1)
3. Performing vehicle and fleet level assessments based on input from the FAA and the results of (1) and (2).

Each university using in-house expertise and tools in complementary areas.

Aircraft Performance Analysis History

Most relevant past PARTNER CoE projects:

- Environmental Design Space (EDS) - P14: Georgia Tech
  - Development of EDS (vehicle level) and GREAT (fleet level) analysis tools
  - Support of noise stringency analysis for CAEP/9
  - Support of definition of long-term technology goals for CAEP
- CLEEN EDS - P36: Georgia Tech
  - Previous applied vehicle and fleet level technology assessment
  - Many technology models can be leveraged
- Mission Specification Changes - P43: Stanford, Georgia Tech and BAH
  - Great work that can be leveraged and built upon to look at these effects with technology insertion

In support of other National Programs:

- Environmentally Responsible Aviation (ERA)
  - Providing system analysis support for the ERA technology portfolio assessment for advanced N+2 concepts
- Subsonic Fixed Wing (SFW)
  - Providing system analysis support for the SFW technology portfolio assessment for advanced N+3 concepts (TBW, HWB, etc.)
- NASA Funded N+3 Contracts
  - Work under multiple NRA's to advanced SOA in hybrid electric propulsion systems

Team Approach to Tasks – Year 1

Objectives		Georgia Tech	Stanford	Purdue
1	**Harmonize Fleet Assumptions**	Lead process, coordinate industry, government participation, provide basis for discussion	Support assumptions definition, provide expert knowledge	Support assumptions definition, provide expert knowledge
2	**Advanced Vehicle and Technology Modeling**	CLEEN GE proprietary technology modeling, additional non-proprietary technology modeling, Provide tech models to SU and PU	Input into non-proprietary technology modeling	N/A
3	**Vehicle and Fleet Assessments**	Perform vehicle and fleet level assessments for CLEEN and non-proprietary technologies	Provide trade factors for mission specification changes. Provide tech factors for any tech modeled in (2)	Sample problem demonstrating capabilities of FLEET

GEORGIA TECH TASKS

Developing Fleet Assumptions

- **Objective:** Develop common fleet assumptions for future analyses
  - Agreement on list of available technologies
  - Applicability of each technology to different vehicles
  - Technology availability for each technology
  - Fleet replacement assumptions including entry into service opportunities for future aircraft by aircraft size class
  - Forecast assumptions
  - Airport noise assessment assumptions (ANGIM)
  - Vehicle retirement rate assumptions
  - Availability of advanced (i.e., non-tube-and-wing / turbofan) configurations
  - Baseline vehicles for each aircraft class

- **Impact:**
  - Document of agreed upon fleet assumptions for broader use
  - Can be referenced by multiple programs across government, industry, academia

Modeling of Technologies and Advanced Configurations

- **Objective:** Model advanced technologies at the aircraft level to feed into fleet assessment
  - Non-proprietary technology modeling
  - Proprietary CLEEN technology modeling
  - Mission specification changes
- **Sub-Tasks:**
  - Boeing CMC Nozzle (Noise; Fuel complete)
  - GE Open Rotor (Fuel / Noise / Emissions)
  - GE FMS-ATM
  - GE FMS-Engine
  - P&W GF (Fuel / Noise)
  - Non-proprietary technology modeling as identified from Task 1 / FAA
  - Provide public-domain 2013-2014 GT models to Stanford and Purdue for use in SUAVE / FLEET
- **Interactions:**
  - Purdue and Stanford for 2013-2014 non-proprietary EDS technology models
  - Purdue and Stanford input on non-proprietary technology modeling
  - GE / PW / Boeing for CLEEN assessments
- **Impact:**
  - System level assessment of CLEEN contractor technologies
  - Documented modeling methods for newly developed technology models
  - Copy of pre-existing NASA report describing NASA funded technology models applied in prior work under PARTNER P36

Fleet Level Assessments

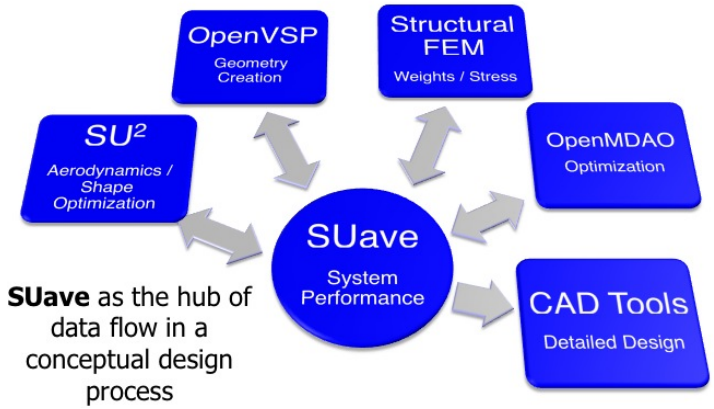
- **Objective:** Use fleet assumptions and technology models from Tasks 1 & 2 to conduct fleet assessment
  - Use GREAT (Fuel & Emissions) and ANGIM (Noise)
  - Public and proprietary scenarios
- **Sub-Tasks:**
  - Perform GREAT/ANGIM analysis using proprietary technology set
  - Perform GREAT/ANGIM analysis on non-proprietary technology set
- **Interactions:**
  - Provide non-proprietary AEDT fleet vehicle definitions to ASCENT Project 11
- **Impact:**
  - GREAT and ANGIM results for defined fleet scenarios
  - Influence of mission specification changes on fleet metrics

STANFORD TASKS

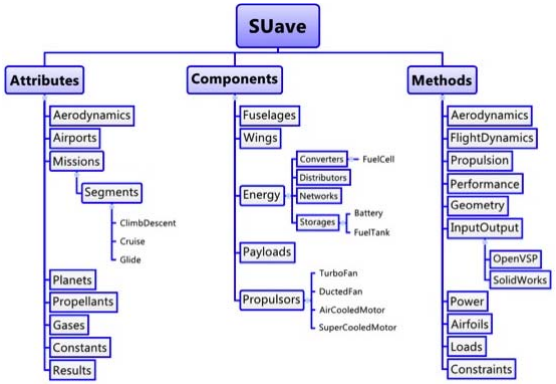
Objective 1 and 2 Contributions

- Leverage experience on a number of similar efforts:
  - ICAO/CAEP Long-Term Technology Goals for Fuel Burn (2009-11)
  - PARTNER Project 43 (2012-14)
  - ICCT Technical Advisory Group for technology cost estimation (Tecolote, 2013-present)
- Help broaden time horizons (beyond 2030), aircraft class applicability, and technology "baskets"
- Then, integrate technologies into vehicles, using SUave framework, to assess levels of performance
- Resulting vehicles can be propagated through the fleet to create future estimates

	Single Aisle				Twin Aisle			
	2024 - Evolutionary	2024 - Stretch	2024 - Aggressive		2024 - Evolutionary	2024 - Stretch	2024 - Aggressive	
		2034 - Evolutionary	2034 - Stretch	2034 - Aggressive		2034 - Evolutionary	2034 - Stretch	2034 - Aggressive
Viscous Aerodynamic Efficiency								
Nacelle	1.0%	3.2%	3.5%	3.5%	0.2%	2.5%	3.0%	3.0%
Wings	0.0%	2.0%	6.9%	9.8%	0.0%	2.0%	11.8%	11.8%
Empennage & Fuselage	0.0%	2.0%	4.0%	4.0%	0.0%	2.0%	4.0%	4.0%
LTTG Values (aircraft level)	2%	4%	7%	9%	2%	5%	8%	10%
Non-viscous Aerodynamic Efficiency								
Wings (in % improvement in drag)	6.8%	10.1%	11.4%	13.2%	4.0%	7.3%	16.0%	17.7%
Reduction of loads (active smart wings) - in % fuelburn	1.5%	1.5%	2.0%	3.0%	0.0%	1.5%	2.0%	3.0%
LTTG Values (aircraft level)	2%	4%	6%	7%	2%	4%	6%	7%
Engine								
Configuration	Direct Drive (Leap Engine)	GTF (PW1000G)	Improved GTF	Open Rotor	Direct Drive (GE90X)	Direct Drive	Direct Drive	Direct Drive
%SFC Improvement	16%	17%	22%	30%	10%	12%	14%	16%
%SFC Improvement modeled by Tecolote	15.3%	17.5%	19.6%	TBD	6%	10%	14%	TBD
LTTG Values (Propulsion)	13%	14%	15%	28* %	6%	8%	10%	12** %
LTTG Values (Thermodynamics)	3%	4%	5%	3* %	2%	3%	4%	5** %
Structures (aircraft level)	4%	12%	14%	22%	4%	12%	14%	22%
LTTG Values (aircraft level)	10%	15%	20%	20* %	10%	15%	20%	25** %

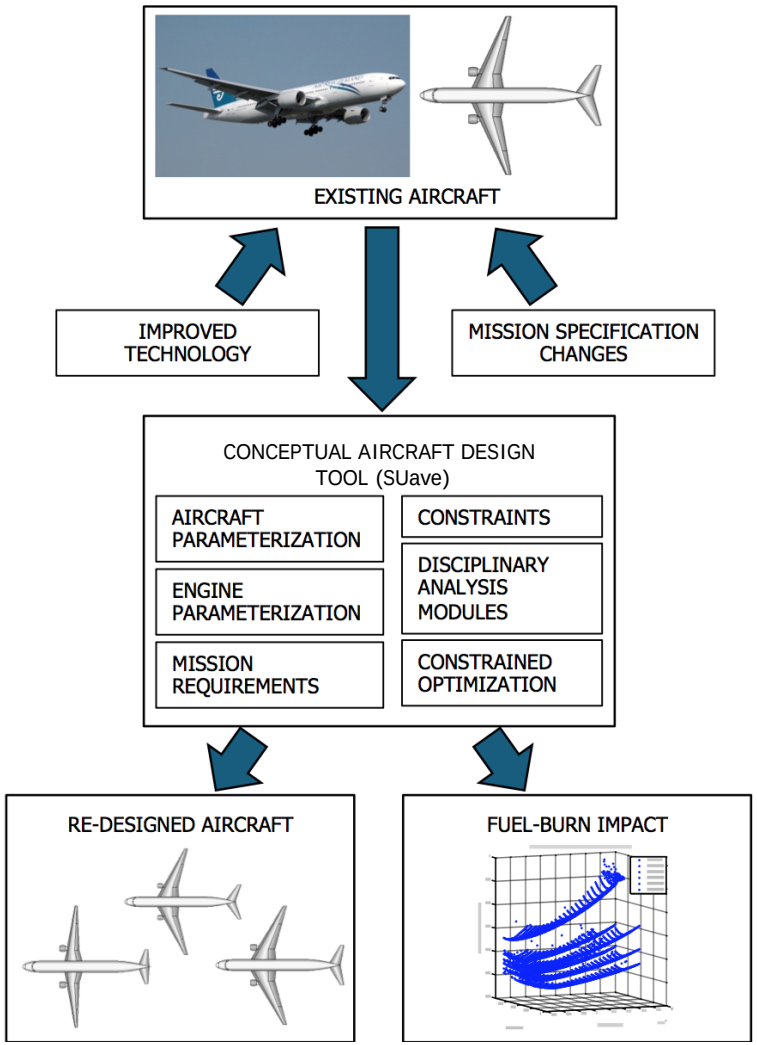


SUave as the hub of data flow in a conceptual design process



Objective 2 and 3 Contributions

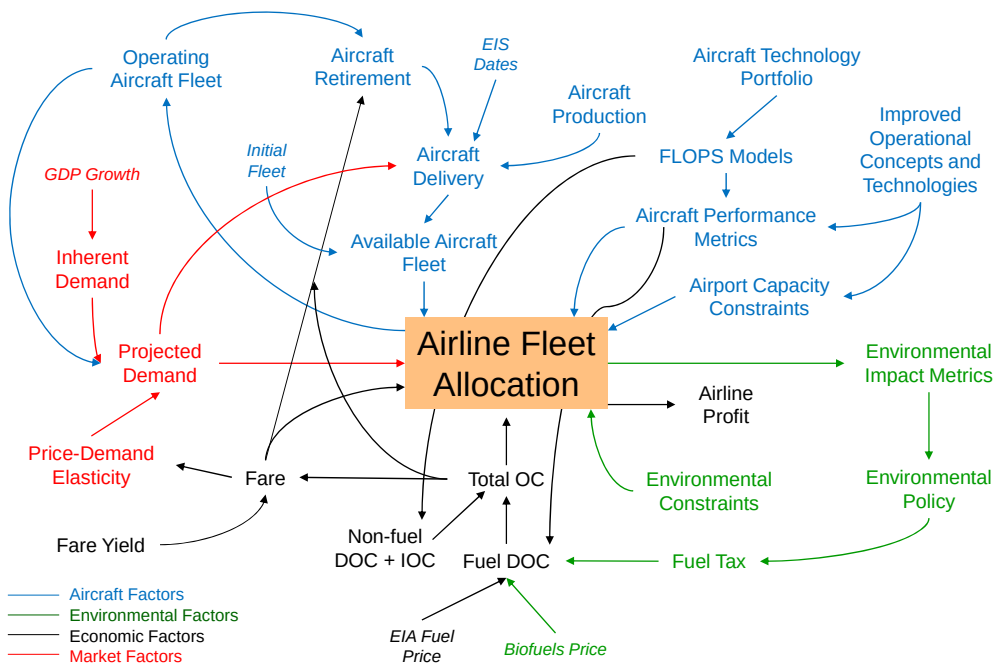
- Task 2 design efforts include both the redesign of future aircraft with advanced technologies, as well as the investigation (continuing the work in P43) into the potential of mission specification changes:
  - Payload / range characteristics
  - Cruise Mach number and altitude
  - Allowable span
  - Possibly, TOFL changes
- Results of Task 2 design efforts will be provided as technology factors to enable fleet-level propagation using harmonized fleet assumptions
- Task 3 involvement mainly as an input provider but also to help assess the outcome of the fleet-level simulations



PURDUE TASKS

Purdue Supporting Of Fleet Modeling

- Purdue's FLEET (Fleet-level Environmental Evaluation Tool) provides the ability to assess impact of various technology scenarios at the fleet-level
  - MATLAB-based, modular structure makes it easy to add, remove or modify sections to suit new assumptions
  - Supports quick implementation of model assumptions made in task 1 or new aircraft that may have been modeled in task 2
- A distinguishing feature from other similarly-motivated tools is FLEET's resource allocation approach to simulate how a service provider might deploy their fleet of existing and new aircraft to satisfy:
  a) their own goals (e.g., meet profit goal while satisfying demand)
  b) Constraints imposed on them by regulators (e.g., constrained number of operations at an airport, use of alternative fuels)



Near-Term Activities for Objective 3

- During the initial months of the project, the Purdue team will begin "sample" FLEET runs using the set of aircraft models developed at Purdue for the aforementioned NASA project, aiming to:
  - Explore how initial conditions evolve into various future scenarios that may deviate from the FAA's terminal area forecast or other future air traffic / air transportation predictions,
  - Demonstrate where FLEET has flexibility to adjust and perturb future economic scenarios, and
  - Familiarize our FAA colleagues with capabilities and limitations of FLEET.
- These initial "sample" runs will position the Purdue team to contribute to the more comprehensive fleet-level studies that build upon the harmonized fleet assumptions and consistently modeled new technologies and aircraft developed during Tasks 1 and 2.
  - Will work with teams from Georgia Tech and Stanford to define clearly the inputs needed by FLEET
  - As necessary, the Purdue team will also provide appropriate cost predictions with cost-estimating models consistent with our previous efforts

Project External Interfaces & Potential Collaboration

- Linkages with other AEE tools and analyses:
  - Will provide vehicle level performance results for use by Goals and Targets analysis, potentially other analyses
  - Will provide AEDT vehicle definitions of CLEEN/N+1/N+2 vehicles for use in analysis (NOI-11 – Rapid Fleet-Wide Environmental Assessment)
  - Will provide common fleet assumptions that can be used in other AEE analyses
  - Using fleet fuel, emissions, and noise assessment capability from Georgia Tech NOI-11 effort (GREAT/ANGIM)
  - Building on PARTNER Project 43: Will assess vehicle- and fleet-level potential for mission specification changes

So What's Next?

- Georgia Tech to finish industry technology modeling under CLEEN
- Series of workshops to be defined to bound fleet assessment scenarios
  - Fleet growth assumptions
  - Technology development assumptions
  - Will be contact all of your organizations for input
- Purdue and Stanford to demonstrate tool and analysis capabilities to integrate into next phase

Contributors

- Georgia Tech
  - Dr. Dimitri Mavris, Dr. Jimmy Tai, Dr. Holger Pfaender, Mr. Christopher Perullo, Mr. Ryan Donnan, Mr. Marcus Bakke, Mr. Benjamin Bitoun
- Stanford
  - Dr. Juan J. Alonso, Mr. Anil Variyar, Dr. Michael Colonno
- Purdue
  - Dr. William Crossley, Dr. Daniel DeLaurentis, Mr. Kushal Moolchandani, Mr. Parithi Govindaraju