Project 010 Aircraft Technology Modeling and Assessment

Georgia Institute of Technology, Purdue University, Stanford University

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- FAA Award Number: 13-C-AJFE-SU-004
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Project Funding Level

The project is 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 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

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Principal Investigator: Dimitri Mavris
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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. This is a multi-step process involving the system assessment of FAA CLEEN program technologies by Georgia Tech, assessment of the impact of mission specification changes on public domain aircraft performance by Stanford, and the impact of future fleet modeling assumptions on system wide fleet fuel burn and emissions by Purdue.

The research is conducted as a collaborative effort in order to leverage capabilities and knowledge available from the multiple entities that make up the ASCENT university partners and advisory committee. Georgia Tech has partnered with Purdue University and Stanford University to complete the following objectives.

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

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

Table 1: University Contributions

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

All three universities contributed to the development of harmonized fleet assessment assumptions. These assumptions formed the basis of both the proprietary and public domain modeling work currently being performed.

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

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

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

Major Accomplishments

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

Fleet Level Workshop Assumption Setting

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

Technology Level Workshop Assumption Setting

Final fleet assessment scenarios have been developed through the work of the team. These scenarios, presented in 0, provide a brief summary of the fleet assessment scenarios. The scenarios are descriptive, but tool agnostic. The defined fleet scenarios are intended to provide bounding cases on future U.S. fleet-wide performance to inform technology development and goal setting.

Demonstration of FLEET

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

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 (section 0). The Stanford team has also supported the team's activities for the preparation and conduct of both the fleet-level and technology workshops.

Task 1: Developing Fleet Assumptions

Objective(s)

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

Research Approach

Research Approach Overview

The approach taken here is to reduce the overwhelming dimensionality by selecting a small number of well-defined scenarios. The scenarios should encompass future states that are important for specific consideration of significant changes that could occur and also to bind some of the most important future outcomes that could conceivably occur. Therefore, the first goal of the workshop series was to define a range of scenarios to bound aviation's environmental impacts in the future and to examine the effects of aircraft technology on these impacts.

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

Fleet Workshops

Based on the Fleet Scenario Workshops that were conducted through Summer and Fall 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 2. 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.

	GDP Growth (%/year)	Energy Price ($/bbl)	Population Growth (%/year)	International Trade (%/year Asia)	Industry Competetivenes s (cent/ASM)	Airport Noise Limitations (% airports noise limited in future)	Cost of CO2 Emissions ($/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

TABLE 2: MATRIX OF SCENARIOS AND DEMAND AND ECONOMIC 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 3: MATRIX OF SCENARIOS AND FLEET EVOLUTION 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

TABLE 4: MATRIX OF SCENARIOS AND AIRCRAFT TECHNOLOGY MODEL FACTORS

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 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 the 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 1. 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

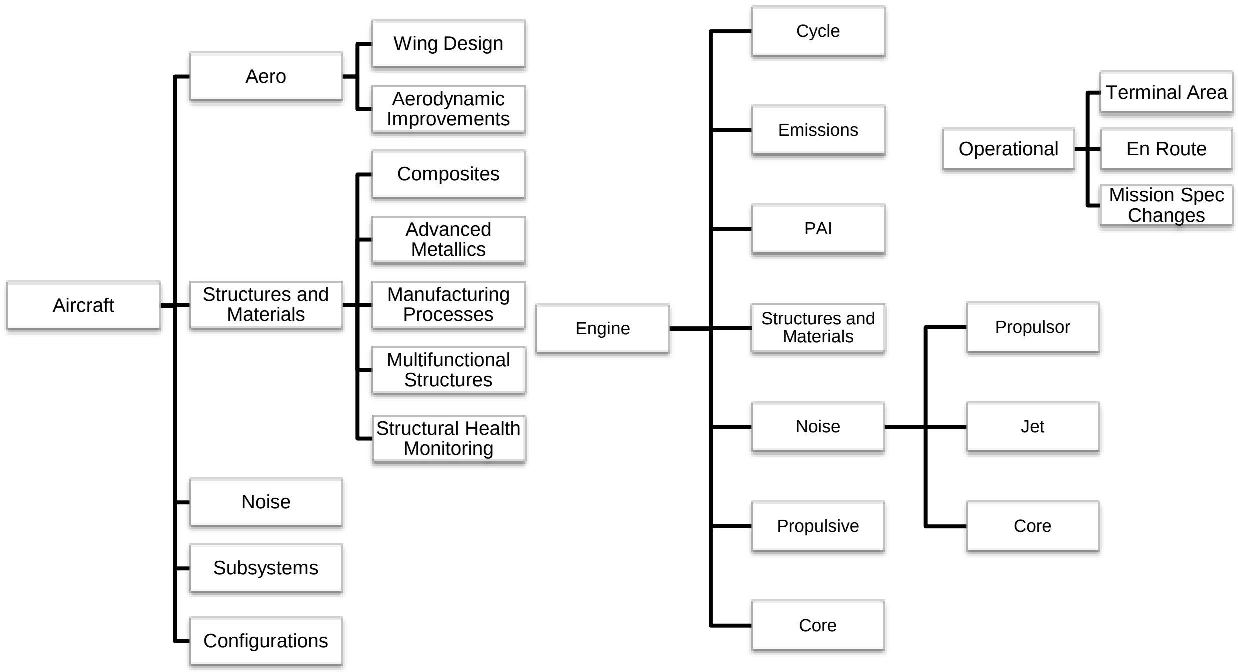


Figure 1: Technology Categorization

There are a few technology categories in Figure 1 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 1, 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 2. The figure shows 1st generation wing design; however, all technology areas had a consistent structure, with the contents of each colored box adjusted accordingly.

Survey Format

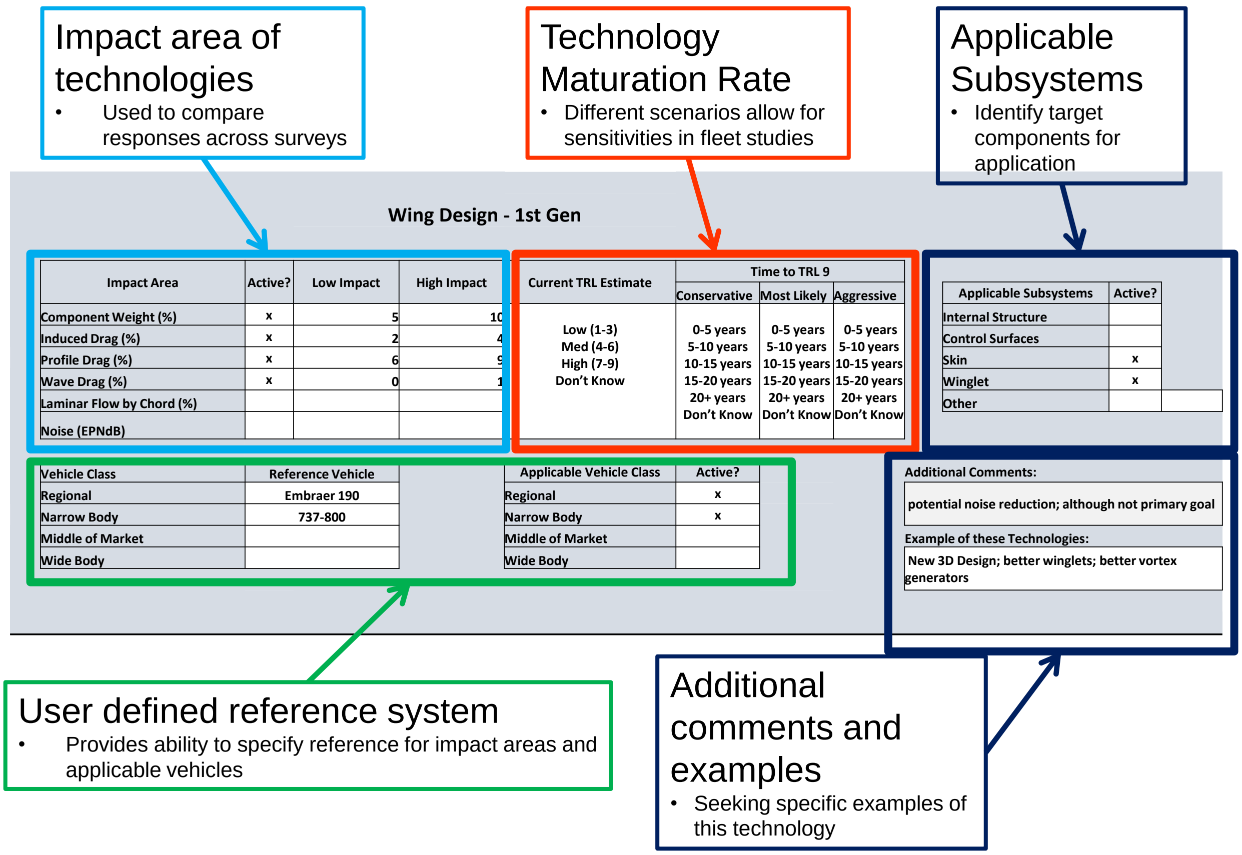


Figure 2: Technology Roadmapping Survey 1 Format

Working clockwise from the upper left of Figure 2, participants were asked for information on the impact of each generation within a technology category. The impact areas were chosen to be at an intermediate level of fidelity. For example, the wing design impacts were solicited as percent reductions from the current state of the art for weight, drag, laminar flow, and noise. Since multiple technologies could be included in a first generation wing design, participants were asked to list the total benefits for all technologies being considered. Moving to the right, the red box asked for the current TRL and estimated time to TRL 9. The current TRL estimate was grouped into low (TRL 1-3), medium (TRL 4-6), and high (TRL 7-9). This grouping was selected to allow for multiple technologies to be included in a generation, reduce the possibility of asking for sensitive data, and to account for some level of uncertainty in the technology development process. Under the time to TRL 9, responses were sought for three scenarios, a conservative, most likely, and aggressive technology progression. Possible responses were grouped into 5 year bins up through 20+ years. Moving to the upper right, applicable subsystems were listed for each technology area with check boxes that participants could easily select. On the lower left, participants were asked to provide a reference system which they used to estimate the reductions listed in the impact areas. Vehicle applicability was also requested to identify applicable size classes for the technology. Finally, write-in boxes were provided in the lower right to allow for any comments and concerns in addition to specific examples of technologies that should be classified within the provided technology area and generation.

Table 5 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 5: 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)	NOx (%) 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 6.

Table 6: 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 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 fixed, 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 3 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 provided, which for the most part was computed as the average of the bounds of the range. 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.

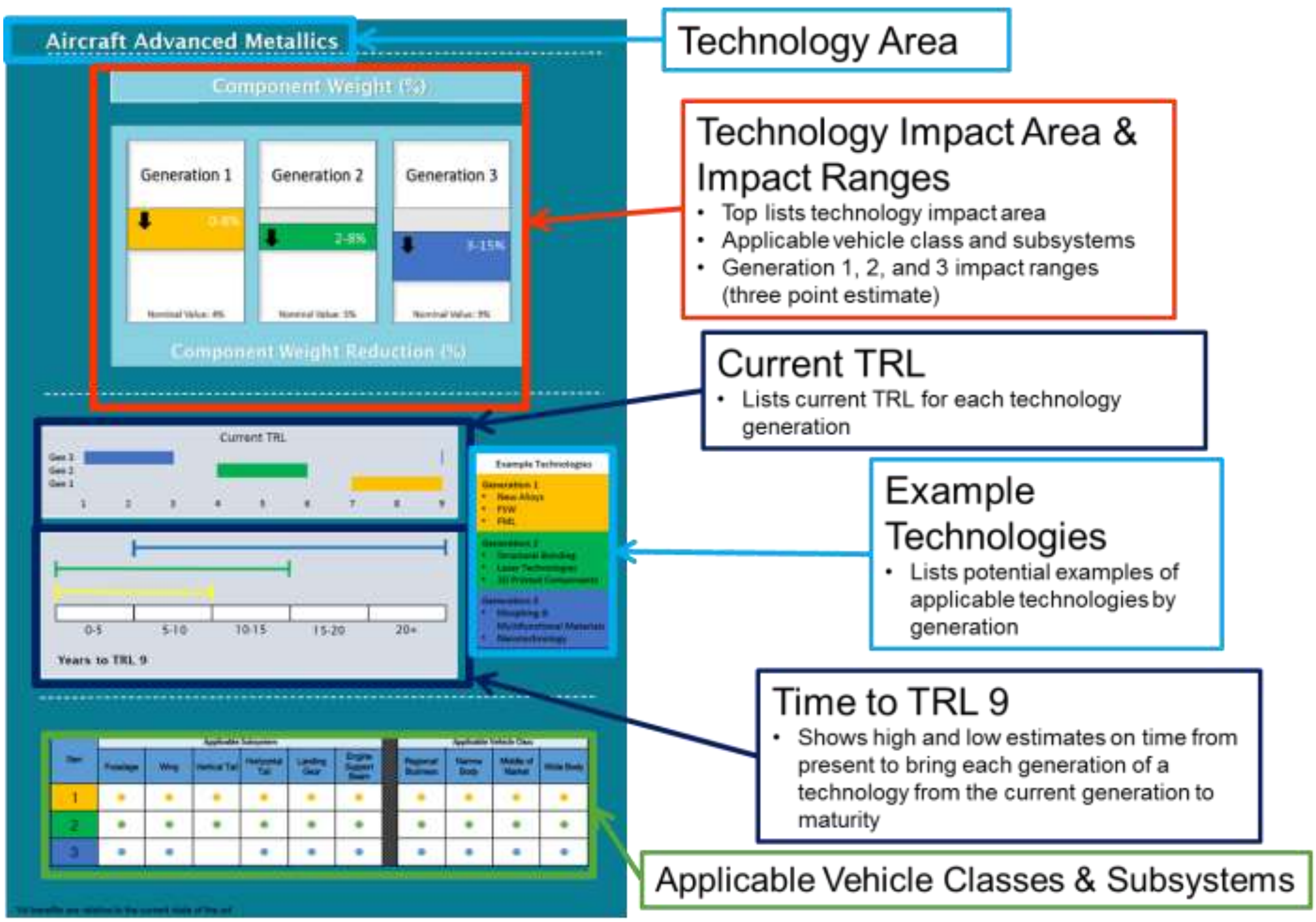


Figure 3: Initial Technology Roadmap Infographic Format Presented at Technology Roadmapping Workshop 2.

Technology Roadmapping Survey 2 Format

The goal of the second Technology Roadmapping Workshop was to send participants the infographics to discuss and provide feedback on the range of responses given in the first workshops. Using the infographics kept the results anonymous, which helped avoid any bias and ensured participants were viewing the results objectively. As seen in Figure 4, the Technology Roadmapping Survey 2 format was straightforward. For each technology area, participants were asked to review the results 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.

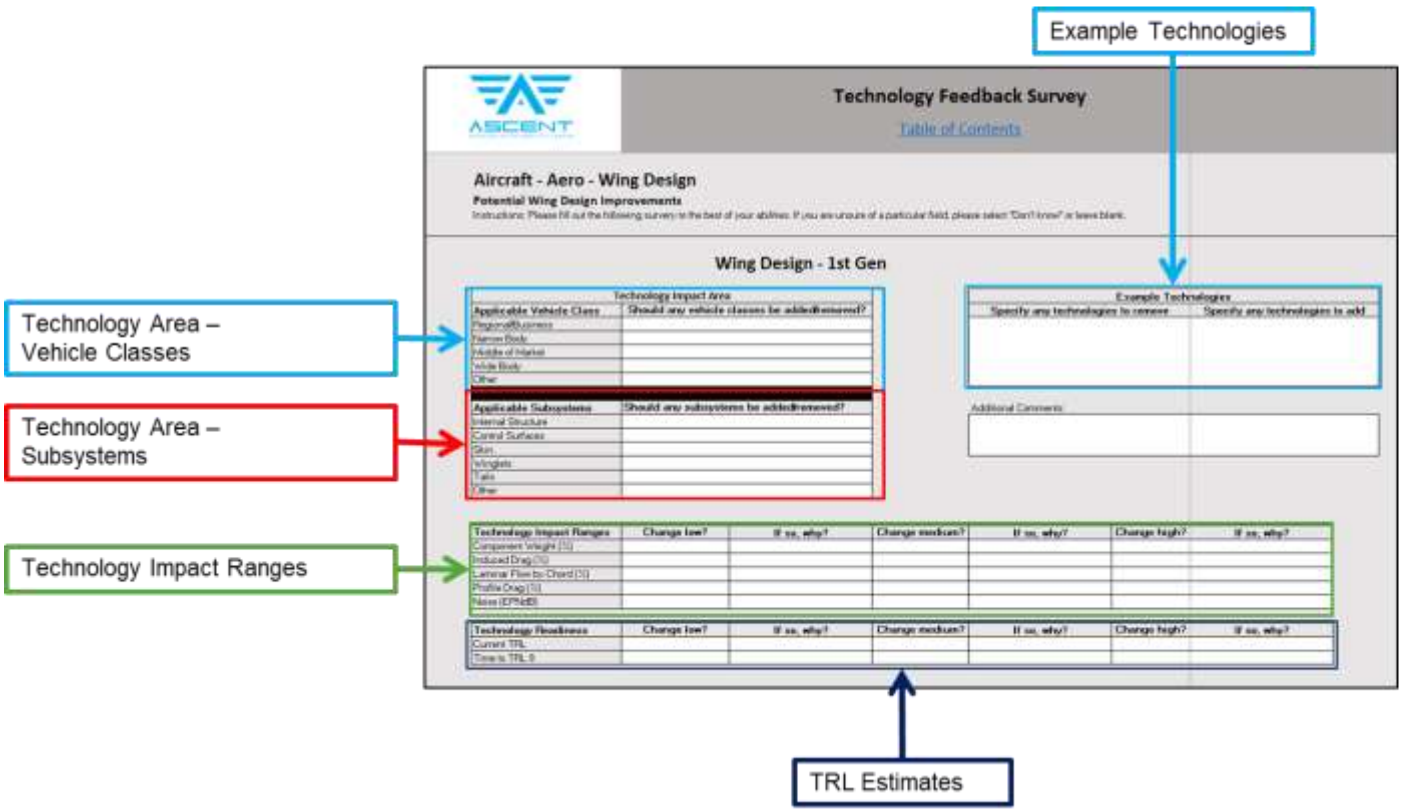


FIGURE 4: TECHNOLOGY ROADMAPPING SURVEY 2 FORMAT

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 low and provided reasoning. They also noted studies to look at 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 it was assigned to. 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 3, 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 5 to Figure 26. These final infographics will be the basis for a document that will be made publically available on the results of this project.

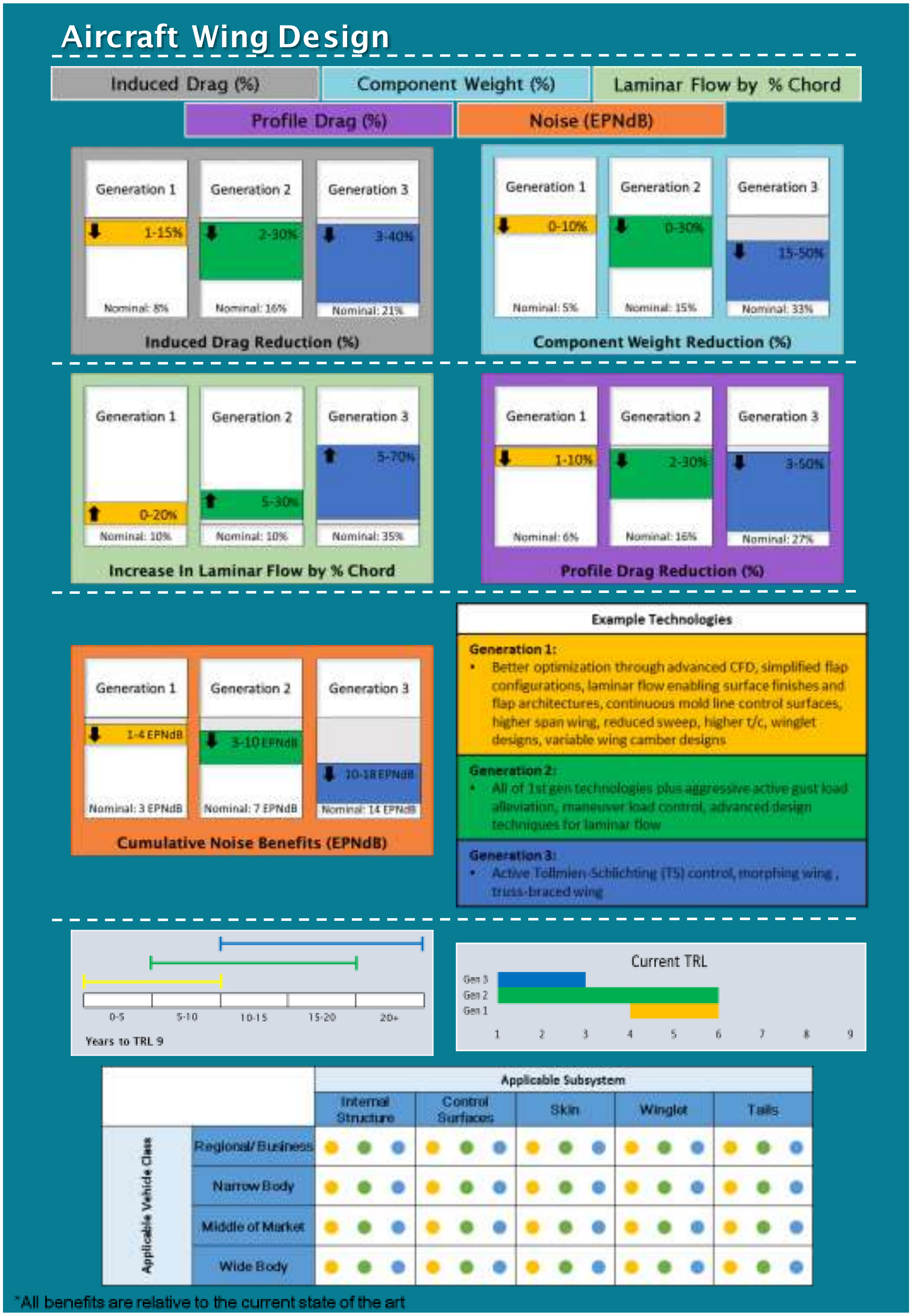


FIGURE 5. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT WING DESIGN

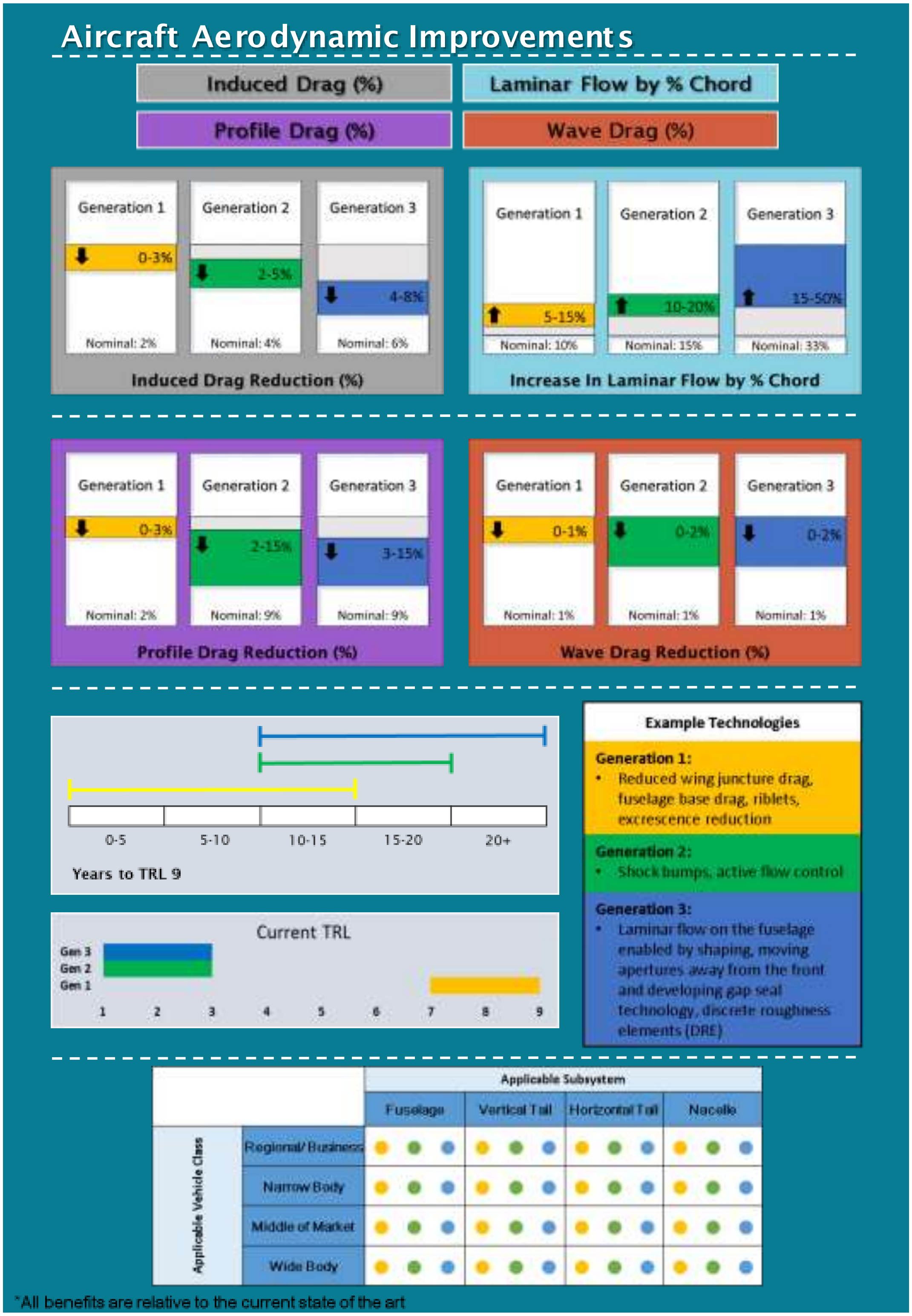


FIGURE 6. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT AERODYNAMIC IMPROVEMENTS

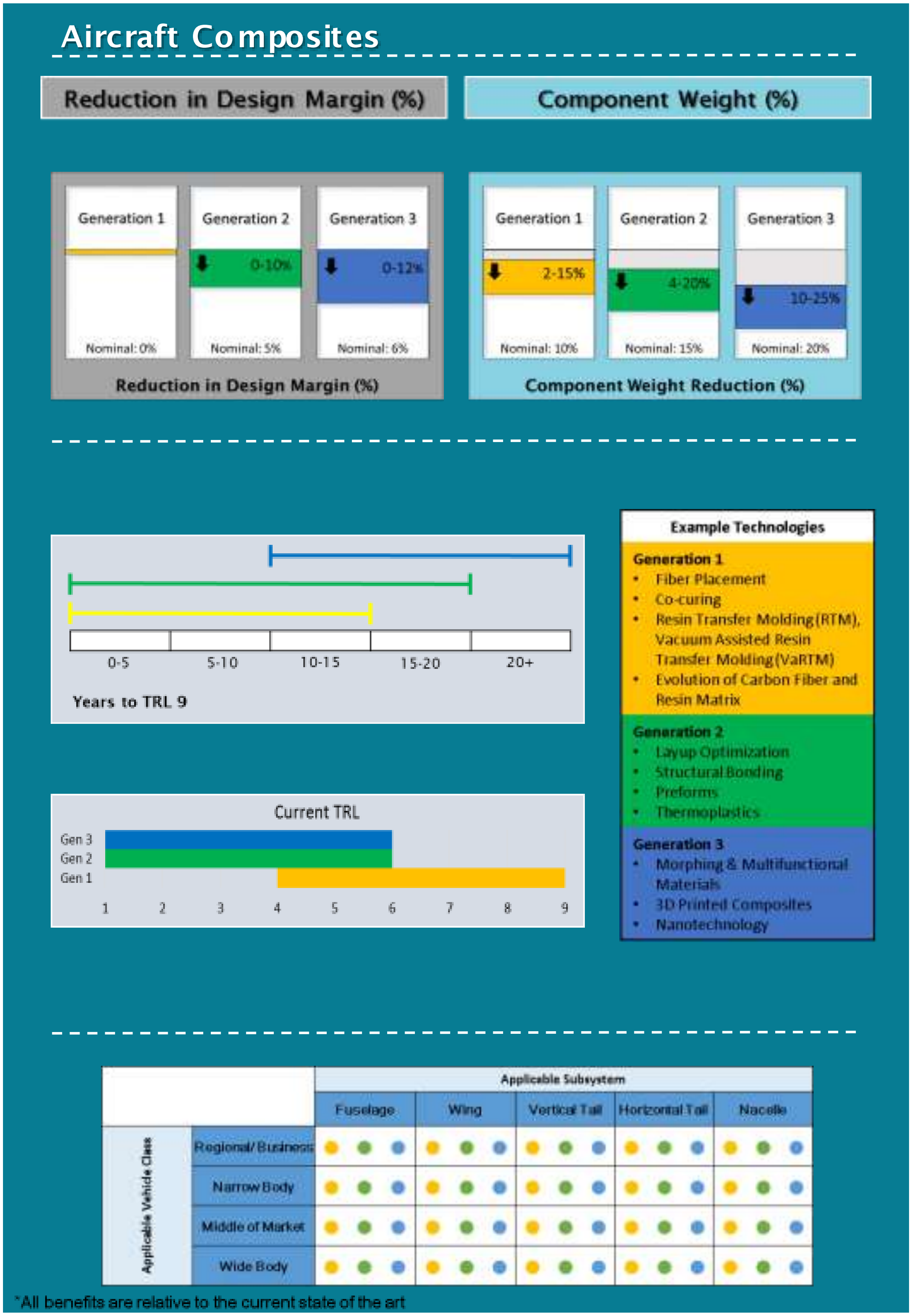


FIGURE 7. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT COMPOSITES

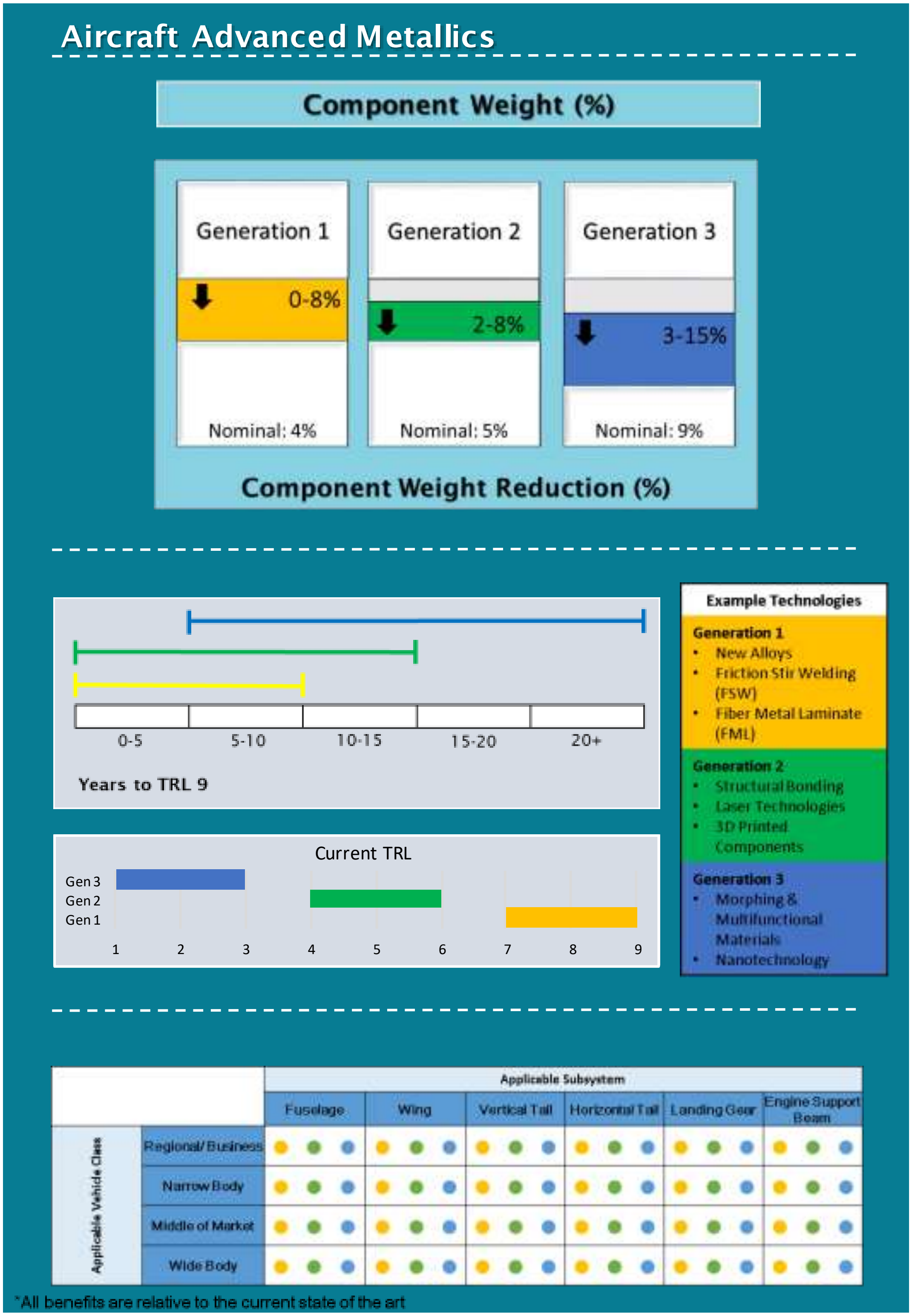


FIGURE 8. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT ADVANCED METALLICS

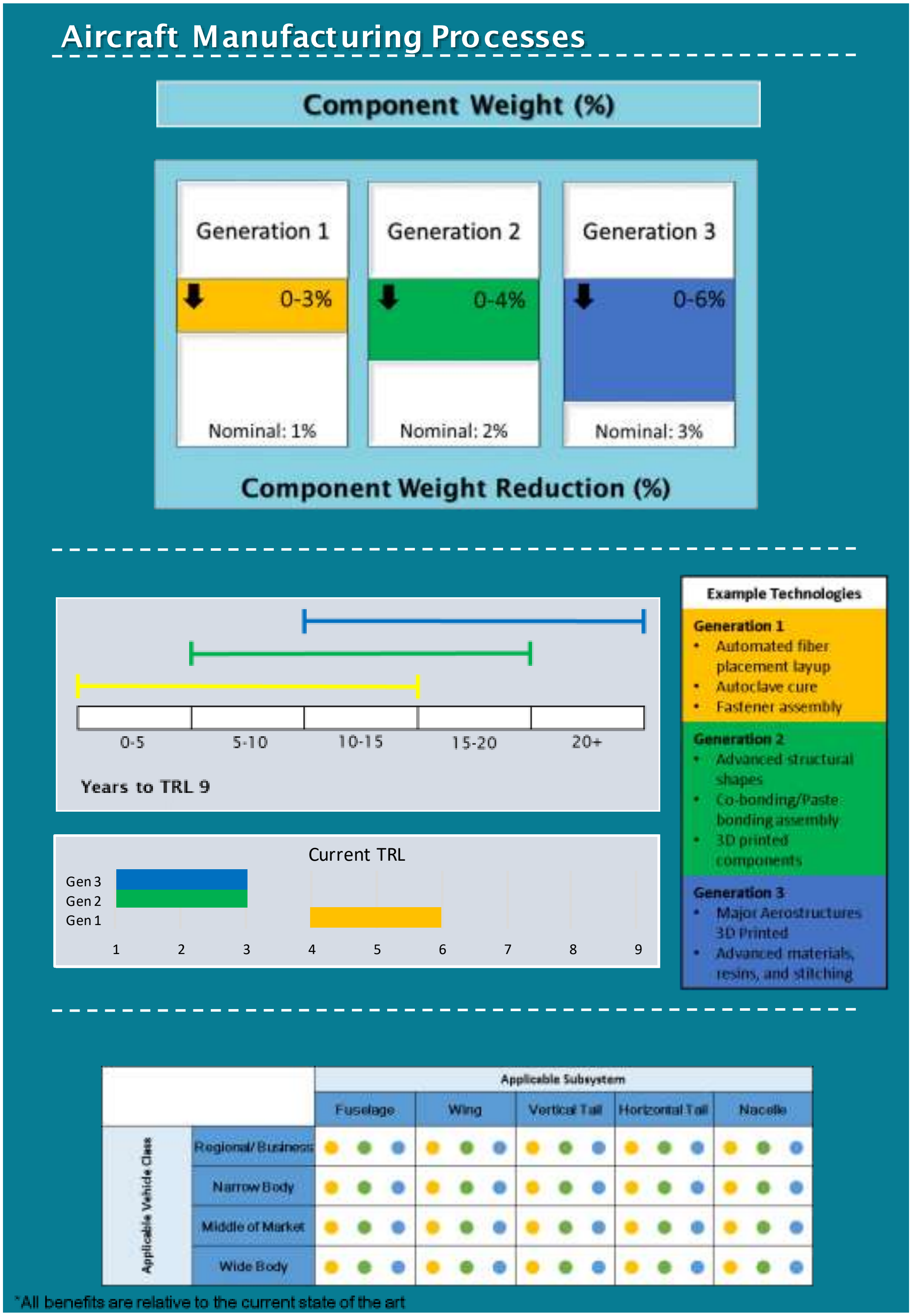


FIGURE 9. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT MANUFACTURING PROCESSES

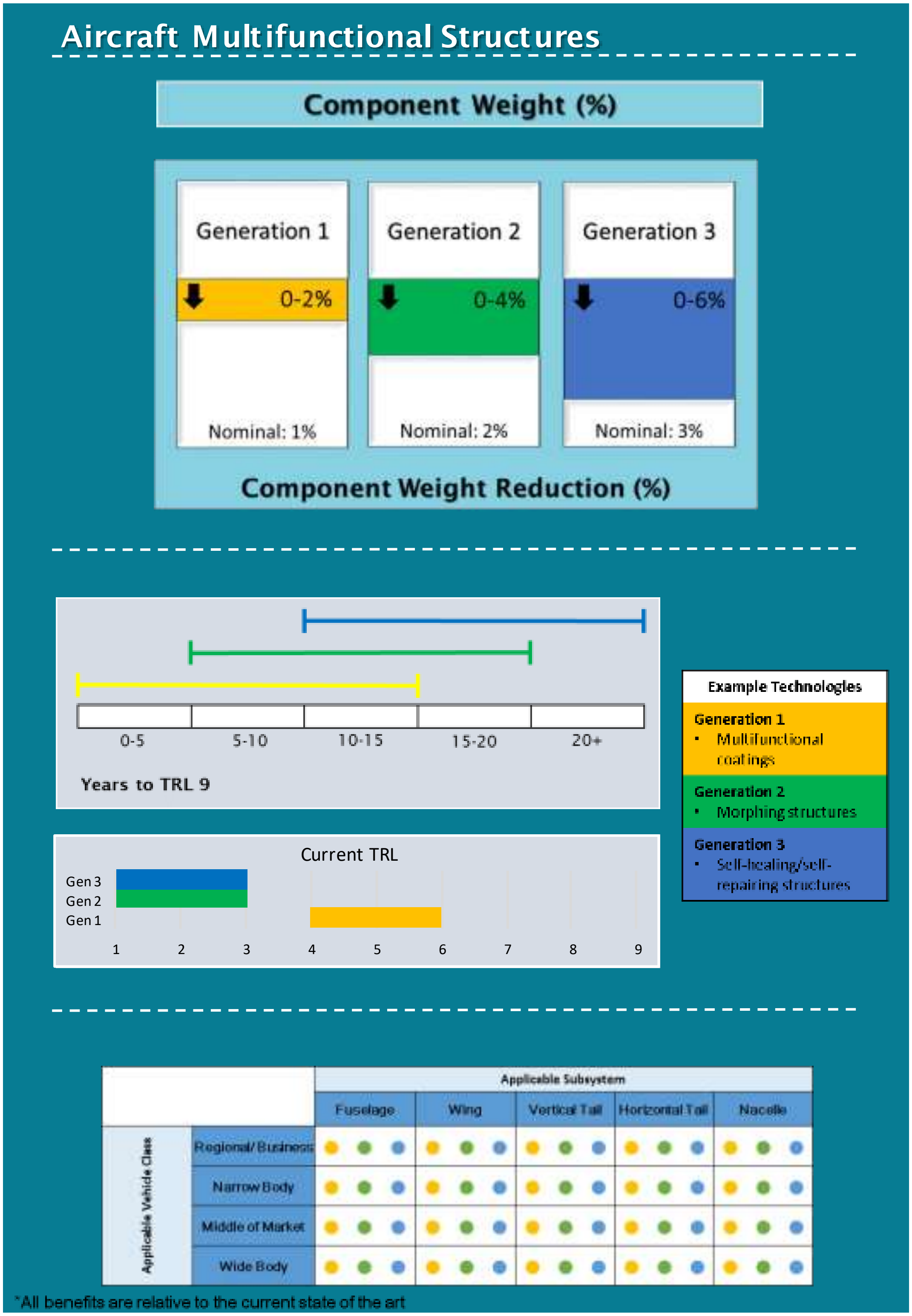


FIGURE 10. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT MULTIFUNCTIONAL STRUCTURES

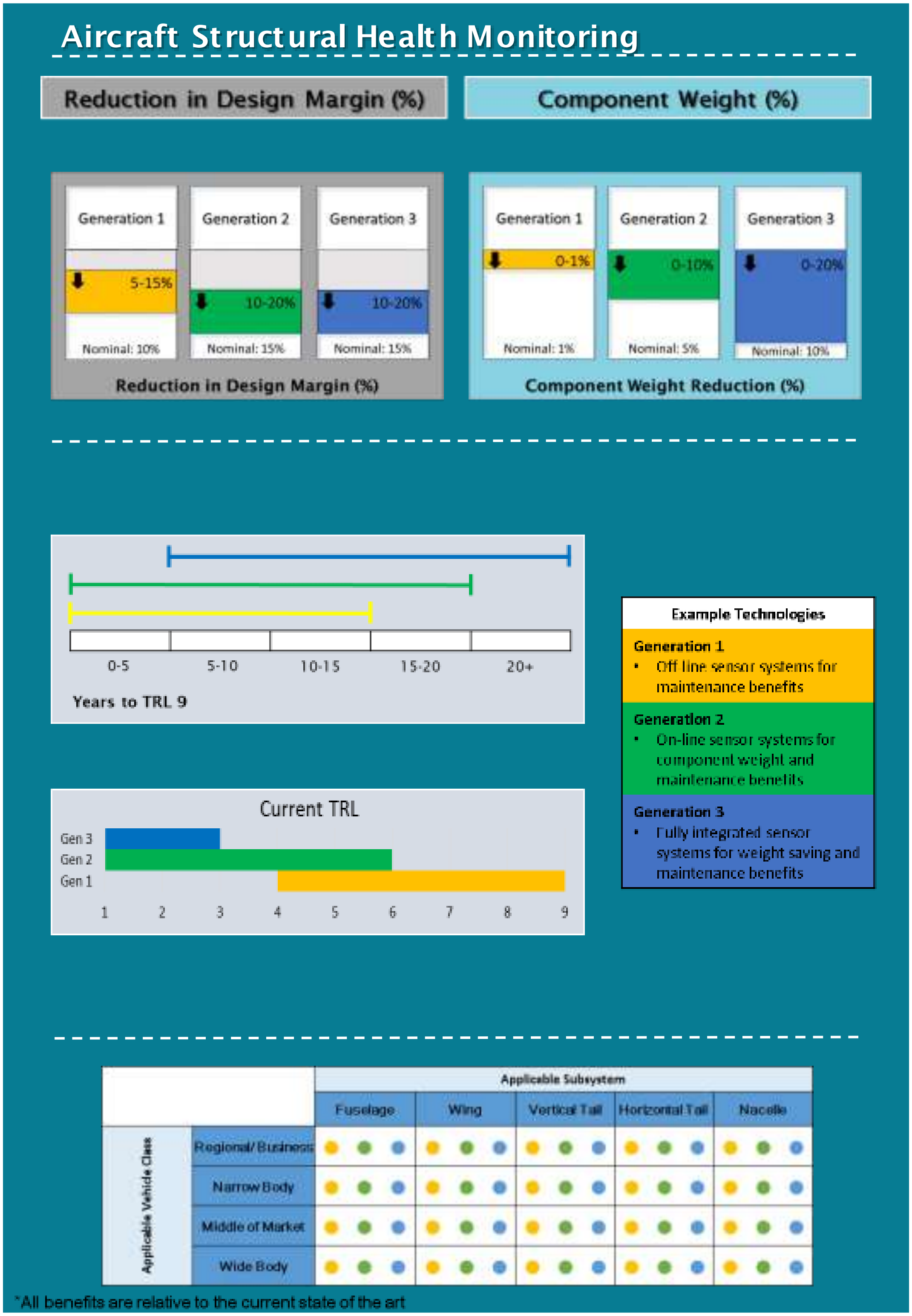


FIGURE 11. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT STRUCTURAL HEALTH MONITORING

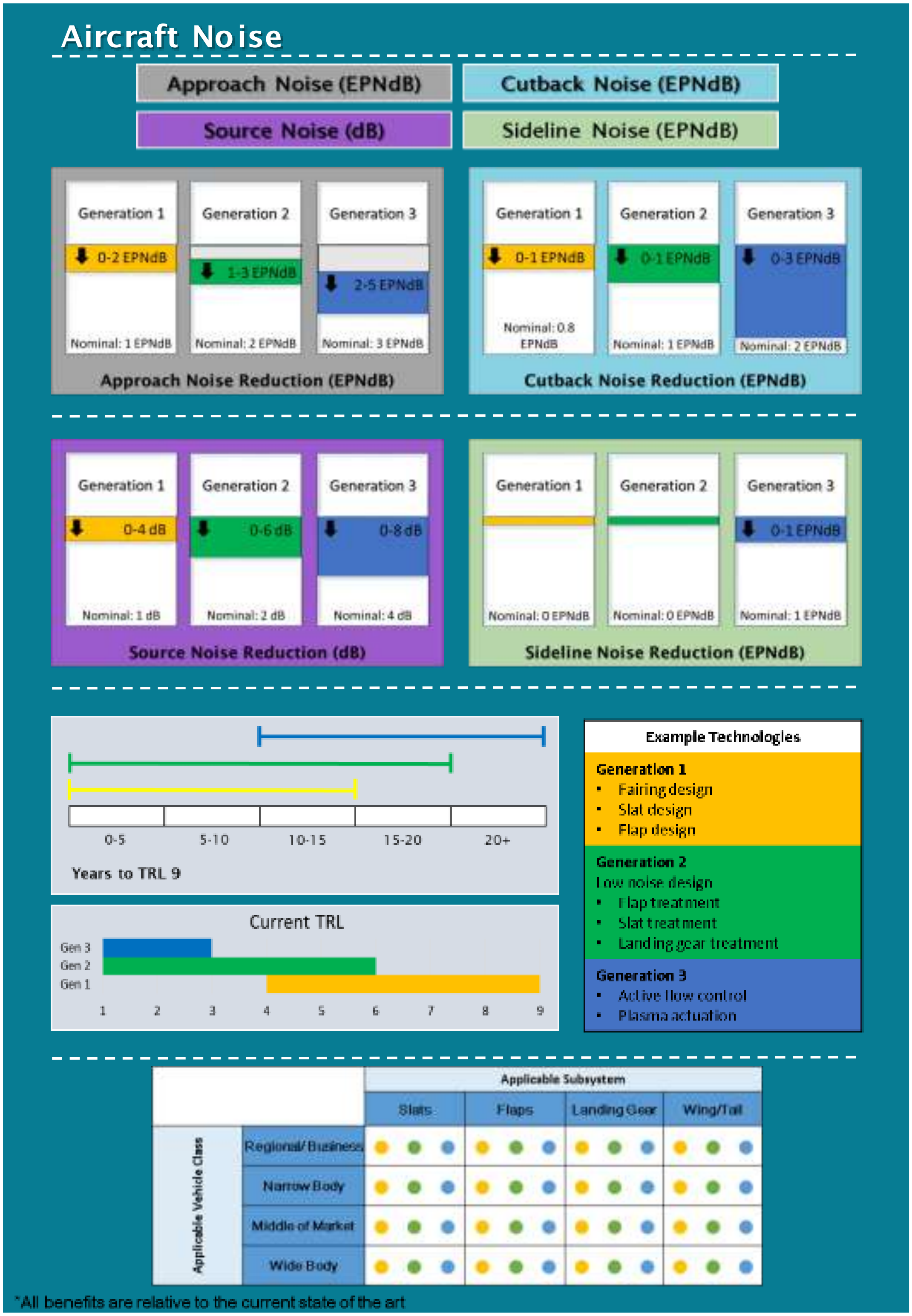


FIGURE 12. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT NOISE

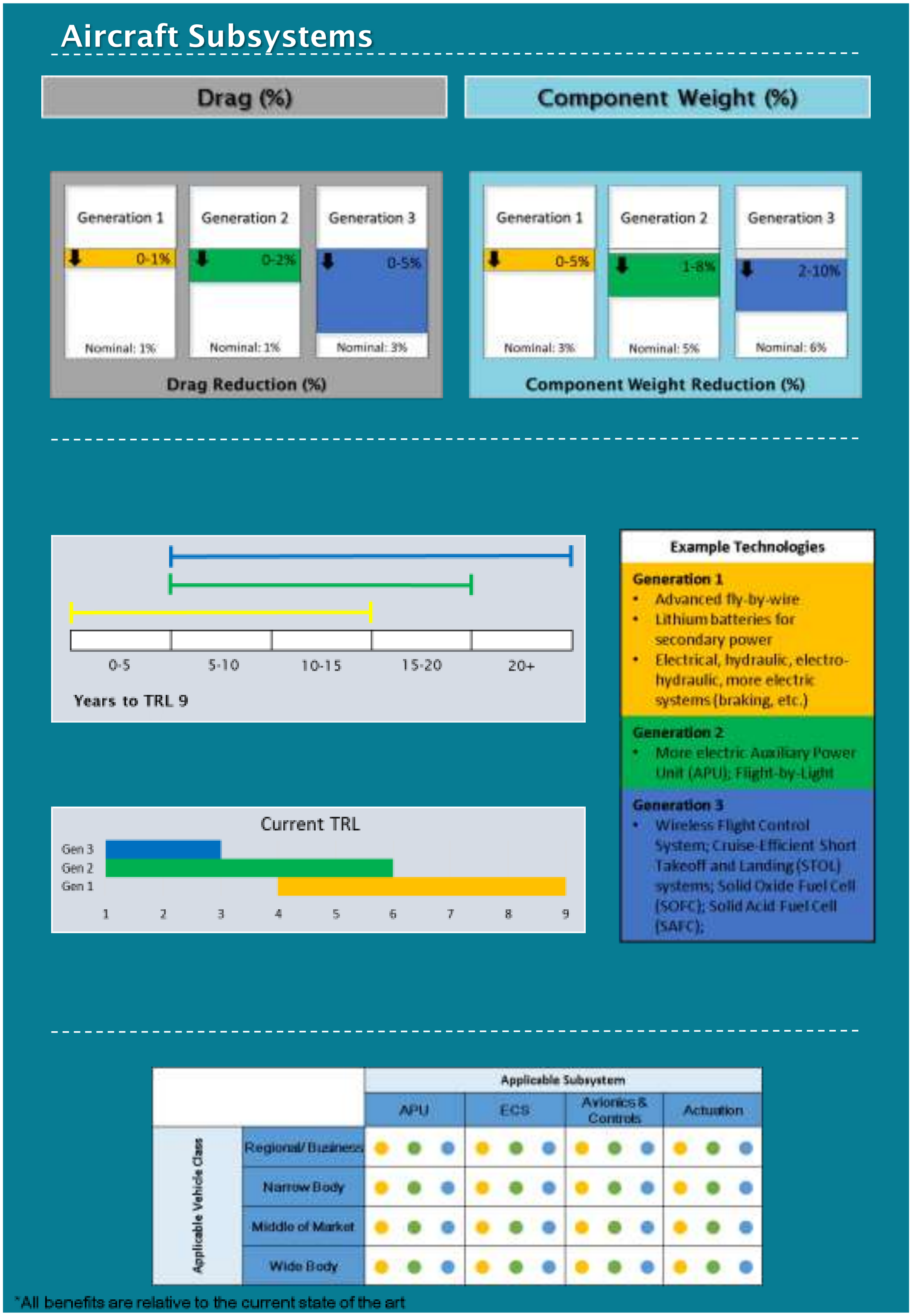
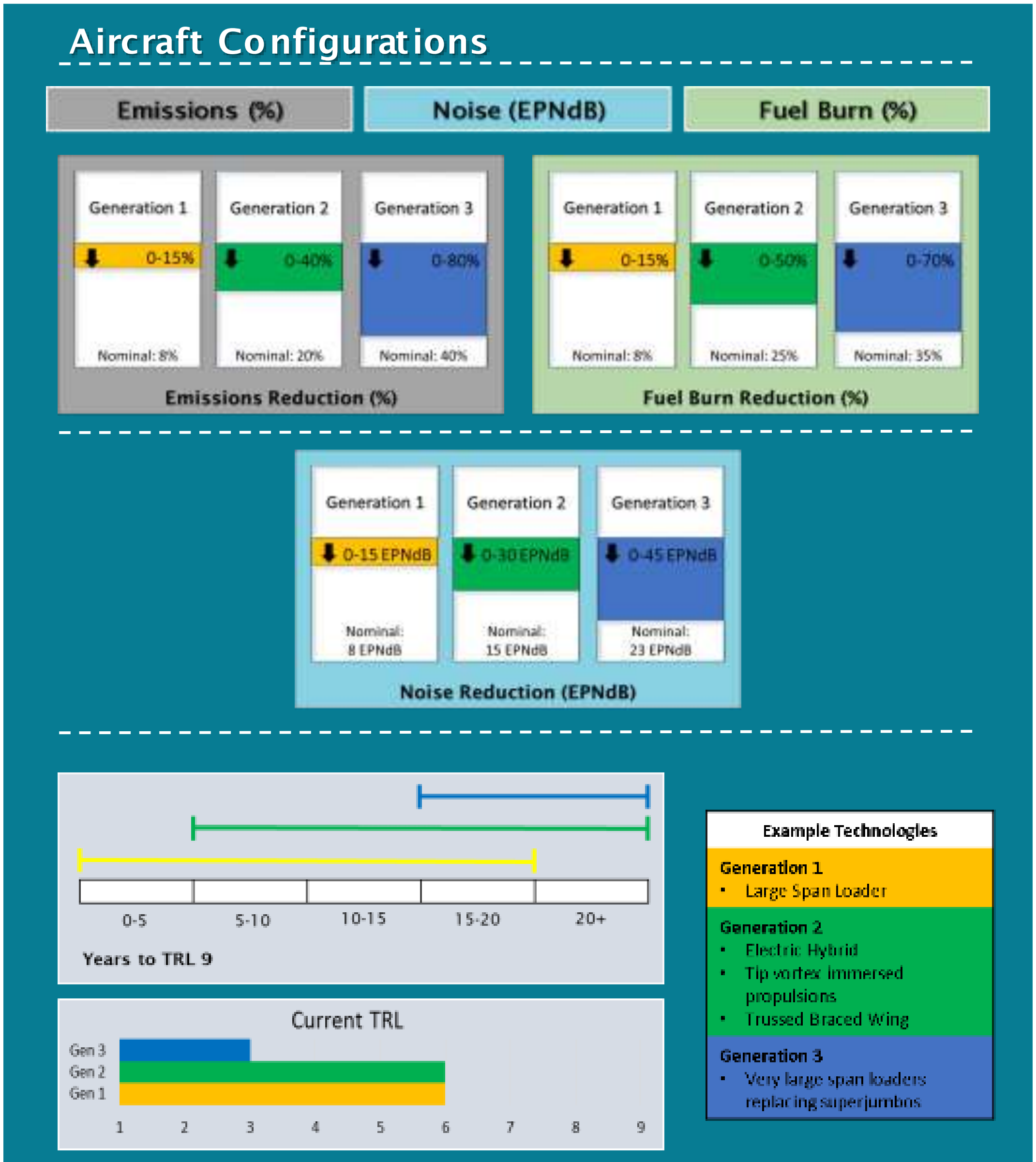


FIGURE 13. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT SUBSYSTEMS



Applicable Vehicle Class		Truss Braced Wing	Hybrid Wing Body	Double Bubble	Electric Hybrid	Tip Vortex Immersed Propulsion	Very Large Span Loader
		Applicable Subsystem					
	Regional/ Business	●	●	● ●	● ●	● ●	
	Narrow Body	●	●	● ●	●	● ●	
	Middle of Market	●	●	●	●	● ●	● ●
	Wide Body		● ●	●		● ●	● ●

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

FIGURE 14. FINAL TECHNOLOGY ROADMAPS FOR AIRCRAFT CONFIGURATIONS

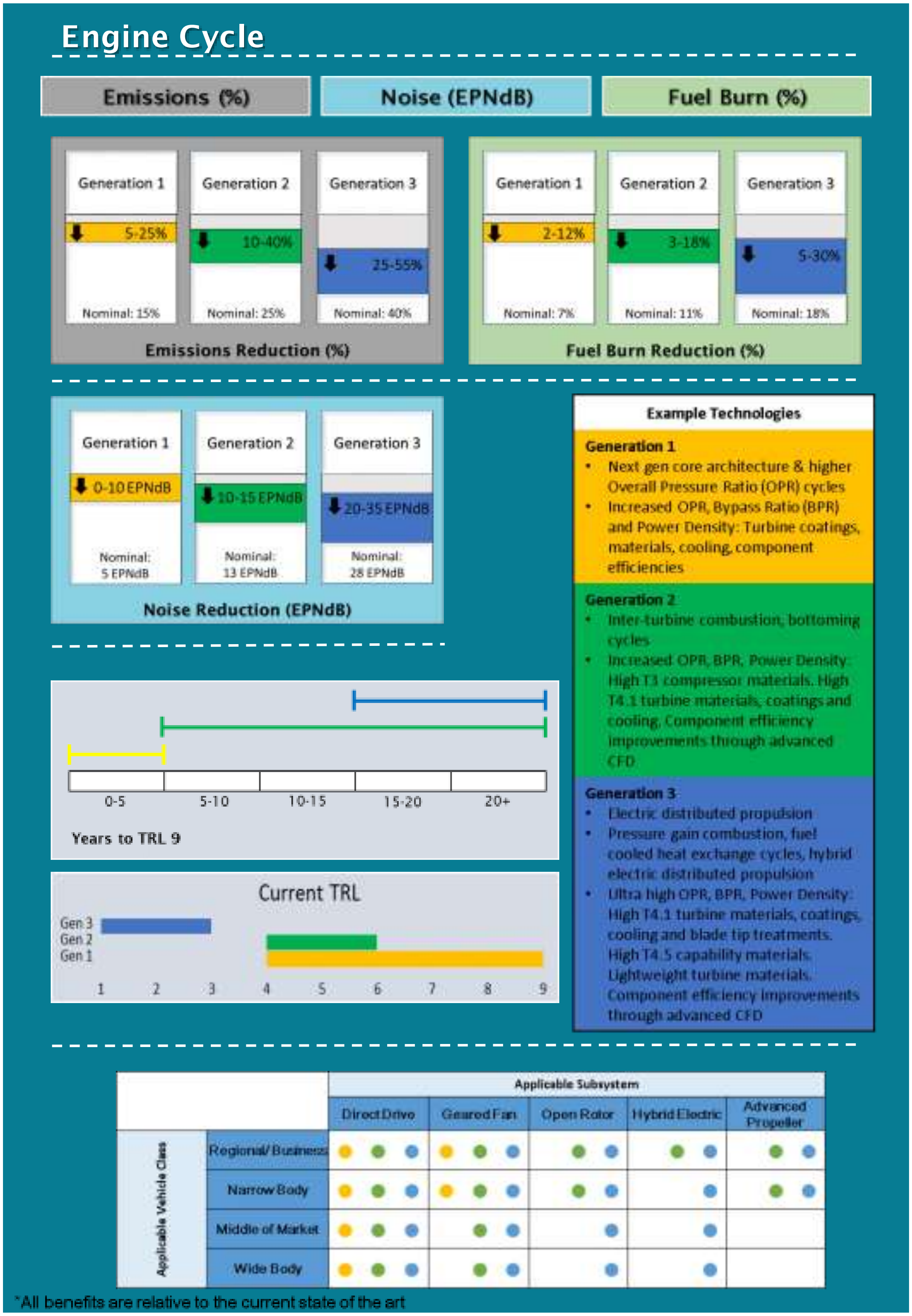


FIGURE 15. FINAL TECHNOLOGY ROADMAPS FOR ENGINE CYCLE

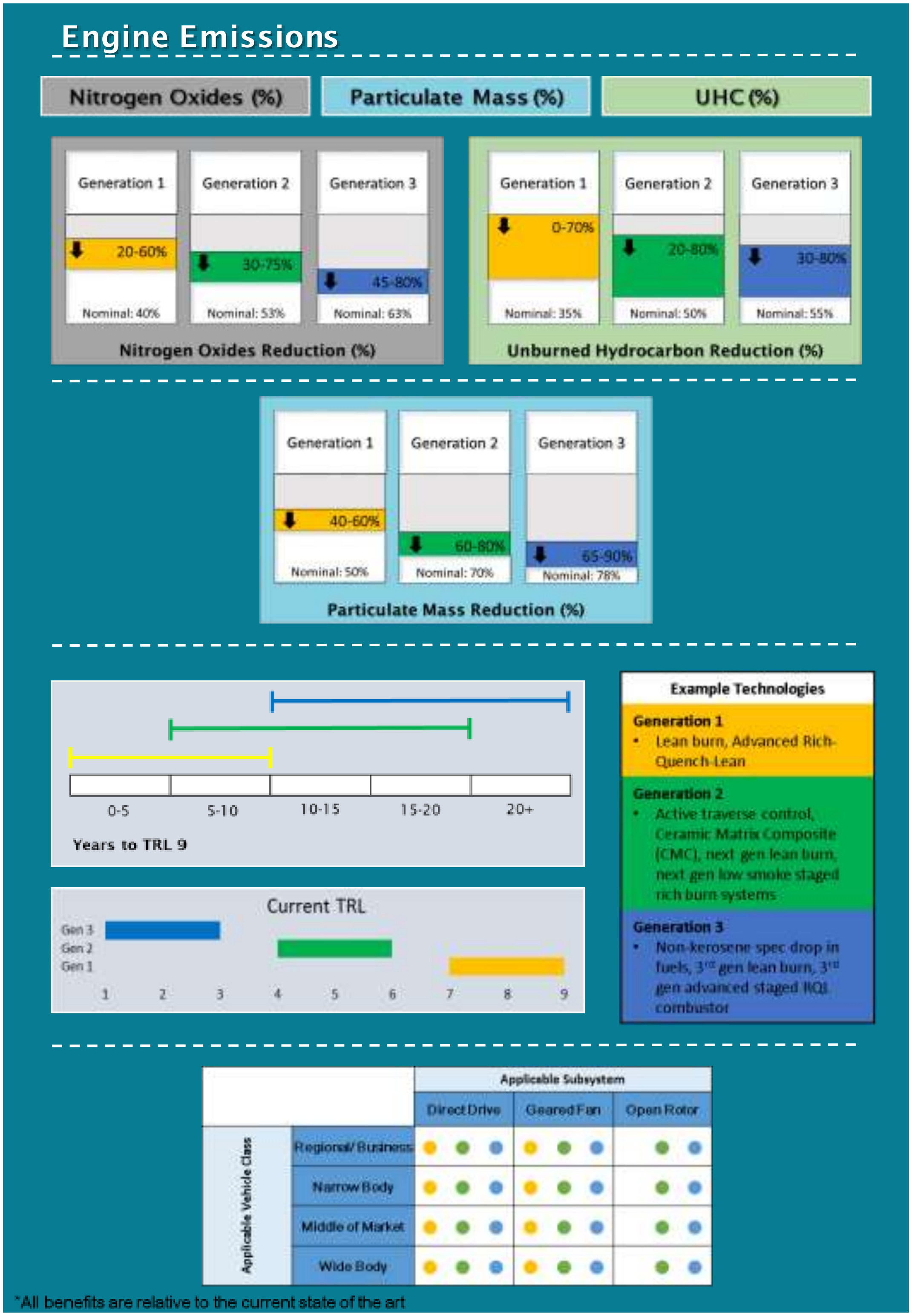


FIGURE 16. FINAL TECHNOLOGY ROADMAPS FOR ENGINE EMISSIONS

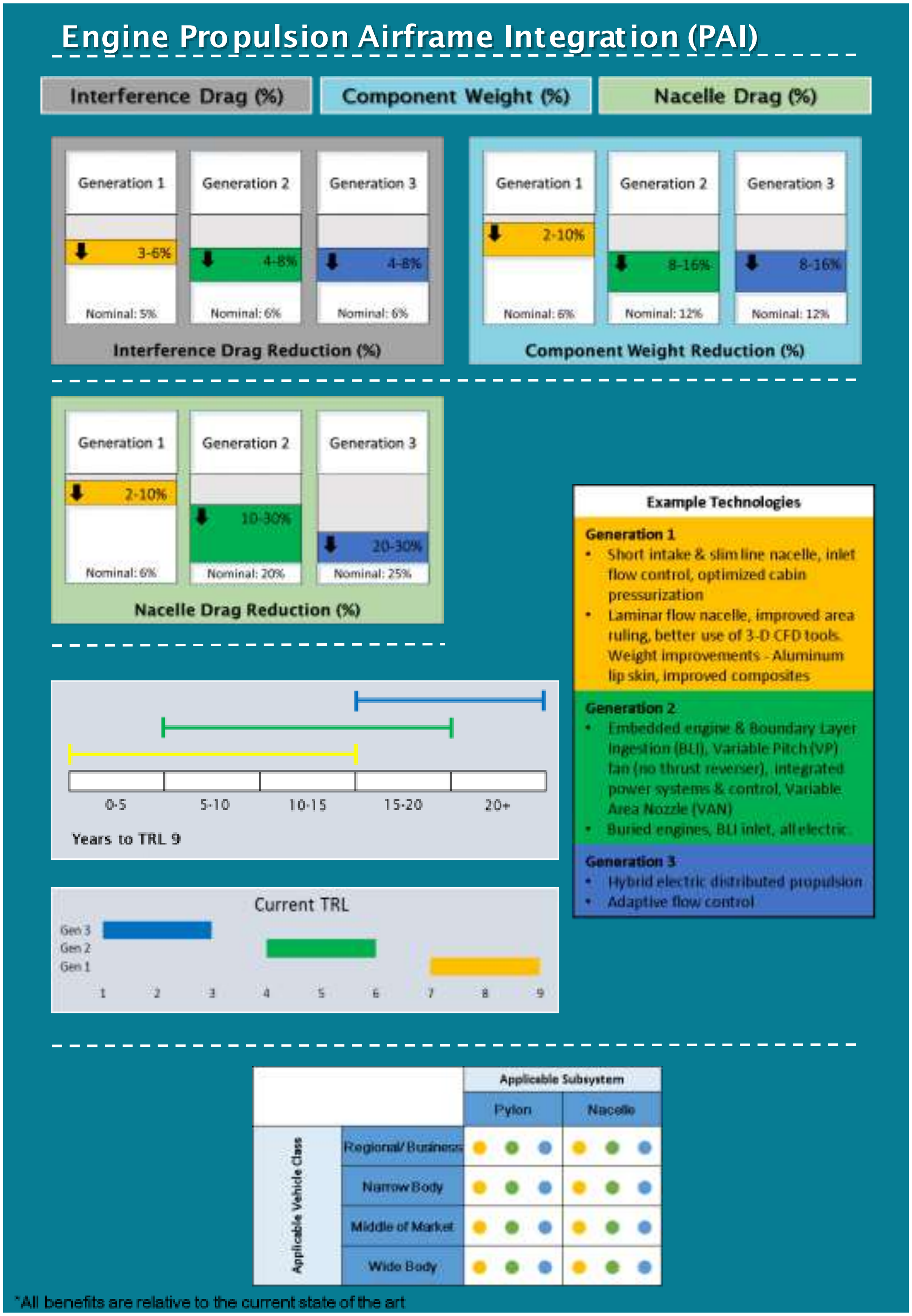


FIGURE 17. FINAL TECHNOLOGY ROADMAPS FOR ENGINE PAI

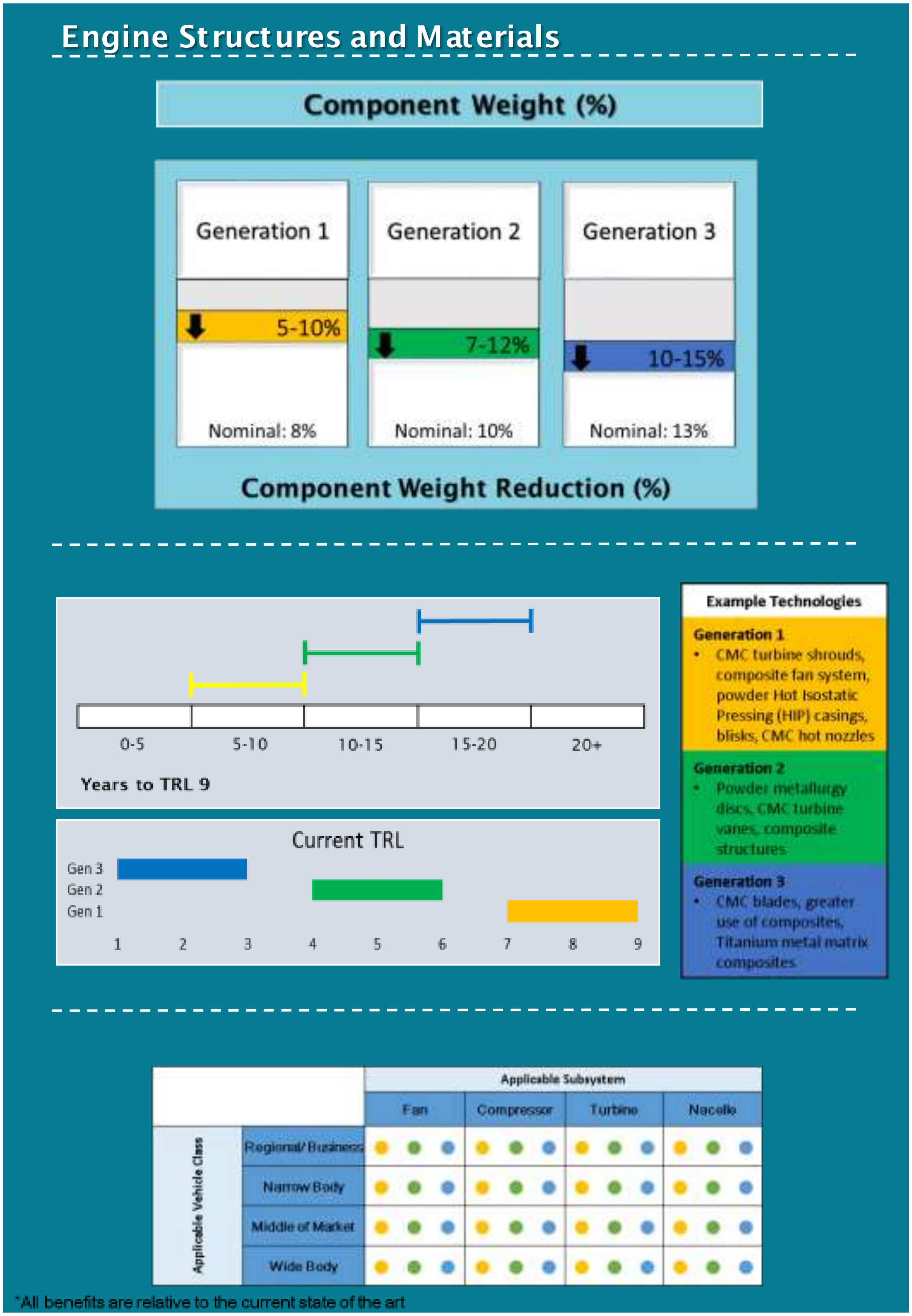


FIGURE 18. FINAL TECHNOLOGY ROADMAPS FOR ENGINE STRUCTURES AND MATERIALS

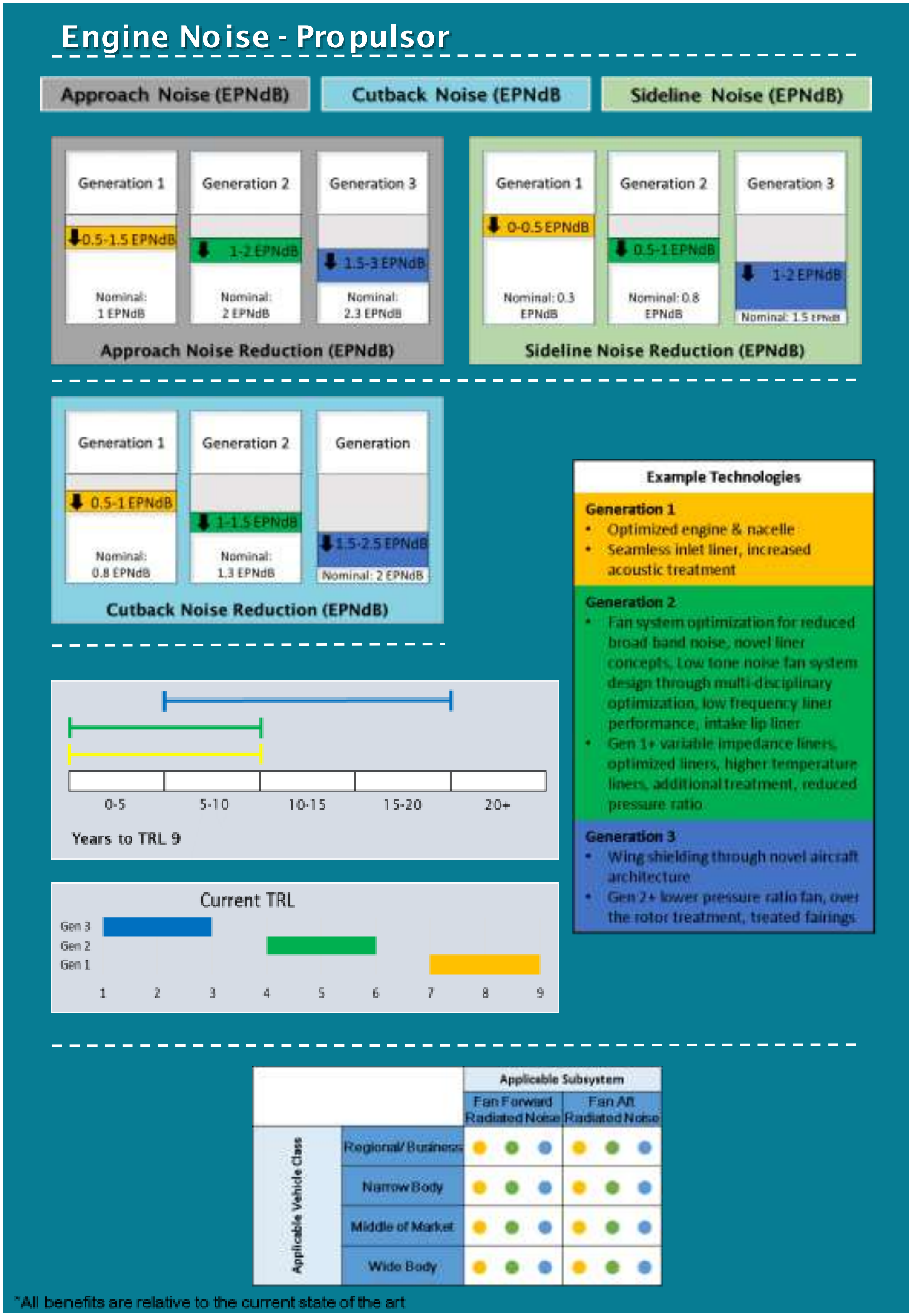


FIGURE 19. FINAL TECHNOLOGY ROADMAPS FOR ENGINE NOISE-PROPULSOR

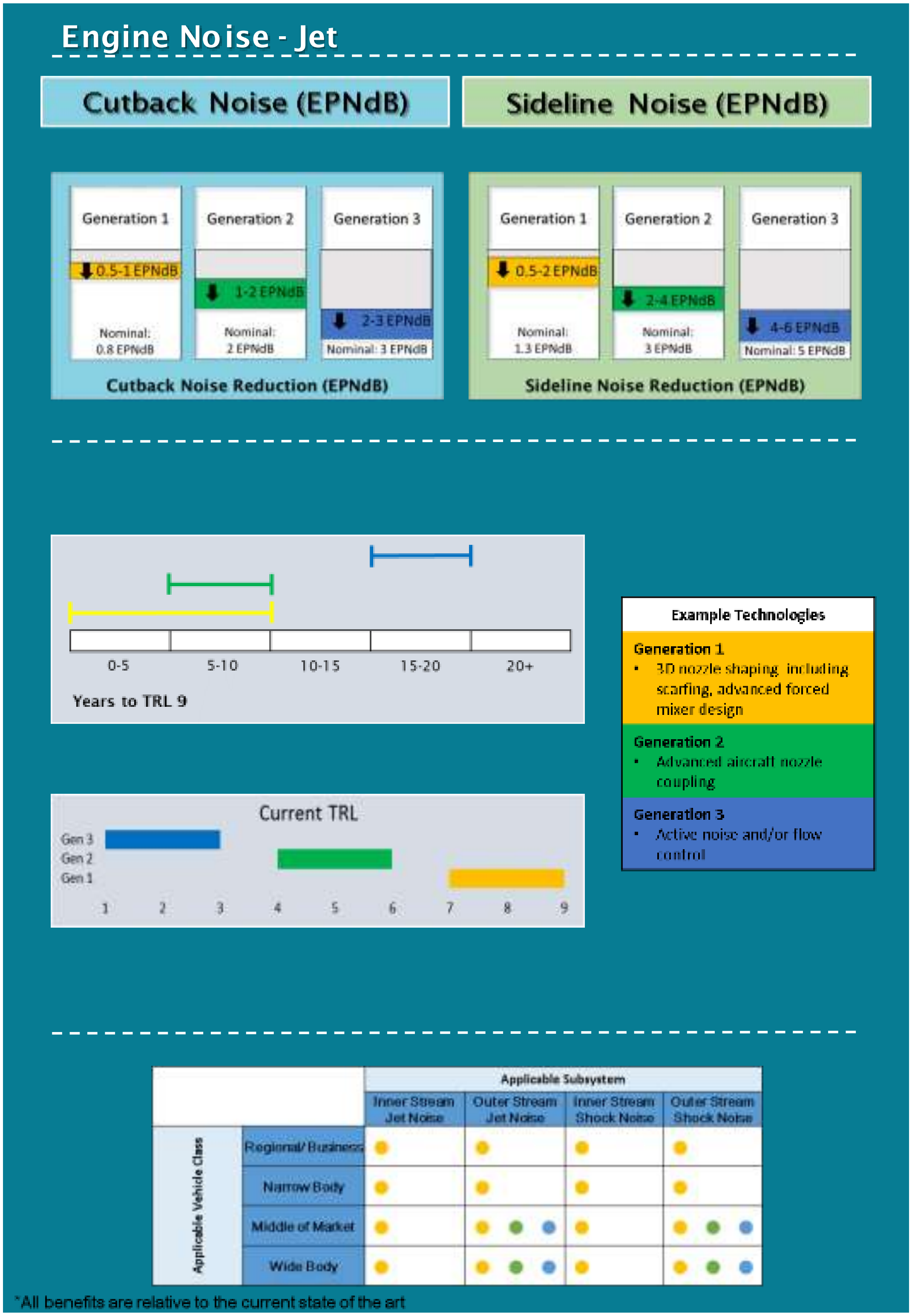


FIGURE 20. FINAL TECHNOLOGY ROADMAPS FOR ENGINE NOISE-JET

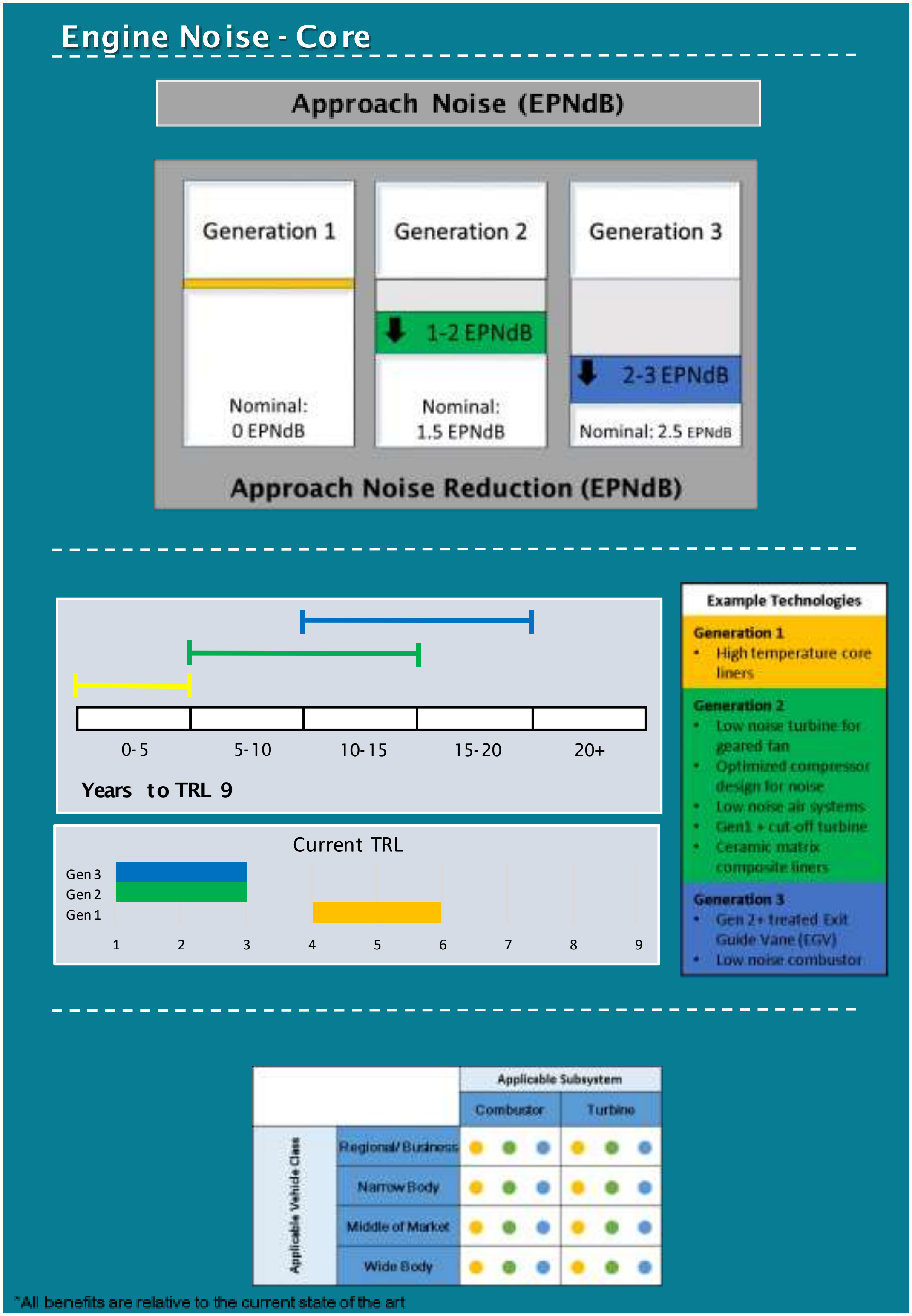


FIGURE 21. FINAL TECHNOLOGY ROADMAPS FOR ENGINE NOISE-CORE

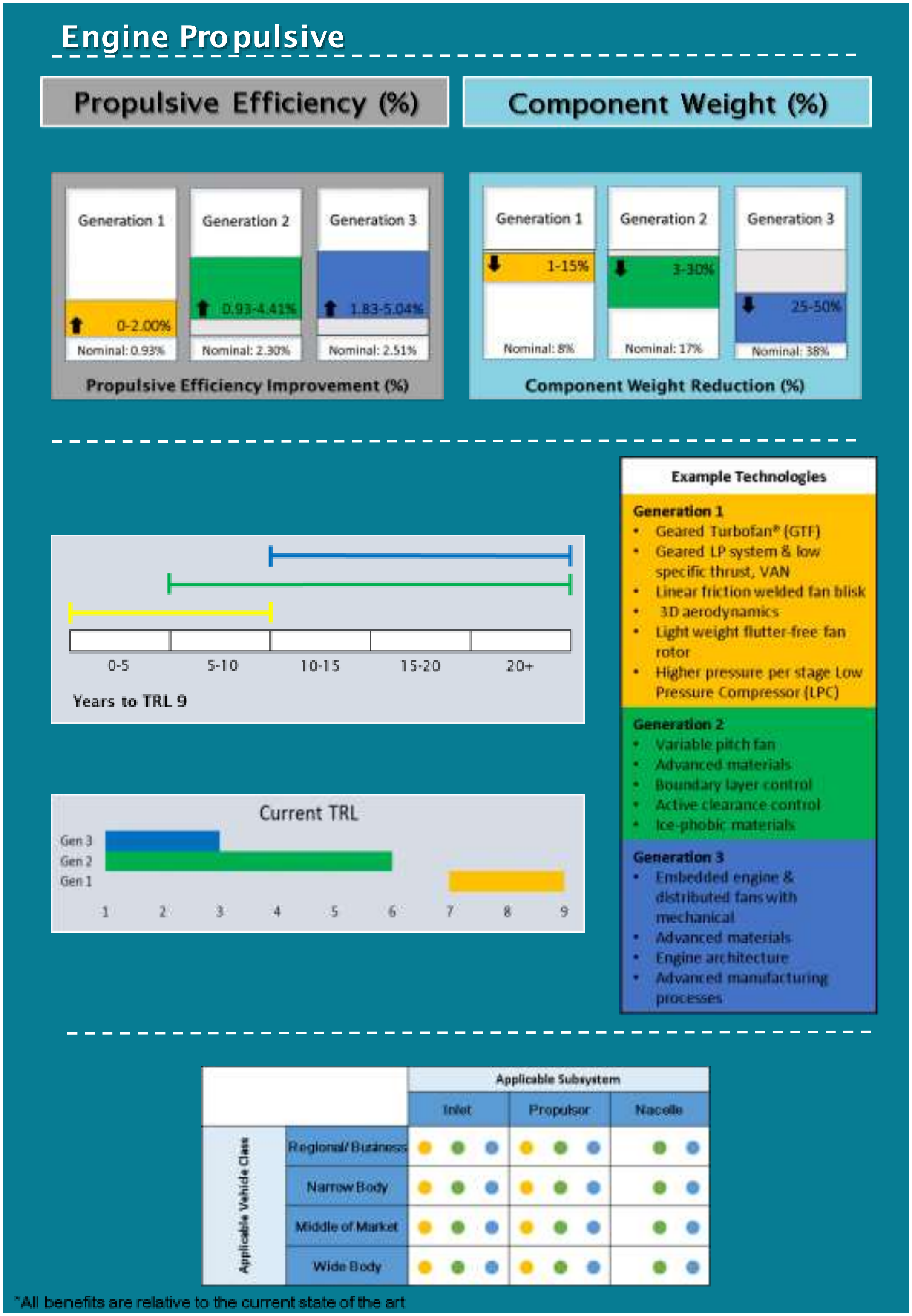


FIGURE 22. FINAL TECHNOLOGY ROADMAPS FOR ENGINE PROPULSIVE

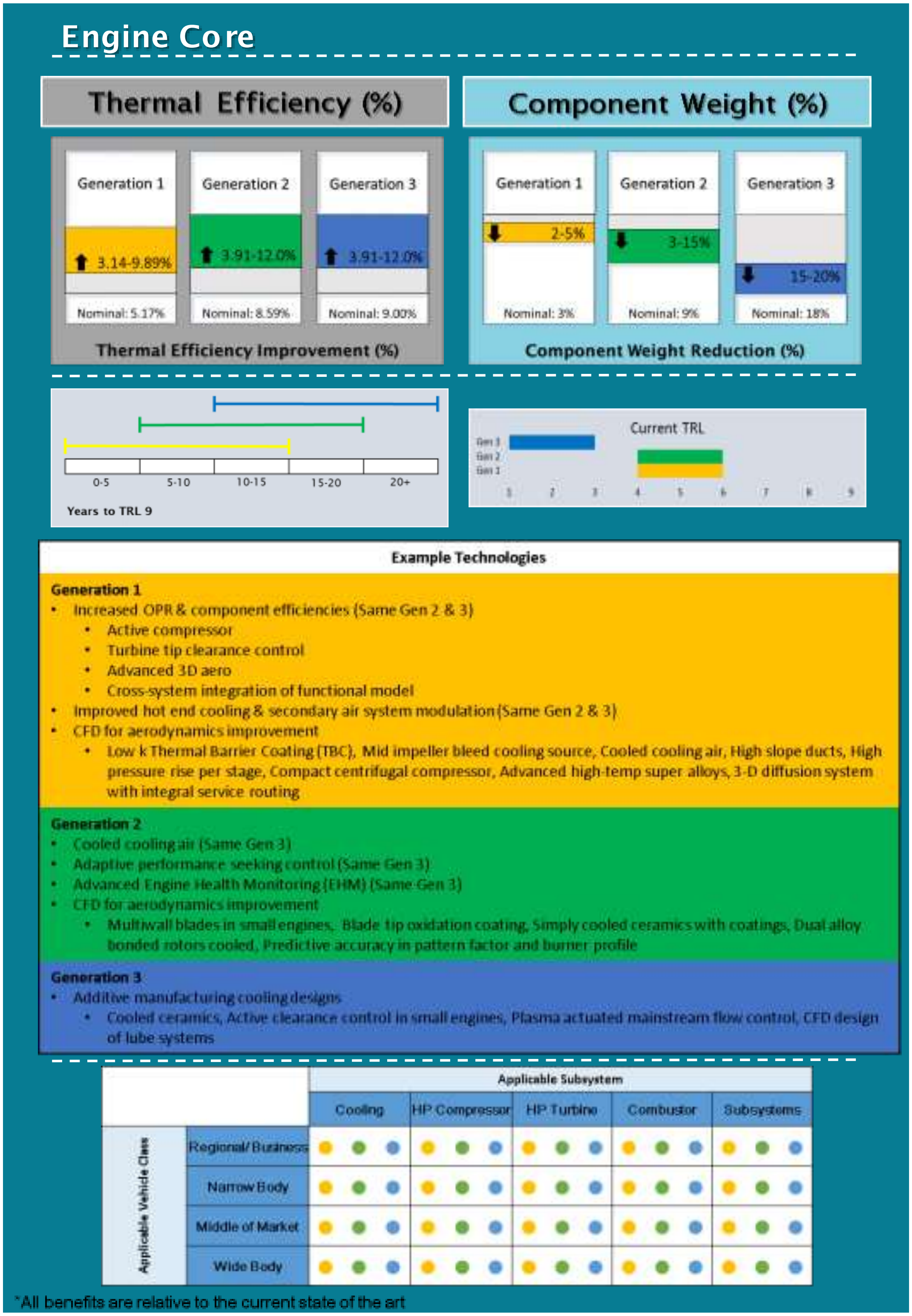


FIGURE 23. FINAL TECHNOLOGY ROADMAPS FOR ENGINE CORE

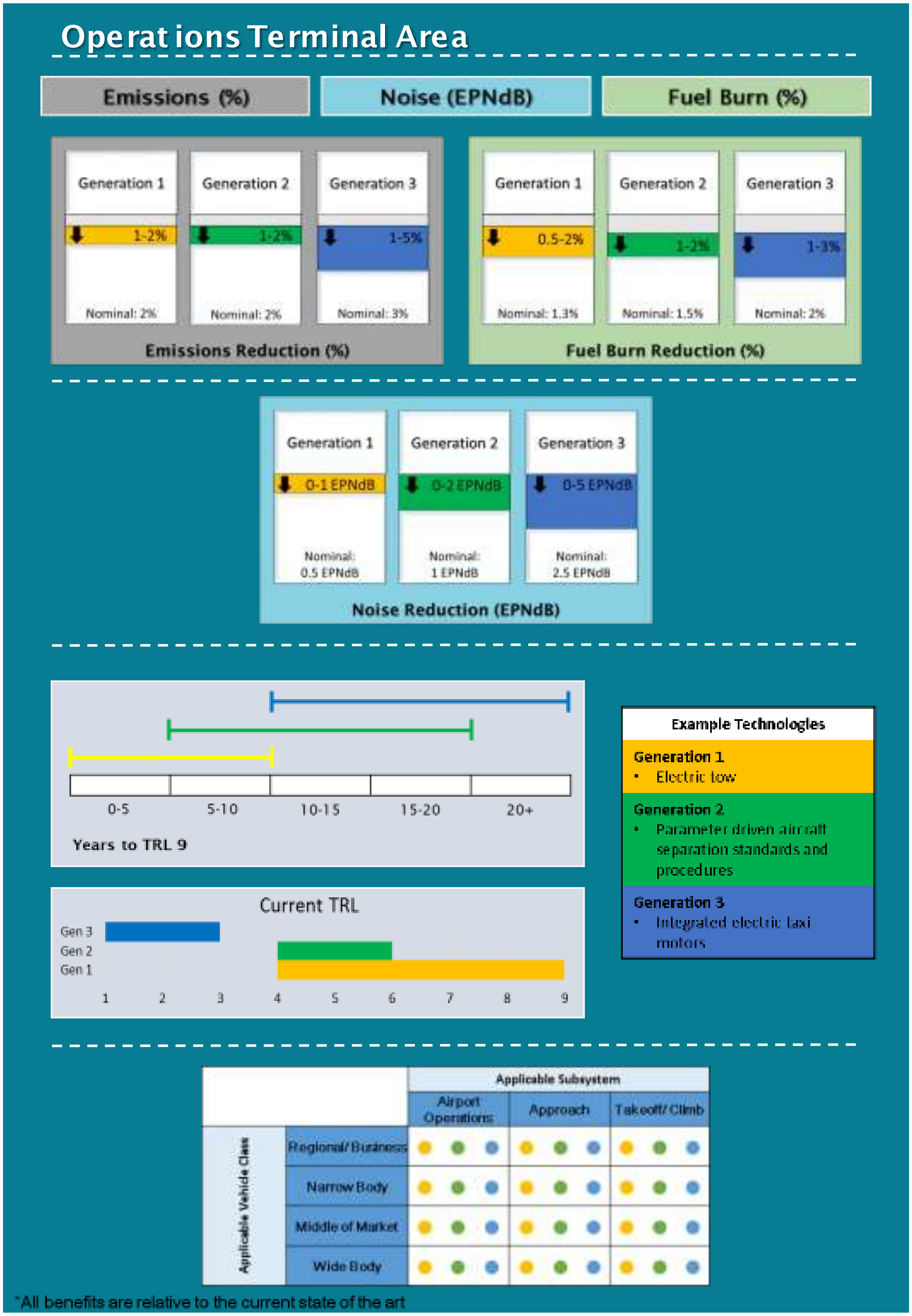


FIGURE 24. FINAL TECHNOLOGY ROADMAPS FOR OPERATIONS TERMINAL AREA

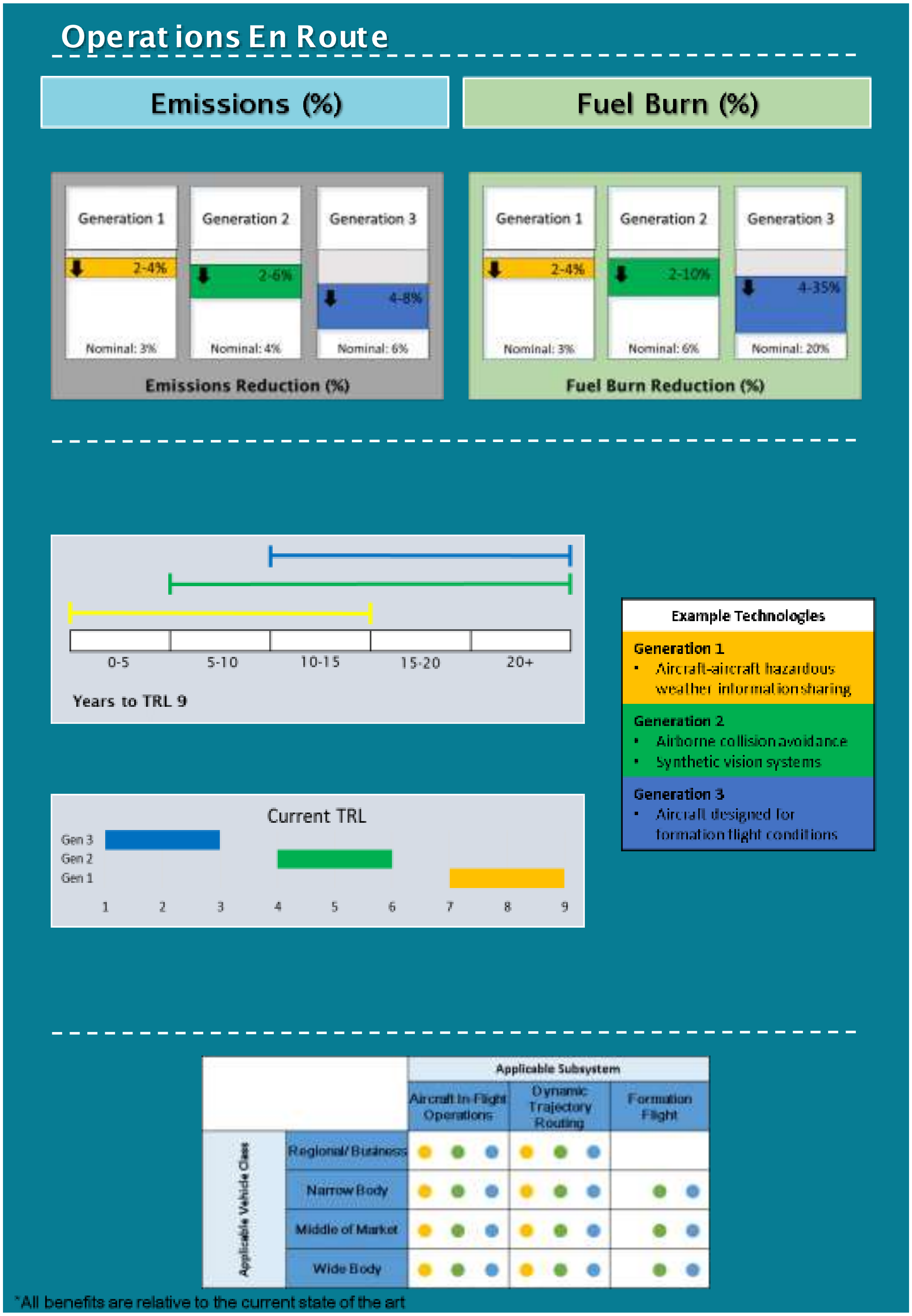


FIGURE 25. FINAL TECHNOLOGY ROADMAPS FOR OPERATIONS EN ROUTE

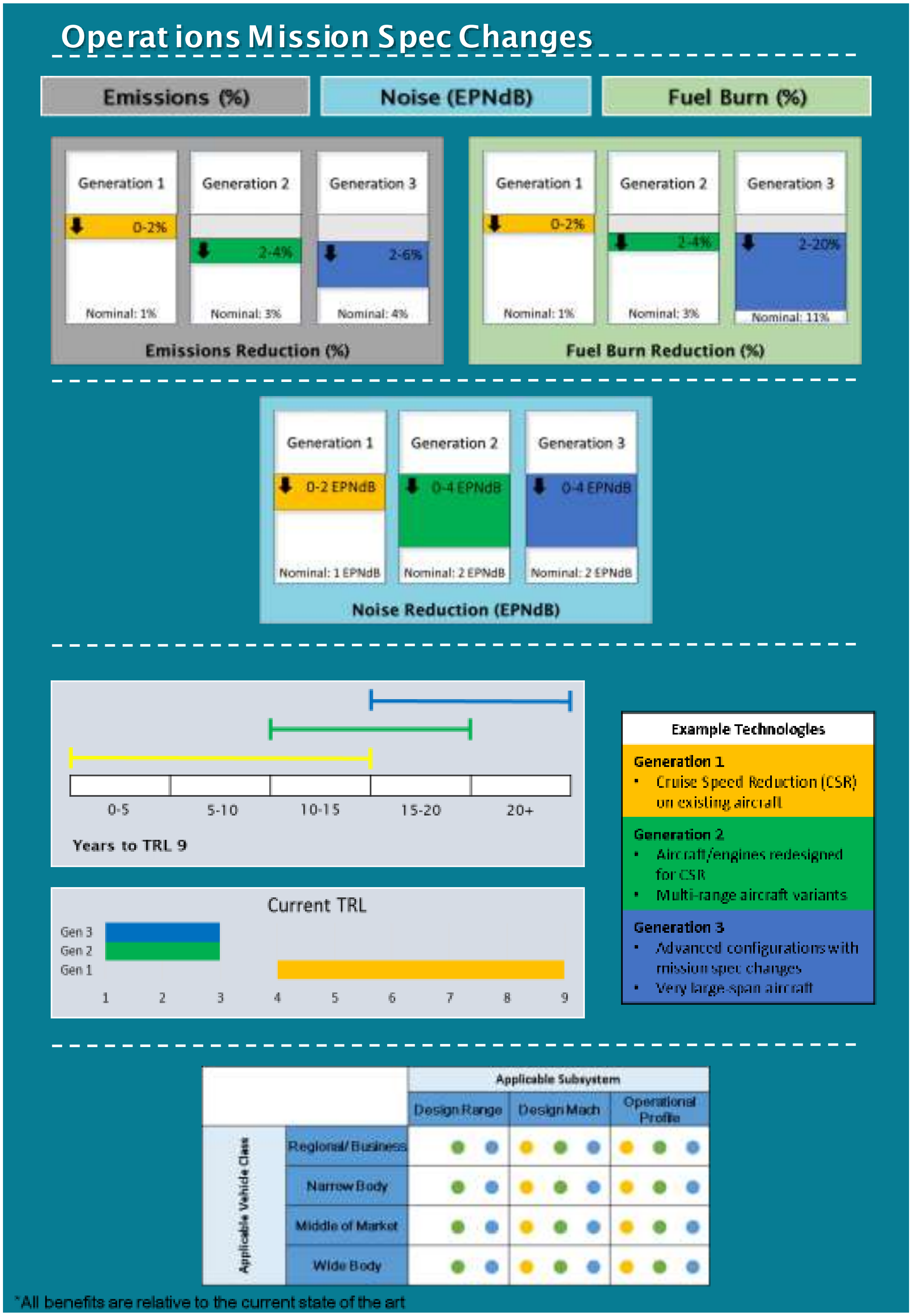


Figure 26. Final Technology Roadmaps for Operation Mission Spec Changes

Milestones

Fleet Workshops
Based on the Fleet Scenario Workshops that were conducted through Summer and Fall 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. These values were outcomes of the Fleet Workshops and were obtained by analyzing the data that was collected from the participants.

Technology Roadmapping Workshops
The first milestone for the Technology Roadmapping Workshops, following the 2015 Annual Report, was to finish review of the survey data and make initial infographic drafts for each technology area. This was accomplished by December 2016. The next milestone was the second Technology Roadmapping Workshop, held in January 2016. During the Workshop the infographics were presented to industry experts as a way to get feedback on the aggregate data from the first Technology Roadmapping Workshop surveys. Responses were asked to be sent back to Georgia Tech by the 8th of February 2016. The final milestone was reviewing the data from the latest responses and making final versions of the infographics. This was accomplished by March 2016. Slight modifications were made to Engine Propulsive and Engine Core infographics in July 2016, based on the results from Task 2.

Major Accomplishments

Fleet Workshops
The major accomplishment for the Fleet Workshops was to get input from experts across organizations and companies to provide feedback on what will be the major drivers that could shape the future of commercial aviation. The participants provided good feedback in terms of defining which descriptors are most important in describing potential future states of aviation as well as plausible settings for nominal, low, and high values. Additionally, participants provided feedback on a setoff provided scenarios as well as potential ideas for additional scenarios. This data was important in formulating a final set of recommended scenarios to be published and feeding into the other tasks.

Technology Roadmapping Workshops
The major accomplishment for the Technology Roadmapping Workshop was getting industry experts, across multiple companies and organizations, to provide meaningful feedback on the future of commercial aerospace. Attending both rounds of Workshops required participants to be committed. Clearly they saw the future benefits in the project results, which is what helped make the Workshops successful. The survey data was really the foundation for this project moving forward into Task 2 and 3. The data effected how he vehicle models were created and along with the scenarios.

Task 2: Modeling of Technologies and Advanced Configurations
Georgia Institute of Technology and Stanford University

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 [1]. More specifically, the vehicles provided were from the assessment scenario named “Aggressive minus CLEEN” or AG-C. This scenario assumed an aggressive introduction of N+1 and N+2 technologies, including technologies currently under development or sponsorship of NASA. Since the scenario had all CLEEN technologies removed, Georgia Tech chose to use those models as advanced technology baselines that would allow Stanford and Purdue to carry out their respective tasks with a relatively common set of vehicle performance assumptions. Stanford used the FLOPS models to create corresponding versions in their vehicle modeling tool, SUAVE and Purdue used the FLOPS models directly within their FLEET tool. For more details on the usage of the models in SUAVE and FLEET please see Sections 0 and 0, respectively. For more details on the technologies included in the AG-C vehicle package, please see Reference [1].

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 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 Section 0.The Environmental Design Space (EDS), developed by Georgia Tech, was used for creating these models. First, the variables within EDS that were applicable to the Technology Roadmap impacts were identified. Then it was determined how these EDS variables must be changed for the results to match the impacts. In most cases, there were EDS variables that related directly to impacts, but for some impacts a parametric study had to be performed. A Vehicle Timetable was created, using assumptions on 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 research and development (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 Timetable, 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.

Identifying Applicable EDS Variables

Once the impact numbers from the Technology Workshop Survey data were finalized, the next step was to translate these impacts using 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 relies on the user providing 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 was created of EDS variables 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 looked at to identify other variables that could be added to EDS that were currently being defaulted. The final list consisted of 89 EDS variables that would be used. The impacts for Operations Terminal Area, Operations En Route, and Operations Mission Spec Changes were not addressed since they are considered fleet level impacts. A list of the final EDS variable selections is provided in Table 7 broken down into the impacts for each technology area.

Table 7. 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

IMPACT	METHOD FOR MODELING IN EDS
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 NOx reduction
Fuel Burn %	
Noise EPNdB	
Engine Cycle	
Emissions %	Percent NOx reduction
Fuel Burn %	
Noise EPNdB	
Engine Emissions	
Nitrogen Oxides %	Percent NOx reduction
Pariculate 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 Section 0. 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 variable 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, 8 different categories of EDS variables were identified as presented in Table 8. A detailed description of the Technology Roadmap DOE Aggregator that was created to automate this process is given in Section 0. The Aggregator used the variable type that had been identified for each EDS variable to determine how to apply the impacts.

TABLE 8. HOW AN IMPACT IS APPLIED TO AN EDS VARIABLE DEPENDS ON THE VARIABLE TYPE

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	

Delta variables are typically percentages, so if the impact is a 74% increase, the new value for the EDS variable is 74 if the baseline value was zero. For DeltaF variables a 74% increase would be represented as 0.74, in other words its decimal form. For noise, in some cases the baseline suppression factor was non-zero, so when determining the new value the baseline was just treated as another one of the K-factors. In the case of jet, core, and propulsive noise the K-factors were chosen based off of a parametric study. The study found suppression factors that produced observer EPNL impact results close to those reported in the survey. This study is detailed further in Section 0. Using the EDS variables that were related to the increase in laminar flow impact required an additional step. First, the EDS variables related to the turbulent transition Reynolds number of different wing surfaces had to 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_NOx, which stands for "Percentage NOx reduction". The impacts for Engine Emissions Nitrogen Oxide Reduction, Engine Cycle Emissions Reduction, and Aircraft Configurations Emissions Reduction were all mapped to PCT_NOx. Since PCT_NOx 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 NOx 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_NOx 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_NOx 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 worksplit 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 Section 0, the propulsive and thermal efficiency were outputs of EDS, so they could not have be changed directly. 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 worksplit between the LPC and HPC constant. The worksplit 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 Very Large Aircraft (VLA) are shown in Figure 27.

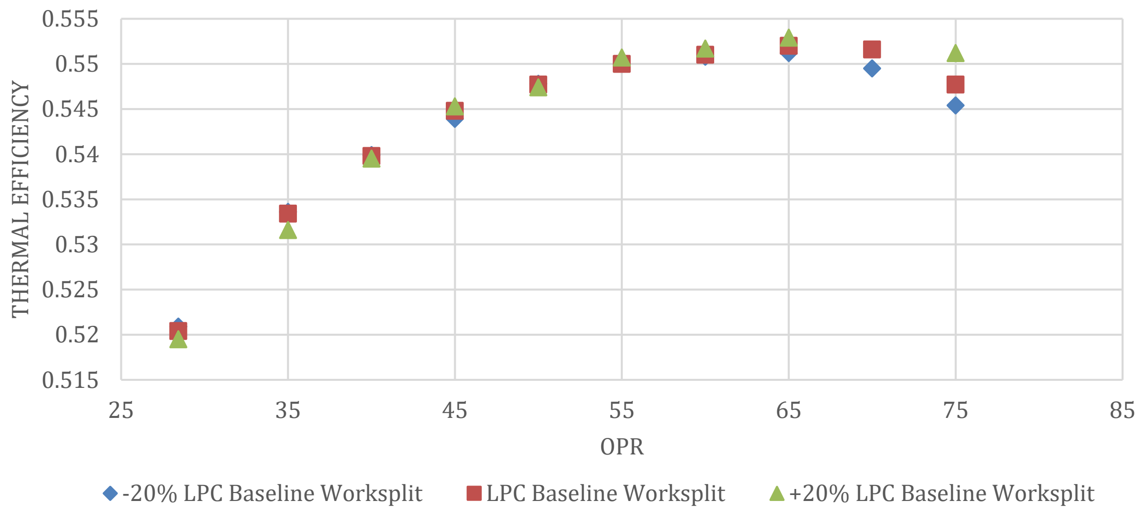


Figure 27. Initial Results of Thermal Efficiency Study For the VLA

As can be seen this graph 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 meant 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 maximum impacts reported in the surveys.

Further studies focused on the large twin-aisle (LTA) and single-aisle (SSA-LSA) aircraft models. The effects of decreasing the amount of cooling required by the high-pressure turbine (HPT) were looked at, lowering it until it was nearly zero. Changing FPR was also looked at 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 increased and decreased up to 20% of the baseline value. Presented in Figure 28 are the initial results of the study for the SSA-LSA. As can be seen there was a positive trend in propulsive efficiency between increasing extraction ratio and also decreasing FPR, but clearly there were diminishing returns.

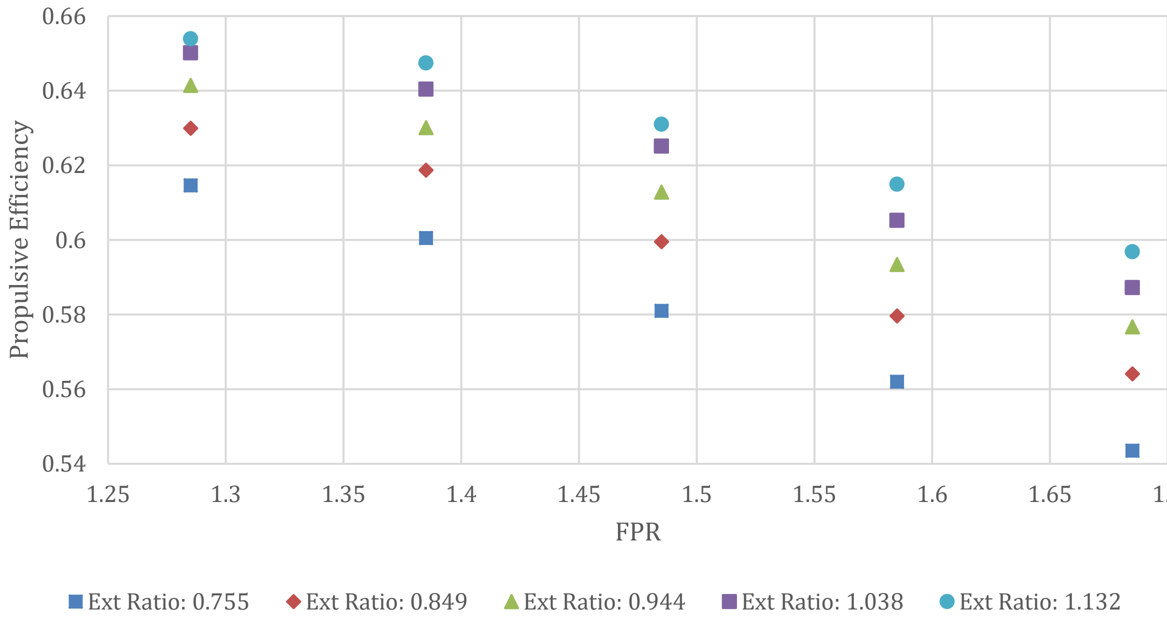


Figure 28. Initial Propulsive Efficiency Sensitivity Study Results for the SSA-LSA

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%.

Similar to the thermal efficiency study, additional cases focused on the LTA and SSA-LSA, reducing the cooling required by the HPT until it was nearly zero. An additional EDS variable that was looked at for the propulsive efficiency study for the LTA was T4max, which was set at takeoff. It was increased from its baseline of 3450˚R to as high as 3850˚R, which was a highly optimistic prediction for future turbofan combustor exit temperatures. When analyzing an ideal fixed turbofan, the general trend is that increasing the burner exit temperature increases specific thrust, which causes propulsive efficiency to decrease and has no effect on thermal efficiency. Due to the dynamics of a real engine, the interrelation between OPR and T4 was seen to actually increase propulsive efficiency. Unfortunately, in this trade study it was also seen that it can cause thermal efficiency to decrease too, often with greater losses than the gains in propulsive efficiency. This further highlights the constant balancing act required to be performed by engine designers.

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 29, 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.

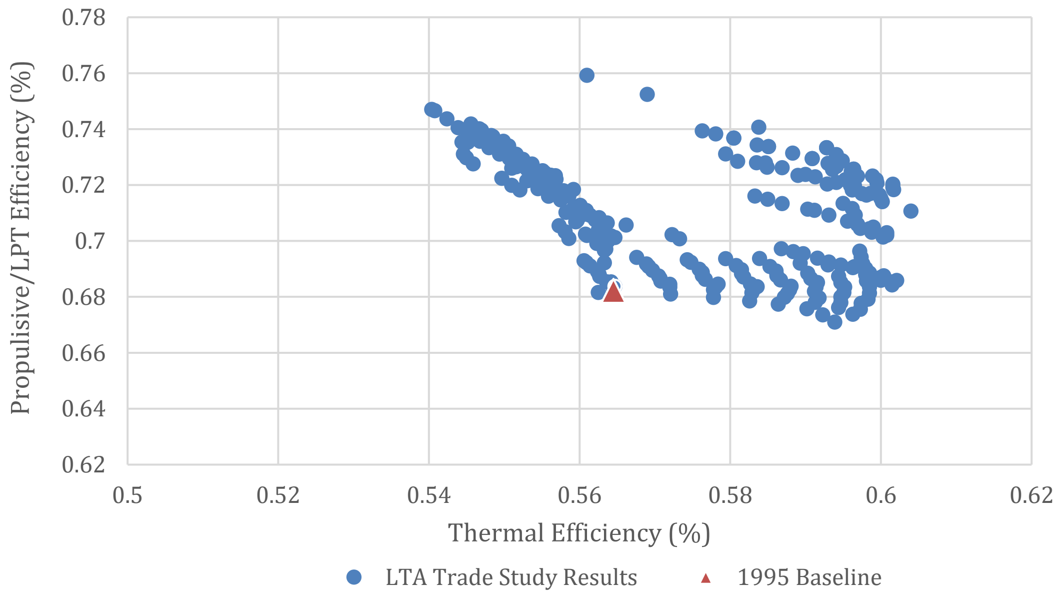


FIGURE 29. LTA EFFICIENCY TRADE STUDY RESULTS SHOWING PROPULSIVE EFFICIENCY WITH THE LPT EFFICIENCY DIVIDED OUT AGAINST THERMAL EFFICIENCY.

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 [2]. 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 [3]. 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 [4]. 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 [5]. 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 [6]. The Advance family is an engine architecture that would enter service after 2020. The Advance3 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 [7, 8]. 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 [6]. 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 9. The infographics values for propulsive and thermal efficiency were updated using final vehicles for each generation, with all impacts applied as presented in Section 0.

TABLE 9. 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

Selecting Noise Suppression Factors (Greg)

Approach to Sensitivities

Resulting Noise Suppression Factors

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 30. On the Scenario Input sheet each row was a case. The user defined what the case's Technology Level and Vehicle Class was 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 grabbed 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.

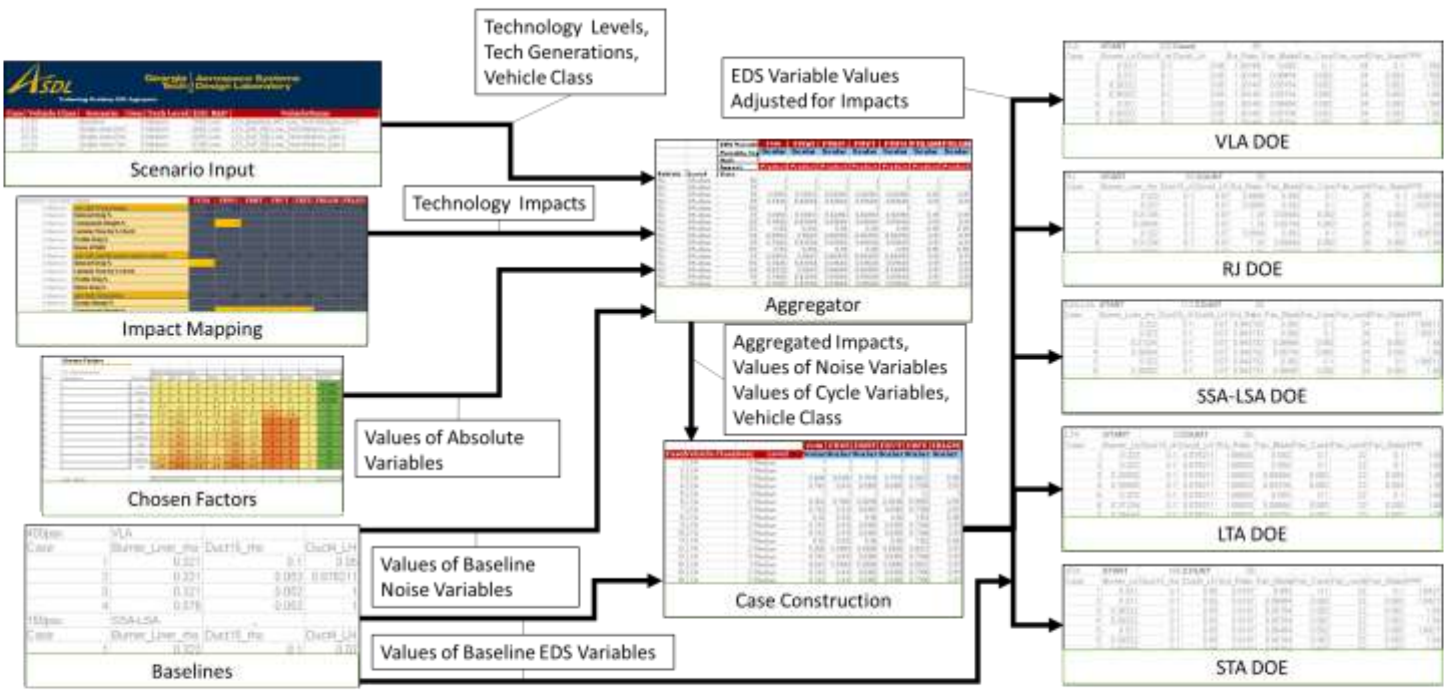


FIGURE 30. TECHNOLOGY ROADMAP DOE AGGREGATOR DATA FLOW

Scenario Input
The main interface was the Scenario Input sheet, as shown in Figure 31. Each row within the Scenario Input sheet defined a separate case. Cases were created based on the scenario timetables described in Section 0. 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 entry-into-service (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 Section 0. 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 Section 0. Note only three of the 19 impacts are shown Figure 31.

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 31. 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 appropriate 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.

FIGURE 32. 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 in Section 0 earlier.

An exception to that process was the EDS variables for the engine cycle related to thermal and propulsive efficiency. As discussed in Section 0, 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 8.

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 vehicle 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 design of experiments (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 10 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 10. 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 were 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 entry into service (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 33 and the twin-aisle first vehicle is shown in Figure 34. 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.

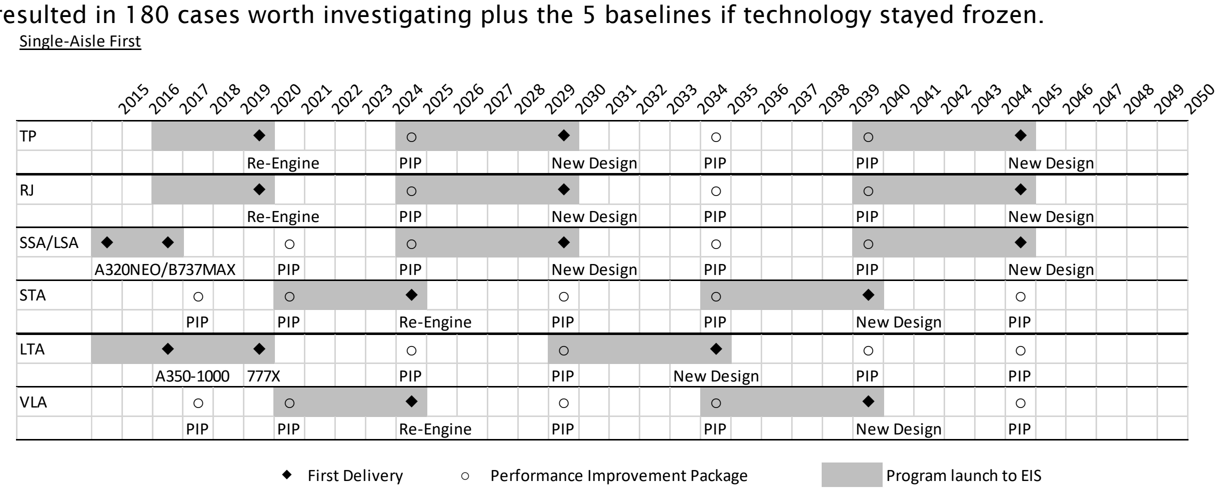


FIGURE 33. VEHICLE REPLACEMENT SCHEDULE FOR SINGLE-AISLE FIRST ASSUMPTION

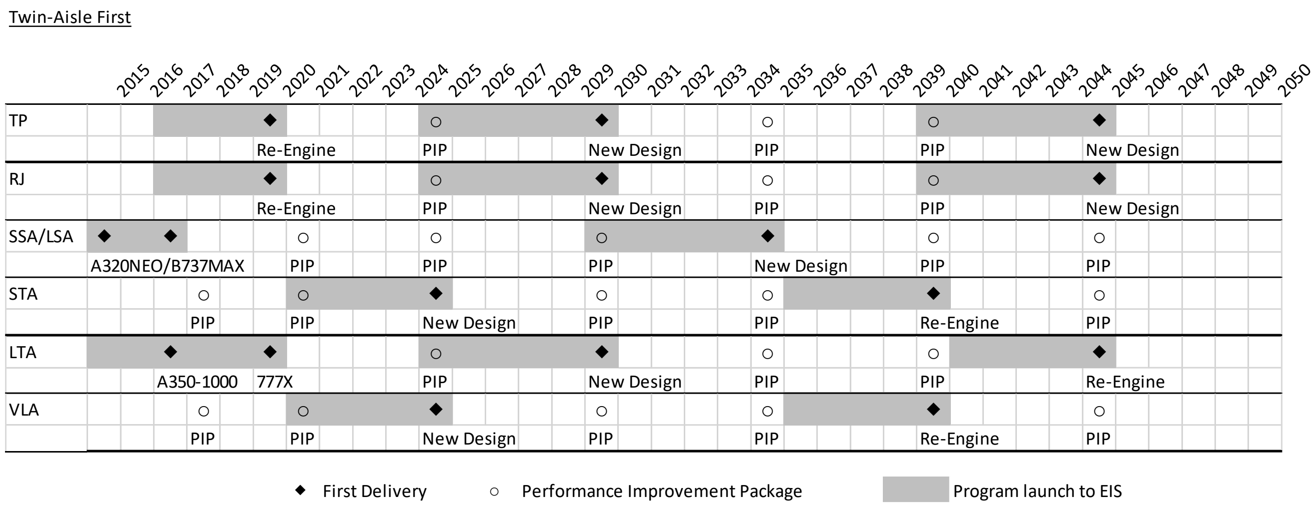


FIGURE 34. VEHICLE REPLACEMENT SCHEDULE FOR TWIN-AISLE FIRST ASSUMPTION

Vehicle Naming Convention & Identification

Each of the 185 cases was 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 Regional Jet (RJ), Single-Aisle (SSA-LSA), and Small Twin Aisle (STA), Large Twin Aisle (LTA), and Very Large Aircraft (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 Tech Level were given intensities of either low, medium, or high. The final part of the name was what the vehicle generation was. This generation often varied from what the generation of technology impacts on the vehicle were. As an example, for a Generation 2 LTA, single-aisle first scenario, with a medium Tech 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_∞ which was the amount of grams of that emission, 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.

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 generation and R&D level increased. The FLEET analysis made the assumption that all vehicles had at least a 15% improvement relative to their baseline vehicles. Any vehicles that did not meet this minimum improvement were modified to agree with this FLEET assumption. Figure 35 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.

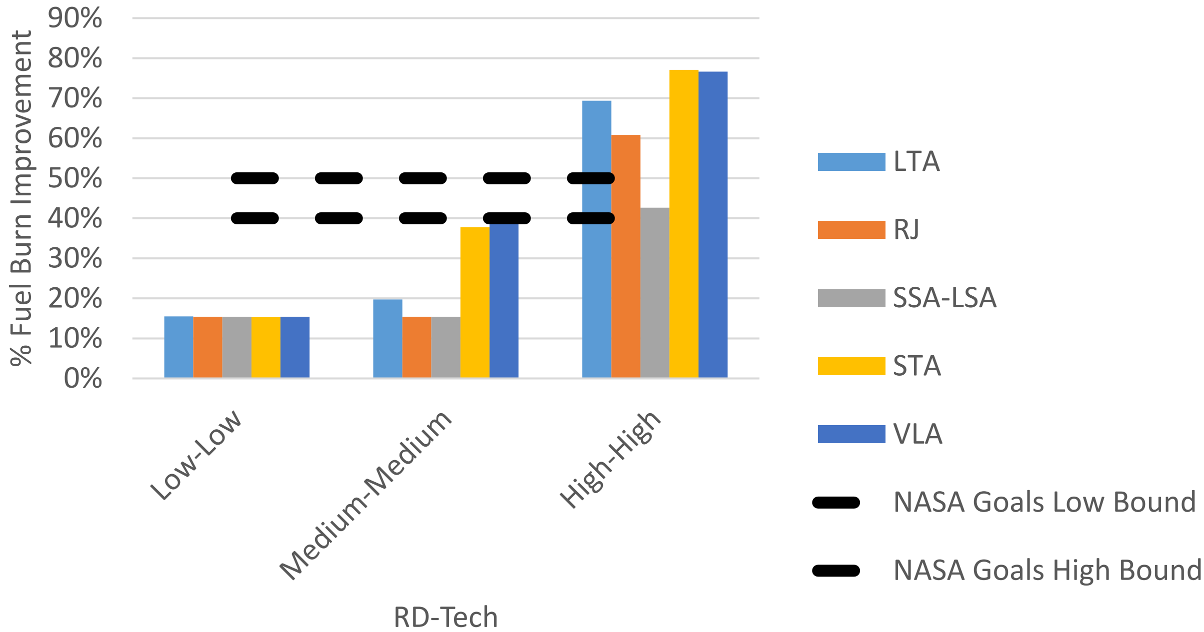


FIGURE 35. PERCENT REDUCTION IN FUEL BURN RELATIVE TO THE BASELINE FOR GENERATION 1 VEHICLES

1.1.1.1 Noise Margin

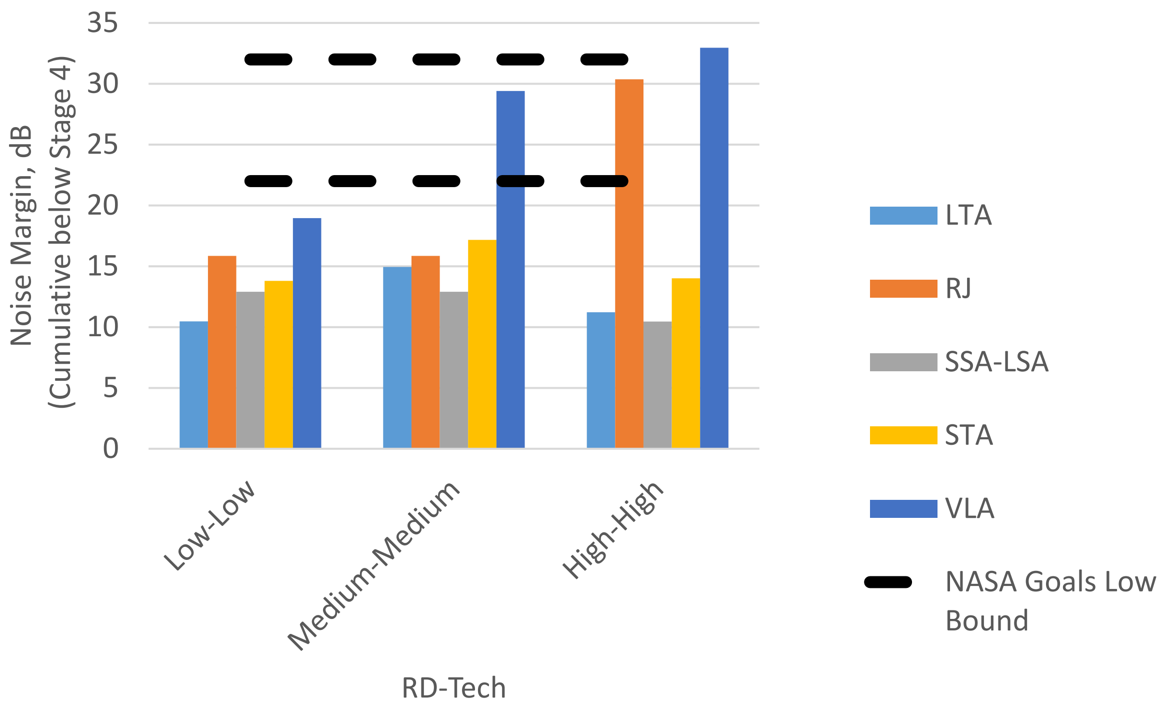


Figure 36. Noise Margin Relative to Stage 4 for Generation 1 Vehicles

1.1.1.2 Nitric Oxide Emissions

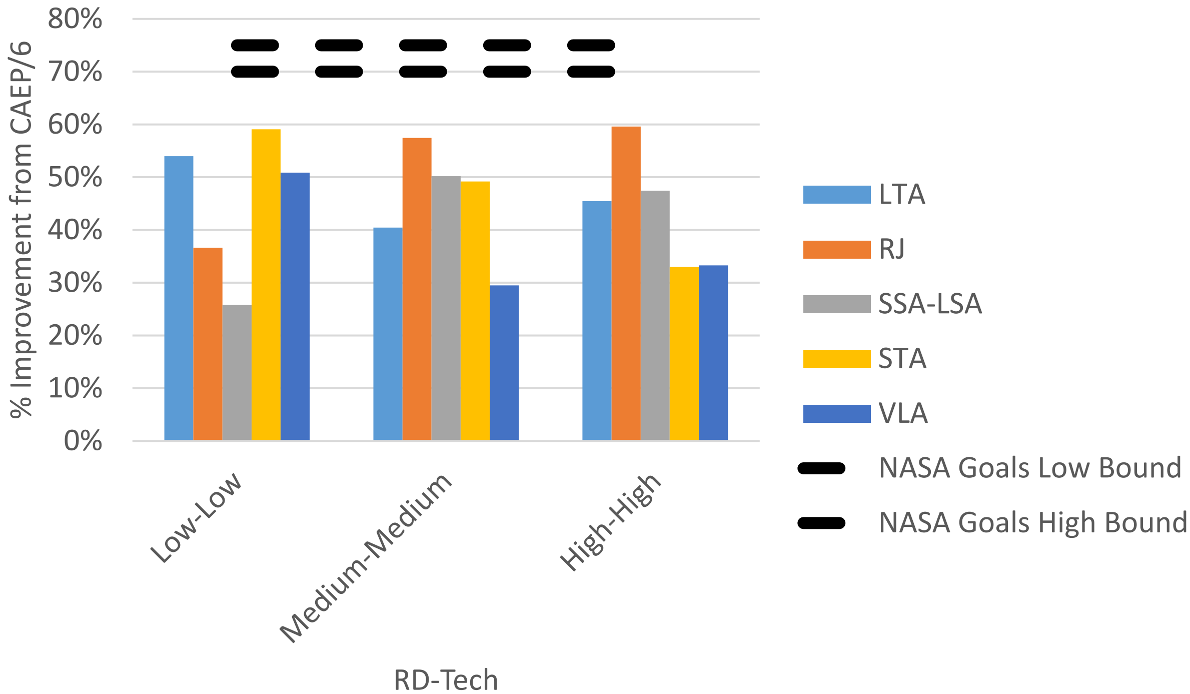


FIGURE 37. NITROUS OXIDE PERCENT IMPROVEMENT RELATIVE TO CAEP/6 FOR GENERATION 1 VEHICLES

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.

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

EQUATION 1

Using this relationship, and adjusting the jet velocity ratio to maximize propulsive efficiency, Figure 38 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.

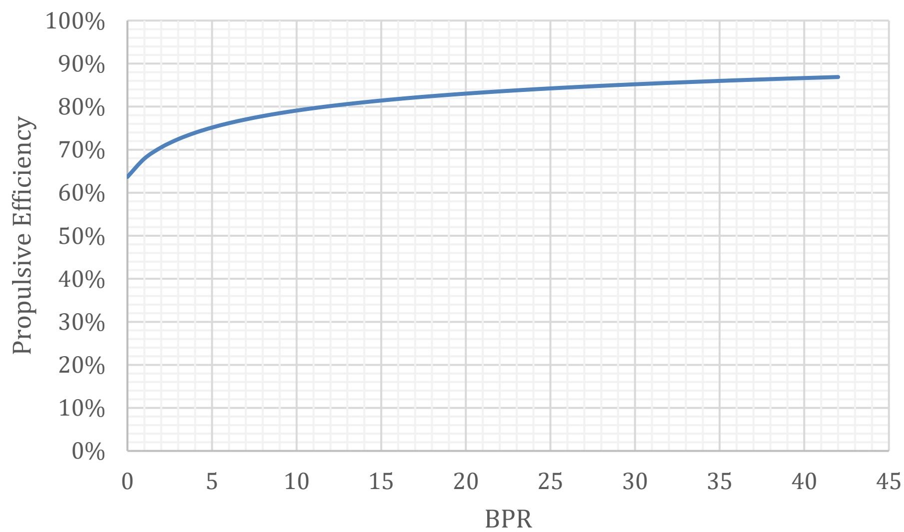


FIGURE 38. PLOT OF CORRELATION BETWEEN BPR AND PROPULSIVE EFFICIENCY

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

SUAVE Modeling of Public Domain EDS Technologies (Stanford)

Over the past few years, pressure to reduce the overall fuel consumption of the commercial aircraft fleet has been growing steadily. Expenses related to fuel are now one of the largest contributors to an airline's direct operating cost, even if the recent (2015-16) 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, we begin to investigate the fuel burn impact of varying design mission specifications (e.g. payload, range, cruise Mach number, and allowable span) of tube-and-wing aircraft is studied. During the first two years of the effort, 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 be modeled using one of our team's fleet-level tools.

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

SUAVE and Improvements to the Design Environment

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

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

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

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

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

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

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

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

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

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

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 the non-standard constraints are fuel margins, which is fuel volume available in the vehicle minus the fuel used to run the mission.

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

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

Figure 39. Sample description of optimization problem design variables , bounds and units

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

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

Optimization

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

<u>VyPy:</u> 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.

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

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

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

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

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

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

Baseline to GT Vehicles

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

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

Mission Specification Change Modeling

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

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

DESIGN VARIABLES:

- Main wing aspect ratio
- Main wing reference area

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

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

CONSTRAINTS:

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

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

Table 11 : B737-800 fuel burn

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

Table 12 : CRJ-900 FUEL BURN

Mno	Fuel burn (kg)
Baseline	22,013
0.76	19,174
0.72	20,434

Table 13 : B767-300ER

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

Table 14 : B777-200ER FUELBURN AND DESIGN PARAMETERS VARIATION

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

Updates for work performed during year 2

Updates to Propulsion Analysis Module

It was observed that the initial results obtained from SUAVE did not match very well the baseline aircraft provided by Georgia Tech for some of the aircraft. The differences in the performance estimates were traced down to small but significant differences in the computation of the drag and the propulsion performance. The aerodynamic analysis routines were modified, especially the prediction of compressibility drag and induced drag, to be more accurate representations of the actual aircraft geometries.

The existing engine model in SUAVE, while predicting accurately the design performance of the turbofan 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 propulsion model was an extension of the existing engine model in SUAVE. A more detailed off-design performance analysis module was implemented. This model used compressor and fan performance maps and Netwon (or damped Newton) iterations to converge the off-design mass flow residuals at the different engine positions. The engine performance estimates were then compared with data provided by Georgia tech and showed reasonable agreement (as shown in Figure 44).

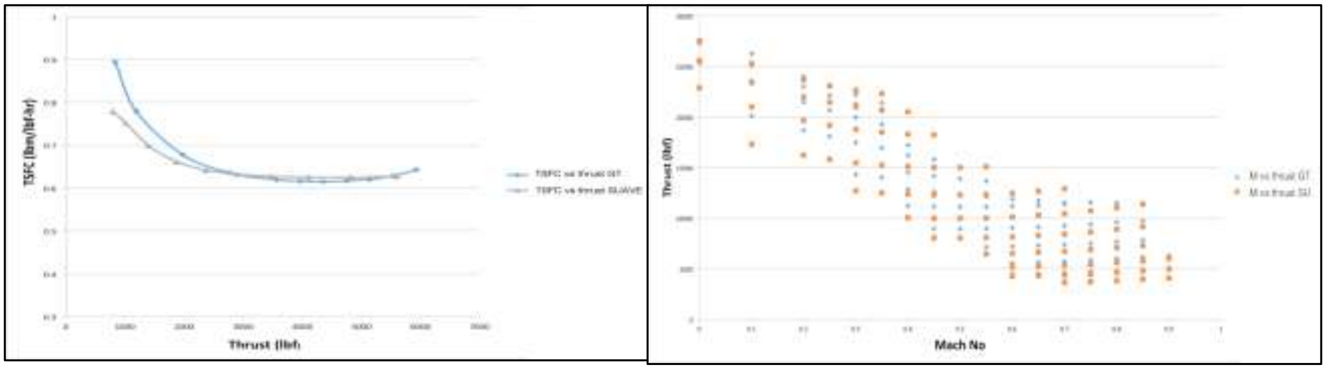


Figure 40 : Comparison of off-design propulsion performance

A second engine model was created in order to interface with the EDS engine decks provided by GT. The engine deck provided 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 reads in the engine deck. The parameters are stored as a database and interpolation models are created for thrust, ram drag and fuel flow rate with respect to the Mach number, altitude and the throttle setting. This ensures that when queried by the mission solver at different conditions, the engine model can provide performance estimates at conditions not specified in the deck by interpolating between the values.

Mission Specification Change Modeling

Once the updates to the propulsion model and the predictions of the baseline aircraft using the updated models were validated, the cruise Mach reduction cases were re-run.

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 41 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 42. 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 MTOW. This implies a reduction in the required lift and thus a reduction in the lift induced drag. A combination of the effect s described above result in the redesigned reduced Mach variants becoming much more efficient than the baseline (Mach) aircraft.

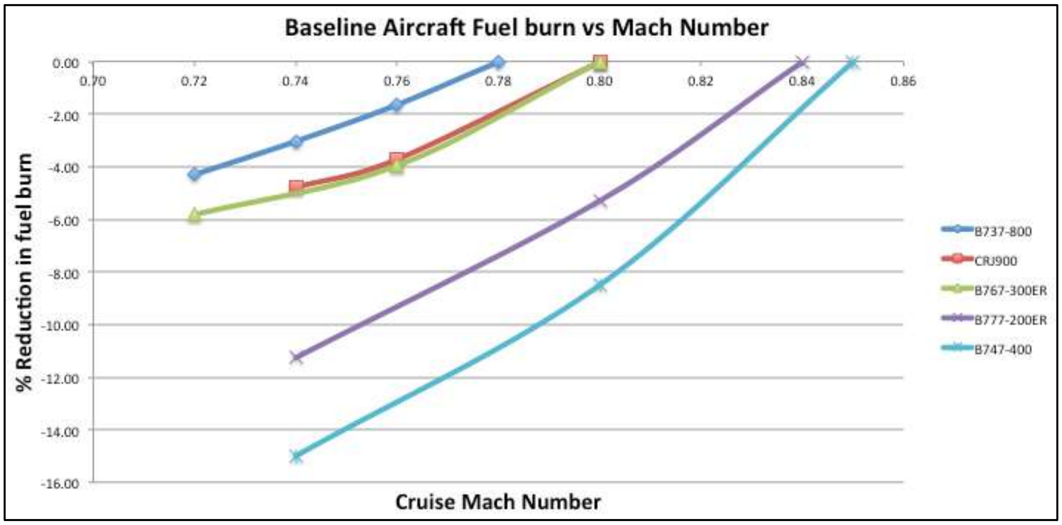


FIGURE 41: REDUCTION IN FUEL BURN WITH CRUISE MACH REDUCTION FOR ALL FIVE AIRCRAFT CLASSES FOR BASELINE TECHNOLOGY LEVELS

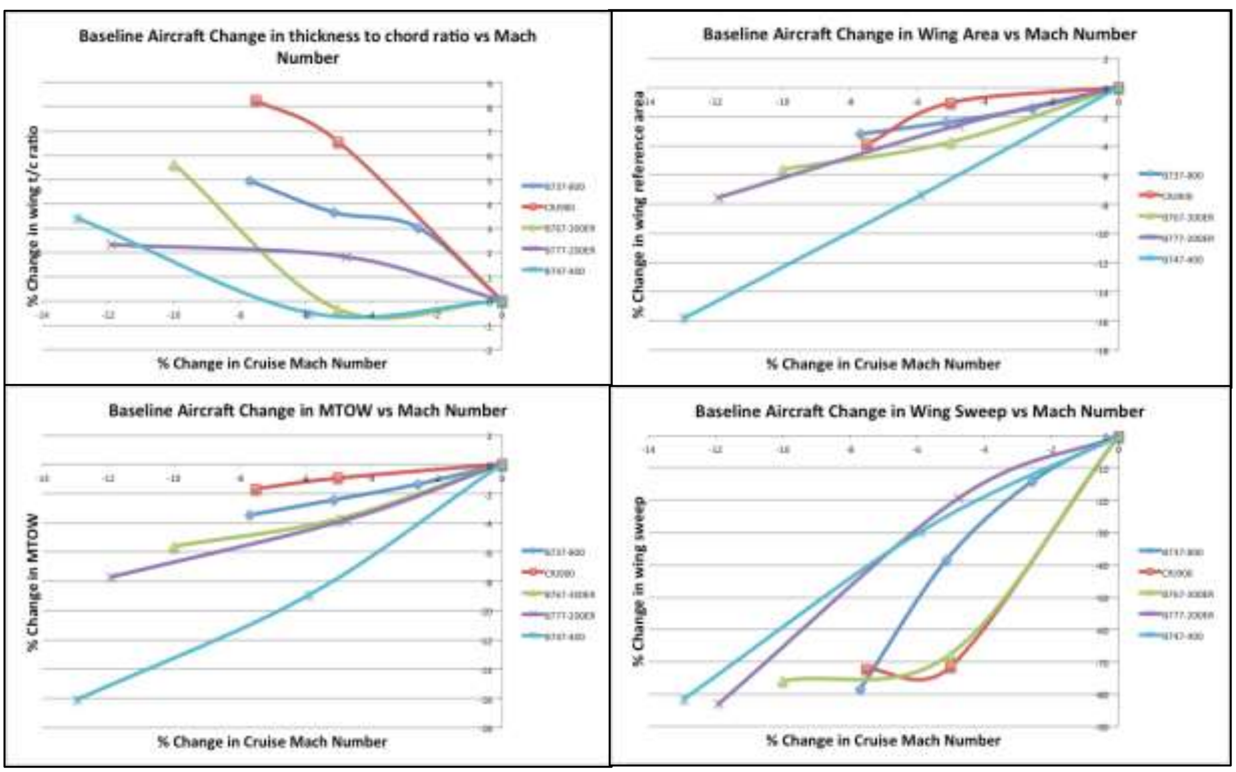


FIGURE 42 : CHANGE IN DESIGN VARIABLES WITH CRUISE MACH REDUCTION

__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 43 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.

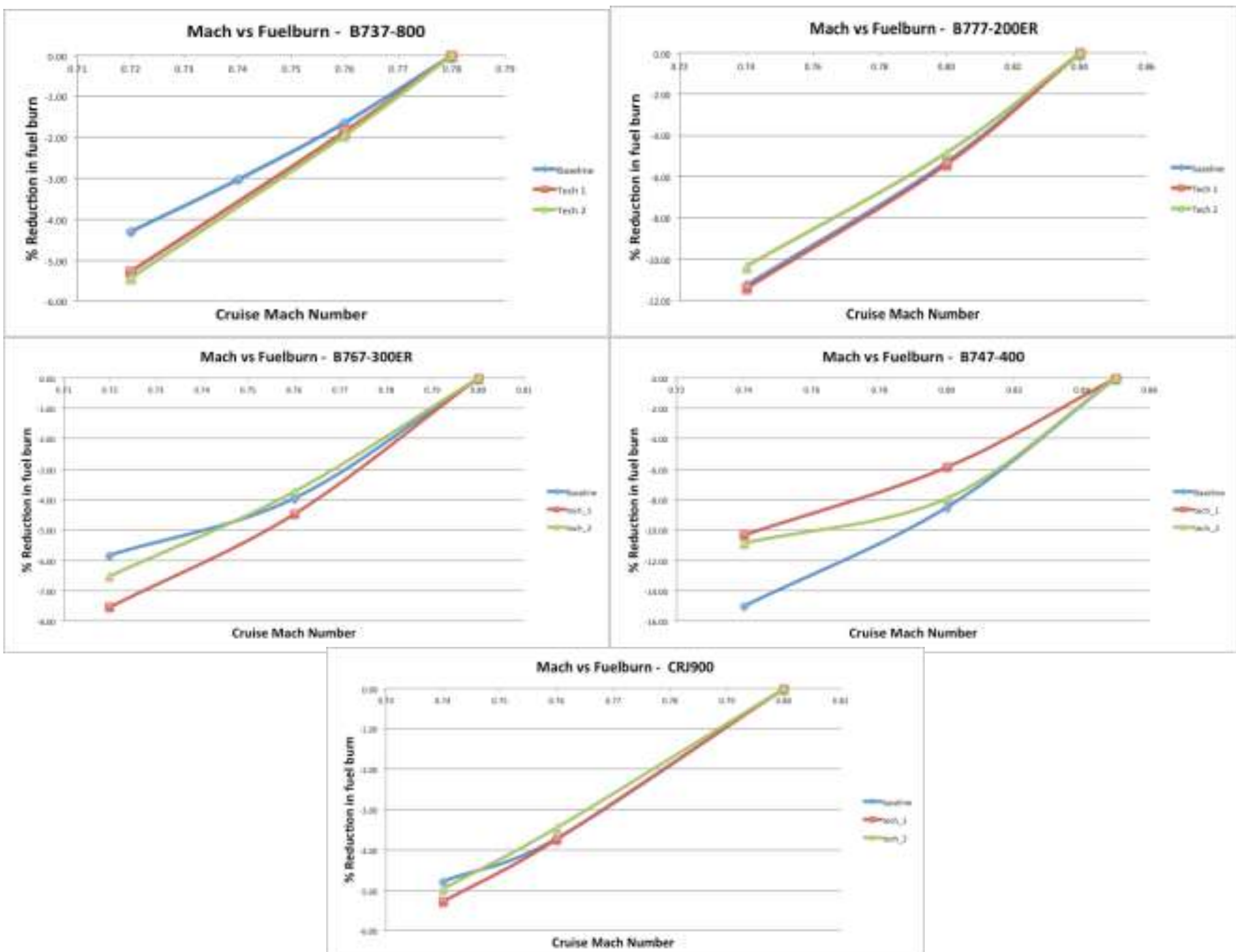


FIGURE 43 : EFFECT OF CRUISE MACH REDUCTION ON TECHNOLOGY VARIANTS

__Off-design Performance over a mission__

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 mission. 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 44. 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. We are looking into this case in more detail to understand the reason for this behavior.

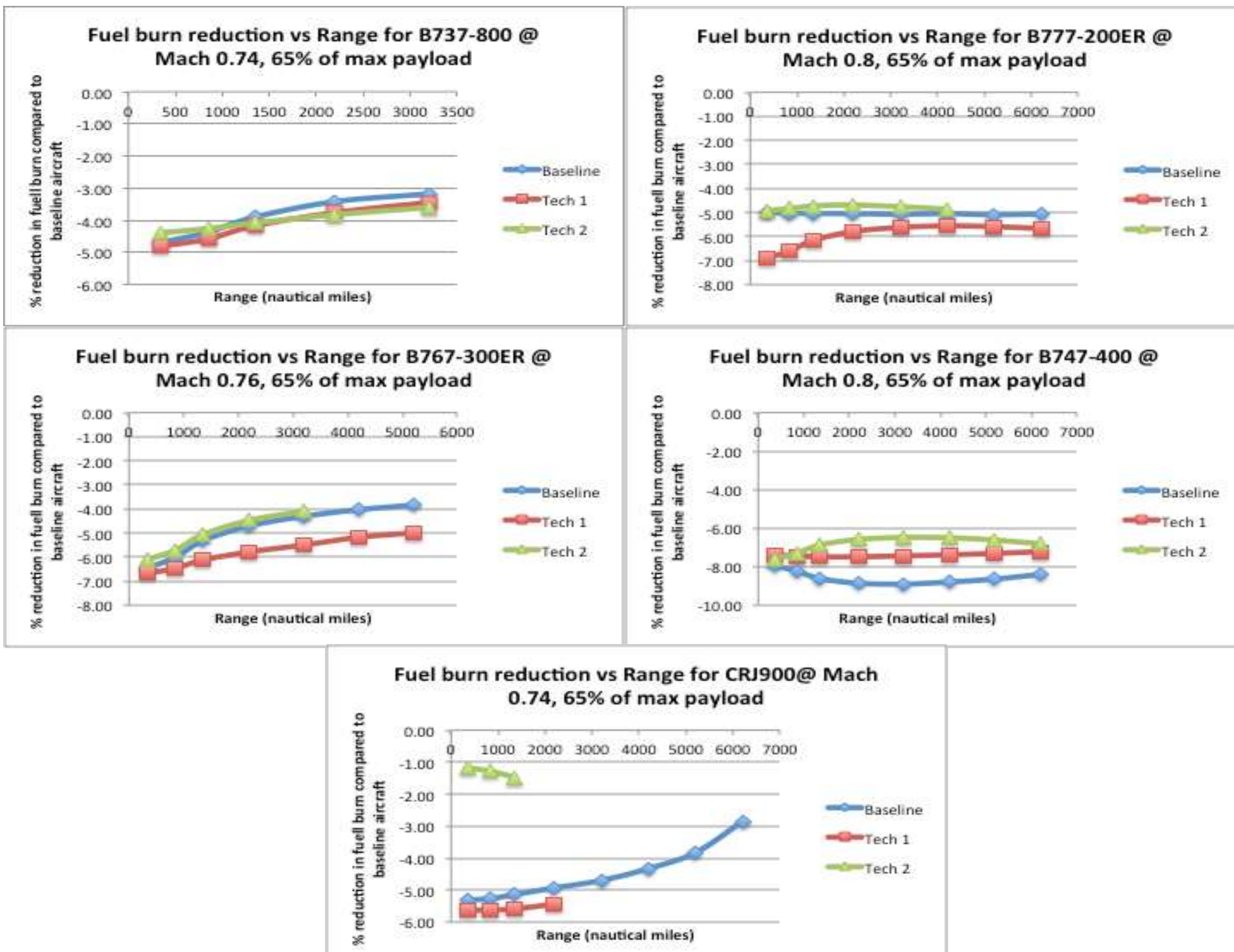


FIGURE 44 : OFFDESIGN PERFORMANCE COMPARISON WRT BASELINES

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 that Project 10 is contemplating.

Milestones

Three major milestones were set for this task for Georgia Tech. First variables in EDS, the vehicle modeling environment used by Georgia Tech, had to be identified that could be changed to model the impacts from the Technology Roadmapping Workshop. Identifying and doing sensitivity testing on the majority of variables was completed by March 2016. Identifying EDS variable values for more difficult impacts, such as propulsive efficiency, was completed by July 2016. The second milestone was completing the Technology Roadmap DOE Aggregator. The Aggregator was built in Excel to automate the process of creating the inputs into EDS for all the future aircraft scenarios that were chosen to be modeled. The Aggregator was completed in July 2016. The final milestone was running the chosen vehicle scenarios, reviewing, and then compiling the results to be passed onto other project participants for the fleet analysis described in Task 3. This milestone was reached by mid-August 2016. All these milestones were met in accordance with the timeline that was projected following the 2015 Annual Report.

Major Accomplishments

The overall major accomplishment for this task was developing a variety of aircraft models for future scenarios for five different aircraft vehicle classes. Completing this task was pivotal to the progression of the project. These aircraft models are the basis for the fleet analysis performed by both Georgia Tech and Purdue University. As a result, they have a major impact on the findings of this project. Another major accomplishment was developing the process to move from the Technology Roadmapping Survey results to sizing and synthesizing aircraft and engine models. A logical set of steps had been hypothesized at the beginning of the project, but they were never carried out until this past year. As was described in the Research Approach in Section 0, a number of roadblocks were found along the way. In the end a way was found around them and the goals of the task were accomplished. Perhaps just as importantly, a sound process that can be followed in the future developed.

Task 3: Fleet Level Aircraft Technology Benefits Assessment

Georgia Institute of Technology, Purdue University

Objective: Fleet Level Technology Assessment

The fleet level aircraft technology benefit assessment at Georgia Tech will be performed using GREAT/ANGIM, which was developed at Georgia Tech for the purpose of the FAA seeking to complement the Aviation Environmental Design Tool (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 Global and Regional Environmental Aviation Tradeoff (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 Airport Noise Grid Interpolation Method (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.

Research Approach

FLEET Sample Case (Purdue)

FLEET Overview

The Fleet-Level Environmental Evaluation Tool (FLEET) is a computational simulation tool developed to assess how aviation's fleet-level environmental impacts – in the form of CO_2, NO_x emissions and noise – evolve over time. Central to FLEET is an aircraft allocation model that represents airline operations and decision-making. Additionally, the tool has a system dynamics-inspired approach that mimics the economics of airline operations, models the airlines' decisions regarding retirement and acquisition of aircraft, and represents passenger demand growth in response to economic conditions. The overarching objective of FLEET is to enable an understanding of how variation in external factors such as market conditions, policy implementation, and technology availability will affect aviation environmental impacts into the future. The objective in exercising FLEET in this project period was to inform FAA and its partners about the workings of FLEET, its unique inputs and outputs, and a demonstration of its ability to compute estimates of emissions based on fleet level and technology scenarios [9,10,11,12,13,14,15,16].

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

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

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

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

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. Figure 45 shows the raw data and curve fitting results.

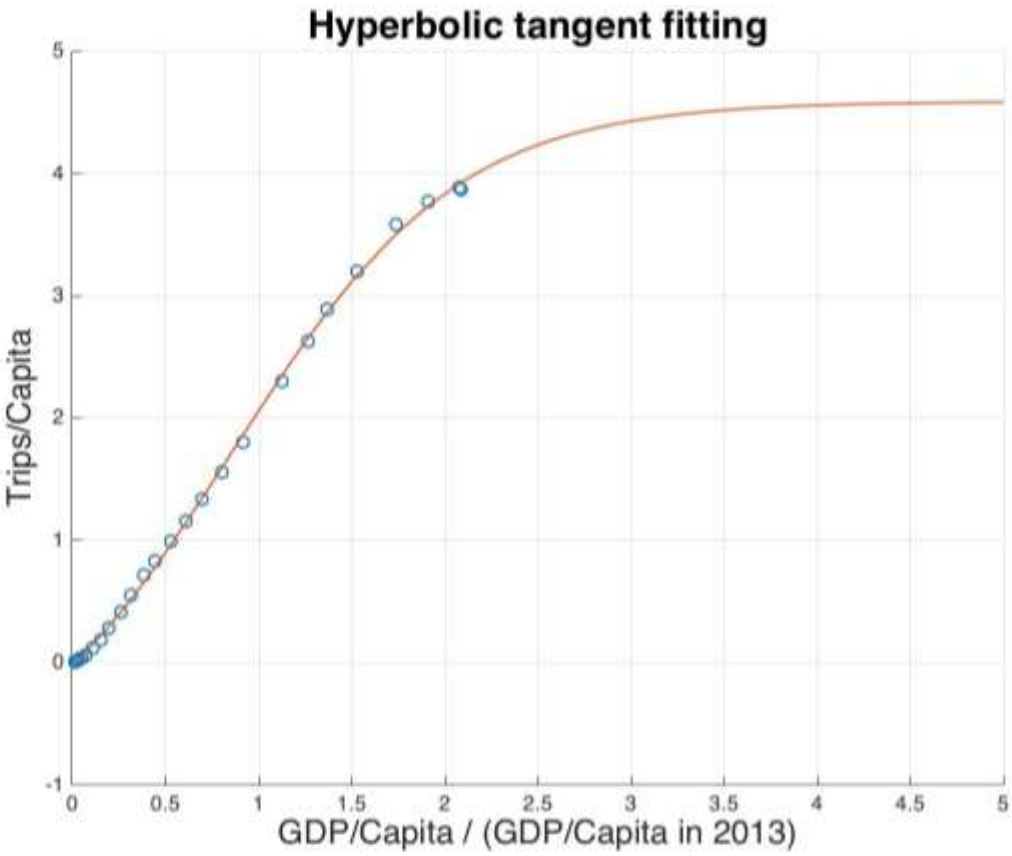


FIGURE 45: TRIPS PER CAPTIA, GDP PER CAPTIA AND CURVE-FITTING RESULT

Then, the demand growth rate in each continent in year n can be represented in Equation 3.

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

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 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.

Description of exercised scenario setups

In the second project year, Purdue exercised FLEET with seven scenarios which were identified together with the ASCENT 10 Project partners. This activity also serves to identify enhancements necessary in FLEET to accommodate simulation of all the scenarios to be examined under ASCENT-10. The seven scenarios examined are:

A. Current Trends Frozen Technology
B. Current Trends Best Guess
C. Current Trends with High R&D

D. High Demand with High R&D
E. High Demand with Low R&D
F. Low Demand with High R&D
G. Low Demand with Low R&D

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 either begin or end 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[17].
- Jet fuel prices grow according to the Energy Information Administration (EIA) reference fuel price case [17] and adjusted it to meet the ASCENT survey fuel price, $77/bbl, by 2050.
- Only the Representative-In-Class and Best-in-Class aircraft from Table 13 are included in the simulation. Aircraft from the Best-in-Class are produced until 2050. No New-in-Class or Future-in-Class aircraft are included in this scenario.

Table 15: Aircraft used in Simulation Studies

Aircraft Types in Study				
	Representative-in-Class	Best-in-Class	New-in-Class	Future-in-Class
SRJ	Canadair RJ200/RJ440	Embraer ERJ145		
RJ	Canadair RJ700	Canadair RJ900	GT Gen1 DD RJ (2020)	GT Gen2 DD RJ (2030)
SA	Boeing 737-300	Boeing 737-700	GT Gen1 DD SA (2017)	GT Gen2 DD SA (2035)
STA	Boeing 757-200	Boeing 737-800	GT Gen1 DD STA (2025)	GT Gen2 DD STA (2040)
LTA	Boeing 767-300ER	Airbus A330-200	GT Gen1 DD LTA (2020)	GT Gen2 DD LTA (2030)
LQ	Boeing 747-400	Boeing 777-200LR	GT Gen1 DD LQ (2025)	GT Gen2 DD LQ (2040)

In **Table 15**, the aircraft labeled as "GT Gen1 DD" are the Generation 1 aircraft modeled by Georgia Tech with a 'Direct Drive' engine. The 2nd Generation aircraft are labeled as "GT Gen2 DD". These include aircraft that belong to the following classes - regional jet (RJ), the single aisle (SA), the small twin aisle (STA), the large twin aisle (LTA), and the large quad (LQ). 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(in Table 13) models will vary.

The 'Current Trends Best Guess' and 'Current Trends with High R&D' scenarios, in addition to the 'Current Trend 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 with High R&D' and 'High Demand with Low R&D' scenarios assume a constant annual GDP growth rate of 5.9% for airports in Asia, 5.3% for airprots in Latin Ameirca, 4.2% for airports in Europe, and 4.0% for airports in America. The high R&D and low R&D case accounts for the rate of change and amount of investments in technology.

The 'Low Demand with High R&D' and 'Low Demand with Low R&D' scenarios use a constant annual GDP growth rate of 3.3% of airports in Asia 2.7% for airports in Latin America, 0.6% for airports in Europe, and 1.8% for airports in the United States.

Description of Results of the Scenario Runs with FLEET

The remainder of this section describes Purdue's representation of the "ASCENT 10 Project" scenario simulations using FLEET with the seven scenario setups aforementioned. The EIS dates of the Current Trend and High R&D and the corresponding aircraft modeled represents the GDP growth rate and EIS date setups for the other two scenarios. The purpose of the analysis is not to compare the quality of FLEET vs. Global and Regional Environmental Aviation Tradeoff (GREAT), but to understand the difference in results for the same scenario so the FAA can benefit from the different approaches to this difficult forecasting problem.

Figure 46 shows the normalized demand satisfied values for the results from simulations using the FLEET. Clearly, the demand increases to as much as 3.25 times the 2005 value by 2050. The passenger demand uses historical data for the years 2005 through 2014. After 2014, passenger demand changes as a function of two factors: the demand change due to economic factors, referred to as the “inherent demand growth”, and the demand change due to passenger response to changes in ticket prices charged by the airlines, referred to as the “price-demand elasticity”.

As mentioned earlier, in the current simulation, the GDP growth (inherent demand growth) is the major contributor to the total passenger demand growth (defined by the GDP growth rate evolution discussed in Section).

Table 16: 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 16 shows the percent GDP growth rate, for each continent and demand scenario in 2013, used to determine the evolution of the passenger demand growth rate throughout the simulation period. The initial population growth rates for all demand scenarios in 2013 were set to 0.58%, 1.26%, 0%, 2.6%, 1.10%, 1.10% for North America, South America, Europe, Africa, Asia, and Oceania respectively. Results from Current Trend Best Guess and Current Trend High R&D indicate that the normalized demand increases by a factor of 2.8 by 2050. In Low Demand scenarios, results show the normalized passenger demand in 2050 is about 2.5 times larger than the passenger demand by 2005. In High Demand scenarios, the passenger demand in 2005 increases by a factor of about 3.25 by 2050. The results reveal that GDP growth rate has a positive correlation with normalized passenger demand.

Both demand and CO_2 emissions values normalized to their respective 2005 values, and the normalization factors are the same for every scenario because in 2005 every scenario is identical in its setup. Results from the Current Trend Best Guess scenario and Low Demand Low R&D suggest that CO_2 emissions from US-related airline operations would increase by a factor of about 1.5 from their 2005 level by the year 2050, whereas results from the Low Demand High R&D and Current Trend High R&D scenarios suggest a decrease in CO_2 emissions by a factor of 0.65 and 0.95 respectively by 2050 (Figure 46). The CO_2 emissions for the High Demand High R&D, Current Trend Frozen Tech, and High Demand Low R&D increase by a factor of 1.08, 2.41, and 2.49 respectively by 2050. 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 can further decrease the number of aircraft operations and reduce emissions even further.

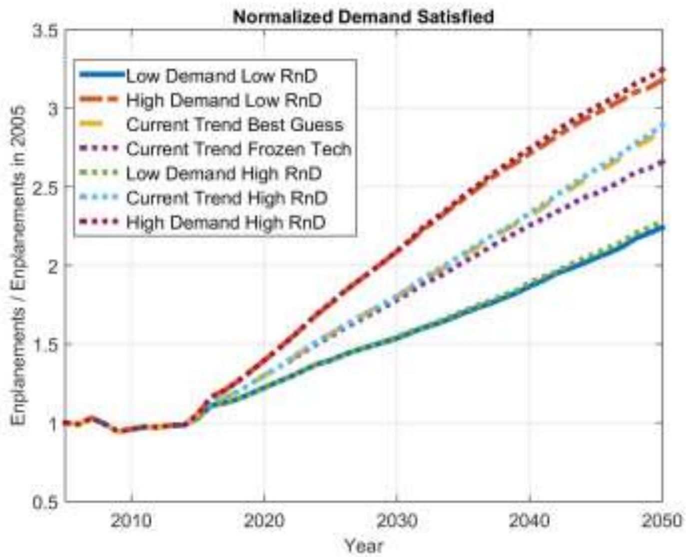


Figure 46: Normalized demand growth from 2005 to 2050

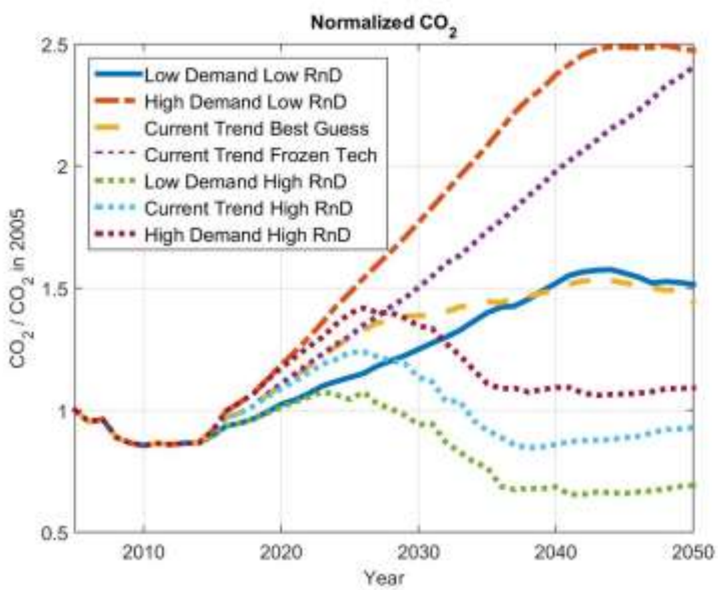


Figure 47: Normalized fleet-level emissions from 2005 to 2050

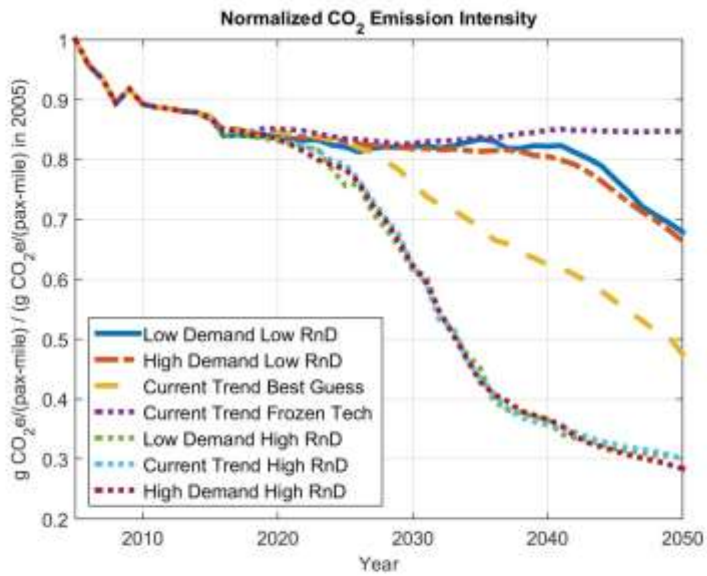


Figure 48: Normalized Fleet-level CO_2 Emission Intensity from 2005 to 2050

Figure 48 shows the CO_2 emission intensity (measured as CO_2 emission per passenger miles), normalized by the 2005 value, for all seven scenarios throughout the simulation period. The Current Trend High R&D and High Demand High R&D scenarios have the lowest emission intensities of 0.30 and 0.29 respectively by 2050. This suggests that the emission intensities in both scenarios reduced to 30% and 29% of their values in 2005 by 2050. The emission intensities in the Current Trend Buest Guess, High Demand Low R&D, and Low Demand High R&D scenarios reduced to 49%, 68.5%, and 69% of their respective values in 2005 by 2050. The Current Trend Frozen Tech scenario has the highest emission intensity of 0.85 times the value in 2005 by 2050. The evolution of the CO_2 emission intensities for all scenarios during the simulation period is dependent on the combined effect of variations in passenger demand and fleet utilization on the FLEET route network. Despite the decrease in emission intensities throughout the simulation, which indicates 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 every scenario.

Figure 49 and **Figure 50** show the deployed fleet by aircraft class and type respectively, normalized by the values in 2005, for all seven scenarios in the FLEET study. Notably, the FLEET airline begins to operate a higher fraction of "GT N+2" Single Aisle (SA) future-in-class aircraft as this becomes available. Because this very efficient aircraft offer better economic returns and the retirements of representative and best-in-class class 1 aircraft create the demand for aircraft to satisfy the passenger demand, this leads to an "up-gauging" of the fleet on shorter routes. Furthermore, the airline flies very few trips using class 5 aircraft, primarily due to the class 6 Large Quad (LQ) aircraft, which has a capacity of 430 passengers, serving the relatively few long-range high-demand routes in the FLEET route network.

From **Figure 50**, for the High Demand scenarios (higher GDP growth rates in every continent), the number of aircraft deployed from 2005 to 2050 increases by a much larger multiple (as high as 2.75) than the number of aircraft deployed in Low Demand scenarios (factor of 1.5) over the same time period. From **Figure 48**, the significant change in CO_2 emission intensity trend slopes around the mid 2020s and 2030s in High R&D scenarios corresponds to the availability of New-in-Class and Future-in-Class aircraft. Additionally, the relatively constant trend in CO_2 emission intensity in the Current Trend Frozen Tech scenario after 2020 is primarily due to the lack of next-gen aircraft.

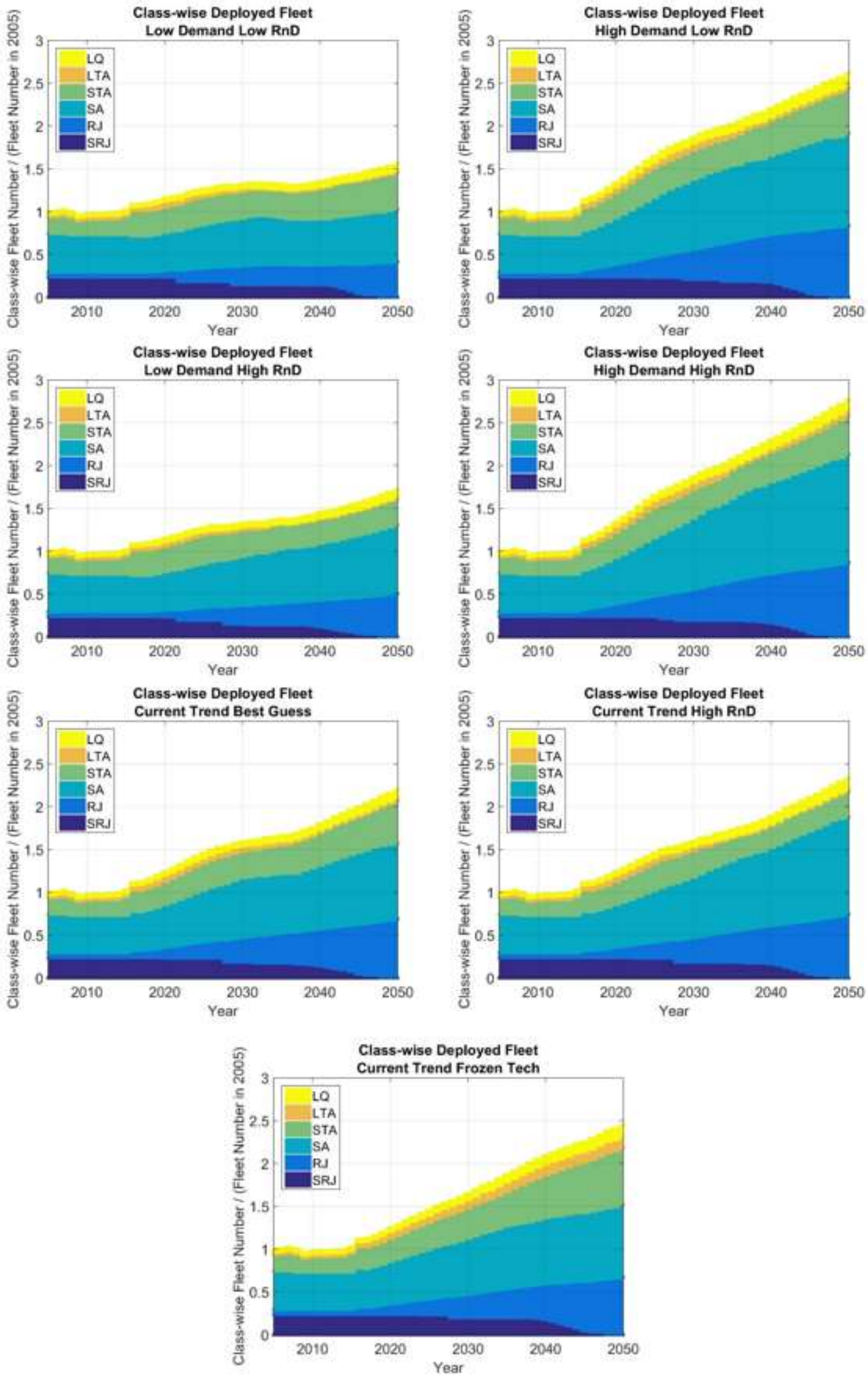


Figure 49: Normalized Deployed fleet by aircraft class (FLEET Run)

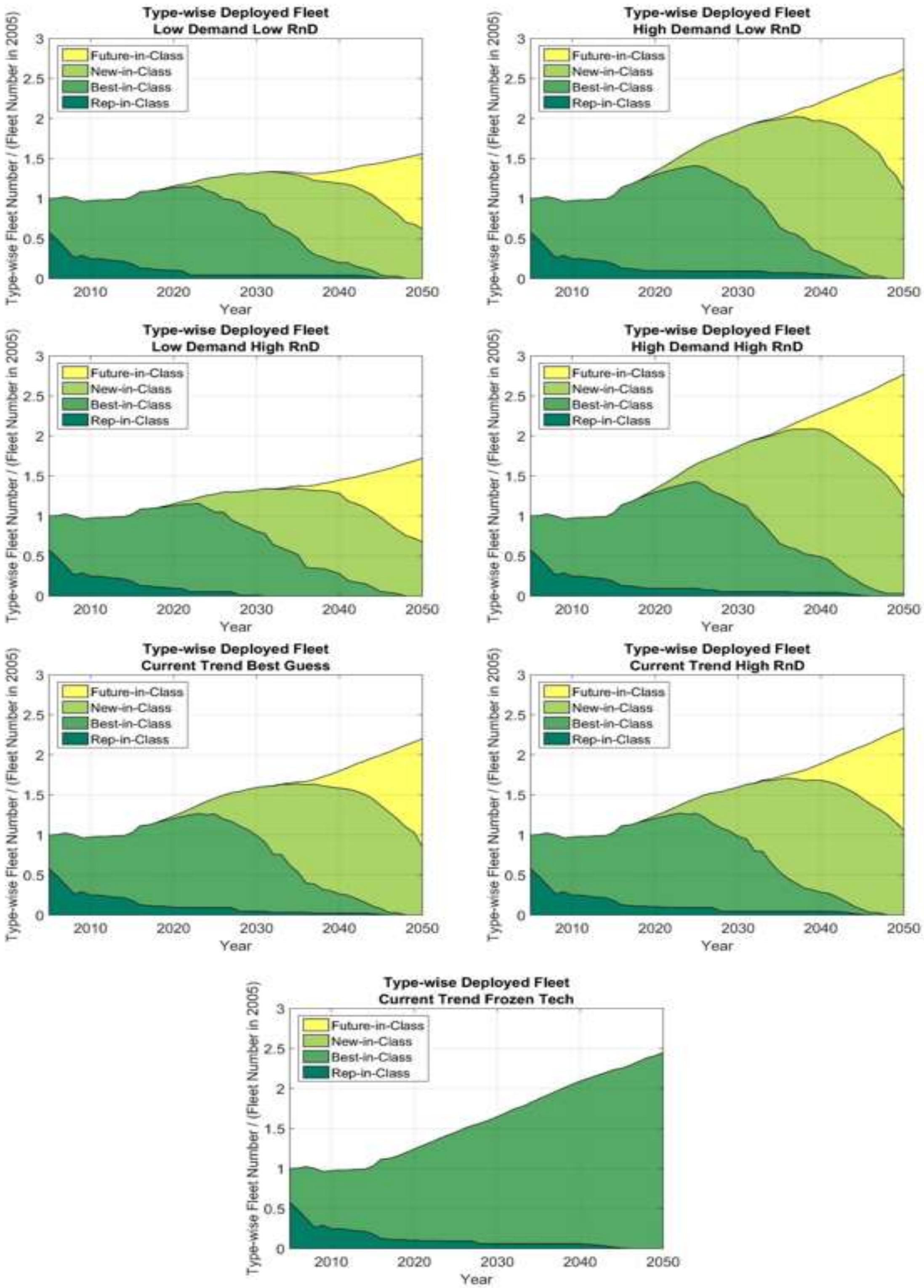


Figure 50: Normalized Deployed fleet by aircraft type (FLEET Run)

Comparison of aircraft types reveals that the airline retains some older aircraft for a longer duration; for instance, **Figure 50** shows that there are some representative-in-class aircraft still operating past 2040 and some best-in-class aircraft operating until 2050. **Figure 50** also shows a 10% - 25% larger fraction of future-in-class aircraft in the High R&D scenarios fleet when compared to Current Trends Best Guess Scenario. In Low Demand scenarios, the demand for aircraft to satisfy the increasing passenger demand is lower than Current Trend scenarios. Hence, airlines can acquire enough “newer” aircraft to replace their old generation aircraft, which results in a shorter fleet turn-over duration.

In summary, the Purdue team successfully demonstrated FLEET’s capabilities for analyzing the scenarios developed by the ASCENT 10 Project partners. Current work involves resolving some of the remaining inconsistencies in scenario modeling assumptions and resulting metrics between FLEET and GREAT. The demonstrations in the past two 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.

Mission Specification Trades (Stanford)

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

Publications

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Outreach Efforts

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

Awards

None

Student Involvement

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

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

Plans for Next Period

The team intends to finalize the fleet analysis by February 2017 and conclude the project shortly thereafter.

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