Project 010 Aircraft Technology Modeling and Assessment: Phase I Report

Georgia Institute of Technology, Purdue University, Stanford University

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Executive Summary

Georgia Tech, Purdue, and Stanford partnered to investigate the impact of aircraft and vehicle technologies and the future state of demand for aviation on future environmental impacts of aviation. In the context of this research, environmental impacts includes direct CO_2 emissions and noise. The research was 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. The primary objective of this research project was to support the Federal Aviation Administration (FAA) in modeling and assessing the potential future evolution of the next generation aircraft fleet. Research under this project consisted 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).

The team organized a series of virtual workshops to identify and define a standard set of assumptions to use as inputs to aircraft and fleet level modeling tools. A total of four workshops were held with a range of experts from industry, government, and academia. Two of the workshops focused on defining technology impact and development assumptions; the other two workshops focused on identifying and defining the values of factors important to fleet impacts modeling. The outcome of the technology modeling workshops is a series of infographics that provide recommended assumptions that can be used in any aircraft or engine conceptual design tool. Based on the variation in responses, the technology infographics contain minimum, nominal, and maximum estimates of the impact on natural metrics, such as lift-to-drag ratio, or structural efficiency relative to a current day baseline. Estimates are provided for twenty-two key impact areas for technology impact level, maturation rate, current Technology Readiness Level (TRL), applicable subsystems, and applicable vehicle size classes. Estimates are provided for near, medium, and far terms implementation to enable creation of N+1, N+2, and N+3 representative vehicles through modeling and simulation. Minimum, nominal, and maximum estimates of these metrics can be used to provide probabilistic estimates of future vehicle performance.

In order to develop suitable assumptions for the forward looking fleet level analysis incorporating new vehicle technologies, it is necessary to forecast the future. However, most forecasts are extrapolations of the current status quo and trends, which assume an undisturbed continuation of historical and recent developments. In order to enable exploration of this assumption space, the two fleet workshops focused on the development of a standard methodology for capturing potential future states of technology and fleet development. The fleet impact, or the combined impact of multiple aircraft of varying technology levels flying within a given year, is defined broadly though demand and retirement assumptions. Demand is driven by external factors such as Gross Domestic Product (GDP) growth and ticket price. Retirement rates are also dependent on certain external factors. The first fleet workshop defined the external factors that are most important to fleet and technology evolution. A second workshop was held to define quantitative inputs for the defined factors. The outcome is a table of recommended scenarios for use in fleet analysis. The scenarios capture the most pessimistic and optimistic assumptions on technology availability, demand growth, and retirement assumptions. When run as a suite of scenarios, they provide a wide view on the potential future state of noise, fuel burn, and emissions of the fleet.

Georgia Tech and Purdue exercised their respective fleet analysis tools (GREAT and FLEET) applying the technology and fleet scenarios defined through the community workshops. The results show that fleet direct carbon dioxide (CO_2) emissions are unlikely to remain at or below 2005 levels without the addition of significant alternative fuels to offset direct emissions. Given the current state of new technology aircraft and projected introduction rates, it will take until 2030 for technology to have significant impact on direct CO_2 emissions due to the time it takes to turnover existing aircraft. It was also found that the rate of technology maturation and introduction (i.e., new aircraft) is more important to reducing direct fleet CO_2 emissions than reducing demand. Lowered demand certainly helps in reducing fleet CO_2, but inserting technology as soon as possible has the largest impact on achieving carbon-neutral growth and CO_2 emission levels below 2005 by 2050. Both the GREAT and FLEET tools predicted similar impacts for CO_2 emissions. There was more variation between tools in the predicted noise levels of the future fleet, both Purdue and Georgia Tech found significant reductions in noise contour area are possible under a wider range of demand and technology assumptions. However, as is the case with fuel burn, the rate of new technology introduction is the primary driver of reducing noise since noise is a non-linear phenomenon and older, louder aircraft will dominate until retired.

The outcome of this study is intended to provide a glimpse into the future potential states of aviation, but also to provide future researchers with a standard set of assumptions which can be reevaluated and applied in a consistent manner in future years.

Table of Acronyms

AEDT	Aviation Environmental Design Tool
ANGIM	Airport Noise Grid Integration Model
APU	Auxiliary Power Unit
ASPM	Airspace System Performance Metrics
BADA	Base of Aircraft Data
BPR	Bypass Ratio
BTS	Bureau of Transportation Statistics
CAEP	Committee on Aviation Environmental Protection
CLEEN	Continuous Lower Energy, Emissions, and Noise
CMC	Ceramic Matrix Composite
CMO	Current Market Outlook
DNL	Day-Night Level
DOE	Design of Experiments
ECU	Electronic Control Unit
EDS	Environmental Design Space
EIA	Energy Information Administration
EIS	Entry into Service
EPNL	Effective Perceived Noise Level
ETS	Emissions Trading System
EU	European Union
FAA	Federal Aviation Administration
FLOPS	Flight Optimization System
FPR	Fan Pressure Ratio
GDP	Gross Domestic Product
GMF	Global Market Forecast
GREAT	Global and Regional Environmental Analysis Tool
GTF	Geared Turbofan
HPC	High Pressure Compressor
HPCPR	High Pressure Compressor Pressure Ratio
HPT	High Pressure Turbine
HWB	Hybrid Wing Body
ICAO	International Civil Aviation Organization
LPC	Low Pressure Compressor
LPCPR	Low Pressure Compressor Pressure Ratio
LSA	Large Single Aisle
LTA	Large Twin Aisle
MSC	Mission Specification Changes
NEE	Noise Equivalent Energy
NPSS	Numerical Propulsion System Simulation
nvPM	Non-volatile Particulate Matter
OEM	Original Equipment Manufacturer
OPR	Overall Pressure Ratio
PAI	Propulsion Airframe Integration
R&D	Research and Development
RJ	Regional Jet
RPM	Revenue Passenger Miles
SA	Single-Aisle (Includes both SSA and LSA Classes)
SSA	Small Single Aisle
STA	Small Twin Aisle
SUAVE	Stanford University Aerospace Vehicle Environment
TRL	Technology Readiness Level
TSFC	Thrust Specific Fuel Consumption
UHC	Unburned Hydocarbons
USD	U.S. Dollars
VLA	Very Large Aircraft

University Participants

Georgia Institute of Technology
- P.I.(s): Dr. Dimitri Mavris (PI), Dr. Jimmy Tai (Co-PI)
- FAA Award Number: 13-C-AJFE-GIT-006
- Period of Performance: August 1, 2014 – August 31, 2017

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 – May 31, 2017

Stanford University
- P.I.(s): Dr. Juan J. Alonso
- FAA Award Number: 13-C-AJFE-SU-004
- Period of Performance: August 1, 2014 – May 31, 2017

Project Funding Level

The project was funded at the following levels: Georgia Institute of Technology ($985,000); Purdue University ($209,969); Stanford University ($215,000). Cost share details for each university are below:

The Georgia Institute of Technology has agreed to a total of $985,000 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.

Purdue University provides matching support through salary support of the faculty PIs and through salary support and tuition and fee waivers for one of the graduate research assistants working on this project. While Purdue University provides the majority of the 1:1 cost share for the Aviation Sustainability Center of Excellence (ASCENT) 10-Purdue, an in-kind matching contribution of just under $20,000 comes from a gift of the RDSwin-Pro aircraft design software from Conceptual Research Corp.

Stanford University has met or exceeded its matching funds contribution using a combination of elements. Firstly, Stanford University is cost sharing, through tuition reductions for the students working on this project for the entire period of performance. In addition, our partners at the International Council for Clean Transportation are providing in-kind cost-sharing for the remainder amount 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
Co-Investigator: Jimmy Tai
Technology Modeling Technical Lead: Christopher Perullo
Fleet Modeling Technical Lead: Holger Pfaender and Elena Garcia
Students: Matt Reilly, Braven Leung, Marcus Bakke, Ryan Donnan

Purdue University
Principal Investigator: Daniel DeLaurentis
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Students: Kushal Moolchandani, Parithi Govindaraju, Nithin Kolencherry, Ogunsina Kolawole, Hsun Chao

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, Emilio Botero and Tim MacDonald.

Project Overview

Georgia Tech, Purdue, and Stanford partnered to investigate the impact of aircraft and vehicle technologies on future environmental impacts of aviation. Impacts assessed at the fleet level include direct CO_2 emissions and noise. The research was 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 partnered with Purdue University and Stanford University.

The primary objective of this research project was to support the Federal Aviation Administration (FAA) in modeling and assessing the potential future evolution of the next generation aircraft fleet. Research under this project consisted 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 the FAA Continuous Lower Energy, Emissions, and Noise project (CLEEN I), Georgia Tech was selected as the lead for all three objectives described above [1]. Stanford and Purdue supported the objectives as shown in Table 1, listing the high-level division of responsibilities amongst the universities.

Table 1: University Contributions

Objectives		Georgia Tech	Stanford	Purdue
1	Harmonize Fleet Assumptions	Lead process, coordinate industry, government participation, provide basis for discussion	Support assumptions definition, provide expert knowledge	Support assumptions definition, provide expert knowledge
2	Advanced Vehicle and Technology Modeling	Use **EDS** for public domain technology modeling, Provide tech models to Stanford and Purdue	Input into public domain technology modeling	Develop cost, fuel burn, block hour values for aircraft models from Georgia Tech
3	Vehicle and Fleet Assessments	Perform vehicle and fleet level assessments using **GREAT** and **ANGIM**	Provide trade factors for mission specification changes using **SUAVE**. Provide tech factors for some tech modeled in (2)	Fleet-level assessments using **FLEET**

EDS – Environmental Design Space
GREAT – Global and Regional Environmental Analysis Tool
ANGIM –Airport Noise Grid Integration Method
SUAVE – Stanford University Aerospace Vehicle Environment
FLEET – Fleet-Level Environmental Evaluation Tool

Georgia Tech led the process of conducting four virtual workshops to collect feedback from industry, academia, and government on potential future scenarios for fleet and technology evolution and evaluation. This work was performed under objective (1) and the outcome is a set of technology and fleet evolution descriptors in a format suitable for use in a wide variety of modeling tools and future analyses. Under objective (2), Georgia Tech used the EDS conceptual modeling tool to create future representative vehicles consistent with the technology evolution scenarios defined under objective (1). Finally, Georgia Tech exercised the GREAT and ANGIM toolsets under objective (3) to assess potential future fleet-wide impacts of aviation.

Stanford provided input based on its experience in 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 ASCENT Project 10:

Fleet Level Workshop Assumption Setting

Fleet assessment scenarios have been developed by Georgia Tech using input from the project team and virtual workshops comprising industry, university, and government experts. The scenarios are descriptive and are defined through standard future state descriptors such as Gross Domestic Product (GDP) growth, fuel price, and high or low investment in technology. Using these well understood descriptors allows the defined scenarios to be used in a wide range of modeling tools. The defined fleet scenarios are intended to provide bounding cases on future U.S. fleet-wide performance to inform technology development and goal setting.

Technology Level Workshop Assumption Setting

Georgia Tech defined technology development assumptions that are used to drive fleet level predictions of key environmental metrics. These are called technology development roadmaps (or infographics), which provide key information on technology impact, readiness, and estimated development time until entry into service. The technology roadmaps are intended to support future modeling efforts and are tool agnostic.

Evaluation of Impact of Demand and Technology on Future Fleet CO_2 and Noise

Georgia Tech and Purdue used their respective fleet and vehicle simulation models to predict the fleet noise and CO_2 resulting from the defined technology and fleet evolution scenarios. The results indicate that the rate of technology insertion is the major driving factor in reducing fleet wide CO_2 emissions. While CO_2 is a major contributor to the climate, other factors such as particulate matter and contrails were not investigated in the scope of this project. Reducing noise below current levels appears to be achievable even with significant operations growth; however, noise reduction is also dependent on the rate of technology insertion.

Demonstration of FLEET

Purdue used their FLEET modeling tool to simulate 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. With further studies, Purdue assessed the sensitivity of future aviation emissions to variations in fuel prices, market demand, and the dates of technology availability leveraging the outcomes of the fleet and technology workshops. This demonstration of FLEET capabilities preceded the studies to investigate the scenarios defined for this project.

Vehicle-Level Assessment of Mission Specification Changes

The group at Stanford University has focused on (a) the development of the necessary analysis and optimization capabilities within the Stanford University Aerospace Vehicle Environment (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 study of the fuel-burn-reduction opportunities afforded by decreases in cruise Mach number when re-designing (including airframe and engine) these aircraft. All redesigned vehicles have been validated and tested and have been done at current levels of technology and also at more advanced (N+1 and N+2 levels) levels of technology. These improved vehicles have been provided to the rest of the team, so that they can insert such vehicles in the fleet-level analyses done with the Georgia Tech GREAT and Purdue FLEET tools (Task #3 Section). 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 Technology and Fleet Evolution Scenarios

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 trends, which assume an undisturbed continuation of historical and recent developments. This type of forecasting is necessary and useful, but misses 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. This Task focused on the development a standard methodology for capturing potential future states of technology and fleet development. Technology impact is fundamentally captured through the impact of a technology on vehicle performance, emissions, and noise, coupled with the availability of a technology on a given platform within a given timeframe. The fleet impact, or the combined impact of multiple aircraft of varying technology levels flying within a given year, is defined broadly though demand and retirement assumptions. Demand is driven by external factors such as GDP growth and ticket price. Retirement rates are also dependent on certain external factors. This task first conducted virtual workshops to define the external factors that are most important to fleet and technology evolution. A second round of workshops was held to define quantitative inputs to the defined factors.

Summary of Resulting Technology Evolution Scenarios

This section provides a brief overview of the outcomes of the two fleet and technology workshops. A complete description of the data identification, solicitation, and reduction processes for both fleet and technology are described in sections 0 and 0, respectively.

Two fleet workshops were held. The first workshop focused on defining important descriptors and worldviews. The second workshop focused on defining ranges for the selected parameters and defining interesting variations. The team then used the results of both workshops to define a set of scenarios with well-defined parameter settings.

Research Approach

Research Approach Overview

The approach taken was to reduce the overwhelming dimensionality of conventional fleet analysis by selecting a small number of well-defined scenarios. The selected scenarios should encompass future states that are important for specific consideration of significant changes that could occur and also to bind 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 was combined to fully define future bounding scenarios and assess the potential of aircraft technology to improve aviation's environmental impact. The fleet level trends and technology trending workshops are discussed in the following sections.

Fleet Workshops

Based on the Fleet Scenario Workshops that were conducted through the summer and fall of 2015, the team created a series of conclusions from the data obtained from the workshop participants. This includes prioritizations of the factors that describe a scenario as well as evaluations of some provided suggested example scenarios and scenarios that the participants were able to customize. This was then used by the team in the first half of 2016 to formulate a number of scenarios through a series of discussions. The final selection stands at twelve scenarios, which are shown in **Table 3**. The specific settings for each of the scenarios are colored by nominal (blue), low (purple), and high (orange). These values were outcomes of the Fleet Workshops and were obtained by analyzing the data that was collected from the participants.

Fleet Workshop One

The goal of the first workshop was to determine what defines a world view or scenario. Therefore, the workshop was designed to gather feedback on the descriptors including variables, ranges of values and importance. Additionally, some initial worldviews were shown to solicit comments from the workshop participants.

This was done in order to define a range of scenarios to bound aviation's environmental impacts in the future and examine effects of aircraft technology on these impacts. The workshop was used to gather feedback on the assumptions for use in future U.S. fleet assessments to 2050 and was composed of the following sections:

- Relative importance of descriptors
- Selection of descriptor ranges (high, medium, low values over next 35 years)
- Selection of descriptor values for worldviews proposed

The initial list of worldview descriptors was down selected and refined by the team in order to focus the workshop on key factors, yet still allow the participants a good amount of room to further refine the list of key descriptors. The descriptors selected to be discussed at the workshop were broken into categories and were then individually presented with background information, a description, the impact on aviation, definition of units, as well as a specific question to answer for selecting a specific numerical answer. These descriptors proposed to the workshop participants are detailed in this section.

Each descriptor was presented to workshop participants on a single slide. An example of a descriptor is shown in **Error! Reference source not found.** for GDP. The idea was to comprehensively present a quick overview of each descriptor that was preselected and introduce the audience to it by showing a brief description and an explanation on how it might impact aviation. Additionally, background information with references was also included. This was then punctuated by specific units and a direct question to answer in the survey to be filled in by the participants.

In order to create the final scenarios, a series of two fleet workshops were held to engage participants from industry, academia, and government and to 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.

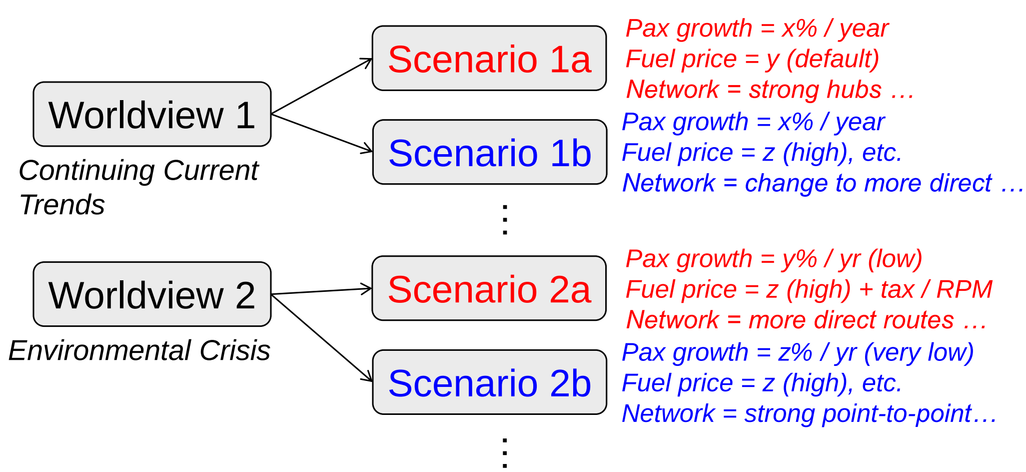


Figure 1: Decomposition of Fleet Assumptions into Worldview and Scenarios

An example of this is shown in Figure 1, where worldviews and scenarios were be used to derive specific assumptions listed on the right. Revenue Passenger Miles (RPM) is a high level metric of aviation demand activity and represents the product of passengers multiplied by miles travelled. 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. Of those available, the three most commonly used were selected to provide the current trends or values that illustrate the importance of a specific descriptor. These 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. The following subsections provide in-depth descriptions of each of the descriptor categories listed above.

Economic Factors

Gross Domestic Product (GDP) Growth

The first descriptor is probably one of the most important economic variables: gross domestic product. GDP describes the overall economic development of a specific region or country and is thought to be representative of a nation's wealth. Changes in GDP are primarily due to two components. First is the change in economic activity, when expressed in per capita terms. This introduces the second component such as the change in population. Together, these drive changes in the overall wealth of a country. As shown in Figure 2, aviation trip demand is highly correlated to GDP per capita. Large increases in travel trip demand occur when growing from low levels. Smaller increases in travel demand occur 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 percent per year. The question asked from attendees was: What is the future annual change of U.S. GDP growth?

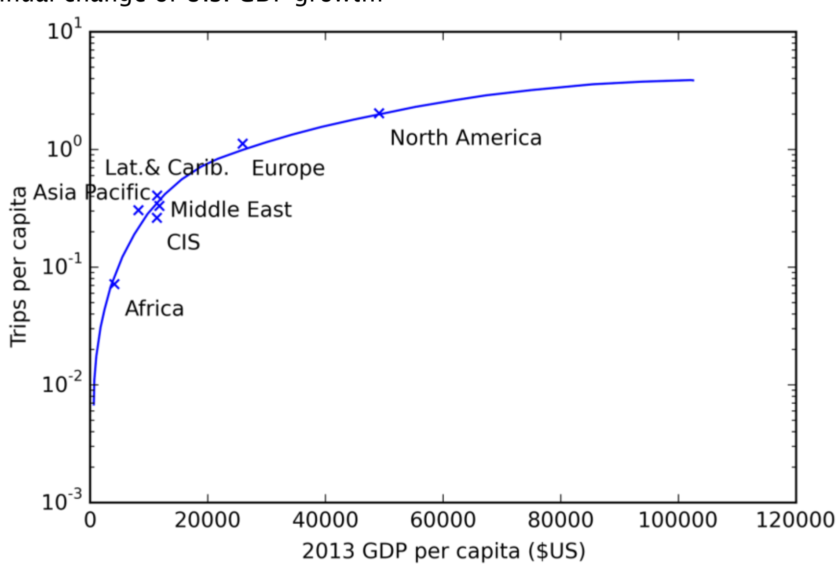


Figure 2: Aviation Demand is Driven by per capita GDP, Adopted from [2]

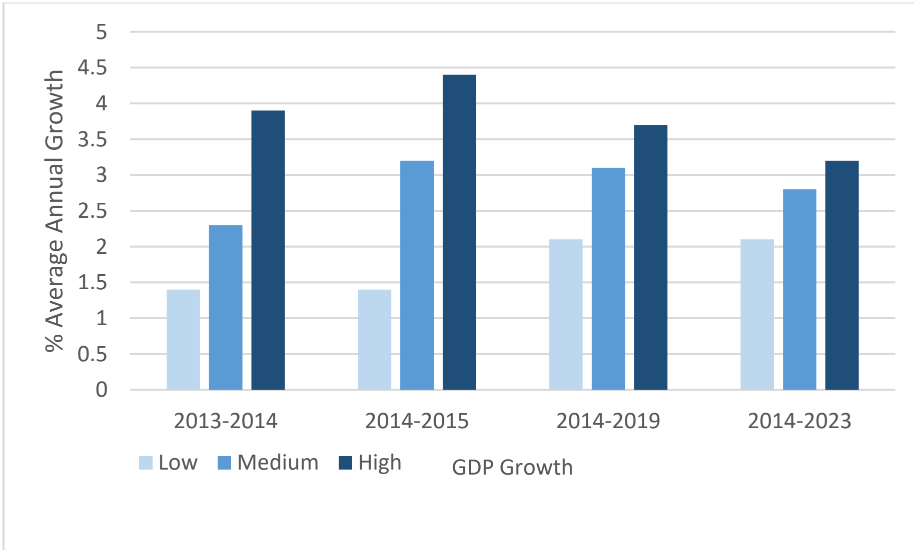


Figure 3: GDP Growth [2]

Figure 4: 10 Year Treasury Inflation Indexed Security Interest Rate

Figure 5: 10 Year Treasury Constant Maturity Interest Rate

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 regarding 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 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?

Population Growth
Population is another underlying factor that is a large driver of economic activity that can lead to increased passenger traffic. Figure 6 shows the global population growth since 1950, with a forecast to 2050. The question asked attendees was: What is the future average annual U.S. population growth?

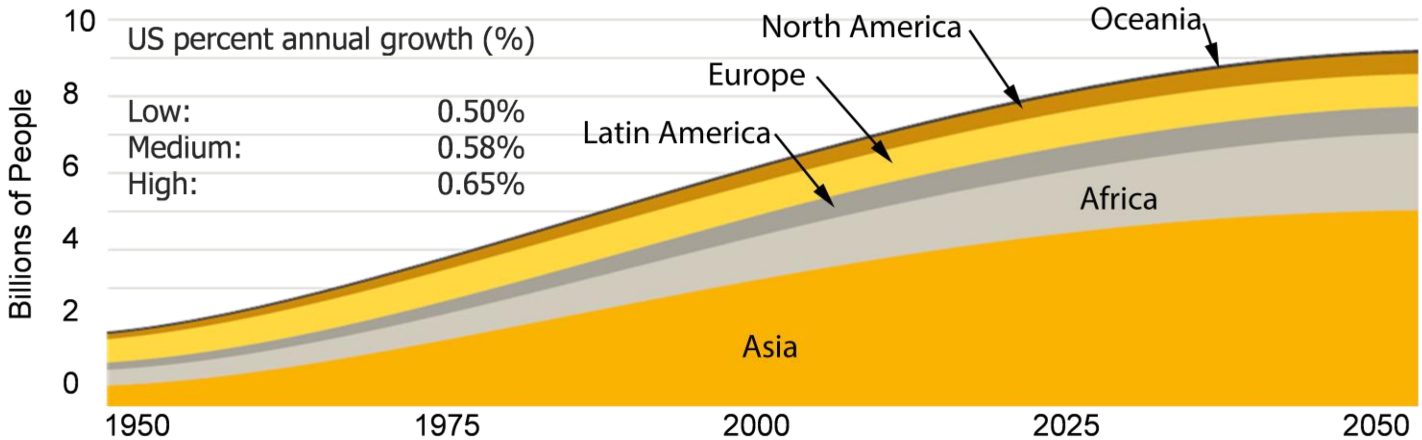


Figure 6: Global Population Growth, Adopted from [**2**] and U.S. Census 2014 Projections

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 shows the employment population ratio and the participation rate for the core working age groups. It shows that the participation rate has significantly increased as women entered the labor force. This trend has been reversing itself slightly due to various demographic factors. Also noticeable is the effect of recessions as people leave and re-enter the labor force.

Figure 8 shows the age distribution side of the demographics. These two factors together have an effect on aviation demand with regards to available income as well as travel behavior differences between different age groups.

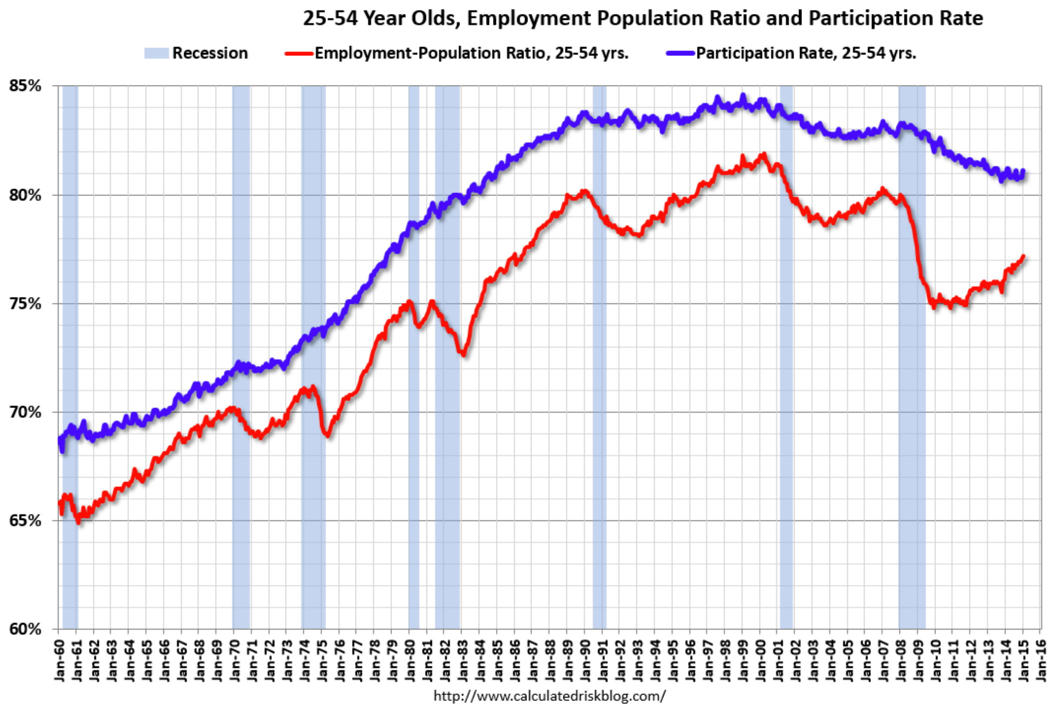


Figure 7: Participation and Employment-Population Ratio [Calculated Risk from BLS Data]

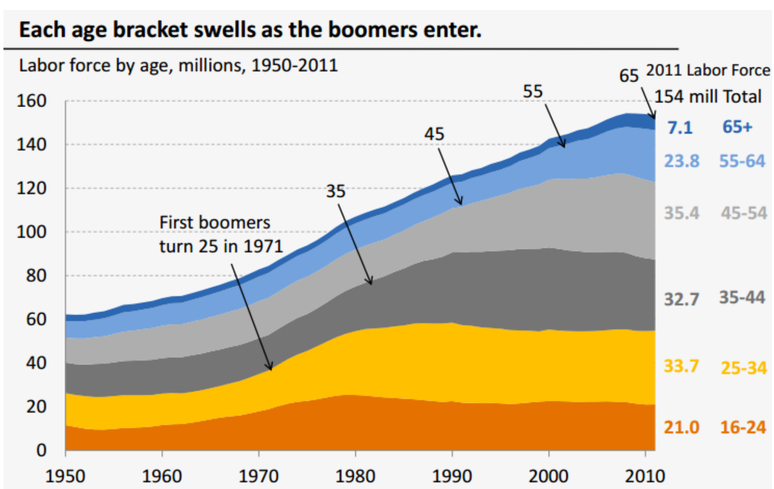


Figure 8: Age Distribution, Adopted from [2]

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 U.S. 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 U.S. 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?

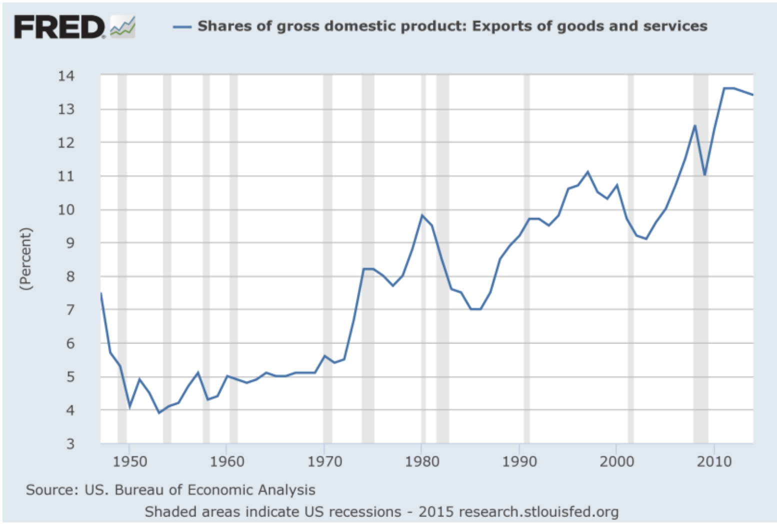


Figure 9: U.S. Share of Exports to GDP

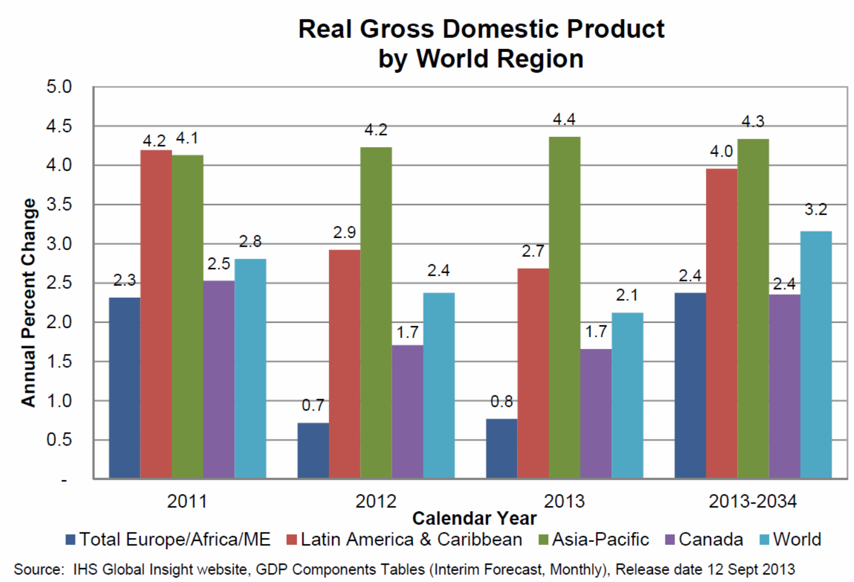


Figure 10: Global GDP Growth Rates [3]

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?

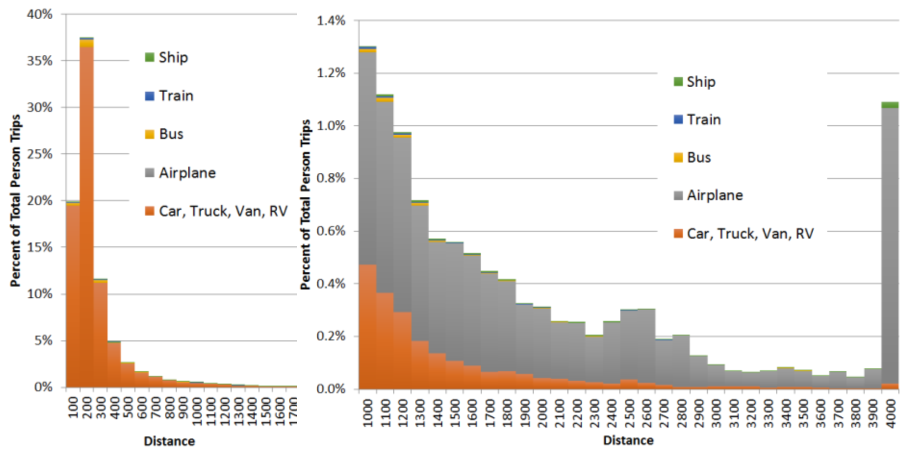


Figure 11: Total person Trip Distribution [5]

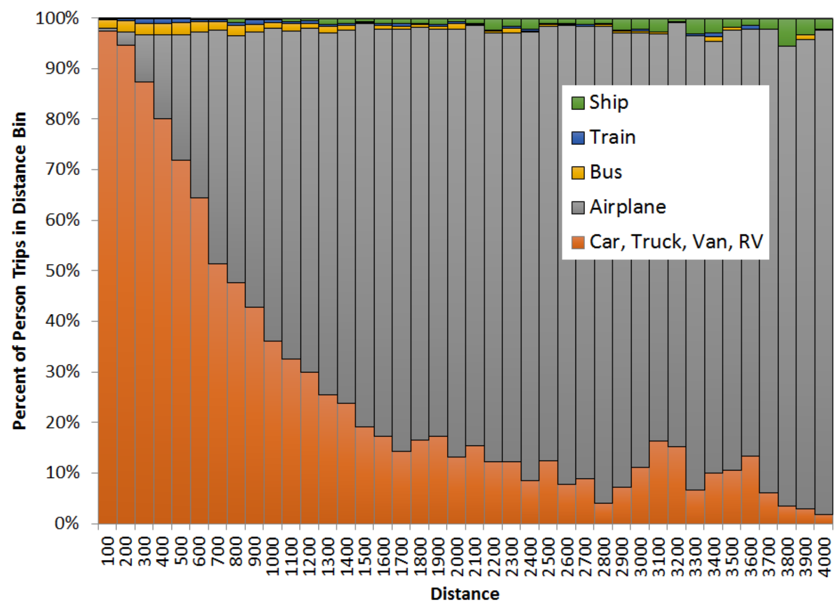


Figure 12: Modal share as a Function of Distance [2]

Energy Price

The price paid for energy, specifically in the case of aviation the price of aviation fuels, is an important factor that determines the cost of travel for aviation. Figure 13 shows the price of oil both in recent decades as well as in the near future. The underlying fundamental factor is the price that refineries charge to produce aviation fuels and pay for the raw crude oil. Therefore, the attendees were asked the following question: What is the future trend of the oil price?

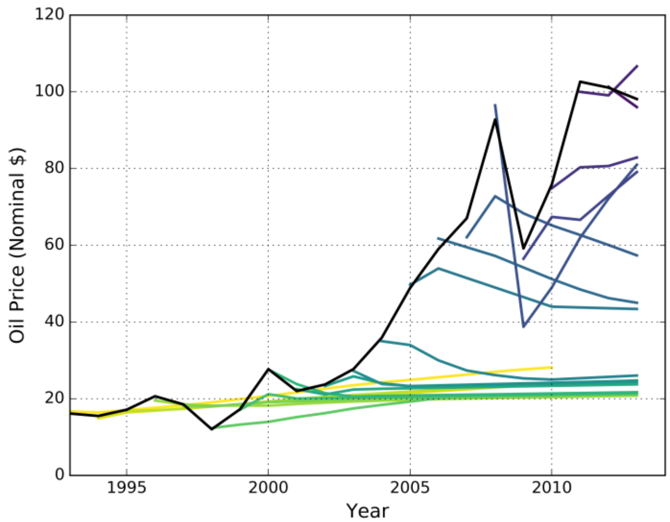


Figure 13: Analysis of EIA Annual Energy Outlook Forecasts [2]

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

CO_2 Emissions

CO_2 emissions are directly proportional 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 in the future. The charge in effect currently in Europe is through the European Emissions Trading System (ETS), whose trends are shown in **Figure 16**. It shows the EU ETS annual cap (Cap), annual verified emissions from sources covered by the EU ETS (Emissions), annual offsets surrendered for compliance (Offsets) and average annual future rolling prices (CO_2 price) [7]. Due to variety of charging schemes possible, the question asked the attendees was simplified to: What is the future average cost of CO_2 emissions?

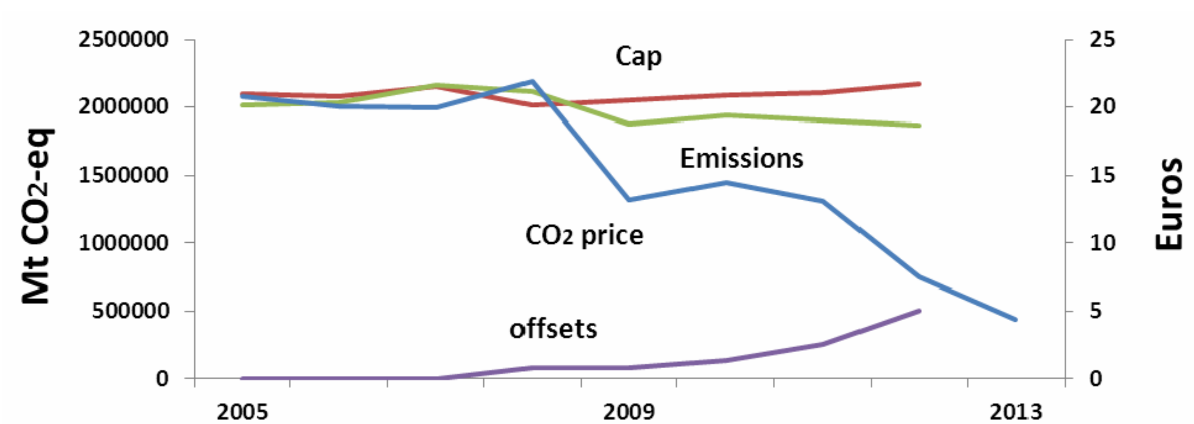


Figure 16: European ETS CO_2, Price and Quantity [2]

NO_x Emissions

NO_x Emissions are of concern due to the effect on the air quality in communities surrounding airports. NO_x emissions are of particular interest as there are existing airport charges related to NO_x emissions and Heathrow recently proposed a significant increase in their NO_x charges [2]. Therefore, concerns about NO_x 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 NO_x emissions at these U.S airports?

Airport Abbreviation	Airport Name
ATL	Hartsfield - Jackson Atlanta Intl
BOS	Boston Logan Intl
BWI	Baltimore/Washington Intl
CLT	Charlotte Douglas Intl
DCA	Ronald Reagan Washington National
DEN	Denver Intl
DFW	Dallas/Fort Worth Intl
DTW	Detroit Metropolitan Wayne County
EWR	Newark Liberty Intl
FLL	Fort Lauderdale/Hollywood Intl
HNL	Honolulu Intl
IAD	Washington Dulles Intl
IAH	George Bush Houston Intercontinental
JFK	New York John F. Kennedy Intl
LAS	Las Vegas McCarran Intl
LAX	Los Angeles Intl
LGA	New York LaGuardia
MCO	Orlando Intl
MDW	Chicago Midway
MEM	Memphis Intl
MIA	Miami Intl
MSP	Minneapolis/St. Paul Intl
ORD	Chicago O`Hare Intl
PHL	Philadelphia Intl
PHX	Phoenix Sky Harbor Intl
SAN	San Diego Intl
SEA	Seattle/Tacoma Intl
SFO	San Francisco Intl
SLC	Salt Lake City Intl
TPA	Tampa Intl

Figure 17: Core 30 U.S. Airports

The additional question was asked: What percent of the Core 30 U.S. airports do you envision will charge for NO_x emissions? A list of Core 30 airports given to the participants is shown in Figure 17. They are the core airports used by the FAA to measure Airspace System Performance Metrics (ASPM) [3].

Non-Volatile Particulate Matter Emissions

The inclusion of non-volatile particulate matter (nvPM) emissions was due to the concern about the effects of these emissions on air quality, which could result in an impact on health and economic considerations such as airline operational charges. Non-volatile particulate matter emissions are the primary pollutant impacting air quality and community health impacts in the vicinity of airports.

The background information presented was limited to mentioning that standards 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, the operational details, and type of the aircraft used. If the number of operations increases, then the noise emissions per aircraft operation have to decrease in order to avoid increasing 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 metric selected in this case for noise limits was defined as the percentage of the core 30 U.S. airports that could have noise limits similar to a quota count system that tries to enforce the maximum noise limits by capping the operations counts that are allowed, depending on the noise levels of the aircraft used. This can be used in modeling by forcing airline and manufacturer decisions through possible operational limits which can then 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?

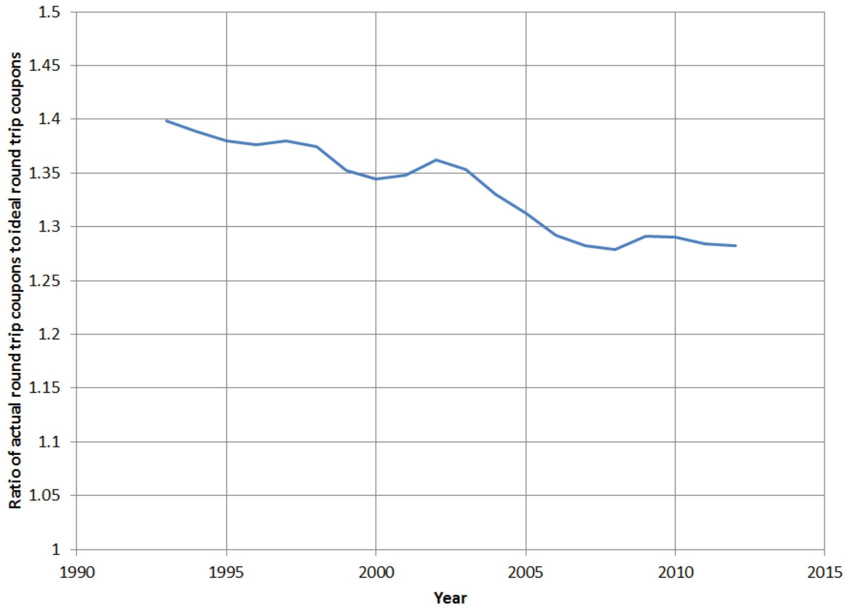


Figure 18: Ratio of Actual to Ideal Round Trip Coupons [4]

Travel Attractiveness

This refers to the amenities provided during travel such as how long it takes to go from leaving home to boarding the plane, how many flights are offered in a given time period, cabin comfort, and seat pitch. 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. This means that if more than one mode is available for a traveler, that the relative share given to aviation would be increased or decreased relative to the current status quo. 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 is compared. Equal 50 means it is even to average competing mode, 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 unit 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 that 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 regulations. Reducing regulations – such as slot limits – 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 used for this factor are relative normalized levels represent the extremes of open or restrictive with current in the middle. 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 Research and Development (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 and accelerate the time at which manufacturers decide to launch new aircraft with the specific technology. The modeling use would be implemented 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 approximately 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?

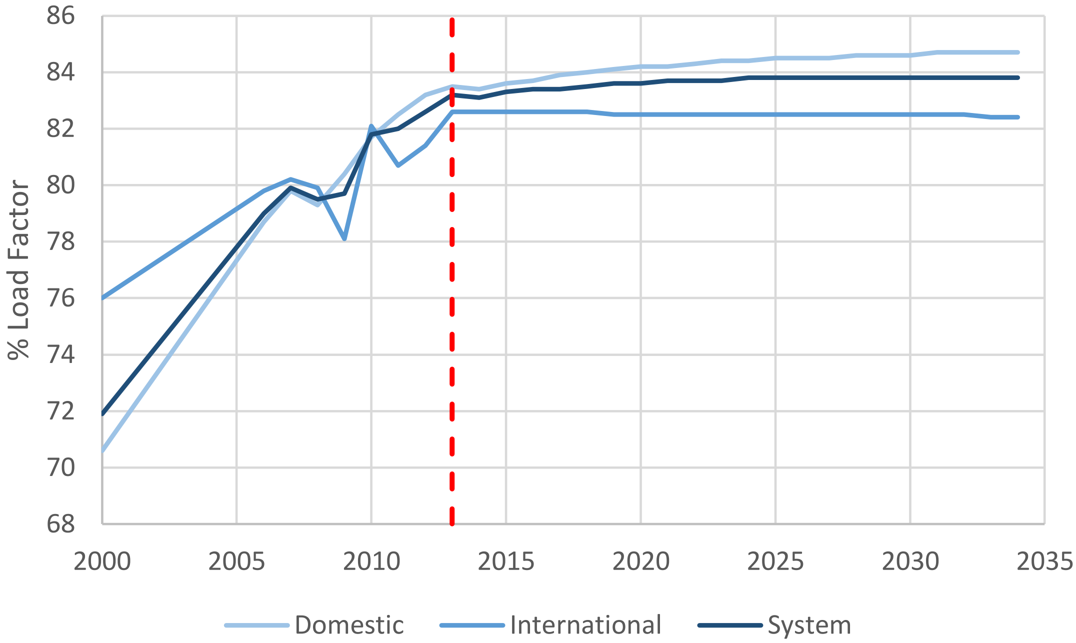


Figure 21: FAA Forecast Load Factor [3]

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 were used to generate a ranking of importance of the listed descriptors. **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 CO_2 Emissions
Population Growth
International Trade
Airport Noise Limitations
Industry Competitiveness
Amount and Speed of Technology R&D Investment

This result was used to create the materials for the second workshop, where a number of worldviews were created using variations of each descriptor that came out of the first workshop.

Fleet Workshop Two

The goal of the second workshop was to select specific worldviews and scenarios of interest and define the corresponding values for each descriptor identified in Fleet Workshop One. Furthermore, the relationship between the worldviews defined and technology insertion opportunities and their timing was also explored. The worldviews proposed to the workshop attendees included two reference scenarios, several demand driven scenarios and two scenarios hinging on the level of environmental constraints imposed.

The first reference worldview used demand growth forecasts and considered the environmental effects in 2050 if no new technology was introduced, holding all aircraft at present day in service technology through 2050. This "Frozen Technology" worldview is not realistic, and is introduced only as a baseline. The second reference worldview is one where “Current Trends” are allowed to continue in all descriptors including technology introduction. This would be considered the most likely scenario with the moderate technology improvement expected without additional government investment.

The workshop participants were also asked to define descriptor values for four worldviews considering different levels of demand. Two of these worldviews saw prosperity driving a high level of demand across the globe and then explored two technology development options. The first sub-scenario considered the environmental impact caused by high demand without additional technology investment. The second sub-scenario examined to what extent accelerated technology investment could alleviate the environmental impact of a demand increase. Conversely, two sub-scenarios were defined probing the different technology investment schedules under a low or stagnated demand worldview. It should be noted that these worldviews were later expanded to include additional very high demand scenarios, and suppressed technology investment scenarios.

Finally, two worldviews were proposed focusing on the application of environmental constraints to reflect the impact of both operational/capacity restrictions and financial disincentives in the form of increased energy costs. This gave rise to an “Environmental Bounds Low” worldview where demand is suppressed, non-compliant aircraft are retired early, and technology investment must be high to meet the environmental constraints. Alternatively, an “Environmental Bounds High” worldview was offered, where demand increased significantly over time, aircraft were retired late and technology investment was not driven by environmental constraints.

Based on the worldviews defined, the workshop participants were asked to identify the importance of each descriptor (GDP, Population growth, etc…) under each worldview. Participants were also asked to set a value for the descriptor (Low/Medium/High) under each scenario proposed. Participants were given the opportunity of defining a custom scenario if they saw a need for it. Figure 23 illustrates a portion of the survey distributed to participants in order to collect descriptor values and importance for each scenario. The questions were presented at the workshop and provided in Excel form as a sheet to be filled out by the participants and returned.

The following columns contain different world views. Fill out each column for each corresponding world view, answering these questions:
What is the value of the descriptor for this world view?
Importance of the descriptor for the specific scenario: + important, - not important
Setting for that particular scenario (High/Medium/Low)

Descriptor	World View 1: High Demand/Prosperity	World View 2: Environmental Constraints	World View 3: Low Demand	Custom World View:
GDP Growth (%/yr)				
Interest Rates (%/yr)				
Population Growth (%/yr)				
Labor Force Composition				
International Trade (as a share of GDP)				
Modal Competition (% share)				
Energy Price ($/bbl)				

Figure 23: Worldview Definition Questionnaire Example

The participant responses were collected, summarized and used to define sub-scenarios within each worldview as illustrated by the Figure 24 below.

Worldviews

- 1) Current Trends
  - Useful as baselines for comparison – what difference is technology making?

Scenarios	GDP Growth (%/year)	Energy Price ($/bbl)	Cost of CO2 Emissions ($/MT)	Population Growth (%/year)	International Trade (%/year Asia)	Airport Noise Limitations (% airports noise limited in future)	Industry Competitiveness (cent/ASM)	Amount and Speed of Technology R&D Investment (relative)
1a: Current Trends Fixed Tech	2.8	77	21	0.58	4.3	25	12	0
1b: Current Trends In-Production Only	2.8	77	21	0.58	4.3	25	12	0
1c: Current Trends	2.8	77	21	0.58	4.3	25	12	1.02

- Scenario 1a:
  - Current fleet technology and efficiency do not improve any more from current in-service
- Scenario 1b:
  - Currently out of production aircraft are retired and replaced with in-production vehicles, but no newer technology vehicles are brought into production
- Scenario 1c: Continuing Current Development
  - Technology improves at historic rates with medium settings for all important descriptors

	Units	Low	Medium	High
GDP Growth	%/year	1.8	2.8	4
Energy Price	$/bbl	41	77	181
Cost of CO2 Emissions	$/MT	0	21	85
Population Growth	%/year	0.45	0.58	0.68
International Trade	%/year Asia	3.3	4.3	5.9
Airport Noise Limitations	% of airports noise limited in the future	4	25	95
Industry Competitiveness	cent/ASM	20	12	8
Amount and Speed of Technology R&D Investment	relative	0.52	1.02	1.71

21

Figure 24: Example Summary of Data Collected from Participants Regarding Each Worldview

Another aspect investigated in this second workshop was fleet evolution, which is a key factor in allowing new technologies to enter the fleet. The workshop participants filled out surveys probing the future of very large and quad engine aircraft, and the likelihood of narrow body vs wide body aircraft development programs being first. Participants also answered questions regarding aircraft development program duration, and the interval between new aircraft or improvement package programs in the future. While these questions helped establish when new aircraft (incorporating the new technologies) are available to enter the fleet, productions rates will affect the rate at which the new aircraft can actually replace previous models. Therefore, workshop participants were also asked to answer questions regarding maximum and minimum production rates for each aircraft type.

The results of the second fleet workshop were compiled and the team had several internal discussions and formulated a final set of scenarios based on the results of the two workshops. These are shown in **Figure 25** as an overview how they align with the different corners of the scenario trade space. A final set of tables containing all scenarios with settings for each are detailed in Table 3 to Table 5.

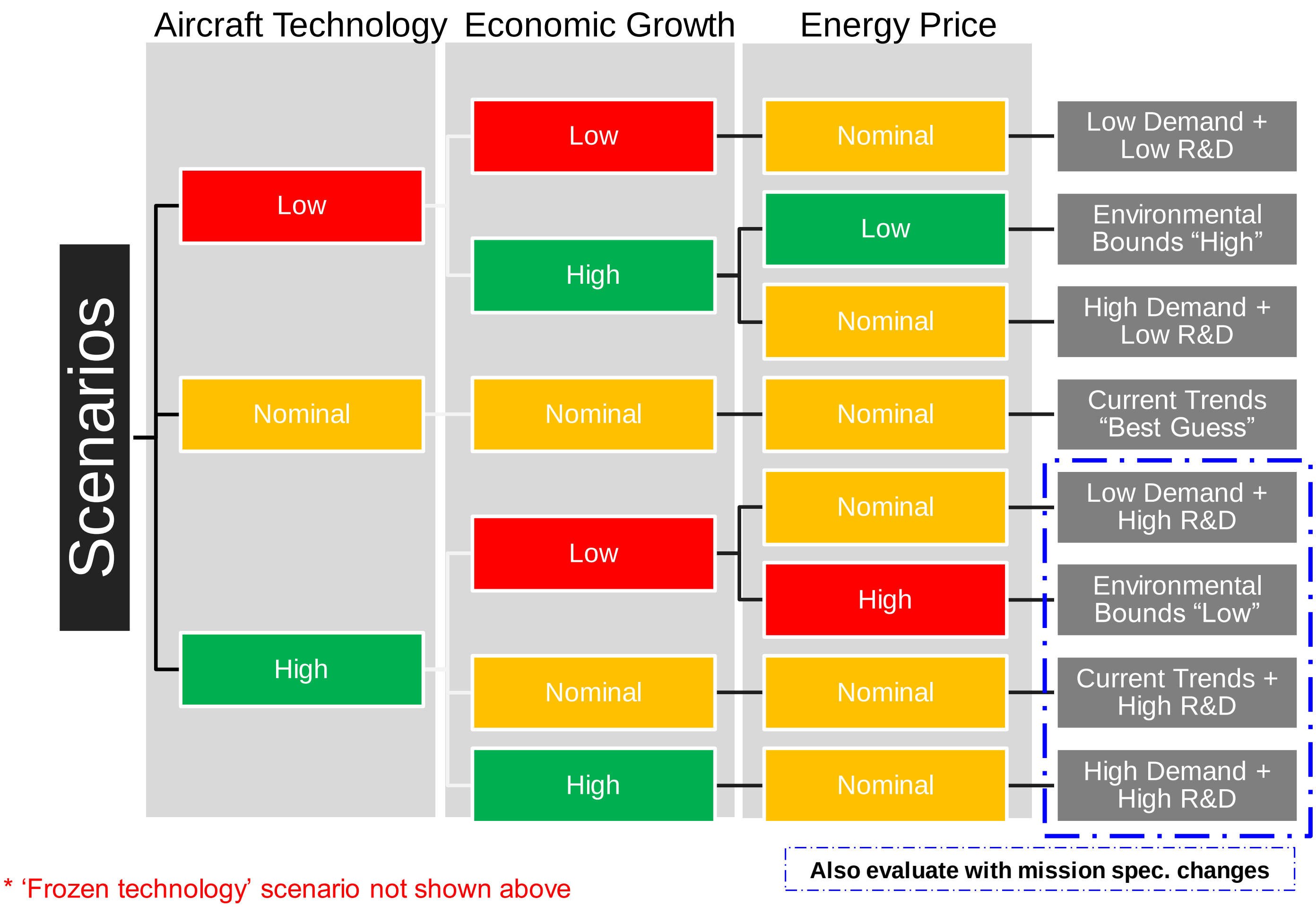


Figure 25: Scenario Tree Overview

Table 3 to Table 5 show the final matrix of scenarios. The scenarios are listed by row, whereas the columns list the final worldview descriptors with specific settings for each scenario. Each cell is colored from low to nominal to high settings.

Table 3: Matrix of Scenarios and Demand and Economic Model Factors

	GDP Growth (%/year)	Energy Price ($/bbl)	Population Growth (%/year)	International Trade (%/year Asia)	Industry Competetiveness (cent/ASM)	Airport Noise Limitations (% airports noise limited in future)	Cost of CO2 Emissions ($/MT)
Current Trends "Best Guess"	2.8	77	0.58	4.3	12	25	21
Current Trends + High R&D	2.8	77	0.58	4.3	12	25	21
Current Trends + High R&D + Mission Spec.	2.8	77	0.58	4.3	12	25	21
Current Trends Frozen Tech - In-Production Only	2.8	77	0.58	4.3	12	25	21
Environmental "Bounds" - Low	1.8	181	0.45	3.3	12	95	85
Environmental "Bounds" - High	4	41	0.68	5.9	12	4	0
High Demand (Including Global) + High R&D	4	77	0.58	5.9	12	25	21
High Demand (Including Global) + Low R&D	4	77	0.58	5.9	12	25	21
Low Demand (Including Global) + High R&D	1.8	77	0.58	3.3	12	25	21
Low Demand (Including Global) + Low R&D	1.8	77	0.58	3.3	12	25	21
Very High Demand with Noise Limits - Low R&D	4	41	0.68	5.9	12	95	0
Very High Demand with Noise Limits - High R&D	4	41	0.68	5.9	12	95	0

(orange)	High
(light blue)	Nominal
(purple)	Low

Table 4: Matrix of Scenarios and Fleet Evolution Model Factors

	Fleet Evolution Schedule	Aircraft Retirement	Production Capacity
Current Trends "Best Guess"	Nominal - Twin Aisle First in 2020s	Nominal	No Limits
Current Trends + High R&D	Nominal - Twin Aisle First in 2020s; Adjusted sequence if necessary for first application of new configuration/ architecture/ mission spec. change	Nominal	No Limits
Current Trends + High R&D + Mission Spec.	Nominal - Twin Aisle First in 2020s; Adjusted sequence if necessary for first application of new configuration/ architecture/ mission spec. change	Nominal	No Limits
Current Trends Frozen Tech - In-Production Only	Nominal - Twin Aisle First in 2020s	Nominal	No Limits
Environmental "Bounds" - Low	Nominal - Single Aisle First in 2020s	Early (relative to historical data)	No Limits
Environmental "Bounds" - High	Nominal - Twin Aisle First in 2020s	Late (relative to historical data)	Limits
High Demand (Including Global) + High R&D	Nominal - Twin Aisle First in 2020s	Nominal	No Limits
High Demand (Including Global) + Low R&D	Nominal - Twin Aisle First in 2020s	Nominal	No Limits
Low Demand (Including Global) + High R&D	Nominal - Twin Aisle First in 2020s	Nominal	No Limits
Low Demand (Including Global) + Low R&D	Nominal - Twin Aisle First in 2020s	Nominal	No Limits
Very High Demand with Noise Limits - Low R&D	Nominal - Twin Aisle First in 2020s	Late (relative to historical data)	Limits
Very High Demand with Noise Limits - High R&D	Nominal - Twin Aisle First in 2020s	Late (relative to historical data)	Limits

Table 5: Matrix of Scenarios and Aircraft Technology Model Factors

	Amount and Speed of Technology R&D Investment (relative)	TRL 9 Dates	Benefit Levels	Aircraft Configurations	Engine Architectures	Mission Specification Changes
Current Trends "Best Guess"	1.02	Medium	Medium	"Gen 1" Advanced High AR Wing Type 2035+ (check median gen 1 TRL 9 date response)	"Gen 1" as expected; "Gen 2" Open Rotor Type Benefits 2035+	None
Current Trends + High R&D	1.71	Early - Emphasis over benefit level	High	All 3 generations as responded in surveys, Gen 1 2025+, Gen 2/3 2035+	All 3 generations as responded in surveys, Gen 2/3 2035+	None
Current Trends + High R&D + Mission Spec.	1.71	Early - Emphasis over benefit level	High	All 3 generations as responded in surveys, Gen 1 2025+, Gen 2/3 2035+	All 3 generations as responded in surveys, Gen 2/3 2035+	3 generations. 2nd gen redesign for cruise speed reduction. Include range variants
Current Trends Frozen Tech - In-Production Only	0	N/A	N/A	None	None	None
Environmental "Bounds" - Low	1.71	Early - Emphasis over benefit level	High	All 3 generations as responded in surveys, Gen 1 2025+, Gen 2/3 2035+	All 3 generations as responded in surveys, Gen 2/3 2035+	3 generations. 2nd gen redesign for cruise speed reduction. Include range variants?
Environmental "Bounds" - High	0.52	Late	Low	None	None	None
High Demand (Including Global) + High R&D	1.71	Early - Emphasis over benefit level	High	All 3 generations as responded in surveys, Gen 1 2025+, Gen 2/3 2035+	All 3 generations as responded in surveys, Gen 2/3 2035+	3 generations. 2nd gen redesign for cruise speed reduction. Include range variants
High Demand (Including Global) + Low R&D	0.52	Late	Low	None	None	None
Low Demand (Including Global) + High R&D	1.71	Early - Emphasis over benefit level	High	All 3 generations as responded in surveys, Gen 1 2025+, Gen 2/3 2035+	All 3 generations as responded in surveys, Gen 2/3 2035+	3 generations. 2nd gen redesign for cruise speed reduction. Include range variants
Low Demand (Including Global) + Low R&D	0.52	Late	Low	None	None	None
Very High Demand with Noise Limits - Low R&D	0.52	Late	Low	None	None	None
Very High Demand with Noise Limits - High R&D	1.71	Early - Emphasis over benefit level	High	All 3 generations as responded in surveys, Gen 1 2025+, Gen 2/3 2035+	All 3 generations as responded in surveys, Gen 2/3 2035+	3 generations. 2nd gen redesign for cruise speed reduction. Include range variants

Technology Roadmapping Workshops Overview

The goal of the technology roadmapping workshops was to develop a range of scenarios bounding the possible future of technology, including their impacts and likely entry into service. This information was then used to model advanced aircraft technologies and advanced vehicles expected to enter the fleet through 2050. Technology Workshop 1 was held virtually on June 10th and 11th of 2015 to solicit feedback from government, industry, and academia on a wide range of aircraft technology topic areas. From the results, infographics were created that document the suggested scenarios including technology impact, time to entry into service, and examples of specific technologies. Technology Workshop 2 was followed up by a virtual workshop held on February 16th of 2016 to evaluate the infographics and get a final consensus on the technology evolution scenarios. In addition to guiding the modelling of advanced aircraft, a publically available document will be prepared from the final infographics.

Attendees to the technology roadmapping workshops 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 technology evolves?

Maturation Rate – How quickly does each generation of a technology mature to technology readiness level (TRL)[1] 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 Roadmapping Survey 1 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 26**. 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.

[1] "Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest." - NASA

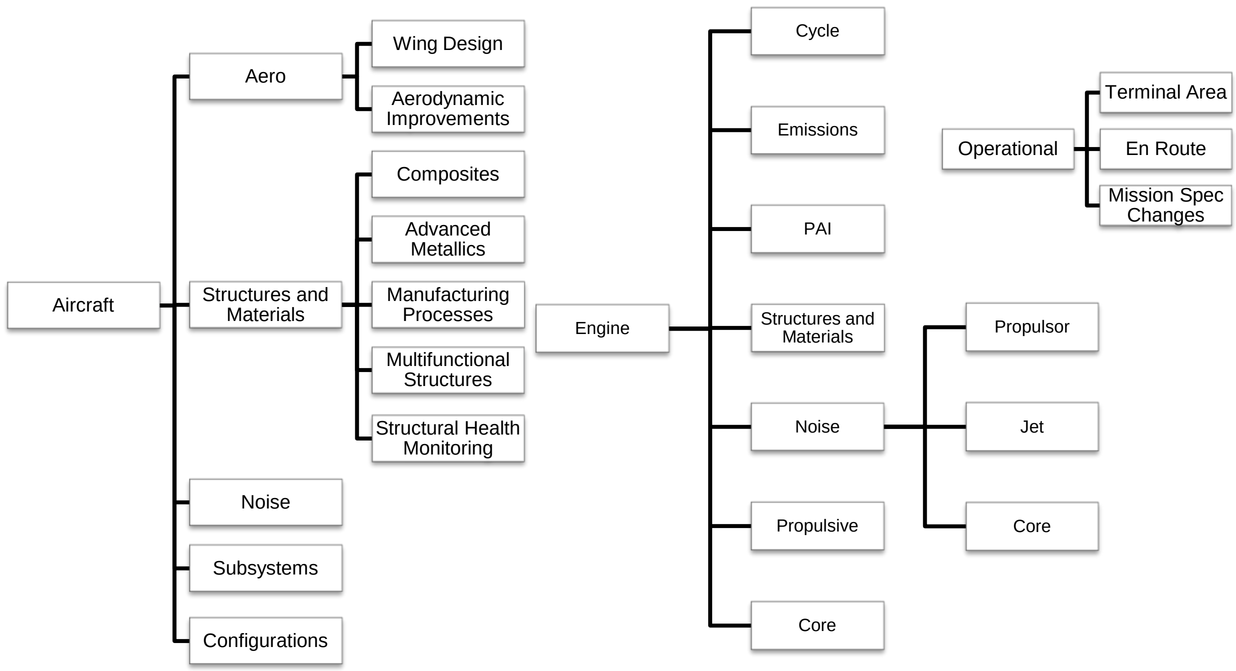


Figure 26: Technology Categorization

There are a few technology categories in Figure 26, which may require further explanation. Engine PAI for example stands for Propulsive Airframe Integration and relates to technologies such as boundary layer ingestion. Many of the technologies that affect Engine Propulsor Noise also affect Engine Jet Noise. Since this survey was mainly focused on turbofan powered aircraft, the major differentiator between the two is that any technology associated with fan noise is related to Engine Propulsor Noise, while technology associated to jet and shock noise is only related to Engine Jet Noise.

For each of the technology categories in Figure 26, 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 27. The figure shows 1st generation wing design; however, all technology areas had a consistent structure, with the contents of each colored box adjusted accordingly.

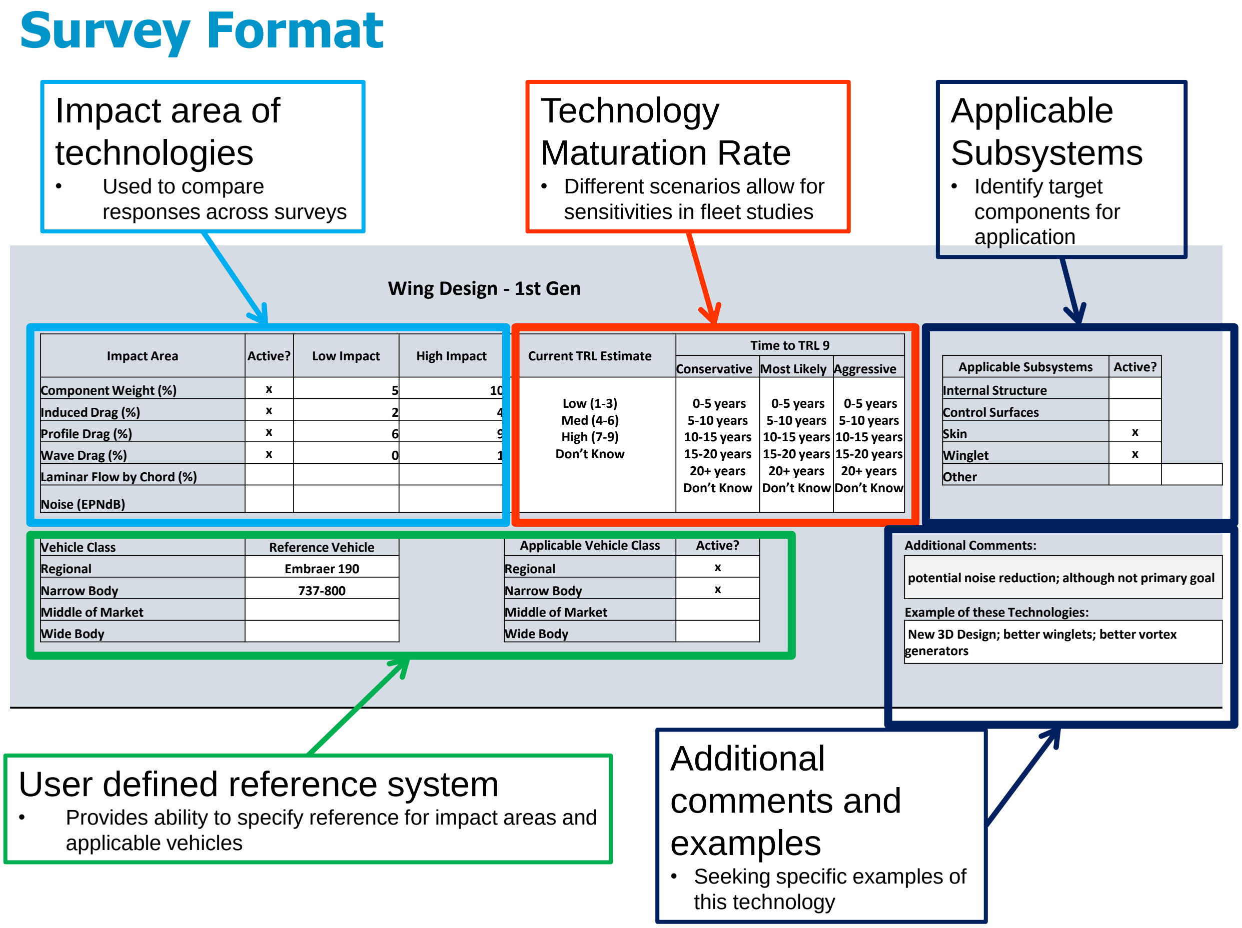


Figure 27: Technology Roadmapping Survey 1 Format

Working clockwise from the upper left of Figure 27 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, or what has also been referred to as the natural metric. 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 Technology Readiness Level (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 6 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 6: List of Impact Areas and Applicable Subsystems for Each Technology Category

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

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

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

Category	Examples	Impact Areas	Applicable Subsystems
Operations Mission Specification Changes	Cruise speed reduction (CSR) Range/payload design characteristics Maximum allowable span (see configurations) Take-off and landing field lengths	Fuel Burn (%) Noise (EPNdB), via weight reduction Emissions (%)	Design Range Design Mach 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 7.

Table 7: Technology Generation Examples

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

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

Technology Roadmap Infographic Development

Following the first Technology Roadmapping Survey, a large dataset of responses was collected. The results were combed through to identify any logical inconsistencies and gross outliers. For example, it was observed that for one of the respondents there were times when their Generation 2 and 3 impacts were less than their Generation 1 impacts. This respondent was contacted and it was found that they were giving their impacts relative to the previous generation. For example, their Generation 3 impact was the improvement from Generation 2. These responses were adjusted, so that they were all relative to a 1995 baseline aircraft like the other responses.

The aim of the Technology Roadmap infographics was to effectively convey the range of impacts for each generation. An infographic was made for each of the 22 technology areas. Figure 28 provides a diagram of the initial infographic format that was developed. On each infographic, a bar graph was included for each impact within that technology area. The high and low values from the responses were used to define the technology impact range for each generation. A nominal impact value was also provided. The infographics also included examples of technologies broken into the generation they would be introduced. In addition, they had graphics that showed the range of responses for the "year to TRL 9" and "Current TRL" for each generation. Finally, at the bottom of the infographics was a matrix showing what respondents thought the applicable subsystems for that technology area's impacts were, for a given vehicle class and generation.

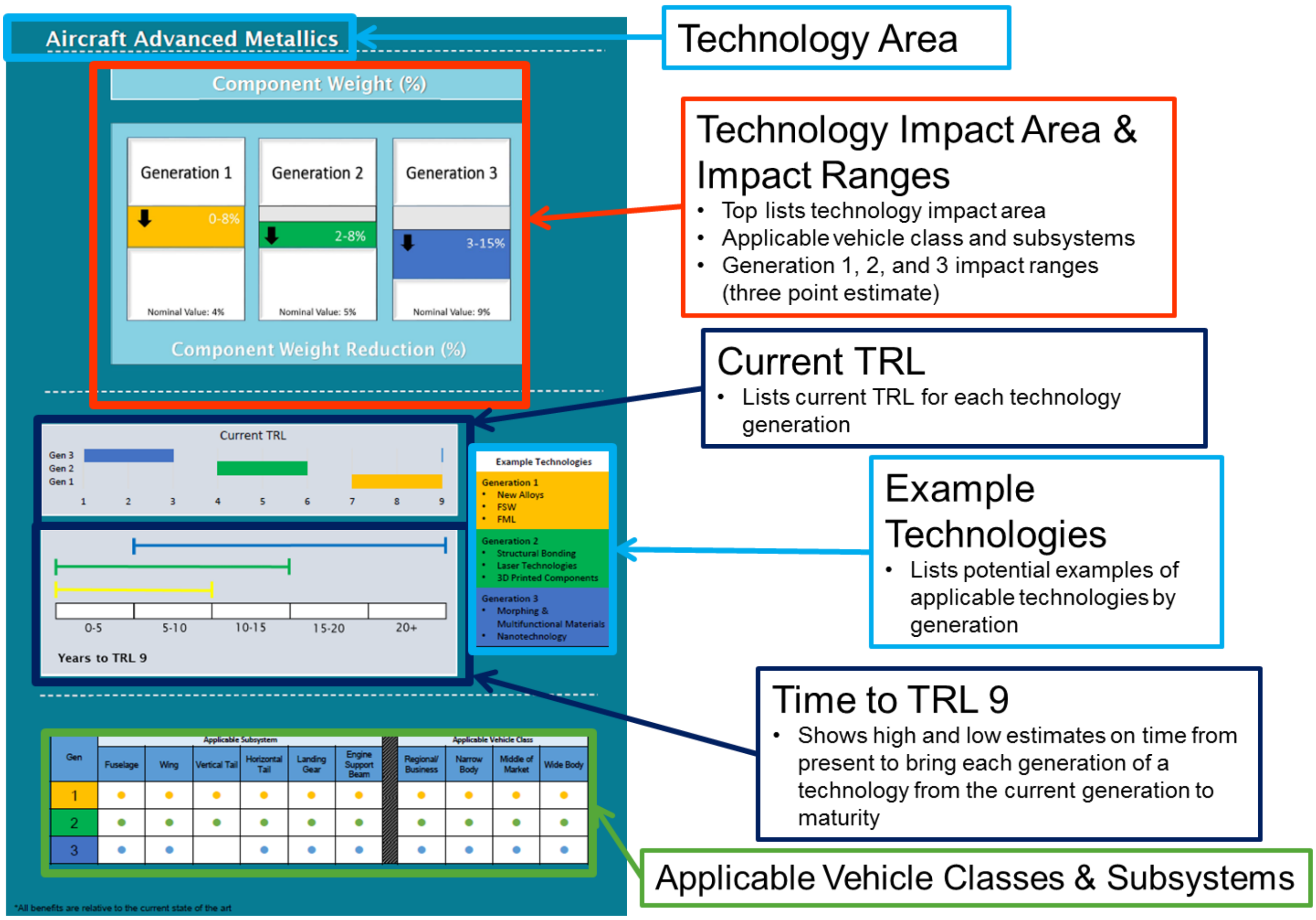


Figure 28: Initial Technology Roadmap Infographic Format Presented at Technology Roadmapping Workshop 2

Technology Roadmapping Survey 2 Format

The goal of the second Technology Roadmapping Workshop was to send participants the infographics to review and provide feedback on the range of responses given in the first workshops. Using the infographics format kept the results anonymous, which helped avoid any bias and ensured participants were viewing the results objectively. As seen in Figure 29, the Technology Roadmapping Survey 2 format was straightforward. For each technology area, participants were asked to review the resulting infographics, one generation at a time. For a given generation, participants were first asked if there were any applicable vehicle classes, applicable subsystems, or example technologies that they thought should be added or removed. Then participants were asked to review the low, nominal, and high technology impact values for that generation. If participants believe an impact value needed to be changed they were asked to explain why. Similarly, for the Current TRL and Time to TRL 9 participants were asked to review the range of values and explain any suggested changes. Throughout the survey participants were encouraged to leave answers blank if they felt they did not have the background to comment on a particular technology impact area.

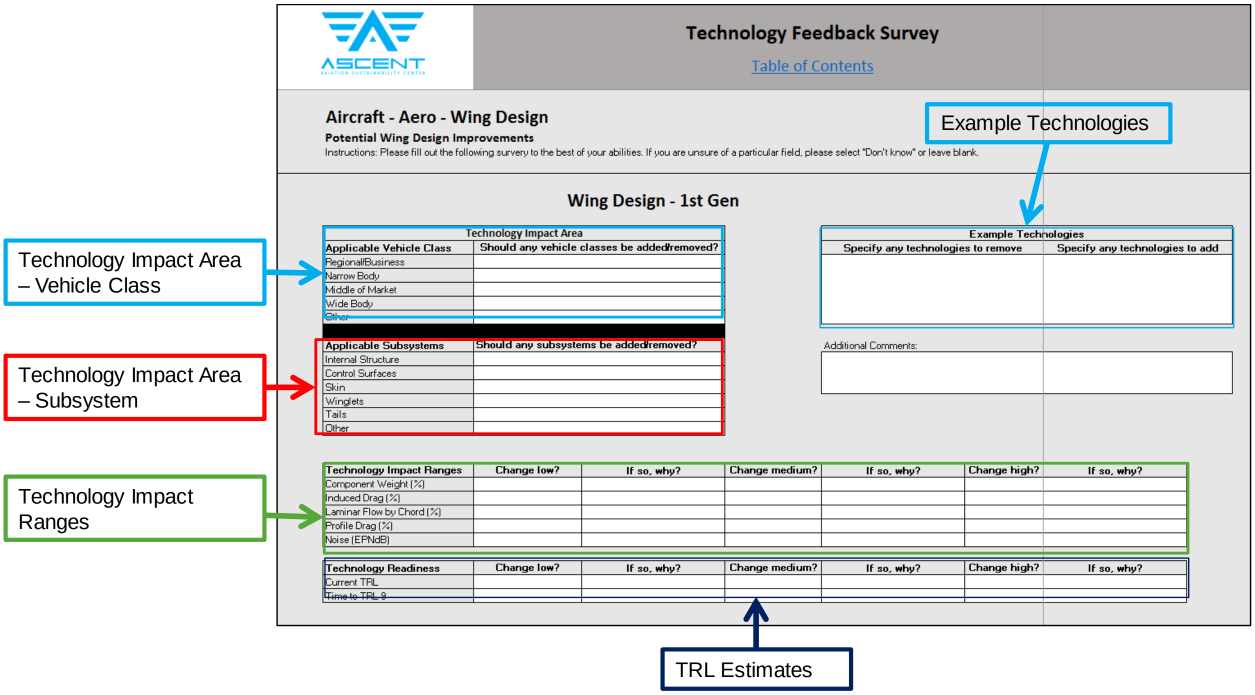


Figure 29: Technology Roadmapping Survey 2 Format

Final Revisions to Technology Roadmap Infographics

Among the responses from the Technology Roadmapping Workshop 2 there was only one technology impact area where respondents felt the impact values should be significantly adjusted, namely Engine Emissions. For both improvement in Particulate Matter and Nitrogen Oxide emissions respondents felt the high values were too extreme and provided justification and noted studies to review for adjusting the values.

Most comments were concerned with the example technologies given on the infographics. Participants either felt that a technology was under the wrong entry-into-service generation, or was not appropriate for the technology area in which it was assigned. For example, additive manufacturing was originally listed as a Generation 1 technology for Engine Emissions. A respondent noted that, while it might be used on test stands, it would mostly not see use in production until Generation 2. Other comments focused on slight adjustments to the “Time to TRL 9” ranges. Overall, the survey feedback was generally showed agreement with the initial infographics. There was some confusion over the matrix at the bottom of the infographics. As seen in Figure 28, in the original infographics, on the left side of the matrix subsystems are listed. A dot was placed to indicate what generations the subsystem would be affected by improvements in the technology area. Separated on the right side of the matrix different vehicles were listed. Similar to the subsystems, a dot was placed to indicate the generations that a vehicle class would be affected by improvements in a technology area. The overwhelming response was that the matrix should really indicate what vehicle and what subsystems on that vehicle were affected by a technology area, instead of separating them. The culmination of these suggestions for the infographics can be seen in Figure 30 to Figure 51. These final infographics will be the basis for a document that will be made publically available on the results of this project.

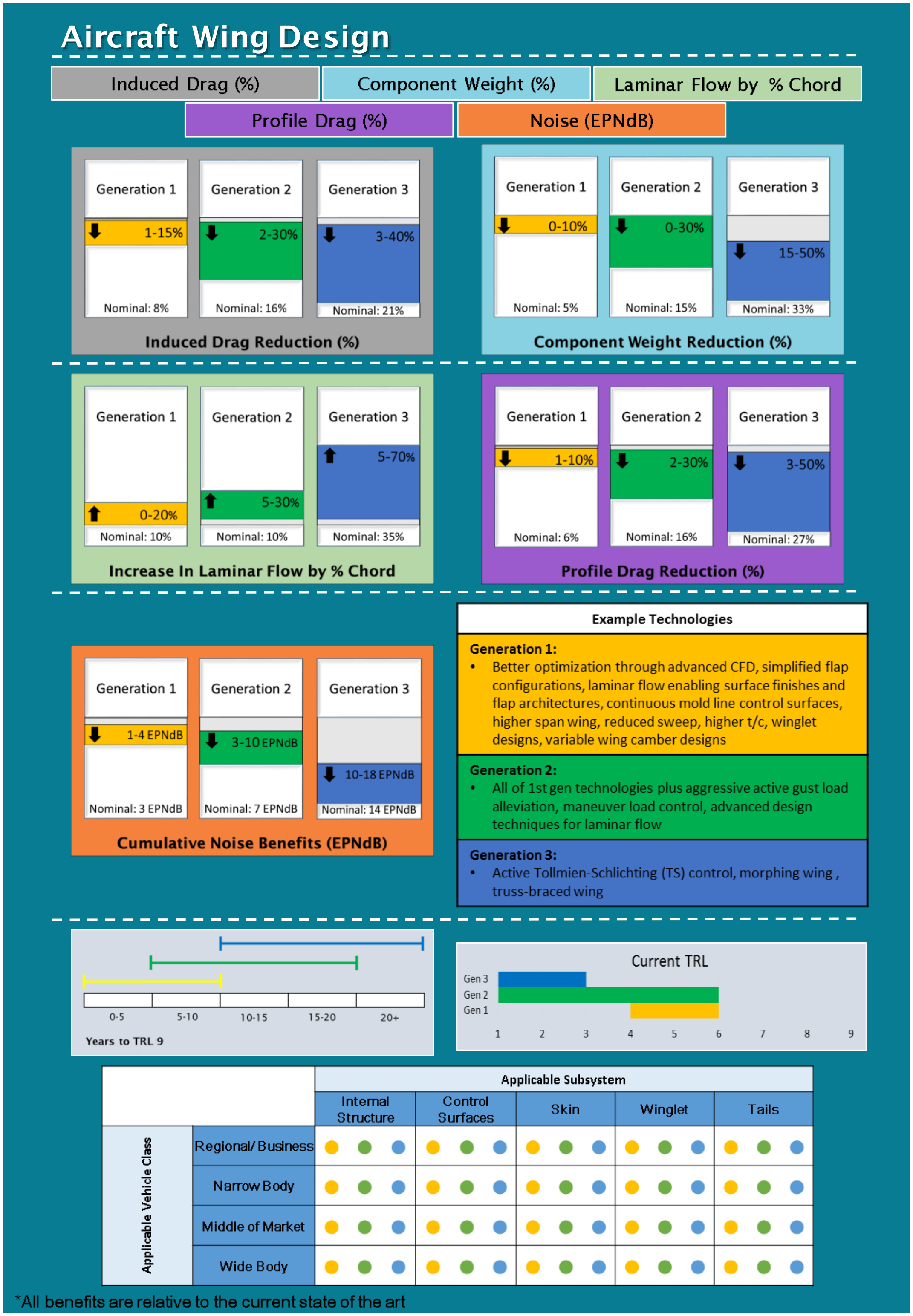


Figure 30: Technology Roadmaps for Aircraft Wing Design

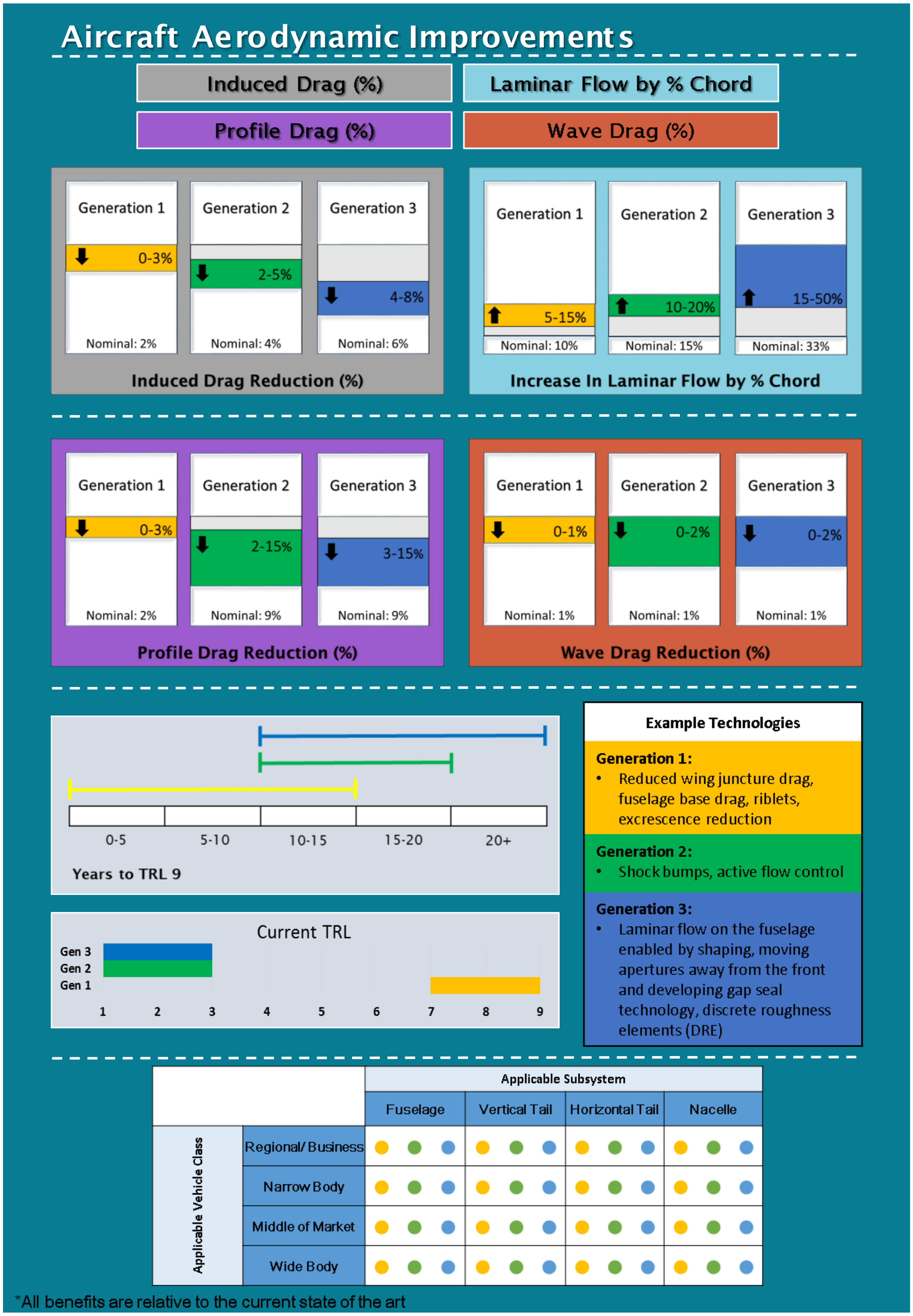


Figure 31: Technology Roadmaps for Aircraft Aerodynamic Improvements

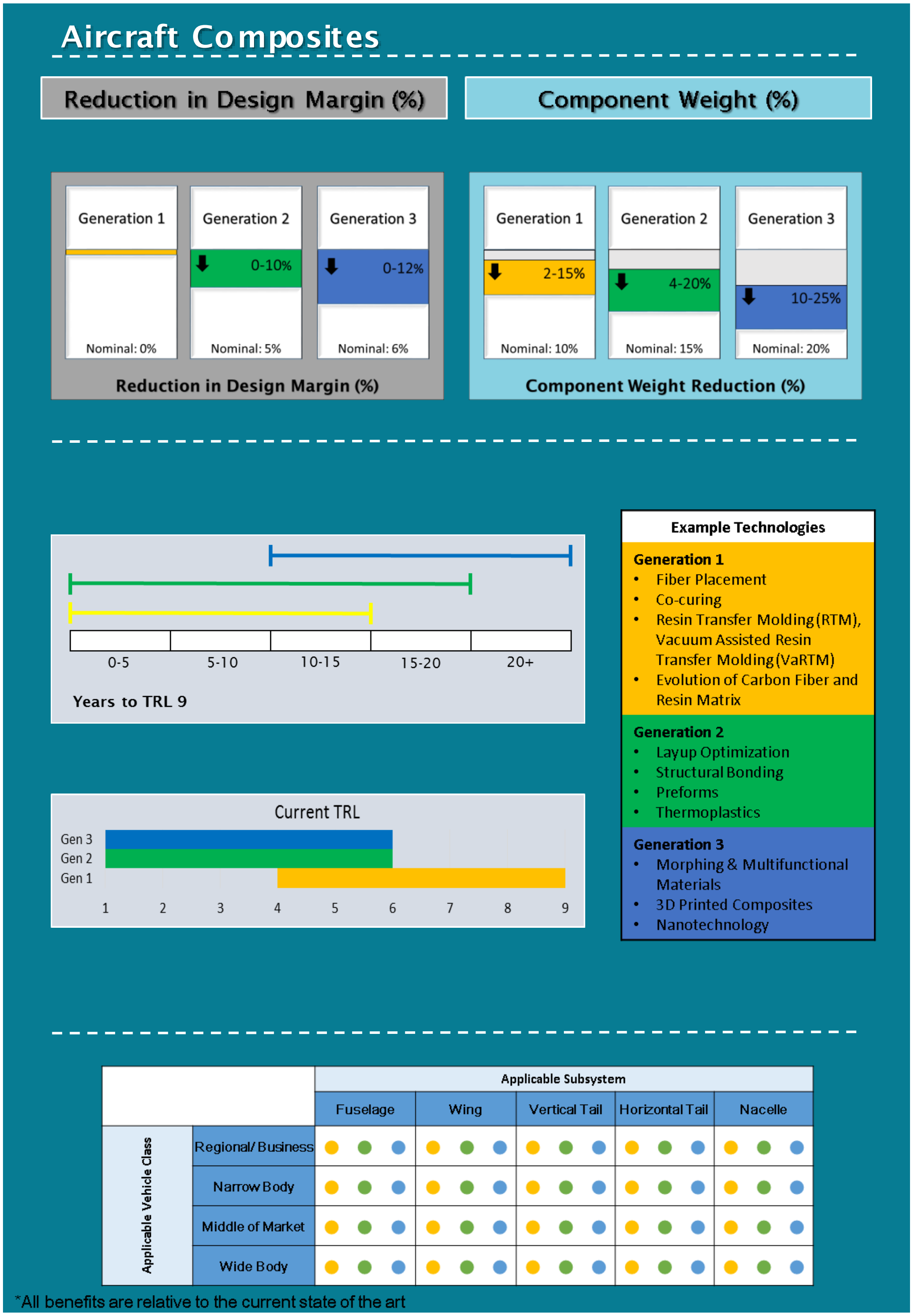


Figure 32: Technology Roadmaps for Aircraft Composites

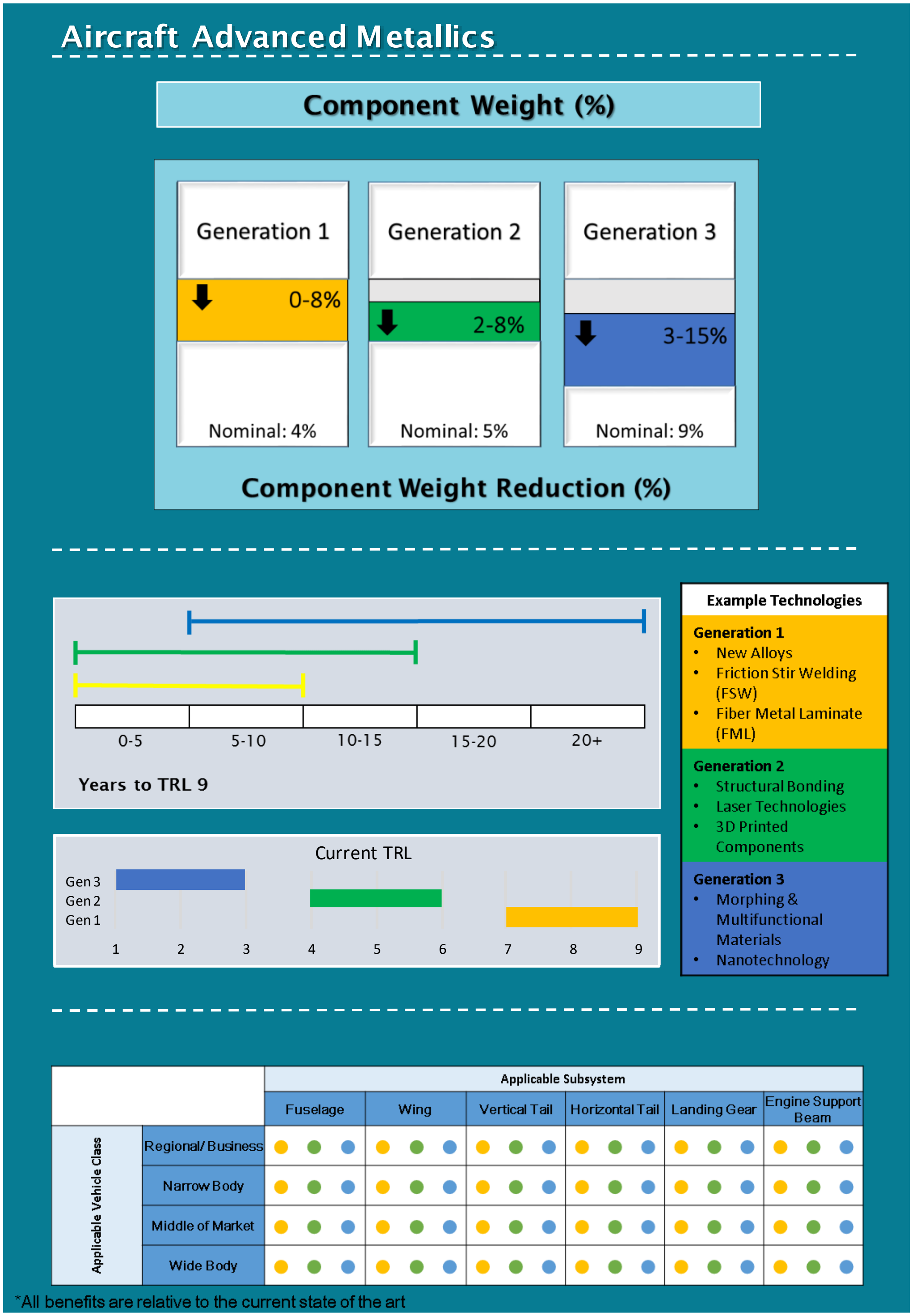


Figure 33: Technology Roadmaps for Aircraft Advanced Metallics

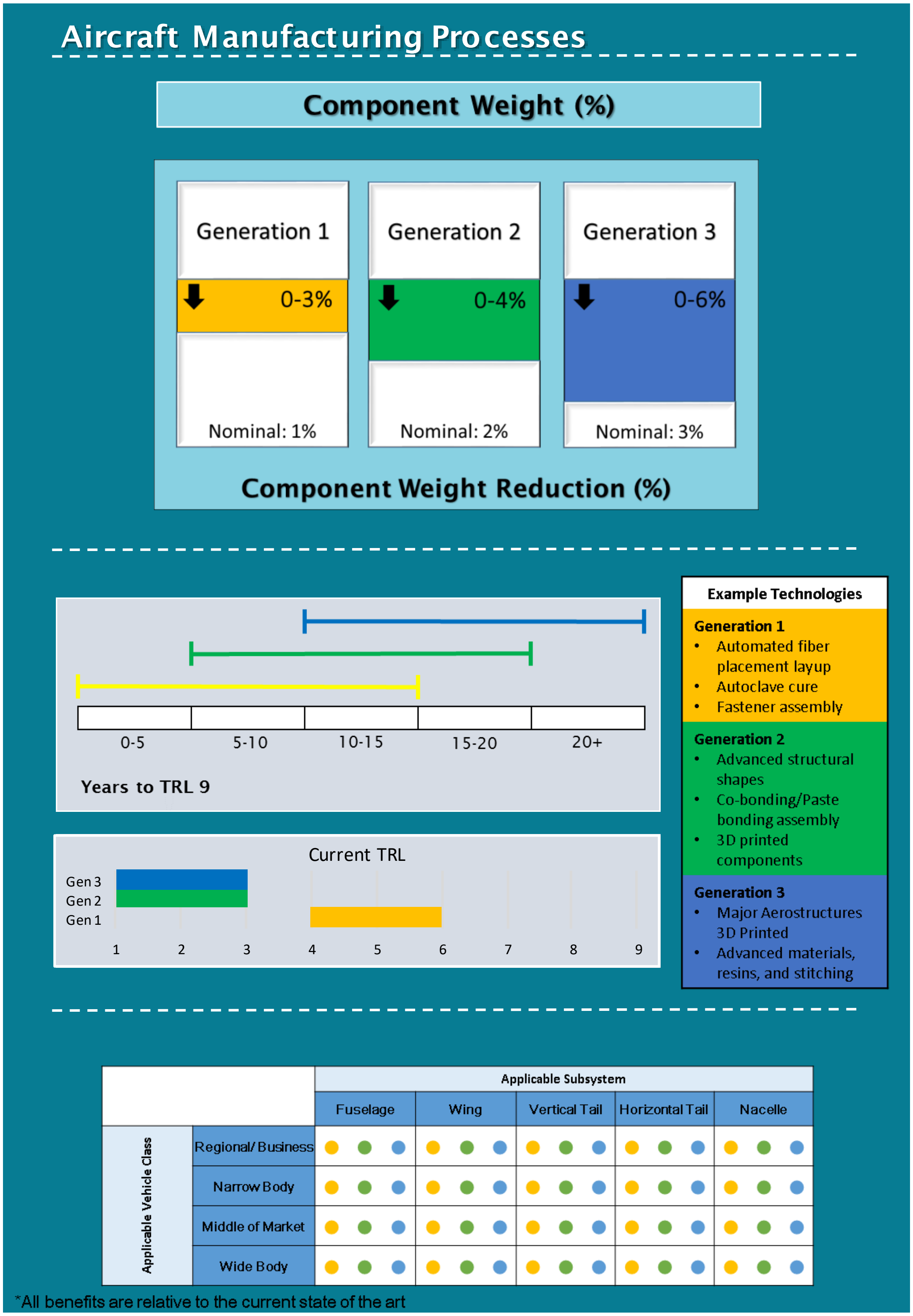


Figure 34: Technology Roadmaps for Aircraft Manufacturing Processes

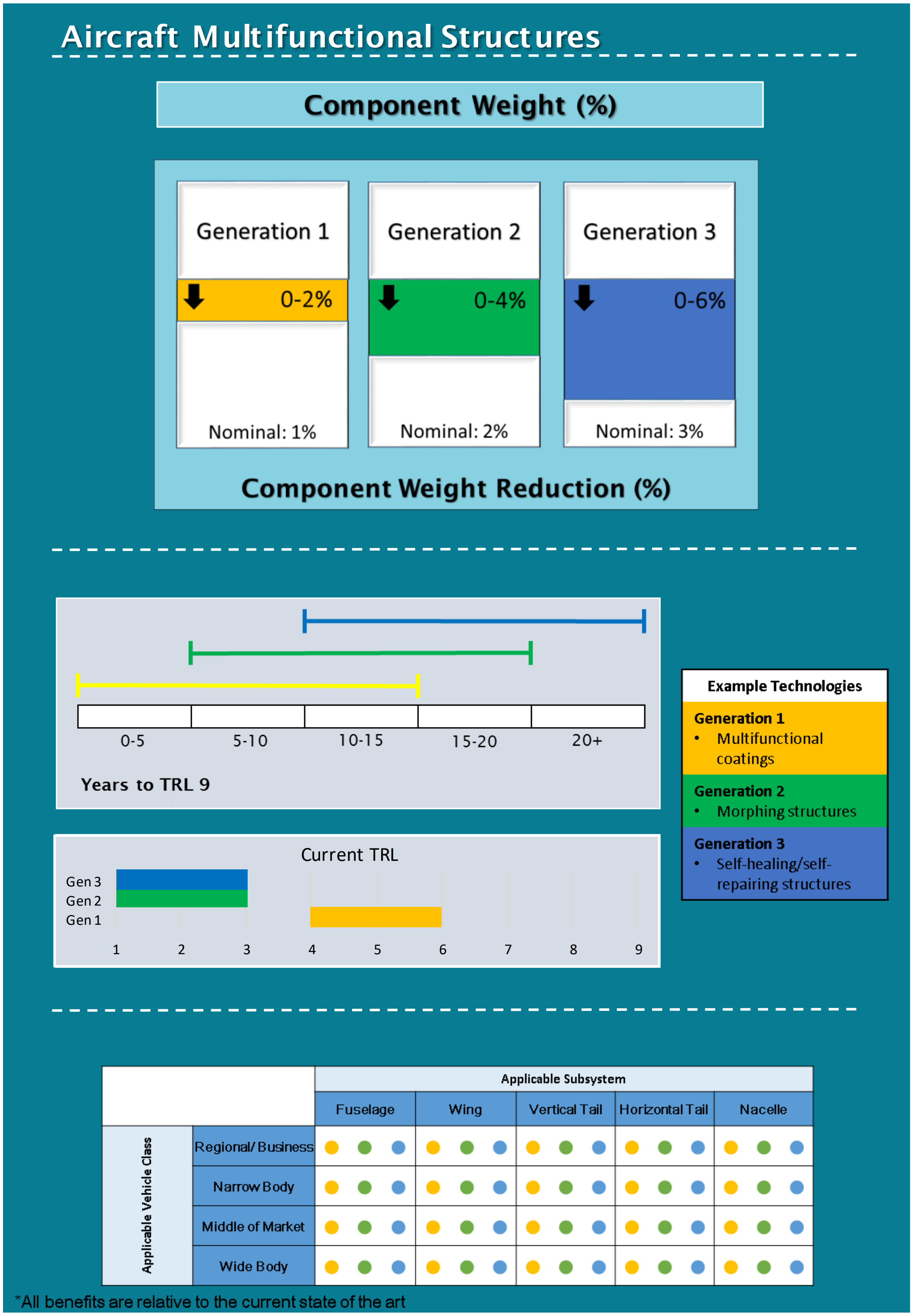


Figure 35: Technology Roadmaps for Aircraft Multifunctioning Structures

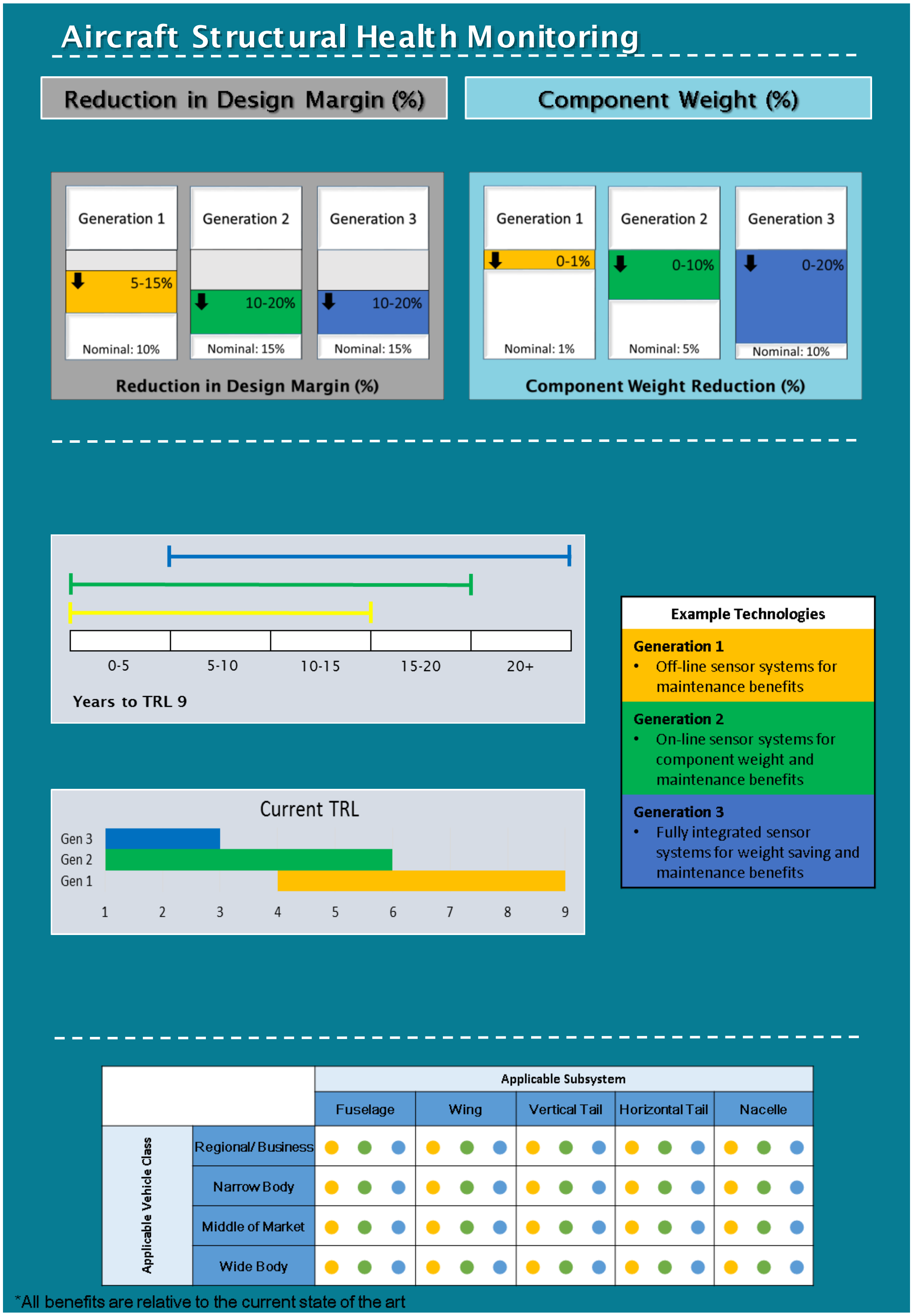


Figure 36: Technology Roadmaps for Aircraft Structural Health Monitoring

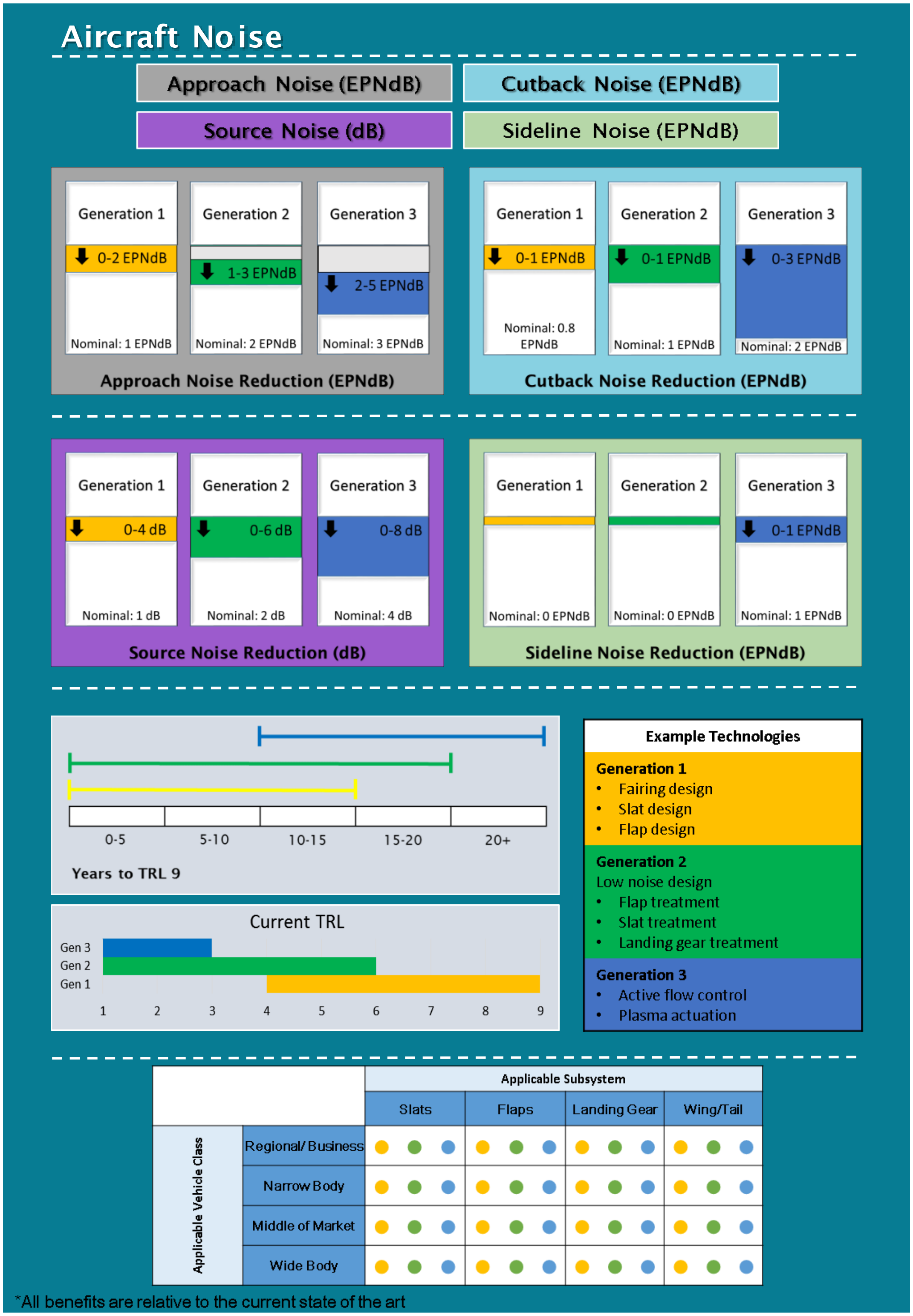


Figure 37: Technology Roadmaps for Aircraft Noise

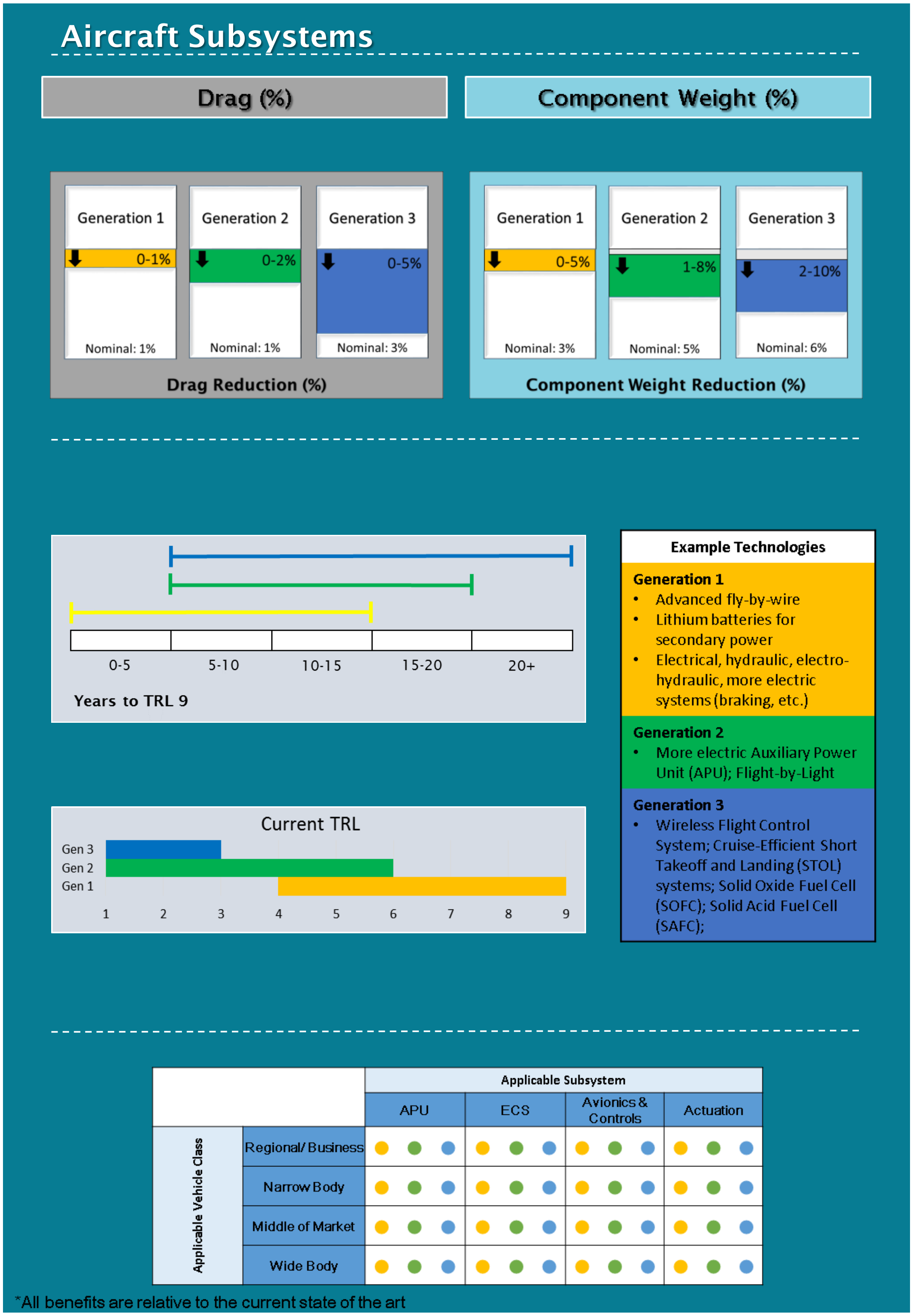


Figure 38: Technology Roadmaps for Aircraft Subsystems

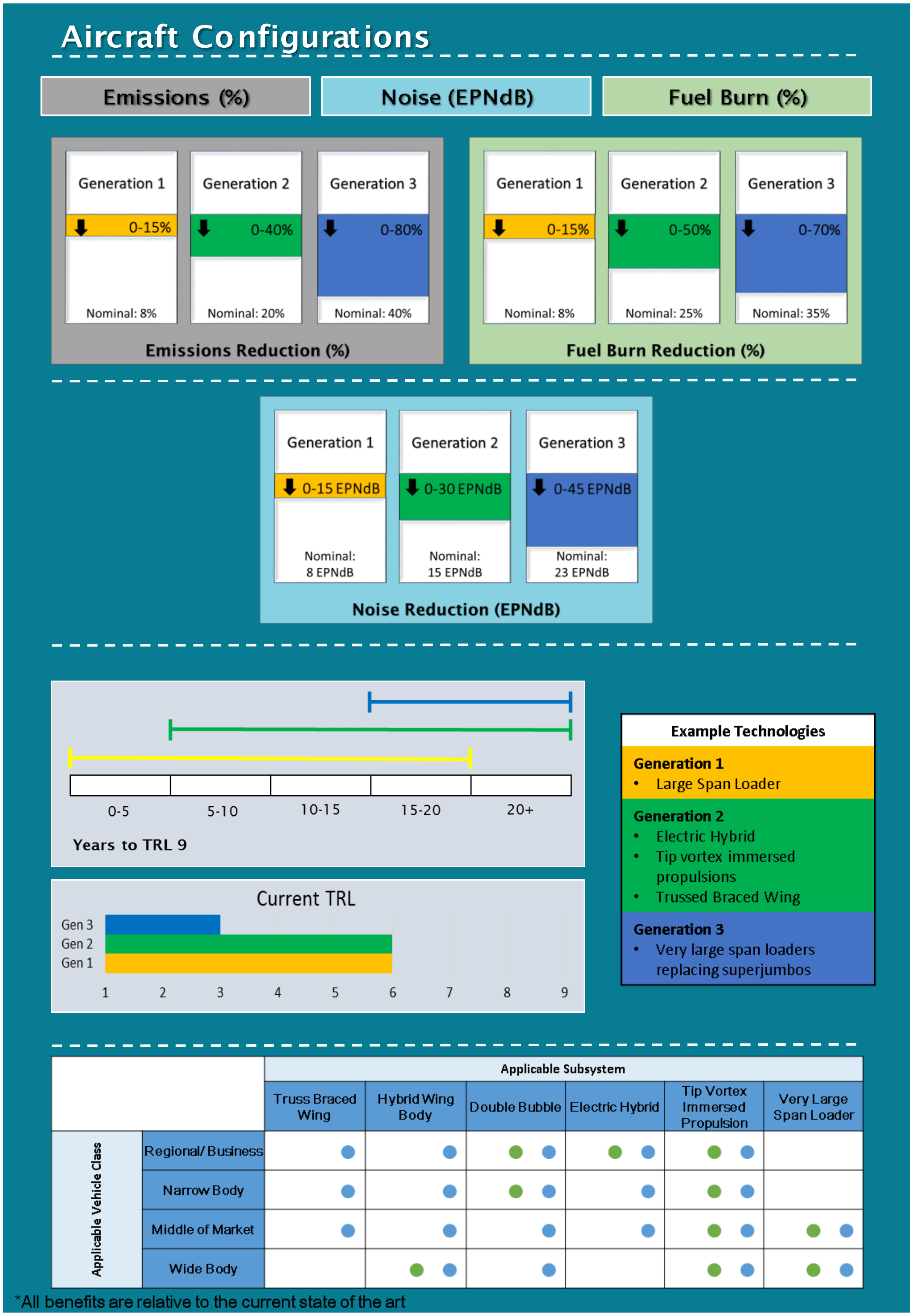


Figure 39: Technology Roadmaps for Aircraft Configurations

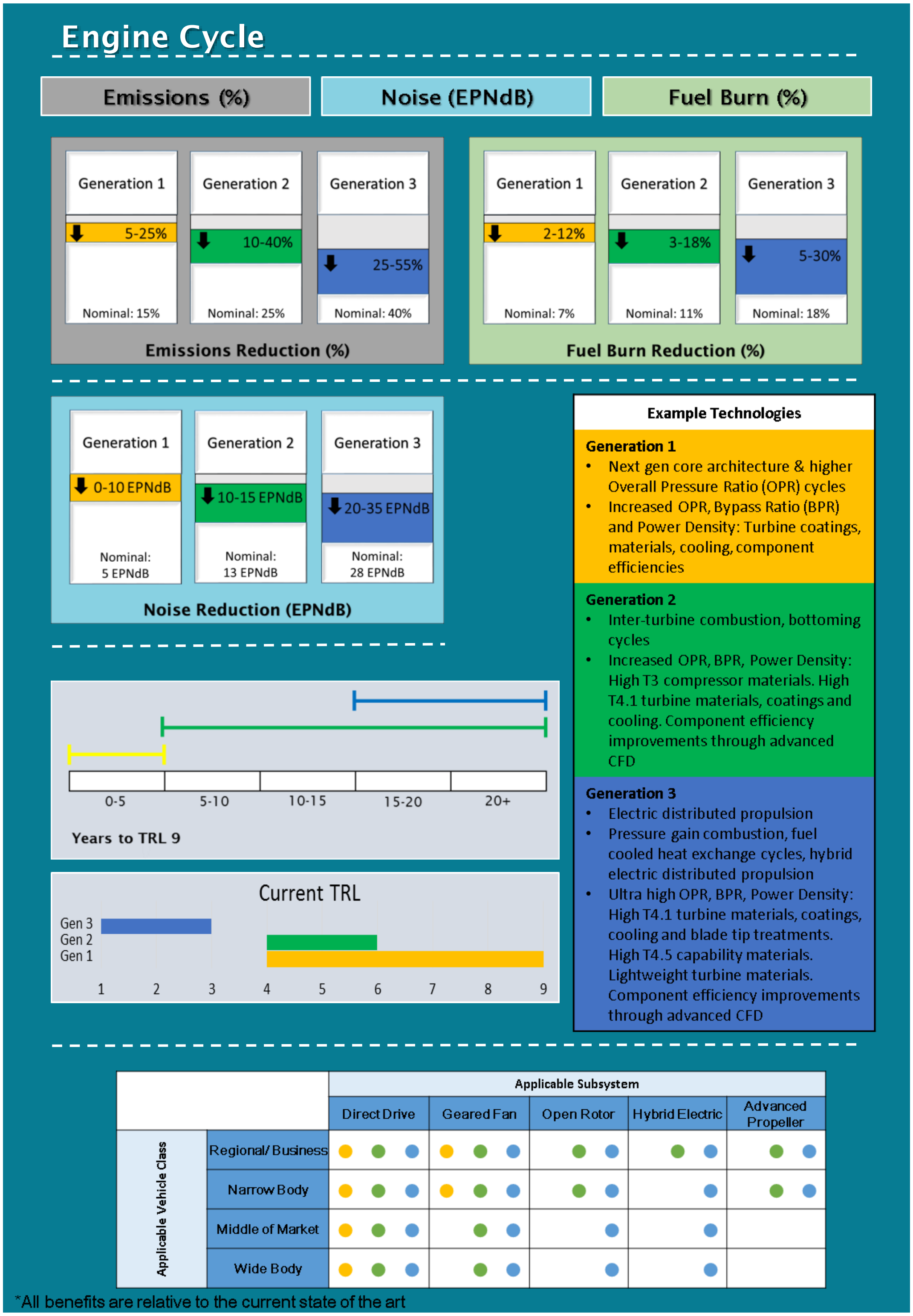


Figure 40: Technology Roadmaps for Engine Cycle

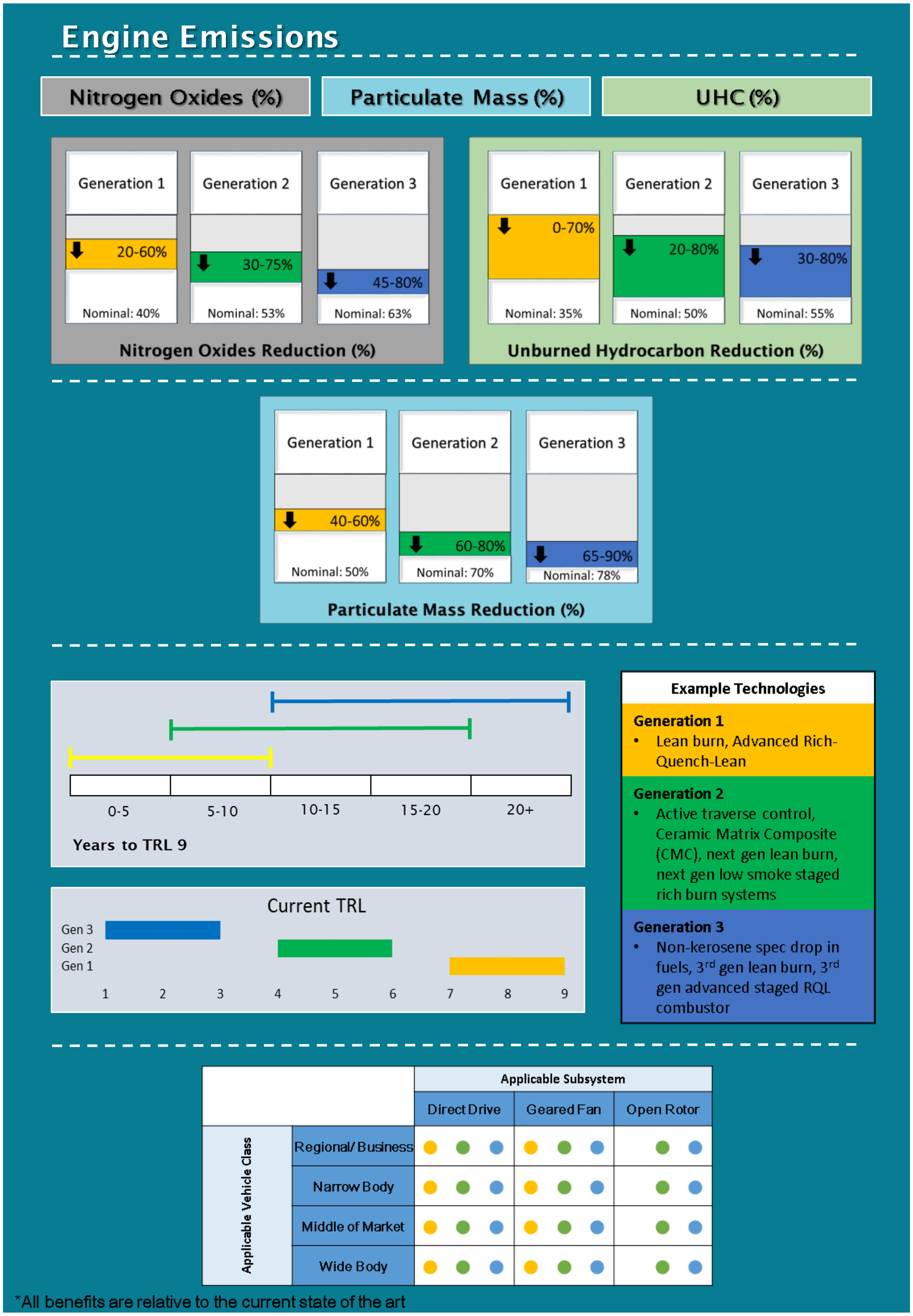


Figure 41: Technology Roadmaps for Engine Emissions

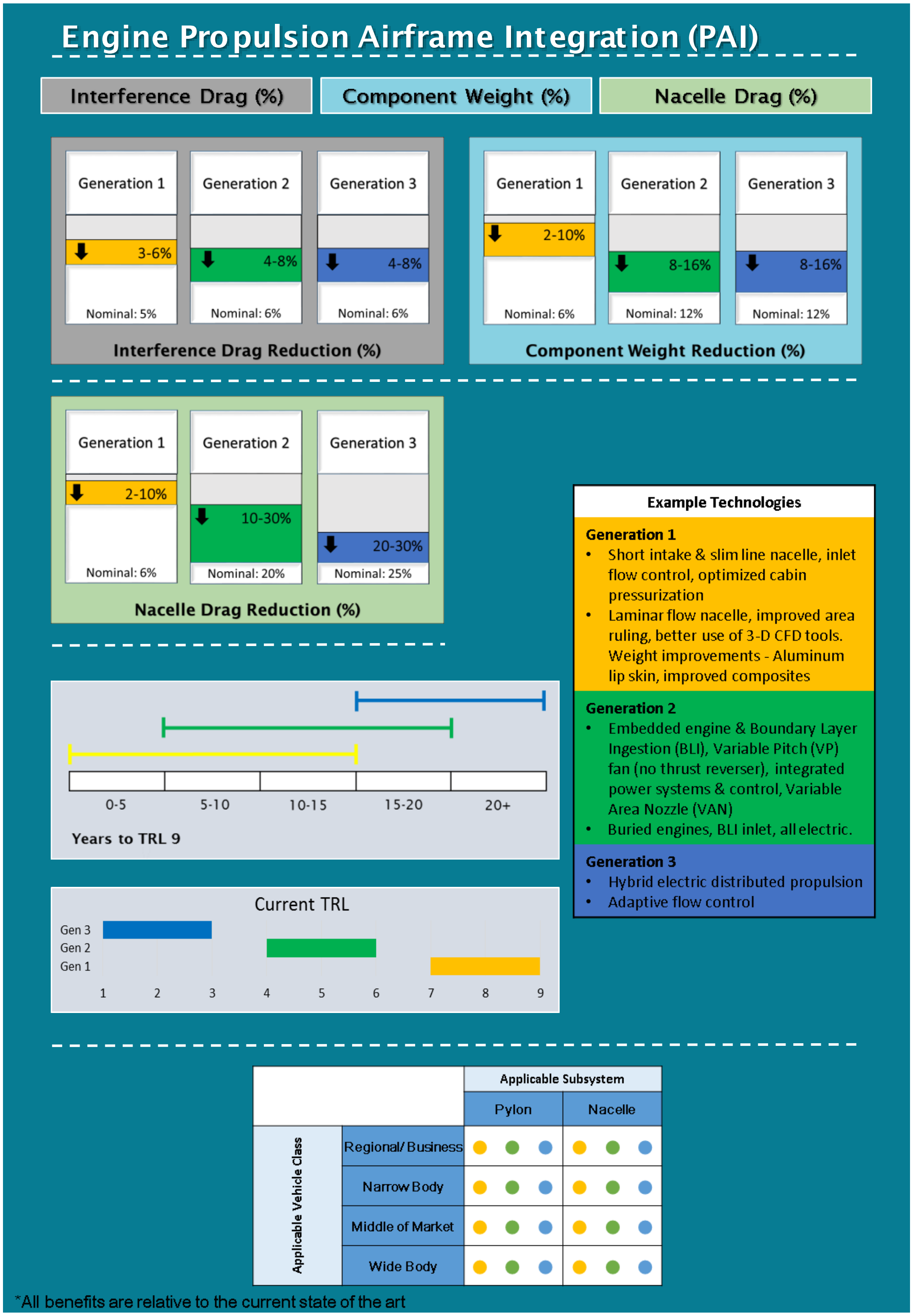


Figure 42: Technology Roadmaps for Engine PAI

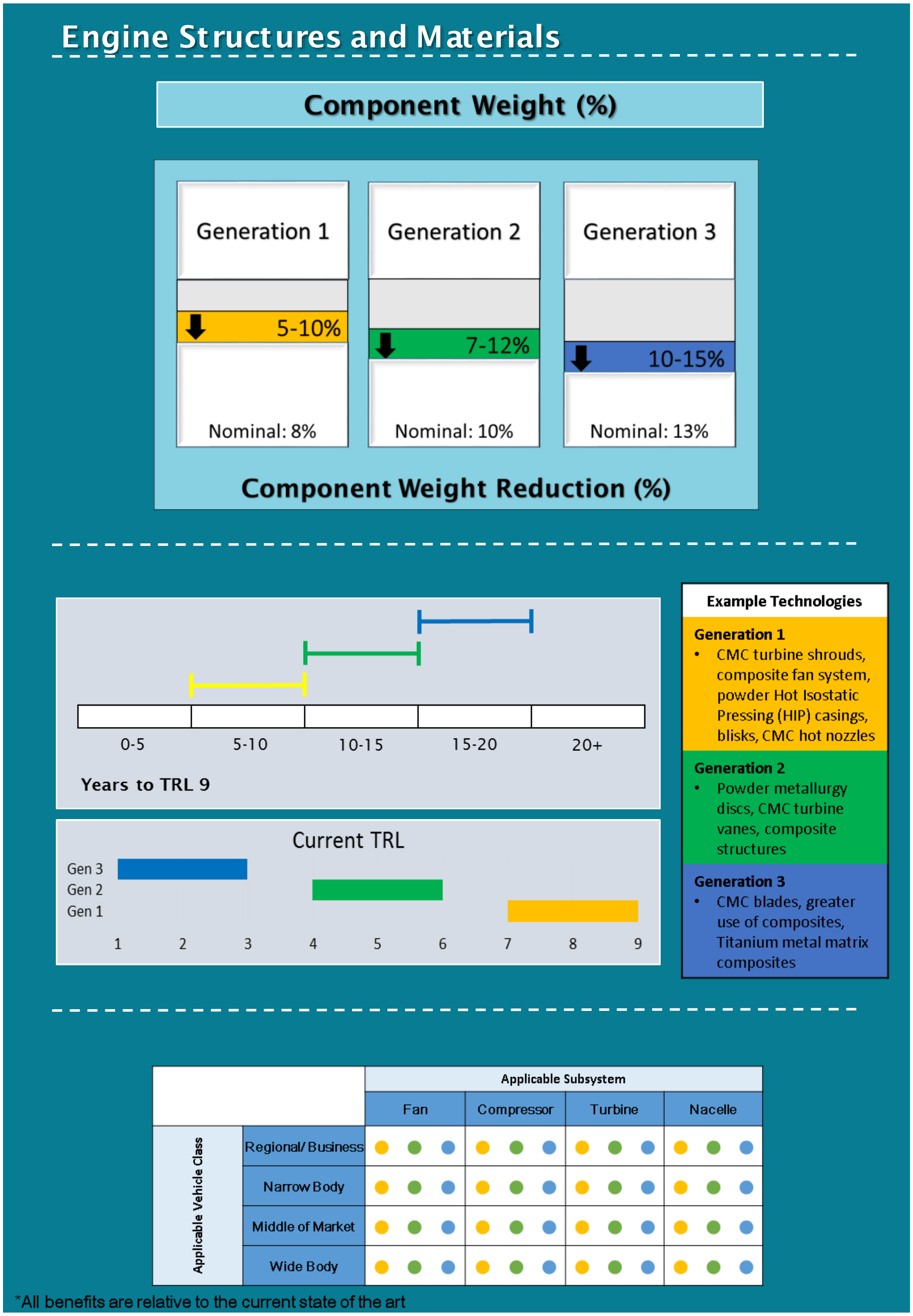


Figure 43: Technology Roadmaps for Engine Structures and Materials

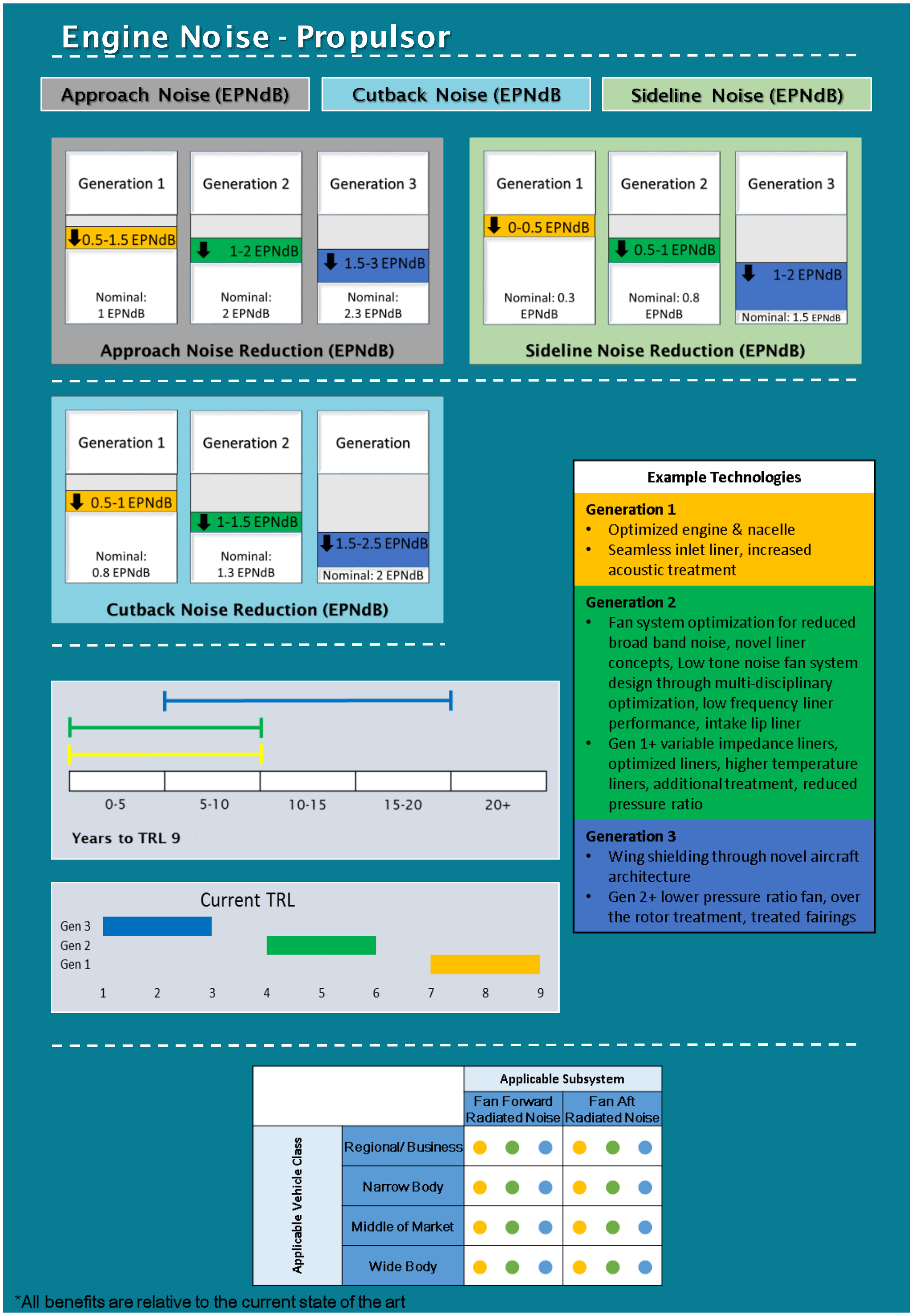
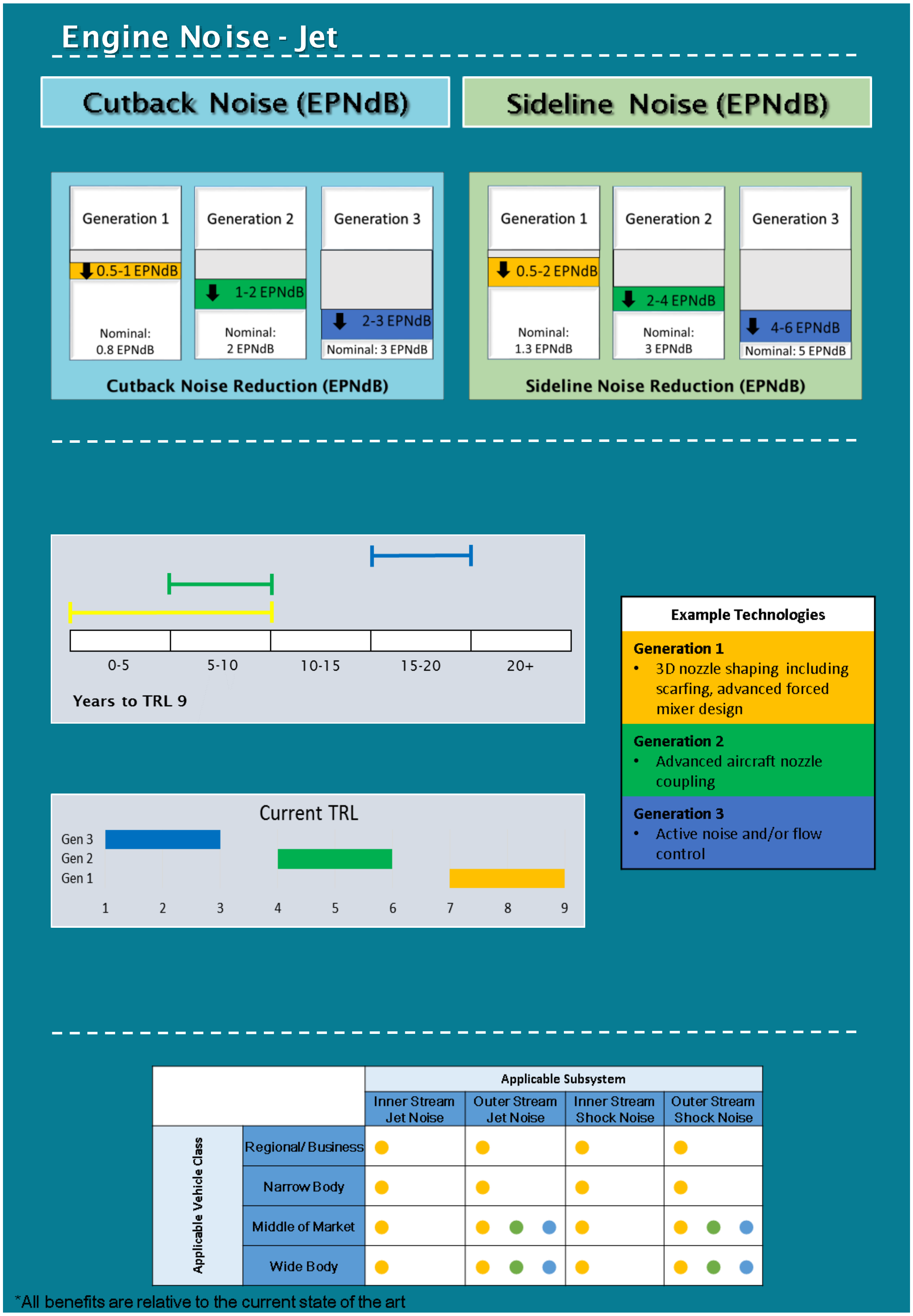


Figure 44: Technology Roadmaps for Engine Noise-Propulsor



	Applicable Subsystem			
Applicable Vehicle Class	Inner Stream Jet Noise	Outer Stream Jet Noise	Inner Stream Shock Noise	Outer Stream Shock Noise
Regional/ Business	●	●	●	●
Narrow Body	●	●	●	●
Middle of Market	●	● ● ●	●	● ● ●
Wide Body	●	● ● ●	●	● ● ●

*All benefits are relative to the current state of the art

Figure 45: Technology Roadmaps for Engine Noise-Jet

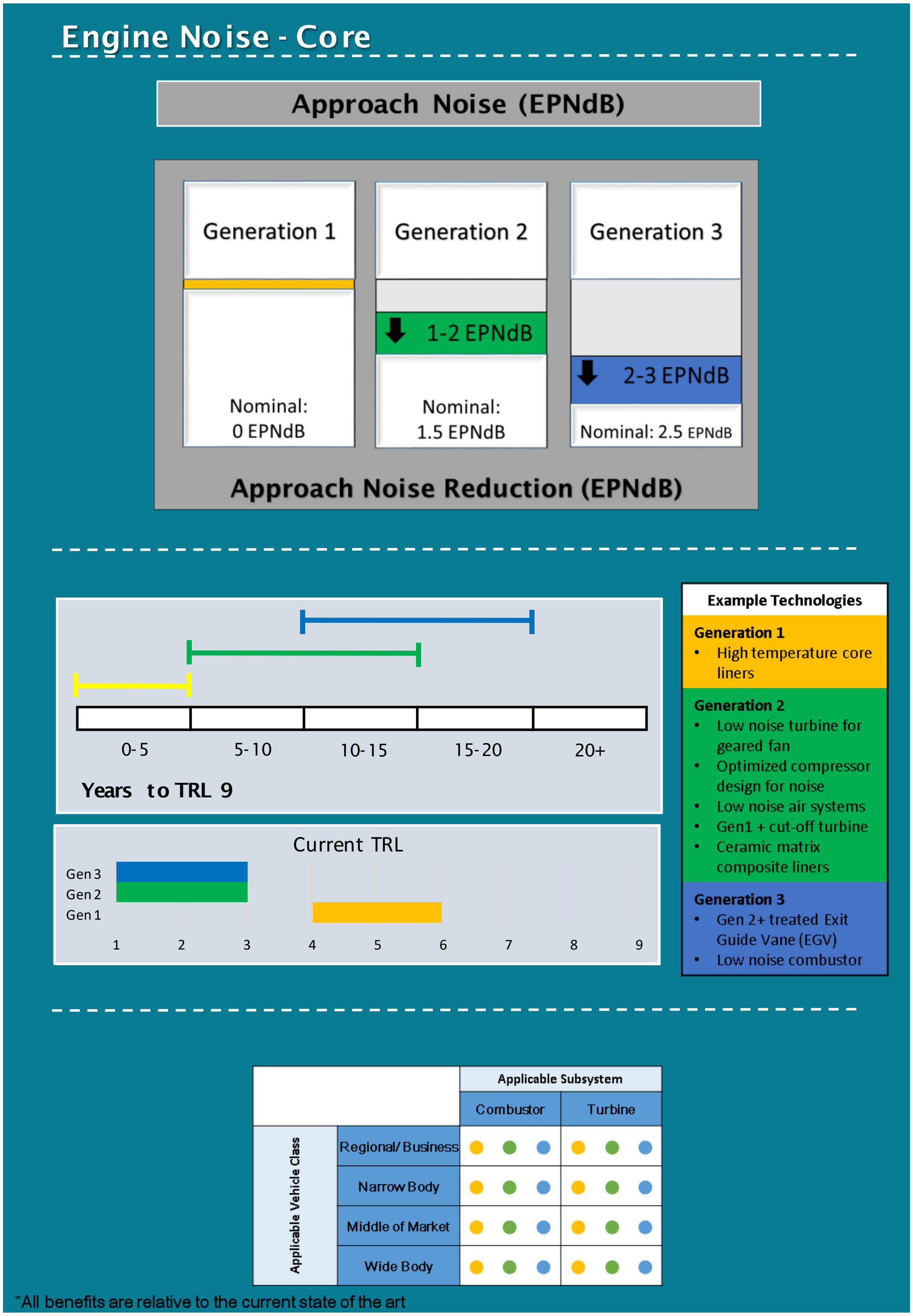


Figure 46: Technology Roadmaps for Engine Noise-Core

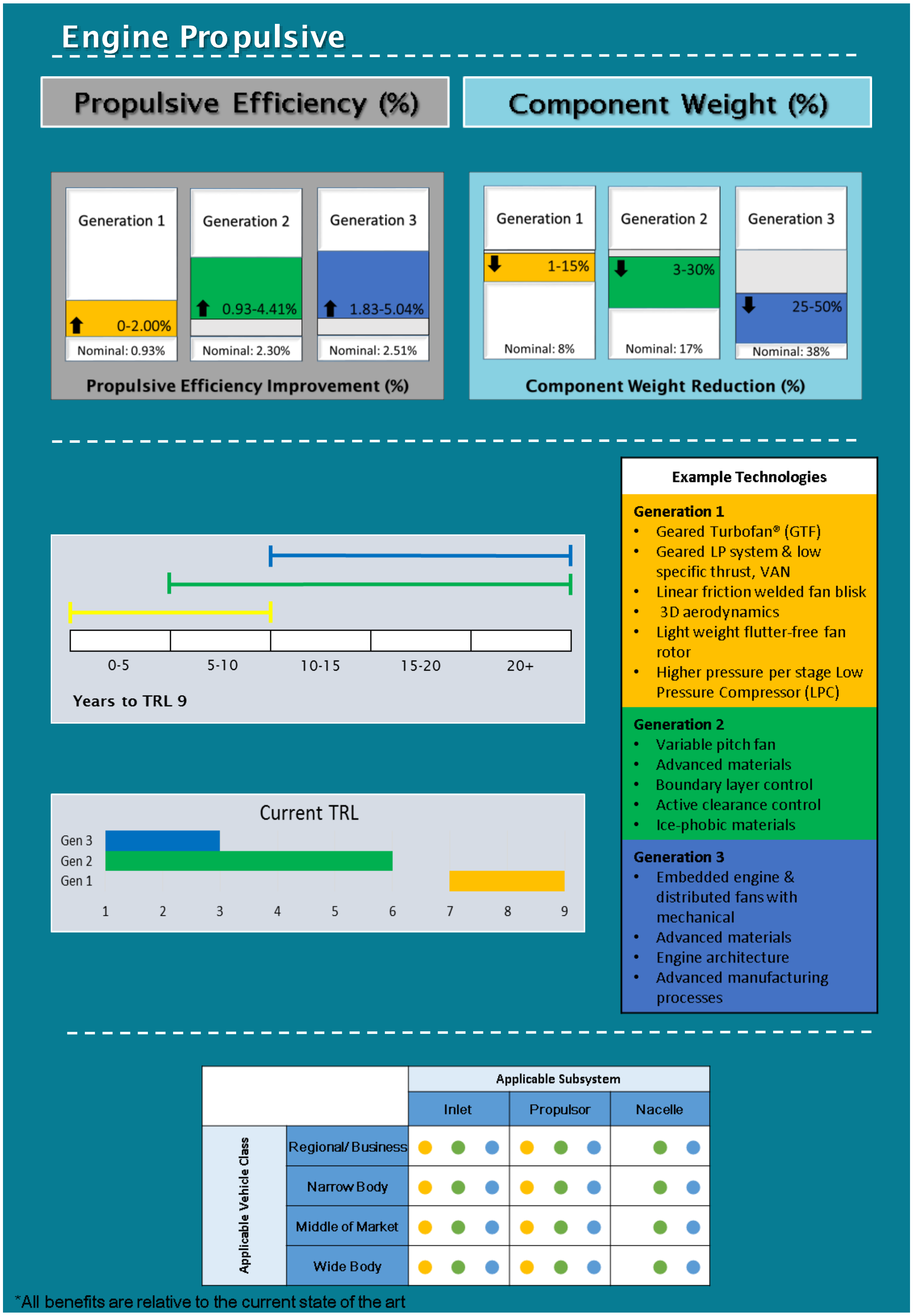
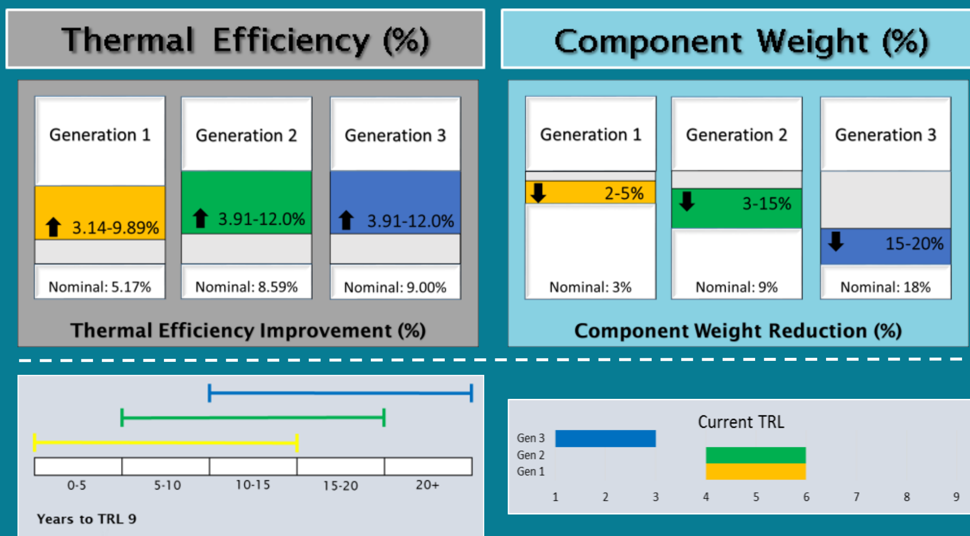


Figure 47: Technology Roadmaps for Engine Propulsive Efficiency Technologies

Engine Core



Example Technologies

Generation 1
- Increased OPR & component efficiencies (Same Gen 2 & 3)
  - Active compressor
  - Turbine tip clearance control
  - Advanced 3D aero
  - Cross-system integration of functional model
- Improved hot end cooling & secondary air system modulation (Same Gen 2 & 3)
- CFD for aerodynamics improvement
  - Low k Thermal Barrier Coating (TBC), Mid impeller bleed cooling source, Cooled cooling air, High slope ducts, High pressure rise per stage, Compact centrifugal compressor, Advanced high-temp super alloys, 3-D diffusion system with integral service routing

Generation 2
- Cooled cooling air (Same Gen 3)
- Adaptive performance seeking control (Same Gen 3)
- Advanced Engine Health Monitoring (EHM) (Same Gen 3)
- CFD for aerodynamics improvement
  - Multiwall blades in small engines, Blade tip oxidation coating, Simply cooled ceramics with coatings, Dual alloy bonded rotors cooled, Predictive accuracy in pattern factor and burner profile

Generation 3
- Additive manufacturing cooling designs
  - Cooled ceramics, Active clearance control in small engines, Plasma actuated mainstream flow control, CFD design of lube systems

		Applicable Subsystem				
		Cooling	HP Compressor	HP Turbine	Combustor	Subsystems
Applicable Vehicle Class	Regional/Business	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
	Narrow Body	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
	Middle of Market	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
	Wide Body	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●

*All benefits are relative to the current state of the art

Figure 48: Technology Roadmaps for Engine Core Technologies

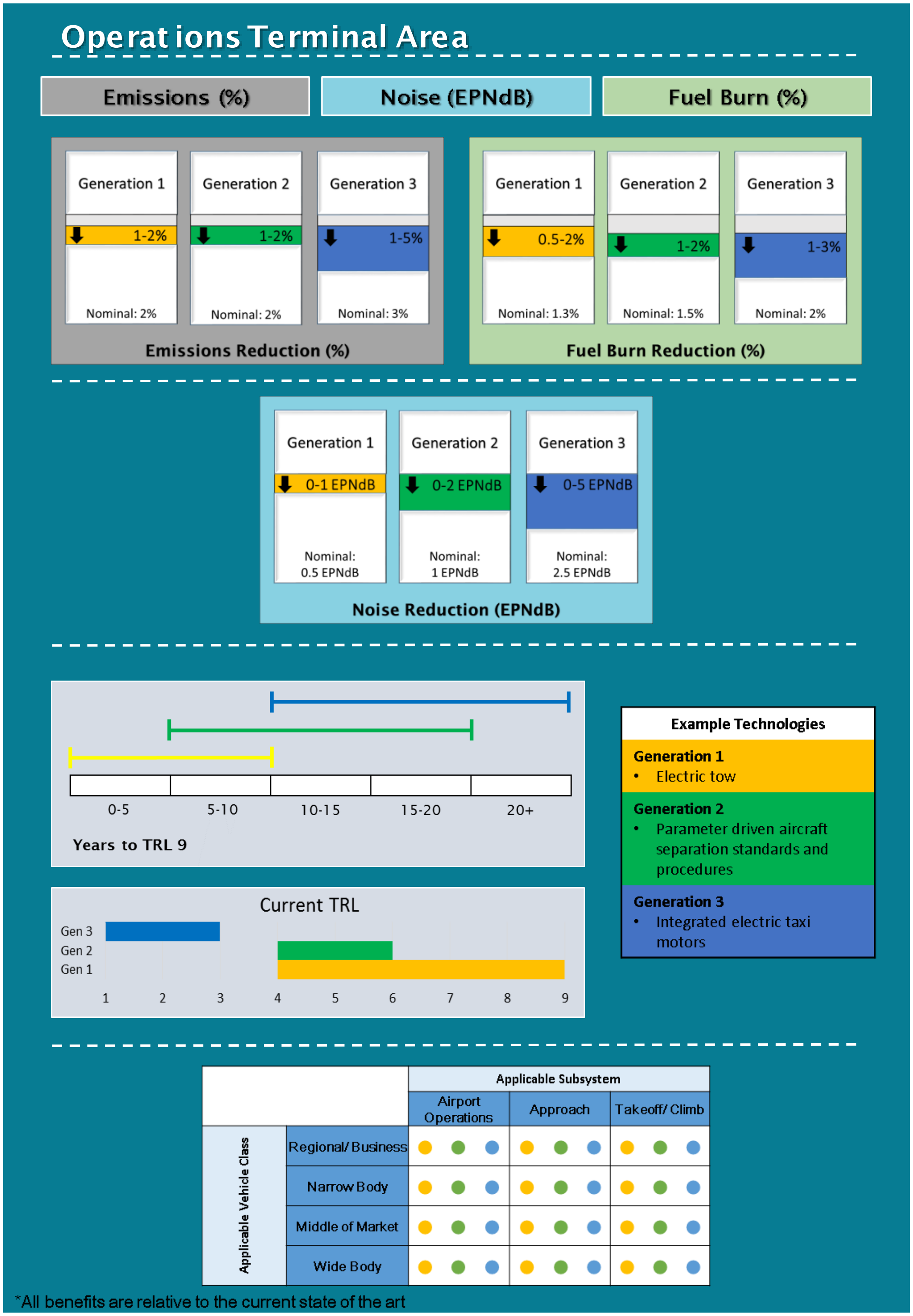


Figure 49: Technology Roadmaps for Operations Terminal Area

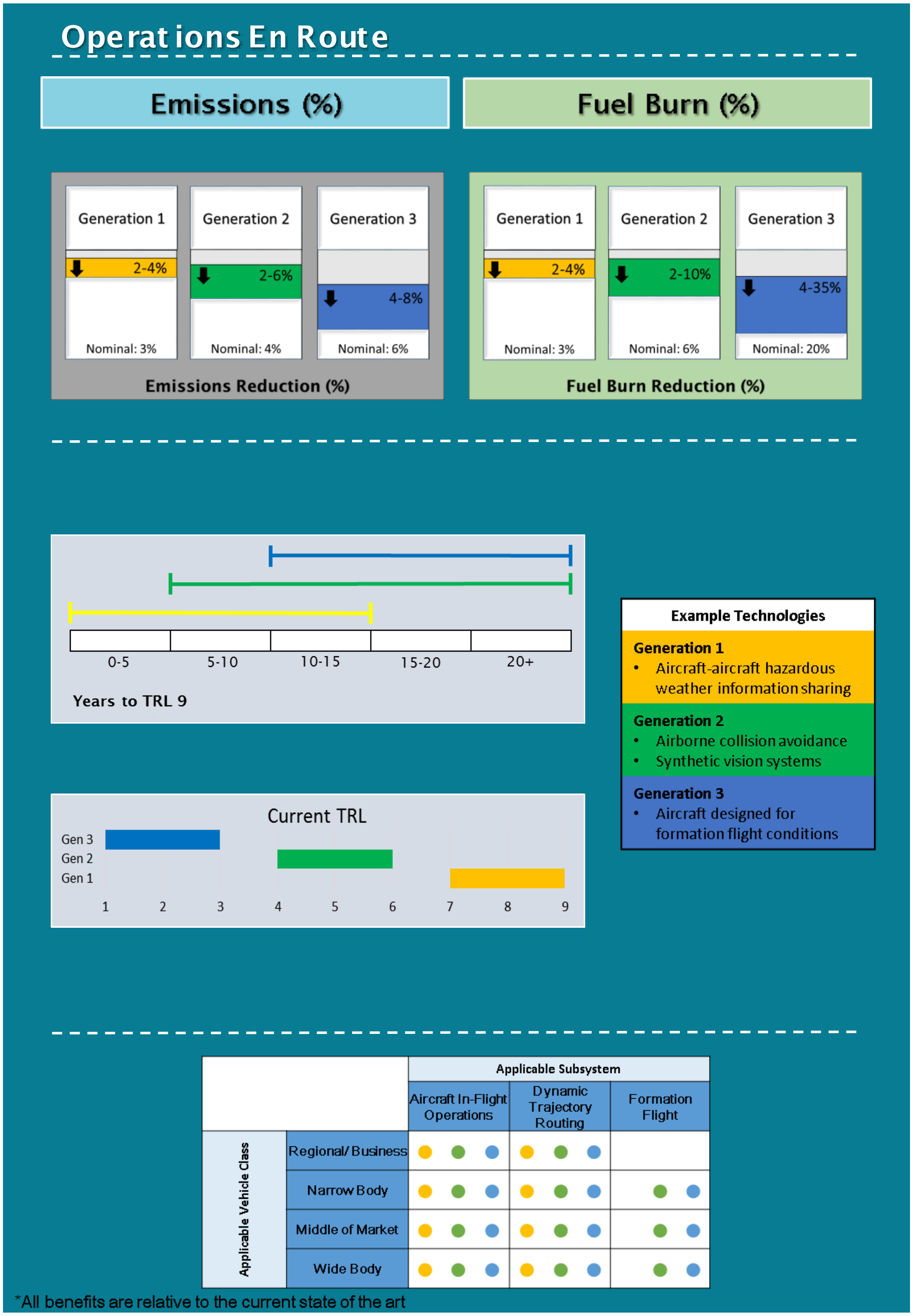


Figure 50: Technology Roadmaps for Operations En Route

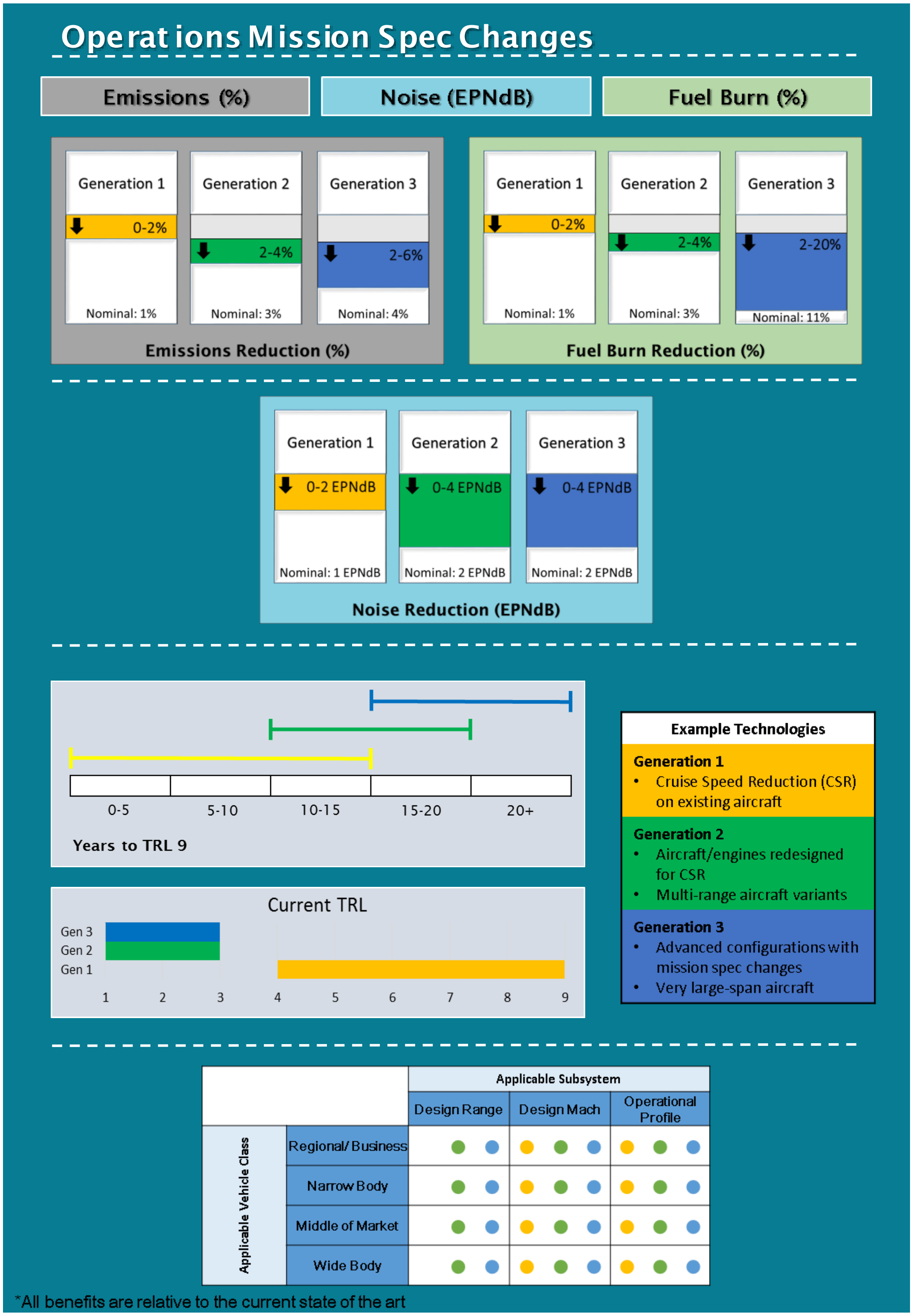


Figure 51: Technology Roadmaps for Operation Mission Spec Changes

Task #2: Vehicle Modeling

Objective: Description of Advanced Vehicles Provided to Purdue and Stanford

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 Flight Optimization System (FLOPS) aircraft models from the 2014 CLEEN assessments performed under PARTNER Project 36 [4]. 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[2], 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. The FLOPS vehicles in the final set of Purdue's FLEET analysis were consistent with the vehicles described in this section. 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 [4].

Research Approach

Modeling of Technologies and Advanced Configurations Process Overview

The overarching goal was to create models of aircraft that showed improvements from a 1995 baseline vehicle, and matched the values participants had come up with during the Technology Roadmap survey. This was done for five standard vehicle classes, the regional jet (RJ), single aisle (SA), small twin aisle (STA), large twin aisle (LTA), and very large aircraft (VLA). The final vehicle results were used during the fleet analysis by both Georgia Tech and Purdue. Further details on the Technology Roadmap Survey is provided in the Task #1 section. The Environmental Design Space (EDS), developed by Georgia Tech, was used to create these models. First, the variables within EDS that were applicable to the Technology Roadmap impacts were identified. In most cases, there were EDS variables that related directly to impacts, but for some impacts a parametric study had to be performed to identify appropriate modeling inputs (see following sections). A Vehicle Timetable was created from the results of the fleet workshops to identify when improved versions of different vehicle classes would enter the fleet. The spread of the "years to TRL 9" data from the Technology Roadmap survey were mapped to three different R&D levels. For example, the maximum value for "years to TRL 9" for a given technology area generation was treated as a low R&D level scenario. This mapping was used to decide what year the three technology generations for each impact began, for each of the three different R&D levels. Using the Vehicle Timetables in Figure 58 and Figure 59, the technology generations that were active during a vehicle generation could be determined for a given R&D level. This allowed vehicle models to then be created for different scenarios. As noted, these final vehicle models were then used as the basis for both Georgia Tech and Purdue's fleet analysis, described in the Task #3 section.

Identifying Applicable EDS Variables

Once the impact numbers from the Technology Workshop Survey data were finalized, the next step was to translate these impacts to variables native to the Environmental Design Space (EDS). EDS was the environment used by Georgia Tech to develop physics-based models of individual aircraft. Creating these models relied on the user to provide values for a large number of variables that define both the physical and theoretical aspects of the aircraft. The team started with existing models Georgia Tech had previously developed that were representative of 1995 versions of each vehicle class. The variables of these baseline models were then systematically changed to model the effects of the impacts predicted by the Technology Workshop surveys. For each impact, a list of EDS variables was created that could potentially be changed to model that impact. EDS is based off of a number of NASA tools, including Numerical Propulsion System Simulation (NPSS), Weight Analysis of Turbine Engines (WATE++), and FLOPS. The manuals of these tools were also reviewed to identify other variables that could be implemented within EDS that were fixed by default. The final input list consisted of 89 EDS variables. A list of the final EDS variable selections is provided in Table 8 broken down into the impacts for each technology area.

[2] N+1 is indicative of technologies with TRL 4-6 by 2015; N+2 indicates a TRL of 4-6 by 2020.

Table 8: Mapping of Technology Roadmap Impacts to EDS Variables

Impact	Method For Modeling In EDS
Aircraft Wing Design	
Induced Drag %	Lift dependent drag factor
Component Weight %	Total wing weight
Laminar Flow by % Chord	Percent LF on wing upper and lower surface
Profile Drag %	Lift independent drag factor
Noise EPNdB	Approach, Cutback, and Sideline Noise Suppression Factor on Trailing Edge Wing, Trailing Edge Flap, and Leading Edge Slats
Aircraft Aerodynamic Improvements	
Induced Drag %	Lift dependent drag factor
Laminar Flow by % Chord	Percent LF nacelle, fuselage, vertical tail, and horizontal tail upper and lower surfaces
Profile Drag %	
Wave Drag %	
Aircraft Composites	
Design Margin %	Empty Weight Margin
Component Weight %	Total wing, horizontal tail, vertical tail, and fuselage weight
Aircraft Advanced Metallics	
Component Weight %	Total wing, horizontal tail, vertical tail, fuselage, land gear main, and landing gear nose weight
Aircraft Manufacturing Processes	
Component Weight %	Total wing, horizontal tail, vertical tail, and fuselage weight
Aircraft Multifunctional Structures	
Component Weight %	Total wing, horizontal tail, vertical tail, and fuselage weight
Aircraft Structural Health Monitoring	
Design Margin %	Empty Weight Margin
Component Weight %	Total wing, horizontal tail, vertical tail, and fuselage weight
Aircraft Noise	
Approach Noise EPNdB	
Cutback Noise EPNdB	
Source Noise dB	Approach, Cutback, and Sideline Noise Suppression Factor on Main Landing Gear, Nose Landing Gear, Trailing Edge Horizontal Tail, and Trailing Edge Vertical Tail
Sideline Noise EPNdB	
Aircraft Subsystems	
Drag %	Lift independent drag factor
Component Weight %	Auxiliary power unit, Instrument Group, Hydraulics Group, Electrical Group, and Avionics Group Weight
Aircraft Configurations	
Emissions %	Percent NO_x reduction
Fuel Burn %	
Noise EPNdB	
Engine Cycle	
Emissions %	Percent NO_x reduction
Fuel Burn %	
Noise EPNdB	
Engine Emissions	

Impact	Method For Modeling In EDS
Nitrogen Oxides %	Percent NO_x reduction
Particulate Mass %	
UHC %	
Engine PAI	
Interference Drag %	
Component Weight %	Factor for bare engine weight to engine pod weight
Nacelle Drag %	SWETN
Engine Structures and Materials	
Component Weight %	Fan Containment Material density
Engine Noise - Propulsor	
Engine Approach Noise - Propulsor	Approach Noise Suppression Factor on Inlet and Fan Discharge Noise
Engine Cutback Noise Propulsor	Cutback Noise Suppression Factor on Inlet and Fan Discharge Noise
Engine Sideline Noise - Propulsor	Sideline Noise Suppression Factor on Inlet and Fan Discharge Noise
Engine Noise - Jet	
Cutback Noise EPNdB	Cutback Noise Suppression Factor on Jet Takeoff Noise
Sideline Noise EPNdB	Sideline Noise Suppression Factor on Jet Takeoff Noise
Engine Noise - Core	
Approach Noise EPNdB	Approach Noise Suppression Factor on Fan Discharge Noise
Engine Propulsive	
Propulsive Efficiency %	Improvement modeled adjusting FPR, Extraction ratio at Aero Design Point, HPT chargeable (exit) cooling effectiveness, HPT non-chargeable (inlet) cooling effectiveness, and Maximum T4 (set at Take Off)
Component Weight %	Weight of miscellaneous propulsion systems, Fan Blade Material Density, Fan Stator Material Density, Fan Case Material Density, Inlet Nacelle Material Density and Bypass Nozzle Weight
Engine Core	
Thermal Efficiency %	Improvement modeled adjusting FPR, LPCPR, HPCPR, HPT chargeable (exit) cooling effectiveness, and HPT non-chargeable (inlet) cooling effectiveness
Component Weight %	Material Density of Burner Liner and Blades, Stators, and Disks of HPC, LPC, HPT, and LPT

In a number of cases there were no EDS variables that could be tied directly to an impact. For example, observer effective perceived noise level (EPNL) impacts are not directly related to noise suppression factors. Changes in observer EPNL can only be observed after the model is run. To reconcile this, parametric studies were run to analyze how observer EPNL was impacted by changing noise suppression factors related to wing design, propulsive, jet, and core noise. This is detailed further in the following sections. For Aircraft Noise, source noise impacts were provided in dB, which can be applied directly through noise suppression factors. By applying these suppression factors it was reasoned that the Aircraft Noise impacts for observer EPNL would be accounted for in terms of approach, sideline, and cutback.

Translating Impacts to EDS Variable Ranges

Once appropriate EDS variables had been chosen, the next major task was to determine how the impact values would be applied to the baseline values of the EDS variables. In some cases, it was seen that implementing stated impacts from the technology roadmaps could be done by simply adding, subtracting, or multiplying. In other cases, modeling the impacts required running a parametric study to determine the relationship between the EDS variable and impacts. After analyzing the EDS variables selected, eight different categories of EDS variables were identified as presented in **Table 9**. A detailed description of the Technology Roadmap Design of Experiments (DOE) Aggregator that was created to automate this process is given in the following sections. The Aggregator used the variable type that had been identified for each EDS variable to determine how to apply the impacts.

Table 9: Options for Applying Technology Impact to an EDS Variable

Variable Type	Description	Formula (K# Represents Individual Impact)
Scalar	Multiplicative	=Baseline*((1+K1/100)*(1+K2/100)*(1+K3/100)*…*(1+Ki/100))
Delta	Added together	=Baseline + (K1+K2+K3+…+Ki)
Noise	Combined on decibel scale	=Sum[(1*largest Ki) + (0.75 * 2nd largest Ki) + (0.5 * 3rd largest Ki) + (0.33 * 4th largest Ki)+ (0.16 * 5th largest Ki) + (0.08 * 6th largest Ki)….]
DeltaF	Added together as fraction/decimal	=Baseline + (K1+K2+K3+…+Ki)/100
Switch	Turns on or off from its baseline state if there is an impact	1 or 0
Absolute	Replaces baseline. Chosen based on parametric studies or must be set to zero	

Performing Sensitivity Checks On Benefit Ranges

For scalar and delta type EDS variables, a sensitivity study was run using the one-at-a-time method. This involved applying the Generation 3 maximum impact to a given EDS variable, while keeping all other EDS variables at their baseline values. A case was run for each EDS variable, for all five aircraft class models, to see if the model would run at the limits of this projected future design space.

Results of Sensitivities

In addition to checking if an impact could actually be modeled, the sensitivities helped confirm that the right variable type had been identified for each EDS variable. The only EDS variable that posed a problem was PCT_NO_x, which stands for "Percentage NO_x reduction". The impacts for engine emissions nitic oxides reduction, engine cycle emissions reduction, and aircraft configurations emissions reduction were all mapped to PCT_NO_x. Since PCT_NO_x was a DeltaF type variable, the impacts would typically be added together. Unfortunately, the combination of the maximum values of these three impacts resulted in a NO_x reduction value greater than 100%, which is not possible. It was decided that the largest of these three impacts would be used as representative of all three when modeling the vehicles. This does not mean the same one of these impacts was always dominant. For example, for a vehicle modeled with all Generation 2 impacts, at a high technology level, the impact values for engine emissions engine cycle, and aircraft configurations on PCT_NO_x were 75%, 40%, and 40% respectively, so engine emissions dominated. For a high technology level vehicle with a Generation 2 engine emissions impact, and Generation 3 engine cycle and aircraft configurations impacts, the impact values on PCT_NO_x were 75%, 40%, and 80% respectively, so aircraft configuration dominated instead.

Considerations for Noise and Engine Efficiency

Since observer EPNL and thermal and propulsive efficiency were output metrics of sizing, getting the correct impact values required first understanding the relationship between them and the EDS variables that affect them. This involved a full factorial approach to sensitivity analysis, where the effects of changing the multiple EDS variables together was looked at. The main parameters that could have be modified to improve propulsive efficiency were extraction ratio (Ext_Ratio), fan pressure ratio (FPR), and maximum burner exit temperature (T4max). Thermal efficiency could have been improved by increasing the overall pressure ratio (OPR) and modifying the work split between the low-pressure compressor ratio (LPCPR) and high-pressure compressor ratio (HPCPR). Note that OPR was not a direct EDS variable, but was the product of the EDS variables for LPCPR, HPCPR, and FPR. Both efficiencies could have also have been improved by decreasing the amount of cooling need by the engines using the EDS variables s_HPT_ChargeEff and s_HPT_NonChargeEff. For noise, increasing noise suppression factors could have continued to lower observer EPNL results, but with diminishing returns.

Conducting Parametric Studies for Engine Cycle Variables

As noted in the previous section, the propulsive and thermal efficiency were calculated outputs of EDS, so they could not be directly input. In order to get the impacts reported in the workshop surveys, the engine cycle parameters that affect efficiency were changed. A parametric study was conducted for both thermal efficiency and propulsive efficiency. The goal was to first vary applicable cycle parameters over wide ranges to analyze trends in the efficiencies. From this analysis the team believed it would then be able to choose cycle parameters values to reach the low, nominal, and high efficiency values for each generation. These studies had to be repeated for each vehicle class, since the baseline models did not all have the same engines. The selected engine cycle parameters were then arranged as a look-up table that could be searched when constructing the EDS cases for the different technology scenarios that were modeled.

Thermal Efficiency Studies

The thermal efficiency sensitivity study was conducted by first increasing OPR by keeping FPR constant and increasing LPCPR and HPCPR, keeping the work split between the LPC and HPC constant. The work split was then modified to see the effects of shifting 20% more of the work to the LPC and then 20% more of the work to the HPC. The results of the first set of sensitivities for the VLA are shown in Figure 52.

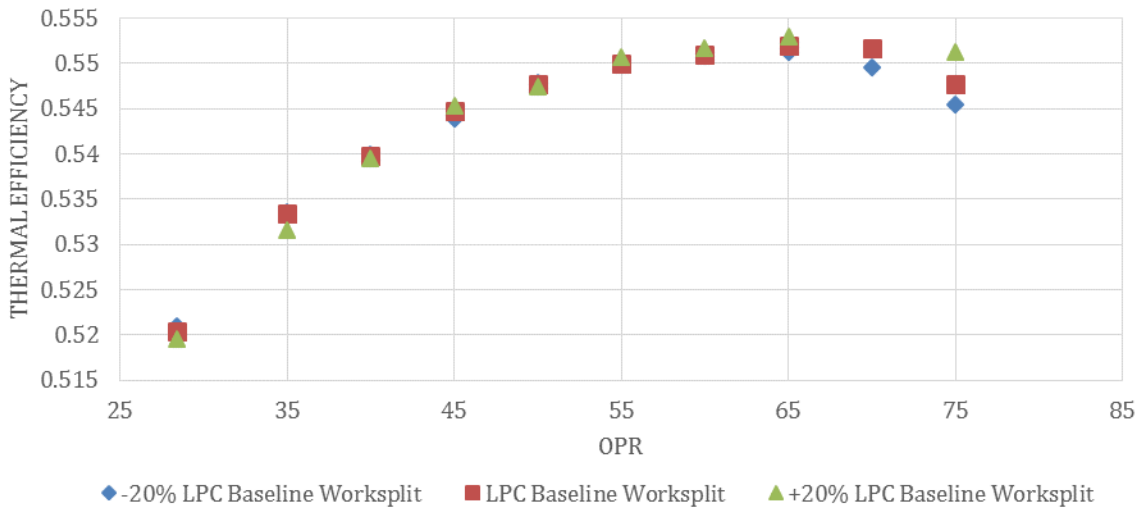


Figure 52: Initial Results of Thermal Efficiency Study for the VLA

As can be seen, the thermal efficiency peaked at 55.2%, which was only a 6.2% relative percent increase from the baseline of 52%. The surveys expected a maximum relative percent increase of 30%, which in the case of the VLA would mean a thermal efficiency of 67.6%. An OPR of 75 was used as an aggressive upper limit for these studies. Note that for an OPR of 75 the theoretical maximum thermal efficiency for a gas turbine was calculated as 70.9%. Similar results were seen for the other four vehicles, where the relative thermal efficiency values were still far away from the projected impacts initially reported in the workshop surveys.

Further studies focused on the LTA and large and small single-aisle (SSA-LSA) aircraft models. The effects of decreasing the amount of cooling required by the high-pressure turbine (HPT) were examined, lowering it until it was nearly zero. The impact of changing FPR was also investigated using the same range of FPR values used during the initial propulsive efficiency studies. As previously noted, these studies used a full factorial approach. Therefore, if the FPR was changed, all cases that had been run with that previous FPR, changing OPR and cooling, were repeated. For the LTA the baseline thermal efficiency was 56.5% and from this process a maximum thermal efficiency of 60.4% was achieved, or a relative percent increase of 6.9%. For the SSA-LSA the baseline thermal efficiency was 49.5% and a maximum thermal efficiency of 54.2% was achieved, which translated to a relative percent change of 9.5%. These efforts began to call into question how reasonable the survey predictions were. As will be detailed further, it should be noted these maximum thermal efficiencies did not correspond the parameters to maximize propulsive efficiency.

Propulsive Efficiency Studies

The propulsive efficiency studies began by decreasing the FPR until it reached a hard lower limit of 1.25. In addition, the extraction ratio was perturbed 20% in either direction of the baseline value. Presented in Figure 53 are the initial results of the study for the SSA-LSA. There was a positive trend in propulsive efficiency between increasing extraction ratio and also decreasing FPR, but clearly there were diminishing returns.

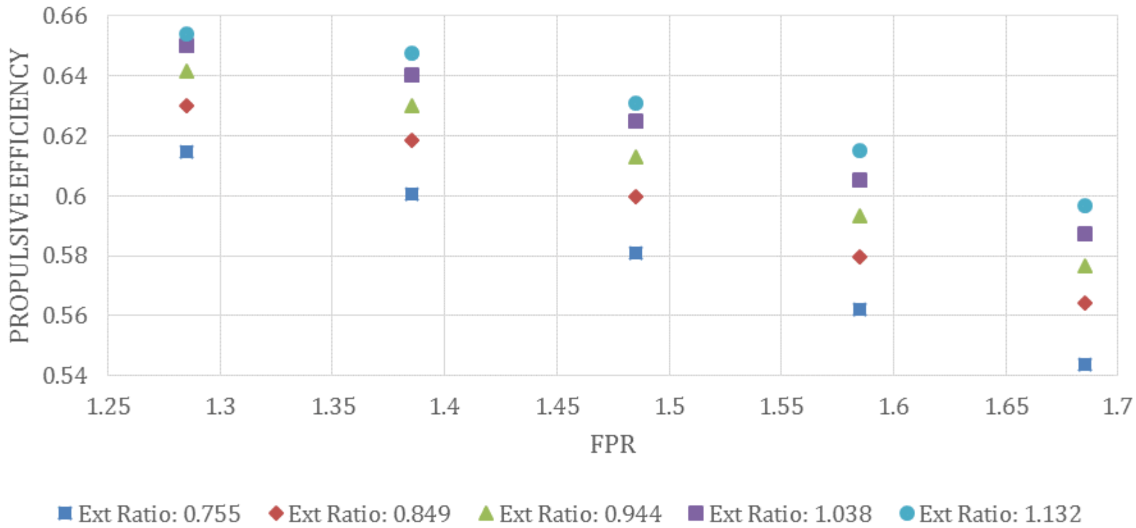


Figure 53: Initial Propulsive Efficiency Sensitivity Study Results for the SSA-LSA

The baseline propulsive efficiency for the SSA-LSA is 57.7% and the maximum propulsive efficiency reached in this study was 65.4%, which was only a relative change of 13.3%. This was below even the Generation 1 maximum impact gathered from the survey of 20%.

For the LTA the maximum propulsive efficiency achieved was 70.6%, which was a relative percent increase of 10.4% from the baseline. A maximum relative percent increase of 18.5% was achieved for the SSA-LSA. It was known that some companies have accounted for propulsive efficiency by dividing out the efficiency of the LPT. Doing this resulted in the maximum relative percentage change from the baseline becoming 11.3% and 18.9% for the LTA and SSA-LSA, respectively. Again these results were below even the maximum Generation 1 impact prediction of a 20% relative percent increase. In addition, the parameters to achieve these maximum propulsive efficiency increases did not correspond with the parameters to maximize thermal efficiency. This concern is best exemplified by Figure 54, which has the thermal efficiency of all the cases run for the LTA plotted against their propulsive efficiency with the LPT efficiency divided out. The figure shows a Pareto frontier, meaning there was a compromise occurring between propulsive and thermal efficiency.

Given the results of this study an alternative solution was proposed. The disparity between the survey and the trade study possibly could have been attributed to the fact that most industry experts spoke of engine improvements in terms of bypass ratio (BPR) and OPR instead of thermal and propulsive efficiency. A literature search was conducted to determine what academia and the aerospace industry believed OPR and BPR values would be over the next three generations for the five different aircraft classes that were modeled. The end goal was to then use those findings as a more credible basis for the engine cycle parameters. The infographics would then be updated based on the final results.

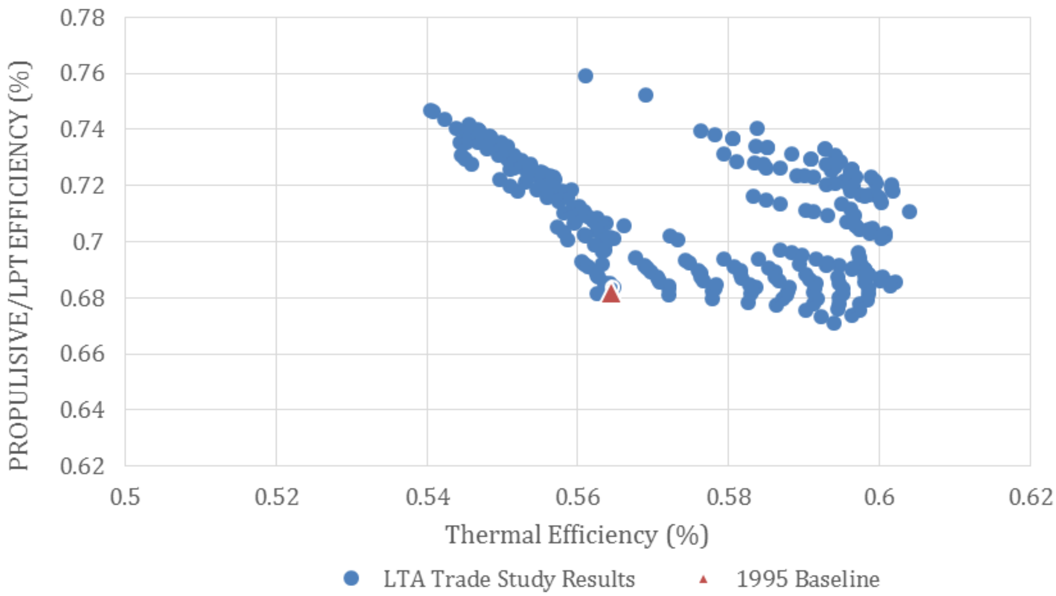


Figure 54: LTA Efficiency Trade Study Results Showing Propulsive Efficiency against Thermal Efficiency

Generation 1 OPR & BPR Research

Generation 1 aircraft were viewed as those entering service in the near term, from 2015 to 2018. The Airbus A320neo, which entered service in January 2016, was a 189 passenger, single aisle jetliner [5]. Neo stands for new engine option, and customers are provided with the choice of either the Pratt & Whitney PW1100G Geared Turbofan (GTF) or the CFM International LEAP-1A turbofan. The A320neo was seen as a fair representation for the LSA. Pratt & Whitney's GTF is reported to have an HPCPR of 16:1 leading to an OPR of 50:1. The engine has a BPR of 12:1. The GE LEAP-1A first saw service on an A320neo in July 2016. It's purported to have a BPR of around 11:1, with a confirmed HPCPR of 22:1 and OPR of 40:1. The LEAP-1C will be powering the Comac C919, which is a narrow-body aircraft that will hold 156-168 seats, making it comparable to the SSA-LSA. The basic engine parameters for the LEAP-1C are the same as the LEAP-1A, it just has a slightly smaller fan causing it to have less thrust.

The Rolls Royce Trent XWB is a three-shaft turbofan currently seeing use on the Airbus A350 XWB, which holds between 250 and 440 passengers depending on the variant [6]. Together they entered commercial service in January 2015. The Trent XWB has a BPR of 9.6:1 and OPR of 50:1. Based on the large seat capacity range the Trent XWB was used as the basis for both LTA and VLA engine cycles.

The GE Passport is a regional and small business jet engine scheduled to first see service in 2018 on the Bombardier Global 7000 [7]. Development of the Passport benefitted greatly from the technology of the CFM International LEAP family of engines. Based on its FAA engine certificate data sheet, the Passport has a BPR of 5.6:1, OPR of 45:1 and HPCPR of 23:1 [8]. Georgia Tech already has Generation 1 regional jet (RJ) model that was used, which has a HPCPR of 22:1 and OPR of 47:1. The HPCPR for the Passport was used as a basis for the Generation 2 RJ engine.

Generation 2 OPR & BPR Research

Research for Generation 2 engine cycles focused on the 2020 to 2030 timeframe. Both the Vision 10 and 20 from Rolls Royce's Future Programmes gave good insight into the progression of turbofan technology [9]. The Advance family is an engine architecture that would enter service after 2020. The Advance3 is the larger three-shaft version seen as the next evolution for Rolls Royce from the Trent XWB, and as a stepping stone towards future geared turbofans. It was chosen to represent the Generation 2 engine for the LTA with a BPR and OPR of over 11:1 and 60:1 respectively. The Advance2 is the two-shaft member of the family that would service aircraft in the 150 passenger market, making it an appropriate representation for the STA and SSA-LSA Generation 2 engines. The Advance2 is targeted to have a HPCPR of 22:1 and a similar BPR to the Advance3. Since the LTA baseline is modeled with a two-shaft engine this HPCPR was also used for the LTA Generation 2 engine cycle.

The Boeing 777X is currently under development with the 777-9 variant slated to hold 400-425 passengers making it a comparable basis for the LTA [10,11]. The 777X will be powered by GE Aviation's GE9X, which is approximated to achieve a BPR of 10:1, HPCPR of 27:1, and OPR of 60:1. Entry into service for the Boeing 777X is targeted for late 2019.

For Generation 2 Regional Jets there was limited quantitative information to be found. Based on historical trends, progress for RJ type aircraft tended to trail behind the larger aircraft classes due to space limitations. With this in mind the GE Passport HPCPR was used, but OPR was increased to be on par with the Trent XWB and BPR was also made more aggressive.

Generation 3 OPR & BPR Research

Rolls Royce's Vision 20 again provided some guidance when looking at Generation 3 engine cycles. The intention of the Advance3 is to be an intermediate step to the three-shaft, geared UltraFan™, as noted in Reference [9]. The current figures for this engine are a bypass ratio greater than 15:1 and OPR greater 70:1, with an entry into service beyond 2025. This engine was viewed as most applicable to the LTA. A large theme in discussions on Generation 3 powerplants was the diminishing gains in efficiency from increasing BPR. Most papers were focused on the implementation of open rotors or even alternative powerplants to gas turbines entirely. Without sufficient information it was decided that the Generation 2 cycle parameters would be reused for the other aircraft.

Identifying Appropriate FPR & Cooling Variables

Since BPR was an output parameter of engine sizing, the next step was to adjust the FPR and cooling required by the HPT to get within the range of the BPR values found, using the OPR and HPCPR values that were identified. After the FPR was found LPCPR was determined by dividing the OPR by the product of FPR and HPCPR. The engine cycle parameters chosen for every vehicle for every vehicle are presented in **Table 10**. The infographics values for propulsive and thermal efficiency were updated using final vehicles for each generation, with all impacts applied as presented in the following sections.

Table 10: Engine Cycle Parameters Chosen for Each Vehicle Class for Every Generation

FPR					
Generation	**RJ**	**SSA-LSA**	**STA**	**LTA**	**VLA**
0	1.629	1.685	1.643	1.58	1.758
1	1.55	1.58	1.54	1.58	1.55
2	1.55	1.58	1.54	1.58	1.55
3	1.55	1.58	1.54	1.28	1.55
OPR					
Generation	**RJ**	**SSA-LSA**	**STA**	**LTA**	**VLA**
0	38.51	30.55	30.63	39.89	28.43
1	47.41	40	40	52	52
2	50	60	60	60	60
3	50	60	60	70	60

Technology Roadmap Design of Experiments (DOE) Aggregator

In order to generate the DOE tables for EDS for any combination of impacts from different generations, an easy to use dashboard interface was created in Excel. Having a DOE Aggregator helped avoid any potential mistakes from manually creating the DOE tables. The DOE Aggregator was also flexible enough to allow new impact values to be input, allowing this process to be repeated in the future with new surveys. The dashboard was created without the use of macros in order to allow ease of transfer across different organizations and machines.

Overall Layout of Technology Roadmap DOE Aggregator

A diagram of the overall flow of data through the DOE Aggregator is provided in Figure 55. On the Scenario Input sheet each row was a case. The user defined what the case's Technology Level, Vehicle Class, and what the Technology Generation was for each Technology Area. This case information then flowed into the Aggregator sheet, which used the information to look up what the impact values were in the Impact Mapping Sheet. It also found the correct values of the absolute type EDS variables from the Chosen Factors sheet. Impacts were aggregated for each variable according to their variable type. They were then passed on to the Case Construction sheet. The correct baseline EDS values were taken from the Baselines sheet based on what Vehicle Class was given for the case in the Scenario Input sheet. The impacts were then applied to these baselines, according to their variable type, or were replaced entirely if they were absolute type variables. Finally, from the Case Construction sheet cases were filtered into their correct vehicle DOE sheet. The baseline values for the EDS variables that were not modified were taken from the Baselines sheet to complete each DOE.

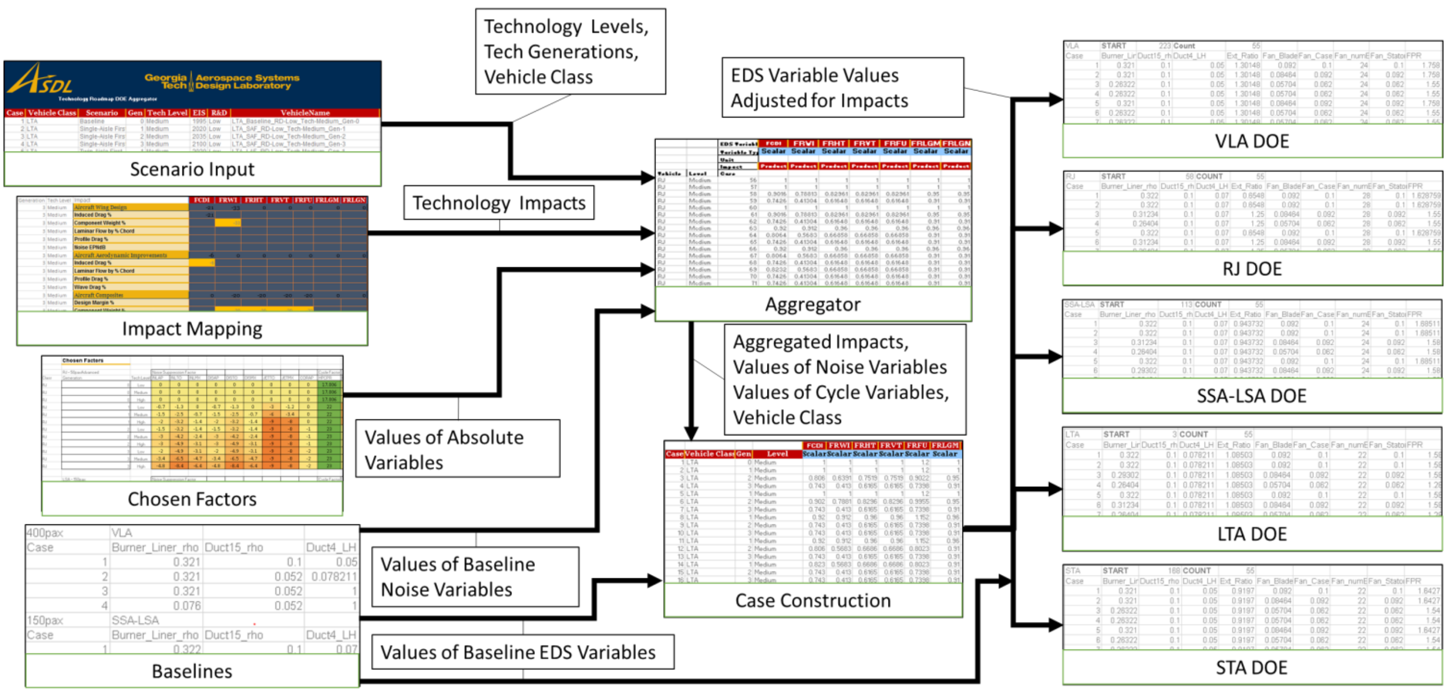


Figure 55: Technology Roadmap DOE Aggregator Data Flow

Scenario Input

The main interface was the Scenario Input sheet, as shown in Figure 56. Each row within the Scenario Input sheet defined a separate case. Cases were created based on the scenario timetables described in the next sections. The scenario timetables provided information specific to each vehicle class. The first column was simply the case number, which was used for tracking purposes throughout the DOE Aggregator. The second column was where the user defined the Vehicle Class for each case, whether it was a VLA, RJ, SSA-LSA, LTA, or STA. The third column contained information on what scenario was being modeled, whether it was the baseline, twin-aisle vehicles entering the market first, or single-aisle vehicles entering the market first. This input did not affect DOE results, but was a reference to which scenario timetable the case was created from. Similarly, the fourth column, which gave the vehicle generation, was also a reference to the timetable. Vehicle generations ranged from 0 to 3. The fifth column was where the user defined the technology level. This referred to how great the technology's impact would turn out to be once it was fully developed. The user had the choice between Low, Medium, and High. Only a single overall technology level was chosen for each case and it effected what values are used from the Impact Mapping sheet. The EIS year for the vehicle was given the sixth column and was a reference from the scenario timetables. The seventh column was the R&D level, which can be Low, Medium, and High. R&D level was not used directly by the DOE Aggregator but was important when creating the cases, as described in the next sections. The technology generation for all 19 technology impact areas had to be defined in columns 9 through 27. These technology generations were chosen by the user based on the R&D level and “Years to TRL 9”. This process is also described in the following sections. Note only three of the 19 impacts are shown Figure 56.

ASDL Georgia Tech Aerospace Systems Design Laboratory

Technology Roadmap DOE Aggregator

Case	Vehicle Class	Scenario	Gen	Tech Level	EIS	R&D	VehicleName	Aircraft Wing Design	Aircraft Aerodynamic Improvements	Aircraft Composites
1	LTA	Baseline	0	Medium	1995	Low	LTA_Baseline_RD-Low_Tech-Medium_Gen-0	0	0	0
2	LTA	Single-Aisle Firs	1	Medium	2020	Low	LTA_SAF_RD-Low_Tech-Medium_Gen-1	0	0	0
3	LTA	Single-Aisle Firs	2	Medium	2035	Low	LTA_SAF_RD-Low_Tech-Medium_Gen-2	2	2	2
4	LTA	Single-Aisle Firs	3	Medium	2100	Low	LTA_SAF_RD-Low_Tech-Medium_Gen-3	3	3	3
5	LTA	Twin-Aisle First	1	Medium	2020	Low	LTA_LAF_RD-Low_Tech-Medium_Gen-1	0	0	0
6	LTA	Twin-Aisle First	2	Medium	2030	Low	LTA_LAF_RD-Low_Tech-Medium_Gen-2	1	1	1
7	LTA	Twin-Aisle First	3	Medium	2045	Low	LTA_LAF_RD-Low_Tech-Medium_Gen-3	3	3	3
8	LTA	Single-Aisle Firs	1	Medium	2020	Medium	LTA_SAF_RD-Medium_Tech-Medium_Gen-1	1	0	0
9	LTA	Single-Aisle Firs	2	Medium	2035	Medium	LTA_SAF_RD-Medium_Tech-Medium_Gen-2	3	3	3

Figure 56: Technology Roadmap DOE Aggregator Scenario Input Tab

Impact Mapping

Impact Mapping was the sheet where the subcategories for all 19 vehicle impacts were mapped in a matrix to their corresponding EDS variables. Each subcategory had a value for all three generations for all three technology levels. The values of the subcategories, like Induced Drag % and Component Weight %, were summed in the rows labeled with the top-level impacts, like Aircraft Wing Design.

Generation	Tech Level	Impact	FCDI	FRWI	FRHT	FRVT	FRFU	FRLGM	FRLGN
3	Medium	Aircraft Wing Design	-21	-33	0	0	0	0	0
3	Medium	Induced Drag %	-21						
3	Medium	Component Weight %		-33					
3	Medium	Laminar Flow by % Chord							
3	Medium	Profile Drag %							
3	Medium	Noise EPNdB							
3	Medium	Aircraft Aerodynamic Improvements	-6	0	0	0	0	0	0
3	Medium	Induced Drag %	-6						
3	Medium	Laminar Flow by % Chord							
3	Medium	Profile Drag %							
3	Medium	Wave Drag %							
3	Medium	Aircraft Composites	0	-20	-20	-20	-20	0	0
3	Medium	Design Margin %							
3	Medium	Component Weight %		-20	-20	-20	-20		
3	Medium	Aircraft Advanced Metallics	0	-9	-9	-9	-9	-9	-9
3	Medium	Component Weight %		-9	-9	-9	-9	-9	-9
3	Medium	Aircraft Manufacturing Processes	0	-3	-3	-3	-3	0	0
3	Medium	Component Weight %		-3	-3	-3	-3		

Figure 57: Impact Mapping Tab in Technology Roadmap DOE Aggregator

Aggregator

The Aggregator sheet was the first step in creating the DOE tables. Each row represented a case from the Scenario Input sheet. For each EDS variable identified, this sheet determined what impacts were related to it. For the subset of impacts related to the variable, the sheet then looked at the Scenario Input sheet to find what the Tech Level for the case was and what the generations were for the impacts in the subset. The sheet then looked at the Impact Mapping sheet for each impact to find the value that was mapped to the EDS variable for that Technology level and Generation. The values for impacts in the subset were then combined based on what variable type the EDS variable was, as explained earlier.

An exception to that process was the EDS variables for the engine cycle related to thermal and propulsive efficiency. As discussed earlier, the values for FPR, Ext_Ratio, LPCPR, HPCPR, s_HPT_ChargeEff, and s_HPT_NonChargeEff were chosen based on a literature search on future engine cycles. Propulsive efficiency was a subcategory of Engine Propulsive and was largely a function of FPR and Ext_Ratio. Thermal Efficiency was a subcategory of Engine Core and was mainly a function of OPR (FPR, LPCPR, and HPCPR). Both were effected by s_HPT_ChargeEff, and s_HPT_NonChargeEff, which were related to the cooling required by the HPT. On the Scenario Input sheet the user had the option to choose different generations for Engine Propulsive and Engine Core. The mixing of engine cycle parameters from different generations though greatly increased the chance of the case failing. To account for this the Aggregator sheet used the lower of the generations between Engine Propulsive and Engine Core and the case’s Technology Level and vehicle to look up the engine cycle parameters on the Chosen Factors sheet.

The EDS variables related to Engine Noise for the core, propulsor, and jet were also chosen like the values for the engine cycle, but were based entirely on a parametric study. Different generations were able to be entered for the core, propulsor, and jet engine noise without a problem. The Aggregator sheet then simply grabs the correct values from the Chosen Factors for the provided generation, vehicle and Technology Level. Combining noise variables was more involved than the other EDS variables. The Aggregator sheet had to determine the size order of the impacts, which included treating the baseline value as an impact. With the size order known the values were then combined following the rules in Table 9.

Case Construction
The Case Construction sheet first looked up the baseline value for the cases from the Baselines sheet based on what vehicle the case was using. The combined impacts from the Aggregator sheet were then taken and added to, multiplied by, or simply replaced the baseline value, depending on the EDS variable type. In the case of noise variables the baseline values were already needed by the Aggregator sheet when determining the new noise suppression factors, so these values were able to be put directly into place.

Baseline Vehicles
The Baselines sheet contained the baseline vehicles previously developed by Georgia Tech. For all five vehicles there were four cases. In all instances Case 1 was the baseline used since it represented a vehicle that entered into service in 1995. For future studies though the baseline could easily be transitioned to one of the other cases. The 1995 baseline for the RJ did not have a low pressure compressor (LPC), so the RJ Case 2 was modified to have values appropriate for a 1995 vehicle, but with a LPC. This modified case was then used as the RJ baseline moving forward.

Chosen Factors
The Chosen Factors sheet was where noise suppression factors, from the parametric study, and the engine cycle parameters, based on the literature review, were found. For a given generation and vehicle there was no difference in the engine cycle parameters for different Technology Levels, because there was not enough information found to base that differentiation on.

Vehicle DOEs
A DOE table contained a row for each vehicle case and contained all the information that EDS needed to read in. Creating the DOE tables for each vehicle relied on all the cases for the same vehicle being together on the Scenario Input sheet. For each case the DOE sheet then went through all the EDS variables in the baseline EDS DOE table. If the EDS variable was one of the ones that had been modified, the DOE sheet obtained its new value from the Case Construction sheet. Otherwise it used the baseline value.

Table 11 shows a subset of the final DOE sheet for the VLA, with only six of the over 300 EDS variables in a DOE shown. The "START" number 223 was the row in the Case Construction sheet where the VLA cases started, not the Scenario Input sheet case number. "Count" was the number of VLA cases counted in the Scenario Input sheet. The only manual step for the user was that the row formula had to be dragged down, or rows would be deleted so that the number of cases matched the "Count".

Table 11: Subset View of Final DOE Table for the VLA from the Technology Roadmap DOE Aggregator

VLA	START	**223**	Count	**55**		
Case	Burner_Liner_rho	Duct15_rho	Duct4_LH	Ext_Ratio	Fan_Blade_rho	Fan_Case_rho
1	0.321	0.1	0.05	1.30148	0.092	0.1
2	0.321	0.1	0.05	1.30148	0.08464	0.092
3	0.26322	0.1	0.05	1.30148	0.05704	0.062
4	0.26322	0.1	0.05	1.30148	0.05704	0.062

Using Technology Roadmap DOE Aggregator
In order to use the Technology Roadmap DOE Aggregator the most probable cases first had to be defined. Defining a case first involved assigning what scenario, vehicle class, and vehicle generation were being used. Using a vehicle replacement

schedule the EIS year for the case vehicle could be determined. An R&D level was then chosen which, along with the "Year to TRL 9" data from the infographics, allowed the EIS year for the three generations of each technology area to be determined. The technology area EIS years were compared to the vehicle EIS year to identify what generation of each technology area was being used for that case. Finally, the case was assigned a technology level, which indicated how great the impacts of the technology areas would end up being. Cases were made for every combination of the two scenarios, five vehicle classes, three vehicle generations, three R&D levels, and three technology levels. Complete case definitions were inserted as a row in the Scenario Input sheet of the DOE Aggregator, which then created five DOEs separated into each vehicle class. These DOEs were then modeled using EDS.

Vehicle Timetable & Scenarios

With the capability provided by the Technology Roadmap DOE Aggregator over 800 billion different technology scenarios were able to be considered. To narrow down to the important ones first a replacement schedule was created. It identified the likely year for introduction of re-engined models, performance improvement packages, and new designs for each vehicle class from 2015 out to 2050. This replacement schedule was then used to assess what the EIS year would be for each vehicle class whether a twin-aisle or single-aisle vehicle was introduced first. The replacement schedule for the single-aisle first vehicle is shown in Figure 58 and the twin-aisle first vehicle is shown in Figure 59. For each of the 19 technology impact categories the "Years to TRL 9" was forecasted for the next three generations assuming a low, medium, or high R&D level, to get EIS dates for that technology. For a given R&D level, the EIS year of the generations for each vehicle was used to determine what the generation each technology impact would be on that vehicle based on the technology EIS years. Technology packages were made for all three vehicle generations for all five vehicles for all three R&D levels for both single-aisle and twin-aisle scenarios. This resulted in 90 cases. In addition, the surveys had provided the information to differentiate levels of technology effectiveness for each generation. Considering the three technology levels resulted in 180 cases worth investigating plus the 5 baselines if technology stayed frozen.

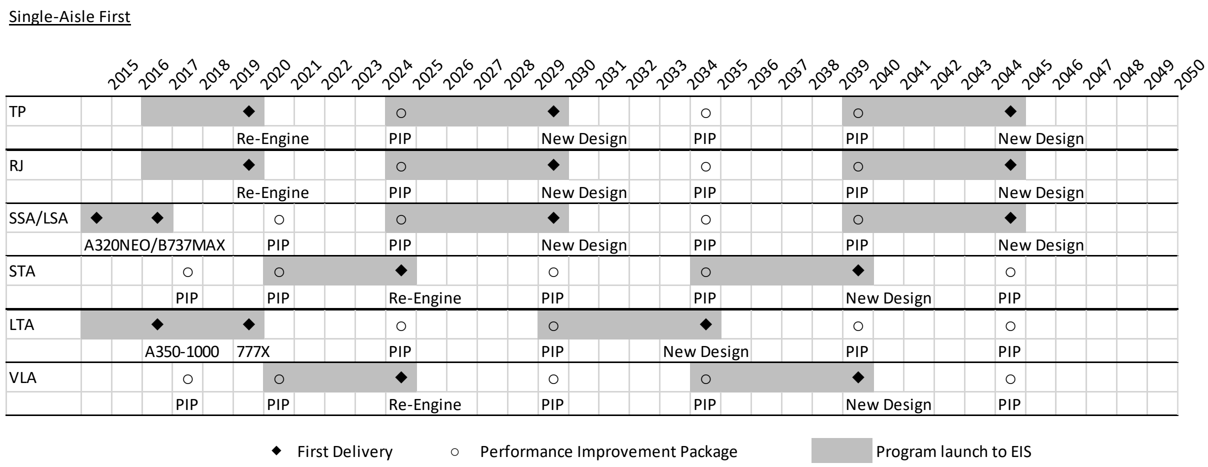


Figure 58: Vehicle Replacement Schedule for Single-Aisle First Assumption

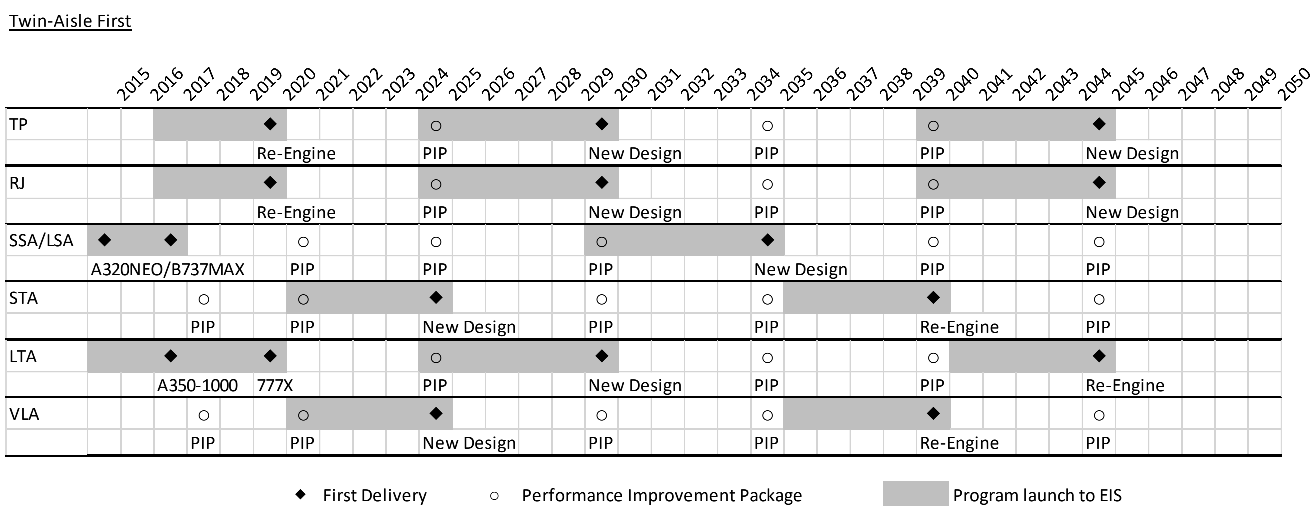


Figure 59: Vehicle Replacement Schedule for Twin-Aisle First Assumption

Vehicle Naming Convention & Identification

Each of the 185 cases were given a name based on its vehicle class, scenario, generation, technology level, and R&D level. The five vehicle size classes under investigation were the RJ, SSA-LSA, and STA, LTA, and VLA. The passenger classes they corresponded to were 50, 150, 210, 300, and 400 passengers, respectively. Keep in mind when looking at the scenarios that the focus of using these five vehicles was on their passenger sizes, not their names. The scenario could be either the baseline, single-aisle first, or twin-aisle first. Single-aisle first and twin-aisle first were shortened to SAF and LAF in the vehicle name. Both the R&D and Technology Level were given intensities of low, medium, or high. The final part of the name was what the vehicle generation was. This generation often varied from the generation of technology impacts on the vehicle. As an example, for a Generation 2 LTA, SAF scenario, with a medium Technology Level and a high R&D Level, the vehicle name was LTA_SAF_RD-High_Tech-Medium_Gen-2.

Importing DOE Tables & Running EDS

Within the file-folder system for EDS were CSV files for each vehicle. The cases and heading were copied from the appropriate DOE sheets in the Technology Roadmap DOE Aggregator and then pasted as values into the CSV files. The 55 cases for each vehicle were then submitted to Condor, which was Georgia Tech's cluster computing network for running cases for different environments like EDS. A script was written to rename the AEDT files output by EDS to match the vehicle naming convention. These AEDT files were used for generating vehicle noise reports and also contained the information for moving forward to fleet level impact analysis. The script also placed the engine deck and flops files for each case in folders using the correct naming convention.

Vehicle Modeling Results

The main metrics from the vehicle results that were analyzed were fuel burn, emissions, and noise. Fuel burn was compared across vehicles by computing the percent reduction in the design block fuel relative to the appropriate baseline. Noise was compared by looking at the noise margin. Noise margin was the difference between the actual aircraft cumulative noise and the Stage 4 noise limit. For emissions only the reduction in nitric oxide relative to the CAEP/6 limit was compared. The CAEP/6 limit was given in terms of D_p/F_∞ , defined as the grams of NOx emitted divided by the thrust in kilo-Newtons, during the LTO-cycle, divided by the thrust rating of the engine. The CAEP/6 limit for an aircraft changed as a function of engine overall pressure ratio. CAEP/6 is shown to facilitate direct comparison to the NASA goals available at the time of this study.

Fuel Burn

The fuel burn results for all the vehicles showed the trends that would be expected, with the same or greater fuel burn reduction as the vehicle generation and R&D level increased. **Figure 60** provides the final results for the Generation 1 vehicles assuming a Single-Aisle First Scenario. Also overlaid on this bar graph were the high and low values for the NASA Subsonic Transport System Level Measures of Success. These were Near Term (2015-2025) desired technology benefits.

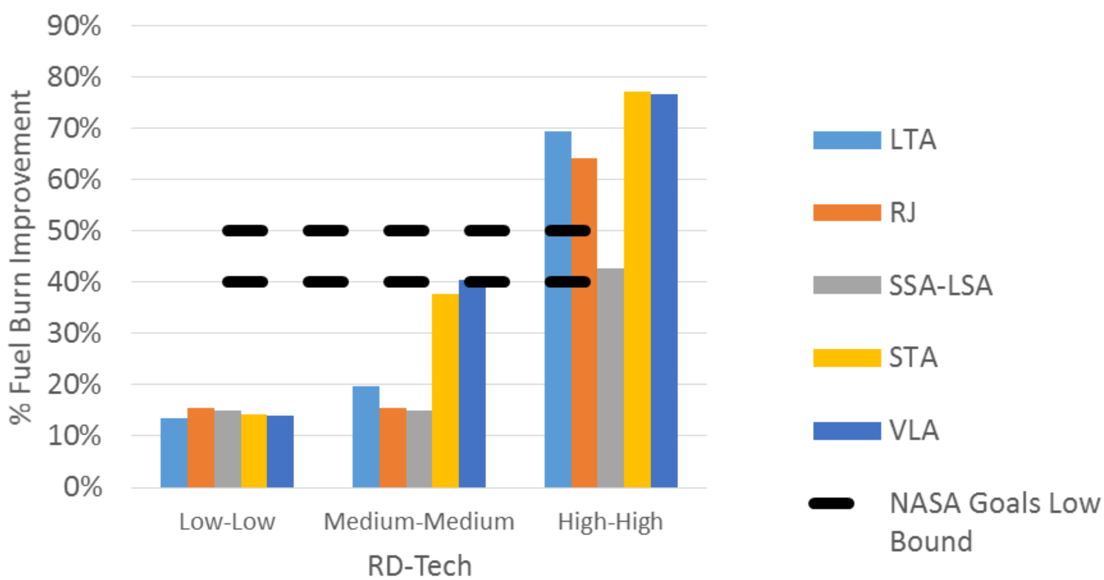


Figure 60: Percent Reduction in Fuel Burn Relative to the Baseline for the Single-Aisle First, Generation 1 Vehicles

Noise Margin

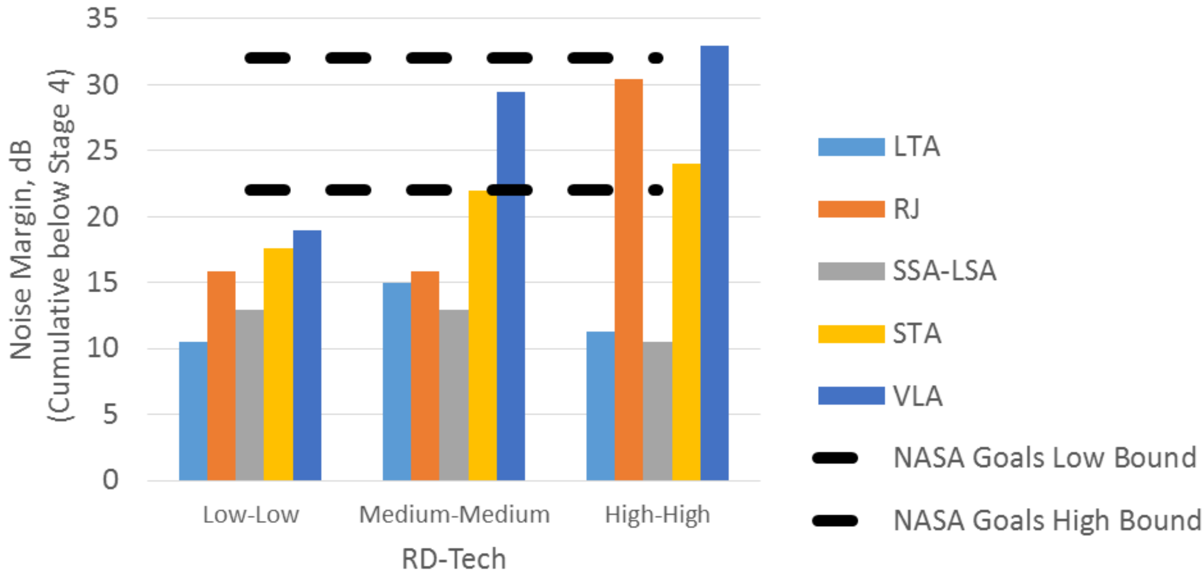


Figure 61: Noise Margin Relative to Stage 4 for Single-Aisle First, Generation 1 Vehicles

Nitric Oxide Emissions

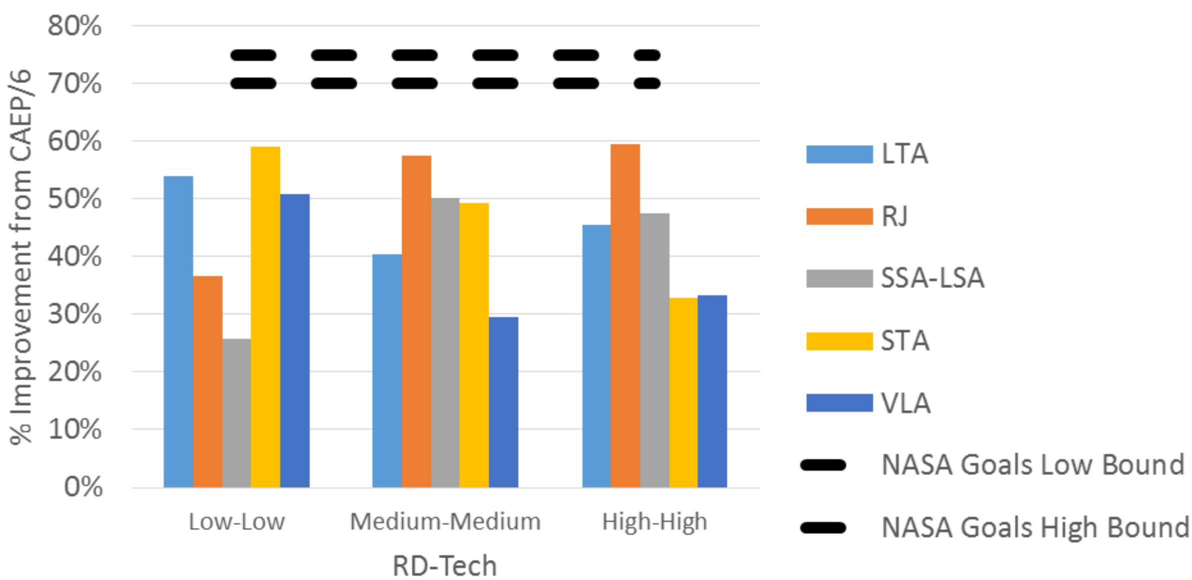


Figure 62: Nitric Oxide Percent Improvement Relative to CAEP/6 for Single-Aisle First, Generation 1 Vehicles

Propulsive Efficiency

In order to update the propulsive efficiency improvement values on the Engine Propulsive infographic, a correlation between BPR and propulsive efficiency was used. The correlation was created by assuming a core velocity of 1660 ft/s and a flight speed of Mach 0.8 at 35,000 ft. It also assumed that, for that core velocity and a given BPR, the optimal jet velocity ratio to maximize propulsive efficiency was able to be achieved. Jet velocity ratio was the ratio between core velocity and bypass velocity. Propulsive efficiency could theoretically be derived as a relationship between bypass ratio, core jet velocity, freestream velocity, and velocity ratio, as given in Equation 1.

$$\boldsymbol{\eta_p = \frac{\left(u_c + BPR\left(\frac{u_c}{V_{ratio}}\right) - (1+BPR)u_o\right)u_o}{\left(\frac{u_c^2}{2}\right) + BPR\left[\left(\frac{1}{2}\right)\left(\frac{u_c^2}{V_{ratio}^2}\right)\right] - (1+BPR)\left(\frac{u_o^2}{2}\right)}}$$

EQUATION 1

Using this relationship, and adjusting the jet velocity ratio to maximize propulsive efficiency, Figure 63 was created which plotted BPR against the theoretical peak propulsive efficiency. The BPR output by EDS for each case was used to determine what its propulsive efficiency would be based on this relation, assuming jet velocity was maximized. The propulsive efficiency for each case was compared to the propulsive efficiency for its respective 1995 baseline to determine what the percent improvement was. The low and high percent improvement values for each vehicle generation were found across all vehicle classes. The nominal values for each vehicle generation were then found as the average of the percent improvement values for that generation across all vehicle classes. The results were used to create the final Engine Propulsive infographic.

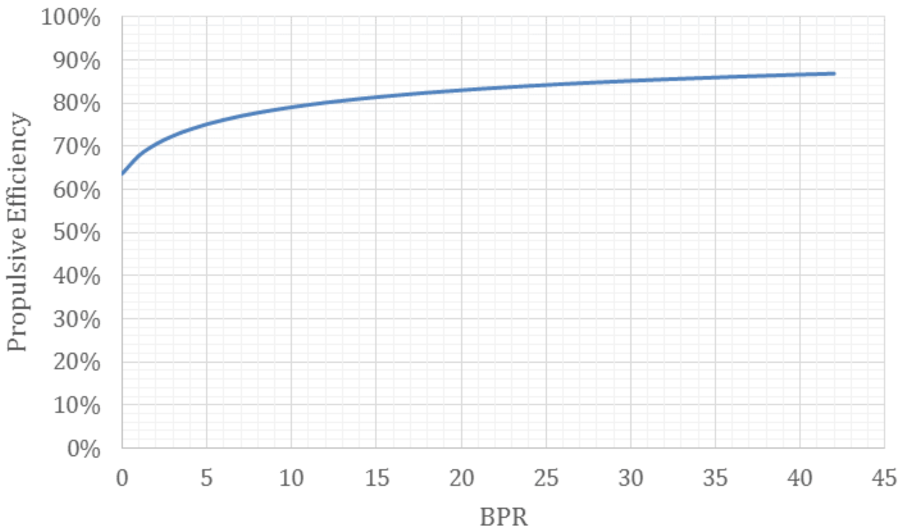


Figure 63: Plot of Correlation between BPR and Propulsive Efficiency

Thermal Efficiency

In order to update the thermal efficiency improvement values on the Engine Core infographic, Equation 2 was used which provides the theoretical thermal efficiency based on OPR and the heat capacity ratio. The thermal efficiency value was calculated for every case using an OPR that was the product of the HPCPR, LPCPR, and FPR values put into the DOE for that case. A heat capacity ratio of 1.4 was assumed. The thermal efficiency for each case was compared to the thermal efficiency for its appropriate 1995 baseline to determine what the percent improvement was. The minimum value for each vehicle generation was found as the lowest percent improvement for that vehicle generation, across all vehicle classes. Similarly, the maximum value was found as the highest value for that vehicle generation, across all vehicle classes. The nominal values were found by taking the average of thermal efficiency improvements for a given vehicle generation. These results were implemented in creating the final Engine Core infographic.

$$\eta_{thermal} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{OPR^{\frac{\gamma-1}{\gamma}}}$$

EQUATION 2

Mission Specification Change Modeling (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 (2015-16) 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, the fuel burn impact of varying design mission specifications was investigated, focusing on the cruise Mach number of tube-and-wing aircraft. Thus the Stanford team 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. 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 then 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 the results that can be carried forward to fleet-level analyses.

Introduction to SUAVE
SUAVE is a conceptual level aircraft design environment that incorporates multiple information sources to analyze unconventional configurations [12]. 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.

Analysis Capabilities in SUAVE
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.

Vehicle: 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 nautical mile (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.

Mission: Beyond just looking at different vehicles over the same mission, SUAVE is used 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, one could optimize for a 1,000 nmi mission, but add a constraint that the maximum range of the aircraft be 2,500 nmi. Just as one must specify what parameters would define each vehicle, one must build the missions from the different segments available. For example, in Project 10, in order to ensure 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.

Vehicle-Mission Connections: 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.

Procedure: 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 a non-standard constraint is the fuel margins; which is the fuel volume available in the vehicle minus the fuel used to run the mission.

Optimization using SUAVE

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 Project 10 at Stanford University, Stanford has 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. SUAVE's code structure is general enough to be driven from a variety of optimization packages.

In the development of SUAVE, one of the major objectives was to build it to be 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 $g_j(x)$ and m inequality constraints $h_k(x)$ 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.

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 64: Sample Description of Optimization Problem Design Variables, Bounds and Units

Furthermore, within SUAVE the design variables can be defined in any user preferred name and then "aliased" 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 results of interest for our problem. If one is trying to meet Stage 4 Noise levels, one cares only about generating a cumulative total of 10 dB, not 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.

Link to Optimization Packages

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[13]: 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[14]: 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[15]: 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[16]: 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.

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.

Improvements to SUAVE Capabilities as part of ASCENT 10
At Stanford, a considerable amount of effort has been devoted 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. As part of this validation effort for this project, five baseline representative aircraft and their technology variants were modelled and their performance parameters like fuel burn were compared with the corresponding aircraft generated by the Georgia Tech team. It was observed that the initial results obtained from SUAVE did not match well enough with the baseline aircraft provided by Georgia Tech (GT) for some of the aircraft. The differences in the performance estimates were traced down to differences in the computation of the drag and the propulsion performance.

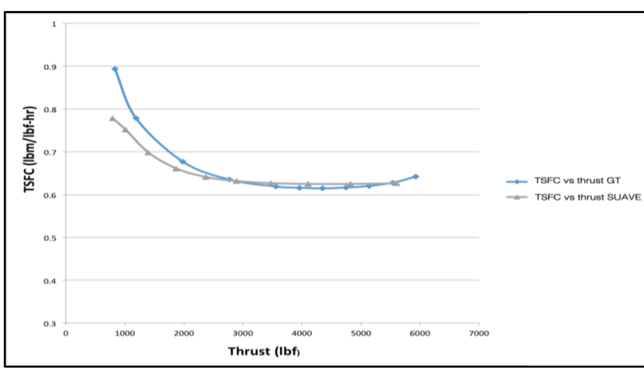
Simple changes to the compressibility drag and induced drag prediction routines were made, resulting in aerodynamic predictions better matching the GT results. These changes were fairly minor from the code standpoint.

The major improvement to SUAVE was the addition of multiple propulsion analysis modules to supplement the existing models for prediction of turbofan/turbojet performance. The existing engine model in SUAVE, while predicting accurately the design performance of the turbofan/turbojet engines, were seen to inaccurately predict the off-design performance of the engine (especially at very low Mach numbers). In order to fix the issue, two new turbofan analysis models were created and integrated into SUAVE.

The first analysis module was based on the off-design analysis methodology described in the propulsion analysis text by Mattingly [17]. Here the off-design residuals for speed matching were computed using functional iteration. No speed/efficiency maps were used and overall component efficiencies were assumed to be constant. While this resulted in improved off-design predictions without significant cost overhead, the level of accuracy required for this effort was not met by the model so the model was not used any further and a more detailed off-design analysis module based on the descriptions in the propulsion analysis course notes (AA283 [18]) by Prof. Brian Cantwell at Stanford and the work in the NASA N+3 Aircraft Concept Designs and Trade studies, Final Report Volume 2[19] was added.

The off-design propulsion analysis model is an extension of the existing engine model in SUAVE. The model solves the 0D flow equations through a turbofan engine, computing the non-dimensional properties at each engine section and the non-dimensional thrust associated with the engine. The mass flow and thrust are then scaled based on the desired thrust at design point. At design point, the mass flows, component speeds, polytropic efficiencies and turbine temperature are known. For off-design analysis, these parameters are treated as unknowns. The mass flows and component speeds and the temperatures are obtained for each evaluation point using Newton/damped Newton iterations. An initial guess for these unknowns is provided (normally the values at design point). During each iteration, the polytropic efficiencies for the components and the speeds are obtained using compressor and fan maps. These maps are generated using the methodology described in the NASA N+3 Aircraft Concept Designs and Trade studies, Final Report Volume 2[19]. However the capability to read in actual component map data and building a surrogate using Gaussian Process Regression is also added to SUAVE. At each iteration, the off-design mass flow residuals (flow/speed matching equations) are computed at the different engine stages and these are driven to zero using Newton iterations. The Jacobians of these residual equations are computed analytically. This is done by symbolically differentiating the propulsion analysis code and analytically computing the required Jacobian terms.

To test and validate the new analysis modules, these are compared with engine performance data provided by Georgia Tech for the different aircraft engines and the results showed reasonable agreement. (**Figure 65**) The thrust and specific fuel consumption predicted by the engine models are compared with the values predicted by GT generated engine data for different throttle settings at the cruise condition (as shown in the plot on the left (**Figure 65**)) and at different Mach numbers and atmospheric conditions at max throttle (as shown in the plot on the right (**Figure 65**)). Comparisons are also ongoing with Embraer to further validate and improve the propulsion model.



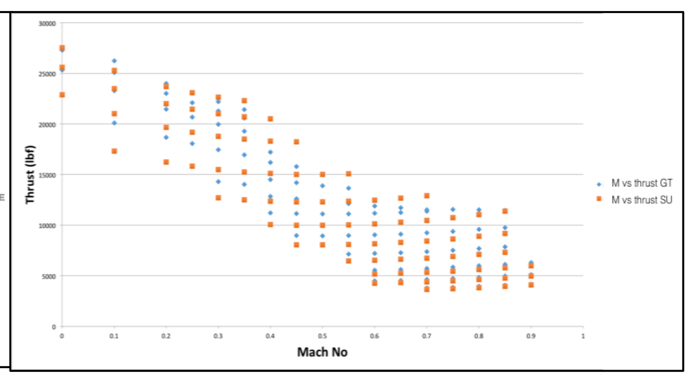


Figure 65: Comparison of Off-Design Propulsion Performance

While the engine models provided fairly good predictions of engine performance, in order to ensure that the any discrepancy associated with engine performance was removed, the capability to use engine decks provided by GT with the SUAVE aircraft models was developed. This was also critical for the inclusion of next gen propulsion technology into the SUAVE models. For this a third engine model was created in order to interface with the EDS engine decks provided by GT. The engine deck file contained the thrust, ram drag, specific fuel consumption and fuel flow rate for a set of Mach numbers, altitudes and throttle settings. The engine model was capable of reading in the engine deck file and the input parameters are stored as a database. Then using the data from the deck, interpolation models are created for thrust, ram drag and fuel flow rate with respect to the Mach number, altitude and the throttle setting. When queried by the mission solver at different evaluation (atmospheric) conditions, the engine performance estimates are evaluated by interpolating between the given data and the outputs are fed back into the mission solver in SUAVE.

With the addition of these propulsion analysis modules, the baseline aircraft models were seen to match better with the baseline models provided by GT and these were then used for further analysis/design. More details on the baseline aircraft models are described next.

Baseline Aircraft Modelling

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 and the performance estimates including fuel burn, 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 off-design 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 aircraft classes. The level of agreement is within the expected differences that would be seen in similar analysis and conceptual design tools.

Reduced Cruise Mach aircraft design (with and without technology)
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 consists of SUAVE linked up with a gradient based optimizer, SNOPT via PyOPTa python based optimization framework. The design variables used consist of the geometric parameters of the aircraft wing. Initially the engine component pressure ratios and bypass ratio as well as the design thrust (which determines the engine size) were also used as design variables. However the final set of optimizations were run using the engine decks and so the design thrust was the only engine parameter used as a design variable. The cruise altitude of the aircraft is also used as design parameter. The design variables and constraints used for the final set of results are shown below.

DESIGN VARIABLES:
- Main wing aspect ratio
- Main wing reference area
- Main wing sweep
- Main wing thickness to chord ratio
- Engine design thrust
- 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 Takeoff Weight (TOW) and the sum of the Operating Empty Weight (OEW), payload and mission and reserves fuel) 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. Initially the pressure ratio at the combustor inlet and the fan diameter were constrained to be less than equal to the values on the baseline aircraft but the pressure ratio constraint was removed for the engine deck based optimizations. These constraints ensure that the sizing/redesign of the aircraft is realistic and the aircraft is feasible.

CONSTRAINTS:
- Takeoff field length
- Fuel burn (positivity)

Fuel balance: TOW – (OEW+payload+reserves+fuel burn)
Wing span
Fan diameter

Effect of cruise Mach reduction

As expected, redesigning the existing aircraft for reduced cruise Mach numbers resulted in low Mach variants that were more fuel efficient than the existing models. Figure 66 shows the percentage reduction in fuel burn for the baseline technology scenario for all five aircraft classes. It is observed that the percentage reduction in fuel burn is significantly larger (more than 10%) in the larger payload range aircraft (the B777 and B747). The smaller aircraft also show a reduction in fuel burn as cruise Mach number is reduced but the reduction are smaller in magnitude (closer to 5%). Some of the interesting design trends observed during this study are shown in Figure 67.

We see that the redesigned aircraft in all 5 aircraft classes exhibit similar trends. The redesigned aircraft have a lower wing reference area compared to the baseline aircraft. This results in a reduction in wing weight and lower wing drag (parasite) contributing to the improvement in mission performance. The wings are also de-swept as the cruise Mach number is reduced until, for some cases, the lower bound of 5 degrees is met. Similarly the average thickness to chord ratio of the wings increases at lower cruise Mach numbers. These changes are permitted by the reduced effect of compressibility drag at lower cruise Mach numbers. The de-sweeping and increase in wing thickness results in a further reduction in wing weight. The reduction in wing weight and reduced fuel burn due to lower drag results in a reduction in the overall maximum take-off weight (MTOW). This implies a reduction in the required lift and thus a reduction in the lift induced drag. A combination of the effects described above result in the redesigned reduced Mach variants becoming much more efficient than the baseline (Mach) aircraft.

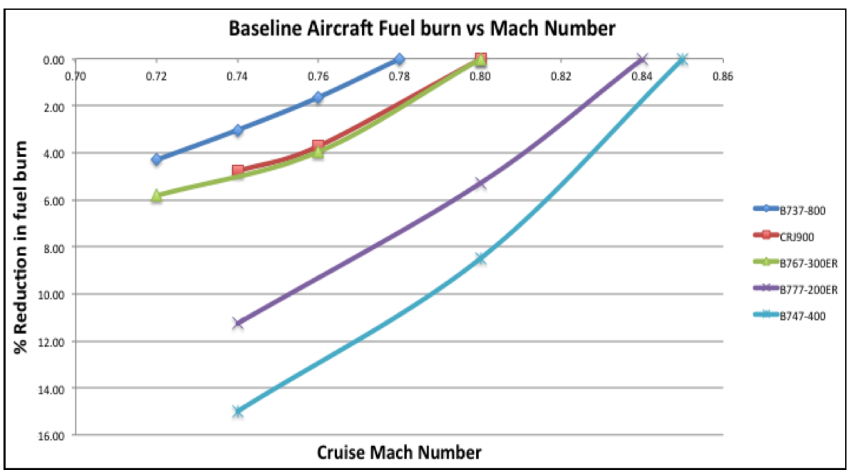


Figure 66: Reduction in Fuel Burn with Cruise Mach Reduction for all Five Aircraft Classes for Baseline Technology

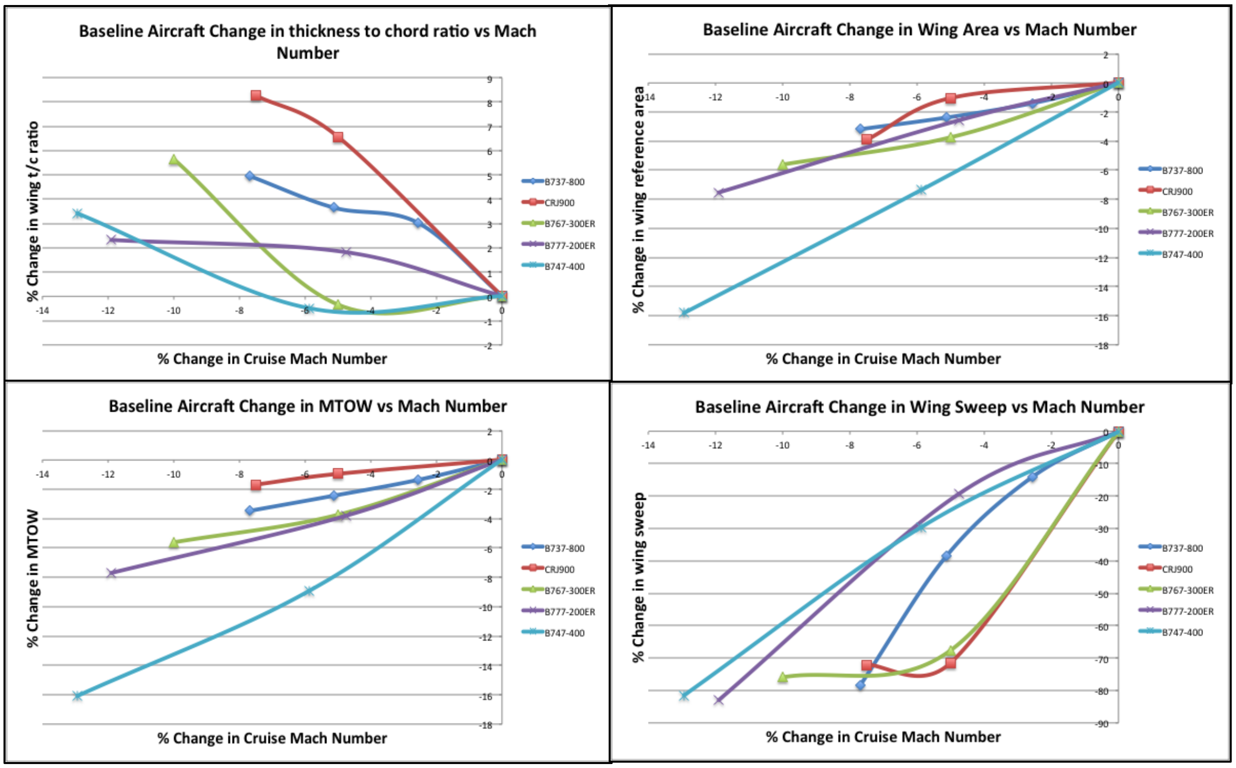


Figure 67: Change in Design Variables with Cruise Mach Reduction

Effect of Technology Variants

The results shown above were for the baseline technology scenario. However it is also important to study how cruise Mach reduction affects the higher technology variants. For this, the technological baselines were modelled in SUAVE based on the corresponding EDS models provided by Georgia Tech. Then these aircraft were redesigned for reduced cruise Mach numbers. **Figure 68** shows the effect of cruise Mach reduction on the fuel burn of the technology variants of the 5 aircraft classes for the baseline and two improved technology levels.

For the higher technology derivatives, the results shown are with respect to the baseline Mach number at the corresponding technology level to isolate the effect of cruise Mach reduction. It is observed that for all 5 aircraft classes, cruise Mach reduction at the higher technology levels is as effective as the for the baseline technology levels. Thus the percentage reductions in the technology 1 and 2 scenarios, can be represented using the same factors associated with the baseline technology scenario if required. The effect of the aircraft class is similar to that observed for the baseline case with the larger aircraft (B777, B747) showing a larger percentage reduction in fuel burn with Mach reduction, while the smaller aircraft classes show a smaller improvement. The trends exhibited by the design parameters mirror those of the baseline technology aircraft presented above and so are not shown again.

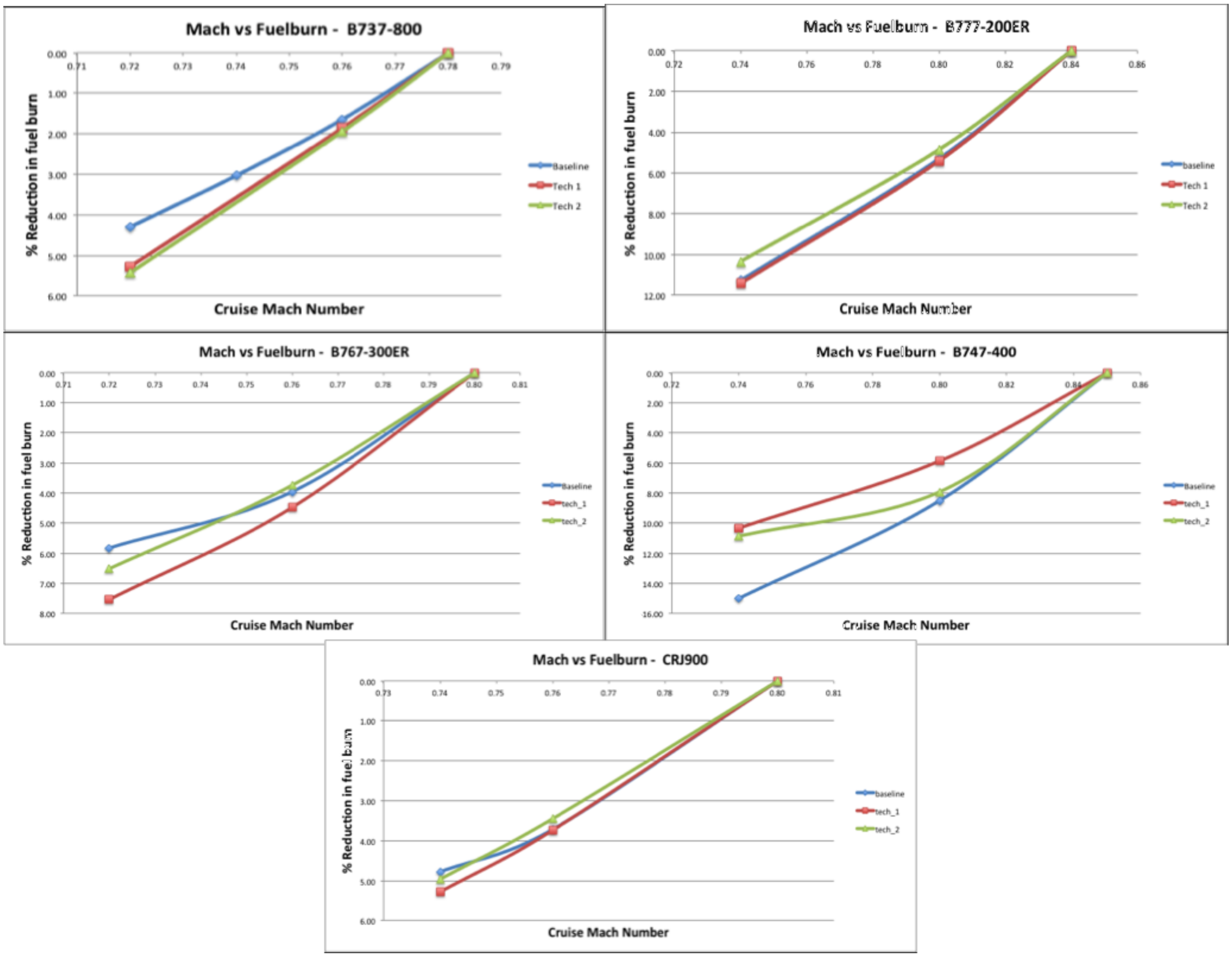


Figure 68: Effect of Cruise Mach Reduction on Technology Variants

Conclusions/Interface with other members of the team/ product of our work

All the percentage reduction values shown above were for the design mission. However, once the aircraft (baseline and higher technology for all 5 classes) were re-designed for cruise Mach reduction, in order for Georgia Tech and Purdue teams to perform fleet level analysis, the re-designed aircraft were flown for a set of off-design missions. The performance (fuel burn) of the aircraft for the off-design missions was compared to the performance of the baseline aircraft also flown for the same off-design missions. The results obtained are shown in Figure 69**.** Except for the second technology scenario for the CRJ900 (CRJ900 tech 2), most the other results show similar trends. The results in general indicate that at ranges significantly lower than the design range, the percentage reductions in fuel burn are not as high as at the higher ranges. However overall, the redesigned aircraft are more fuel efficient than the baseline aircraft for all the off-design missions. For the CRJ900 Tech 2 scenario also the redesigned aircraft are more fuel efficient for the off-design missions than the baseline aircraft. The percentage reductions, however, are different from the other aircraft and from the baseline and the Tech 1 scenario of the CRJ900, too.

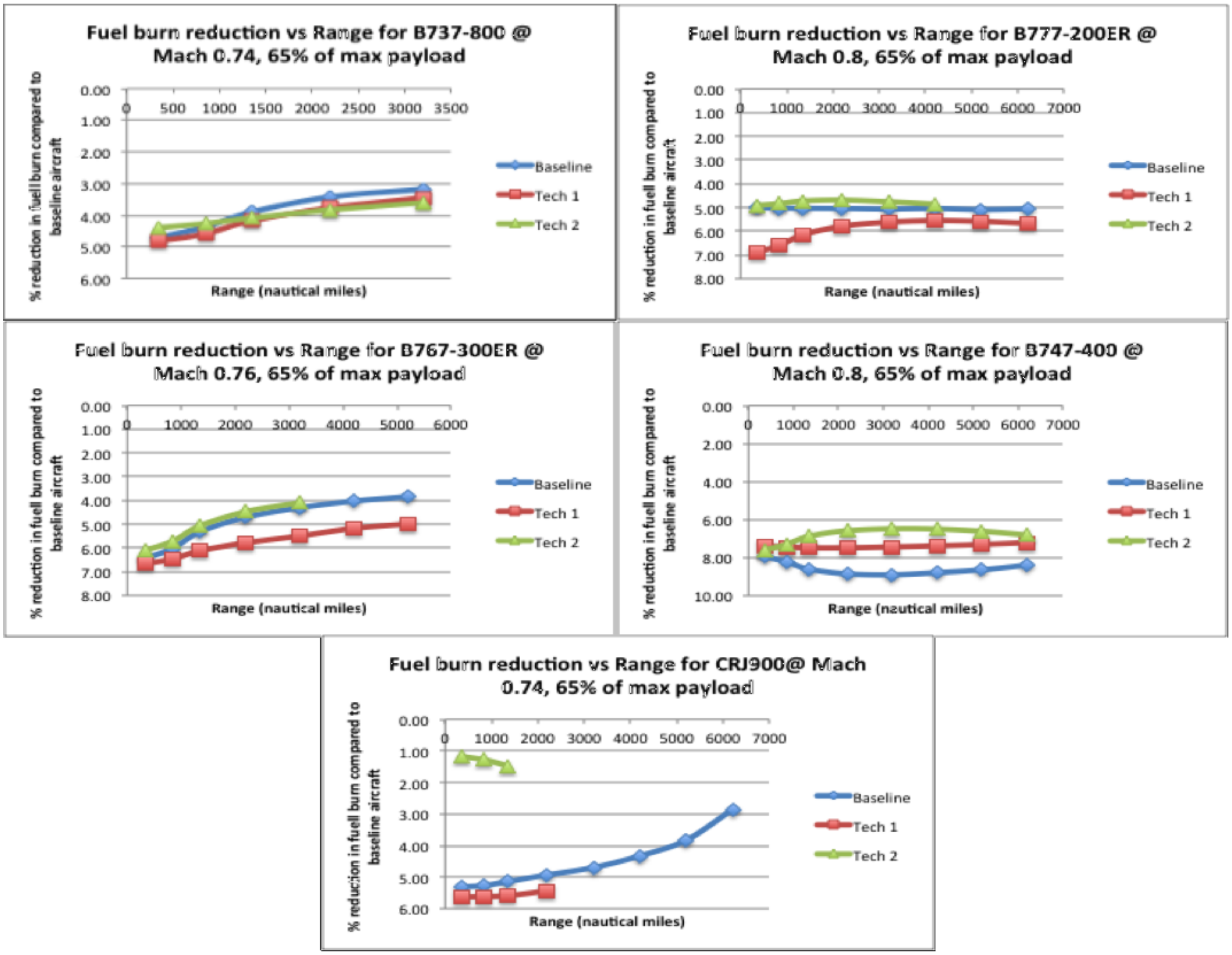


Figure 69: Off-Design Performance Comparison WRT Baselines

All of the results discussed in this section were compiled into the form of a series of improvement factors (multiplicative factors) that could be applied directly to the existing baseline aircraft models in GT's EDS and GREAT tools. Similar comments can be made about the FLEET tool used at Purdue. Using these performance factors for particular aircraft, flown distance, and payload, the actual fuel burn of the reduced cruise Mach number aircraft can be quantified. These fuel burn reductions can then be factored into the fleet-level calculations for the various scenarios.

Task #3: Fleet Level Aircraft Technology Benefits Assessment

Objective: Fleet Level Technology Assessment

The fleet and technology assumptions described in prior sections were assessed using the Georgia Tech GREAT and Purdue FLEET fleet level assessment tools. The following sections provide a brief description of the tools followed by major assumptions and a high level summary of results including comparisons between the two tools. The final subsection provides a detailed summary and analysis of each tool's respective output.

Fleet Analysis Tool Overviews

GREAT (Georgia Tech) Overview

The fleet level aircraft technology benefit assessment at Georgia Tech will be performed using the Global and Regional Environmental Aviation Tradeoff tool (GREAT) and the Airport Noise Interpolation Method (ANGIM), which was developed at Georgia Tech for the purpose of the FAA seeking to complement the AEDT with a lower fidelity screening tool capability that will allow for consideration of a large number of policy scenarios that could be quickly analyzed and reduced to a manageable set of scenarios for more focused, high fidelity analysis in AEDT. Georgia Tech has developed the GREAT tool, which provides a quick means of quantifying the impact of new technologies applied at the aircraft level to assess fleet-wide interdependencies on fuel burn and emissions. Noise and noise exposure are calculated through the ANGIM. Designed to assess the system-wide impacts resulting from the implementation of vehicle-level technology improvements, the GREAT tool synthesizes forecasted operational activity growth, fleet composition evolution, and aircraft-level performance estimates to project fleet-level fuel burn and emissions over time. With its efficient computational algorithm, GREAT can be executed in batch mode to explore multiple scenarios and produce visualizations that highlight the relative contributions of various subsets of the fleet. ANGIM was developed in parallel with GREAT to enable rapid calculation of airport-level DNL contours. By leveraging SAE-AIR-1845 standards to pre-calculate a repository of single-event aircraft grids, ANGIM efficiently pairs airport flight schedules and runway layouts to rapidly produce airport-level DNL decibel grids with runtimes on the order of seconds per airport. Users can plot any contour level desired and measure contour areas and shapes. Population exposure counts can be quickly estimated by overlaying these DNL grids on airport-level population grids derived from 2010 Census-block data using a proportional area-weighted scheme. Recent research efforts have paired ANGIM with GREAT's schedule forecasting to produce similar visualizations of changes in contour areas and population exposure over time. Both GREAT and ANGIM are designed to accept EDS project aircraft as inputs. Both tools maintain flexibility to accept aircraft designs from other vehicle-level design tools as well, provided they adhere to established standards such as those presented in SAE-AIR-1845 and BADA documentation.

FLEET (Purdue) 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 [20,21,22,23,24,25,26,27].

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:

- Representative-in-class aircraft are the most flown aircraft in 2005 (base year for FLEET)
- Best-in-class aircraft are the ones with most recent entry-in-service dates in 2005
- 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
- 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. These classes represent the mix of aircraft sizes in the airline fleet. For the representative- and best-in-class aircraft, the six FLEET aircraft classes are: 1) Small Regional Jet up to 50 seats (SRJ), 2) Regional Jet, 3) Small Single Aisle, 4) Large Single Aisle, 5) Small Twin Aisle, and 6) Large Twin Aisle. Then, to match the new aircraft models provided by the Georgia Tech team, FLEET uses five new- and future-in-class aircraft classes numbered from 2 to 6 and leaves class 1 empty, recognizing that there are currently (in 2016/2017) no orders for future 50-seat regional jets. The FLEET new- and future-in-class divisions are: 2) Regional Jet (RJ), 3) Single Aisle (SSA-LSA), 4) Small Twin Aisle (STA). 5) Large Twin Aisle (LTA), and 6) Very Large Aircraft (VLA).

FLEET uses a nonlinear relationship to evaluate the demand growth rate in different continents, which is based on the historical data of trips/capita vs. GDP/capita, as shown in **Figure 70**. In other words, if all the continents had the same GDP growth rate, the continents with higher GDP/capita would have a lower trips/capita growth rate.

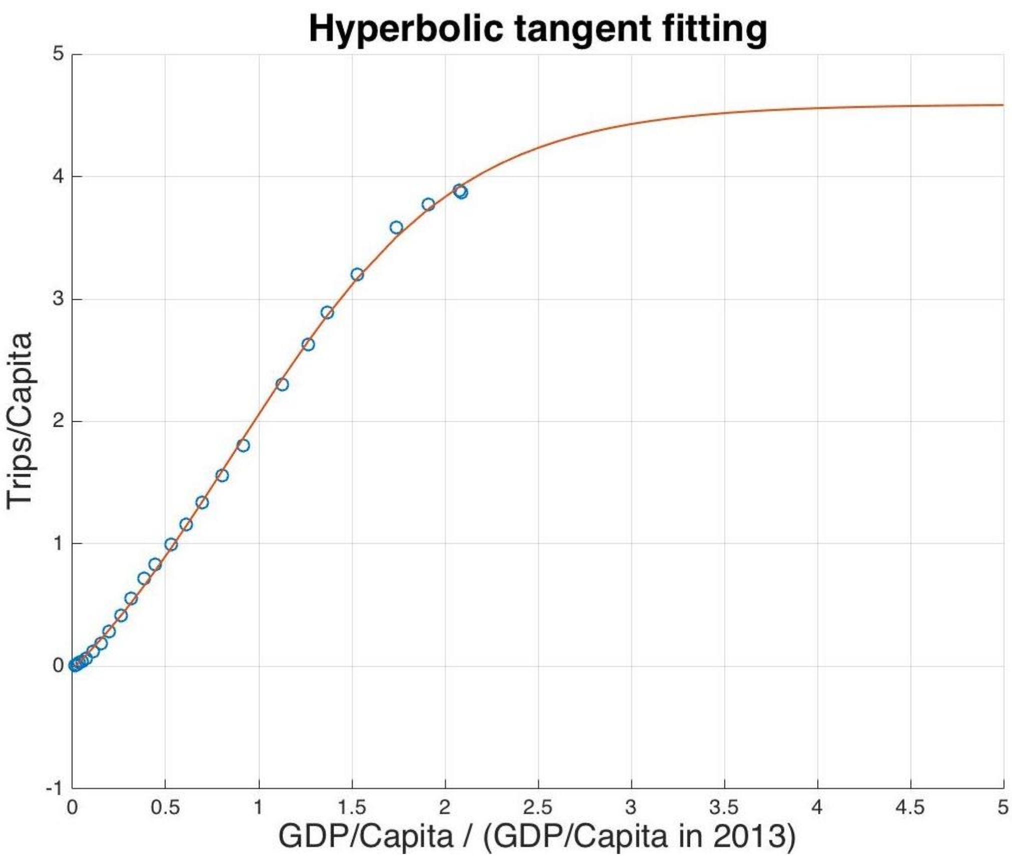


Figure 70: Curve Fitting of Historical Trips Per Capita as a Function of GDP Per Capita

The demand growth rate in each continent in year n can be represented as shown below.

$$Dem_G^n = \frac{f'(GDP_C^n)GDP_C^n}{f(GDP_C^n)} \times \frac{GDP_G^n - Pop_G^n}{Pop_G^n + 1} + Pop_G^n$$

Equation 3

Dem_G^n shows the demand growth rate in year n, while $f(GDP_C^n)$ and $f'(GDP_C^n)$ represent the curve-fitting function and its first derivative, respectively. GDP_c^n and GDP_G^n show GDP per capita and GDP growth rate, while Pop_G^n represent population growth rate. Finally, the model used the GDP and the population in each continent in 2005 from World Bank [28] as initial settings. And, according to the GDP growth rate and population growth rate historical data and predictions, it tracks the demand for each continent from 2005 to 2050 simulation year.

Modeling Assumptions

Since Georgia Tech's GREAT and Purdue's FLEET are different toolsets, the fleet scenarios described in Table 3 to Table 5 had to be interpreted in different ways to be compatible with each toolset. Each of the following subsections describes the Georgia Tech (GREAT) and Purdue (FLEET) approach.

GREAT (Georgia Tech)
Population Growth

One of the important underlying trends for aviation demand is the amount of people wanting to travel by air. This means that the population count is a fundamental underlying factor. As such the population growth given in percent per year was one of the important descriptors with settings from the workshops. **Figure 71** shows the US Census population forecast estimate, which was used a starting point for the time series to be matched to the scenario values.

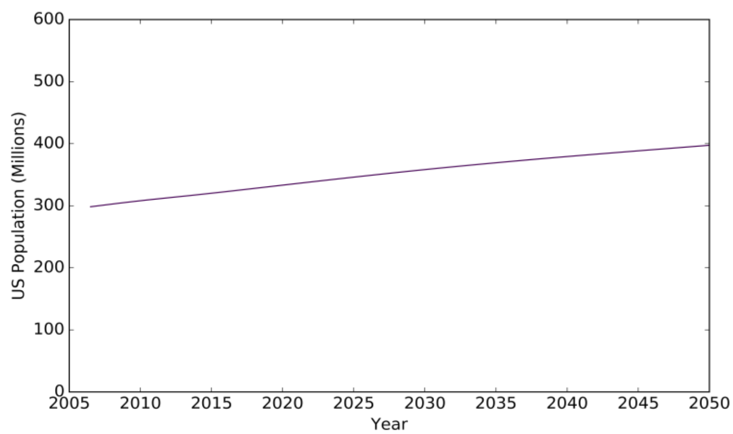


Figure 71: U.S. Population Growth [29]

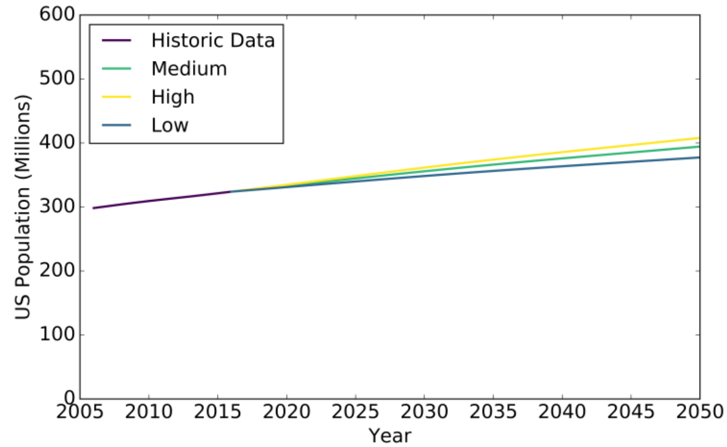


Figure 72: Population Growth Variation

The U.S. Census Bureau population projections, as shown in **Figure 71**, were used as a starting point and then scaled in order to match the values obtained from the workshops for the different scenarios. These range from 0.45 to 0.58 to 0.68 percent per year as the trend to 2050. The adjusted time series are shown in **Figure 72**.

GDP Growth

The next fundamental descriptor of important is the Gross Domestic Product (GDP). The workshop outcomes were defined GDP Growth rates again specified as an average percent per year to 2050. This similarly was applied to and underlying time series by scaling the average of the entire time period in order to achieve the selected values. The three target values in this case were 1.8, 2.8, and 4.0. The underlying time series is the data used by the FAA Aerospace Forecast, shown in Figure 73, which is based on macroeconomic projections by Global Insight [3]. The resulting time series for the low, medium, and high values are shown in Figure 74.

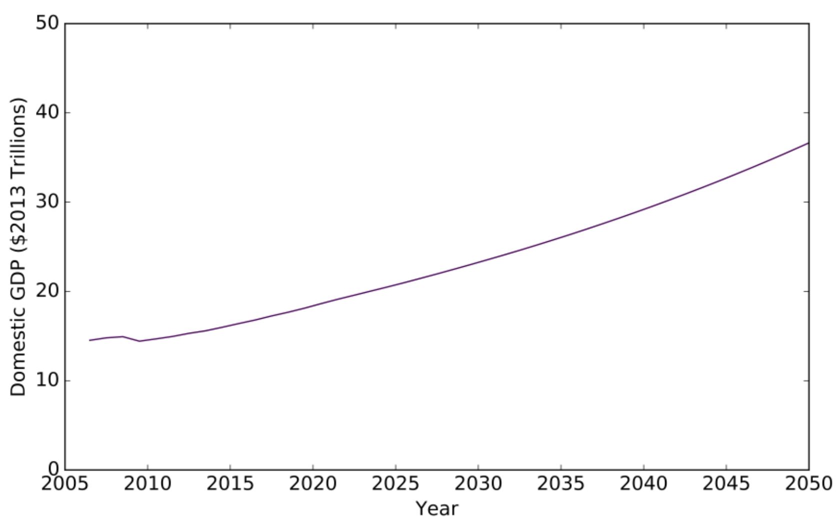


Figure 73: U.S. GDP from FAA Aerospace Forecast [3]

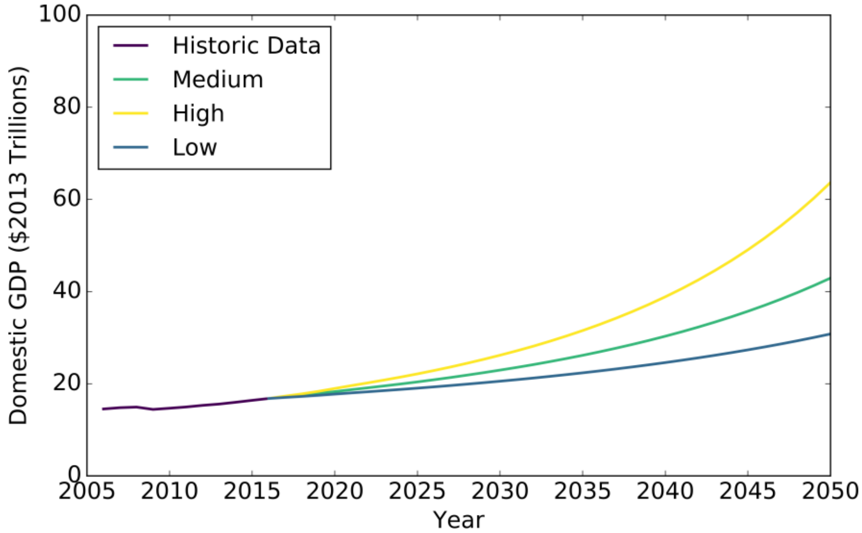


Figure 74: U.S. GDP Variation

The combined GDP and population time series were then combined to compute a GDP per capita time series. The result is a time series that can be used to predict passenger trips per year. The relation is shown in Figure 75.

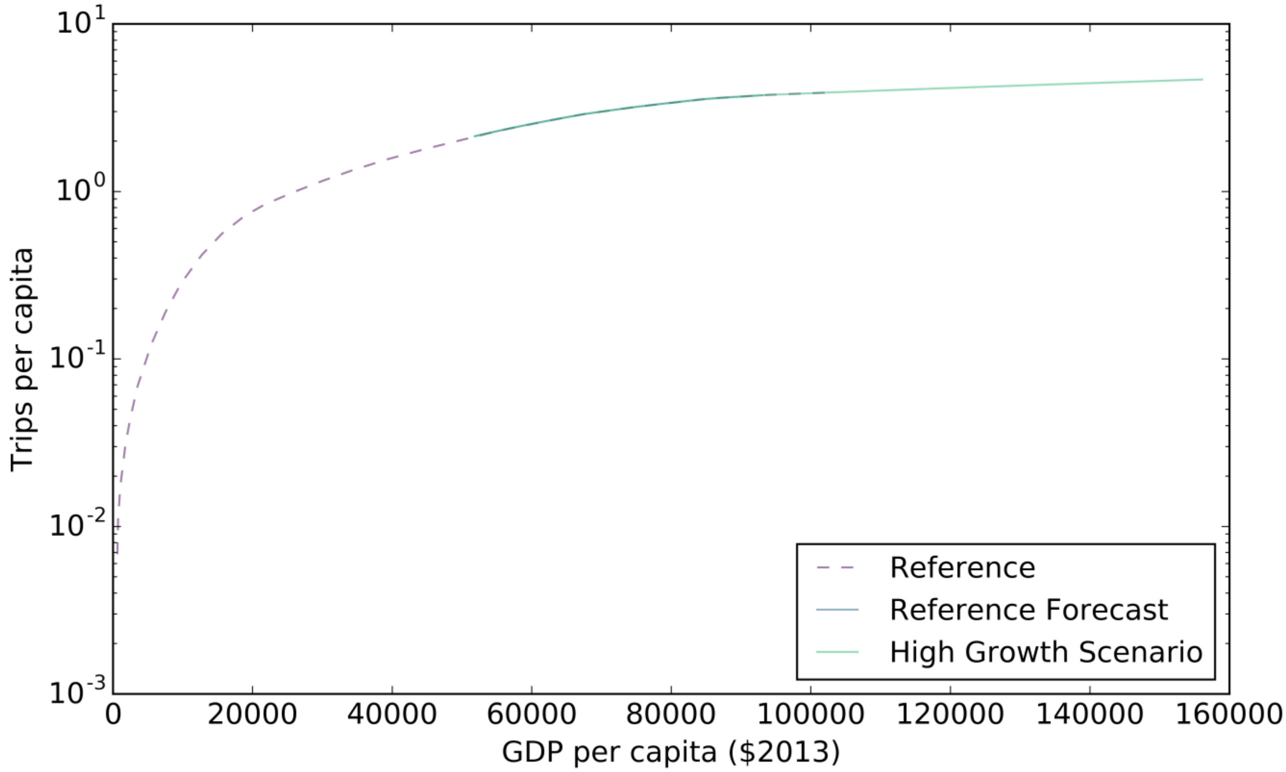


Figure 75: Relation of Trips per Capita per Year to GDP per Capital [29, 30]

The result of this can then be used to compute a scaled demand in revenue passenger miles (RPM) which is the demand input into the model.

International Trade

As a surrogate for international trade the workshops asked for the growth rate in foreign GDP, since changes in GDP in foreign countries can be an indicator of changes in international trade, assuming that the share of international trade for each country changes slowly compared to the absolute change in GDP. Therefore the descriptor that was selected to be most significant was GDP growth in Asia. The values ranged from 3.3, to 4.3, to 5.9 percent per year. These average values were again applied to the international GDP time series provided in the FAA Aerospace Forecast in order to scale these values to the selected value. Additionally, the team decided to also apply similar relative scale factors to the rest of the global GDP growth time series used in the FAA Aerospace Forecast, even though these descriptors were deemed to be of lesser importance by the workshop attendees.

Energy Price

The energy price as defined by the workshops was implemented as a shift of the FAA Aerospace Forecast's jet fuel price time series. Since the workshop results were given in dollars per barrel of oil in 2050, the FAA Aerospace Forecast's refiner's acquisition cost was scaled appropriately. In order to then arrive at a jet fuel price, it is appropriate to look at the ratio of the jet fuel price to the refiner's acquisition cost of oil. This factor, which is known as crack spread, in a competitive environment should be relatively stable. An analysis of various forecasts and historical price data has shown this to be on the order of 1.2, that is that refineries will charge an approximately 20% markup for equal volumes of jet fuel as compared to unrefined oil. This includes many production related efficiencies as well as revenues of other petroleum products as well as any profit that the market might allow. Therefore, after scaling the refiner's acquisition cost, the resulting jet fuel price is simply scaled by the crack spread to arrive at the future jet fuel price.

Industry Competitiveness

The industry competitiveness was chosen by the workshop participants as a significant descriptor. This descriptor is implemented as a simple value of non-fuel direct operating cost. This will influence the potential ticket price that airline customers would see and therefore shift the demand and supply balance. However, this value was constant for all scenarios.

Airport Noise Limitations

The airport noise limitations were implemented as a reduction factor on the number of allowable aircraft operations. This factor was determined by running the model entirely unconstrained and obtaining the contour area in the base year and for out years of the pertinent aircraft technology insertion scenarios. Once this was obtained, the out year contour areas if they were found to be larger than the base year contour area were used to scale the allowable operations in those out years.

Cost of CO_2 Emissions

The potential cost of CO_2 emissions could manifest itself in a number of ways, depending on the actual implementation of any charging, offsetting, or market scheme. Since the details of any implementation are unknown or uncertain, this cost was implemented as an additional cost to the airline, which acts similar to an implied increase in the price of jet fuel. The unit conversion from metric ton CO_2 to gallon of jet fuel brings each dollar per metric ton CO_2 into roughly the range of a cent increase in jet fuel price per gallon. The values from the workshops were simply used to define a time series ending in 2050 with the specified values. This was implemented as a linear increase to those values starting in 2020.

Fleet Evolution Schedule

The schedule of when new technology aircraft would become available through EIS was defined with the following tables. Depending on the scenario either a single aisle first or twin-aisle first schedule was used. The difference being whether a new design aircraft past 2020 would be focused either on a single aisle size or twin-aisle size aircraft. This means that depending on the scenario the difference becomes what technologies on new aircraft are introduced into actual use depending on the size class of the aircraft.

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
TP						◆					○					◆					○					○					◆					
						Re-Engine					PIP					New Design					PIP					PIP					New Design					
RJ						◆					○					◆					○					○					◆					
						Re-Engine					PIP					New Design					PIP					PIP					New Design					
SSA/LSA	◆		◆				○				○					◆					○					○					◆					
	A320NEO/B737MAX						PIP				PIP					New Design					PIP					PIP					New Design					
STA				○			○				◆					○					○					◆					○					
				PIP			PIP				Re-Engine					PIP					PIP					New Design					PIP					
LTA			◆			◆					○					○					◆					○					○					
			A350-1000			777X					PIP					PIP				New Design						PIP					PIP					
VLA				○			○				◆					○					○					◆					○					
				PIP			PIP				Re-Engine					PIP					PIP					New Design					PIP					
							◆	First Delivery					○	Performance Improvement Package													Program launch to EIS									

Figure 76: Single Aisle First Schedule

Aircraft Retirement

The aircraft retirement curves which effectively prescribe what percent or original aircraft sold in a given year are still in operation when they reach a certain age. This analysis uses a nominal (medium) curve that is a clamped sigmoid function with a 50% point of about 30 years, which means that after 30 years only 50% or aircraft originally sold in the same year remain in service. This is based on fleet inventory analysis and represents a rough average of aircraft useful service life in the past decades. The scenario setting of "Early" (Low) corresponds to a curve with a midpoint of 10 years, which is a very aggressive fleet turn over assumption. Conversely, the setting of "Late" (High) corresponds to a curve with a midpoint of 40 years, which would represent an extension of the lifetime compared to historical trends. The specific values are shown in **Figure 77**.

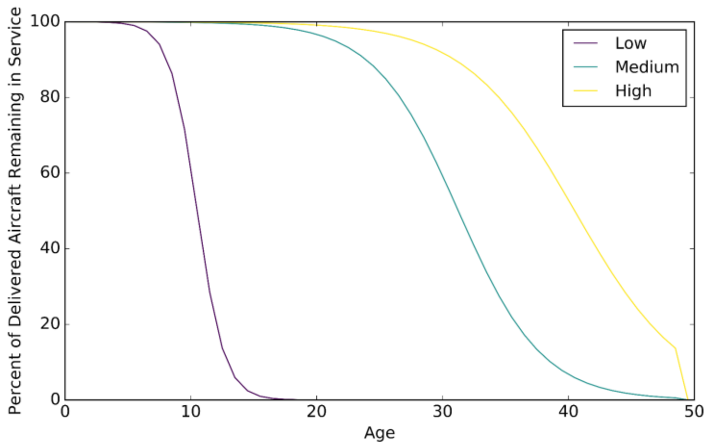


Figure 77: Aircraft Retirement Curves

Production Capacity
Scenarios with production capacity limits were run with a cap imposed on the number of new aircraft being allowed to enter service in a given year. This has the effect of reducing demand somewhat. However, in high or very high demand scenarios this effect is overshadowed by the noise limits that might be increased.

Aircraft Technology
All aircraft technology factors, as defined in the scenarios, are modeled at the vehicle level. In the fleet analysis these factors are represented by different vehicles that are included in the entry into service slots shown in Figure 76.

FLEET (Purdue)

Description of Inherent Demand Model
The market demand model in FLEET is driven by economic growth in each continent and tries to represent two assumptions. First, a higher income per capita results in higher market demand and, second, there is an upper bound for number of trips per person because everyone has only 24 hours per day.

Based on the historical data from Airbus Company, which include trips per capita and GDP per capita in several countries, the model used hyperbolic tangent function to fit the historical data because of two reasons. The hyperbolic tangent function is analytic, and it asymptotically approaches an upper bound.

Description of Exercised Scenario Setups
Purdue ran FLEET with fourteen scenarios that were identified together with the ASCENT 10 Project team and grouped into five categories. This activity also serves to identify enhancements necessary in FLEET to accommodate simulation of all the scenarios examined under ASCENT-10. The fourteen scenarios in five groups examined are:

- Current Trend Economic Environment
  - Current Trends "Best Guess"
  - Current Trends Frozen Technology
  - Current Trends High and High Research and Development
- High Research and Development (R&D)
  - Low Demand and High R&D
  - Current Trends High and High R&D
  - High Demand and High R&D
  - Very High Demand and High R&D with Noise Limits
- High Research and Development with Mission Specification Change (MSC)

Low Demand and High R&D with MSC
High Demand and High R&D with MSC
Current Trends High and High R&D with MSC
Very High Demand and High R&D with Noise Limits with MSC
Low Research and Development
Low Demand and Low R&D
High Demand and Low R&D
Very High Demand and Low R&D with Noise Limits
Environmental "Bounds"
Environmental "Bounds" – Low
Environmental "Bounds" – High

The "Current Trend Frozen Technology" scenario setup in FLEET is defined as follows:

- A network of 169 airports including U.S. domestic routes and international routes that have either their origin or destination in the U.S.
- The annual gross domestic product (GDP) grows at a constant value of 4.3% in Asia, 4.2% in Latin America, 2.4% in Europe, and 2.8% for airports in the United States.
- The annual population growth rate at a constant value of 1.1% in Asia, 1.26% in Latin America, 0% in Europe, and 0.58% for the United States.
- Jet fuel prices grow according to the Energy Information Administration (EIA) reference fuel price [29] case and adjusted it to meet the ASCENT survey fuel price, $77.08/bbl, by 2050.
- Carbon emission prices grow linearly from $0/MT in 2020 to $21/MT by 2050.
- Only the Representative-In-Class and Best-in-Class aircraft from **Table 12** are included in the simulation. No New-in-Class or Future-in-Class aircraft are included in this scenario; when the airline needs a new aircraft due to retirement or fleet growth, it acquires an aircraft with the same characteristics as the Best-in-Class aircraft until 2050.

Table 12 shows the various aircraft used in the FLEET simulations. These appear in rows according to the FLEET aircraft class, with the corresponding aircraft labels and, for the new- and future-in-class aircraft, the EIS date used in the study. In Table 12 the aircraft labeled with "GT Gen1 DD" are the Generation 1 aircraft modeled by Georgia Tech with a 'Direct Drive' engine. The Generation 2 aircraft are labeled as "GT Gen2 DD". These include aircraft that belong to the following classes - regional jet (RJ), single aisle (SSA-LSA), small twin aisle (STA), large twin aisle (LTA), and very large aircraft (VLA). Based on the amount and speed of technology incorporated into aircraft, in each of the scenarios, the New-in-Class and Best-in-Class aircraft models will vary. Given the observation that new orders for 50-seat aircraft have diminished to zero, there are no small regional jet (SRJ) aircraft in the new- and future-in-class technology ages.

Table 12: 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 [SRJ]	Embraer ERJ145 [SRJ]		
Class 2	Canadair RJ700 [RJ]	Canadair RJ900 [RJ]	GT Gen1 DD RJ (2020)	GT Gen2 DD RJ (2030)
Class 3	Boeing 737-300 [SSA]	Boeing 737-700 [SSA]	GT Gen1 DD SSA-LSA (2017)	GT Gen2 DD SSA-LSA (2035)
Class 4	Boeing 757-200 [LSA]	Boeing 737-800 [LTA]	GT Gen1 DD STA (2025)	GT Gen2 DD STA (2040)
Class 5	Boeing 767-300ER [STA]	Airbus A330-200 [STA]	GT Gen1 DD LTA (2020)	GT Gen2 DD LTA (2030)
Class 6	Boeing 747-400 [LTA]	Boeing 777-200LR [LTA]	GT Gen1 DD VLA (2025)	GT Gen2 DD VLA (2040)

The ‘Current Trends “Best Guess”’ and ‘Current Trends and High R&D’ scenarios, in addition to the ‘Current Trends Frozen Technology’ scenario setup also incorporate the New-in-Class and Future-in-Class aircraft into their fleet mix. The High R&D case has higher speed and amount of technology investments accounted for in their aircraft development than the Best Guess case.

The ‘High Demand and High R&D’ and ‘High Demand and Low R&D’ scenarios assume a constant annual GDP growth rate of 5.9% for in Asia, 5.3% for in Latin America, 4.2% for in Europe, and 4.0% for in America. Routes in the FLEET network serving cities in these regions see their inherent demand grow based upon these higher than baseline assumed GDP growth rates. The low R&D case represents a slower rate of change and amount of investments in technology than the Best Guess case.

The ‘Low Demand and High R&D’ and ‘Low Demand and Low R&D’ scenarios use a constant annual GDP growth rate of 3.3% in Asia, 2.7% in Latin America, 0.6% in Europe, and 1.8% in the United States. This leads to lower-than-baseline demand growth.

The ‘Very High Demand and High R&D with Noise Limits’ and ‘Very High Demand and Low R&D with Noise Limits’ scenarios have the same GDP growth rate setting as ‘High Demand’ scenarios. But, the fuel prices grow according to the EIA reference fuel price case with a slight adjustment so that the fuel price in 2050 meets the fuel price corresponding to the $41.00/bbl price indicated by the ASCENT survey respondents. These two scenarios do not include carbon emission prices. For these two scenarios, the fleet-level noise area constraint is initiated after 2020. The limitation on the total noise area (based upon the sum of the 65 dB DNL contour area estimates for all U.S. airports in the FLEET network) decreases from no limit in 2020 to 50% of the 2005 total noise area level by 2050. Then, the high R&D and low R&D cases account for the rate of change and amount of investments in technology. **Figure 77** shows the three sets of the adjusted fuel prices based on the EIS reference fuel price scenario and the matching of the ASCENT survey respondents’ estimates of 2050 prices.

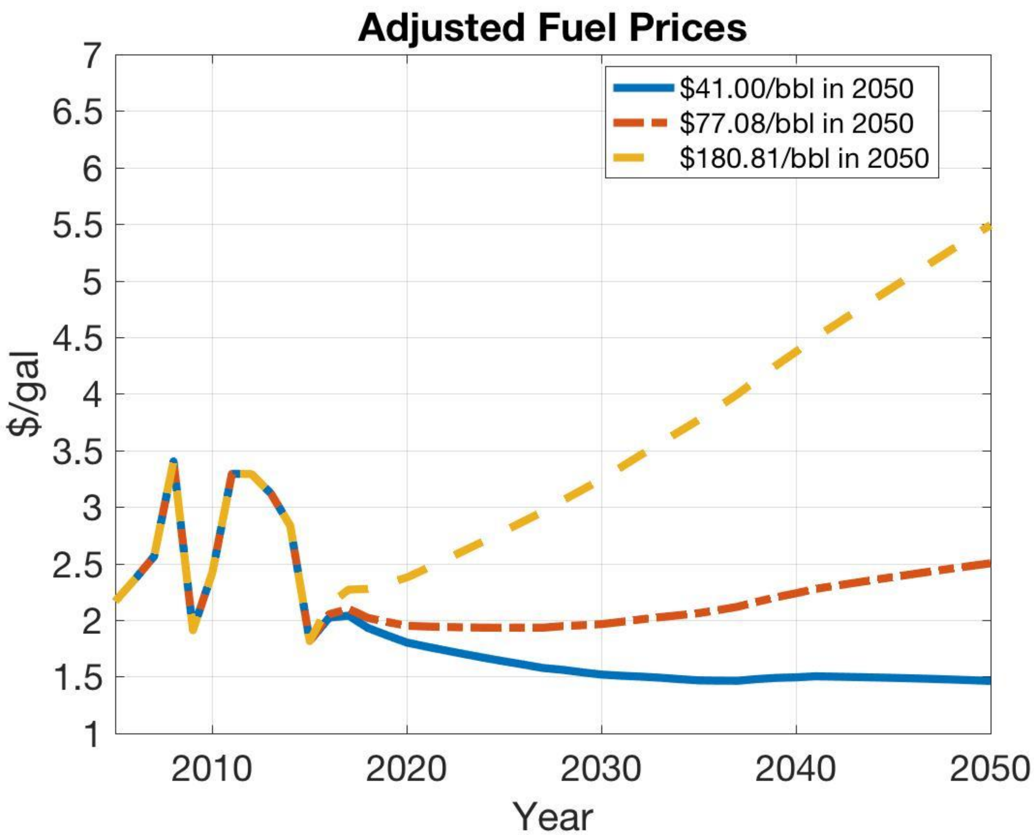


Figure 77: Adjusted Fuel Prices

The ‘Mission Specification Change’ scenarios assess the environmental impacts of aircraft whose mission profile use slower cruise speed than current aircraft; the Task #2 section above describes the modeling of these aircraft. FLEET captures both the reduced fuel consumption of these aircraft and the impact that the slower-cruising aircraft might have on utilization of these aircraft. These scenarios in the ‘MSC’ group have the same economic environment and technology development setting as the ones in the ‘High R&D’ group.

The ‘Environmental “Bounds” – High’ scenario has the same GDP growth rate, fuel price growth, carbon emission price profile, and aircraft technology improvement rate settings as ‘Very High Demand and High R&D with Noise Limits’ scenario, but, this ‘Environmental “Bounds” – High’ scenario has no noise limitations. This scenario seeks to investigate what might occur to lead to a high impact of aviation on the environment.

The ‘Environmental “Bounds” – Low’ scenario has the same GDP growth rate, carbon emission price profile, and aircraft technology improvement rate settings as ‘Low Demand and High R&D’ scenario. The fuel prices are adjusted to meet ASCENT survey fuel price, $180.81/bbl, by 2050. The ‘Environmental “Bounds” – Low’ scenario also initiates the noise constraint to limit total 65dB noise contour area. This scenario seeks to investigate what might occur to lead to a low impact of aviation on the environment.

Description of High R&D Aircraft Models

In the case of the high R&D aircraft models, FLEET allocated the single aisle aircraft (Class 3) on some trans-Atlantic routes, even though the design range was only 2960 nmi. This prompted questions regarding the correct implementation of the FLOPS aircraft models in the scenarios and the implication of using a prescribed load factor when describing the operating missions of the aircraft. The results for the Class 3 aircraft are most striking, but other aircraft classes demonstrate similar behavior under the high R&D assumptions.

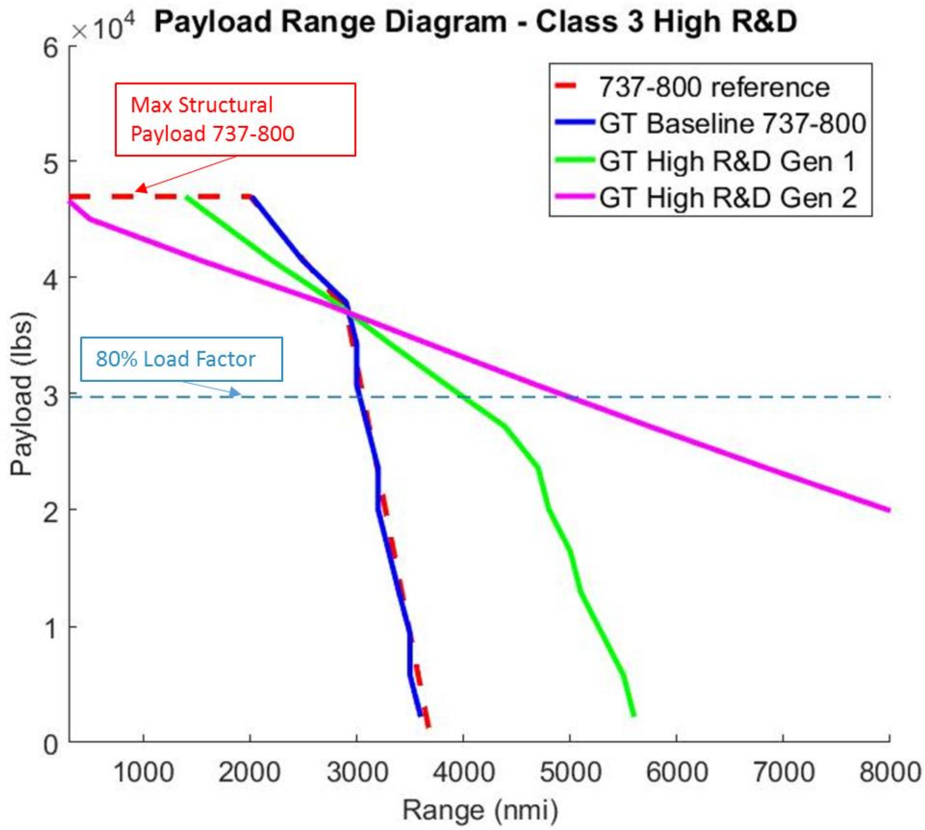


Figure 78: Payload Range Diagram for High R&D Class 3 Aircraft

Figure 78 depicts the payload range diagrams for the three different technology ages of Class 3 aircraft used in FLEET. With the operating mission defined so that the aircraft carries 80% of the passenger load factor, these Class 3 aircraft can operate at a maximum range of 3028 nmi, 3999 nmi, and 4991 nmi, in order of increasing technology age. The reason for the slope change in the payload range diagram for the GT High R&D Gen 1 and GT High R&D Gen 2 aircraft compared to the baseline aircraft has to do with the combination of improved technology and constant fuel volume limit. In the case of the GT High R&D Gen 2 aircraft model, the fuel volume limit is not reached even at an operating range of 8000 nmi because the fuel efficiency of this aircraft is very good. The non-smooth line segments associated with the fuel volume limit are an artifact of the iterative approach with a fairly large tolerance used to determine the range values quickly. Other aircraft classes with this technology level showed similar behavior in aircraft performance.

Based on preliminary studies into limiting the routes for these high R&D aircraft models to their design range, or the maximum range at 80% load factor, the ASCENT-10 project team chose the option where high R&D aircraft were allowed to fly routes limited to the maximum operating range at 80 % load factor. This allowed these 150-seat single aisle aircraft (with High R&D) to operate on several trans-Atlantic routes, which increases the airline profit in the FLEET model. The team feels this has some recent precedents for this with some airlines currently offering trans-Atlantic flights on this class of aircraft with greatly reduced seating capacity.

Description of Noise Constraint Implementation

This section describes how Purdue developed the noise model for FLEET and incorporated the total noise area metric as a constraint for noise-limited scenarios. The constraints setup in FLEET allocation are linear equations in terms of $x_{k,j}$, where $x_{k,j}$ is the number of roundtrips of an aircraft type k on a route j. Purdue used a linear equation in terms of $x_{k,j}$ to approximate the noise at each airport. The calculated approximate noise area at each airport is determined from the equation below.

$$Area_i = \sum_{k=1}^{24}\left[\begin{Bmatrix}\left(\left(P_k \cdot \delta_i^{TO} + Q_k \cdot \left(1-\delta_i^{TO}\right)\right) \cdot \left(NEE_k^{TO} \cdot x_{k,i}^{TO}\right) + \cdots\right. \\ \left(P_k \cdot \delta_i^{arr} + Q_k \cdot (1-\delta_i^{arr})\right) \cdot \left(NEE_k^{arr} \cdot x_{k,i}^{arr}\right)\end{Bmatrix}\right] \cdot \frac{1}{10000}$$

Equation 4

where *NEE* is the Noise Energy Equivalent (NEE=$10^{(EPNL/10)-7}$), $x_{k,i}$ is the number of roundtrips by aircraft k at airport index I, *P* is the daytime passenger aircraft regression coefficient, *Q* is the night time passenger aircraft regression coefficient and δ is the day ratio at that airport [30].

FLEET uses the total noise area metric, which is a sum total of the noise areas across all the noise-limited airports in the FLEET network, as a constraint to limit the number of flight operations across all of the noise-limited airports. Because of the manner in which FLEET represents all U.S. domestic flights and all international flights with origin or destination in the U.S., FLEET represents all operations at the U.S. airports and only some of the operations at international airports in the airline network, so only the noise-limited airports are included in this constraint. The noise constraint is given by

$$\sum_{\substack{i\epsilon\, noise-limited \\ airports}} (noise\ area_{2050})_i \leq \Lambda \cdot \sum_{\substack{i\epsilon\, noise-limited \\ airports}} (noise\ area_{2005})_i$$

Equation 5

where Λ is a global FLEET parameter that specifies the limit on the noise area. For scenarios that are noise-limited, the constraint is initiated in the year 2020. The limit on the total noise area decreases linearly from the year 2020 so that in the year 2050, the total noise area across all the noise-limited airports is Λ times that of the total noise area across all the noise-limited airports in 2005.

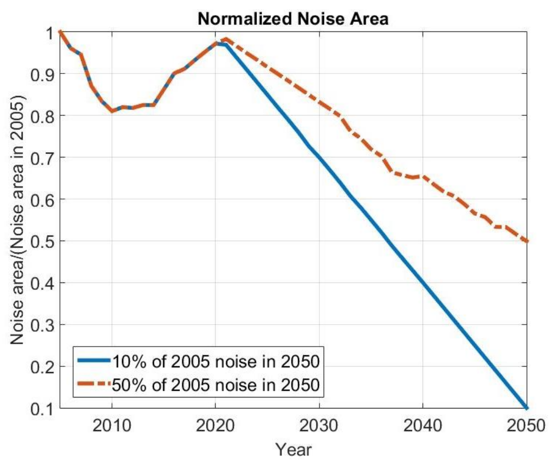


Figure 79: Normalized Noise Area in a Noise-Limited Scenario

Figure 79 shows the evolution of the normalized total noise area across all the noise-limited airports for two cases:

Case 1: Total noise area in the year 2050 is 10 % of the total noise area in 2005.
Case 2: Total noise area in the year 2050 is 50 % of the total noise area in 2005.

As can be seen in Figure 79 the noise constraint is initiated in the year 2020. In case 1, the noise constraint is active all through the simulation for that particular scenario; this is a very noise-restrictive constraint. In order to meet this noise constraint, there is a significant decrease in the demand satisfied over the course of the simulation timeframe

In case 2, the noise constraint is active till 2032 and then resumes being active in 2048. This indicates that the introduction of newer aircraft, which are lighter and use smaller engines leading to lower noise levels, is enough between 2032 and 2048 to have a cumulative noise area lower than the imposed limitations for case 2.

Description of Relief Crew Adjustments

This section describes how Purdue accounted for relief crew members on long haul flights. The Title 14 Code of Federal Regulations (CFR) Part 117 – FLIGHT AND DUTY LIMITATIONS AND REST REQUIREMENTS: FLIGHTCREW MEMBERS (EFF. 1-4-14) [31] determined the number of relief flight crew members required on each flight. FLEET aircraft models have two flight crew members for flights that are eight hours or less, three flight crew members (1 relief flight crew member) for flights over eight hours but less than 13 hours and a flight crew of four members (2 relief crew members) on a flight up to 17 hours. The block time of a particular flight leg alone, determined the number of relief crew members required on the flight leg. In the case of cabin crew members, the following factors affected the number of relief cabin crew members:

- Block time of the flight leg,
- Whether the flight was a domestic or an international flight,
- Number of passenger seats and their split across the different cabin classes.

Based on Title 14 CFR Part 121.467 - Flight attendant duty period limitations and rest requirements: Domestic, flag, and supplemental operations [32], cabin crew members across international and domestic flights were limited to a scheduled duty period of 14 hours per calendar day. For simplicity, each relief crew member was assumed to weigh 200 lbm (to reflect crew member plus their baggage). The relief flight crew was accounted for in the direct operating costs and the relief cabin crew was accounted for in the indirect operating costs.

Modeling Mission Specification Change Scenarios in FLEET

This section describes how Purdue modeled the scenarios that included mission specification changes. The scenarios adjusted for mission specification changes were implemented by adjusting data for the FLOPS aircraft models initialized in FLEET, with block hour and fuel consumption changes based on six different operational ranges provided by Stanford. Upon receiving the percentage change in fuel and block hours between the baseline aircraft and the reduced cruise Mach number aircraft models generated by Stanford's SUAVE tool as described in the Task #2 section. the Purdue team utilized the data to adjust the baseline aircraft model in FLOPS. First, the data from Stanford was curve-fit to facilitate the mapping of the changes in block hours and fuel consumption to the payload-range data tables for the aircraft models in FLOPS. Then, the block hour and fuel consumption data for the feasible segments in the payload-range tables, representing each FLEET baseline aircraft modeled in FLOPS, were adjusted using the factors obtained from the data curve-fit. Next, the adjusted FLOPS block hour table was compared with the original baseline block hour table, and segments in the payload-range tables where the block hours exceeded certain thresholds for relief crew (flight and cabin crew) duty periods were adjusted to accommodate for increased flight and cabin crew per the relevant CFRs. Lastly, FLOPS was re-run to obtain updated payload-range data tables based on the aforementioned adjustments, which represented the aircraft models initialized in FLEET runs for the mission specification change scenarios.

Summary and Comparison of Fleet Benefits Assessment

This section presents combined results from GREAT (Georgia Tech) and FLEET (Purdue) runs for the scenarios defined in Table 3 through Table 5. Focus is placed on macro trends and drivers across the scenarios, namely technology level and demand. Here, it is important to remember that a "high" level of technology assumes a combination of increased technology impact to vehicle performance and rapid introduction of technologies to new vehicles. A "low" technology level assumes both a delayed introduction of new technology and low impact. "Nominal" technology is intended to represent a continuation of current technology trends. In the two following subsections, results from multiple GREAT and FLEET scenarios are combined onto single plots to examine the high level effects of demand and technology on fleet noise and CO_2. All scenarios present noise and fuel burn in the context of U.S. touching operations. More detailed discussions are provided for the GREAT runs and FLEET runs in the following sections.

Fuel Burn and CO_2 Impacts

The first combined result plot, shown in Figure 80, shows the variation in direct CO_2 emissions across both fleet tools and all defined scenarios. Quantile plots are used which show the spread in CO_2 relative to 2005 that is present across all of the scenarios. For example, in 2030, the minimum predicted relative CO_2 is about 60% of 2005 levels for one scenario and as high as 185% of 2005 levels for the worst case scenario. Most of the scenarios predict somewhere between 100% (the same) of 2005 levels and an increase to 140% of 2005. Since there are 12 scenarios with widely varying assumptions, one expects significant variation in the results.

Examining further out years, it appears less likely that direct CO_2 emissions can be held to 2005 levels. To restate, only the direct CO_2 emissions were considered in this study. The impact of alternative fuels would change the results shown proportional to the respective fuels life-cycle impact. Reductions below current CO_2 levels are unlikely until 2035, and in many of the scenarios, the 2050 relative CO_2 level exceeds the 2005 level. Less obvious, but worth noting is the small bump between 2020 and 2030 for the -25%/+75% quantile points. This bump is indicative of the time it takes for new technology to enter the fleet and lower CO_2. Even with new aircraft available immediately, it takes time for older, less efficient aircraft to be retired.

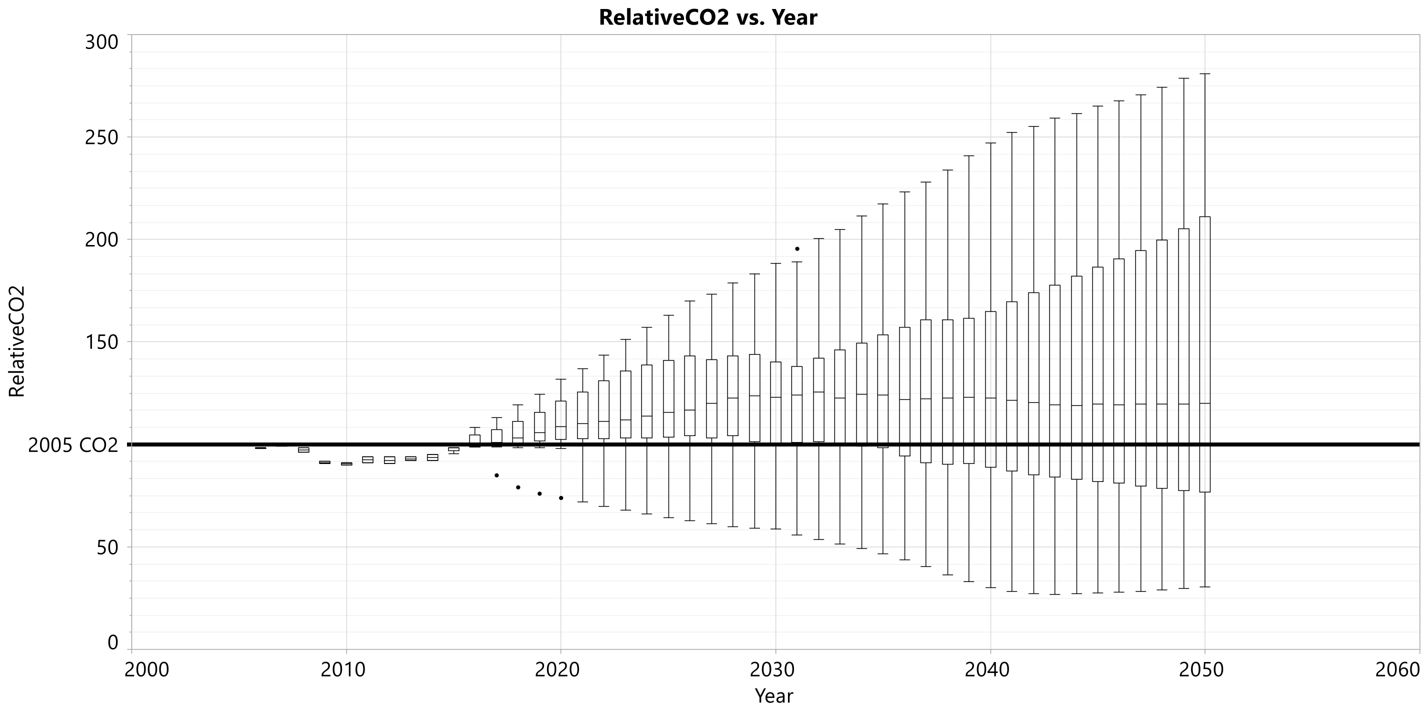


Figure 80: Direct CO_2 Emissions Variation Across All Scenarios

The results shown in Figure 80 can be further decomposed into the major drivers of technology and demand, shown in Figure 81 and Figure 82, respectively. In Figure 81 the variation is due to differences in technology and in Figure 82 the variation is due to variation in demand. The dots that appear in the high technology level scenario are a plotting anomaly due to their large difference from the average trajectory. From the technology level decomposition, it is clear that high technology impacts and rapid insertion are critical to achieving carbon neutral growth. This is true regardless of demand level, which is one of the primary causes of the wide range of outcomes. This is partly by design however, since the scenarios created here were on purpose chosen to show the possible range of outcomes. Breaking down direct CO_2CO_2 emissions by demand shows that low or nominal demand is required to achieve carbon neutral growth for every year between now and 2050. The "very high" demand case in Figure 82 also assumes that operations would be constrained by airport noise. The assumptions were made in GREAT to keep airport noise equal to or less than 2010 contour area and in FLEET to have the contour area at 50% of the 2010 contour area. This shows that high demand may also have an adverse impact on noise contour area, to be further explored later.

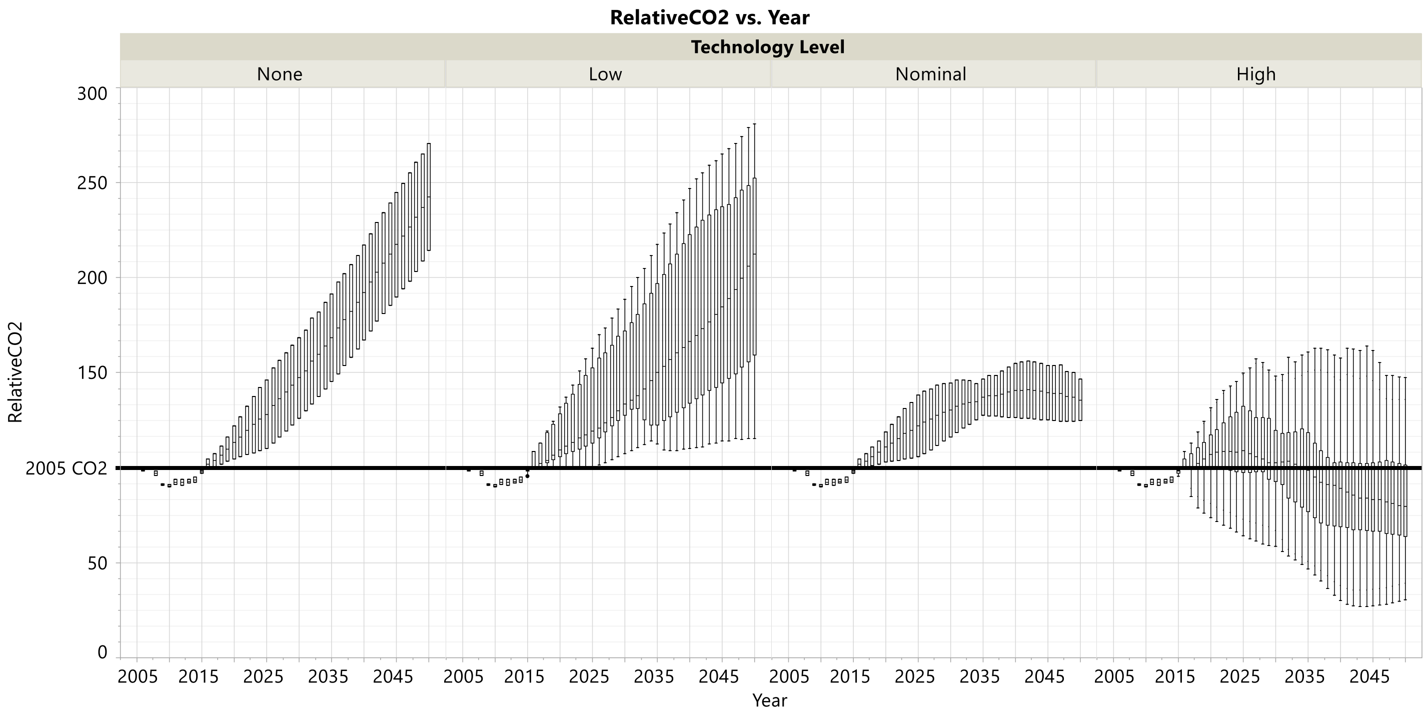


Figure 81: Direct CO_2 Emissions Variation across All Scenarios as Function of Technology Level

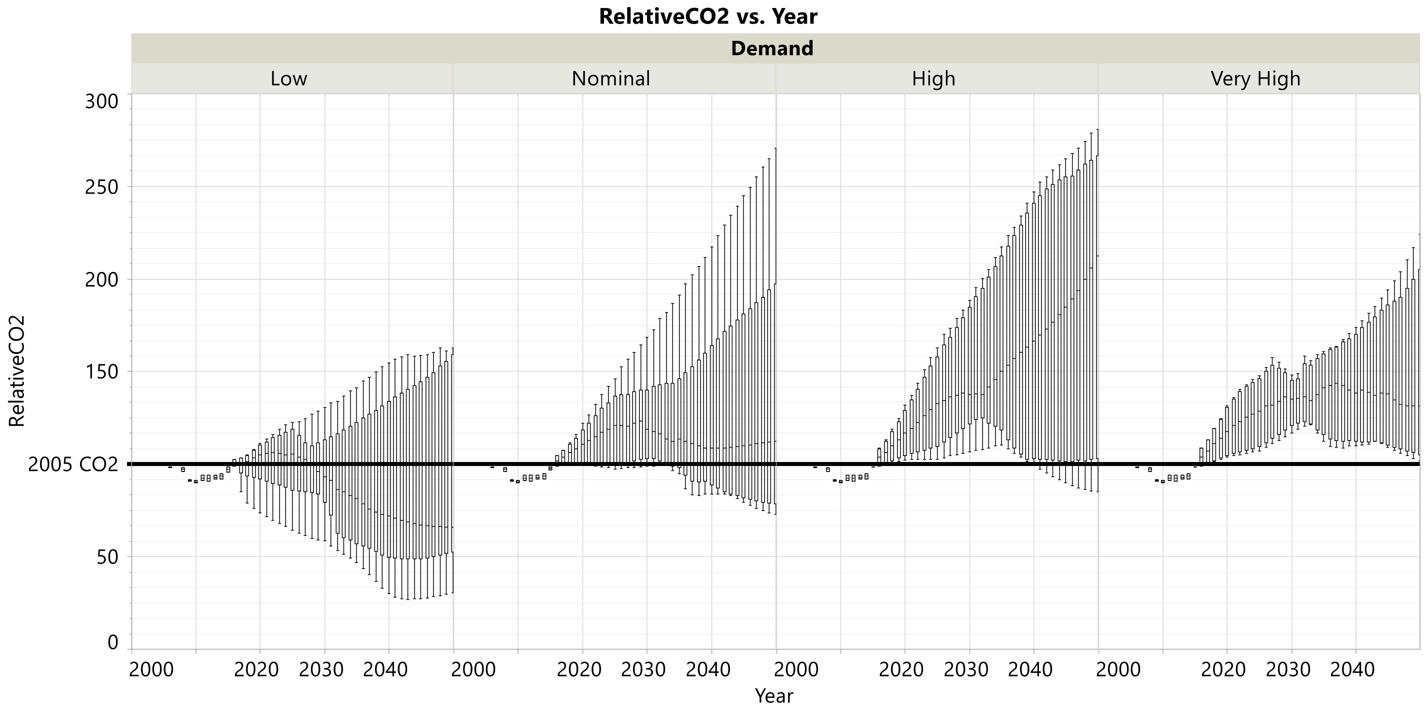


Figure 82: Direct CO2 Emissions Variation Across All Scenarios as Function of Demand

Since future demand is such a large driver of direct CO_2 emissions, it is worth examining the relative predicted operations vs. year, shown in Figure 83. Based on the scenario drivers, demand is expected to increase between 2 and 4 times current operations by 2050. Much is this is driven by an assumption of strong Asian market growth. Even though initially international travel to Asia is not a significant portion of the overall demand, the quite high growth rates become even larger in the high growth in Asia. Additionally, all international travel demand was linked to the scenario assumptions for growth in Asia. This assumption was agreed upon for consistency. Therefore, high demand growth rates for all international demand sustained over several decades then serve to this becoming the dominant factor in future demand for air travel.

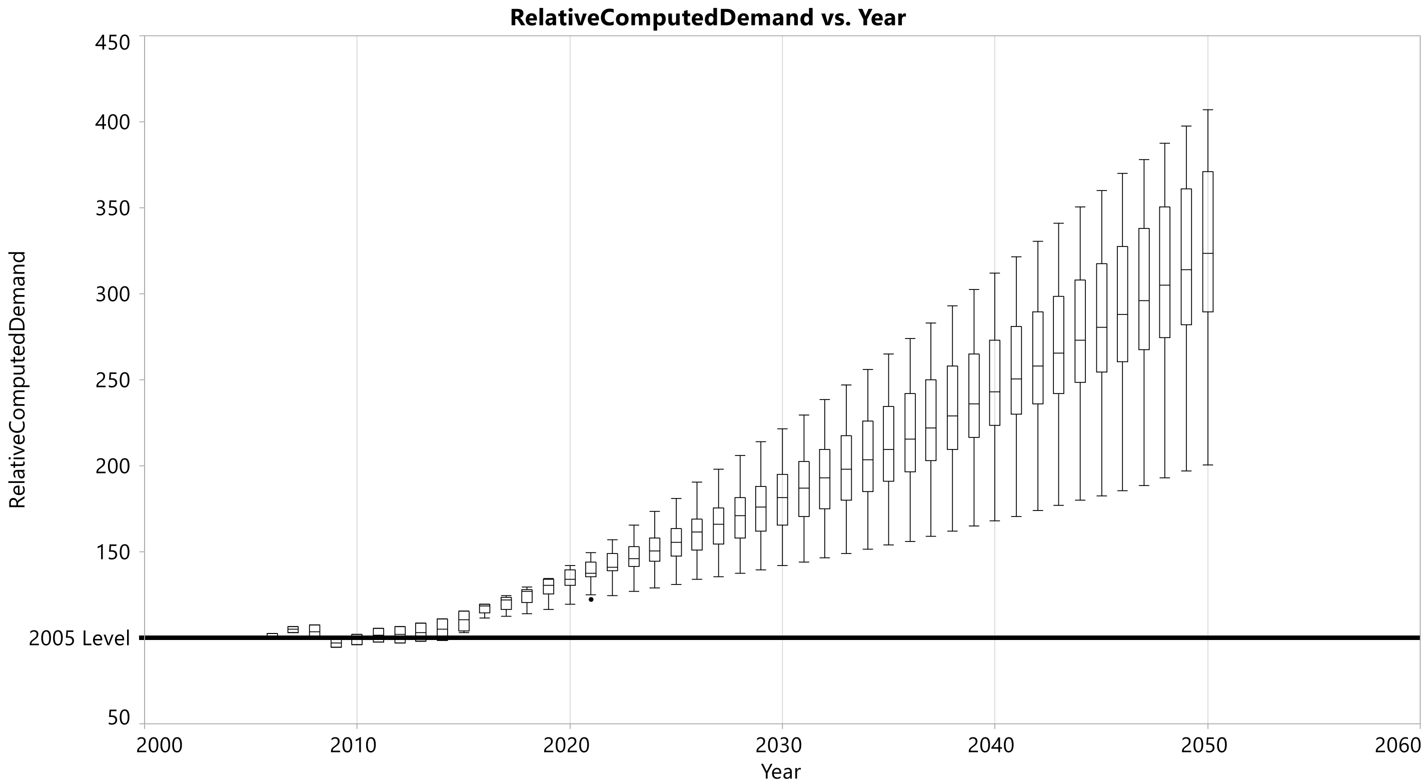


Figure 83: Variation in Future Predicted Demand across All Scenarios

The above figures present combined results from FLEET and GREAT; however, part of the intent of this work was to use two tools, built on different modeling approaches, with similar assumptions in order to corroborate results and predictions. Figure 84 subdivides the results shown in Figure 80 by simulation tool. The plot style has been changed to show trends better. The plot below still shows variation in direct CO_2 emissions across all scenarios; however, darker areas indicate that more of the scenarios go through these areas of the plot. Beyond 2030, three distinct "fingers" emerge. While the absolute CO_2 emissions are slightly different between GREAT and FLEET, the order of magnitude is similar. As expected, the highest direct emissions are produced in the scenarios with the highest demand and lowest technology level. The clustering of scenarios below the 2005 CO_2 levels all include high technology levels. Figure 85 colors the scenarios according to demand. Here, the results are more mixed. While high demand leads to high direct CO_2 emissions, the results of nominal and low demand are more dependent on technology levels. The very high demand case constrains operations to maintain or decrease noise areas below 2010 levels. As a result, one can see that noise constrained operations will have a significant impact on direct CO_2 emissions, but will not reduce them below 2005 levels. In this sense, direct CO_2 emissions are more difficult to achieve than noise area reductions.

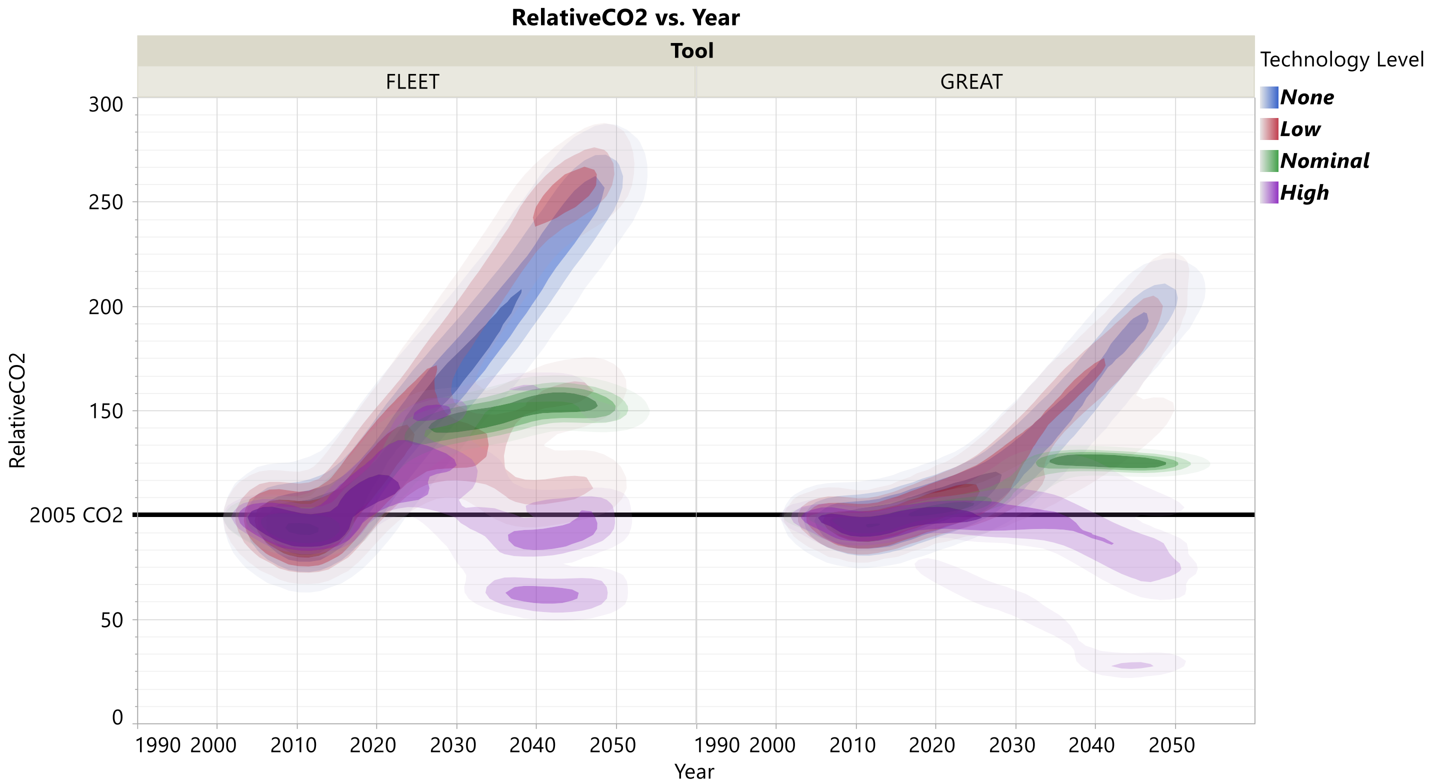


Figure 84: Comparison between FLEET and GREAT Direct CO_2 Emissions Predictions vs. Technology Level

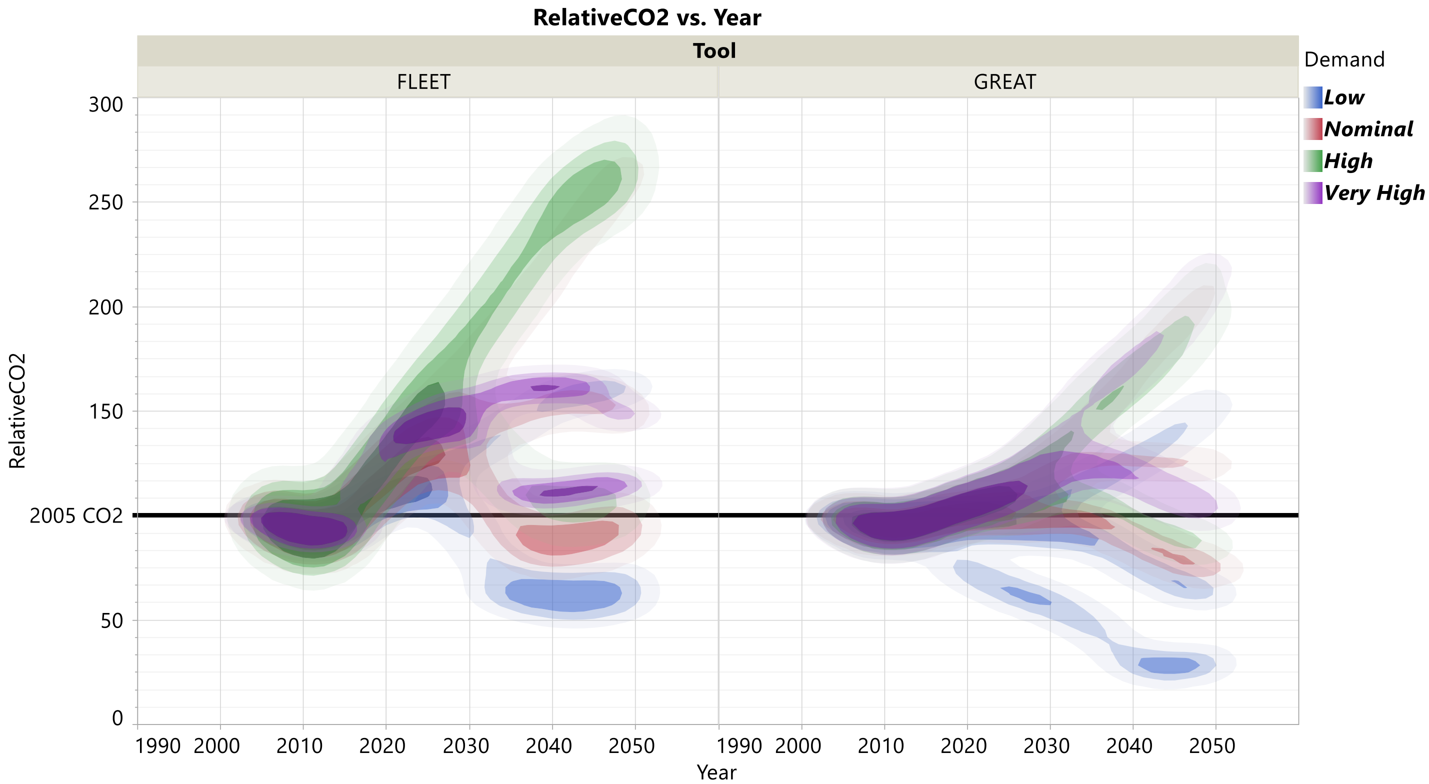


Figure 85: Comparison between FLEET and GREAT Direct CO2 Emission Predictions vs. Demand

Figure 85 further investigates the strong impact of technology as modeled in both fleet-level tools. Recall, a "low" or "high" technology level, as used in the preceding discussion, actually consists of two distinct assumptions, the technology impact on the vehicle, and the rate at which new technology is introduced to the fleet. The rate at which new technology is introduced is heavily dependent on the retirement rate of older aircraft, especially for lower demand scenarios. Figure 86 colors the scenarios according to the aircraft retirement assumptions. Here, it is apparent that early retirement drives fleet turnover and reduces direct CO_2 emissions in out years. This trend holds for both tools.

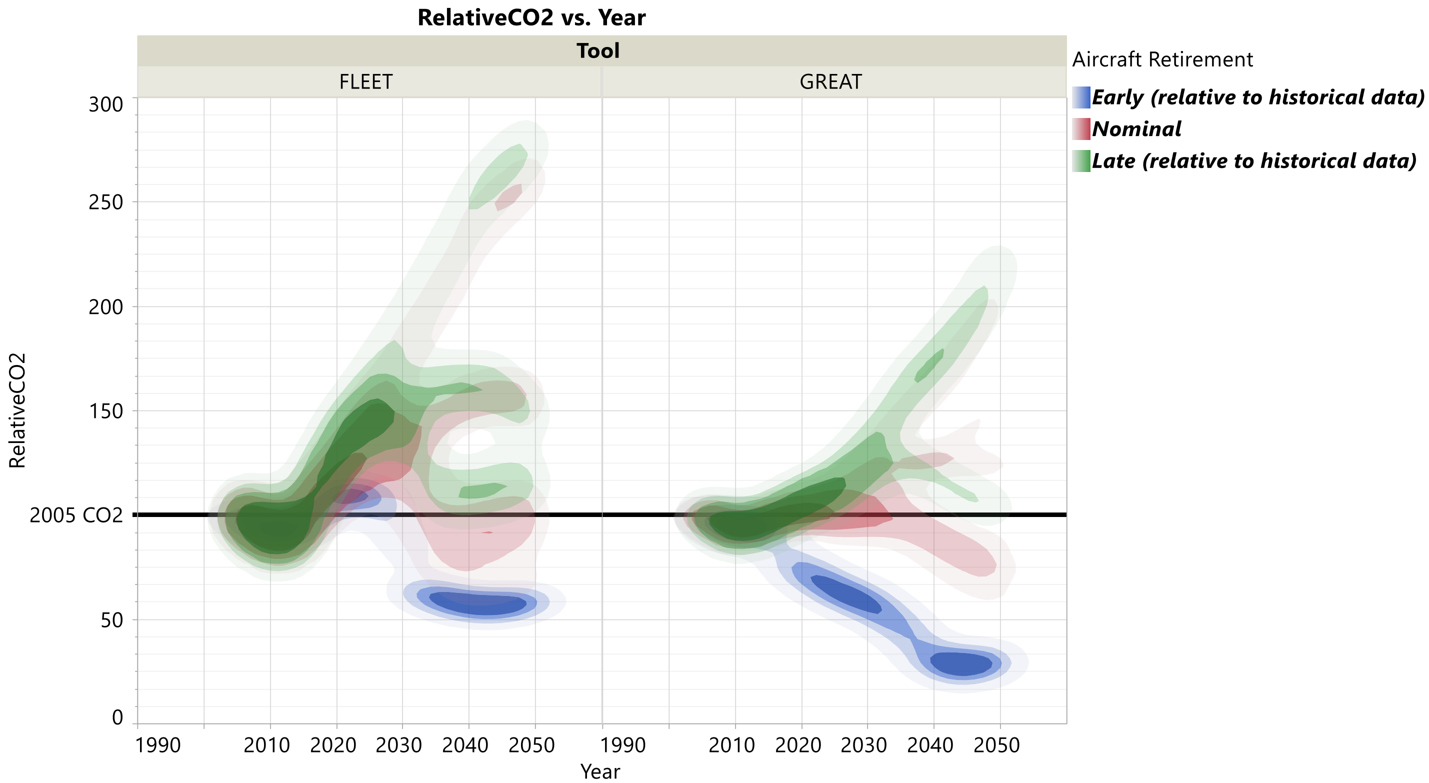


Figure 86: Comparison Between FLEET and GREAT Direct CO2 Emission Predictions vs. Retirement Rates

In summary, with nominal or low demand, which includes a doubling of operations by 2050, carbon neutral growth is achievable only with increased focus on technology maturation and insertion into the fleet. It is critical to get new technologies developed and placed on aircraft as soon as possible, and in a manner that encourages airlines to retire their current fleet in favor of the newer aircraft. Unfortunately, the long life span and development timelines of commercial aircraft make achieving this goal very difficult.

Noise Impacts

Fleet noise can be examined in a similar manner as fuel burn. Figure 87 shows 65 DNL contour area as predicted by GREAT and FLEET. The methodologies for computing noise area are different between the two tools. GREAT uses the aircraft models described in the Task #2 section combined with the predicted operations to perform a noise analysis at a single runway airport. A representative fleet mix is used to calculate contour areas for 2010 through 2050 in 10 year increments. FLEET uses the area equivalency method combined with predicted certification noise values to predict contour area changes at major airports. A simple addition of the contour area at each U.S. airport in FLEET provides a “total area” for the entire airline network; these values appear normalized with respect to the total area in the base year of 2005. FLEET’s noise prediction module runs more quickly; therefore, FLEET has noise prediction results for every year, whereas GREAT predicts in ten year increments.

Immediately obvious in Figure 87 is that GREAT shows a wide spread in potential 2050 65 DNL contour area, but FLEET universally predicts that other than in the frozen technology scenario, that noise will be reduced, regardless of future technology or demand.

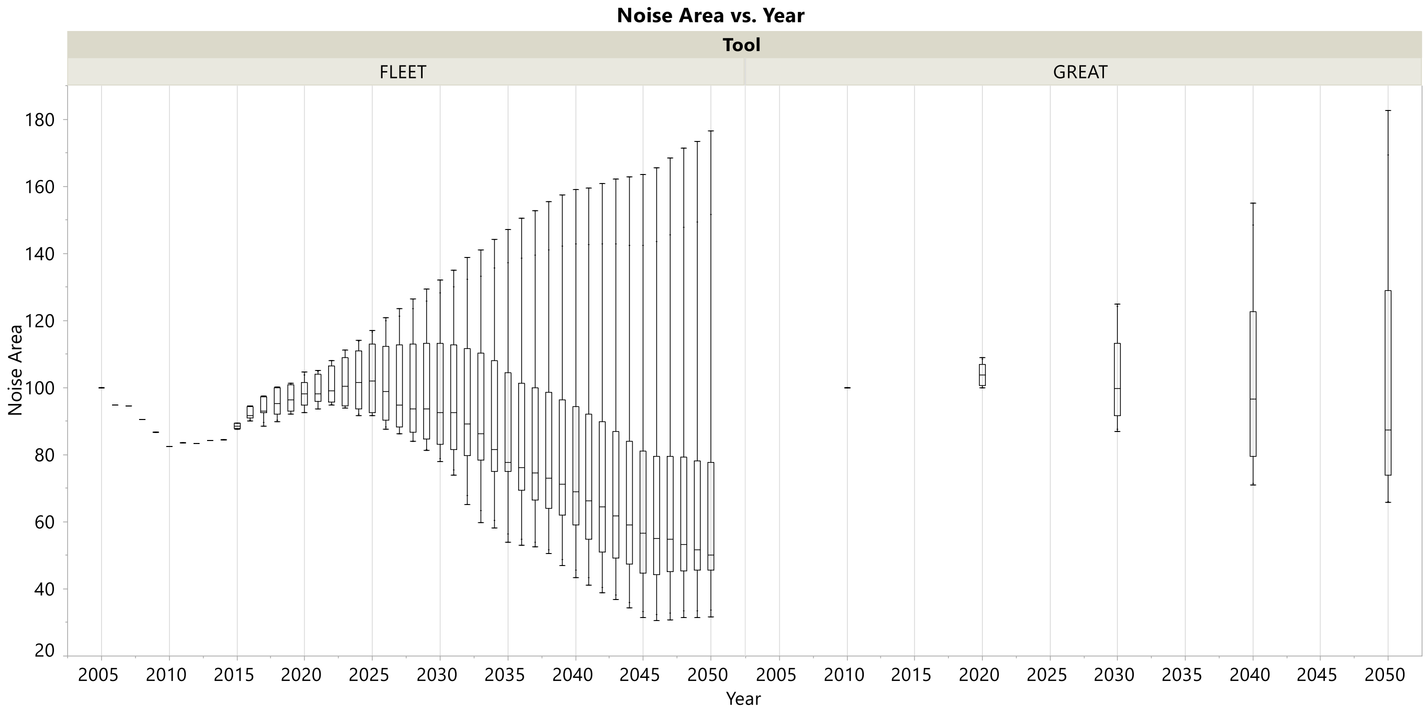


Figure 87: 65 DNL Contour Area Variation Across all Scenarios

GREAT and FLEET Detailed Results

GREAT Fleet Detailed Results

To visualize and observe trends in the fleet over time, noise and fuel burn results from each scenario were aggregated and compared side-by-side in plots, such as the one shown in Figure 89. Noise results are displayed with columns and represent the 65 DNL (day-night average sound level) Noise Area, as calculated using the Airport Noise Grid Interpolation Method (ANGIM) and Global and Regional Environmental Aviation Tradeoff (GREAT) tools. The data for 65 DNL Noise Area is shown for years 2010, 2020, 2030, 2040, 2050. Each noise data point is normalized to year 2010. The 65 DNL Noise Area is a suitable noise exposure metric that helps indicate whether overall noise has increased or decreased through time.

Fuel burn metrics are overlaid on the same plot using the dotted trend lines, and is a direct function of the relative CO_2 emissions. Again, no alternative fuels were assumed in this analysis; however, the life equivalent CO_2 emissions of any given fuel can be used to directly scale the fuel burn results. The fuel burn is shown in the plot for each year over a period spanning 2005 to 2050, alongside noise. Each year for fuel burn is normalized to the year 2005. Each plot displays the trends in noise and fuel burn of several scenarios, with the “Current Trends Frozen Tech” as reference.

A common color scheme was developed for the GREAT results discussion and is shown in **Figure 88**. Grey and black are used to indicate the two baseline cases, frozen technology and the current trends “best guess” which is indicative of a business as usual scenario. Shades of blue are used to indicate increasing demand but with Low Technology R&D Levels. This provides a view of the role of demand in a slow technology development landscape. Green is used to mark the two Environmental Bounds scenarios. Recall, the intention of these two scenarios is to estimate the absolute best and worst case scenarios from an environmental perspective. Finally, shades of red are used to evaluate the impact of demand while holding technology development to a high, rapidly developing level. The following plots compare these sets of scenarios with the goal of isolating impacts to draw general conclusions.

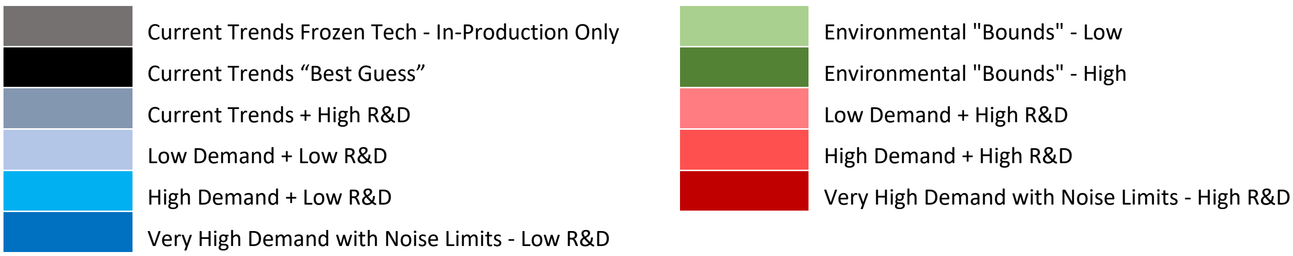


Figure 88: Scenario Color Scheme Legend for Noise & Fuel Burn Plots

Figure 89 shows the three current trends scenario with the frozen technologies, “best guess”, and High R&D scenarios. This plot is useful to bound direct CO_2 emissions as a function of technology with current demand levels. The frozen technology scenario is unrealistic, and assumes that the current in production aircraft will be continue to be produced forever, but provides insight into how much current technology trends are already offsetting future CO_2 increases. The High R&D scenario shows that reducing carbon dioxide levels below 2005 are possible with current demand trends, but reaching the current global goals of 50% reductions in 2050 appear to be quite difficult. Recall that the High R&D scenario assumes both a high level of technology impact and more rapid introduction of new technologies into the fleet. It is also apparent that technology has a large impact on contour noise area.

Figure 90 shows variation in demand with low technology R&D. Recall, this means technology impacts are low and the introduction of new technology is slower than historical trends. A few important observations can be made by comparing with the trends just presented in **Figure 89**. First, reducing demand below current levels obviously reduces direct CO_2 emissions, but does not change the fundamental shape of the curve. The ‘kink’ necessary to bend the curve downward must be introduced through technology infusion, as seen below. The impact of demand on noise is also much smaller than that of technology. These trends are more readily apparent if the reader compares **Figure 90** and **Figure 91**; these two figures both show the impact of varying demand on noise and fuel burn, but **Figure 91** shows the impact at high levels of technology investment. The differences between the two plots are greater than variation in demand, once again indicating technology investment is the primary driver of future fleet emission and noise reductions. It must be restated that even more important than the direct impact of the technology is the rate at which new technology is introduced into the fleet. An aircraft’s typical lifespan lies between 15 to 30 years, therefore there is significant lag in new technology having a real world impact.

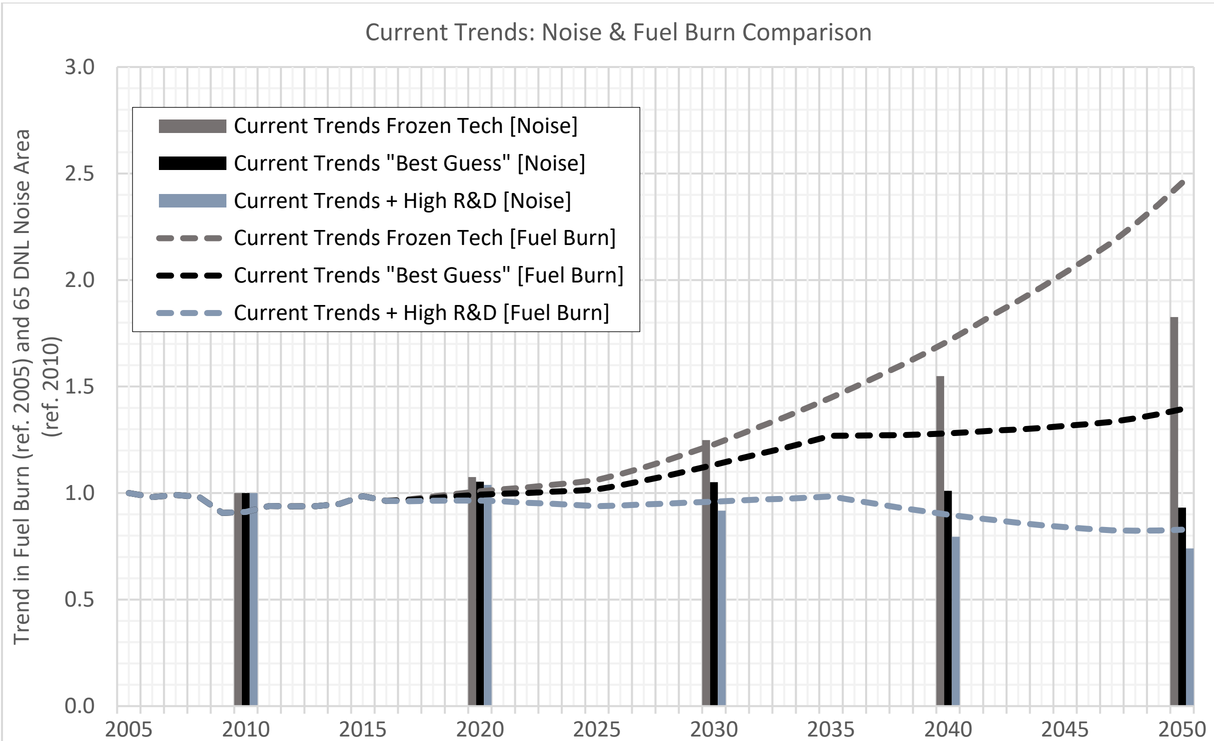


Figure 89: Noise & fuel Burn Comparison – Current Trends

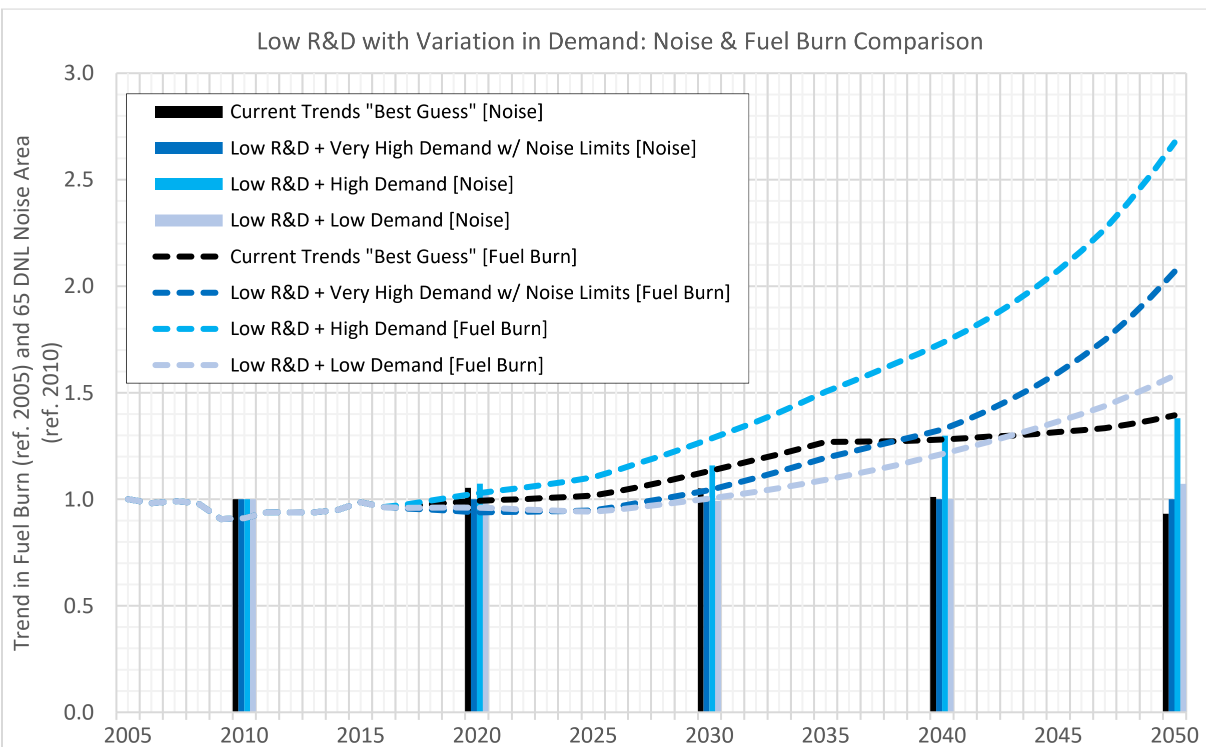


Figure 90: Noise & Fuel Burn Comparison – Low R&D with Variation in Demand

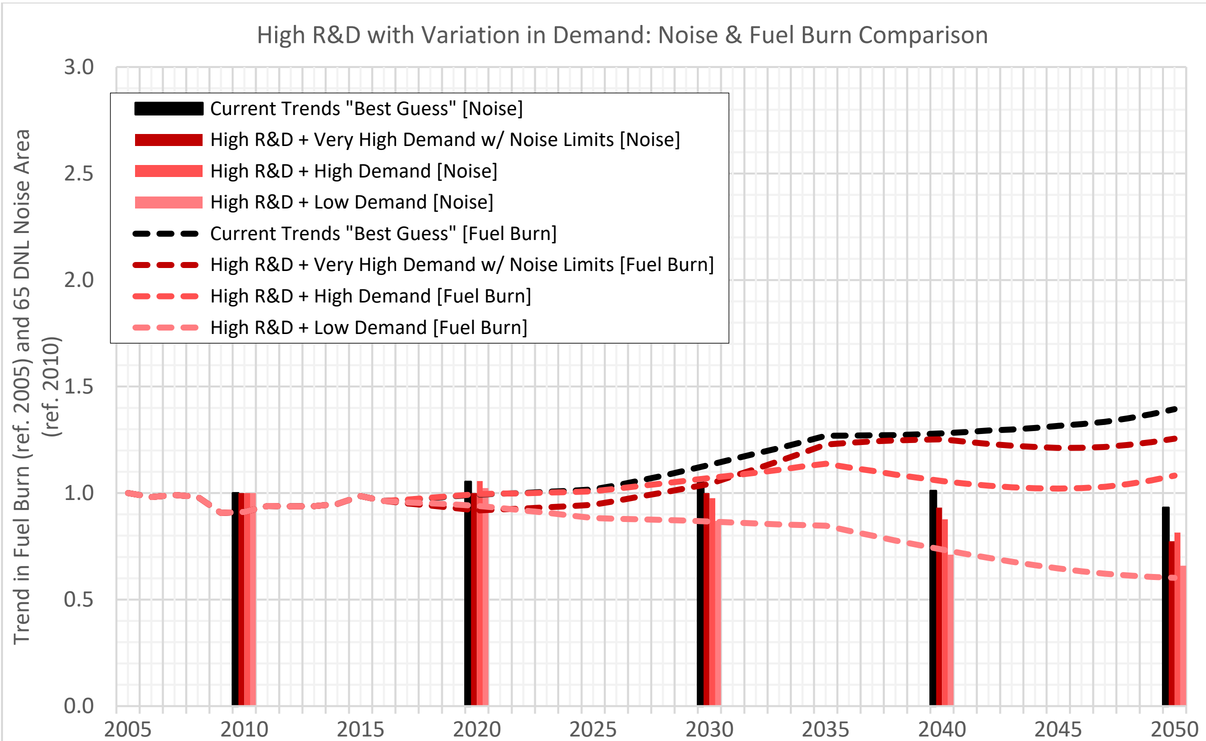


Figure 91: Noise & Fuel Burn Comparison – High R&D with Variation in Demand

Figure 92 shows the two extreme bounding cases on fuel burn and direct CO_2. The best case scenario from an emissions perspective is perhaps an odd and unlikely one from a U.S. economic perspective. In order to achieve the significant reductions shown, GDP growth and airline demand must be stagnant coupled with large increases in technology development, presumably through increases in R&D spending. While unlikely since R&D spending is usually tied to a healthy economy, it shows that significant reductions are achievable under the right circumstances. The upper bounding scenario is more likely and includes a combination of significant economic growth coupled with large airline demand increases and a rate of technology maturation slower than today. While aircraft and engine OEMs tend to pursue R&D to maintain competitive advantage, it is not entirely impossible to have demand increases large enough that the focus is on meeting production rates rather than significant step changes in aircraft performance and noise levels. The trend is exponential and could result in a tripling of direct CO_2 emissions and a 50% increase in contour areas by 2050.

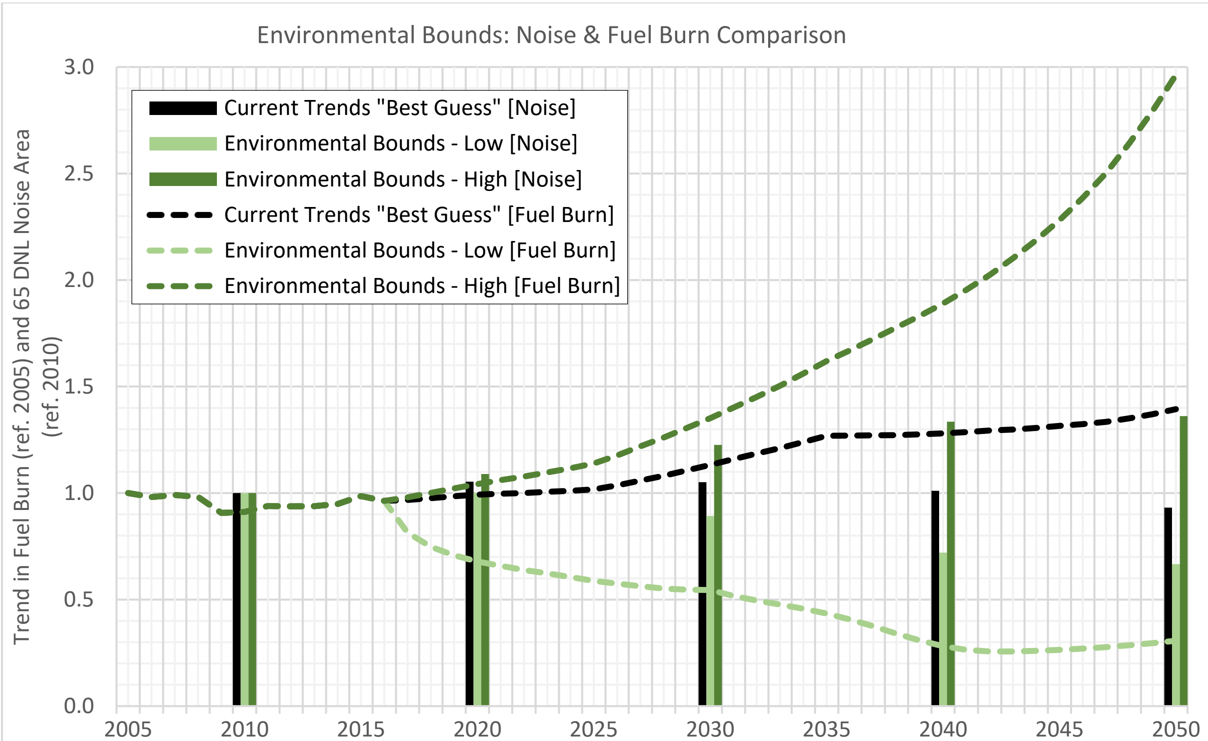


Figure 92: Noise & Fuel Burn Comparison – Environmental Bounds

Finally, Figure 93 and Figure 94 show the impact of varying technology R&D investment against fixed demand. Important to note here is the larger relative impact of technology when demand is high. High demand requires larger numbers of new aircraft. As a result technology is introduced at a more rapid rate than would be the case in a low demand scenario, where aircraft retirement rates are the dominant force in new technology introduction. Nevertheless, from a carbon neutral growth perspective, High R&D is essential regardless of assumed demand increases.

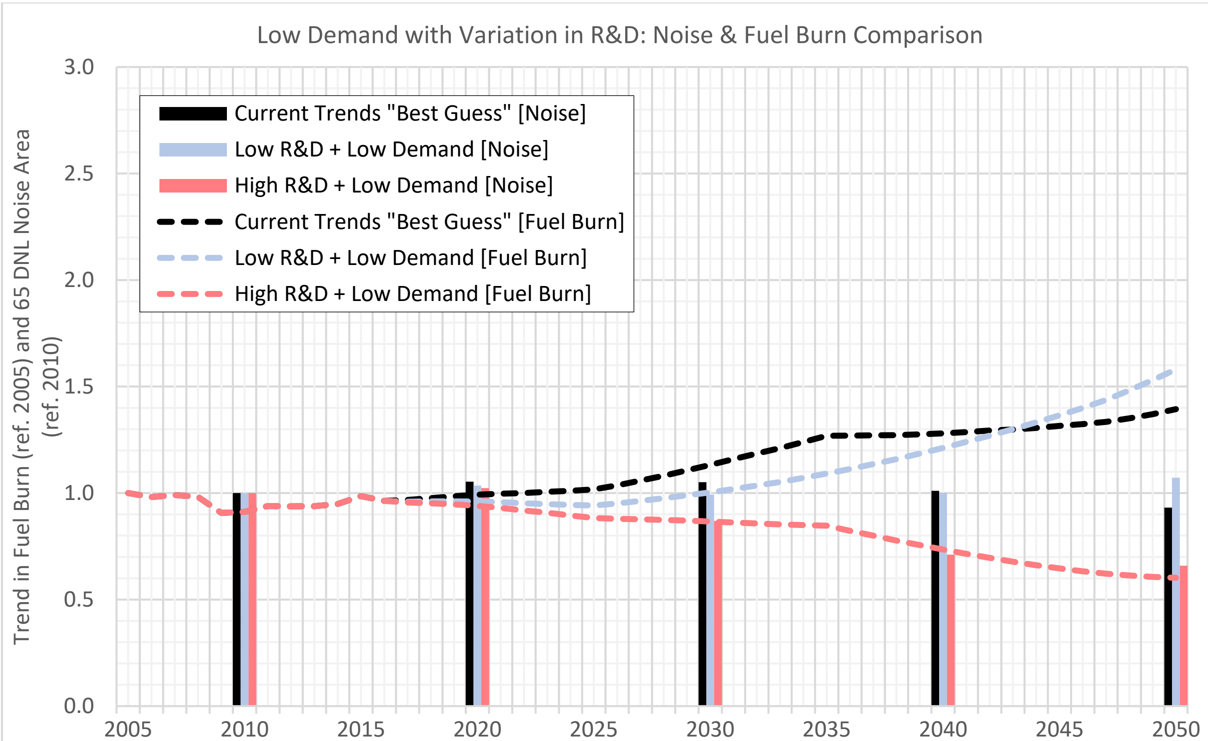


Figure 93: Noise & Fuel Burn Comparison – Low Demand with Variation in R&D

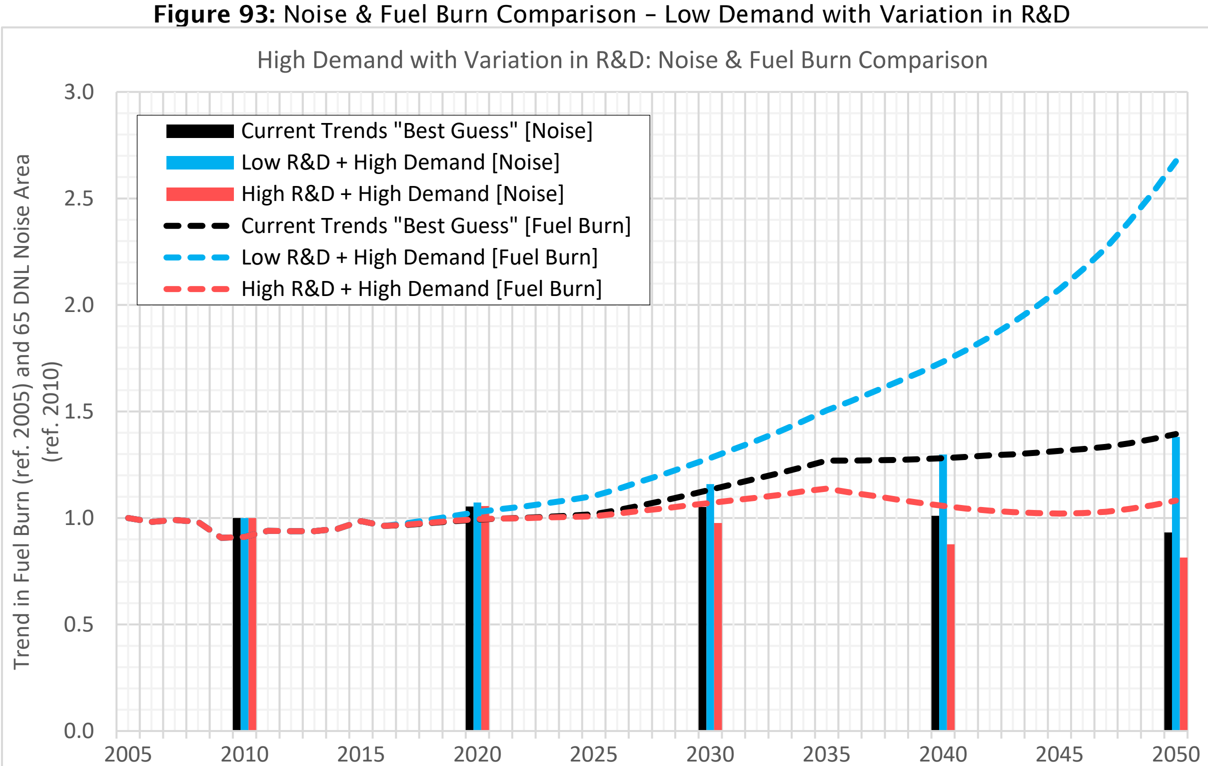


Figure 94: Noise & Fuel Burn Comparison – High Demand with Variation in R&D

FLEET Fleet Detailed Results
The remainder of this section describes Purdue's representation of the "ASCENT 10 Project" scenario simulations using FLEET with the scenario setups aforementioned.

Table 13: Percent GDP Growth Rates for Each Continent Segregated by Demand Scenarios

Scenarios	North America	South America	Europe	Africa	Asia	Oceania
Current Trend	2.8%	4.2%	2.4%	2.8%	4.3%	2.8%
Low Demand	1.8%	2.7%	0.6%	1.8%	3.3%	1.8%
High Demand	4.0%	5.3%	4.2%	4.0%	5.9%	4.0%

Table 13 shows the percent GDP growth rate for each demand scenario type for each continent used in the FLEET model to determine the evolution of the inherent passenger demand growth rate throughout the simulation period. The initial population growth rates for all demand scenarios were set to 0.58%, 1.26%, 0%, 2.6%, 1.10%, and 1.10% for North America, South America, Europe, Africa, Asia, and Oceania respectively. The approach here uses historical demand for trips made between 2005 and 2013, so the yearly GDP growth rates in the table take effect starting after 2013.

Both demand and CO_2 emissions values are normalized to their respective 2005 values. For all scenarios, the demand follows historical data until 2013, when the various trend lines split to demonstrate the predicted future values. **Figure 95** presents the projected demand trends using passenger nautical miles as the measure. Under the current trends assumptions for GDP, the differences in technology levels make some, but little, difference in the demand. The Current Trends + High R&D scenario leads to the highest demand in 2050, because the higher technology aircraft burn less fuel leading to lower operating costs (in fixed year dollars) so that the price elasticity calculation adds some demand on top of the GDP growth rate- and population-driven inherent demand.

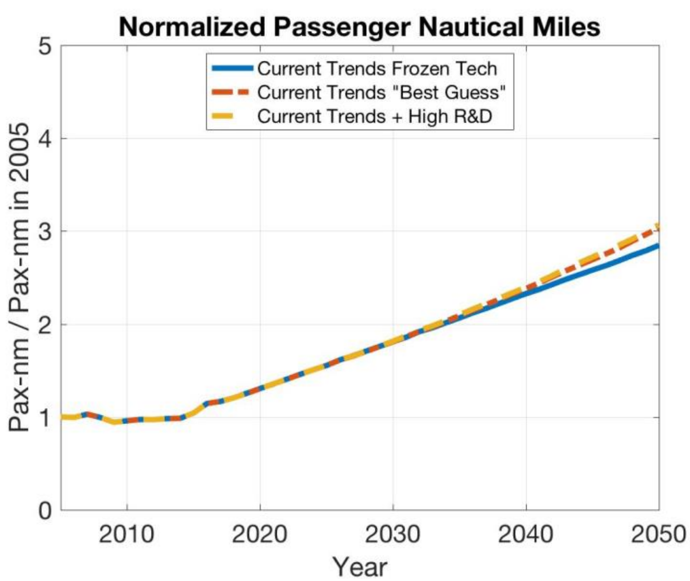


Figure 95: Normalized Passenger Nautical Miles from 2005 to 2050 – Current Trends Scenarios

Figure 96 indicates that CO_2 emissions from U.S.-related airline operations would increase by a factor of about 2.75 from their 2005 level by the year 2050 if no new technology is introduced (this is the "Current Trend Frozen Tech" scenario). This is an unlikely scenario, indicating the upper bound for CO_2 emissions from the current trends assumptions about demand growth. This factor decreases to a factor of 1.45 and 1 in the Current Trend Best Guess and Current Trend High R&D scenarios respectively, where the new technology aircraft become available over time and the airline retires older aircraft from its fleet. With some of the stated goals for 2050 levels of aviation CO_2 to be at or below the 2005 levels of aviation CO_2, the Current Trends High R&D scenario does show some promise of reducing future CO_2 while serving increasing passenger demand.

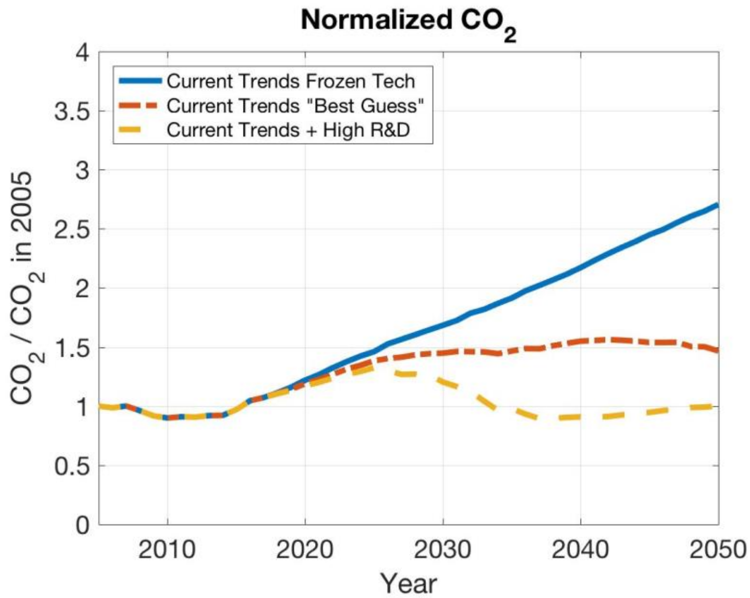


Figure 96: Normalized Fleet-Level Emissions from 2005 to 2050 – Current Trends Scenarios

To help illustrate the role of new technology in the aviation CO_2 predictions, **Figure 97** presents the fleet-wide CO_2 emission intensity (the grams of CO_2 equivalent per passenger mile flown); this value is also normalized using the 2005 level. The Frozen Tech scenario shows a nearly flat trend line from 2014 out to 2050; this scenario assumes that when the airline acquires a "new" aircraft, that aircraft is a "brand new" version of the best-in-class aircraft, so there is no technology advancement. Because of how the airline in FLEET meets future demand, this Frozen Tech trend line shows some deviations as the allocation changes to meet changing demand. In the Current Trend family of scenarios with a best guess at technology introduction and with the high research and development perspective, the fleet-wide CO_2 emission intensities in 2050 relative to 2005 are 0.49 and 0.32, respectively.

The significant change in CO_2 emission intensity trend slopes around the mid-2020s and 2030s in Current Trend High R&D scenario corresponds to the availability of New-in-Class and Future-in-Class aircraft. The High R&D trend line has a clear change in slope in the mid- to late-2030s where there are no "N+3" aircraft to replace the Future-in-Class aircraft, so the airline relies on similar aircraft types to meet the increasing demand.

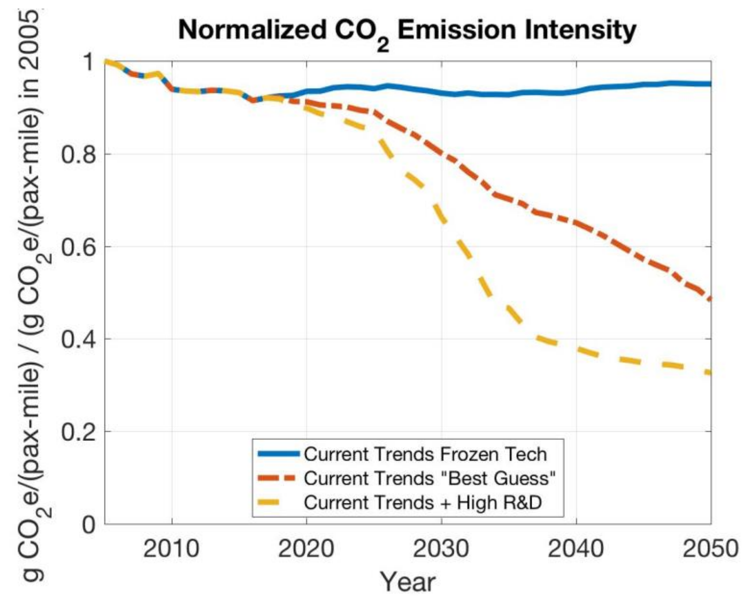


Figure 97: Normalized Fleet-Level CO_2 Emission intensity from 2005 to 2050 – Current Trends Scenarios

Figure 98 displays the relative number of aircraft deployed over time, showing an increasing total number of aircraft in the airline's fleet, while also showing how these aircraft fall into different technology ages or categories. The Frozen Tech scenario shows no New-in-Class or Future-in-Class aircraft; as the airline fleet grows in size, the new aircraft are all Best-in-Class in terms of performance. A small number of representative in class aircraft operate out to their maximum possible age because the small regional jet, in the FLEET model, continues to be profitable on some routes and there is no immediate replacement for these 50-seat jets. In FLEET, the representative-in-class aircraft were still being produced even after their entry in service date, so the last of the representative-in-class aircraft were at most 40 years old. This 40-year maximum possible age matches the maintenance maturity curves used in computing net present value in the retirement model. Also in Figure 98, the "Best Guess" deployed fleet composition shows an increasing airline fleet size, with diminishing numbers of previous technology age aircraft as the next technology age aircraft increase production. The Best-in-Class aircraft make a peak fraction of the fleet around 2025, then the new-in-class peak around 2040, and the future-in-class dominate in 2050 at the end of the scenario. These peaks all occur roughly 20 years after the first of that technology age's aircraft enter service. The fleet size and technology age composition in the High R&D scenario is not strikingly different from the "Best Guess" scenario, even though the High R&D new-in-class and future-in-class aircraft have much lower fuel burn than their counterparts in "Best Guess". This demonstrates that it is difficult for technology improvements to have enough impact on cost to force "earlier" retirement of aircraft already in the airline's fleet.

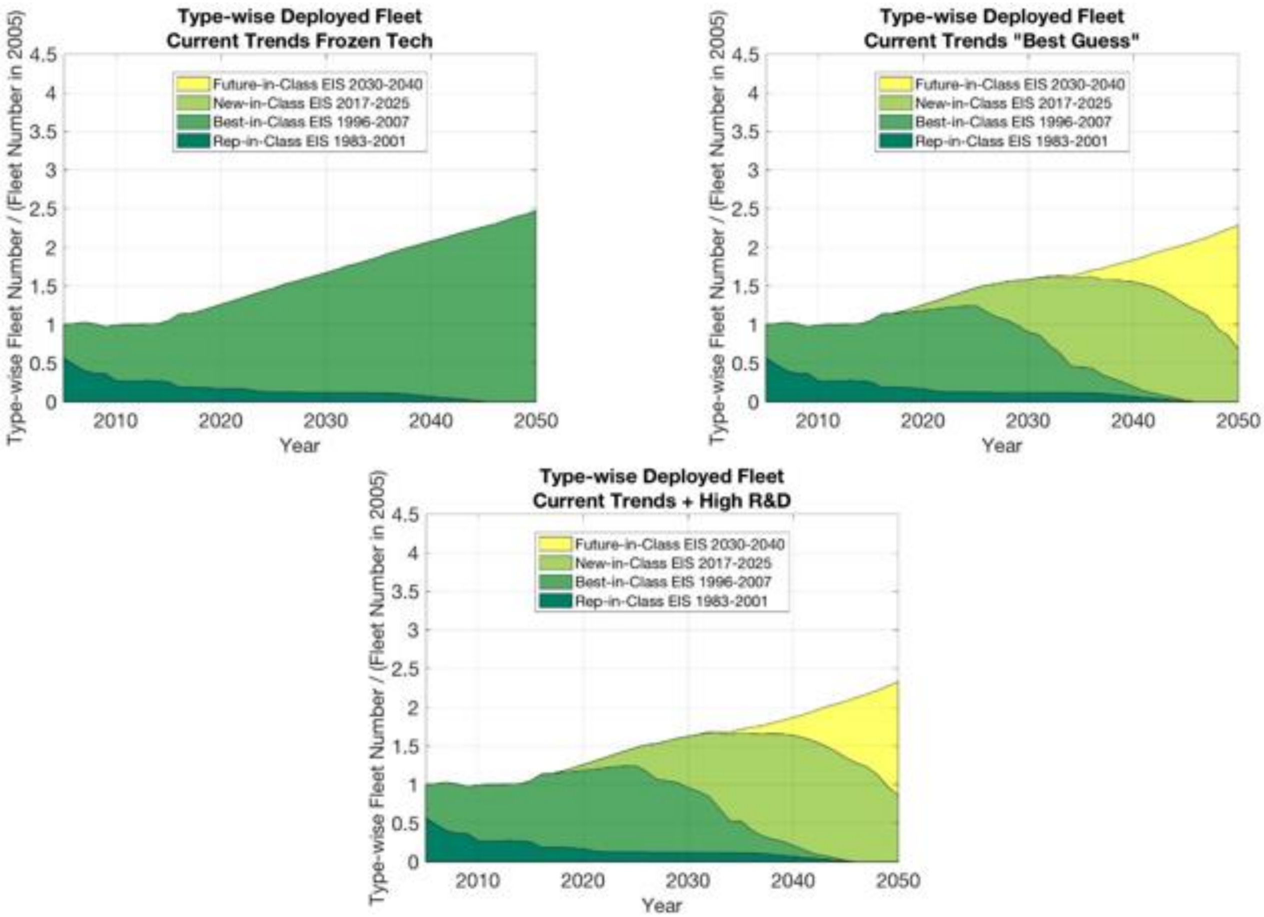


Figure 98: Normalized Deployed Fleet by Type – Current Trends

Figure 99 illustrates the airline fleet growth in a slightly different manner; here, stacked bar charts indicate the deployed fleet by class (or aircraft size) for each year of the scenario. The Best Guess and High R&D scenarios lead the airline to operate a higher fraction of future-in-class single aisle (Class 3) aircraft as this becomes available. The ability of this very efficient aircraft to offer better economic returns, coupled with the retirement of representative- and best-in-class small regional jet (Class 1) aircraft create a need for these aircraft to satisfy the passenger demand, which leads to some up-gauging of the fleet on shorter routes. Further, as mentioned in Section 8.5.4, the High R&D Class 3 aircraft receive notable use on trans-Atlantic routes. Also of interest, the airline flies very few trips using class 5 (Large Twin Aisle – LTA) aircraft, by 2050, in the Current Trend Best Guess and Current Trend High R&D scenarios, primarily due to the technology improvements from the class 6 (VLA) aircraft, which has a capacity of 430 passengers, predominantly serving the few long-range high-demand routes in the FLEET route network**.** Figure 99 also shows that in the Current Trend Frozen Technology scenario, the airline deploys more classes 4 and 5 aircraft and less class 3 aircraft by 2050 relative to the other Current Trend scenarios. This suggests that the airline operates larger class aircraft in order to remain profitable and reduce emissions, when subjected to increasing passenger demand without aircraft of improved technology.

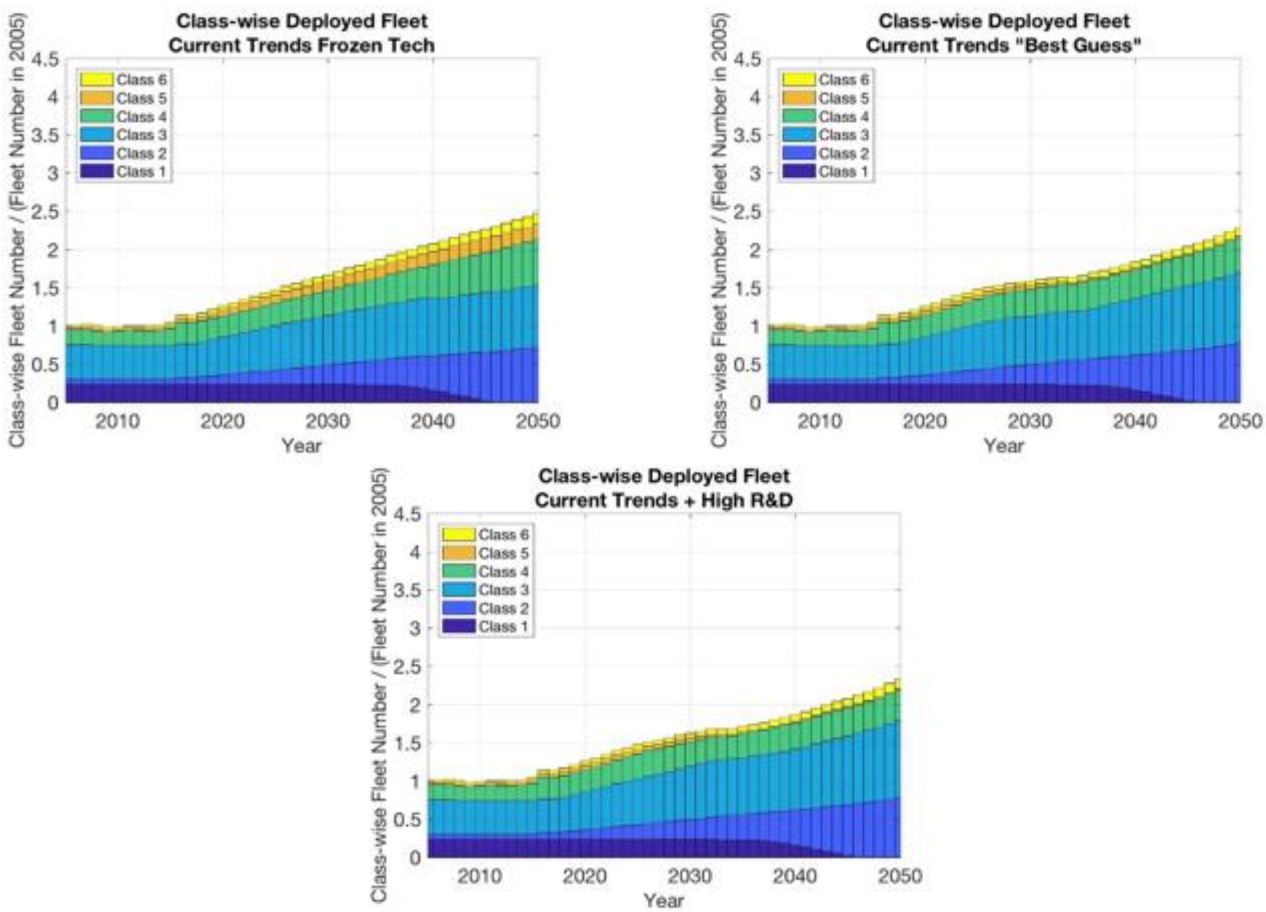


Figure 99: Normalized Deployed Fleet by Class – Current Trends

Figure 100 shows the revenue passenger nautical miles of the airline for the High R&D scenarios throughout the simulation normalized by the value in 2005; the Current Trends Best Guess plot appears along with these High R&D scenarios for reference. The Low Demand High R&D scenario produced the least growth in RPM of about 2.3 times the value in 2005 by 2050. The passenger nautical miles in the High Demand R&D scenario increased to about 4 times respectively of the corresponding values in 2005. Figure 101 shows the fleet-level CO_2 emissions of the High R&D scenarios normalized by the 2005 emission value. The Low Demand High R&D and High Demand High R&D scenarios yielded CO_2 emissions of 75% and 125% respectively of their corresponding 2005 values by 2050. The CO_2 emission intensity normalized by the 2005 value, for the High R&D scenarios throughout the simulation period is presented in Figure 102**.** The emission intensities in the High R&D scenarios by 2050 ranged between 32% and 34% of the corresponding value from each scenario in 2005. Despite the brief period of decreasing CO_2 emissions between the mid-2020s and mid-2030s, indicating that the airline is operating more fuel efficient aircraft, the overall fleet-level emissions show an increasing trend due to the overwhelming demand growth in the scenarios.

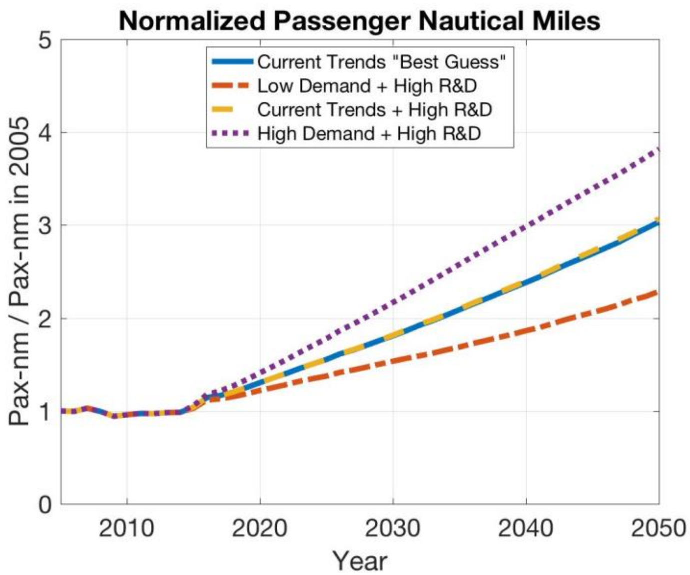


Figure 100: Normalized Passenger Nautical Miles from 2005 to 2050 – High R&D Sciences

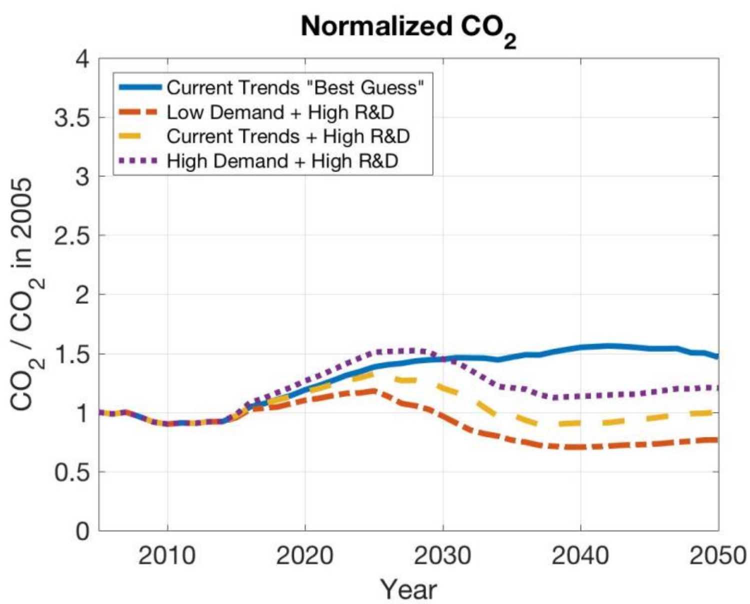


Figure 101: Normalized Fleet-level Emissions from 2005 to 2050 – High R&D Scenarios

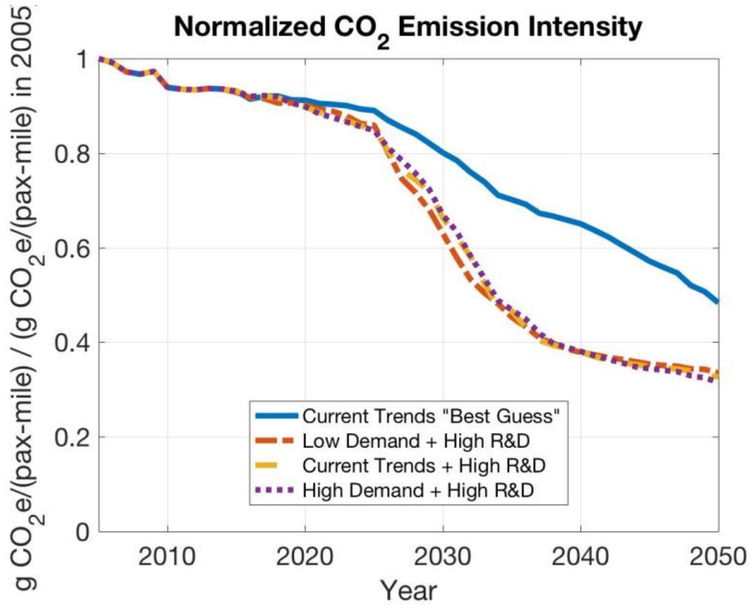


Figure 102: Normalized Fleet-Level CO2 Emissions Intensity from 2005 to 2050 – High R&D Scenarios

Figure 103 and Figure 104 show the deployed fleet by aircraft type and class respectively, normalized by the values in 2005, for High R&D scenarios. The total number of aircraft deployed by the FLEET airline in the Low Demand High R&D and High Demand High R&D scenarios increased by about 75% and 180% of their respective values in 2005 by 2050. Figure 103 reveals the FLEET airline's sensitivity to new technology aircraft due to different variations in demand across the High R&D scenarios. The relatively higher fraction of new-in-class and future-in-class aircraft in the High Demand High R&D scenario suggests that the airline leverages the benefits from next generation aircraft as they become available in order to mitigate carbon emissions due to ever-increasing demand. In the Low Demand scenario, the demand for aircraft to satisfy the increasing passenger demand is lower than that in the other High R&D scenario. Hence, airlines can acquire enough "newer" aircraft to replace their old generation aircraft, which results in a shorter fleet turn-over duration. Figure 104 shows the variation in aircraft fleet by size in the High R&D scenarios. The FLEET airline utilizes a larger fraction of next generation classes 3 and 5 aircraft in the High Demand scenario when compared to the Low Demand, in order to serve demand while reducing CO_2 emissions. The comparison of aircraft types also reveals that the airline retains some older aircraft for a longer duration; for instance, Figure 103 and best-in-class aircraft still operating past 2040.

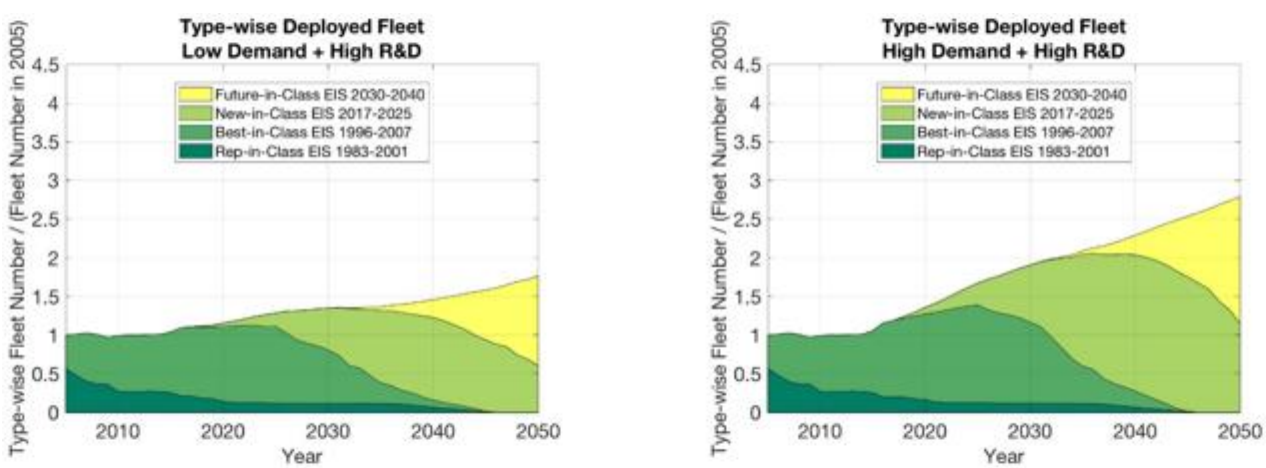


Figure 103: Normalized Deployed Fleet by Type – High R&D Scenarios

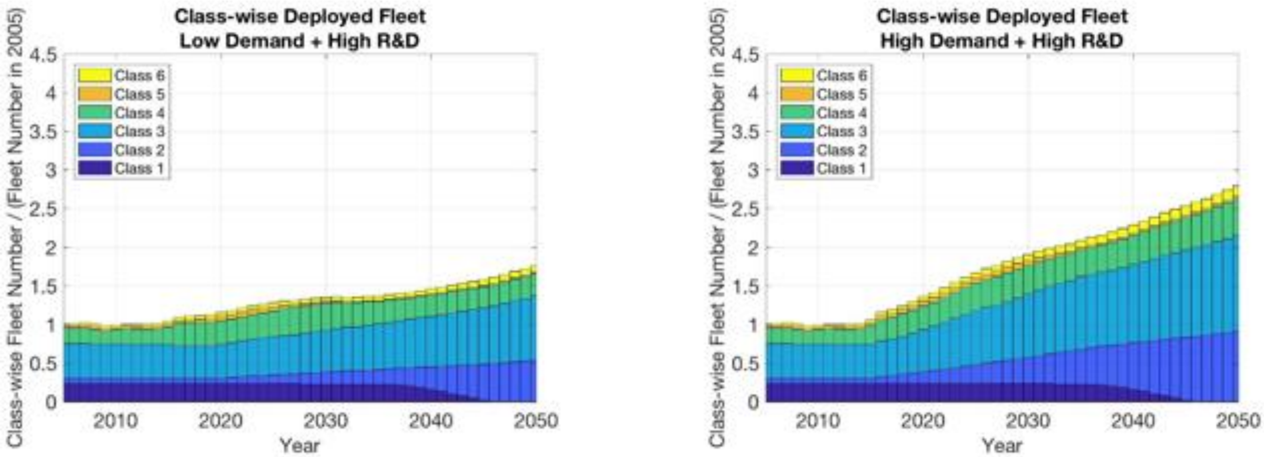


Figure 104: Normalized Deployed Fleet by Class – High R&D Scenarios

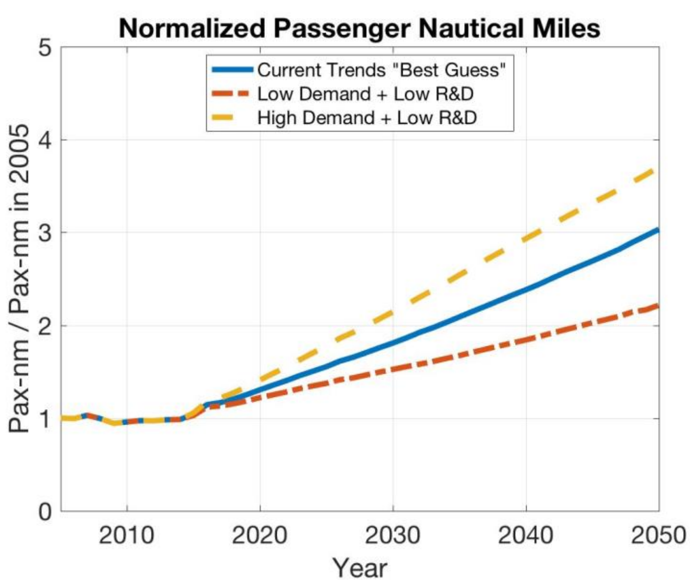


Figure 105: Normalized Passenger Nautical Miles from 2005 to 2050 – Low R&D Scenarios

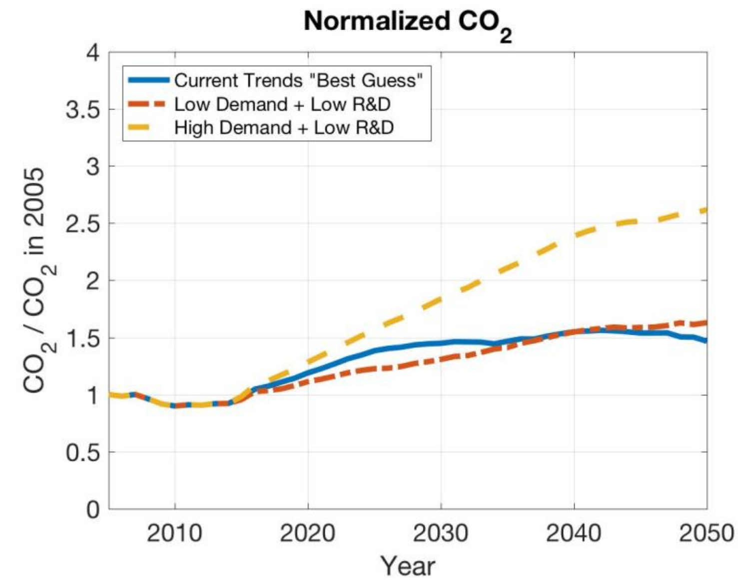


Figure 106: Normalized Fleet-Level Emissions from 2005-2050 – Low R&D Scenarios

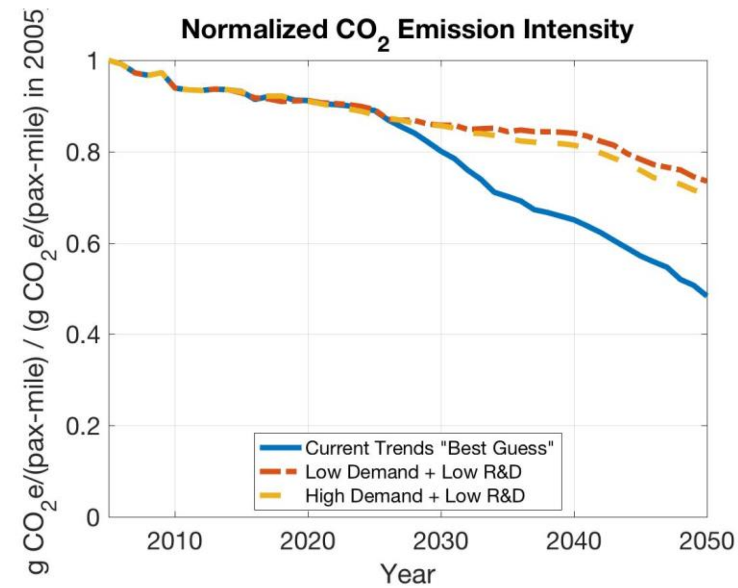


Figure 107: Normalized Fleet-Level CO2 Emission intensity from 2005 to 2050 – Low R7D Scenarios

Figure 105 shows the revenue passenger nautical miles for the Low R&D scenarios throughout the simulation. Similar to other scenarios, the results are normalized by the equivalent values in 2005. As expected, the Low Demand Low R&D scenario produced the lowest growth in RPM of about 2.2 times the value in 2005 by 2050. The passenger nautical miles in the High Demand Low R&D scenario increased to about 280% of the corresponding value in 2005. Figure 105 shows the fleet-level $\mathbf{CO_2}$ emissions for the Low R&D scenarios normalized by the 2005 emission value. The Low Demand Low R&D scenario yielded about 1.6 times the CO_2 emissions in 2005 by 2050 while the High Demand Low R&D scenario yielded fleet-level CO_2 emissions of about 2.6 times the 2005 value by 2050. The CO_2 emission intensity normalized by the 2005 value, for the Low R&D scenarios throughout the simulation period is represented in Figure 107. Low Demand Low R&D and High Demand Low R&D scenarios decreased to about 73% and 70% respectively of the value in 2005. When compared to the Current Trend Best Guess scenario, the Low R&D scenarios yielded a significantly higher emission intensity which stems from delayed introduction and access to new technology aircraft.

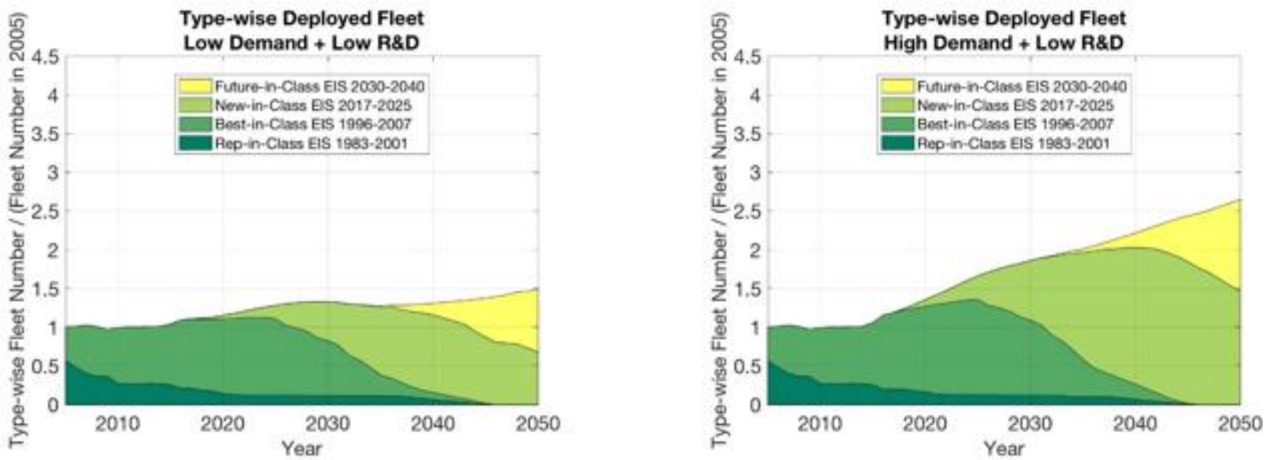


Figure 108: Normalized Deployed Fleet by Type – Low R&D

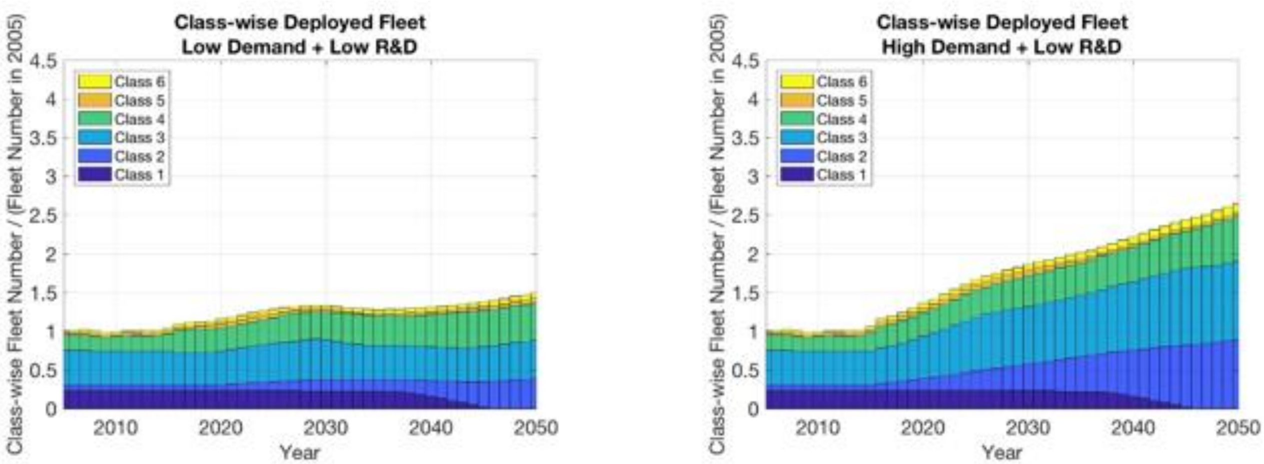


Figure 109: Normalized Deployed Fleet by Class – Low R&D Scenarios

Figure 108 and Figure 109 show the deployed fleet by aircraft type and class respectively for Low R&D scenarios, normalized by the deployed fleet in 2005. The Low Demand Low R&D scenario yielded the least growth in total number of aircraft deployed by the FLEET airline of about 1.5 times the value in 2005 by 2050. The total number of aircraft deployed in the High Demand Low R&D scenario increased to about 2.6 times the number of aircraft deployed in 2005. The significant increase in deployed aircraft in the High Demand scenario, compared to the Low Demand scenario, is due to the difference in demand for air travel between both scenarios.

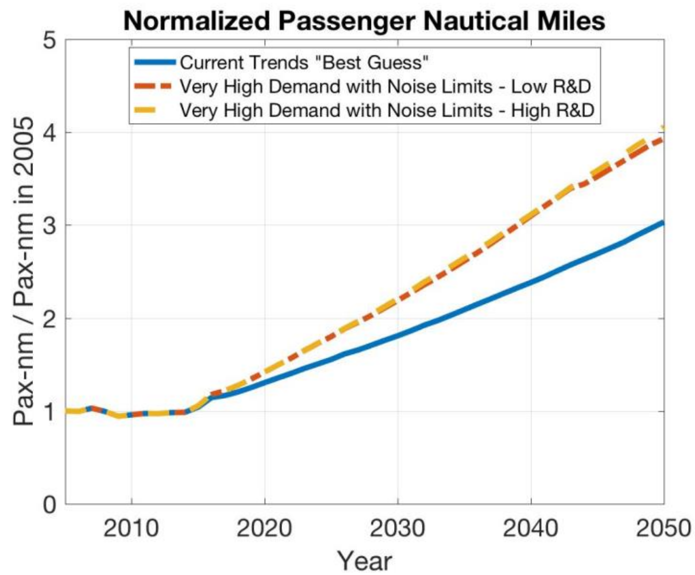


Figure 110: Normalized Passenger Nautical Miles from 2005 to 2050 – Noise Limit Scenarios

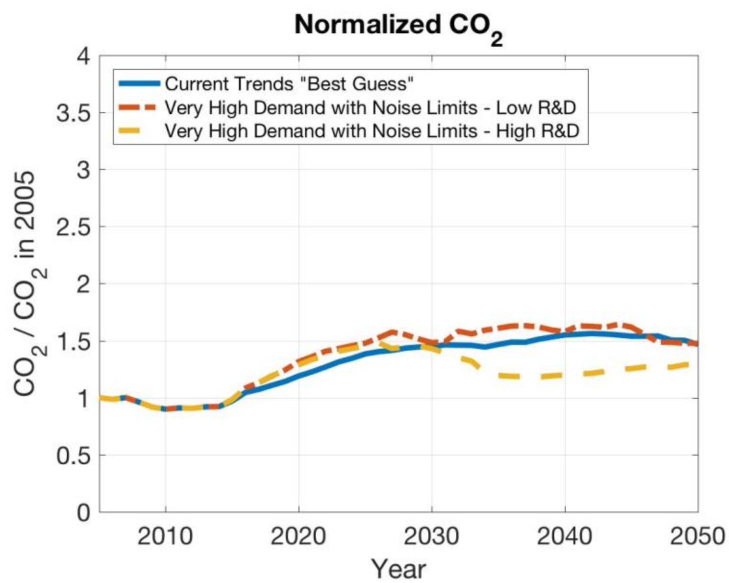


Figure 111: Normalized Fleet-Level Emissions from 2005 to 2050 – Noise Limits Scenarios

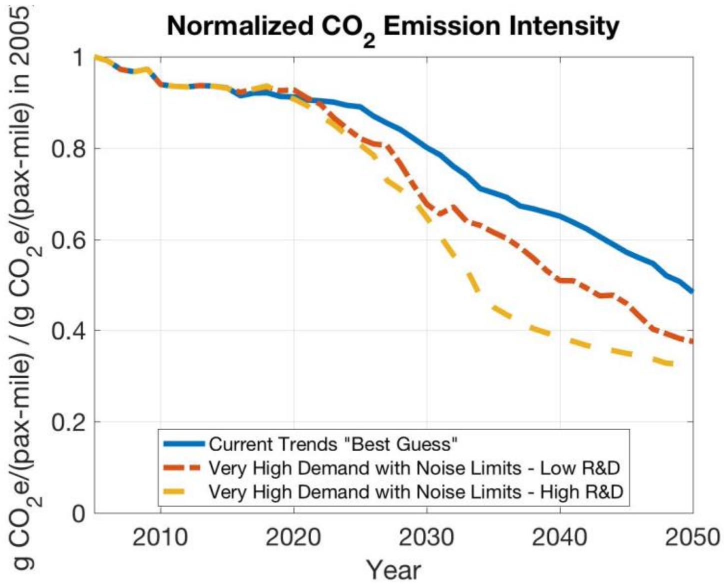


Figure 112: Normalized Fleet-Level CO_2 Emission Intensity from 2005 to 2050 – Noise Limit Scenarios

Figure 110, Figure 111, and Figure 112 show the demand and environmental results for the Very High Demand scenarios with Noise Limits. As with other scenarios, the results are normalized by the equivalent values in 2005. The revenue passenger nautical miles in the Very High Demand scenarios are very close at almost 4 times the 2005 value by 2050, as shown in Figure 110. While there is a significant difference in RPM between the Current Trends Best Guess and the noise-limited Very High Demand scenarios, the 2050 CO_2 emissions are relatively similar amongst all three scenarios as shown in Figure 111. The Current Trends Best Guess and noise-limited Very High Demand Low R&D scenarios yield CO_2 emissions in 2050 of about 1.5 times the 2005 value. The noise-limited Very High Demand High R&D scenario yields in 2050 CO_2 emissions of about 1.3 times the value in 2005. Figure 112 shows the fleet-level CO_2 emission intensity for the noise-limited scenarios normalized by their 2005 emission value. The noise-limited Very High Demand High R&D scenario results in the least emission intensity in 2050 of about 36% of the value in 2005. The difference in CO_2 emissions and intensity between the Low and High R&D scenarios, even though both scenarios have almost similar RPM, is due to the availability of new aircraft technology in the High R&D scenario.

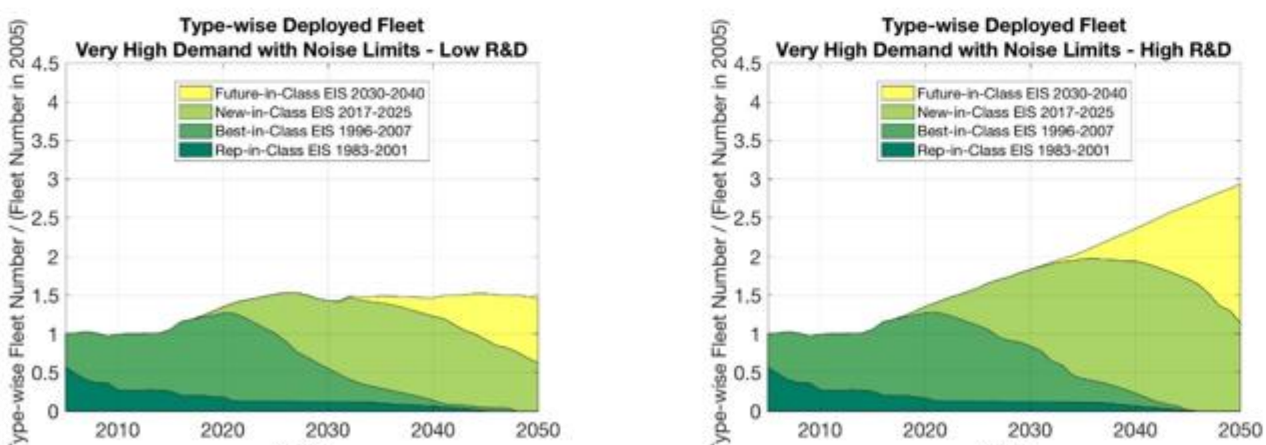


Figure 113: Normalized Deployed Fleet by Type – Noise Limits Scenarios

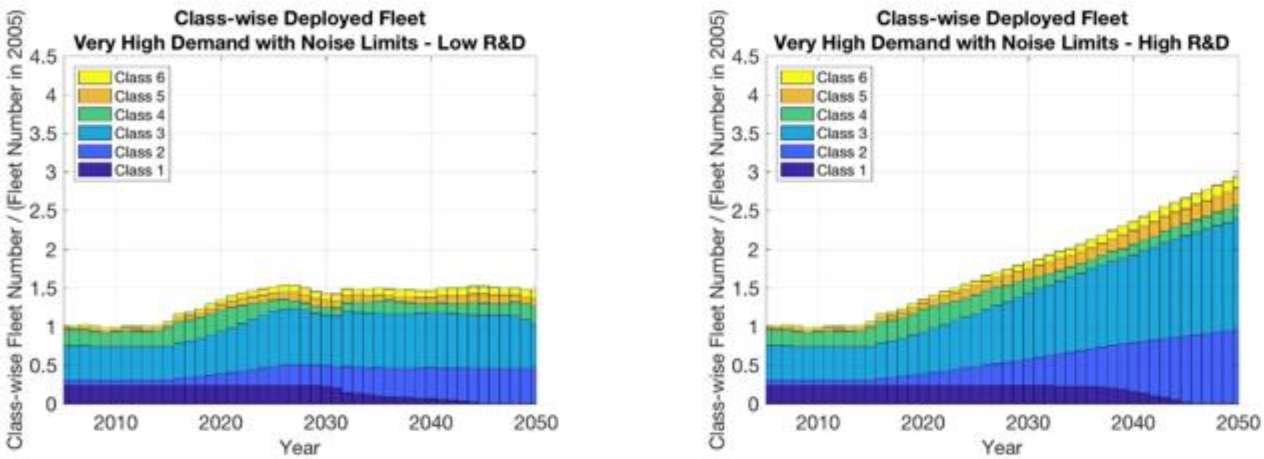


Figure 114: Normalized Deployed Fleet by Class – Noise Limits Scenarios

Figure 113 and Figure 114 show the type-wise and class-wise total number of aircraft deployed by the FLEET airline in the noise-limited Very High Demand scenarios throughout the simulation period, normalized by the total aircraft deployed in 2005. The total number of aircraft deployed by 2050 in the High R&D scenario is almost double the aircraft deployed by the airline in the Low R&D scenario. **Figure 114** shows that the number of next-gen class 3 aircraft deployed by 2050 in the High R&D scenario is significantly more than that deployed in the Low R&D scenario, such that the fairly constant fraction of class 3 aircraft deployed in the Low R&D scenario after 2025 is due to underwhelming demand for air travel.

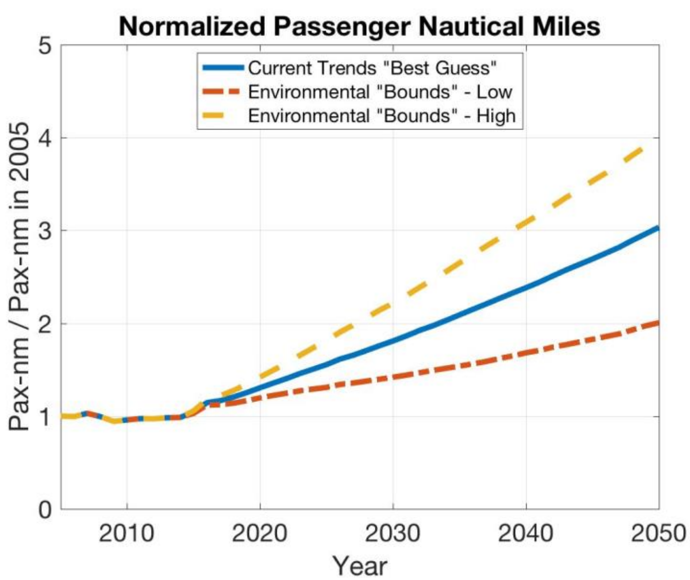


Figure 115: Normalized Passenger Nautical Miles from 2005 to 2050 – Environmental Bounds Scenarios

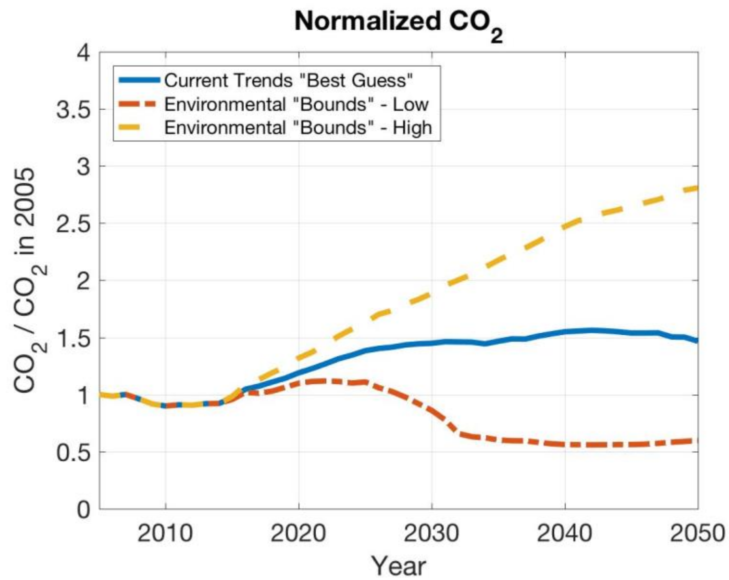


Figure 116: Normalized Fleet-Level Emissions from 2005 to 2050 – Environmental Bounds Scenarios

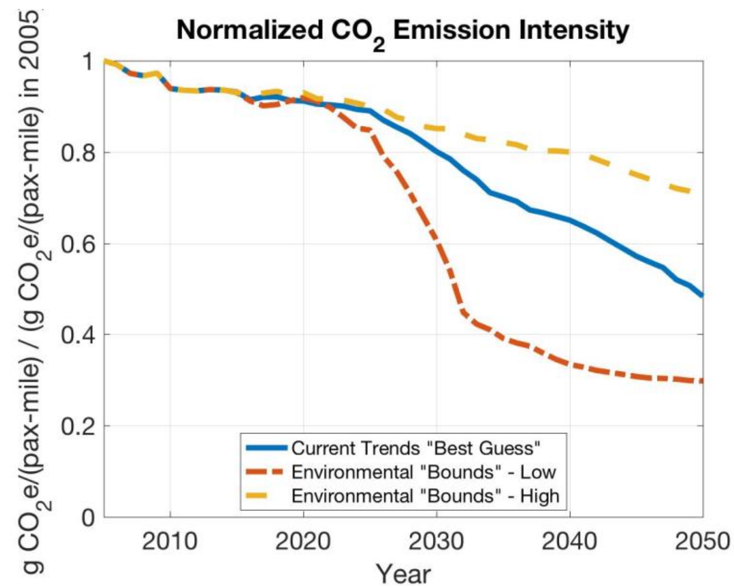


Figure 117: Normalized Fleet-Level CO2 Emission Intensity from 2005 to 2050 – Environmental Bounds Scenarios

The FLEET results, normalized by the 2005 values, from the Environmental Bounds scenario appear in Figure 115 through Figure 117. From Figure 114, the RPM in the Environmental Bounds High scenario by 2050 is almost double (4 times the 2005 RPM value) the corresponding value in the Environmental Bounds Low scenario. Figure 116 shows the fleet-level CO_2 emissions of the airline in the Environmental Bounds scenarios normalized by the 2005 emission value. The Environmental Bounds Low and High scenarios yielded CO_2 emissions of 60% and 260% respectively of their corresponding 2005 values by 2050. The CO_2 emission intensity normalized by the 2005 value, for the Environmental Bounds scenarios throughout the simulation period is presented in Figure 117. The emission intensities in the Environmental Bounds Low and Environmental Bounds High scenario by 2050 are about 30% and 70% of their values in 2005 respectively. The higher RPM, CO_2 emissions and intensity in the Environmental Bounds High scenario is because of higher demand and absence of noise limits when compared to the Environmental Bounds Low scenario.

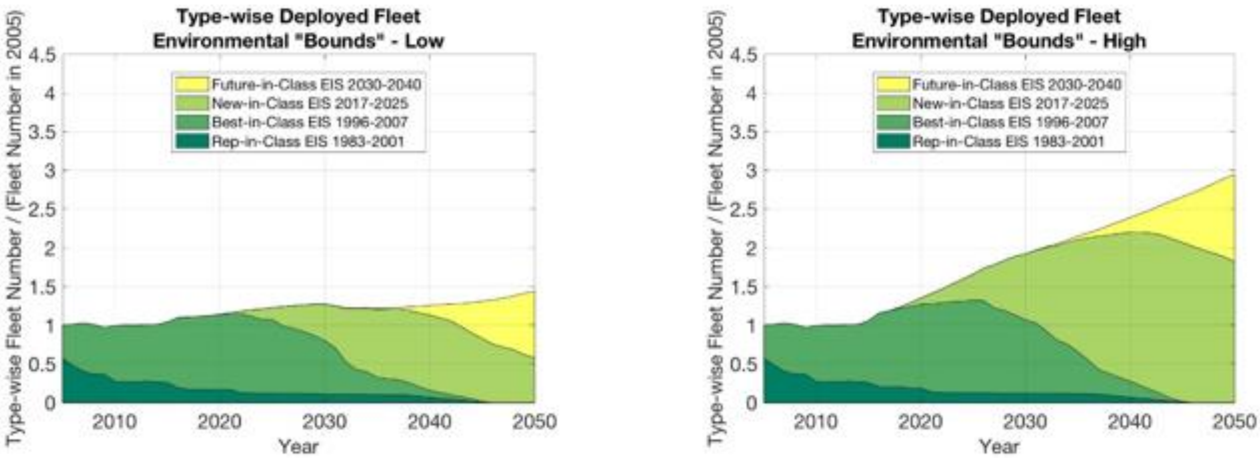


Figure 118: Normalized Deployed Fleet by Type – Environmental Bounds Scenarios

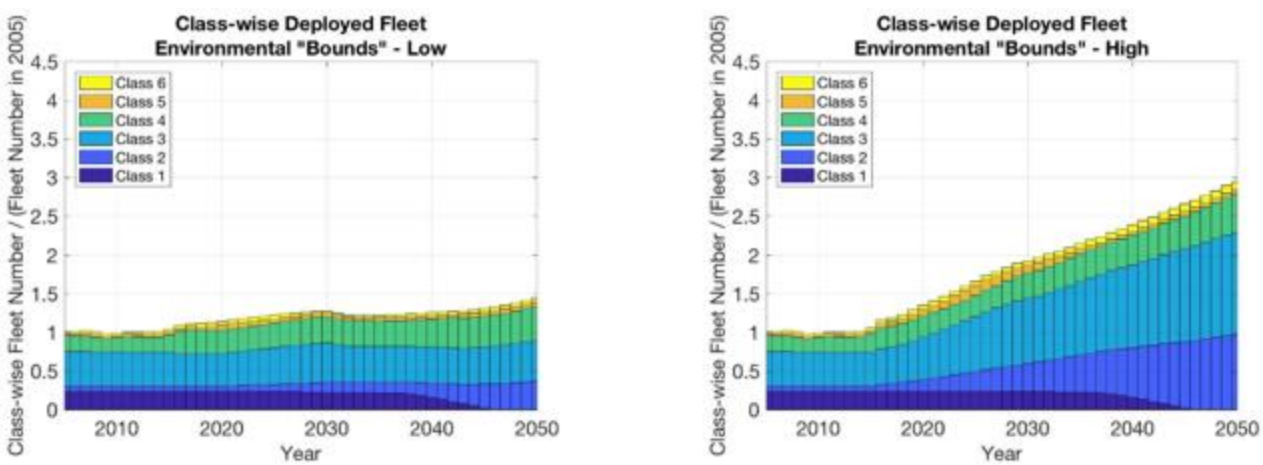


Figure 119: Normalized Deployed Fleet by Class – Environmental Bounds Scenarios

Figure 118 and Figure 119 show the total deployed fleet by aircraft type and class respectively for Environmental Bounds scenarios, normalized by the deployed fleet in 2005. As expected, the Environmental Bounds Low scenario yielded the least growth in total number of aircraft deployed by the FLEET airline of about 1.5 times the value in 2005 by 2050. The total number of aircraft deployed in the Environmental Bounds High scenario increased to about 3 times the number of aircraft deployed in 2005. The significant increase in deployed aircraft in the High Demand scenario, compared to the Environmental Bounds Low scenario, is due to the difference in demand for air travel between both scenarios and noise restriction imposed in the Environmental Bounds Low scenario.

In summary, the GDP growth rates have a positive correlation with CO_2 emissions while R&D levels have a negative correlation with CO_2 emissions, as evidenced by the High Demand Low R&D and Low Demand High R&D scenarios. The technology improvements for airline fleets can reduce emission growths. Moreover, the lower demand and noise-area restrictions can further decrease the number of aircraft operations and reduce emissions even further.

In summary, the Purdue team successfully demonstrated FLEET's capabilities for analyzing the scenarios developed by the largest ASCENT 10 Project team. The demonstrations in the past three years have shown that FLEET is capable of modeling scenarios developed by ASCENT 10 Project partners and provides some unique features that benefit the FAA in tackling challenging fleet-level emissions forecasting problems.

The results from FLEET help indicate how difficult it may be, in future scenarios with increasing demand for air travel, to reduce CO_2 emissions to levels equal or below the levels in 2005. In some scenarios, the future CO_2 emissions do drop below the 2005 level, but not in all scenarios. The approach of FLEET to use an allocation problem to represent scheduling and assignment decisions of a profit-seeking airline, combined with a retirement model to represent when the airline would remove an existing aircraft from its fleet, also illustrates that having the new, more fuel efficient / less CO_2 emitting aircraft rapidly become a major fraction of the airline's fleet is a challenge.

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.

Ogunsina, K., Chao, H., Kolencherry, N., Moolchandani, K., Crossley, W. A., and DeLaurentis, D. A., "A Model of Aircraft Retirement and Acquisition Decisions Based On Net Present Value Calculations," *17th AIAA Aviation Technology, Integration, and Operations Conference*, 2017.

Outreach Efforts

Multiple interactions with government, industry, and academia have occurred during the course of the fleet and technology assumption setting workshops, described in Sections 0 and 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. Current students include Matt Reilly and Braven Leung.

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.

The Purdue University team has had several students work on the ASCENT 10 effort. Parithi Govindaraju assisted with building the allocation model in FLEET; he has defended his PhD thesis and will graduate in 2017 after deposit of the thesis document. Graduate Research Assistants Nithin Kolencherry, Hsun Chao and Kolawole Ogunsina are all continuing in pursuit of their PhD degrees.

Plans for Next Period

This project initially focused heavily on working with industry, government, and academia to establish a set of agreed upon fleet modeling scenarios for future technology assessments. The outcome of work to date includes a set of recommended future scenarios for use in assessing the impact of aviation on fleet wide fuel burn, emissions, and noise. Prior work focused on subsonic transports and this proposed continuation seeks to extend the modeling and assumption setting processes to assess the impact of introducing supersonic commercial aircraft. As such, 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 will continue to collaborate with Purdue University from prior work and will focus on the following objectives.

Research under this research thrust will continue to focus on three primary objectives: (1) Defining Fleet Assumptions; (2) Modeling the impact of vehicle technologies; and (3) assessing the combined impact of vehicle technology and fleet demand and growth.

Georgia Tech will continue to be the lead university with Purdue supporting the objectives as shown in Table 1 in the Project Overview, listing the high-level division of responsibilities amongst the universities.

Table 14: University Contributions

Objectives		Georgia Tech	Purdue
1	Fleet Assumptions & Demand Assessment	Identify supersonic demand drivers and supporting airports	Estimate latent demand and flight schedules for supersonic aircraft
2	Preliminary Vehicle Environmental Impact Prediction	Develop estimates of Key Environmental Indicators (KEI) for supersonic aircraft relative to current technology subsonic, Develop estimates of likely operating altitudes (U.S)	Support with expert knowledge
3	AEDT Vehicle Definition	Test current version of AEDT ability to analyze existing supersonic models	N/A
4	Vehicle and Fleet Assessments	Apply GREAT to estimate impact of supersonics in terms of fuel burn, water vapor, and LTO NOx	Apply FLEET to estimate impact of supersonics in terms of fuel burn, water vapor, and LTO NOx

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