# Project 010 Aircraft Technology Modeling and Assessment

## Georgia Institute of Technology, Purdue University, Stanford University

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**Georgia Institute of Technology**
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- FAA Award Number: 13-C-AJFE-GIT-006
- Period of Performance: August 1, 2014 – August 31, 2015

**Purdue University**
- P.I.(s): Dr. Daniel DeLaurentis, Dr. William A. Crossley (Co-PI)
- FAA Award Number: 13-C-AJFE-PU-004
- Period of Performance: August 1, 2014 – August 31, 2015

**Stanford University**

- P.I.(s): Dr. Juan J. Alonso
- FAA Award Number: 13-C-AJFE-SU-004
- Period of Performance: August 1, 2014 – August 31, 2015

# Project Funding Level
The project is funded at the following levels: Georgia Institute of Technology ($400,000); Purdue University ($59,979); Stanford University ($90,000). Cost share details for each university are below:

The Georgia Institute of Technology has agreed to a total of $400,000 in matching funds. This total includes salaries for the project director, research engineers, graduate research assistants and computing, financial and administrative support, including meeting arrangements. The institute has also agreed to provide tuition remission for the students paid for by state funds.

While Purdue University provides the majority of the 1-1 cost share for ASCENT 10-Purdue, about 10% of the cost share comes from a gift of the RDSwin-Pro aircraft design software from Conceptual Research Corp.

Stanford University has contributed matching funds for a total of $90,000 using a combination of elements. Firstly, Stanford University is cost sharing, through tuition reductions for the students working on this project, approximately $20,000 for the current period of performance. In addition, our partners at the International Council for Clean Transportation are providing in-kind cost-sharing for the remainder though internal and external efforts funded to better understand the impact of cruise speed reduction.

# Investigation Team
Georgia Institute of Technology
Principal Investigator: Dimitri Mavris
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Stanford University
Principal Investigator: Juan J. Alonso
Aircraft Modeling Technical Lead: Anil Variyar
The team also includes two additional graduate students that have been assisting with the technical work and the development of our aircraft optimization framework, SUAVE.

# Project Overview
This year Georgia Tech, Purdue, and Stanford partnered to investigate the impact of aircraft and vehicle technologies on future environmental impacts of aviation. This is a multi-step process involving the system assessment of FAA CLEEN program technologies by Georgia Tech, assessment of the impact of mission specification changes on public domain aircraft performance by Stanford, and the impact of future fleet modeling assumptions on system wide fleet fuel burn and emissions by Purdue.

The FAA's Continuous Lower Energy, Emissions and Noise (CLEEN) program office at the Office of Environment and Energy has established this project to perform research in the area of aircraft technology modeling and assessment. The research will be conducted as a collaborative effort in order to leverage capabilities and knowledge available from the multiple entities that make up the ASCENT university partners and advisory committee. Georgia Tech has partnered with Purdue University and Stanford University to complete the following objectives.

The primary objective of this research project is to support the FAA in modeling and assessing the potential future evolution of the next generation aircraft fleet while supporting the CLEEN program's goals and objectives. Research under this project consists of three integrated focus areas: (1) Developing a set of harmonized fleet assumptions for use in future fleet assessments; (2) Modeling advanced aircraft technologies and advanced vehicles expected to enter the fleet through 2050; and (3) Performing vehicle and fleet level assessments based on input from the FAA and the results of (1) and (2).

Due to extensive experience assessing CLEEN I, Georgia Tech is the lead for all three objectives described above. Stanford and Purdue will support the objectives as shown in Table 1: University Contributions for Year 1, listing the high-level division of responsibilities amongst the universities.

**Table 1: University Contributions for Year 1**

| Objectives | | Georgia Tech | Stanford | Purdue |
|---|---|---|---|---|
| 1 | Harmonize Fleet Assumptions | Drive 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 Boeing and GE proprietary technology modeling, additional public domain technology modeling, Provide tech models to SU and PU | Input into public domain technology modeling | N/A |
| 3 | Vehicle and Fleet Assessments | Perform vehicle and fleet level assessments for CLEEN technologies | Provide trade factors for mission specification changes. Provide tech factors for any tech modeled in (2) | Sample problem demonstrating capabilities of FLEET |

All three universities contributed to the development of harmonized fleet assessment assumptions. These assumptions form the basis of both the proprietary and public domain modeling work to be performed this year.

For the first year of this project Georgia Tech, independent of the two other universities, focused on finalizing the CLEEN I proprietary assessments due to existing non-disclosure agreements and detailed modeling knowledge acquired over the last four years. As part of this work Georgia Tech also performed CLEEN-specific analysis under objectives (2) and (3).

Stanford provided input based on its experience into applicable public domain technology modeling identified under objective (2) across the entire time horizon contemplated in this work. Stanford has also provided trade factors, resulting from redesign/resizing of all vehicle classes to account for changes in mission specification changes for a public domain mission analysis to be completed under objective (3). This task has helped to define the interfaces between Stanford's expertise with assessing mission specification changes and Georgia Tech and Purdue's expertise with fleet analysis.

Purdue has applied their FLEET tool under objective (3), using a subset of the fleet assumptions defined in objective (1) and public domain vehicle performance generated by Georgia Tech in prior years. This activity has demonstrated the capabilities of FLEET for assessment of fleet-level noise and emissions evolution as a result of new aircraft technologies and distinct operational scenarios.

## Major Accomplishments

The following were the major tasks completed under the first year of ASCENT Project 10:

**Fleet Level Workshop Assumptions**

Georgia Tech hosted a virtual workshop with a wide range of government, industry, and university participants on May 14th and a second follow up workshop is planned for August 27th to solicit input on worldviews and scenarios and which descriptors are the most important. Furthermore a number of scenarios have been presented to the workshop attendees.

Responses have been compiled and preliminary cross-section of results are presented in this report. A full set of proposed scenarios is being developed and will be presented back to the workshop participants and will be published in a future report.

**Technology Level Workshop Assumptions**
Georgia Tech hosted virtual workshops with a wide range of government, industry, and university participants on June 10th and June 11th to solicit input on technology impacts and maturation rates in a wide range of topic areas. Responses have been compiled and preliminary results are presented in section 2.4.2. A full set of proposed technology evolution roadmaps is being developed and will be presented back to the workshop participants before publishing in a future report.

**CLEEN Technology Modeling**
Georgia Tech successfully incorporated the GE Flight Management Systems technologies for both the engine and airframe into the fleet assessments. The open rotor was also assessed on a fuel burn and emissions basis. Additionally, noise modeling for the Boeing ceramic matrix composite acoustic exhaust nozzle was completed. Vehicle level impacts and modeling assumptions are provided in a separate, proprietary appendix. However the fleet level impacts are assessed in Task 3.

**Demonstration of FLEET**
Using FLEET, Purdue simulated a series of future aviation scenarios developed in discussion with the FAA, and using public domain Georgia Tech modeled N+1 and N+2 generation aircraft instead of the Purdue modeled aircraft in FLEET. The scenarios simulated include the "Aggressive minus CLEEN" scenario as specified in the CLEEN PARTNER Project 36 report, plus others that studied the impact of capacity constraints at airports and airline competition. With further studies, Purdue assessed the sensitivity of future aviation emissions to variations in fuel prices, market demand, and the dates of technology availability. Thus, Purdue has demonstrated FLEET capabilities to simulate a range of future aviation scenarios as well as its flexibility to handle different inputs.

**Fleet Level Assessment of CLEEN Technology**
Georgia Tech has successfully incorporated all of the CLEEN program technologies into a fleet level assessment of fuel burn, emissions, and noise. The impacts are significant and show CLEEN may lead to a potential fuel savings of an average of 534 million gallons of fuel per year through 2050, leading to a cumulative savings of 24 billion gallons of jet fuel. In addition to significant NOx emission reductions, 65 DNL noise contours could be reduced more than 40% in area, which could enable a 40% increase in operations without increase noise relative to a scenario in which CLEEN technology does not enter the fleet.

**Vehicle-Level Assessment of Mission Specification Changes**
During this first portion of Project 10, the group at Stanford University has focused on (a) the development of the necessary analysis and optimization capabilities within the SUAVE framework, (b) the development and validation (with publicly-available data) of model vehicles in each of the five ICAO/CAEP aircraft classes, and (c) a preliminary study of the fuel-burn-reduction opportunities afforded by decreases in cruise Mach number when re-designing (including airframe and engine) these aircraft. The intent is to transfer the improved vehicles to the GT team, so that they can insert such vehicles in the fleet-level analyses done with GREAT. The Stanford team has also supported the team’s activities for the preparation and conduct of both the fleet-level and technology workshops.

# Task 1: Developing Fleet Assumptions
Georgia Institute of Technology

## Objective(s)
In order to develop assumptions suitable for a forward looking fleet level analysis that incorporates new vehicle technologies, it is necessary to forecast the future. However, most forecasts are extrapolations of the current status quo and current trends, which assume an undisturbed continuation of historical and recent developments. This type of forecasting is necessary and useful, but will miss any significant changes or disturbances to the current market environment. If one considers changes to the status quo or constraints that might prevent current trends to continue, a possibility space of overwhelming dimensionality opens up. This dimensionality makes it intractable to fully explore all possibilities.

## Research Approach
The approach taken here is to reduce the overwhelming dimensionality by selecting a small number of well-defined scenarios. The scenarios should encompass future states that are important for specific consideration of significant changes that could

occur and also to bind at least some of the most important future outcomes that could conceivably occur. Therefore the first goal of the workshop series was to define a range of scenarios to bound aviation's environmental impacts in the future and to examine the effects of aircraft technology on these impacts.

Due to the diverse expertise needed to come to consensus on a set of scenarios, two parallel workshop tracks were undertaken. The first track focused on fleet level trends and assumptions, including future demand and fleet evolution. A second track focused on the state and future of aircraft technologies that reduce fuel burn, emissions, and noise. The information gathered in both these focused workshop tracks is planned to be combined to fully define future bounding scenarios and assess the potential of aircraft technology to improve aviation's environmental impact. The fleet level trends are first discussed in section 0, followed by the technology trending workshops in section 0.

## Major Accomplishments

**Fleet Workshops**
In order to create these scenarios a series of two fleet workshops were held in order to engage participants from industry, academia, and government and gather a diversity of opinions and expertise. The first workshop was held on May 14th 2015. Attendees included representatives from: The U.S. Air Force, Airports Council International – North America, Booz Allen Hamilton, Boeing, Department of Transportation Volpe Center, Embraer, FAA Office of Environment and Energy, FAA Office of Aviation Policy & Plans, Georgia Tech, Honeywell, Mitre, NASA, Pratt & Whitney, Purdue, Rolls-Royce, Stanford, Textron Aviation and Virginia Tech. The purpose of this workshop was to decompose the scenario assumptions for the fleet level analysis into high level descriptions of an envisioned future state, which by themselves could include multiple scenarios. Scenarios themselves, however, were intended to be detailed specific descriptions of a future state within a particular worldview.

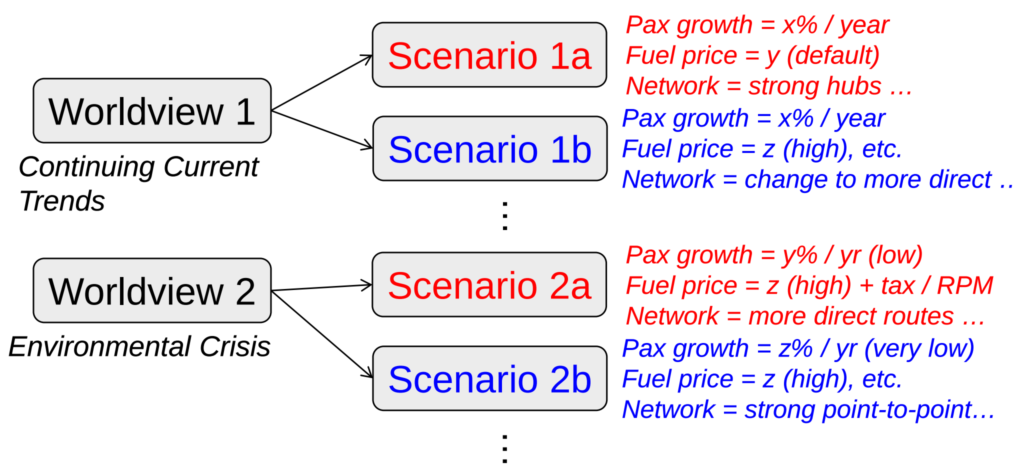


**Figure 1: Decomposition of Fleet Assumptions into Worldview and Scenarios**

An example of this is shown in Figure 1, which shows an example of worldviews and scenarios that could be derived from them with specific assumptions listed on the right. The goal of this first workshop was to agree on a variety of worldview and scenario descriptors by asking the attendees about the relative importance of a list of preselected descriptors. Additionally the attendees were given the opportunity to suggest additional descriptors that were not already listed in the survey. Furthermore, the workshops purpose was to define a set of low/medium/high levels for each descriptor. To this end the workshop materials were created with as specific a definition and quantifiable units of each descriptor as possible.

For the purpose of the workshop the preselected descriptors were grouped into themes that as a whole cover the entire spectrum of assumptions necessary to define future states of aviation. The themes were:
- Economic Factors
- Aviation Industry Factors
- Environmental Factors
- Technological Factors

The potential descriptors were based on existing forecasts out of which the three most common were selected to provide the current trends or values that illustrate the importance of a specific descriptor. The forecasts were:

- FAA Aerospace Forecast
- Boeing – Current Market Outlook (CMO)
- Airbus – Global Market Forecast (GMF)

Furthermore, it should be noted that the specific assumptions and predictions contained in these forecasts are subjective and as a result can vary to some degree – in some cases drastically – between them.

**Economic Factors**

***Gross Domestic Product (GDP) Growth***

The first descriptor is probably one of the most important economic variables. GDP describes the overall economic development of a specific region or country and in thought to be representative of a nation's wealth. Changes in GDP are primarily due to two components. First the change in economic activity, which if expressed in per capita terms introduced the second components as change in population that together drive changes in the overall wealth of a country. As shown in Figure 2, aviation trip demand is highly correlated to GDP per capita and shown large increases in travel trip demand when growing from low levels and small increases when growing from higher levels. Shown in Figure 3 are the levels of the annual percent growth from the FAA Forecast. Therefore the unit for this descriptor was selected as the percent average annual GDP growth in %/year. The question asked attendees was: What is the future annual change of US GDP growth?

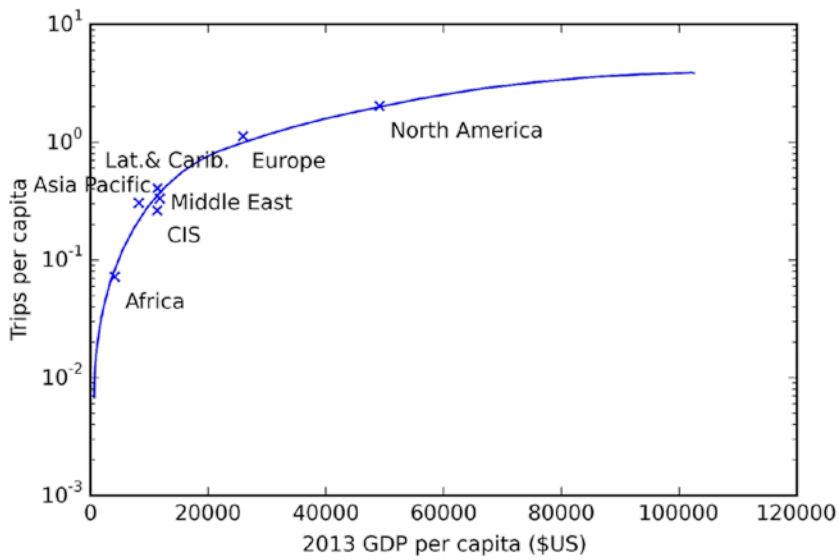


**Figure 2: Aviation Demand is Driven by per Capita GDP, Adopted from [1]**

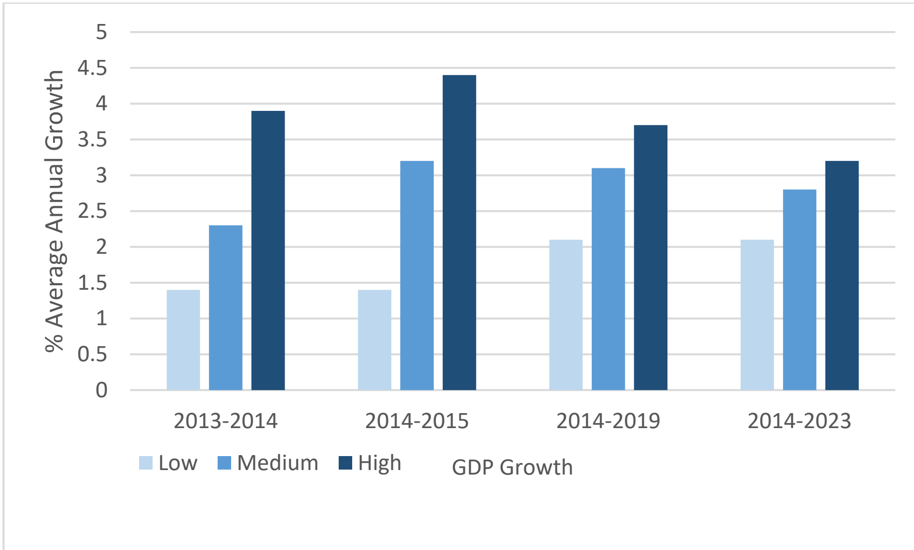


**Figure 3: GDP Growth [2]**

***Interest Rates***

Interest rate is usually the rate at which interest is accrued as a result of borrowing money. The importance for aviation is that it could serve as an important determinant in business decisions to decide whether launching a new aircraft project or purchasing a new aircraft are profitable. The interest rates that firms are offered are usually based on the risk free interest rate plus a risk premium. This together with a few other factors is what is usually termed the cost of money, which is the interest rate used in Net-Present-Value or similar valuation approaches for decision making. Therefore, as an example Figure 4 and Figure 5 show the 10-Year Treasury interest rate development over the last decade. They represent as close as possible the risk free interest rate. Changes in this interest rate can have a significant effect on the interest rate charge to firms since it represent the underlying interest rate upon which most other interest rates are based on. The question asked to the workshop participants was: What is the future long term average real risk free interest rate?


**Figure 4: 10 Year Treasury Inflation Indexed Security Interest Rate**


**Figure 5: 10 Year Treasury Constant Maturity Interest Rate**

***Population Growth***

Population is another underlying factor that is a large driver of economic activity and can lead to increased passenger traffic. The question asked attendees was: What is the future average annual US population growth?

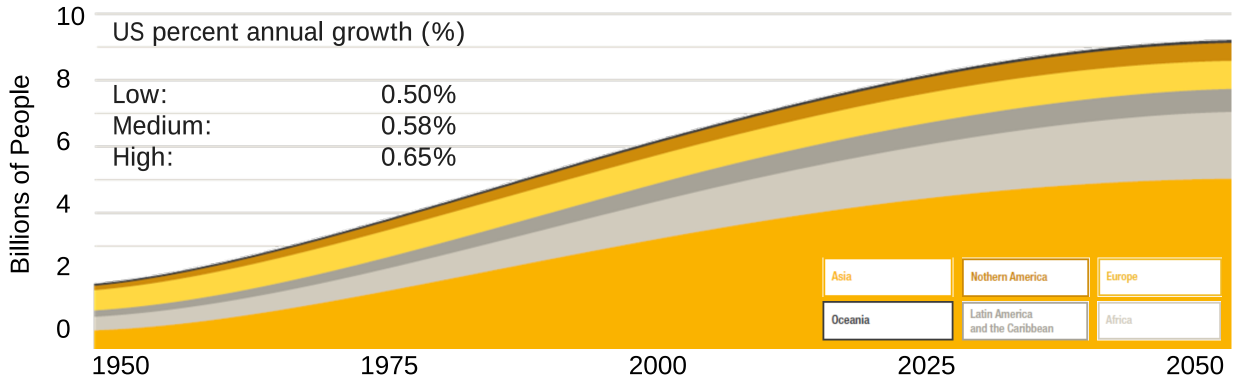


**Figure 6: Global Population Growth, Adopted from [1] and US Census 2014 Projections**

***Labor Force***

The labor force composition describes the makeup and the number of people available to work. Some underlying demographics can cause significant long term shifts. The middle age group tends to travel the most with reduced travel demand in early and old age groups being observed. The question asked attendees was: What is the future average participation rate?

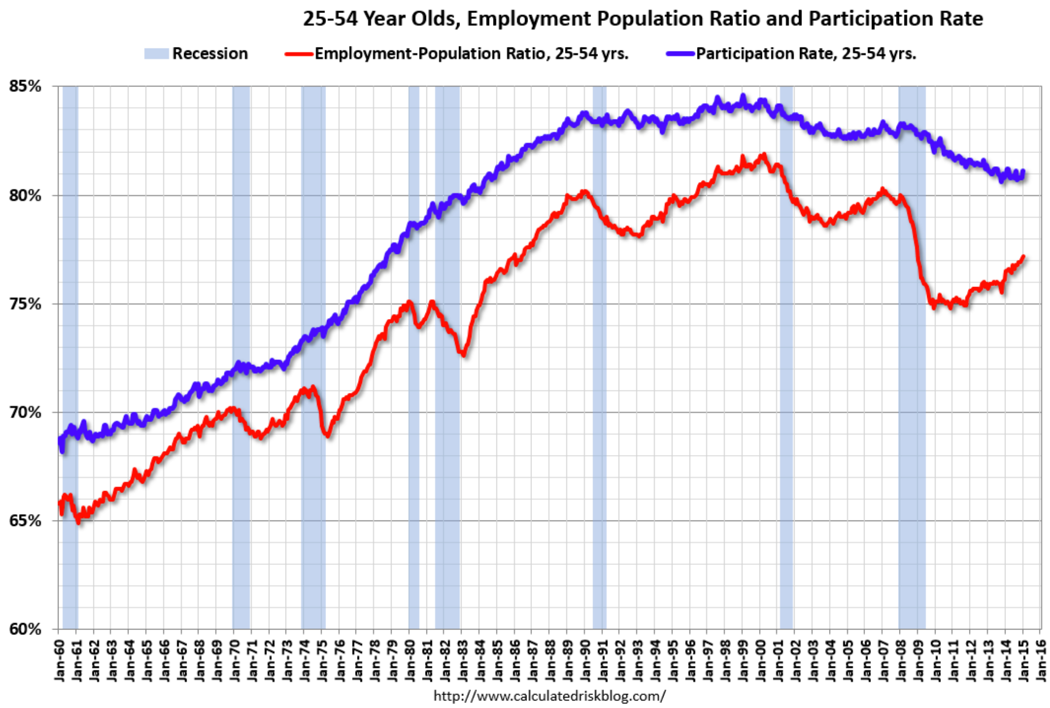


**Figure 7: Participation and Employment-Population Ratio [Calculated risk from BLS DATA]**

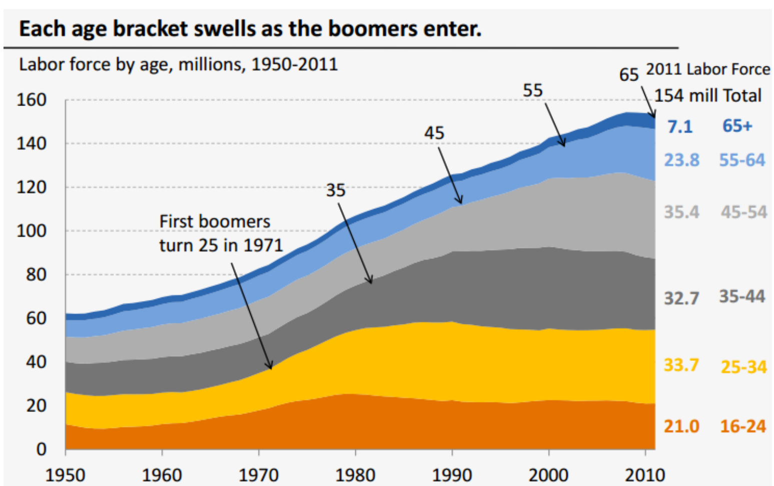


**Figure 8: Age Distribution, Adopted from [3]**

### *International Trade*

International trade measures the exchange of capital, goods, and services across international borders or territories. It can represent a significant portion of a country's GDP. This portion of GDP is highly influenced by global trade policies, that either represent open border or protectionist policies. Therefore, shown in Figure 9 is the trend of the share of exports to GDP for the US for the last 60 years. What can be observed is a long term trend of increases from very low levels. The last few years showed the share of GDP to be as high as almost 14%. Furthermore, the amount of this trade is influenced by the economic growth outside of the US. Therefore Figure 10 shows the economic growth rates around the world that are significant for aviation from the latest FAA Forecast. Attendees were asked the following question: What is the future average GDP growth in the major international trade partner regions?


**Figure 9: US Share of Exports to GDP**

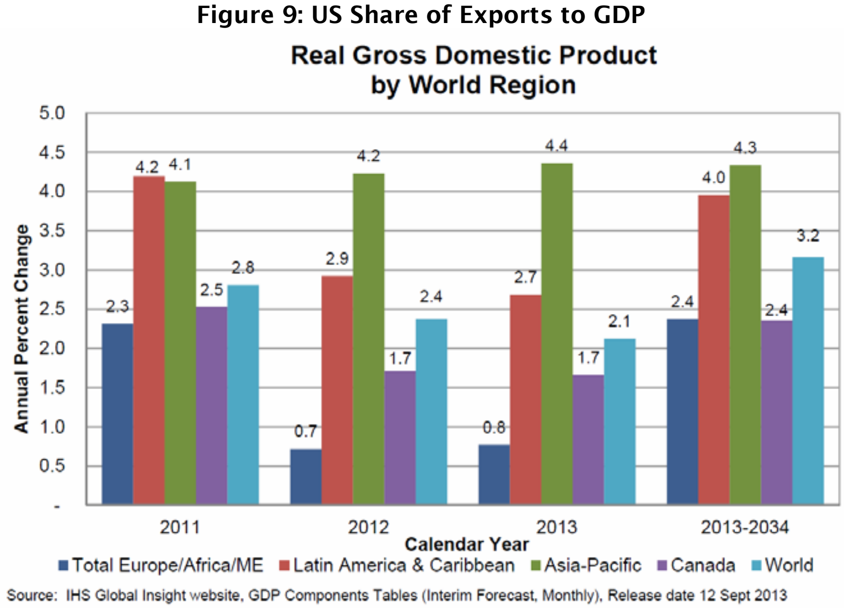


**Figure 10: Global GDP Growth Rates [2]**

***Modal Competition***

Competition between various modes of transportation such as airplanes, cars, trains, buses, etc. represent the popularity of each form of travel. Changes in the modal shares depend heavily on travel times and cost. Significant technological advances in different mode of transportation may change the aircraft travel demand. A common mode share determinant is trip distance. Figure 11 and Figure 12 show the total person trip distribution and the percent share for a few select types of transportation. The data used to create these charts is from the 1995 American Travel Survey. The question asked the attendees was: What is the average future aviation mode share trend for the 400-1000mi distance trips?

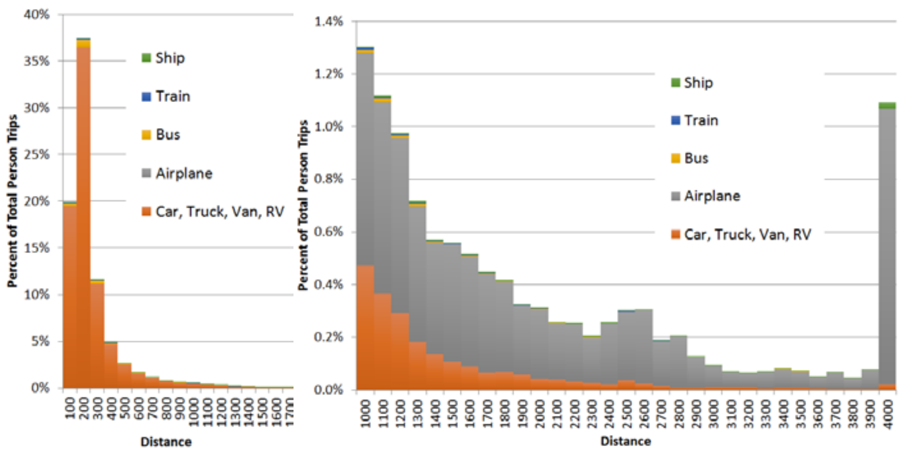


Figure 11: Total Person Trip Distribution [4]

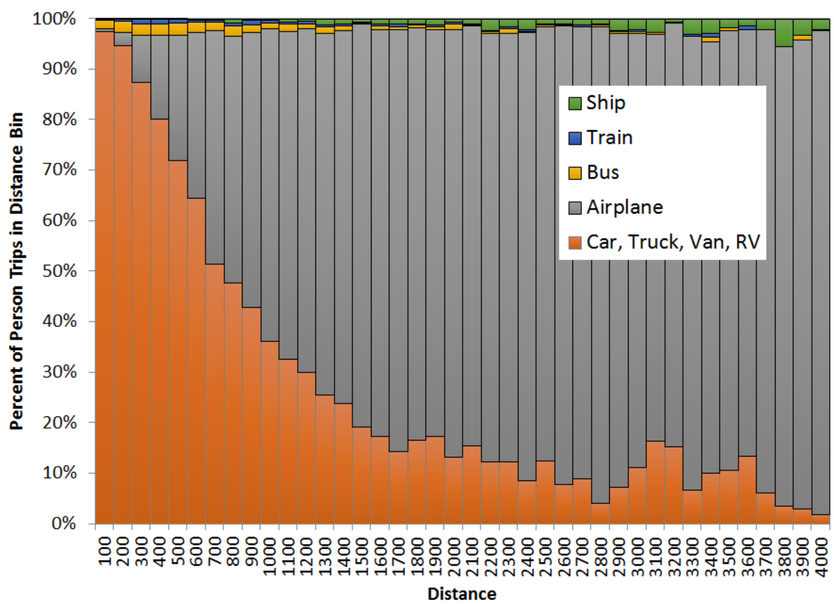


Figure 12: Modal Share as a Function of Distance [4]

***Energy Price***

The price paid for energy, specifically in the case of aviation the price of aviation fuels, are an important factor that determine the cost of travel for aviation. The underlying fundamental factor is the price that refineries that produce aviation fuels pay for the raw oil that is refined. Therefore, the attendees were asked the following question: What is the future trend of the oil price?

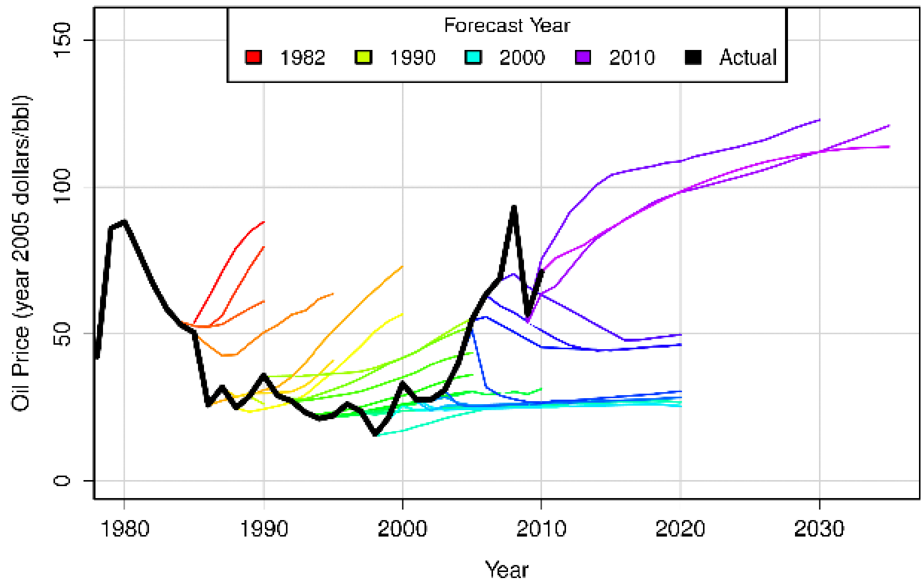


**Figure 13: Analysis if EIA Annual Energy Outlook Forecasts [5]**

Figure 14 and Figure 15 show the survey questions for the economic factors described in the previous sections.

The following **economic factors** have been selected to describe potential world views. Please rank them in their relative slope/sensitivity of potential impact to describe any potential world views.

| | No Impact | Very Low Impact | Significant Impact | Very High Impact | Not Sure |
|---|---|---|---|---|---|
| **GDP Growth (avg. annual growth)** | ○ | ○ | ○ | ○ | ○ |
| **Interest Rates (avg. annual growth)** | ○ | ○ | ○ | ○ | ○ |
| **Population Growth (avg. annual growth)** | ○ | ○ | ○ | ○ | ○ |
| **Labor Force Composition (participation rate)** | ○ | ○ | ○ | ○ | ○ |
| **International Trade** | ○ | ○ | ○ | ○ | ○ |
| **Modal Competition (% share)** | ○ | ○ | ○ | ○ | ○ |
| **Energy Price ($/bbl)** | ○ | ○ | ○ | ○ | ○ |

**Figure 14: Survey Economic Factors Importance**

As mentioned previously, the questions related to the values for each major descriptor required quantitative replies, with attendees asked to indicate low, medium, and high values for possible futures.

| Descriptor | Units | Disagree? | Low | Medium | High | Explanation |
|---|---|---|---|---|---|---|
| GDP Growth (Domestic) | %/yr | ☐ | 2.1 | 2.8 | 3.2 | |
| Interest Rates | %/yr | ☐ | 2.0 | 8.5 | 15.0 | |
| Population Growth | %/yr | ☐ | 0.50 | 0.58 | 0.65 | |
| Labor Force Composition | % | ☐ | 68.0 | 76.0 | 84.0 | |
| GDP Growth: Asia | %/yr | ☐ | 3.6 | 4.3 | 5.0 | |
| GDP Growth: Europe | %/yr | ☐ | 0.6 | 2.4 | 4.2 | |
| GDP Growth: Latin America | %/yr | ☐ | 2.7 | 4.0 | 5.3 | |
| Modal Competition | % | ☐ | 20.0 | 50.0 | 80.0 | |
| Energy Price | $/bbl | ☐ | 40 | 70 | 150 | |

**Figure 15: Economic Factors Ranges**

## Environmental Factors

### *CO2 Emissions*

CO2 emissions are directly proportionate to the amount of fuel consumed. There are concerns about the effects these emissions have on the global climate. Therefore, it is possible that airlines could face some charges for these emissions. The large charge in effect currently in Europe is shown in Figure 16. Due to variety of charging schemes possible, the question asked the attendees was simplified to: What is the future average cost of CO2 emissions?

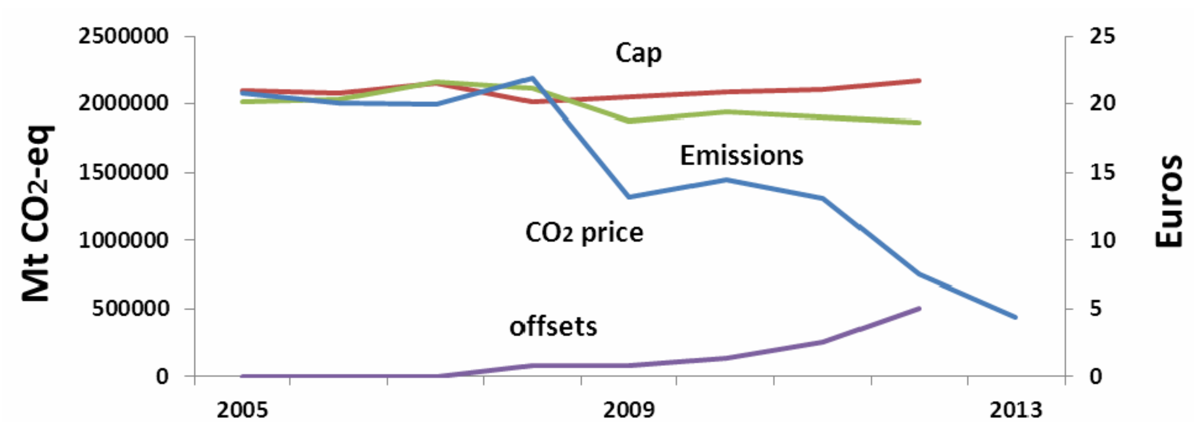


**Figure 16: European ETS CO2 Price and Quantity [6]**

### *NOx Emissions*

NOx Emissions are of concern due to the effect on the air quality in communities surrounding airports. NOx emissions are of particular interest as there are existing airport charges related to NOx emissions and Heathrow recently proposed a significant increase in their NOx charges [7] Therefore, concerns about NOx emissions could result in airline operational charges. The modeling use would be thorough effects of additional costs on demand, airline decisions, and manufacturer decisions. The question asked the attendees was: What is the future average cost of NOx emissions at these U.S airports?

| Loc ID | Reg | Airport Name |
|---|---|---|
| ATL | ASO | HARTSFIELD - JACKSON ATLANTA INTL |
| ORD | AGL | CHICAGO O'HARE INTL |
| LAX | AWP | LOS ANGELES INTL |
| DFW | ASW | DALLAS/FORT WORTH INTL |
| DEN | ANM | DENVER INTL |
| JFK | AEA | JOHN F KENNEDY INTL |
| SFO | AWP | SAN FRANCISCO INTL |
| LAS | AWP | MC CARRAN INTL |
| CLT | ASO | CHARLOTTE/DOUGLAS INTL |
| PHX | AWP | PHOENIX SKY HARBOR INTL |
| IAH | ASW | GEORGE BUSH INTERCONTINENTAL/HOUSTON |
| MIA | ASO | MIAMI INTL |
| MCO | ASO | ORLANDO INTL |
| EWR | AEA | NEWARK LIBERTY INTL |
| SEA | ANM | SEATTLE-TACOMA INTL |
| MSP | AGL | MINNEAPOLIS-ST PAUL INTL/WOLD-CHAMBERLAIN |
| DTW | AGL | DETROIT METROPOLITAN WAYNE COUNTY |
| PHL | AEA | PHILADELPHIA INTL |
| BOS | ANE | GENERAL EDWARD LAWRENCE LOGAN INTL |
| LGA | AEA | LA GUARDIA |
| FLL | ASO | FORT LAUDERDALE/HOLLYWOOD INTL |
| BWI | AEA | BALTIMORE/WASHINGTON INTL THURGOOD MARSHALL |
| IAD | AEA | WASHINGTON DULLES INTL |
| SLC | ANM | SALT LAKE CITY INTL |
| MDW | AGL | CHICAGO MIDWAY INTL |
| DCA | AEA | RONALD REAGAN WASHINGTON NATIONAL |
| HNL | AWP | HONOLULU INTL |
| SAN | AWP | SAN DIEGO INTL |
| TPA | ASO | TAMPA INTL |
| MEM | ASO | MEMPHIS INTL |

**Figure 17: Core 30 US Airports**

The additional question was asked: What percent of the Core 30 US airports do you envision will charge for NOx emissions? The list of Core 30 airports given to the participants is shown in Figure 17.

***Non-Volatile Particulate Matter Emissions***

The inclusion of non-volatile particulate matter emissions was due to the concern about the effects of these emissions on air quality, which could result in airline operational charges. Aircraft emissions influence air quality in surrounding communities. Non-volatile particulate matter emissions are the primary pollutant impacting air quality and community health impacts in the vicinity of airports and also play a minor role in climate impacts.

The background information presented was limited to mentioning that standard and regulations are currently in development and advances in alternative fuels and combustion designs will help mitigate production of particulate matter. The units suggested for numeric responses were dollars per kg nvPM emissions in (USD/kg). The suggested modeling use was primarily through the effect of additional costs on demand, airline decisions, and manufacturer decisions. The questions asked participants were: Do you think that nvPM emissions will have a cost in the future? If so, what percent of the Core 30 U.S.

airports do you envision will charge for nvPM emissions? What is the future average cost of nvPM emissions at these U.S. airports?

***Noise***

Noise here refers to noise produced by aircraft or its components during various phases of flight. The area around airports exposed to significant noise depends on the number of flight operations and the operational details and type of the aircraft used. If the number of operations increase, the noise emissions per aircraft operation have to decrease in order to not increase the relative area. Concern about the effects of airport noise on the health and quality of living could result in airline operational charges. For example, limits on activity and frequency of flights as well as scenarios with more stringent noise constraints could be envisioned. The measure selected for noise was the percent of the core 30 U.S. airports. The use in modeling for this is the effect of airline and manufacturer decisions through possible operational limits and the result can affect aircraft choice. The questions participants were asked to answer were: What percent of the core 30 U.S. airports do you think are currently noise limited? What percent of the core 30 U.S. airports do you envision will be noise limited in the future?

**Aviation Industry Factors**

***Quality of Service***

Quality of service represents the quality or service provided by airlines. This includes services such as new nonstop city pairs as well as greater frequency in flights, thus resulting in more flexible flight times for passengers. Various airline operations scenarios can be modeled which would account for changes in airline quality of service. For example, more frequent flights and new nonstop city pair locations could be modeled by changing flight schedules. Figure 18 shows historical data from the BTS sample ticket database that is one attempt to measure how many passengers travelled on connecting flights instead of travelling on direct flights. This does not necessarily mean a direct flight would have been available, but rather that the passenger did have a connecting flight. Therefore modeling use could be achieved by potentially adjusting how passenger Origin-Destination demand is served by airlines with actual flight connections. The metric used here was the ratio of total to only direct tickets. The question participants were asked was: What is this ratio in 2050?

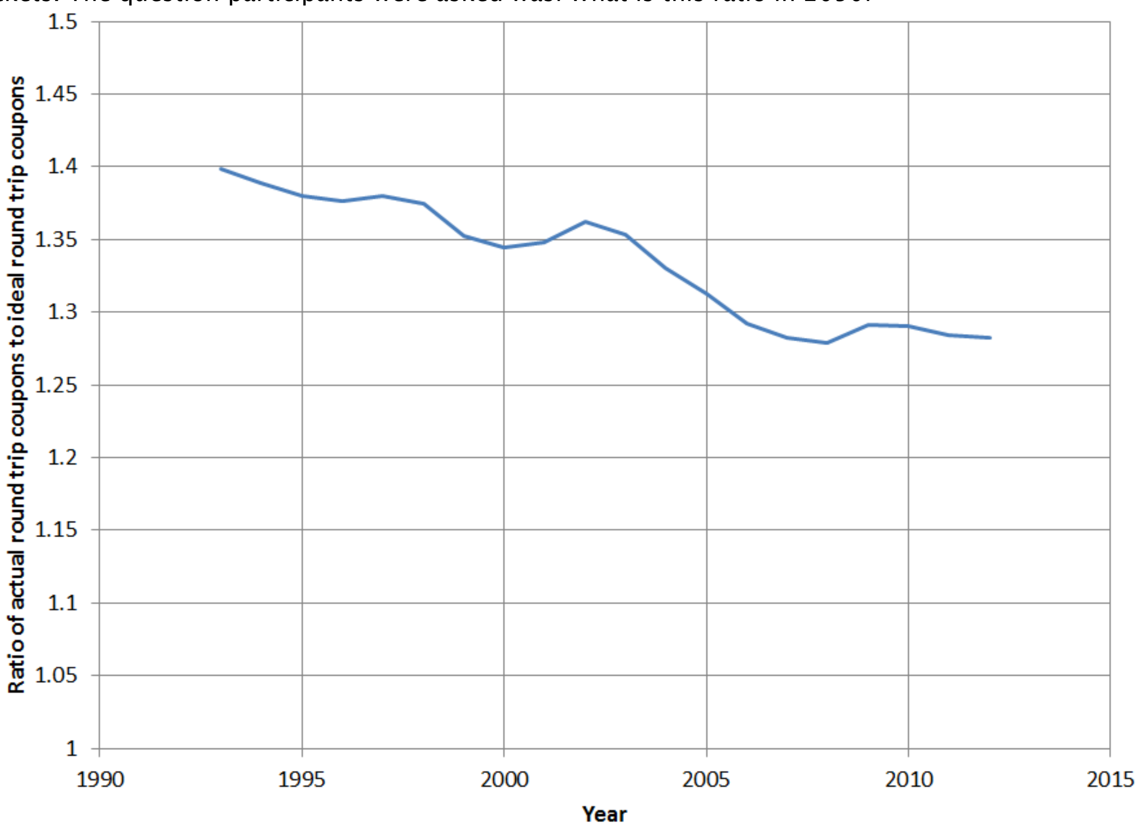

**Figure 18: Ratio of Actual to Ideal Round Trip Coupons [8]**

***Travel Attractiveness***

This refers to the amenities provided during travel such as flexible portal times, cabin comfort, seat pitch, etc. Improvements in travel attractiveness could lead to increases in travel demand. The modeling use would be to adjust mode shares relative to competing transportation modes. The scale of unit is the relative attractiveness on a scale from 0-100. This is then further defined as relative attractiveness to other modes equal 50 means it is even to average competing mode and greater than 50 means better than average competing mode and less than 50 means worse than average competing mode. The question participants were asked was: What is the future average of the relative attractiveness of aviation?

***Industry Competitiveness***

This describes the level of competition between airlines as well as the cost structure. Some examples of this are: Number of airline competitors, airline consolidation, and new entrants to airline market. The units for this factor that were used was: Yield per passenger/seat-mile or revenue per passenger seat-mile. This represents the revenue required to break even which is strongly related to operating costs and the amount airlines can charge. Industry competition can lead to reduced prices and increased travel demand as a result of airlines competing for customers. The modeling use is to utilize the cost structure of airlines which can impact passenger demand. The question participants were asked was: What is the future average relative required passenger yield for airlines?

***Openness of Air Services and Domestic Airline Regulation***

This describes the level of flexibility of air services and domestic airline regulation. Reducing such regulations could give airlines more freedom in planning routes, capacity, and pricing to improve operational efficiency. Some examples of this include: Open Skies Agreements, Lifting Ownership Restrictions, Code Share Agreements, and Gate Slot Assignments. The use in modeling would be through adjusting network structures and capacity. The unit for this factor a relative levels which could be current, open, or restrictive. The question asked participants was: What is the future trend of airline regulations?

The following **aviation industry factors** have been selected to describe potential world views. Please rank them in their relative slope/sensitivity of potential impact to describe any potential world views.

| | No Impact | Very Low Impact | Significant Impact | Very High Impact | Not Sure |
|---|---|---|---|---|---|
| **Quality of Service (ratio of total to only direct tickets)** | ○ | ○ | ○ | ○ | ○ |
| **Travel Attractiveness (relative)** | ○ | ○ | ○ | ○ | ○ |
| **Industry Competitiveness (passenger yield)** | ○ | ○ | ○ | ○ | ○ |
| **Openness of Air Services and Domestic Airline Regulation (relative)** | ○ | ○ | ○ | ○ | ○ |

For the **aviation industry factors**, we have defined lower, middle, and upper possible values based on the associated references. Please indicate if you would like to suggest a change to the impact levels based on your expert knowledge or other sources.

| Descriptor | Units | Disagree? | Low | Medium | High | Explanation |
|---|---|---|---|---|---|---|
| Quality of Service | total/ direct | ☐ | 1.25 | 1.30 | 1.40 | |
| Travel Attractiveness | rel | ☐ | 20 | 50 | 80 | |
| Industry Competitiveness | cent/ ASM | ☐ | 20 | 12 | 8 | |
| Openness of Air Services and Domestic Airline Regulation | rel | ☐ | Open | Current | Restrictive | |

**Figure 19: Aviation Industry Factors Section of the Workshop Questionnaire**

Figure 19 shows the environmental factors section of the workshop questionnaire that participants were asked to fill out. As mentioned previously, the questions related to the values for each major descriptor required quantitative replies, with attendees asked to indicate low, medium, and high values for possible futures.

**The following environmental factors have been selected to describe potential world views. Please rank them in their relative slope/sensitivity of potential impact to describe any potential world views.**

| | No Impact | Very Low Impact | Significant Impact | Very High Impact | Not Sure |
|---|---|---|---|---|---|
| **Cost of CO2 Emissions ($/MT)** | ○ | ○ | ○ | ○ | ○ |
| **Cost of NOx Emissions ($/kg)** | ○ | ○ | ○ | ○ | ○ |
| **Cost of nvPM Emissions cost ($/kg)** | ○ | ○ | ○ | ○ | ○ |
| **Airport noise limitations (Percent of airports)** | ○ | ○ | ○ | ○ | ○ |

For the **environmental factors**, we have defined lower, middle, and upper possible values based on the associated references. Please indicate if you would like to suggest a change to the impact levels based on your expert knowledge or other sources.

| Descriptor | Units | Disagree? | Low | | Medium | | High | | Explanation |
|---|---|---|---|---|---|---|---|---|---|
| Cost of $CO_2$ Emissions | $/MT | ☐ | 0 | | 15 | | 50 | | |
| Cost of CO2 Mechanism | | ☐ Tax | | | ☐ Offset Charge | | ☐ Trading System | | |
| NOx Charges | % of Airports | ☐ | 0 | | 10 | | 100 | | |
| NOx Emissions cost | $/kg | ☐ | 0 | | 12 | | 25 | | |
| nvPM Emissions will have a cost in the future? | | ○ Yes | ○ No | | | | | | |
| nvPM Charges | % of Airports | ☐ | 0 | | 10 | | 100 | | |
| nvPM Emissions cost | $/kg | ☐ | 0 | | ? | | ? | | |
| Noise Limited currently | % of Airports | ☐ | 0 | | 10 | | 100 | | |
| Noise Limited in the future | % of Airports | ☐ | 0 | | 10 | | 100 | | |

**Figure 20: Environmental Factors Section of the Workshop Questionnaire**

Figure 20 shows the environmental factors section of the workshop questionnaire that participants were asked to fill out. As mentioned previously, the questions related to the values for each major descriptor required quantitative replies, with attendees asked to indicate low, medium, and high values for possible futures.

**Technological Factors**

***Amount and Speed of Technology R&D Investment***
This refers to the level of funding and emphasis placed on aerospace technology research and development. Government R&D investment in technology could reduce the uncertainty of technology performance as well as accelerate the time at which manufacturers decide to launch new aircraft with the specific technology. The modeling use would the through the availability of technology and also aircraft performance impacts. The units are a scalar with settings relative to current levels such as current, high and low. The question asked participants was: What is the future trend of government R&D investments relative to current trends?

***Airline Load Factor Development and Limits***
This describes limits imposed on the ratio of revenue passenger miles to available seat miles. This can be a measure of an airline's capability to match supply with demand. Improvements in airline load factors could result in reduced prices, increased travel demand, as well as increased industry competition. The modeling use is through airline supply of aircraft flying relative to passenger demand. The units are percent of aircraft seats occupied. Many forecasts currently suggest that this could peak at ~85% for the domestic U.S. An example of this is shown in Figure 21. Therefore settings for low/medium/high of 82%/83%/85% were suggested. The question participants were asked was: What is the future load factor limit?

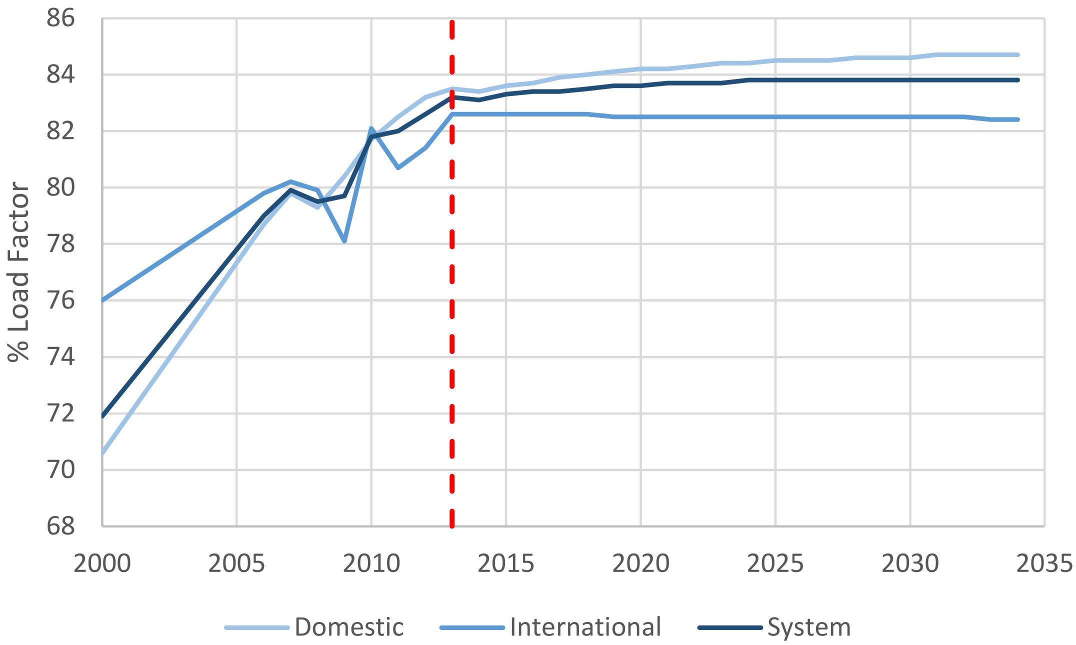


**Figure 21: FAA Forecast Load Factor [2]**

The following **technological factors** have been selected to describe potential world views. Please rank them in their relative slope/sensitivity of potential impact to describe any potential world views.

| | No Impact | Very Low Impact | Significant Impact | Very High | Not Sure |
|---|---|---|---|---|---|
| **Amount and Speed of Technology R&D Investment (relative)** | ○ | ○ | ○ | ○ | ○ |
| **Airline Load Factor Development/Limits (% of seats occupied)** | ○ | ○ | ○ | ○ | ○ |

For the **technological factors**, we have defined lower, middle, and upper possible values based on the associated references. Please indicate if you would like to suggest a change to the impact levels based on your expert knowledge or other sources.

| Descriptor | Units | Disagree? | Low | Medium | High | Explanation |
|---|---|---|---|---|---|---|
| Amount and Speed of Technology R&D Investment | rel | ☐ | 0.5 | 1.0 | 1.5 | |
| Airline Load Factor Development/ Limits | % | ☐ | 82 | 83 | 85 | |

**Figure 22: Aviation Industry Factors Section of the Workshop Questionnaire**

The results of the first workshop are shown in Outreach Efforts. They include a ranking of importance.
Table 2 shows the eight descriptors ranked by the attendees as the most important in order of decreasing importance.

**Table 2: Descriptors in Order of Decreasing Importance**

| |
|---|
| GDP Growth |
| Energy Price |
| Cost of CO2 Emissions |
| Population Growth |
| International Trade |
| Airport Noise Limitations |
| Industry Competitiveness |
| Amount and Speed of Technology R&D Investment |

This was one of the results used to create the materials for the second workshop. For example, a number of specific scenarios have been created using variations of the resultant settings of each descriptor that came out of the first workshop. The second workshop will also pose a number of questions regarding timing of future aircraft and the corresponding technology insertion opportunities, aircraft age in service, and production capacity. The details of the second workshop will be included in a future report.

**Technology Road mapping Workshops Overview**

The goal of the technology road mapping workshops is to develop a range of scenarios bounding possible futures for technology impact and entry into service. Such information will be used to model advanced aircraft technologies and advanced vehicles expected to enter the fleet through 2050. A publically available document will be prepared that documents suggested scenarios including technology impact, time to entry into service, and examples of specific technologies.

Two virtual workshops were held on June 10th and 11th of 2015 to solicit feedback from government, industry, and academia on a wide range of aircraft technology topic areas. Attendees included representatives from: The U.S. Air Force, Booz Allen Hamilton, Boeing, Department of Transportation Volpe Center, Embraer, FAA Office of Environment and Energy, Georgia Tech, Honeywell, Lufthansa, Mitre, NASA, Pratt & Whitney, Purdue, Rolls-Royce, Stanford, Textron Aviation and Virginia Tech. The workshop was constructed to ask for information on examples of first, second, and third generation technologies. The first virtual workshop focused on airframe and operational technologies whereas the second focused on engine and operational technologies. Operational technologies were included in both workshops since they affect both aircraft and engine systems. As discussed during the workshop, participants were made aware that the final results of the survey would be published as aggregated data. Specific identifiers would be removed prior to publication other than a general list of organizations that participated. Participants were also made aware of the primary intent to use the data to quantify the potential aircraft and engine technology to meet the FAA's environmental goals.

In order to solicit meaningful feedback without asking for sensitive, proprietary information the Georgia Tech team constructed a survey that solicited information on technologies in the following areas:

- **Availability** – When will the technology be ready for entry into service (EIS)?
- **Applicability to subsystems and vehicle class** – Where on the aircraft/engine can the technology be applied? What sizes of aircraft are applicable? How does this change as the technology evolves?
- **Maturation Rate** – How quickly does each generation of a technology mature to technology readiness level (TRL) 9?
- **Delineation between different generations of a technology** – How does the technology evolve as it matures over several product generations?
- **Primary impact areas** – What metrics on the aircraft are impacted by the technology?

**Technology Road mapping Survey Format**

A survey format was developed in Microsoft Excel to allow respondents to provide feedback in a structured manner that ensured consistency between responses and reduced the burden of filling out the survey. First, the survey was divided into multiple technology 'topic areas'. Broadly speaking, the technologies were classified into three distinct branches, *engine, airframe, and operational technologies.* Technologies were then further subdivided into technology areas as shown in Figure 23. Workshop participants were asked to provide information on three different generations of each technology area at the right-most level of the tree. It was left to workshop participants to define what constitutes a generational change in a technology area; however, as an example, the use of ceramic matrix composite (CMC) technology within an engine can be broken into different generations. A first generation application may involve the use of CMC on the turbine shroud and other static parts outside of the main flow path. Once more experience is gained with CMC; the material may be used in turbine vanes as a second generation application. Further development may enable the use of CMC on highly stressed rotating parts, such as turbine blades. Participants were asked to provide specific examples in each technology area to help baseline their opinion on delineations between technology generations.

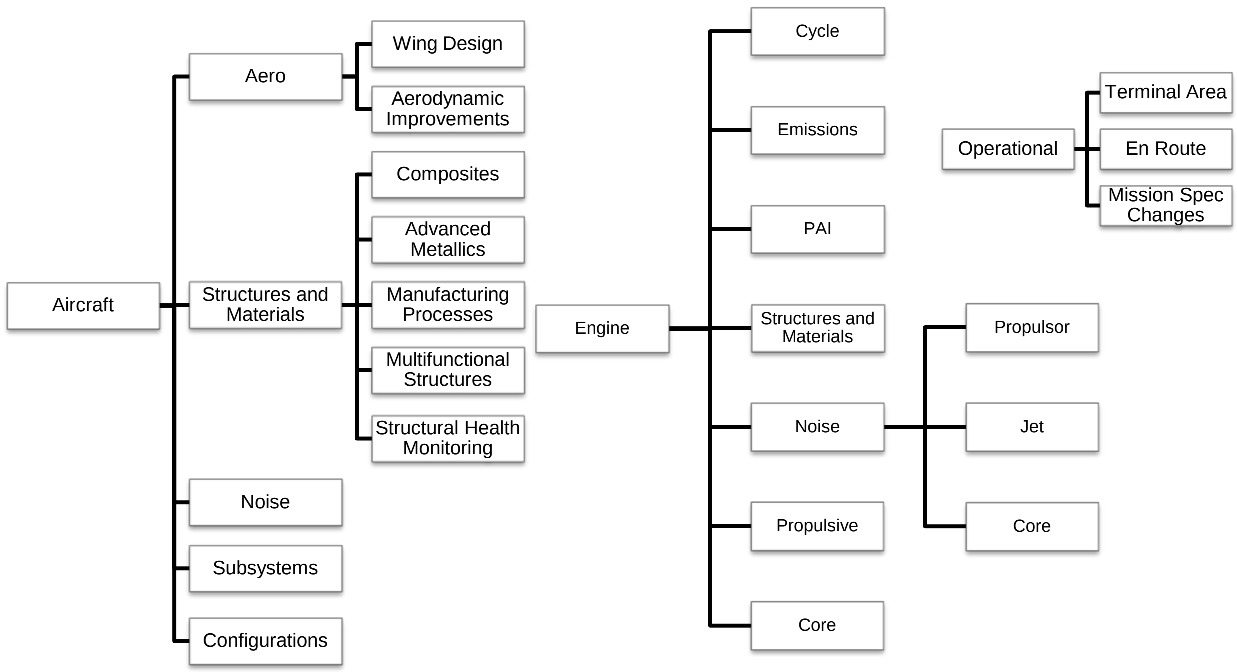


**Figure 23: Technology Categorization**

For each of the technology categories in Figure 23, a Microsoft Excel survey was constructed. Three generations of each category were placed on a single worksheet, all of which had a consistent structure, shown in Figure 24. The figure shows 1st generation wing design; however all technology areas had a consistent structure, with the contents of each colored box adjusted accordingly.

# Survey Format

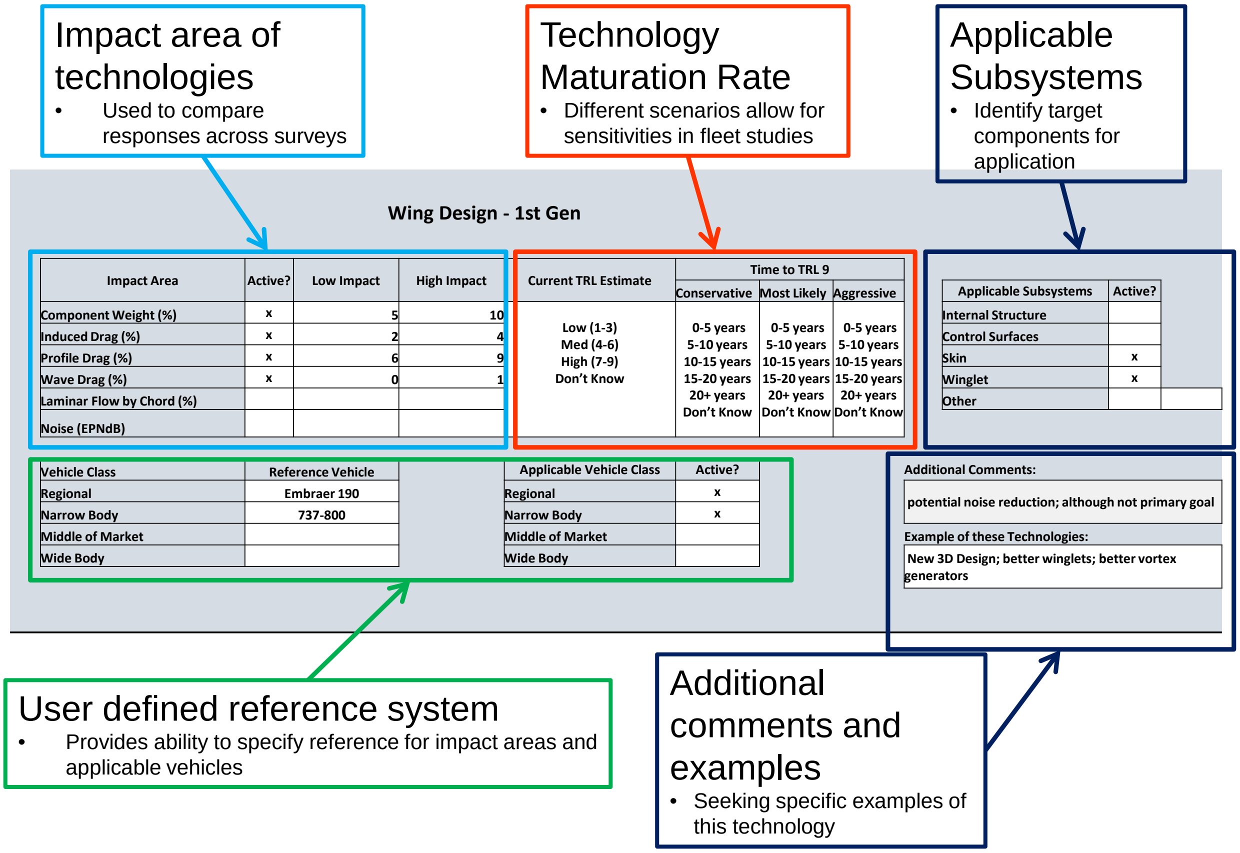


**Figure 24: Technology Road mapping Survey Format**

Working clockwise from the upper left of Figure 24, participants were asked for information on the impact of each generation within a technology category. The impact areas were chosen to be at an intermediate level of fidelity. For example, the wing design impacts were solicited as percent reductions from the current state of the art for weight, drag, laminar flow, and noise. Since multiple technologies could be included in a first generation wing design, participants were asked to list the total benefits for all technologies being considered. Moving to the right, the red box asked for the current TRL and estimated time to TRL 9. The current TRL estimate was grouped into low (TRL 1-3), medium (TRL 4-6), and high (TRL 7-9). This grouping was selected to allow for multiple technologies to be included in a generation, reduce the possibility of asking for sensitive data, and to account for some level of uncertainty in the technology development process. Under the time to TRL 9, responses were sought for three scenarios, a conservative, most likely, and aggressive technology progression. Possible responses were grouped into 5 year bins up through 20+ years. Moving to the upper right, applicable subsystems were listed for each technology area with check boxes that participants could easily select. On the lower left, participants were asked to provide a reference system which they used to estimate the reductions listed in the impact areas. Vehicle applicability was also requested to identify applicable size classes for the technology. Finally, write-in boxes were provided in the lower right to allow for any comments and concerns in addition to specific examples of technologies that should be classified within the provided technology area and generation.

Table 3 provides a complete listing of the impact areas and applicable subsystems Georgia Tech identified for each technology. Examples of each technology area were also provided to participants in order to help baseline responses.

**Table 3: List of Impact Areas and Applicable Subsystems for Each Technology Category**

| Category | Examples | Impact Areas | Applicable Subsystems |
|---|---|---|---|
| **Aircraft Wing Design** | Adaptive Trailing Edge<br>Gust/Maneuver Load Alleviation<br>Hybrid Laminar Flow Control<br>Spiroid Winglets | Component Weight (%)<br>Induced Drag (%)<br>Profile Drag (%)<br>Wave Drag (%)<br>Laminar Flow by Chord (%) | Internal Structure<br>Control Surfaces<br>Skin<br>Winglet Design |
| **Aircraft Aerodynamic Improvements** | Drag reduction coatings<br>Friction-reducing surface coatings<br>Electro-magnetic technologies for drag reduction in cruise | Induced Drag (%)<br>Profile Drag (%)<br>Wave Drag (%)<br>Laminar Flow by Chord (%) | Fuselage<br>Wing<br>Vertical Tail<br>Horizontal Tail |
| **Aircraft Composites** | Damage Arresting Stitched Composites<br>Damage Tolerant Laminates<br>Tow Steered Fiber Composites<br>Hybrid Nanocomposites | Component Weight (%)<br>Reduction in Factor of Safety (%) | Fuselage<br>Wing<br>Vertical Tail<br>Horizontal Tail |
| **Aircraft Advanced Metallics** | Functionally Graded Metallics<br>Curvilinear Stiffened Metal Structures<br>Advanced Superalloys<br>Advanced Powder Metallurgy | Component Weight (%)<br>Reduction in Factor of Safety (%) | Fuselage<br>Wing<br>Vertical Tail<br>Horizontal Tail |
| **Aircraft Manufacturing Processes** | Ultrasonic Shot Peening<br>Out-of-Autoclave Composite Fabrication<br>Post-buckled Structures | Component Weight (%)<br>Reduction in Factor of Safety (%) | Fuselage<br>Wing<br>Vertical Tail<br>Horizontal Tail |
| **Aircraft Multifunctional Structures** | Primary Structure Joining Methodologies<br>Unitized Metallic Structures | Component Weight (%)<br>Reduction in Factor of Safety (%) | Fuselage<br>Wing<br>Vertical Tail<br>Horizontal Tail |
| **Aircraft Structural Health Monitoring** | Wireless Integrated Strain Monitoring and Simulation System<br>Fiber-optic Embedded Composites | Component Weight (%)<br>Reduction in Factor of Safety (%) | Fuselage<br>Wing<br>Vertical Tail<br>Horizontal Tail |
| **Aircraft Noise** | Continuous Moldline Link for Flaps<br>Slat Inner Surface Acoustic Liner<br>Over the Rotor Acoustic Treatment<br>Landing Gear Integration | Approach Noise (EPNdB)<br>Sideline Noise (EPNdB)<br>Cutback Noise (EPNdB)<br>Source Noise (dB) | Slats<br>Flaps<br>Landing Gear<br>Wing/Tail |

| Category | Examples | Impact Areas | Applicable Subsystems |
|---|---|---|---|
| **Aircraft Subsystems** | Solid Oxide Fuel Cell<br>Auxiliary Power Unit<br>Hybrid Wing Ice Protection System<br>Fly-by-Light Systems<br>Lithium Batteries for Secondary Power | Component Weight (%)<br>Fuel Burn (%)<br>Drag (%)<br>On board electrical energy consumption (%)<br>On board pneumatic energy consumption (%)<br>On board hydraulic energy consumption (%) | APU<br>ECU<br>Avionics and Control |
| **Aircraft Configurations** | Large-span aircraft (with or without truss- / strut-braced wings)<br>Lifting fuselage (e.g., double bubble fuselage with conventional engine mounting)<br>Integrated propulsion systems (boundary layer ingestion)<br>Blended/Hybrid wing body (HWB) | Emissions (%)<br>Fuel Burn (%)<br>Noise (EPNdB) | Truss Braced Wing<br>Double Bubble<br>Hybrid Wing/Body |
| **Engine Cycle** | Direct Drive Cycle<br>Geared Fan Cycle<br>Open Rotor Cycle<br>Hybrid Electric<br>Pulse Detonation Core Engine<br>Variable Core Cycle Technology | TSFC (%)<br>Engine Weight (%)<br>Noise (EPNdB)<br>Emissions (%) | Direct Drive<br>Geared Fan<br>Open Rotor |
| **Engine Emissions** | Twin Annular Premixing Swirler (TAPS)<br>Lean Direct Ingestion (LDI)<br>Partially Evaporating Rapid Mixing Combustor (PERM)<br>Lean Premixed Prevaporised Combustor (LPP) | $NO_x$ (%)<br>UHC (%)<br>nvPM (%) | |
| **Engine Propulsion Airframe Integration** | Low Interference Nacelle<br>Natural Laminar Flow<br>Fluidic Vaneless Thrust Reversers<br>Short Inlet<br>Engine placement | Interference Drag (%)<br>Nacelle Drag (%)<br>Component Weight (%)<br>Noise Reduction (EPNdB) | Pylon<br>Nacelle |
| **Engine Structures and Material** | Ceramic Matrix Composite (CMC) Nozzle<br>Polymer Matrix Composite (PMC) Fan Case<br>High Temperature Corrosion Coatings | Component Weight (%)<br>Reduction in Factor of Safety (%) | Fan<br>Compressor<br>Turbine<br>Nacelle |

| Category | Examples | Impact Areas | Applicable Subsystems |
|---|---|---|---|
| **Engine Propulsor Noise** | Fan Vertical Acoustic Splitter<br>Noise Cancelling Stator<br>Fluidic Injection<br>Stator Sweep and Lean<br>Variable Geometry Chevrons | Approach Noise (EPNdB)<br>Sideline Noise (EPNdB)<br>Cutback Noise (EPNdB)<br>Source Noise (dB) | Treated Fan Forward Radiated Noise<br>Treated Fan Aft Radiated Noise |
| **Engine Jet Noise** | Fan Vertical Acoustic Splitter<br>Noise Cancelling Stator<br>Fluidic Injection<br>Stator Sweep and Lean<br>Variable Geometry Chevrons | Approach Noise (EPNdB)<br>Sideline Noise (EPNdB)<br>Cutback Noise (EPNdB)<br>Source Noise (dB) | Inner Stream Jet Noise<br>Outer Stream Jet Noise<br>Inner Stream Shock Noise<br>Outer Stream Shock Noise |
| **Engine Core Noise** | Compressor<br>Combustor<br>Turbine | Approach Noise (EPNdB)<br>Sideline Noise (EPNdB)<br>Cutback Noise (EPNdB)<br>Source Noise (dB) | Compressor<br>Combustor<br>Turbine |
| **Engine Propulsive Efficiency** | Variable Area Nozzle<br>Boundary Layer Ingestion<br>Variable Pitch Fan<br>Ultra High Bypass Ratio Engines<br>Contra-rotating Fan Engines | Propulsive Efficiency (%)<br>Component Weight (%) | Inlet<br>Propulsor<br>Nacelle |
| **Engine Thermal (Core) Efficiency** | Tip Injection for Stability Enhancement System<br>Intercooled Engine Heat Exchanger Installation<br>Flow Control by Aspiration<br>Active Tip Clearance Control | Thermal Efficiency (%)<br>Component Weight (%) | Cooling<br>HP Compressor<br>HP Turbine<br>Combustor<br>Subsystems |
| **Operations in the Terminal Area** | Taxi Bot<br>Controller Managed Spacing<br>Combined Arrival and Departure Runway Scheduling (CADRS)<br>Runway Configuration Management | Fuel Burn (%)<br>Noise (EPNdB)<br>Emissions (%) | Airport Operations<br>Approach<br>Takeoff/climb |
| **Operations En Route** | Operational Airspace Sectorization Integrated System (OASIS)<br>Dynamic Weather Re-routing (DWR)<br>Pair-wise Separation Management (PSM) | Fuel Burn (%)<br>Noise (EPNdB)<br>Emissions (%) | Aircraft in-flight Operation<br>Dynamic Trajectory Re-Routing |

| Category | Examples | Impact Areas | Applicable Subsystems |
|---|---|---|---|
| **Operations Mission Specification Changes** | Cruise speed reduction (CSR)<br>Range/payload design characteristics<br>Maximum allowable span (see configurations)<br>Take-off and landing field lengths | Fuel Burn (%)<br>Noise (EPNdB), via weight reduction<br>Emissions (%) | Design Range<br>Design Mach<br>Operational profile |

In addition to the requested impact areas and example technologies, Georgia Tech provided examples of what may constitute a first, second, and third generation technology in each technology category. Participants were encouraged to modify according to their own knowledge and experience. A complete listing of the Georgia Tech provided examples of first, second, and third generation technologies in provided in Table 4.

**Table 4: technology Generation Examples**

| Category | First Generation | Second Generation | Third Generation |
|---|---|---|---|
| **Aircraft Wing Design** | Winglet designs<br>Variable wing camber designs | Active flow control<br>NLF control<br>HLF control | Active TS control<br>Morphing wing |
| **Aircraft Aerodynamic Improvements** | Riblets<br>Excrescence reduction | Shock bumps<br>Active flow control | Discrete roughness elements (DRE) |
| **Aircraft Composites** | New composite fibers and matrix<br>Optimized composite design solutions | Pre-form technology<br>Efficient manufacturing processes<br>Joining technologies | Self-reacting (adaptive) structures<br>Nano-technologies |
| **Aircraft Advanced Metallics** | New alloys with targeted properties<br>New design solutions | Tailored integral structures<br>Bonding technology | Advanced assembly concepts<br>Self-reacting (self-monitoring) structures |
| **Aircraft Manufacturing Processes** | Automated fiber placement layup<br>Autoclave cure<br>Fastener assembly | Advanced structural shapes<br>Co-bonding/Paste bonding assembly<br>3D printed components | Major Aerostructures 3D Printed<br>Advanced materials, resins, and stitching |
| **Aircraft Multifunctional Structures** | Multifunctional coatings | Morphing structures | Self-healing/self-repairing structures |
| **Aircraft Structural Health Monitoring** | Off-line sensor systems for maintenance benefits | On-line sensor systems for component weight and maintenance benefits | Fully integrated sensor systems for weight saving and maintenance benefits |
| **Aircraft Noise** | Fairing design<br>Slat design<br>Flap design | Flap treatment<br>Slat treatment<br>Landing gear treatment | Active flow control<br>Plasma actuation |
| **Aircraft Subsystems** | Advanced fly-by-wire<br>Lithium batteries for secondary power<br>More electric aircraft | Proton exchange member fuel cells<br>Fly-by-light | Solid acids as fuel cell<br>Solid oxide fuel cell |
| **Aircraft Configurations** | Large Span / Trussed Braced Wing | Lifting fuselage<br>Conventional engine mounting | Boundary layer ingestion<br>Engines mounted above fuselage |

| Category | First Generation | Second Generation | Third Generation |
|---|---|---|---|
| **Engine Cycle** | Geared turbofan<br>Advanced turbofan | Open rotor/unducted fan<br>Counter-rotating fan | Adaptive cycle<br>Pulse detonation<br>Embedded distributed multi-fan |
| **Engine Emissions** | Twin annular premixing swirler<br>RWL combustor | Lean direct injection<br>Active combustion control<br>Lightweight CMC liners | Ultra compact low-emission combustor |
| **Engine Propulsion Airframe Integration** | Reduced nacelle weight | Buried engines<br>Boundary layer ingestion inlet | Adaptive/active flow control |
| **Engine Structures and Material** | CMC nozzle<br>Advanced TBC coatings | Ubiquitous composites<br>Advanced turbine superalloys | Advanced powder metallurgy disk<br>Blisk and Bling concept |
| **Engine Propulsor Noise** | Rotor sweep/lean<br>Rotor speed optimization<br>VAN | Zero hub fan<br>Soft vane<br>Active stator | Over-the-rotor treatment<br>Active blade tone control |
| **Engine Jet Noise** | Advanced long duct forced mixer<br>Variable geometry chevrons | High frequency excitation<br>Beveled nozzle | Fluidic injection<br>Microjets |
| **Engine Core Noise** | Advanced core treatment | Bulk absorber materials<br>2 DOF/tailored absorbers | Low noise combustor |
| **Engine Propulsive Efficiency** | Variable fan nozzle<br>Very high BPR fan<br>Zero hub fan | Ultra high BPR fan<br>Low FPR fan | Active distortion tolerant fan<br>Embedded engines with inlet flow control |
| **Engine Thermal (Core) Efficiency** | Advanced combustor<br>Advanced cooling technologies | Variable flow splits<br>Ultra compact low-emission combustor<br>Clearance control | Active film cooling<br>Active flow control |
| **Operations in the Terminal Area** | Wake detection and prediction<br>Taxi bot | Parameter driven aircraft separation standards and procedures | Integrated air/ground network for voice and data |
| **Operations En Route** | Aircraft-aircraft hazardous weather information sharing | Airborne collision avoidance<br>Synthetic vision systems | Trajectory negotiation 4D Ts<br>Delegated separation digital communications |
| **Operations Mission Specification Changes** | CSR on existing aircraft | Aircraft/engines redesigned for CSR<br>Multi-range aircraft variants | Advanced configurations with mission spec changes<br>Very large-span aircraft |

**Road mapping Preliminary Results**

The results were compiled and the low, high, and average impacts for each technology category, impact area, and generation were calculated. <u>It should be noted that the plots shown in this report represent an amalgamation of the raw data and the final suggested roadmaps may change as Georgia Tech has more time to analyze the responses</u>. A snapshot is shown in Figure 25, which contains the results for Aircraft Wing Design. The chart shows the low and high estimates for impacts subdivided by generation in the vertical direction and impact in the horizontal direction. The dark blue bars represent the range of estimates on the low impact side; the red bars represent the range of impacts on the high side. The correct way to read the chart is to choose a 'square' at the intersection of an impact (top) and generation (right side). Then look to the left axis for the percent reduction from the state of the art in the same units associated with a given impact. Notice that the range of predictions in estimates increases as the generation changes. This makes intuitive sense, as it is harder to predict benefits for technologies that are further down the development pipeline. Blanks indicate no responses were received, single lines indicate only a single response was provided for that impact area and generation. The provided results should be treated as preliminary until a consensus is agreed upon amongst workshop participants in a virtual workshop to be held later in 2015.

Georgia Tech will use the collected data to develop a series of roadmaps that provide recommended minimum and maximum impact values for each generation of a technology. Note that efforts are still underway to come up with a technically consistent set of recommended impacts that take into account differences in respondents' answers. Georgia Tech will be assessing minimum and maximum ranges and leveraging vast technology modeling experiences to develop a roadmap for each technology area. These roadmaps will be presented back to the working group in a follow on workshop where participants will be asked to comment on the down selected modeling recommendations for future technology availability.

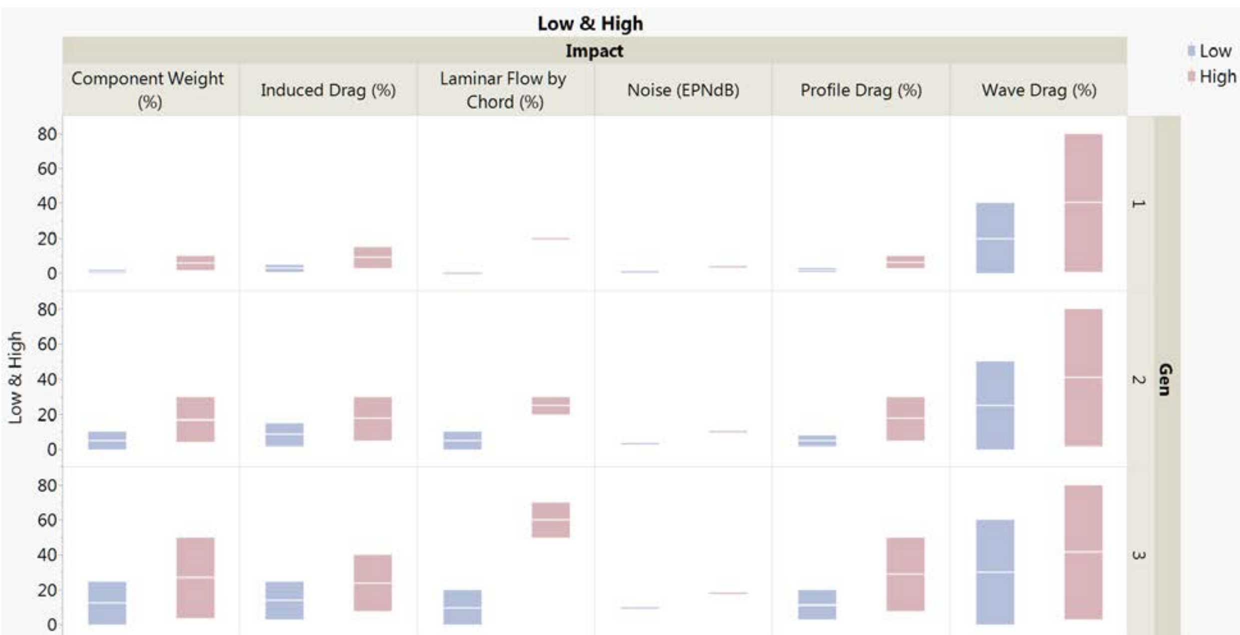


**Figure 25: Aircraft Wing Design Impact Ranges**

In addition to estimate impacts by technology generation, results have been compiled for current estimated TRL, and the min, average, and maximum time it will take to evolve to TRL 9. Shown below is a sample of the data which is presented in the same manner as the impact ranges. Because three generations of technology were solicited, it is likely that most respondents listed first generation technologies as high starting TRL, second generation as medium TRL, and third generation as low TRL. The Georgia Tech team is looking for anomalies in this trend to see if certain technologies might be expected to have a faster development time. Future analysis will generate a consistent set of roadmaps that combine the current TRL, time to TRL 9, and impact ranges. As discussed, this roadmap will be presented back to the workshop participants in a follow up discussion to provide them opportunity to provide final feedback on suggested maturation rates, technology impacts, and example technologies for each category.

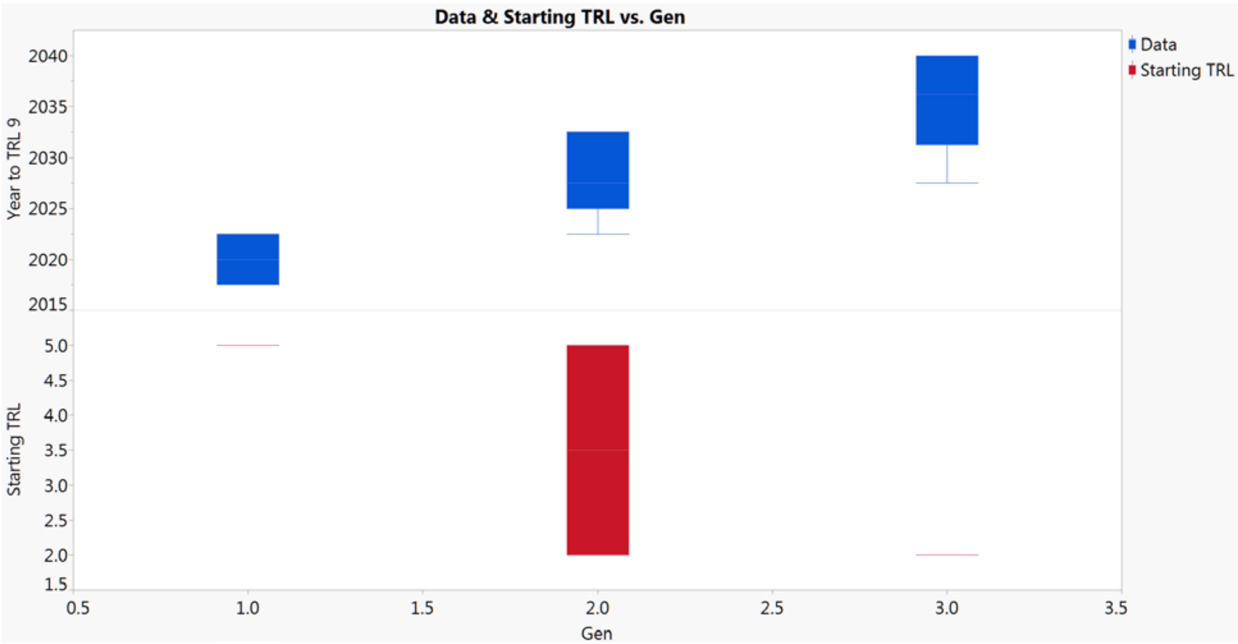


**Figure 26: Aircraft Wing Design Technology Maturation Rate**

Additional data was collected for applicable subsystems and vehicle classes; however, the Georgia Tech team is still working on the best way to visualize that data set. Future analysis will use the presented 'raw' data to develop recommended technology evolution scenarios back to the survey group for consensus. The final scenario recommendations will be published in a separate report later in 2015.

# Task 2: Modeling of Technologies and Advanced Configurations

## CLEEN Modeling (Georgia Tech)

This year Georgia Tech finalized vehicle level modeling of the Boeing CMC nozzle, GE flight management systems for air traffic management and engine controls, and the GE open rotor engine. Modeling assumptions and detailed vehicle results have been provided to the FAA as a separate, proprietary appendix.

## Description of Advanced Vehicles Provided to Purdue and Stanford (Georgia Tech)

In order to allow Stanford to assess the impacts of mission specification changes and for Purdue to exercise their FLEET tool, Georgia Tech provided both universities with a set of public domain FLOPS aircraft models from the 2014 CLEEN assessments performed under PARTNER Project 36 [9]. More specifically, the vehicles provided were from the assessment scenario named "Aggressive minus CLEEN" or AG-C. This scenario assumed an aggressive introduction of N+1 and N+2 technologies, including technologies currently under development or sponsorship of NASA. Since the scenario had all CLEEN technologies removed, Georgia Tech chose to use those models as advanced technology baselines that would allow Stanford and Purdue to carry out their respective tasks with a relatively common set of vehicle performance assumptions. Stanford used the FLOPS models to create corresponding versions in their vehicle modeling tool, SUAVE and Purdue used the FLOPS models directly within their FLEET tool. For more details on the usage of the models in SUAVE and FLEET please see sections 0 and 0, respectively. For more details on the technologies included in the AG-C vehicle package, please see Reference [9]. There were significant differences between the vehicle and engine modeling assumptions and impacts between the validated EDS vehicles and SUAVE; however, the teams agreed the fleet level impact were close enough to proceed with a sensitivity of mission specification changes on the fleet level performance.

## SUAVE Modeling of Public Domain EDS Technologies (Stanford)

Over the past few years, pressure to reduce the overall fuel consumption of the commercial aircraft fleet has been growing steadily.  Expenses related to fuel are now one of the largest contributors to an airline's direct operating cost, even if the recent (2015) turn of events and global economic slowdown has substantially decreased the cost of fuel. As a result, many technological and operational changes are being considered to alleviate these issues. In this work, we begin to investigate the fuel burn impact of varying design mission specifications (e.g. payload, range, cruise Mach number, and allowable span) of tube-and-wing aircraft is studied. During the first year of the effort, the Stanford team has focused on aircraft and engine redesigns that consider the reduction of the aircraft cruise Mach number, but that leave all other mission requirements (cabin layout, range, payload, take-off and landing field lengths, etc.) unchanged. Representative aircraft from all ICAO (International Civil Aviation Organization) classes are chosen and redesigned for variations in the design cruise Mach number. Future work will also focus on changes in the payload/range characteristics and even increasing the allowable wing span. The effects of improvements in aerodynamic, structural and propulsion technology expected over the next 20 years can also be taken into account in the context of technology scenarios for which the baseline aircraft could be redesigned. The work is done using a conceptual design environment developed at Stanford from scratch, the SUAVE environment, that represents all aspects of the design (including both the engine and the airframe) using an appropriate level of fidelity. Results from aircraft redesigns indicate that variations in design mission specifications for existing technology aircraft can result in significant reductions in fuel burn that can be modeled using one of our team's fleet-level tools.

The following sections describe, in sequence, the improvements that the Stanford team has made to the capabilities and optimization framework in SUAVE under the sponsorship of ASCENT Project 10, the baseline vehicles for the various aircraft classes, the redesign process followed to come up with new vehicles that operate at reduced cruise Mach numbers, and a summary of preliminary / ongoing results that can be carried forward to fleet-level analyses.

**SUAVE and Improvements to the Design Environment**

At Stanford, we have devoted a considerable amount of effort to improve the SUAVE modelling characteristics (particularly in the off-design engine characteristics) and to create, test, and validate the optimization framework within SUAVE that enables the design of new aircraft capabilities with changed mission specifications. SUAVE is a conceptual level aircraft design environment that incorporates multiple information sources to analyze unconventional configurations. Developing the capability of producing credible conceptual level design conclusions for futuristic aircraft with advanced technologies is a primary directive for SUAVE. Many software tools for aircraft conceptual design rely upon empirical correlations and other handbook approximations. SUAVE proposes a way to design aircraft featuring advanced technologies by augmenting relevant correlations with physics-based methods.

SUAVE is constructed as a modular set of analysis tools written compactly and evaluated with minimal programming effort. Additional capabilities can be incorporated using extensible interfaces and prototyped with a top-level script. The flexibility of the environment allows the creation of arbitrary mission profiles, unconventional propulsion networks, and right-fidelity at right-time discipline analyses.

To date, SUAVE's analysis capabilities have been used to evaluate a wide variety of configurations including traditional commercial transports (of all sizes and speeds), as well as hybrid-electric commercial transports, supersonic vehicles, and even solar-electric unmanned aerial vehicles (UAVs) among others. Of particular interest to SUAVE is the capability to analyze advanced unconventional aircraft configurations, even if these are not the subject of the investigations in Project 10.

Previous work has shown SUAVE's capability to successfully analyze all these classes of aircraft. However, in order to understand the potential fuel burn reductions of redesigning aircraft with mission specification changes, SUAVE must be used to optimize such aerospace vehicles. During the course of the first year of Project 10 at Stanford University, we have conceptualized, developed, implemented, and tested a full optimization environment that works with all of SUAVE's analysis capabilities. In the context of optimization, SUAVE operates as a "black-box" function with multiple inputs and multiple outputs. Several convenient functions are provided to enable connecting the optimization packages to SUAVE more easily. Assuming an optimization algorithm is minimizing an objective subject to constraints by iteratively modifying input variables, SUAVE's code structure is general enough to be driven from a variety of optimization packages. This work explores the use of several, including VyPy, PyOpt, Dakota, and SciPy.

Several optimization studies have already been pursued. The primary example that has guided our development is the optimization of a Boeing 737-800 aircraft in multiple different scenarios. During the development and verification of the optimization framework, the Stanford team has also worked closely with colleagues at Embraer, who have also conducted their own verification studies (compared with their internal conceptual analysis tools) and who have ensured that the optimization problem formulations include all the necessary realistic constraints to be on par with typical industrial practice. Just as in the analysis capabilities, and beyond the canonical B737-800 problem, the optimization environment is being stress-tested with unconventional configurations on separate projects. The hope is that such additional tests will help our work in Project 10 to ensure that both the capabilities in SUAVE are as developed as possible, but that the robustness of the optimization procedures can allow for repeated redesigns in multiple different scenarios.

In the development of SUAVE, one of the major objectives was to build it flexible enough to interface with a multitude of different optimization packages. To adapt SUAVE to all the desired optimization programs, each optimization package must treat SUAVE as a "black-box" where the internal programs run cannot be modified. To formulate SUAVE as a black-box program, the engineer or scientist must specify what inputs need to be defined, how the inputs are connected to the vehicles and missions of interest, how vehicles and missions are connected, and what outputs are going to be returned. In addition, SUAVE allows design parameters, specified by the user, to map to their corresponding parameters inside the code. The general mathematical formulation can be written as a non-linear program:

$$
\begin{aligned}
\underset{\mathbf{x}}{\text{minimize}} \quad & f(\mathbf{x}) \\
\text{subject to} \quad & g_j(\mathbf{x}) = 0 \quad j \in \{1, ..., l\} \\
& h_k(\mathbf{x}) < 0 \quad k \in \{1, ..., m\} \\
& lb_i \leq x_i \leq ub_i, \; i \in \{1, ..., n\} \\
& \mathbf{x} \in \mathbb{R}^n
\end{aligned}
$$

where **x** is a vector containing *n* design variables $x_i$, which are each bounded by lower and upper bounds $lb_i$ and $ub_i$. The objective of interest is f(x), typically the fuel burn of the aircraft through an entire mission, including reserves. There are *l* equality constraints g(x) and *m* inequality constraints h(x), that must be satisfied by the re-designed aircraft. The design variables **x** are typically some subset of the inputs to SUAVE and wrapping functions are provided to enable translation between data dictionaries and design vectors.

When determining the inputs to SUAVE, the parts into which the inputs can be broken are: vehicle inputs, mission inputs, vehicle-mission connections, procedure, and variable setup. By determining what inputs are specified and what missions are performed, the engineer will define what type of problem is being analyzed. Part of the code inputs would be the design variables of interest, but others are just the information required to setup SUAVE to run the analyses.

<u>Vehicle:</u> Within the vehicle inputs, the designer must first choose what type or types of configurations SUAVE will study. Does the designer want to optimize a single aisle aircraft for a 1,000 nmi mission or a family of transoceanic aircraft sharing a common wing where one carries 300 passengers, one carries 350 passengers, and a third aircraft carries 425 passengers? Depending on the type of optimization desired, SUAVE needs to be configured to generate those results. Part of the code inputs is determining what fidelity level or levels will be used to analyze the configurations. A CFD code could have different inputs than a vortex lattice code or even handbook methods. Making sure the necessary data is provided to SUAVE for the desired analyses is the user's responsibility.

<u>Mission:</u> Beyond just looking at different vehicles over the same mission, we'd like for SUAVE to be able to run the same aircraft through different missions. Instead of optimizing the single aisle aircraft for a 1,000 nmi mission and not considering other missions, we could optimize over a 1,000 nmi mission, but add a constraint that the maximum range of the aircraft be 2,500 nmi. Just as we had to specify what parameters would define each vehicle, we must build the missions from the different segments available. For example, in the work the Stanford team has done in Project 10, we have ensured that the proper amount of reserve fuel is used. The reserve fuel is calculated by ensuring that the vehicle can fly a separate "reserve" mission at the end of the traditional mission.

<u>Vehicle-Mission Connections:</u> Once the vehicles and the missions the vehicles need to fly have been constructed, the connection between vehicles and missions needs to be specified. This can be done by creating different configurations of the same vehicle, maybe for takeoff and landing, where flaps are deployed, vehicle geometry has been modified, or specifying that only the 300 passenger aircraft will fly 8,200 nmi. This step tells SUAVE have aircraft-1 run missions 1, 2, 3 while aircraft-2 only does missions 1 and 3. It also specifies what results SUAVE will generate when the analysis is completed.

<u>Procedure:</u> The analysis of the problem requires a set of sequential actions to be performed. This is the procedure. A great example of this would be to resize the horizontal tail of the aircraft after a new wing area is selected by the optimization algorithm to keep the horizontal tail volume constant. Additionally, the types of missions are then set here such as a long range mission and short field takeoff missions. Finally the constraints and objectives that require additional non standard

calculations can be performed as part of the procedure. An example of the non standard constraints are fuel margins, which is fuel volume available in the vehicle minus the fuel used to run the mission.

Variable Setup: The optimization interface provides a concise way to define several important features of the optimization problem. Including variable names (or tags), the initial guess of the variable, the lower and upper bounds, how it should be scaled to yield favorable numerics within the optimizer, and finally its units. Using the information provided in a tabular structure like the one shown below, accepting input vectors becomes much simpler, enabling SUAVE to pattern across multiple optimization packages.

```
# [ tag , initial, [lb,ub], scaling, units ]
problem.inputs = [
    [ 'aspect_ratio'   ,  10.    , (    5.    ,    20.  ) ,   10.  ,    Units.less],
    [ 'reference_area' , 125.    , (   70.    ,   200.  ) ,  125.  , Units.meter**2],
    [ 'sweep'          ,  25.    , (    0.    ,    60.  ) ,   25.  , Units.degrees],
    [ 'design_thrust'  , 24000.  , ( 10000.   , 35000.  ) , 24000. ,  Units.newton],
    [ 'wing_thickness' ,   0.11  , (    0.07  ,    0.20 ) ,    .11,    Units.less],
    [ 'MTOW'           , 79000.  , ( 60000.   ,100000.  ) , 79000. ,      Units.kg],
    [ 'MZFW'           , 59250.  , ( 30000.   ,100000.  ) , 59250. ,    Units.less],
]
```

**Figure 27. Sample description of optimization problem design variables , bounds and units**

Furthermore, within SUAVE we allow the design variable to be defined in any user preferred name and then "alias" it to the internal data structure name. For example, *aspect_ratio* above would be an alias of **problem.vehicle.wings.main_wing.aspect_ratio**. SUAVE uses a very verbose methodology, but if the engineer would like to use a different set of variable names, the functionality is in place. Outputs to be used for the objective function, constraints, and output characteristics of interest can also be defined in the same manner. This flexible naming convention also allows multiple parameters inside of SUAVE to be varied as one design variable in the optimization process. This capability reduces the number of variables and constraints since there are no longer multiple variables with constraints requiring that they be equal.

Code Outputs: After all the code inputs have been provided, and the desired vehicle characteristics, mission profiles, vehicle-mission connections and the SUAVE analysis structure are generated, results are produced. Not all of the code outputs are relevant to the optimization of interest. The code outputs might need to be post-processed to generate the actual result we care about for our problem. If we are trying to meet Stage 4 Noise levels, we care only about generating a cumulative total of 10 dB, not a matching certain levels at each condition. The objective function and constraints should be a subset of the final code outputs produced. Once these parameters have been generated, they can be fed to the optimization package for design studies to be completed.

**Optimization**

With a general interface in place, SUAVE can be incorporated into optimization packages. The flexibility of SUAVE and Python allow optimization with a variety of packages and algorithms. Throughout this section, a variety of optimization packages integrated with SUAVE, as well as various algorithms within these packages that have been applied to various design problems, are discussed.

VyPy: VyPy is a toolbox developed at the Stanford Aerospace Design Lab that exposes useful abstractions for optimization in the context of engineering. Similar to the concept from PyOpt, and serving as an inspiration for the SUAVE data structure, the top level interface is an optimization formulation, with variables, objectives and constraints. Unique to VyPy, these inputs can be defined in a tabular format or in an object oriented format. The problem is then run through a driver or several drivers that each implements an optimization algorithm. At the moment, interfaces for the following algorithms exist: SLSQP, BFGS, COBYLA, and CMA. The interfaces of these drivers have been expanded to permit consistent setup (for example by standardizing the name of common parameters and variable scaling) and consistent data output (like the presentation of the minimized objective and location). Another unique feature is that it handles data based on dictionaries instead of functions, which are especially useful in an engineering context where inputs and outputs are intuitively described with names instead of vector components.

PyOpt: PyOpt is a Python package containing a variety of nonlinear optimizers. The Sparse Nonlinear Optimizer (SNOPT) module, which relies on a Sequential Linear Programming algorithm and quasi-Newton methods, has been used within SUAVE for multiple optimization problems. The Sequence Least Squares Programming (SLSQP) algorithm, which is another quasi-Newton method, has also been used.

There are several more optimization algorithms in the PyOpt package, and all of them can be implemented easily in SUAVE by creating a base interface and attaching them to available SUAVE functions. The exact structure of the interface will depend on the chosen optimization algorithm and can be created based on existing PyOpt documentation.

Dakota: When determining what to expose to outside software and what to only use within SUAVE, Dakota (Design Analysis Kit for Optimization and Terascale Applications) guided this formulation. Dakota is an object-oriented framework developed by Sandia National Laboratories. Designed to work with high performance computers, Dakota together with SUAVE can expand the types of optimization aircraft designers' attempt. Dakota is constructed to connect easily with other "black-box" functions. The user defines the inputs Dakota can change and what results to expect just as the user in SUAVE specifies an input vehicle dictionary and creates an output data set with all the results of the analysis.

Dakota has both gradient and non-gradient based optimization capabilities. Some of the optimization algorithms available in Dakota include, Hasofer-Lind Rackwitz-Fissler (HL-RF), sequential quadratic programming (SQP) from NPSOL, and nonlinear interior-point (NIP) from OPT++.

In addition to optimization capabilities, Dakota combines stochastic expansion methods (such as Stochastic Collocation (SC) and Polynomial Chaos Expansion (PCE)), surrogate models, and Optimization Under Uncertainty (OUU) algorithms to expand the types of problems SUAVE can consider. These methods allow stochastic aircraft defining parameters to be considered as part of the optimization and vehicle analysis. Having the flexibility to deal with uncertainty in certain parameters gives designers the ability to see how certain parameter distributions will propagate through to the final vehicle. With this functionality, Dakota will not only be used as an optimization driver, but also as a tool to trade how certain design inputs can impact the final optimum aircraft.

SciPy: SUAVE is also capable of interfacing with SciPy. In this case, design variables must be inputted via a Python list. SciPy then calls a function designed to return an objective value, which unpacks the variables and interfaces it to a problem set up in SUAVE. Constraints may be handled by either the optimization algorithm, in which case they must be defined in the inputs file, or they must be handled by penalty functions included in the callable SUAVE file. The SciPy optimization package as of the time of writing includes a wide variety of optimization algorithms, including a Nelder-Mead simplex algorithm, SLSQP, and conjugate gradient methods, among others. However, the interface requirements, as well as handling of constraints vary from algorithm to algorithm. As a result, it is up to the user to appropriately ensure that the problem is well formulated.

**Baseline to GT Vehicles (Stanford)**

To capture the effect of the mission specification changes on the fleet wide fuel burn and emissions, aircraft from all the aircraft classes need to be modelled. For this study the CRJ900 is chosen for the Regional Jet, the B737-800 for the Single Aisle, the B767-300ER for the Small Twin Aisle, the B777-200ER for the Large Twin Aisle and the B747-400 for the very large aircraft. The baseline aircraft were modelled using SUAVE.

The baseline aircraft modelled in SUAVE were compared with the baseline aircraft modelled by GT. The geometric and propulsion parameters of the aircraft as well as the performance estimates including fuelburn, design and sea level static thrust are matched to ensure that the fuel burn of the redesigned aircraft computed using SUAVE can be modelled by GT using percentage changes. The fuel burn for a design mission provided by GT and offdesign missions are compared. It was observed the baseline fuel burn and the fuel burn variation with mission range match fairly well for the aircraft modelled by GT and Stanford for all but the B747-400. The level of agreement is within the expected differences that would be seen in similar analysis and conceptual design tools. This discrepancy will be investigated in detail and for the time being this aircraft is not redesigned for mission specification changes.

**Mission Specification Change Modeling**

The next step in this effort is the redesign of the baseline aircraft for mission specification changes. In this effort the Stanford team investigated the effect of cruise Mach reduction i.e. the baseline aircraft are redesigned for a reduced cruise Mach number. This results in aircraft that are significantly more fuel efficient than the baseline aircraft.

The aircraft redesign is posed as an optimization problem with the fuel burn for a design mission minimized for a lower cruise Mach number. For this study the optimization framework is made up of SUAVE linked up with a gradient based optimizer, SNOPT via PYOPT a python based optimization framework. The design variables and constraints used for this problem are shown below. The design variables used consist of the geometric parameters of the aircraft wing and the engine pressure and bypass ratios as well as the design thrust (which determines the engine size). The cruise altitude of the aircraft is also used as design parameter.

DESIGN VARIABLES:

- Main wing aspect ratio
- Main wing reference area
- Main wing sweep
- Main wing thickness to chord ratio
- Main wing taper
- Main wing root and tip twist
- Engine design thrust
- Low pressure compressor pressure ratio
- High pressure compressor pressure ratio
- Fan pressure ratio
- Bypass ratio
- Cruise altitude

The constraints used for this study are mainly feasibility constraints, a positivity constraint on the fuel burn, constraining the fuel margin (difference in the TOW and the sum of the OEW, payload  an fuel (mission and reserves) to be zero to ensure a feasible mission, a constraint on the wing span to match the baseline aircraft's span and constraining the takeoff field length, the pressure ratio at the combustor inlet and the fan diameter to be less than equal to the values on the baseline aircraft. These constraints ensure that the sizing/redesign of the aircraft is realistic and the aircraft is feasible.

CONSTRAINTS:

- Takeoff field length
- Fuelburn (positivity)
- Fuel balance : TOW – (OEW+payload+reserves+fuel burn)
- Wing span
- Combustor inlet pressure ratio
- Fan diameter

It is observed that the fuel burn of the aircraft for the design mission is reduced significantly for the regional jet, small twin aisle and the large twin aisle aircraft. For the B767 (small twin aisle) the fuel burn for the off-design mission increases with the reduction in cruise Mach number. This concerning trend will be investigated further.

The reductions in the fuel burn for the 3 aircraft mentioned above is due to the fact that, as the cruise Mach number is reduced, the compressibility drag of the configuration is also reduced. This allows the wing to be unswept and the thickness to chord ratio of the wing increased, which can be seen in Table 5 where data for the B777-200ER is shown. In turn, this reduces the wing weight resulting in a reduction in induced drag. Thus the thrust requirements for the missions are much smaller. The consequence is a reduction in the design thrust of the aircraft resulting in smaller engine sizes. This allows the engines component pressure ratios and the bypass ratio to be changed while meeting the pressure ratio and the maximum allowable fan diameter constraints, and results in more efficient engines and thus further reduced fuel burn for the aircraft.

**Table 5 : B737-800 fuel burn**

| Mno | Fuel burn (kg) |
|---|---|
| Baseline | 16,616 |
| 0.76 | 12,417 |
| 0.72 | 12,587 |

**Table 6 : CRJ-900 FUEL BURN**

| Mno | Fuel burn (kg) |
|---|---|

| | |
|---|---|
| Baseline | 22,013 |
| 0.76 | 19,174 |
| 0.72 | 20,434 |

**Table 7 : B767-300er**

| Mno | Fuel burn |
|---|---|
| Baseline | 69,067 |
| 0.76 | 69,331 |
| 0.72 | 70,939 |

**Table 8 : B777-200ER FUELBURN AND DESIGN PARAMETERS VARIATION**

| AR | Sref (m2) | Sweep (deg) | Design Thrust(N) | t/c | MTOW( kg) | taper | lpc Pressure ratio | hpc pressure ratio | fan pressur e ratio | bypass ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.6 | 427 | 31 | 73,000 | 0.1 | 66,280 | 0.182 | 1.26 | 20 | 1.58 | 8.2 |
| 8.8 | 418 | 26 | 40,000 | 0.13 | 57,760 | 0.1 | 1.46 | 21 | 1.62 | 7.2 |
| 8.6 | 426 | 19.43 | 40,000 | 0.13 | 57,940 | 0.1 | 1.5 | 21 | 1.51 | 8.64 |

Over the course of the next 3 months, the Stanford University team intends to pursue a series of activities that firm up the preliminary results discussed here and that mature and improve the optimization capabilities we have created in SUAVE for mission specification changes of new aircraft. In particular, the ultimate objective is to assess the fleet-level impacts of introducing new aircraft with mission specification changes. Once the baselining effort between SUAVE and EDS is complete, and the Stanford and GT teams are confident that the absolute values of fuel burn for the same aircraft and mission calculated with different tools compare satisfactorily, the performance of the re-designed aircraft carried out with SUAVE will be provided to GT / GREAT in the form of tables of improvement factors for a particular aircraft as a function of the actually-flown cruise Mach number, the mission range, and the actual level of payload carried. This will enable seamless integration between SUAVE and the GT GREAT tool. Jointly with GT, the Stanford team would also like to continue to validate the off-design behavior of the engine models that we have created for SUAVE so that the validity of the results cannot be questioned. The Stanford team is planning a paper for the AIAA SciTech 2016 conference which will provide

## Task 3: CLEEN Fleet Level Aircraft Technology Benefits Assessment

### CLEEN Fleet Level Technology Assessment (Georgia Institute of Technology)

**Fleet Assessment Process and Assumptions**
With the completion of the Georgia Tech modeling efforts that covered the all of the CLEEN funded industry technologies; there is sufficient detail to complete a fleet-level assessment to identify the benefits of the modeled technologies for the CLEEN Program. This process was laid out in several steps. First, fleet-level replacement assumptions were identified based on announced upcoming product introductions and historical information on time between aircraft projects. Once fleet-level replacement assumptions were defined, the aircraft technology packages can be generated for different scenarios and timeframes. This involves selecting technologies for each scenario based on expected availability. Finally, EDS is used to generate vehicle level results for fuel burn, NOx, and emissions in addition to the detailed mission information needed to run the GREAT rapid fleet-level assessment tool and compute fleet-level environmental impacts. A detailed discussion on GREAT, including major assumptions and validation can be found in [10].

The GREAT tool is an interactive environment that allows for infusion of new technologies and propagates the results to assess the fleet-level implications [11]. This screening tool can be used as a lower fidelity means to assess a multitude of possible scenarios.

The screening tool incorporates the Terminal Area Forecast (TAF) and CAEP/8 retirement curves to determine the future operations of the fleet. The user has the ability to introduce vehicles with new technologies to quantify the fleet-wide environmental metrics from 2006 to 2050 and compare different technology introduction scenarios [11,12]. For years beyond the extent of the TAF a linear extrapolation of number of operations was used for this analysis. Predictions of fuel burn, NOx emissions, and noise impact are determined for flights within the United States and leaving from the United States. Further detail on the fleet prediction methods used by GREAT can be found in [11] and [12]. Georgia Tech used the ANGIM tool to predict fleet noise contours using generic runway configurations. While many runway configurations were analyzed, only the single runway, uni-directional area contours are presented in this report for simplicity of visually comparing noise.

The three major elements that drive fleet performance are:
- Fleet Growth (How many future operations will there be?)
- Fleet Retirement (How many years is an aircraft in service before being replaced with a new variant?)
- Fleet Replacement (When are new aircraft available?)
- Technology Assumptions (How efficient are new aircraft to enter the fleet?)

The fleet growth was predicted using the TAF forecast; however, GT used retirement curves based on [10], and summarized in section 0. Section 0 discusses fleet replacement assumptions and provides technology assumptions for the aircraft used in this analysis.

**Fleet Retirement Assumptions**
In order to predict how long an aircraft is in service before being replaced by a new variant, Georgia Tech constructed parametric retirement curves, shown in Figure 28. These curves are represented for narrow and wide body aircraft. The curves represent the percent of aircraft surviving after a specified number of years in service for each size category. Further details on how these curves are implemented in GREAT can be found in [10].

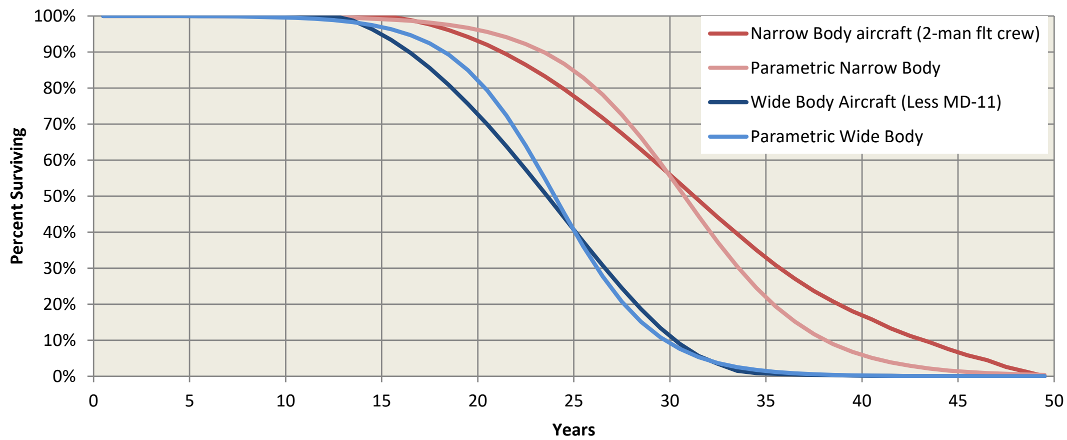


**FIGURE 28: RETIREMENT CURVE COMPARISON**

## Fleet Replacement Assumptions

Fleet replacement assumptions were defined for two generations of new aircraft and the associated technology, termed N+1 and N+2. These scenarios were based on available public domain information regarding upcoming industry aircraft projects. New aircraft were defined for each of the five representative aircraft size classes for each of the two technology generations. Previous work has found that using five classes, regional jet, single aisle, small twin aisle, large twin aisle, and very large aircraft, provide an appropriate balance between having to develop an EDS model for every aircraft currently in the fleet that will need to be replaced vs. accuracy by using one aircraft per size class to represent replacements from the starting year [13,14].

In order to determine the introduction rate of new technology, the percentage of new and replacement vehicles that would contain these technologies was defined. Figure 29 shows the percent of replacement vehicles that consist of new vehicles defined by EDS. For example, in 2015, 0% indicates that all of the replacements will be current, in-production aircraft. In 2018, 25% of the RJ replacements will be new technology vehicles, defined by EDS, and the remainder will be in-production. It is assumed that in the N+1 timeframe the geared fan will only be present on the single aisle and regional jet. This is consistent with industry product announcements until the end of this decade. In order to avoid specifics on orders and engine selection by airlines, it was assumed that the geared fan and direct drive engines are split evenly for a given vehicle. For example, the RJ/N+1 in 2018 has 25% of replacements coming from future (EDS) vehicles. 50% of those future vehicles will be direct drive and 50% will be geared fans. (Meaning 12.5% of replacements will be direct drive and 12.5% will be geared fan, with the remaining 75% being current in-production aircraft).

For the N+2 aggressive scenario aircraft the open rotor was assumed to replace the direct drive replacements for the regional jet and single aisle classes. A 50/50 split was maintained between the geared fan and direct drive on the wide body aircraft. Four year linear phase-ins between generations of aircraft were assumed. This is consistent with historical data showing the transition from the 737 classic to 737NG series of airplanes.

| 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 |

**FIGURE 29: CLEEN FLEET REPLACEMENT ASSUMPTIONS**

For the regional jet class, the N+1 replacements were assumed to enter service in at 2018, consistent with the Bombardier C-series slated to enter service later this decade. A 10 year product development cycle is then assumed which results in an N+2 RJ entering service in 2028. The single aisle N+1 enters service in 2016 to represent the arrival of the 737MAX and the A320neo. Again a 10 year development cycle is assumed for the next aircraft resulting in an N+2 single aisle in 2025. For the STA, the announcement of the 787-10 formed the basis for a new N+1 aircraft in 2018. A shorter development cycle was assumed for the N+2 introduction since the 787-10 is a derivative aircraft and it is feasible for both a new product and derivative to be developed simultaneously. (Such as is the case with the 737MAX and 777X). The LTA N+1 enters service in 2018 to represent the 777X and a 10 year development cycle is used to set the LTA N+2 entry into service. Finally, 2020 was assumed to be a re-engining opportunity for the wide body large quad, resulting in a shorter timeframe to introduce a new aircraft in 2027.

**Technology Scenarios and Packages**

Once the fleet replacement assumptions have been defined technology packages for each class and generation of aircraft can be created. For this assessment three overarching technology scenarios were defined: Evolutionary (EV), Aggressive (AG) and Aggressive without CLEEN technologies (AG-C). The Evolutionary and Aggressive scenarios represent different levels of technology available for implementation in new aircraft in more conservative and optimistic conditions, respectively. The Aggressive without CLEEN scenario was created in order to look at the delta impact of the modeled CLEEN technologies by looking at their impact when removed. For each scenario vehicles were defined for the N+1 and N+2 generations. N+1 packages are labeled as EV and AG, whereas N+2 packages have a '2' in the name (EV2, AG2).
 shows the list of technologies considered and their inclusion in different generational technology packages. A blank cell in the row to the right of the technology name indicates that the technology is not included in a given package. Text in a cell in the row to the right of the technology name indicates that the technology was included in a technology package (e.g. EV2 – evolutionary scenario N+2 aircraft).

The technology list in Table 11 contains both N+1 and N+2 public domain technologies developed in prior years, as well as modeled CLEEN funded technologies (shaded in grey). In addition to public domain technologies modeled under this project, public domain, EDS technology models developed under NASA Environmentally Responsible Aviation (ERA) and NASA Fixed Wing (FW) sponsorships were also used in the PARTNER Project 36 fleet-level analysis. Descriptions of technology models completed under NASA funding are expected to be released as NASA contractor reports at a later date. Note that the GE FMS technologies were applied starting the EV scenario since a majority of the associated technologies can be integrated into existing aircraft and engine platforms. Therefore, the possibility for retrofit and performance improvement packages is accounted for.

**Table 11: Technology Package Definition**

| | | Packages | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Aft Cowl Liners | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 2 | Blisk | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 3 | Combustor Noise Plug Liner | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 4 | Composite Technologies (2010 Baseline) | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 5 | Excrescence Reduction | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 6 | Fixed Geometry Core Chevrons | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 7 | PMC Fan Blade with Metal Leading Edge | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 8 | Polymer Matrix Composites (PMC) - Bypass Duct | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 9 | Polymer Matrix Composites (PMC) - Fan Case | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 10 | Polymer Matrix Composites (PMC) - Fan Stator | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 11 | Polymer Matrix Composites (PMC) - Nacelles | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 12 | Ti-Al - LPT Aft Blades | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 13 | Variable Area Nozzle | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 14 | Zero Splice Inlet | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 15 | Winglet | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 16 | Ti-Al - LPT Vane | EV | | | | | |
| 17 | Advanced TBC Coatings - HPT Vane | EV | | | | | |
| 18 | Advanced TBC Coatings - LPT Vane | EV | | | | | |
| 19 | Boeing CMC Exhaust Core Nozzle | | EV2 | AG | | AG2 | |
| 20 | Boeing Adaptive Trailing Edge | | EV2 | AG | | AG2 | |
| 21 | Honeywell Cooling | | EV2 | AG | | AG2 | |
| 22 | Rolls-Royce Cooling | | EV2 | AG | | AG2 | |
| 23 | Advanced GF Cycle | | EV2 | AG | | AG2 | |
| 24 | Advanced Powder Metallurgy Disk - HPC Last Stage Disc | | EV2 | AG | AG-C | AG2 | AG2-C |
| 25 | Advanced Powder Metallurgy Disk - HPT Disc | | EV2 | AG | AG-C | AG2 | AG2-C |
| 26 | Advanced Powder Metallurgy Disk - LPT First Stage Disc | | EV2 | AG | AG-C | AG2 | AG2-C |
| 27 | Advanced Turbine Superalloys - LPT Last Stage Disc | | EV2 | AG | AG-C | AG2 | AG2-C |
| 28 | AFC Tail | | EV2 | AG | AG-C | AG2 | AG2-C |
| 29 | Continuous Moldline Link for Flaps | | EV2 | AG | AG-C | AG2 | AG2-C |
| 30 | Damage Arresting stitched composites- Fuselage | | EV2 | AG | AG-C | AG2 | AG2-C |
| 31 | Damage Arresting stitched composites- Wing | | EV2 | AG | AG-C | AG2 | AG2-C |
| 32 | Highly Loaded Compressor | | | | | AG2 | AG2-C |
| 33 | Landing Gear Integration - Main | | EV2 | AG | AG-C | AG2 | AG2-C |
| 34 | Landing Gear Integration - Nose | | EV2 | AG | AG-C | AG2 | AG2-C |
| 35 | Lightweight CMC Liners | | EV2 | AG | AG-C | AG2 | AG2-C |
| 36 | Low Interference Nacelle | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 37 | Natural Laminar Flow - Nacelle | EV | EV2 | AG | AG-C | AG2 | AG2-C |
| 38 | Over the Rotor Acoustic Treatment | | | | | AG2 | AG2-C |
| 39 | TAPS II | EV | EV2 | AG | | AG2 | AG2-C |
| 40 | CMC HPT Vane + Hi Temp Erosion Coating | | EV2 | | | AG2 | AG2-C |
| 41 | CMC LPT Vane + Hi Temp Erosion Coating | | EV2 | AG | AG-C | AG2 | AG2-C |
| 42 | DRE for HLFC - Wing | | | | | AG2 | AG2-C |
| 43 | Advanced TBC Coatings - HPT Blade | | EV2 | AG | AG-C | | |
| 44 | Advanced TBC Coatings - LPT Blade | | EV2 | AG | AG-C | | |
| 45 | Soft Vane | | EV2 | AG | AG-C | | |
| 46 | Ti-Al - LPT Foreward Blades | | EV2 | AG | AG-C | | |
| 47 | Compound Rotor Sweep for UHB Fan | | | | | AG2 | AG2-C |
| 48 | Short Nacelle Lip Liner | | EV2 | AG | AG-C | AG2 | AG2-C |
| 49 | Riblets - Fuselage | | | | | AG2 | AG2-C |
| 50 | Riblets - Wing | | | | | AG2 | AG2-C |
| 51 | Active Turbine Clearance Control | | | | | AG2 | AG2-C |
| 52 | Active Turbine Flow Control | | | | | AG2 | AG2-C |
| 53 | Advanced Turbine Superalloys - HPT Blades | | | | | AG2 | AG2-C |
| 54 | Advanced Turbine Superalloys - LPT Blade | | | | | AG2 | AG2-C |
| 55 | Cooled Cooling - Turbine | | | | | AG2 | AG2-C |
| 56 | Out-of-Autoclave Composite Fabrication - Fuselage | | | | | AG2 | AG2-C |
| 57 | Out-of-Autoclave Composite Fabrication - Wing | | | | | AG2 | AG2-C |
| 58 | Thrust Reversers - Nacelles | | | | | AG2 | AG2-C |
| 59 | Active Compressor Clearance Control | | | | | AG2 | AG2-C |
| 60 | N+2 Advanced TBC Coatings - HPT Blade | | | | | AG2 | AG2-C |
| 61 | N+2 Advanced TBC Coatings - LPT Blade | | | | | AG2 | AG2-C |
| 62 | Primary Structure Joining Methodologies - Fuselage | | | | | AG2 | AG2-C |
| 63 | Primary Structure Joining Methodologies - Wing | | | | | AG2 | AG2-C |
| 64 | Active Film Cooling | | | | | AG2 | AG2-C |
| 65 | Highly Loaded HP Turbine | | | | | AG2 | AG2-C |
| 66 | Slat Inner Surface Acoustic Liner | | | | | AG2 | AG2-C |
| 67 | Solid Oxide Fuel Cell Auxiliary Power Unit | | | | | AG2 | AG2-C |
| 68 | Noise Cancelling Stator (GTF) | | | | | AG2 | AG2-C |
| 69 | Gust Load Alleviation | | | | | AG2 | AG2-C |
| 70 | GE FMS-Engine | EV | EV2 | AG | | AG2 | |
| 71 | GE GMS Air Traffic Management | EV | EV2 | AG | | AG2 | |
| 72 | Open Rotor | | | | | AG2 | |

The technology packages identified in Table 11 were generated through significant iteration between the FAA and Georgia Tech. The EDS representation of the geared turbofan engine is included in the EV and AG scenarios; however, the AG-C scenarios are constrained to current technology geared fans. It is also worth noting that the TAPS II combustor, an N+1 technology slated for entry into service in 2016, was carried into the AG2-C scenario since some form of advanced combustor technology would be required to meet CAEP emission standards due to increased OPR in the N+2 timeframe. This is discussed further in the fleet NOx results presented in Figure 32.

**Vehicle Level Results**

Once the technology packages and engine cycles were chosen they were modeled on the five notional vehicles in different size classes in order to assess their impacts on fuel burn, noise, and emissions both on an absolute basis, and relative to the CLEEN Program goals. Extensive vehicle redesign was not performed, but the vehicle's wing and tail areas were allowed to vary to capture the effects of reduced vehicle weight potential that results from reducing the fuel that must be carried. Vehicle design capabilities did not change, in other words, the vehicle design range and payload were maintained. Wing sweep and general configuration were not altered. Fuselage size was maintained so that payload capacity would remain constant. A list of other major vehicle sizing assumptions is provided below:

- Aircraft thrust-to-weight and wing loading is held constant.
- Fuselage size is kept the same as the baseline aircraft in order to maintain payload capability.
- Design point is unchanged from baseline aircraft.
- Wing and tail areas are allowed to scale.
- Other aircraft geometries are held constant to the baseline aircraft.

Specific Vehicle Results are proprietary, and therefore not included in this report. Results include fuel burn reduction relative to a baseline aircraft in each size class, NOx reduction relative to CAEP/6, cumulative noise reduction below Stage IV, and relevant design parameters for each aircraft. For each aircraft a fan pressure ratio sweep was performed to identify the optimal cycle for each set of technologies.

**Fleet-Level Results**

Fleet-level fuel burn results were generated using GREAT in combination with the technology assumptions from with the replacement assumptions defined in Figure 29. The resulting fuel burn values are shown in Figure 30. Four scenarios are shown in the results. Business as usual (BAU), is the datum line and represents the case of the current fleet technology level being fixed in perpetuity. In other words, the current in-production aircraft will be produced forever with no change in technology level. Any new aircraft introduced into the fleet to meet demand are current in-production aircraft with no further technology insertion. The BAU scenario provides the foundation for calculating percent reductions in fleet fuel burn.

The next scenario, EV or Evolutionary, represents the EV and EV2 packages from Table 11mbeing used for N+1 and N+2 vehicle replacement in Figure 29 respectively. Evolutionary represents a conservative level of technology development and introduction. The EV scenario does contain all modeled CLEEN technologies. Next, the AG or Aggressive scenario is plotted, representing a more optimistic level of technology development and introduction.

Finally, the AG-C scenario is included to show the effect of removing all modeled CLEEN technologies, including the second generation geared fan and open rotor, from the fleet analysis. The y-axis shows fleet fuel burn normalized to 2006 levels.

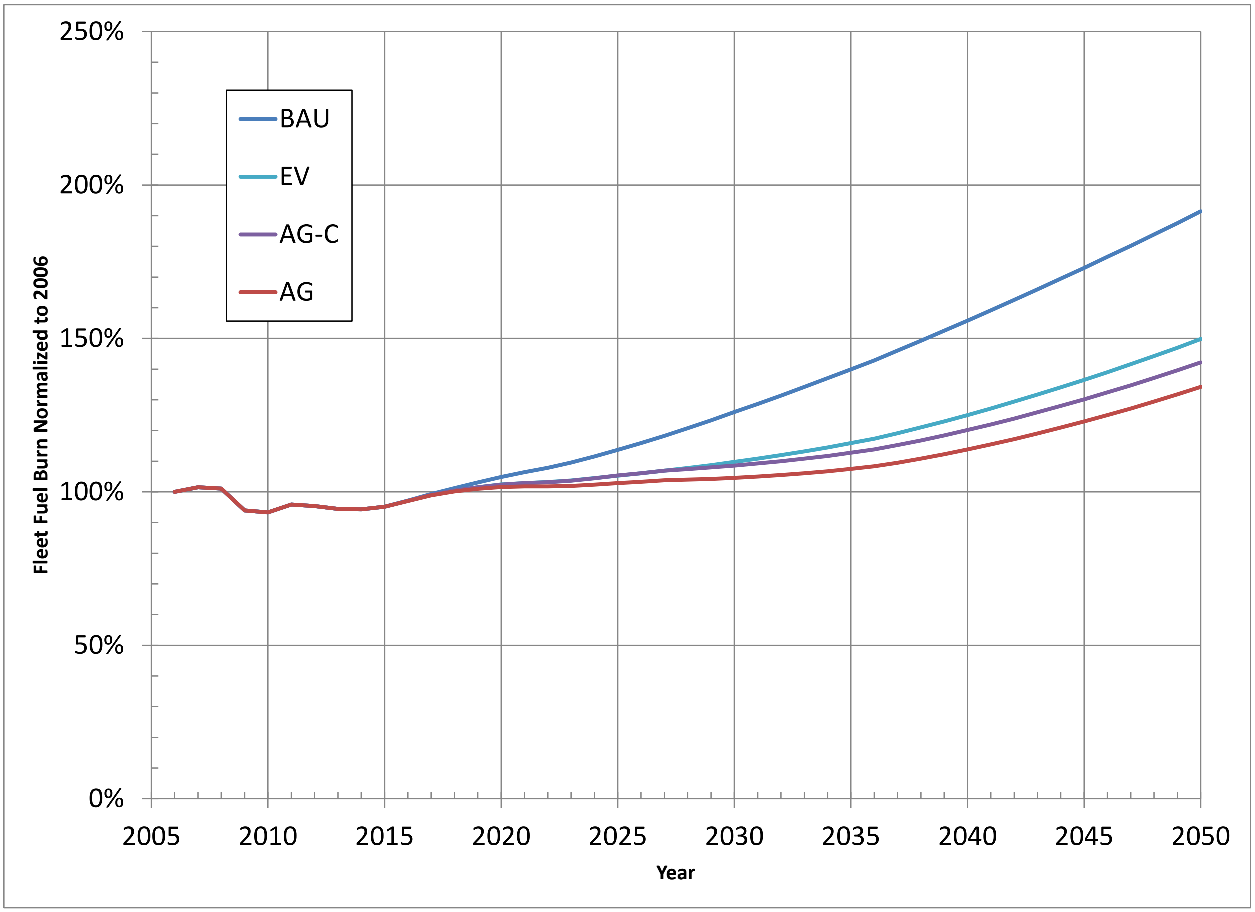


**FIGURE 30: FLEET-LEVEL FUEL BURN IMPACT**

In addition to looking at overall fuel burn trends over time, the reductions provided by each scenario relative to the BAU baseline are shown in Table 9 for different years.

**TABLE 9: FLEET FUEL BURN REDUCTIONS**

| | Reductions | | |
|---|---|---|---|
| Scanrio | EV | AG | AG-C |
| 2020 | -3% | -3% | -2% |
| 2025 | -7% | -10% | -7% |
| 2030 | -13% | -17% | -14% |
| 2050 | -22% | -30% | -26% |

The evolutionary scenario reduces fuel burn by 3% over the BAU scenario by 2020, increasing to a 22% reduction by 2050. The aggressive technology scenario provides further benefit, with fuel burn reductions 1 – 8% greater than the evolutionary scenario as the fleet evolves from 2020 to 2050. This is driven by additional technologies and earlier technology introduction.

The AG-C scenario shows benefits less than the AG scenario, but greater than the EV scenario, as expected. The difference between the AG and AG-C scenarios represents the benefits of the modeled CLEEN technologies at the fleet level, with 3-4% lower fleet fuel burn from 2025 through 2050.

In order to add context to the impact of the CLEEN technologies, the difference between the AG and AG-C scenarios was translated into absolute fuel burn savings using Form 41 Schedule P-12(a) for scheduled and non-scheduled domestic and international fuel burn. Fuel burn savings over year along with cumulative savings are shown in Figure 31. Between 2020 and 2050 the CLEEN technologies modeled in this study help contribute to an average of 534 million gallons of fuel saved per year. This adds up to just over 24 billion gallons of fuel saved by introduction of advanced technologies developed under the CLEEN Program. This is a significant benefit, with gains beginning as early as 2018.

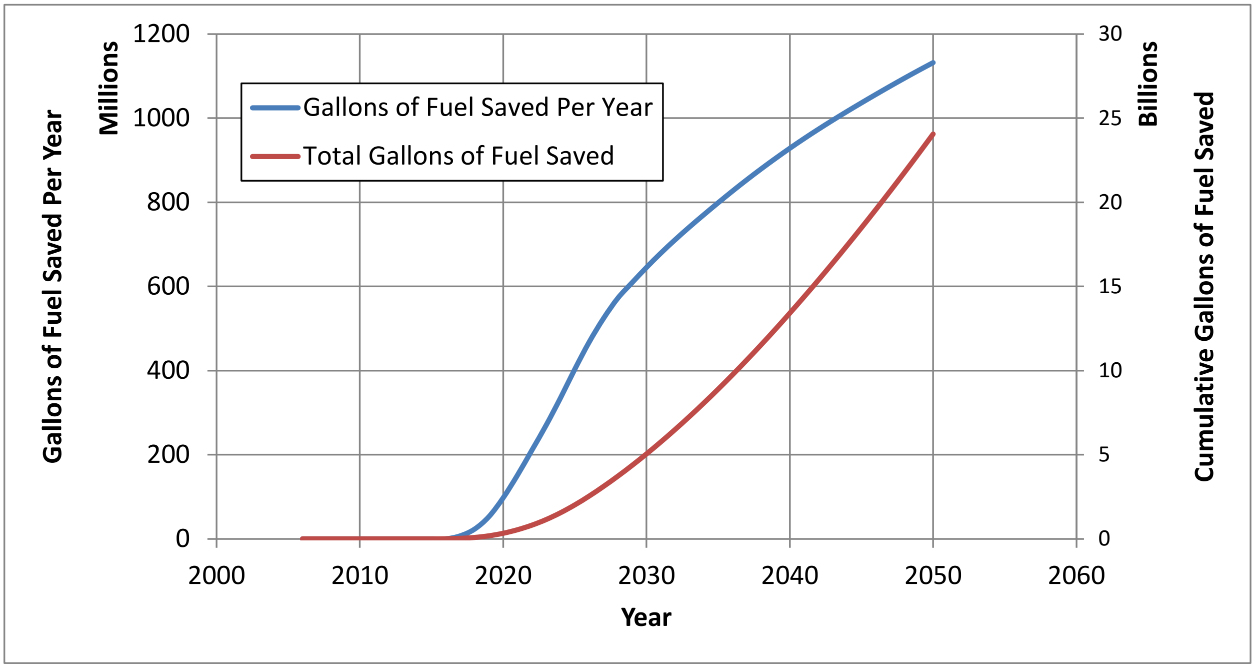


**FIGURE 31: POTENTIAL FUEL BURN SAVINGS PROVIDED BY CLEEN TECHNOLOGIES MODELED IN THIS STUDY**

It should be noted that the CLEEN technologies do not exist in isolation and will not enter the fleet in isolation. Future product aircraft will take advantage of CLEEN technologies alongside other technologies in development, such as those N+1 and N+2 public domain technologies represented in this analysis. In many cases, these technologies may have positive interaction, providing benefit in enabling engine and aircraft redesigns for greater benefit.

Similar studies were performed for NOx and the results are shown in Figure 32. Fleet NOx impacts were calculated by computing the ICAO landing and takeoff (LTO) cycle NOx emissions for both the BAU, in-production aircraft and for the advanced configurations generated using EDS. Then, using the operations per vehicle class, total LTO emissions per year can be calculated. The emissions results have some trends that merit further explanation.

Even though all of the N+1 and N+2 vehicles provided large vehicle level NOx reductions, the fleet-wide NOx is relatively constant. This can be explained by the interrelationship between fuel efficiency and emissions. As engine overall pressure ratio is increased the engine efficiency increases; however, the combustor entry temperature also rises. As a result the flame temperature and NOx formation also increases. This is why the CAEP/6 standard allows for more LTO NOx as OPR increases. There is an intrinsic trade between reduced NOx and reduced emissions. For the fleet results shown in Figure 32, the advanced combustors and TAPS II are keeping NOx levels reduced relative to the case with no advanced combustor technology. AG-C shows the impact of not having an advanced combustor in the N+1 timeframe. There is an increase in NOx that parallels the increase in operations. While total NOx is still reduced below the baseline through 2027, this effect is solely due to fuel burn reductions.

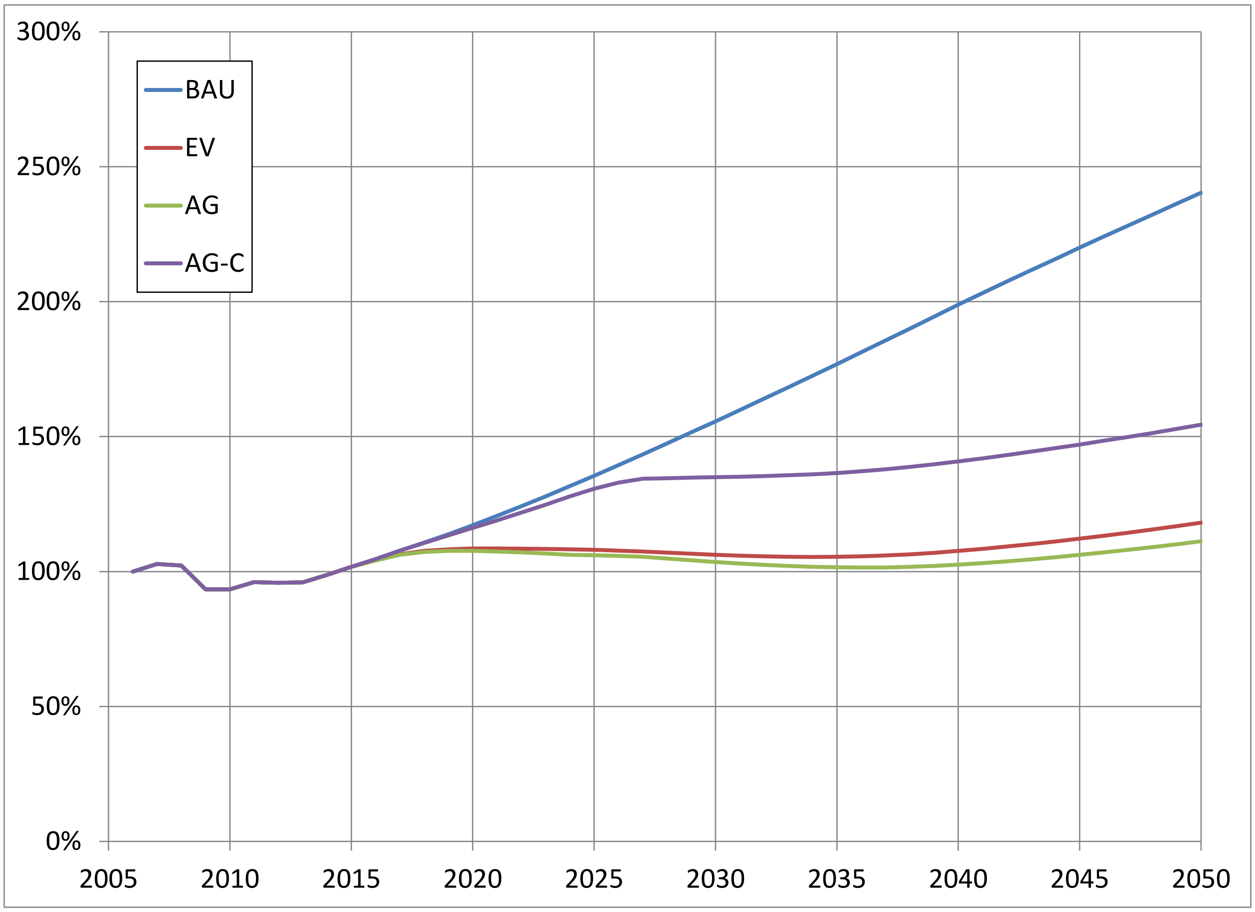


**FIGURE 32: FLEET-LEVEL LTO NOx IMPACT**

The results of this fleet-level analysis indicate the significant benefits of CLEEN funded technologies to fuel burn and LTO NOx, while also demonstrating the strong potential of aircraft technology to affect aviation's future fleet fuel burn and NOx emissions. Additionally, the results highlight the importance of acceleration of environmentally beneficial technologies. CLEEN's intent to accelerate maturation of these technologies results in earlier transition into service and thereby earlier realization of significant environmental benefits.

In addition to updates to the noise and fuel burn predictions, Georgia Tech assessed the fleet noise benefits due to CLEEN technologies. Georgia Tech used the ANGIM tool to rapidly assess the fleet noise impact of CLEEN. More information on ANGIM can be found in [15]. In order to assess fleet noise, grids of single event level (SEL) noise are required for each aircraft size in each of the fleet evolution scenarios. In order to generate SEL grids, noise-power-distance curves are generated using ANOPP within EDS. The NPD grids are combined with the EDS generated AEDT fleet database xml files for each of the future technology aircraft. The resulting files are processed through the AEDT algorithms in order to predict the SEL grid for each aircraft. ANGIM uses the operations schedules from GREAT to combine the SEL grids for all of the aircraft operating at the notional airport in a day. The summing of SEL grids over the course of a 24 hour period provides the Day Night Level (DNL) grid. The 65 dB contour is commonly plotted as the outer line to consider the level of noise exposure to the area.

The same scenarios used to generate fleet fuel burn and emissions reductions were used to generate fleet noise contours. Shown in Figure 33 through Figure 37 are the 65 DNL fleet noise contours for 2010 through 2050 in ten year increments. Starting with 2010 (Figure 33), there is no change between the scenarios since new vehicles have not yet entered the fleet. Moving to 2020 (Figure 34), the business as usual case actually increases in contour area due to the increase in operations. The light grey contour shown in the 2020 – 2050 contours represents the 2010 area for comparison. In 2020 there is a difference between the three technology scenarios, but the differences are minor since there has not been significant time for new vehicles to enter the fleet in this time frame. Moving on to 2030 (Figure 35), there is more noticeable separation between the contours. Whereas in 2020, the EV and AG contours still exceeded the baseline 2010 footprint, the technology introductions by 2030 have started to reverse the direction of area growth. The 2030 contours for all three technology scenarios are now smaller than the 2010 datum year (light grey contour). More separation between the three technology scenarios also becomes apparent in 2030. The AG-C starts to become noticeably larger, especially at the left side (approach) of the contour. In 2040 and 2050 (Figure 36 & Figure 37), as the new technology vehicles replace the existing fleet, not only does the 65 DNL footprint fall significantly within the 2010 baseline, and the corresponding BAU 2050 contour, but there is noticeable difference between the AG and AG-C scenarios at both the approach and departure sides of the contour.

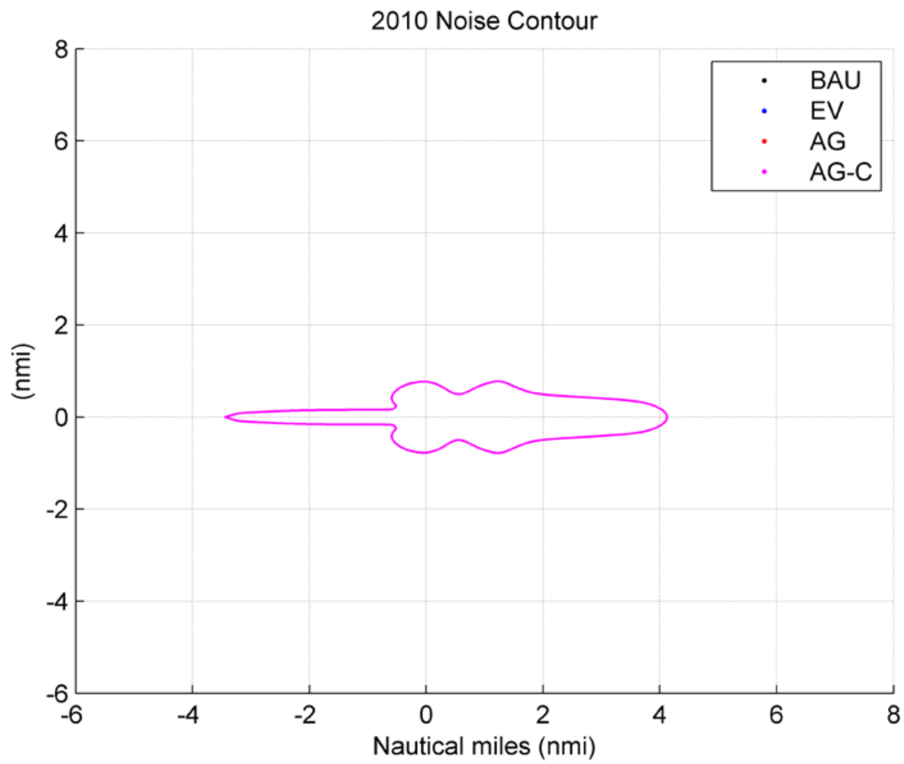


**FIGURE 33: 2010 FLEET NOISE CONTOUR**

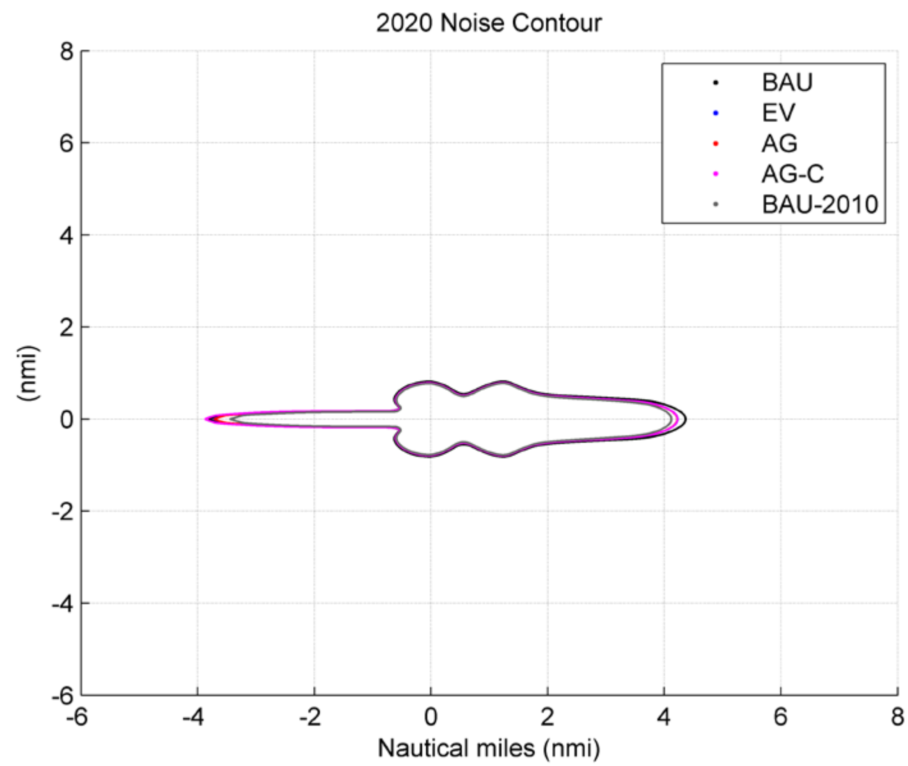


**FIGURE 34: 2020 FLEET NOISE CONTOUR**

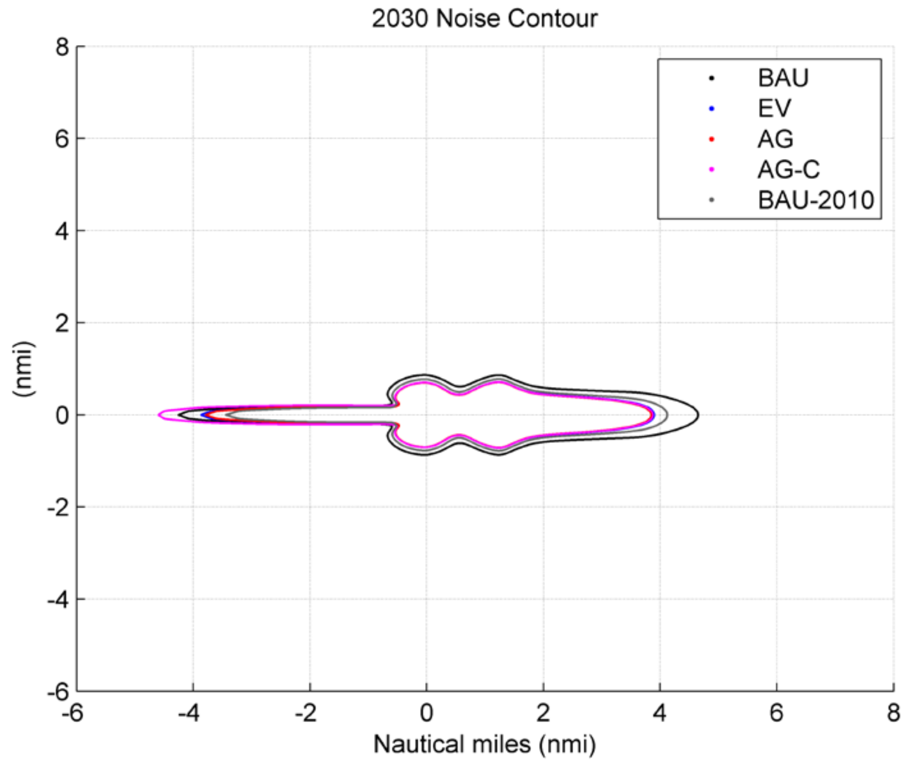


**FIGURE 35: 2030 FLEET NOISE CONTOUR**

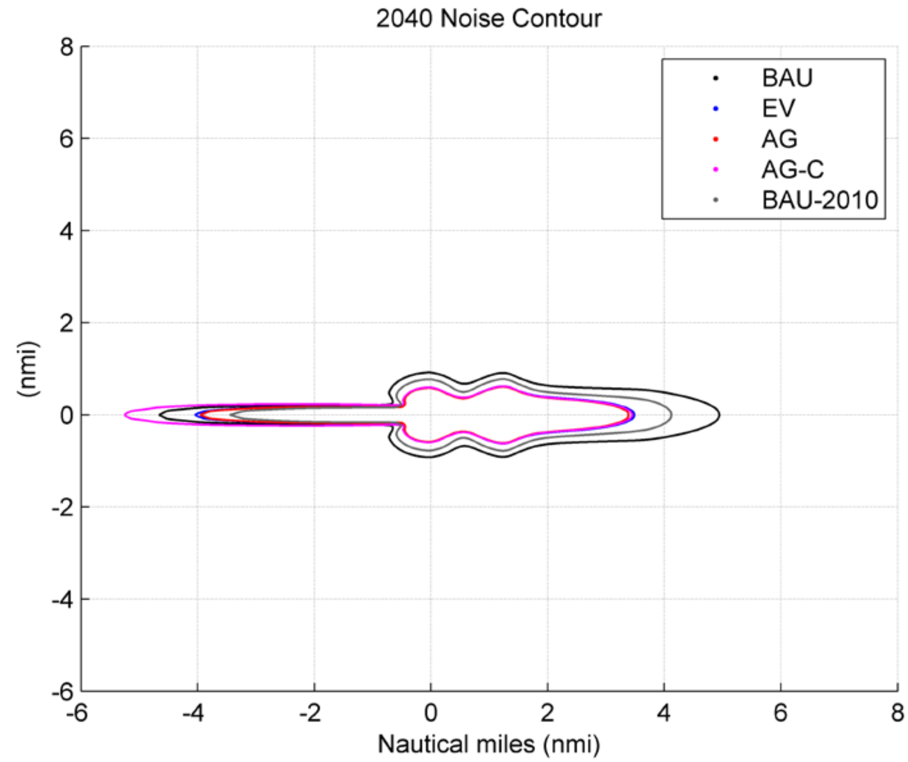


**FIGURE 36: 2040 FLEET NOISE CONTOUR**

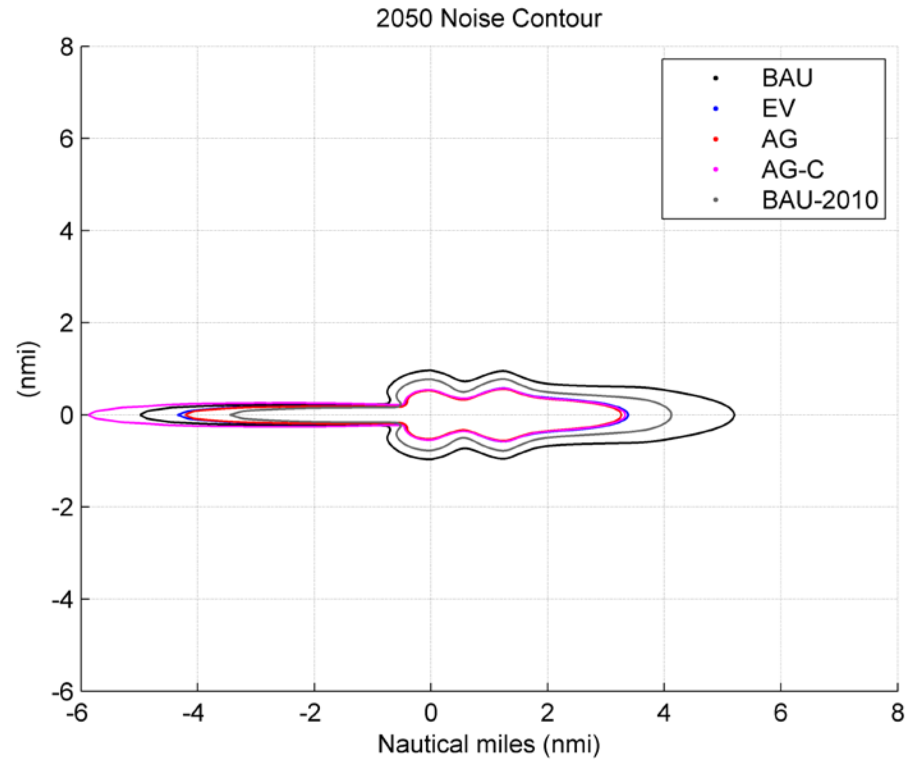


**FIGURE 37: 2050 FLEET NOISE CONTOUR**

In addition to graphical representations of the fleet noise, comparisons can be made between the areas enclosed by the 65 DNL contour for each fleet scenario. Figure 39 shows reductions relative to the BAU contour area in each year. Note that significant separation forms between AG-C and both the Evolutionary (EV) and Aggressive (AG) scenarios. This is due to the removal of the geared turbofan and other CLEEN noise suppression technologies that exist in the AG and EV scenarios in both the N+1 and N+2 timeframes. In total, through 2050 the AG-C scenario helps reduce the contour area by an additional 14% relative to the BAU case. Since noise tends to be treated as a constraint, one could also view the reduction in contour noise area as a trade for increased operations at the same level of noise exposure. If the operations in the TAF are scaled for the AG-C scenario until the AG-C and AG contour areas are equal in 2050, then 40% more operations are required. In other words, viewed from this perspective, CLEEN technologies could help contribute to a 40% increase in operations without significant increase in noise. Obviously the exact increases are airport dependent; however, the order of magnitude should remain similar and is quite significant.

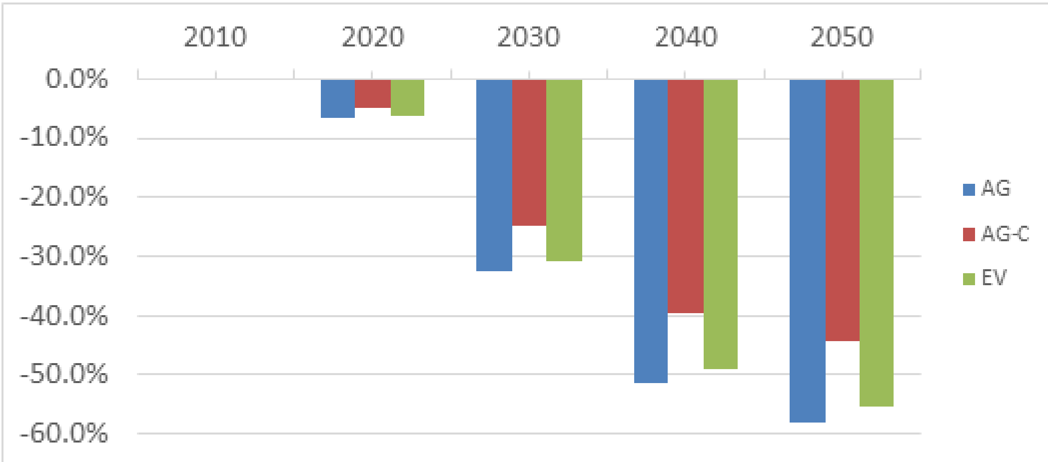


FIGURE 38: FLEET NOISE AREA REDUCTION BY SCENARIO VERSUS YEAR

## FLEET Sample Case (Purdue)

### FLEET Overview

The Fleet-Level Environmental Evaluation Tool (FLEET) is a computational simulation tool developed to assess how aviation's fleet-level environmental impacts – in the form of $CO_2$, $NO_x$ emissions and noise – evolve over time. Central to FLEET is an aircraft allocation model that represents airline operations and decision-making. Additionally, the tool has a system dynamics-inspired approach that mimics the economics of airline operations, models the airlines' decisions regarding retirement and acquisition of aircraft, and represents passenger demand growth in response to economic conditions. The overarching objective of FLEET is to enable an understanding of how variation in external factors such as market conditions, policy implementation, and technology availability will affect aviation environmental impacts into the future. The objective in exercising FLEET in this project period was to inform FAA and its partners about the workings of FLEET, its unique inputs and outputs, and a demonstration of its ability to compute estimates of emissions based on fleet level and technology scenarios [16,17,18,19,20,21,22,23].

While several studies exist that investigate either the environmental impact of aviation or the problem of aircraft allocation, these studies do not incorporate a simultaneous assessment of environmental impacts of aviation along with modeling of airline operations and an evolution of passenger demand and airline fleet mix and technology level. FLEET provides the ability to assess the impact of future aircraft concepts and technologies on fleet-wide environmental metrics while also considering economics and operational decisions of airlines and policy implementation. It goes beyond the aircraft-specific technological improvements, and its results reflect relationships between emissions, market demand, ticket prices, and aircraft fleet composition over a period of many years. Given the complexity of studying the aviation industry and the increasing importance being given to its environmental impact, the capabilities provided by FLEET, it is hoped, would help all stakeholders make informed decisions.

FLEET can be used for simulating a number of scenarios defined by setting values for various input parameters. FLEET groups available aircraft in four technology age categories:

1. Representative-in-class aircraft are the most flown aircraft in 2005 (base year for FLEET)
2. Best-in-class aircraft are the ones with most recent entry-in-service dates in 2005
3. New-in-class aircraft are either aircraft currently under development that will enter service in the future or concept aircraft that incorporate technology improvements expected in the future
4. Future-in-class aircraft are those aircraft expected to include another generation of technology improvements and therefore expected to enter in service a date further in the future

The aircraft within each technology age category further subdivide into six classes, based upon notional or typical seat capacity.

A "baseline" scenario setup in FLEET is defined as follows:

- A network of 169 airports including U.S. domestic routes and international routes that either begin or end in the U.S.
- The gross domestic product (GDP) grows at a constant value of 2% per annum, which results in an inherent or underlying demand growth of 2.8% per annum.
- Jet fuel prices grow according to the Energy Information Administration (EIA) reference fuel price case [24].
- A set of aircraft types in each of the four technology age categories, along with assumed dates of entry into service. Those used in the present demonstration appear in Table 10. The first new- and future-in-class aircraft enter into service at the years shown in Table 10.

**Table 10: Aircraft used in Simulation Studies**

| Aircraft Types in Study | | | | |
|---|---|---|---|---|
| | Representative-in-Class | Best-in-Class | New-in-Class | Future-in-Class |
| Class 1 | Canadair RJ200/RJ440 | Embraer ERJ145 | Small Regional Jet (2018) | "Magic Wand" Small Regional Jet (2028) |
| Class 2 | Canadair RJ700 | Embraer 170 | GT N+1 DD RJ (2018) | GT N+2 DD RJ (2028) |
| Class 3 | Boeing 737-300 | Boeing 737-700 | GT N+1 DD SA (2016) | GT N+2 DD SA (2025) |
| Class 4 | Boeing 757-200 | Boeing 737-800 | GT N+1 DD STA (2018) | GT N+2 DD STA (2024) |
| Class 5 | Boeing 767-300 | Airbus A330-200 | GT N+1 DD LTA (2018) | "Magic Wand" GT N+1 DD LTA (2030) |
| Class 6 | Boeing 747-400 | Boeing 777-200ER | GT N+1 DD LQ (2020) | GT N+2 DD LQ (2027) |

In Table 10, the aircraft labeled as "GT N+1 DD" are the N+1 generation aircraft modeled by Georgia Tech with a 'Direct Drive' engine. These aircraft include the regional jet (RJ), the single aisle (SA), the small twin aisle (STA), the large twin aisle (LTA), and the large quad (LQ).

Additional factors work as switches to turn-on or turn-off constraints in the problem formulation; for example, airport capacity constraints can be used as desired by "turning-on" the relevant switch.

During this first year project period, Purdue demonstrated FLEET capabilities by simulating a series of scenarios developed in discussion with the FAA; the basic idea was to use FLEET to simulate a scenario used by Georgia Tech in a previous PARTNER Project 36 study supporting the CLEEN Program. For the FLEET simulations, Purdue used the aircraft models provided by Georgia Tech in the new- and future-in-class categories; these aircraft models differ from those used in Purdue's previous FLEET studies. These are the "GT" labeled aircraft in Table 10. Table 11 lists the scenarios that were simulated as part of this demonstration.

**Table 11: Demonstration of Tasks Completed Using FLEET For Year One**

| | Task | Scenario Description |
|---|---|---|
| 1 | Replicate "aggressive minus" CLEEN scenario | FLEET "baseline" scenario with the aircraft Entry Into Service (EIS) dates set as those specified in the CLEEN Project 36 report. |
| 2 | Capacity constraints | Similar to above with airport capacity constraints turned on. |
| 3 | Duopoly model and Price-demand elasticity | Similar to scenario 1 above, but using a duopoly of airlines, instead of the default monopoly. |
| 4 | FLEET sensitivity runs | A series of scenarios with GDP varying as low (1% growth), medium (2%), and high (3%), and fuel prices varying as the EIA specified low, reference, and high scenarios. |
| 5 | Sample full scenarios | A series of scenarios with varying EIS dates, aircraft technology improvements, introduction and replacement assumptions, and changes in travel demand. |

| | | |
|---|---|---|
| | High technology infusion (baseline EIS, accelerated EIS, and altered retirement, replacement rates)<br>Low technology infusion, low travel demand and high fuel cost | |

**Description of Results of "Aggressive minus CLEEN" Scenario Run with FLEET**

The remainder of this section, describes Purdue's representation of the "Aggressive minus CLEEN" scenario simulation using FLEET with the "baseline" setup, and with the EIS dates for new- and future-in-class changed to match those in the CLEEN PARTNER Project 36 report [9]. These dates and the corresponding aircraft modeled are shown in Table 10 above. The purpose of the analysis is not to compare the quality of FLEET vs. Global and Regional Environmental Aviation Tradeoff (GREAT), but to understand the difference in results for the same scenario so the FAA can benefit from the different approaches to this difficult forecasting problem.

Figure 39 shows the normalized demand satisfied values for the results from simulations using the FLEET and the GREAT tool. Clearly, using FLEET the demand increases by a factor of 3.49 by 2050 as compared to its 2005 value. In FLEET, the passenger demand uses historical data for the years 2005 through 2008. After 2008, passenger demand changes as a function of two factors: the demand change due to economic factors, referred to as the "inherent demand growth", and the demand change due to passenger response to changes in ticket prices charged by the airlines, referred to as the "price-demand elasticity".

As mentioned earlier, in the current simulation, the GDP growth (inherent demand growth) is set at a constant 2% per year throughout the period of simulation and is the major contributor to the total passenger demand growth (here, 2.8% increase per year, or 1.4 times the GDP rate). In contrast, results from GREAT indicate that the normalized demand increases by a factor of 2.59 by 2050 (demand growth from 2035 to 2050 is computed using a linear extrapolation of the data from the last four years), which is based on the prediction provided by the FAA Aerospace Forecasts. The methodology employed by FAA involves a combination of short-term forecasts based on monthly schedules published by airlines, and medium- and long-term forecasts based on the results of econometric models [25]. The passenger demand served by the airline(s) in the FLEET and GREAT simulations appear in Figure 39. With the higher inherent demand and some impact of price elasticity as new aircraft enable the airline to operate more efficiently, the demand served by the airline in the FLEET model exceeds that served by the airlines in the GREAT model.

Results from FLEET suggest that $CO_2$ emissions from US-related airline operations would increase by a factor of 1.73 from their 2005 level by the year 2050, whereas results from GREAT suggest an increase by a factor of 1.54 by 2050 (Figure 40). The GREAT results here are the same as the "AG-C" curve appearing in Figure 30, above.

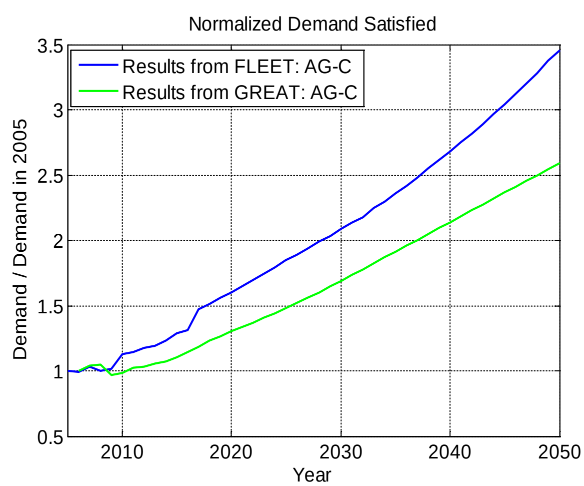


Figure 39: Normalized demand growth from 2005 to 2050

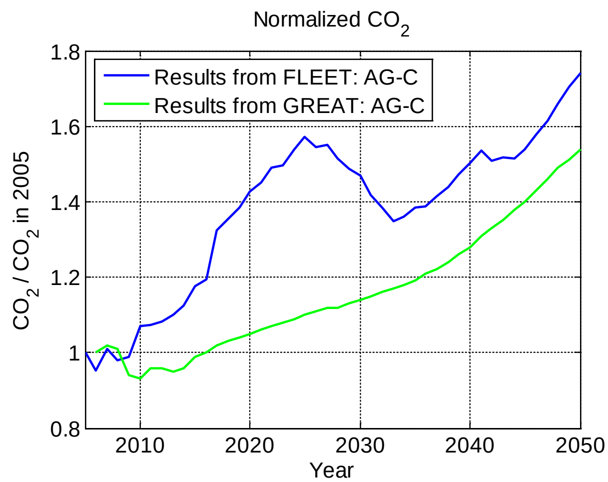


Figure 40: Normalized fleet-level emissions from 2005 to 2050

The FLEET simulation results include a noticeable drop in normalized $CO_2$ emissions between 2025 and 2033 primarily due to introduction of future-in-class aircraft; however, after 2033, $CO_2$ emissions from serving increasing demand outpaces improvements from technology. Results from GREAT show a monotonic growth in normalized $CO_2$ emissions from aviation throughout the period of simulation. The fact that FLEET uses a resource allocation-based approach that encourages the airline to use the more fuel-efficient aircraft in a way that maximizes profit leads to the increasing and decreasing normalized $CO_2$ emissions in the FLEET model.

Both demand and emissions values are normalized to their respective 2005 values, and the normalization factors are unique to FLEET and GREAT. This is so, because the underlying transportation networks are different. For example, GREAT results account for cargo operations, the fraction of which (of the total operations) increases from 1.51% in 2006 to 5.32% by 2050. FLEET does not model and simulate cargo operations (though the contribution of cargo operations to the overall emissions predicted by GREAT appears to be small). A second, and more substantial, difference necessitates the use of normalized emissions is that GREAT models a much larger airline network, with 15,267 routes as compared to 4,268 routes in FLEET.

Figure 41 and Figure 42 show the fleet allocation by aircraft class and type respectively for the FLEET study. Notably, the FLEET airline begins to operate a higher fraction of “GT N+2” class 2 and 3 future-in-class aircraft as these become available. Because these very efficient aircraft offer better economic returns than the class 1 aircraft, this leads to an “up-gauging” of the fleet on shorter routes. Further, the airline flies very few trips using class 6 aircraft, primarily due to the Class 5 Large Quad (LQ) aircraft, which has a capacity of 430 passengers, serving the relatively few long-range high-demand routes in the FLEET route network.

Comparison of types shows that the airline retains some older aircraft for a longer duration; for instance, Figure 42 shows that there are some representative-in-class aircraft still operating past 2040 and some best-in-class aircraft operating until 2050. Additionally, the new-in-class aircraft never form a substantial portion of the airline’s fleet, because the future-in-class aircraft, which lead to higher profit in the FLEET model, become available very soon after the new-in-class aircraft entered service. For instance, the EIS for the future-in-class Class 4 N+2 Short Twin Aisle (STA) aircraft is only six years after the EIS of the new-in-class Class 4 N+1 STA aircraft.

In 2025, the new-in-class aircraft have become about 25% of the airline and the future-in-class are just appearing. This is the first inflection point in the $CO_2$ emissions trend. Because the future-in-class aircraft appear to provide the most profit-related benefit, from 2025 onwards – when the $CO_2$ emissions start their downturn – the fraction of best-in-class aircraft continues to shrink, the fraction of new-in-class aircraft stays about constant, and the future-in-class become an ever increasing percentage of the fleet. By 2035, when the $CO_2$ emissions begin their upturn, the demand growth does appear to overwhelm the advantages of an ever increasing fraction of the most efficient future-in-class.

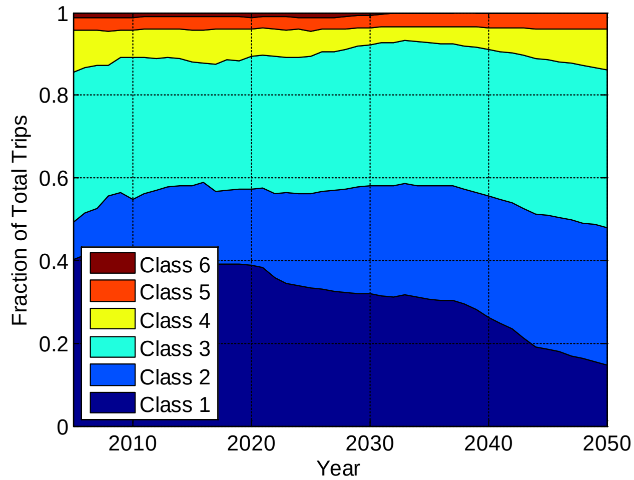


**Figure 41: Variation in fleet allocation by aircraft class (FLEET Run)**

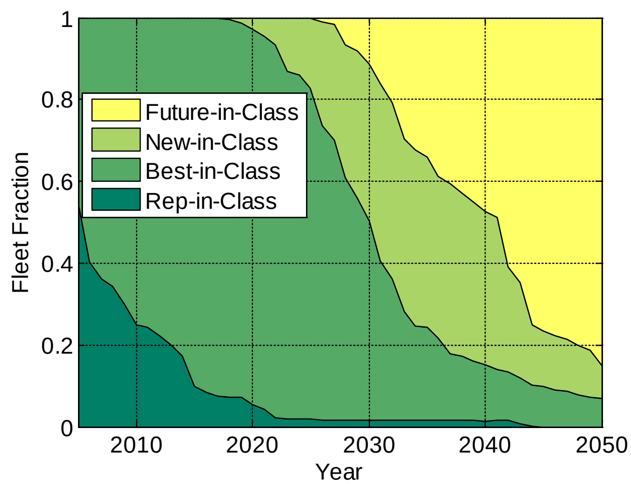


**Figure 42: Variation in fleet allocation by aircraft type (FLEET Run)**

Figure 43 and Figure 44 show a replacement schedule comparison between the results from FLEET and the schedule listed in the PARTNER Project 36 report for the Large Twin Aisle (LTA) aircraft. The replacement schedule trends from FLEET match closely with CLEEN fleet replacement assumptions (obtained from Georgia Tech's GREAT tool). As expected, there are some variations caused due to a combination of delivery limits imposed, retirement decisions and yearly fleet allocations. The slopes of the replacement schedules are sensitive to parameters in the retirement model such as the depreciation factor, interest rate and financing period.

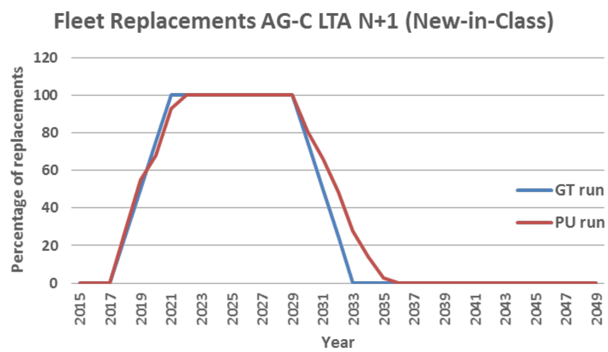


**Figure 43: Fleet replacement schedule comparison for N+1 Direct Drive LTA**

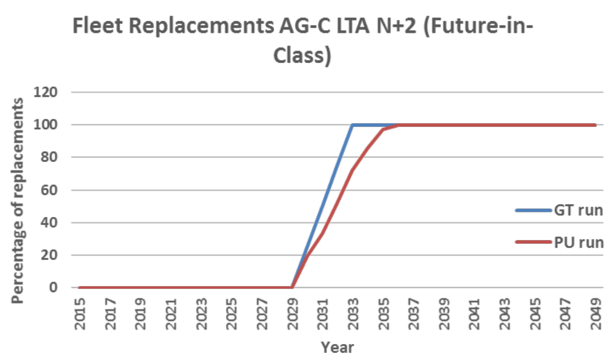


**Figure 44: Fleet replacement schedule comparison for N+2 Direct Drive LTA**

Figure 45 shows the variation in the fleet size by aircraft type over time for the results obtained from FLEET. The FLEET network is much smaller and the FLEET airline uses fewer aircraft compared to the representation in GREAT. However, in FLEET, the number of aircraft operated by the airline from 2005 to 2050 increases by a much larger multiple (factor of 2.5) than the number of aircraft represented in GREAT (factor of 1.67) over the same time period. Figure 46 shows the average $CO_2$ emissions (in lbs. per passenger nautical mile) for the period of simulations. The change in the slopes of the trends around the years 2025 and 2033 correspond to the 'inflection points' in the fleet-level emissions trends seen in Figure 2, and the fleet turnover trends seen in Figure 42. Also, note that in the period from 2023 through 2033 (Figure 45), the total fleet size remains reasonably constant despite the increasing demand. This indicates the FLEET airline changes the allocation to better serve the demand without increasing the fleet size. Despite the emissions per passenger nautical mile decreasing year-on-year, which indicates that the airline is operating more fuel efficient aircraft, the overall fleet-level emissions shows an increasing trend due to the overwhelming demand growth.

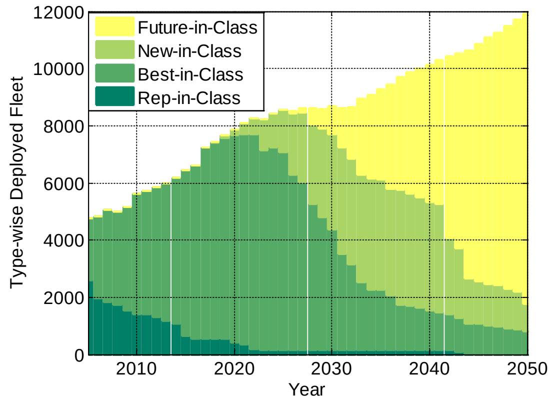


**Figure 45: Variation in total fleet composition by aircraft type (FLEET Run)**

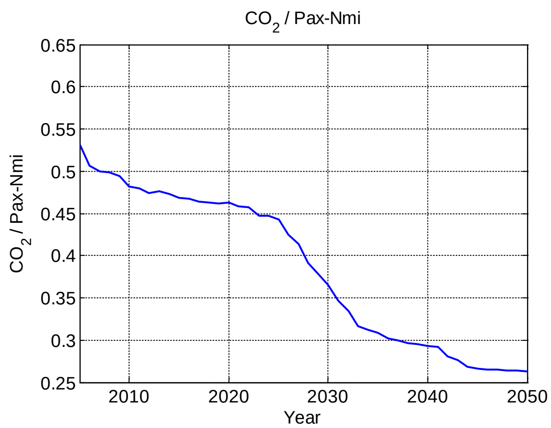


**Figure 46: Variation in average $CO_2$ emission per passenger nautical mile (FLEET Run)**

Similar to the "Aggressive minus CLEEN" scenario described here, we have also simulated and are currently analyzing the results from other scenarios as mentioned in Table 10 above. Together, these simulations will demonstrate the capabilities of FLEET for assessment of fleet-level emissions evolution as a result of new aircraft technologies and distinct operational scenarios, amongst others. These capabilities of FLEET would be beneficial to the FAA in tackling challenging fleet-level emissions forecasting problems.

### Mission Specification Trades (Stanford)

During this first portion of Project 10, the group at Stanford University has focused on (a) the development of the necessary analysis and optimization capabilities within the SUAVE framework, (b) the development and validation (with publicly-available data) of model vehicles in each of the five ICAO/CAEP aircraft classes, and (c) a preliminary study of the fuel-burn-reduction opportunities afforded by decreases in cruise Mach number when re-designing (including airframe and engine) these aircraft. The intent is to transfer the improved vehicles to the GT team, so that they can insert such vehicles in the fleet-level analyses done with GREAT. The Stanford team has also supported the team's activities for the preparation and conduct of both the fleet-level and technology workshops.

## Publications

T. W. Lukaczyk, A. D. Wendorff, M. Colonno, E. Botero, T. D. Economon, J. J. Alonso, T. H. Orra, and C, Ilario, "SUAVE: An Open-Source Environment for Multi-Fidelity Conceptual Vehicle Design," 16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, doi:10.2514/6.2015-3087, June, 2015.

## Outreach Efforts

Multiple interactions with government, industry, and academia have occurred during the course of the fleet and technology assumption setting workshops, described in Section 0 of this report.

## Awards
None

## Student Involvement
Of the Georgia Tech students, Benjamin Bitoun, Marcus Bakke, Ryan Donnan, and Arturo Santa-Ruiz, Marcus Bakke and Ryan Donnan have graduated and have been employed by Boeing and Pratt and Whitney, respectively.

On the Stanford University side, Anil Variyar, Trent Lukaczyk, Emilio Botero, Tim MacDonald, and Ved Chirayath have participated in the work presented here, and the development of the SUAVE framework. Dr. Lukaczyk has recently completed his doctoral degree and has started a UAV company. Mr. Chirayath is completing his dissertation by the end of the calendar year (2015) and is currently working at the NASA Ames Research Center in the Earth Sciences division.

Both Purdue Graduate Research Assistants worked on this project for the entire first year of effort; both are still graduate students at Purdue.

## Plans for Next Period
Georgia Tech has held a follow on fleet workshop discussion on August 27, 2015 in order to present back out the results of the first fleet workshop. Responses were collected from the participants on proposed scenarios in addition to feedback on timing of future new and upgrade vehicle availability within the fleet. Georgia Tech will also continue to combine the fleet and technology workshop responses into a single, coherent roadmap that will be published at a later date. The roadmap will contain suggested, standardized technology and fleet evolution scenarios and settings that should be considered by others when performing a system level technology analysis. This roadmap is expected to be released late in 2015. Georgia Tech will also work with Purdue and Stanford to use the results of the fleet and technology workshops to execute selected fleet scenarios of interest to provide insight into potential future benefits scenarios.

Over the course of the next 3 months, the Stanford University team intends to pursue a series of activities that firm up the preliminary results discussed here and that mature and improve the optimization capabilities we have created in SUAVE for mission specification changes of new aircraft. In particular, the ultimate objective is to assess the fleet-level impacts of introducing new aircraft with mission specification changes. Jointly with GT, the Stanford team would also like to continue to validate the off-design behavior of the engine models that we have created for SUAVE so that the validity of the results cannot be questioned. The Stanford team is planning a paper for the AIAA SciTech 2016 conference which will provide details of all this work. During the remainder of the coming year, the Stanford team will continue to refine the mission specification changes designs in all five aircraft classes for inclusion in future scenarios / worldviews through fleet-level modeling.

Purdue will instantiate their FLEET simulation tool with harmonized assumptions from Task 1 and public domain vehicle and technology representations from Georgia Tech. Purdue will conduct studies with FLEET, so instantiated, to assess fleet-wide emissions impacts across the range of scenarios formed from harmonized fleet assumptions and technology alternatives.

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