TECOLOTE
RESEARCH

Final Report
Aviation Fuel Efficiency Technology Assessment

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Preface

This report has been prepared for the International Council on Clean Transportation (ICCT) by Tecolote Research, Inc. (Tecolote), to provide independent, transparent estimates of the incremental benefits and costs of applying carbon dioxide (CO_2) reducing technology packages to new aircraft. The report assesses two Entry-Into-Service (EIS) dates for implementation of technology packages that are aligned with potential implementation dates for the International Civil Aviation Organization's (ICAO) CO_2 standard. The Tecolote team expresses our appreciation to Ms. Anastasia Kharina, Dr. Daniel Rutherford, and Dr. Mazyar Zeinali for their review and critique of the analyses. The contributions from the members of the study's Technical Advisory Group (TAG) have been invaluable in formulation, generation, and review of the technology packages and resulting cost estimates. Tecolote acknowledges the contribution of the cost estimating model from Mr. Craig Nickol of the NASA Environmentally Responsible Aviation (ERA) Project Office. Tecolote also acknowledges the technical contributions of subject matter experts (SME) from Dayton Aerospace, Inc., and Design, Analysis, and Research Corporation (DARcorporation). Tecolote is fully responsible for the content of this report.

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1 Executive Summary

This study assesses the cost effectiveness of aircraft efficiency improvements via a thorough assessment of the technological potential to improve next generation aircraft fuel efficiency. The study extends the International Civil Aviation Organization's fuel burn long-term technology goals (LTTG) review[1] by estimating the cost effectiveness of incrementally improved new aircraft designs. The study provides a comprehensive, rigorous assessment of efficiency technology packages at a level of detail appropriate to inform high-level policy discussions.

The study estimates potential efficiency improvements under various scenarios and the resulting cost impact to operators and manufacturers, providing insight into the economic drivers of advanced technology infusion. This study aggregates potential technologies into discrete technology packages for specific aircraft classes in order to quantify the incremental benefits and costs of those technology packages. The technology packages are aircraft type specific and take into consideration the pace of technology development and maturation, associated costs, derived fuel burn reductions, as well as underlying hurdles for certification on particular technologies. Technologies were limited to those that would not require requiring major changes to the underlying infrastructure (e.g., airport changes).

This study provides transparent cost estimates categorized by aircraft types and two EIS dates (2024 and 2034) for three reference aircraft across a broad range of Maximum Takeoff Weights (MTOW). Those applicable aircraft are: Regional Jet (RJ) – Embraer E190, Single Aisle (SA) – Airbus A320-200, and Small Twin Aisle (STA) – Boeing 777-200ER. Cost estimates are provided in discounted values relative to baseline fuel, maintenance, and production costs for the reference aircraft. The study applies a framework for incorporating technologies into Deployment Scenarios (DS), labeled Evolutionary, Moderate, and Aggressive, corresponding to increasing pressure to reduce fuel burn, enabling the characterization of the marginal operator and manufacturer costs impacts for incremental improvements.

Every phase of the analysis was reviewed and endorsed by an independent Technical Advisory Group (TAG) consisting of experts within the aviation industry. Independent technical Subject Matter Experts (SMEs) were consulted to ensure the technology assessments and inputs were relevant and within the scope of the study. The rigorous review and critique from SMEs and the TAG were invaluable to define relevant technology improvements, identify their maturation and degree of influence, quantify aircraft performance parameters, characterize operations and maintenance impacts, and provide independent evaluation of cost estimate results and underlying ground rules and assumptions.

The cost estimation framework utilized US government (Department of Defense and National Aeronautics and Space Administration, or NASA) sponsored software tools, the Automated Cost Estimating Tool (ACEIT) and the Probabilistic Technology Investment Ranking System (PTIRS). ACEIT

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[1] Report of the Independent Experts on the Medium and Long Term Goals for Aviation Fuel Burn Reduction from Technology. 2010. ICAO Doc 9963 ENGLISH ISBN 978-92-9231-765-2.

provided a framework to standardize the estimating process to develop, report, and share the cost estimates. PTIRS contained the underlying cost estimating methodologies for nonrecurring aircraft development costs, recurring costs for aircraft production, as well as annual maintenance costs. PTIRS was developed for and sponsored by the NASA ERA project to support the evaluation of advanced vehicle concepts and technologies that reduce fuel burn, noise and/or emissions.

This study developed cost benefit results by comparing costs for the 2024 and 2034 EIS years to a non-improved reference aircraft for each assessed aircraft class (RJ, SA, STA) and deployment scenario. Total Operator Costs (TOC) included the amortization of the cost to mature the technologies and develop/certify new aircraft and engines, the purchase of the resulting aircraft to support the identified market demand over a ten-year period, maintenance and fuel costs over a defined number of operational years, and the resulting income from the residual value after a typical first operator lifetime. The cost estimates are bounded by the overall construct of the inputs, assumptions, and constraints of estimating the cost of technology maturation, aircraft and engine development, production, operation, and maintenance.

Given the underlying uncertainties in technical parameters and cost estimate inputs, a Monte-Carlo simulation methodology was applied to estimate the potential cost range for each scenario. All cost results were normalized to the expected value (the statistical mean) to allow a consistent comparison across scenarios.

The overall findings of the study are summarized below.

- The development of incrementally more fuel-efficient new aircraft types increases overall manufacturing and development costs while providing fuel and maintenance savings. The level of fuel efficiency that provides direct economic benefits to operators differs across EIS years and technology deployment scenarios depending on the relative magnitude of these offsetting factors.
- Overall, the results suggest that the fuel burn of new aircraft types can be reduced by approximately 25% in 2024 and 40% in 2034 in a cost-effective manner compared to the reference aircraft, as defined by seven years of operation and a discount rate of 9%, the estimated cost of capital for airlines. These aircraft would provide net savings to the first operator while reducing fuel burn and associated CO_2 emissions. Additional improvements would become cost-effective by varying assumptions, for example the use of a lower discount rate (3%) to reflect a social cost of capital.
- Among the technology classes, the largest share of modeled fuel burn savings in this study were attributable to propulsion technologies, followed by aerodynamic improvements (especially in the more aggressive scenarios) and then technologies to reduce structural weight.
- This study was based on implementing currently identified technologies that could be matured in time for deployment; it does not consider aggressive or exotic technologies that may be able to achieve more aggressive reductions.
- Total ownership costs were dominated by operator capital expenditures (51%-57% of TOC) and fuel costs (36%-42%), while maintenance costs played a relatively small role in determining net costs across scenarios (5%-8%).

- TOC savings increase over time, with substantial fuel and maintenance savings accruing beyond the base seven year operational period used in the study.
- Among the various assumptions investigated, the net TOC impacts of advanced aircraft were found to be most sensitive to assumptions about market capture. Where a manufacturer captures less market share than anticipated, operator capital costs increase as technology maturation and development costs need to amortize over a smaller number of aircraft. The risk of escalating costs and subsequent decrease in product viability may lead to risk adverse manufacturers to introduce products with lower levels of fuel efficiency than predicted based upon deterministic economic factors alone.

2 Study Construct

This section of the report details the overall objective, study approach, and team members that assisted in the study. This section provides a high-level overview of the study framework and insight into the approach, coverage, and the roles each team played in the study.

2.1 Objective

Interest in the relationship between aircraft and global warming has been high since the Intergovernmental Panel on Climate Change (IPCC) published the first comprehensive examination of aviation's impact on climate change.[2] Due to its speed and convenience in safely transporting people and goods, the aviation sector is vital to our modern economy. At the same time, the climate impact of aircraft is believed to be substantial—at least 2.5% of anthropogenic CO_2 emissions and 3.5% to 4.9% of historical radiative forcing after including the impact of nitrogen oxide (NO_x) emissions and influence on cloud formation.[3] Furthermore, demand for air travel is expected to grow significantly, with especially high growth rates in developing markets such as China and India.[4] Lacking strong controls for aviation, it has been estimated that the aviation sector may be responsible for as much as 15% of anthropogenic CO_2 emissions by 2050 should current climate protection goals be pursued for other sectors but not aviation.[5]

This study builds off the International Civil Aviation Organization's (ICAO) 2010 fuel burn LTTG.[6] That study identified that fuel burn of new single and small twin-aisle aircraft could be reduced by 29% and 25%, respectively, in the year 2020 and as much as 48% in 2030 when compared to a 2000 reference technology baseline. This study provides an assessment of available and emerging technologies to enhance fuel efficiency that could be implemented into new aircraft during the 2024 and 2034 time periods using similar baseline aircraft.

The goal of the study is to generate a robust, transparent, and independent estimate of the incremental benefits and costs of advanced technology aircraft compared to appropriate baseline aircraft with EIS dates consistent with new type designs affected by ICAO's CO_2 standard.[7] The cost estimates take into consideration the current state of aircraft efficiency improvements and the future state given certain

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[2] Intergovernmental Panel on Climate Change (1999). Aviation and the Global Atmosphere. https://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1

[3] Lee, D.S., Fahey, D.W., Forster, P.M. *et al.* (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment.* 43: 3520-3537

[4] http://www.boeing.com/commercial/market/long-term-market/world-regions/

[5] Lee, D.S.; Lim, L.; Owen, B. Shipping and aviation emissions in the context of a 2°C emission pathway. Accessed at http://www.transportenvironment.org/sites/te/files/publications/Shipping%20and%20aviation%20emissions%20and%202%20degrees%20v1-6.pdf

[6] Report of the Independent Experts On Fuel Burn Reduction Technology Goals, CAEP-SG/20101-WP/11, Committee On Aviation Environmental Protection (CAEP) Steering Group Meeting, Toulouse, France, 8-12 Nov 2010. Doc 9963 ENGLISH ISBN 978-92-9231-765-2.

[7] ICCT (2013). International Civil Aviation Organization's CO_2 Certification Requirement for New Aircraft. http://www.icao.int/environmental-protection/Documents/CO2%20Metric%20System%20-%20Information%20Sheet.pdf

economic and financial assumptions. These cost estimates examined three major aircraft configurations and implemented technologies consistent with the LTTG study.

The study focused on three aircraft types—Single Aisle, Small Twin Aisle, and Regional Jet.[8] These classes cover a broad range of MTOW values and enable the extension to predict cost benefits for aircraft of other sizes. Reference aircraft were established to support the evaluation of fuel-burn savings and production costs. The reference aircraft selected for each class were: 1) Embraer E190–RJ; 2) Airbus A320-200–SA; and 3) Boeing 777-200ER–STA.

The study extends and refines the earlier LTTG analysis in several important ways. It provides a more thorough evaluation of potential technologies to reduce aircraft fuel burn for new type designs consistent with potential applicability dates for ICAO's CO_2 standard (i.e., 2024 and 2034). It expands the LTTG analysis to include regional jet aircraft and incorporates detailed engine performance modeling using the GasTurb model. Most importantly, this study estimates the full economic implications of developing and deploying new fuel efficiency technologies, taking into account technology maturation, aircraft development, recurring production costs, and fuel and maintenance savings relative to the non-improved reference aircraft. Finally, the study bounds key uncertainties using probabilistic modeling approaches and through sensitivity analysis for key variables, including market capture, fuel price, discount rates, and other factors.

2.2 Study Approach

The study approach emphasizes on process rigor, the collective input of SMEs, evaluation of key assumptions and input from the TAG and Tecolote, and cost modeling developed and refined by Tecolote senior cost analysts for NASA and the Department of Defense (DoD). The overall study was conducted in three major phases, with a formal review and approval gates before commencement of the next phase of the study.

- **TECHNOLOGY IDENTIFICATION.** This phase established the years of analysis; the aircraft classes to be considered for the analysis; the reference aircraft to be used as the comparative basis for each aircraft class; identified potential technology improvements in the areas of propulsion, structures and aerodynamic; assessed the applicability and fuel efficiency impact of each technology specific to each aircraft type; and determined the underlying cost estimating methodologies to use for determination of TOC. Each individual technology was assessed by the SMEs and their results were reviewed and approved by the TAG.
- **DEPLOYMENT SCENARIO EVALUATION.** The second phase of the study dealt with identifying packages of compatible technologies for each aircraft class to achieve increasing levels of fuel efficiency. These technology packages were the basis for the deployment scenarios analyzed in the study. This phase consisted of assessing the aggregate fuel efficiency impact, determining the resulting technical characteristics (e.g., mass, thrust), and quantifying the resulting impact of technologies

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[8] Blended Wing Body aircraft were excluded from the study due to modeling limitations.

to cost estimating input parameters (e.g., design heritage, complexity factors, etc.) for each deployment scenario.

- **COST ESTIMATION.** The final phase of the study consisted of finalizing study parameters (e.g., market demand, market capture, fuel prices, etc.), calculating TOC for each deployment scenario, running Monte-Carlo simulation, and conducting sensitivity analysis on key input parameters. Total operator cost consists of the cost for an operator to procure the aircraft, the fuel and maintenance cost for seven years of operation, and the income obtained from reselling the aircraft to the secondary market after its first lifetime. Procurement costs contained amortization of all technology development and system development costs as well as a target profit over the calculated development and production costs.

This study made use of several software models and tools to compute the benefits and costs of implementing new technologies to reduce CO_2 emissions from commercial aircraft. These models and tools were integrated to generate costs of technology maturation, development, and production according to the EIS year and respective technology infusion scenarios, i.e., evolutionary, moderate, and aggressive.

For technology maturation costs, SMEs estimated the duration of efforts to mature the respective technology, the staffing or manpower required achieving the target maturity, and the uncertainty associated with effort. These inputs created the notional project profile (using Microsoft Project) used to calculate the probabilistic schedule and cost using the Joint Analysis of Cost & Schedule (JACS)[9] for each scenario and aircraft type. JACS is a software application within the ACEIT[10] suite developed in 2010 to support integrated cost and schedule modeling for NASA. JACS has been used for the majority of analyses to support identification of official cost and schedule budgets/targets for major missions.[11] JACS has also been used by technology development groups within NASA to assess the cost and time to mature a technology to a demonstrative state. ACEIT itself was formulated by the United States Air Force (USAF) in the mid-1980's to provide a framework for conducting cost estimating related activities ranging from databases to regression analysis, inflation modeling, cost modeling, and Monte-Carlo simulation. ACEIT is a US-Government funded and directed tool suite that is developed, maintained, and procured through Tecolote Research. ACEIT includes several software applications within the suite.

To support the quantification of aircraft technical parameters that were the key drivers for aircraft development and production cost, the Piano 5[12] model was used to calculate the mass and thrust that fed into the cost model. Piano 5 was also used to generate fuel burn profiles for each aircraft deployment scenario. Separately, the GasTurb[13] model was used to calculate performance parameters used to estimate engine development and production costs. These parameters along with Piano 5 thrust values were used to estimate engine mass.

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[9] www.aceit.com/aceit-suite-home/product-info/jacs

[10] https://www.aceit.com/

[11] https://oig.nasa.gov/audits/reports/FY15/IG-15-024.pdf

[12] http://www.piano.aero/

[13] http://www.gasturb.de/

The underlying cost estimating methodologies for system development, production, and maintenance costs were obtained from NASA's PTIRS[14] and implemented within a cost tool developed by the Department of Defense called the Automated Cost Estimator (ACE).[15] ACE is a software application within the ACEIT tool suite that was first developed in 1989 by the USAF to allow standardized and repeatable cost estimation models containing temporal characteristics and Monte-Carlo simulation modeling. ACE has undergone rigorous testing and validation of its underlying calculation algorithms to verify that the modeling platform provided accurate results.[16] Since its development, ACE has been chosen as the primary platform for developing cost estimates for the major services (USAF, Army, Navy, Marine Corps) within the Department of Defense.[17] Just like JACS, ACE is an application within the ACEIT suite. JACS is currently in use by NASA as a central tool in their Joint Confidence Level (JCL) process to support the identification of the level of funding for all NASA projects over $250 million US dollars.[18] The result of using JACS in the JCL process has resulted in NASA obtaining improved performance in meeting cost objectives.[19] PTIRS was developed for and sponsored by the NASA ERA Project to support evaluation of infusion of advanced vehicle concepts and technologies that reduce fuel burn, noise and/or emissions. During its development PTIRS went through a vigorous validation process[20] before being accepted by NASA for use in estimation of the impacts of technology infusion.

A key construct of the study is to identify and determine the characteristics of a modified/new aircraft containing fuel reduction technology while holding the overall characteristics of payload size (number of passengers) and range constant. This causes a challenge in estimating costs of the aircraft as the majority of cost estimating methodologies use size as the driving input parameter. In the case of PTIRS cost estimating methodologies, mass is the parameter used to represent size. A consideration when using mass-based estimating relationships is to understand the underlying data points used to formulate the equation and the behavior of the input parameters to total cost. Historically, for the major of large manufactured systems, as performance (e.g., payload size, aircraft range) increases for an aircraft there is a corresponding increase in the size of the system to achieve this performance increase. In this manner, a performance increase drives a mass increase, which causes a cost increase. The challenge in this study is to estimate the development and manufacturing cost impacts of new technologies while holding the payload and range approximately constant. In these scenarios, some fuel efficiency technologies causes a decrease in mass (e.g., due to the use of lightweight materials), which after

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[14] P. Frederic, G. M. Bezos-O'Connor, C. Nickol, "Cost Analysis Approach in the Development of Advanced Technologies for Green Aviation Aircraft." Encyclopedia of Aerospace Engineering – Green Aviation Volume. June 2015

[15] https://www.aceit.com/aceit-suite-home/product-info/ace

[16] Tecolote Research, "ACEIT Test Plan", updated upon each release and delivered to an independent US Government ACEIT Working Group (AWG) upon every release since 2003 verifying the tool's accuracy in implementing prior and new features

[17] https://www.aceit.com/docs/default-source/Compliance-Documentation/aceit-certification-compliance-documentation-summary.pdf?sfvrsn=6, "ACEIT Certification/Compliance Documentation"

[18] National Aeronautics and Space Administration. NASA Procedural Requirements (NPD) 7120.5E NASA Space Flight Program and Project Management, http://nodis3.gsfc.nasa.gov/, August 14, 2012.

[19] General Accounting Office (GAO)-14-338SP Assessments of Selected Large-Scale Projects 2014, p. 10

[20] P. Frederic, "PITRS Final Report, Appendix N – Support Document for Verification and Validation of PTIRS Model". April 2014

resizing would also lead to a lower mass and cost for unimproved, legacy subsystems if the estimating equations were used without adjustment. To correct for this effect, a mass adjustment factor was applied to the cost estimating equations to avoid potential overestimation of cost savings of introducing structural technologies into derivative designs (see Section 4.4.3.6).[21]

Fuel costs were based on a model which factored in survivability and flight hours based on the year of operation for an aircraft. The basis for the fuel consumption for each deployment scenario was developed from the output of the Piano 5 model. This fuel consumption reduction was used in the calculation to estimate the fuel costs for each deployment scenario.

To support economic evaluation of the investment and expenses incurred, all costs were phased in over appropriate time periods. These cost streams were discounted back to 2013 to assess the discounted costs. Through discounting the hurdle imposed by a large near-term investment could be appropriately evaluated compared to savings obtained several decades in the future.

Given the underlying uncertainty inherent in forecasting, the potential variability of each input parameter to the cost model and the underlying cost estimating equations was evaluated. This variability was either determined by objective methods or based on SME evaluation. For items that were overall study assumptions (e.g., discount rate, market demand, etc.), uncertainty distributions were not specified for use in the model but rather sensitivity analyses were run to quantify the potential impact on the study if the underlying assumption was varied.

By using validated tools, calibrated and verified models, conducting detailed subsystem-level cost/technical analysis, addressing via Monte-Carlo simulation the underlying model input uncertainties and model prediction error, and implementing an independent technical review team, the results are believed to be credible and defensible.

2.3 Study Teams

The study was a collaborative effort across several teams, each with specific functions.

- **TECOLOTE** generated cost estimates for aircraft efficiency improvement using cost estimating and simulation experts based upon the study inputs, assumptions, and assessments.
- For technical inputs, the study relied upon **SUBJECT MATTER EXPERTS** to assess the technology areas and quantifying the impacts of infusion.
- The **TECHNICAL ADVISORY GROUP** acted as the steering committee and consisted of members with specific and broad expertise relevant to this work.
- **INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION** staff contributed fuel burn modeling using the Piano model and facilitated communication between Tecolote and the TAG.

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[21] This approach was developed by Tecolote to estimate the impact of weight reducing technologies on a variety of vehicles, including spacecraft, aircraft, and launch vehicles. The approach has been used on cost estimates that have gone through independent formal review by US government analysts since 2005.

2.3.1 Cost Estimation and Analysis Team (Tecolote)

TECOLOTE (www.tecolote.com) provided the cost and simulation experts to estimate the various configurations and aggregate the total cost estimates. Tecolote is an employee-owned corporation specializing in providing analytically-based decision-making tools and supporting cost, schedule, and risk analyses on large scale projects and programs being acquired by its clients. Tecolote is the largest and oldest firm specializing in cost estimations for high technology acquisition programs, providing decision support analysis for complex programs since 1973. Tecolote supports NASA, Army, Air Force, Navy, Marine Corps, US Coast Guard, and US Special Operations Command, providing cost analysis services for all aircraft types, including fixed wing, rotary wing, unmanned systems, and numerous modification programs. The PTIRS model was developed by Tecolote and used for the NASA Environmentally Responsible Aviation Project within the Aeronautics Research Mission Directorate. The Tecolote team (Table 1) contains over 160 years of accumulated cost analysis experience.

TABLE 1 – TECOLOTE TEAM

Member	Expertise
Darren Elliott	Team Lead
Brian Fields	Cost Lead
James Maury	Technology Lead
Rey Carpio	Lead Reviewer
Chad Bielawski	Cost Analyst
Peter Frederic	Cost Estimator
Richard Nordsieck	Cost Estimator
John Trevillion	Cost Estimator

2.3.2 Technology Subject Matter Experts

In order to conduct detailed technical analysis to support the identification and resulting impact of technology a team of technical experts was established. Tecolote identified a list of potential SME candidates with specific experience and knowledge of commercial aircraft, propulsion systems, structures, aerodynamics and propulsion. Tecolote selected SMEs based on domain knowledge and experience, familiarity with associated technology efforts, and an understanding of development and production of commercial aircraft or aircraft engines. The SMEs combined for an average of more than 30 years of experience each in the areas of aircraft structural design, configuration, aerodynamics and propulsion.

DARCORPORATION (www.darcorp.com) has provided aeronautical engineering software and consulting services since 1991 in the areas of single/multi-engine propeller and jet powered aircraft, Business Jets, Very Light Jets (VLJ), Kit, LSA and Experimental Category aircraft, Vertical Take Off and Landing (VTOL) combat force insertion vehicles, VTOL aircraft, Unmanned Air Vehicle (UAV) for civil and military applications, and hybrid air/ground vehicles. For this study, DARcorporation provided engineering consulting services in the general area of airframe, advanced material, aerodynamic surfaces, and overall aircraft configuration design and analysis. Table 2 identifies the SMEs from DARcorporation.

TABLE 2 – DARCORPORATION TEAM MEMBERS

Member	Expertise
Dr. Willem Anemaat	Aerospace and engineering
Dr. Jan Roskam	Aeronautics and astronautics

DAYTON AEROSPACE, INC. (www.daytonaero.com) has been providing technical consulting and expertise to the US Government and civilian aeronautics industry since 1984. Their staff consists of senior military or civilian, with 25-30+ years of experience, covering all technical and management disciplines in system acquisition and logistics. Dayton Aerospace specializes in supporting both government and industry customers using these highly experienced practitioners. For this study, Dayton Aerospace provided engineering consulting services in the area of propulsion technology and engine maintenance. Table 3 identifies the SMEs from Dayton Aerospace.

TABLE 3 – DAYTON AEROSPACE TEAM MEMBERS

Member	Expertise
Gerry Friesthler	Propulsion engineering
Dave Edmunds	Propulsion system analysis/integration
J. Walter Smith	Propulsion system modeling

2.3.3 Technical Advisory Group

THE TAG is a steering committee, consisting of members with specific and broad expertise relevant to this work. The TAG consisted of members with specific and broad expertise related to aircraft and airframe fuel efficiency technologies, costing methodologies, and aircraft maintenance to guide the work and provide a forum for collaboration and input from major stakeholders from diverse perspectives. TAG members provided invaluable inputs in aerodynamics, model development, engines, propulsion, structures, and economics; as well as supporting identification of different baseline aircraft types based on a diverse coverage of aircraft types, performance and size. Table 4 identifies the membership of the TAG.

TABLE 4 – TAG MEMBERS

Member	Affiliation	Expertise
Professor Juan Alonso	Department of Aeronautics & Astronautics, Stanford University	Aerodynamics and model development
Professor Meyer J. Benzakein	Director, Aerospace and Aviation Collaboration Programs and Propulsion and Power Center, Ohio State University	Engines
Dr. Fayette Collier	Project Manager, ERA Project, NASA	Aircraft technologies
Professor Nicholas Cumpsty	Professor Emeritus, Imperial College London	Engines
Richard Golaszewski	Executive Vice-President, GRA, Incorporated	Economics
William Norman	Formerly United Airlines (MRO Strategy)	Aircraft maintenance
Dr. Dianne Wiley	Independent Aerospace Consultant, Boeing retired	Structures

2.3.2 The ICCT Team

The ICCT is a nonprofit research organization with a mission to dramatically improve the environmental performance and efficiency of personal, public and goods transport modes in order to protect and improve public health, the environment and quality of life. Table 5 identifies the key parties from ICCT that participated in this study.

TABLE 5 – ICCT TEAM MEMBERS

Member	Title
Dr. Daniel Rutherford	Program Director
Dr. Mazyar Zeinali	Aviation Lead (former)
Anastasia Kharina	Researcher

2.4 Study Coverage/Parameters

This study emphasizes process rigor, collective use of Subject Matter Experts, evaluation and inputs from an external independent TAG, and the use of a cost model with strong heritage based on years of proven performance at NASA and the Department of Defense.

The study incorporates many different factors, scenarios, forecasts, assumptions, and inputs—all carefully integrated and calibrated to capture and simulate the 2024 and 2034 flow of finance, development, technology, operations, and maintenance. The general study parameters include three reference aircraft and corresponding aircraft classes. 2024 and 2034, consistent with anticipated implementation of ICAO's CO_2 standard for new type aircraft in 2020 plus a second scenario to allow an additional 10 years of technology development, were selected as EIS years to estimate the relative costs and benefits of improved new type aircraft under three deployment scenarios (DS). The cost results on the study are based on comparing estimated ownership costs for the reference aircraft to each respective deployment scenario.

For estimating future values, the study took into consideration future market forecast and market capture, along with the number of years of manufacture and production. To account for other factors that impact average unit cost, amortization, inflation, discounting, depreciation, and labor rates were incorporated to reasonably simulate future state of deployment scenarios.

2.4.1 Study Aircraft Classes

The three aircraft categories selected for the study provided for a wide range of Maximum Takeoff Weight (MTOW) as well as capturing approximately 85% of the global fuel-burn by commercial aircraft. Initially six aircraft types were evaluated for consideration in the study: Turboprop, Business Jet, Regional Jet, Single Aisle, Small Twin Aisle, and Large Twin Aisle. In discussing the key objectives of the study, it was determined that a focused approach on a smaller subset of aircraft types would yield better results. After assessment by SMEs and the TAG, it was determined that focusing on three potential aircraft types would capture the primary class types being implemented by commercial aviation operators for business and leisure air travel while providing a sharper focus on the aircraft classes that could potentially provide the largest fuel burn reductions.

2.4.2 Reference Aircraft

Establishing appropriate reference aircraft is fundamental to the economic analysis of this study. The reference aircraft provides an anchor point to assess the viability and impact of identified technologies. Secondly, the reference aircraft allows the establishment of an anchor point to assess the economic costs assumed by a manufacturer making aggressive investments. Through this reference case, the study construct allows the detailed assessment of the relative economic impact for pursuing more aggressive fuel reduction. The overall goal of the study is to identify the economic difference for operators (and manufacturers) in procuring aircraft with significant improvements in fuel performance.

To support the evaluation of fuel burn savings as well as to provide a basis for generation of production cost deltas, a specific reference airplane was needed for each type selected for the study. In selecting the reference airplane, a key consideration was having appropriate information on weights and the ability for the Piano 5 platform to accurately model weight breakdowns at the level needed for costing purposes. By establishing reference airplanes that can produce high quality mass and performance data, the study could establish baseline fuel burn and production costs. Upon assessing the impact of technology incorporation on a reference airplane, Piano 5 simulations provided mass and performance data to evaluate the economic impacts of technology incorporation.

The three aircraft types selected were the regional jet (90-120 seats), the single-aisle aircraft (110-210 seats), and small twin aisle (211-400 seats). Together aircraft types provide for a wide range of MTOW as well as capturing approximately 78% of the fuel burn by commercial aircraft operating at US airports in 2014.[22]

The regional jet reference (referred to RJ) is the Embraer 190, the single-aisle reference (referred to as SA) is the Airbus A320-200, and the small twin aisle (referred to as STA) is the 777-200ER. By establishing reference airplanes that can produce high quality mass and performance data from Piano 5, baseline fuel burn and production cost values were established. Upon assessing the impact of technology incorporation on a reference airplane, Piano 5 generated mass and performance data to evaluate the impacts of technology incorporation from a fuel burn and economic standpoint.

As noted above, this study focused on the RJ, SA, and STA classes. These classes together offer a broad range of MTOW values which can be used to predict costs for aircraft of other sizes (see Table 6).

TABLE 6 – REFERENCE AIRCRAFT BY CLASS

Aircraft Class	Reference Aircraft	Engine Type	Approximate Seats
Single Aisle	Airbus A320-200	CFM56-5	110 – 200
Small Twin Aisle	Boeing 777-200ER	PW 4090; RR 895; GE90-94B	211 – 400
Regional Jet	Embraer E190	GE CF34-10E	94 – 120

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[22] US Department of Transportation, BTS Form 41 Traffic (T100 Segment), 2014.

2.4.3 Analysis Scenarios—Entry into Service Years

The study targets an assessment of industry viability to meet upcoming environmental standards being proposed for new type certifications after 2020. To support this analysis, the study identified two Entry-Into-Service (EIS) years for which the modified aircraft would need to be fully certified and be able to enter into an operator's fleet. Given the typical timelines for aircraft system development, manufacture, testing, and certification, an initial EIS year of 2024 was selected. This allowed for the assessment of a limited set of near-term technologies that could be matured and incorporated into new aircraft designs in 2024. This initial near-term timeframe eliminated several technologies as they were too early in the maturation process and would place extreme pressure on a manufacturer to fully implement and meet an early EIS date.

It was determined that an additional ten years would provide a second distinct snapshot of technology benefits/costs by providing a sufficient additional time for the development of a new set of technologies. The next EIS year was set for 2034, representing some 20 years of progress from today's recently certified aircraft (see Table 7).

TABLE 7 – EIS YEARS

EIS Years	Assumed Initiation of Certification	Length of Time for Maturation and Implementation
2024	2020	~ 9 years
2034	2030	~ 20 years

2.4.4 States of the World (Non-Improved State, Reference Case)

The goal of the study is to identify the economic implications for operators to procure aircraft with significant fuel efficiency improvements. The envisioned scenarios are more aggressive than a measured infusion process (for example, current manufacturers' targets of up to 15% fuel burn reduction for new derivative aircraft are seen today, which is less than the 25% reduction estimated under the 2024 lowest technology case).

Two general States of the World were assessed for the 2024 EIS period. The first deployment scenario is the **Non-Improved State** (Reference) corresponding to an operator forgoing technology improvements and continuing to manufacture the reference vehicle. This assumes no incremental benefits in fuel burn or maintenance costs for the reference aircraft. The means that in 2024 a newly delivered A320, 777-200ER, or E-190 are assumed to have the same fuel burn and maintenance costs as the one delivered in 2013. The only change in cost would be that the cost of the 2024 aircraft will be lower due to learning curve reductions achieved between 2013 and 2024. By using current aircraft as the reference configurations, the study minimized potential error introduced by using estimated aircraft design parameters (e.g., subsystem mass, fuel burn, MTOW, etc.) as the basis within the Piano 5 design tool for aircraft resizing due to implementation of new technologies. Separately, the resulting cost model could be tested to verify the predictive capability for projection aircraft like the A320neo. This test case is documented in Section 4.3.3.

It was determined that this would be the representative base case to determine the cost benefit analysis of each deployment scenario for each EIS and aircraft class. Given the limited amount of time to 2024, a manufacturer would need to make an immediate decision to invest in new technologies and would forgo any evolution of the current product line. Instead they would continue to manufacture the current vehicle as they are developing and certifying the enhanced vehicle; in essence, if a manufacturer decides to pursue one of the deployment scenarios it will divert attention and resources to the improved technologies and cease any technology evolution on current vehicles. This state is our reference case with projected learning curve cost reductions realized by the manufacturer of the next ten-plus years.

The second State of the World is **Technology Deployment Scenarios** for various levels of fuel efficiency technology infusion. These States of the World enable assessment of the costs an operator will incur to procure, fuel, and maintain improved aircraft, taking into account that the manufacturer will amortize investments into the price and seek a base profit margin of 20%. These are compared against the Non-Improved State for the respective EIS period.

Prior quantities are an important assumption in cost estimation as they are used to determine the starting point for calculation of all forward production costs. The buy quantity determines the overall quantity from this starting point to use in a production cost estimate. For example, if the prior quantities were 1000 and the buy quantities were 500, then the cost estimate would reflect the costs for units 1001 through 1500.

Table 8 details the prior quantity and buy quantity assumptions as well as production cost points for a 2013, 2024 EIS, and 2034 EIS reference aircraft. The prior quantities are based on review of actual deliveries for the reference aircraft type from the Embraer 2013 Market Outlook. The remaining quantities in the table for 2014-2043 buy quantities are based on overall market forecast for the reference aircraft class and a single-vendor market capture projection. Further information is provided in Sections 2.4.6 through 2.4.9.

TABLE 8 – QUANTITY ASSUMPTIONS

	Prior Qty as of 2013	Purchase Qty (2014-2023)	Total Prior Qty (through 2023)	Buy Qty 2024 EIS (2024~2033)	Total Prior Qty (through 2033)	Buy Qty 2034 EIS (2034~2043)
SA (A320-200)	3,192	2,955	6,147	4,024	10,171	5,477
STA (777-200ER)	983	856	1,839	1,280	3,119	1,913
RJ (E190)	382	572	954	961	1,915	1,614

2.4.5 Technology Deployment Scenarios

To provide a range of potential technology scenarios for evaluation, the individual identified technologies need to be packaged into distinct deployment scenarios. For the analysis, it was determined that three technology infusion scenarios of increasing ambition would be created for each aircraft and EIS year. Through this approach, the study sought to provide multiple data points for the incremental cost of technology and to support the characterization of cost-effectiveness costs. Table 9 summarizes the deployment scenarios.

TABLE 9 – DEPLOYMENT SCENARIOS

Deployment Scenarios	Description
Non-Improved	No technology improvement, continued manufacture of reference aircraft
Evolutionary	Continuing trend of improvement
Moderate	Modest increase in technology investment and deployment
Aggressive	Accelerated levels of technology investment and deployment

Each DS was established by the TAG with consideration of input from the SMEs. To support the economic analysis, the costs of each DS are compared to a non-improved technology scenario based on the continued manufacture of the reference aircraft. The technology deployment scenarios were aircraft class specific and take into consideration the pace of technology development/maturation, associated costs, the derived performance benefits, the underlying hurdles for certification on particular technologies, without requiring major changes to the underlying infrastructure (e.g., airport changes). Through the analysis of these three technology deployment scenarios, relationships between achieving fuel efficiency, CO_2 reduction, and costs can be determined.

2.4.6 Market Forecast

To estimate overall costs it is critical to identify the overall market forecast and the expected market capture for the deployment scenarios. The market forecast identifies the overall potential purchases to meet a forecasted fleet size for each aircraft class. The market capture identifies the estimated capture of this market demand for the technologically enhanced vehicle for a single manufacturer, or vendor. For this study, market forecasts were developed for all aircraft classes for the time period of 2014 through 2043. Additionally, market capture assumptions specific to each aircraft class were developed, but consistent regardless of the EIS year (meaning that for each aircraft type the 2023 EIS and 2034 EIS market capture assumption was the same). All analyses used the same market forecast for the calculation of costs. This means that for all SA deployment scenarios the same market forecast and market capture was used to ensure a common assumption of the number of aircraft procured and being in an operational state.

Tecolote reviewed and analyzed several data sources (Embraer[23], Boeing[24], FAA[25], and Ascend[26]) to develop the market forecast and capture assumptions used in the study. Although recent (2015) market forecasts were available from FAA and Ascend, the most detailed data sources were from the 2013 Embraer and Boeing market forecasts. Analysis was conducted to determine if the newer forecasts differed substantially. Overall the market forecast for SA and STA from Ascend and FAA were in-line with prior analysis. Given that the market forecast and capture assumptions require additional data not

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[23] http://www.embraermarketoutlook.com/

[24] http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/Boeing_Current_Market_Outlook_2015.pdf

[25] https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/2013_Forecast.pdf

[26] http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/

provided in the FAA/Ascend data set, it was concluded that 2013 market forecast data were appropriate for the study in order to avoid mixing and matching assumptions from different datasets and time periods. Appendix A provides the market forecast analysis model.

The basis for the market forecast was Embraer's Market Outlook.[27] The Embraer dataset was selected as the basis for the forecast as it provided detailed information on seat class differentiation in line with the three baseline reference aircraft. This allowed for a direct calculation of prior quantities and the ability to forecast future year quantities. The data set identified fleet size in 2011, projected deliveries in 2012, and estimated fleet size in 2031. From this data, fleet attrition rate was obtained from Embraer by vehicle class and the data was used to forecast the average annual fleet growth required to obtain the 2031 fleet size. An annual forecast model was constructed from this data to estimate fleet size, annual attrition quantity, and estimated purchase quantity by year. This was done by building a model that estimated replacement of the fleet due to attrition and then assuming an initial purchase quantity in 2013 and applying a flat annual percent increase to achieve the overall fleet size. This results in a market forecast that grows over the years from 2013 through 2031. In Table 10 the 2011 and 2031 fleet sizes were obtained directly from the Embraer forecast. The annual fleet growth rate was calculated from these values based on assuming a constant growth rate per year.

In reviewing the Boeing data source, adding the expected deliveries over the time period to the initial fleet size indicated a larger fleet size than shown in the Boeing information. This identified that the expected deliveries were comprised of the overall demand as well as replacement of aircraft due to attrition. It was assumed that aircraft attrition was the driver for these additional quantities and a constant annual attrition rate on the fleet size was calculated from the available data so that the ending fleet size in 2031 would match the Boeing data. This attrition rate was used with the Embraer forecast to calculate annual delivery quantities.

TABLE 10 – MARKET FORECAST

Aircraft Class	Representative Aircraft	Fleet Size (2011)	Fleet Size (2031)	Annual Attrition Rate	Annual Fleet Growth Rate
Single aisle	A320-200	10,215	18,900	2.4%	4.1%
Small twin aisle	777-200ER	3,180	7,085	3.1%	3.1%
Regional jet	E190	1,435	4,020	2.4%	5.3%

Figure 1 provides a visual representation of the model developed through 2031. The chart identifies two variables for each aircraft class representing the annual projected fleet size (right axis) and the columns represent the annual delivery quantities (inclusive of attrition) for each aircraft class (left axis).

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[27] http://www.embraercommercialaviation.com/Pages/Market-Info.aspx

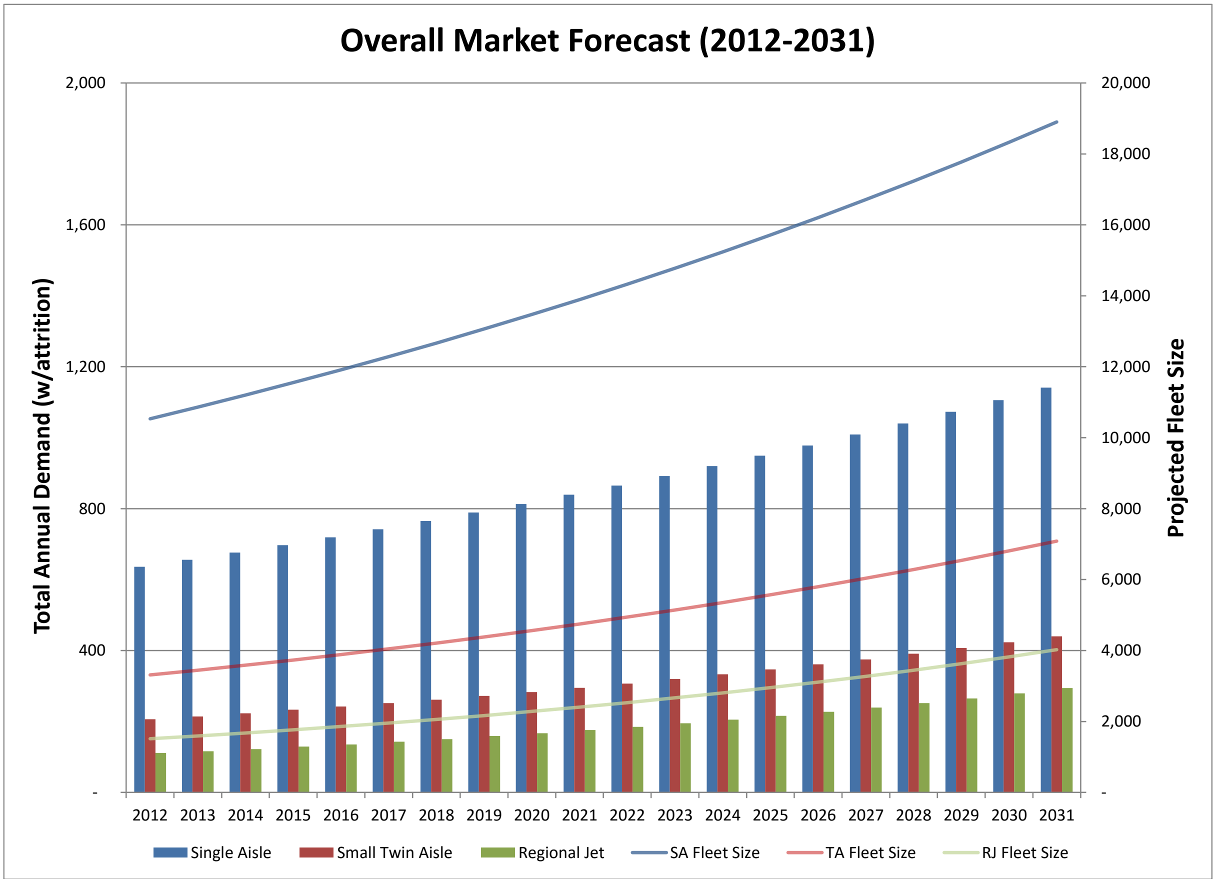

FIGURE 1 – OVERALL MARKET FORECAST

The model assumptions of annual sales increase and attrition were projected out to 2043 to allow for calculation of three time periods: 1) time period before 2024 EIS (2013-2023); 2) ten-year procurement period for the 2024 EIS (2024-2033); and ten-year procurement period for the 2034 EIS (2034-2043). Table 11 shows the overall forecasted demand and fleet size by aircraft class over the timeframe of the analysis.

TABLE 11 – OVERALL FORECAST DEMAND AND FLEET SIZE BY AIRCRAFT CLASS

Aircraft Class	2014-2023 Market Forecast	2024 EIS Market Forecast (2024-2033)	2034 EIS Market Forecast (2034-2043)	Total Market Forecast (2014-2043)
SA (A320-200)	7,797	10,605	14,427	32,829
STA (777-200ER)	2,688	4,013	5,989	12,690
RJ (E190)	1,561	2,613	4,373	8,547

The overall age of the fleet for SA, RJ, and STA differ and that the specific attrition rate for each aircraft class will vary on an annual basis based on the fleet age. However, for the purposes of the study it was determined that using an average assumption for the calculation of attrition is reasonable and allows for consistency across the various aircraft types and EIS years. The assumption of an increasing demand is based on the assessment of the Boeing, Embraer, FAA, and Ascend data sources that indicated an increasing fleet growth. For the purpose of modeling, assuming a constant growth by year does not bias the study into any particular time frame. Additionally, this constant growth provides a conservative economic assumption as the benefits for an increased number of aircraft that provide fuel savings are deferred out in time instead of biasing the study and providing immediate near-term impact.

Due to the potential variability in overall market forecast and the differences assessed between the 2013 Embraer data and the more recent FAA and Ascend data, it was determined that sensitivity analysis on overall market forecast should be conducted. This sensitivity analyses are summarized in Section 5.3.3, with additional detail provided in Appendix P.

2.4.7 Market Capture

This study is dependent on identifying a fleet of aircraft to be purchased by an operator to be operated over a set number of years. Central to this calculation is the determination of the fleet size. The prior section described how the overall market forecast (demand) for each aircraft class was determined. A subset of this demand was needed to be identified to represent a single vendor in the marketplace. This was done by determining a percent of market capture to be obtained by a single vendor and applied to the annual demand to determine the resulting purchase quantity.

Data was collected from 2011[28] and 2012[29] historical aircraft deliveries to provide a baseline market capture by aircraft type. Additional data was taken from the 2015 FAA forecast data[30] and Ascend[31] to review the reasonableness of the market capture assumptions and identify if adjustments to the baseline needed to be taken.

For SA aircraft, 2015 FAA data indicates a lower forecast of market capture (23% versus 38% shown by 2011-2012 data), however indicates a higher overall market demand. In comparing the results the overall quantities estimated indicate similar resulting purchase quantities. SA Ascend data indicates a similar market capture as determined from the 2011-2012 analysis. It was determined that the baseline forecast of 38% was considered reasonable and it was chosen for the market capture calculation.

For STA aircraft, the FAA data indicated that the near-term demand will ramp up significantly and fall off over time. FAA market capture is similar to the baseline at 32% for 2014, but falls over time. Given the slightly lower market capture but higher demand, the data correlates well with the baseline forecast STA purchase quantities. A baseline forecast of 32% was chosen for the market capture calculation.

For RJ aircraft, historical market capture data indicated a 58% market capture; however, both Ascend and FAA indicated changes occurring in this market. FAA showed a reduced market but a 100% capture by Embraer, while Ascend shows a 50% capture and a reduced overall market forecast. In light of

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[28] http://www.embraer.com/pt-BR/ImprensaEventos/Press-releases/noticias/Documents/001-Embraer%20Deliveries%204Q11-Ins-VPF-I-12.pdf

[29] http://www.embraer.com.br/Documents/noticias/003-Embraer%20Deliveries%204Q11-Ins-VPF-I-13.pdf

[30] https://www.faa.gov/data_research/aviation/aerospace_forecasts/

[31] http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/

development plans from emerging manufacturers, 58% historical capture appeared optimistic. The possible RJ market capture range was somewhere between 25% and 50%. For adjustments, the mid-point between the two values (25% and 50%) was taken (37%) as the study RJ market capture. Table 12 provides the results of the market capture analysis and the assumptions used in this study.

TABLE 12 – MARKET CAPTURE

Aircraft Class	Market Capture – Baseline (2011/2012 Data)	Market Capture – Adjustments (Study Assumptions)
SA	38%	38%
STA	32%	32%
RJ	58%	37%

2.4.8 Production Timeframe—Number of Years for Aircraft Production

A key parameter for cost analysis and comparing scenarios is to establish a consistent reference cost basis. For the purposes of this analysis, the maximum amount of years for assessing overall production cost was set at ten years. This allows the final delivery of the 2024 EIS period to end the year prior to the EIS 2034 scenarios. This value was used as the basis for the years of production deliveries into the marketplace for all of the EIS and deployment scenarios. Table 13 shows the 10-year operator procurement periods for aircraft by EIS year.

TABLE 13 – PRODUCTION TIMEFRAME

EIS Year	Time Period for Deliveries	Number of Delivery Years
2024 EIS	2024 – 2033	10
2034 EIS	2034 – 2043	10

2.4.9 Single Vendor Production Quantities

This analysis is based on comparing total operator cost for a deployment scenario to the case. A key parameter is the number of aircraft procured and operated over a ten-year time period. Table 14 provides the estimated single vendor production quantities for each EIS year by aircraft class and reflects the total production during a ten-year timeframe which are based on the overall market forecast and market capture.

TABLE 14 – SINGLE VENDOR PRODUCTION QUANTITIES

Aircraft Class	EIS 2024 Production Quantities	EIS 2034 Production Quantities
SA	4,024	5,477
STA	1,280	1,913
RJ	961	1,614

2.4.10 Operational Years

This study looks at costs from an operator's point of view to determine if there is an economic incentive based on the reduced fuel costs to procure a more expensive aircraft that contains enhanced fuel reduction technology. This requires an identification of the number of years to consider for operations of the acquired aircraft so that operational costs (i.e., fuel, maintenance) can be assessed. For aircraft with enhanced fuel efficiency, the operational costs decrease. This effect is amplified when longer operational period are considered and dampened for shorter time frames.

This study used the average leasing time period[32] as the basis for the number of years for the study. This equates to a seven (7)-year operational time frame. All results in this study are based on estimating all fuel and maintenance costs for aircraft procured over a seven year operational period. Section 5.3.6 contains a sensitivity analysis on this parameter.

This parameter differs from the number of years of aircraft ownership used in this study. The ownership years drives the calculation of income obtained by the operator by reselling the aircraft into the secondary market. The number of ownership years factors into a calculation to determine the depreciation realized and adjusts the income provided to the operator based on the residual purchase value. For scenarios where the initial purchase price is high, for example on aggressive technology scenarios, the resulting income from selling the vehicle after a short period of depreciation could substantially skew the results and bias toward higher cost aircraft. To eliminate this possibility an average time-frame of 17 years for first owner life was used as the basis for this study. This time period reflects the typical life of an aircraft before entering the secondary market[33] and was validated by the TAG.

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[32] Data obtained from Ascend online fleets, http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/ascend-online-fleets.html

[33] Data obtained from Ascend online fleets, http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/ascend-online-fleets.html

3 Technology Evaluation

A key aspect of this study is the determination of the benefits and costs provided by incorporation of new technologies into aircraft. The focus of the technology evaluation was to determine which technologies could mature in time for the 2024 and 2034 EIS windows, to assess applicability to an aircraft class type, to determine the cost of maturing the technology, to compile the individual technologies into deployment scenarios to model anticipated fuel efficiency improvements, and to generate input parameters (e.g., mass, design heritage, complexity factors) to estimate the development, production, fuel, and maintenance costs for each respective deployment scenario. This section details the overall technology evaluation effort and the resulting technology deployment scenarios used in the study.

3.1 Technology Assessment Process

The technology assessment process started with identification of potential technology candidates. The technology candidates were grouped into categories and assigned a code for tracking and traceability within each technology package.

SMEs provided a detailed technology assessment for each candidate technology, including definition, composition, and quantitative measures related to either Piano 5 User Factors or projected fuel burn impacts. The SMEs evaluated if the candidate technologies could be incorporated into the three aircraft classes by the target EIS dates (2024 and 2034). The SMEs used Technology Readiness Levels[34] (TRL) to measure the maturity of a technology. TRLs provide one metric for determining risk associated with the insertion of new technology. For example, a TRL of 6 (technology demonstrated in a relevant environment) is desirable prior to integrating a new technology. The SMEs evaluated the TRL to ensure that they could be matured to TRL-6 prior at level six five years prior to the EIS date.

The SMEs identified and profiled candidate technologies, known development programs and provided a technical assessment to estimate performance gains (fuel burn/efficiency) and availability by the two target dates. In reviewing the technologies, the SMEs identified additional candidates, estimated performance gains (fuel burn, efficiencies), identified if packaging with other technologies was possible, assessed availability to new aircraft manufacturers by the two target EIS dates, and identified if their incorporation would require modifications in other areas of the aircraft. The SMEs evaluated Structural & Aerodynamic and Propulsion technologies.

- **STRUCTURAL & AERODYNAMIC.** The SMEs evaluated each technology separately and assigned Piano 5 User Factor values. These inputs were captured to show and validate incremental improvement in tube and wing architectures from the baseline aircraft. Additionally, the Structural & Aerodynamic SMEs provided a technical risk profile that specifies technology drivers, known specialization and complexities associated with development and production of the technology candidates from the baseline aircraft.

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[34] http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7123_001B_&page_name=AppendixE

- **PROPULSION.** The SMEs provided notional engine data derived from the three thrust configurations for the three reference aircraft. SMEs evaluated contributing technologies for both Growth Derivatives (evolutionary engine modifications to existing platforms pursuant to EIS 2024) and New Engines under development for 2034, as well as the respective performance parameters and estimated efficiency gains by calculating the thrust specific fuel consumption (TSFC) for modeled engine configurations. The analysis included identifying all related technology advancements under consideration by industry manufacturers, for example, incremental fuel burn reductions for Geared Turbo Fan (GTF) designs over the next 3 to 5 years. Physical changes to propulsion systems, e.g., fan diameters, mass, drag, were identified to account for structural design changes to the airframe and wing design to accommodate the propulsion systems. (See Appendix C for candidate technology evaluation.) Additionally, the engine technology component matrix (Appendix D) captured the TRL based on known breadboard and prototype testing thru technology demonstration relevant to each scenario for the three aircraft configurations.

A data collection questionnaire was created to help guide the SMEs to answer specific questions related to the technology candidates. Each candidate was assessed as a standalone component, independent of adjacent or combined improvements between components. Appendix B contains the Technology Evaluation Datasheet questionnaire, and the major areas of evaluation for each technology are listed below.

1. Title (common name)
2. Area of impact: propulsion, aerodynamics, structure, operations
3. Brief description
4. TRL Progression
5. Piano 5 User Factors
6. Technology Maturation
7. Physical Characteristics
8. Rough order of magnitude (ROM) hours and cost to mature the technology to TRL 6
9. Aircraft applicability (Y/N)
   a. Regional Jet
   b. Single Aisle
   c. Small Twin Aisle

Upon evaluation of each technology to each aircraft class for each specific EIS year, a subset of technologies was identified as viable candidates. These technologies were brought forward to the creation of deployment scenarios.

For each technology identified in a deployment scenario the SMEs evaluated the Piano User Factors for the individual technology based on its utilization level. A composite value was created for each Piano user factor based on the aggregate impact of each technology identified for incorporation in the respective deployment scenario. This aggregation was done by implementing a factor methodology where each user factor is a multiplicative factor. Prior to developing the aggregate factor, the SMEs reviewed the individual technologies being implemented and evaluated if they were incompatible; if so the technology package for the deployment scenario was flagged for review and revision as needed. All resulting technology packages used in the study were deemed to consist of compatible technologies.

Additionally, the SMEs reviewed how technologies would affect each subsystem. The composite was then evaluated by the SMEs to ensure consistency and to make sure that the composite values were reasonable. These composite User Factors were then used as inputs into Piano to support vehicle resizing and calculation of mass and performance characteristics for each scenario. These characteristics and the underlying technologies were reviewed and approved by the TAG.

The SMEs then conducted an evaluation of the impact of each technology to the cost estimating parameters of design heritage, development complexity, production complexity, maintenance complexity, and impact to maintenance interval. The technical SMEs developed a low, high, and most likely value for each of these inputs to support the identification of a triangular uncertainty distribution, thereby enabling the ability to run Monte-Carlo analysis.

3.2 Technology Candidates

The TAG and the SMES provided forty-nine (49) specific technologies for evaluation of relevancy and applicability for the EIS 2024 and 2034 timeframes. These technologies covered the areas of:

- Aerodynamic efficiency (viscous)
- Aerodynamic efficiency (non-viscous)
- Structures, Materials and Production
- Systems and configuration
- Propulsion

Table 15 identifies the specific technology candidates evaluated in the study. Appendix C provides a high-level summary of the evaluated technologies.

TABLE 15 – SUMMARY OF EVALUATED TECHNOLOGIES

Aerodynamic efficiency (viscous)	
AV-1	Natural laminar flow on nacelle
AV-2	Hybrid laminar flow on empennage
AV-3	Natural laminar flow on wings
AV-4	Hybrid laminar flow on wings
AV-5	Laminar flow coating/riblets
AV-6	Low-friction paint coating
Aerodynamic efficiency (non-viscous)	
ANV-1	Improved aero/transonic design
ANV-2	Wingtip technologies (for fixed span)
ANV-3	Variable camber with existing control surfaces
ANV-4	Adaptive compliant trailing edge
ANV-5	Active stability control (reduced static margin)
ANV-6	Reduction of loads (active smart wings)
ANV-7	Increased wing span
Structures, Materials and Production	
S-1	All composite fuselage
S-2	All composite wings
S-3	All composite nacelles

S-4	All composite empennage
S-5	Integrated structural health monitoring
S-6	Advanced composite materials
S-7	Advanced airframe metal alloy
S-8	Unitized construction (one piece fuselage barrel, wing box, skins, etc.)
S-9	Out of autoclave curing composites
S-10	Automated tape laying, automated fiber placement
S-11	Composite sandwich construction
S-12	Net shape components (forgings, castings, extrusions, resin transfer 2molding (RTM), resin film infusion (RFI) elimination of machining and fastening)
S-13	Additive manufacturing (for mass customization of cabin interior structures, depot repairs, etc.)
S-14	3-D preforms (aero elastically tailored, braided, woven, stitched)
S-15	Bonded joints, innovations in structural joining
S-16	Damage tolerance concepts (3-D woven composites, Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS), crack arrestment features, stitching, z-pinning, etc.)
S-17	Adaptive and morphing structures (wings, control surfaces, etc.)
S-18	Advanced metallic joining (friction stir welding, advanced welding)
S-19	High temperature materials for insulation, thermal protection
S-20	High temperature ceramics and coatings for engine components
S-21	Innovative load suppression, and vibration and aeromechanical stability control
S-22	Multifunctional materials and structures (noise cancellation, embedded sensors, signal processing, actuators, antenna, lightning strike, etc.)
Systems and configuration	
Sys-1	More electric aircraft
Sys-2	Electric landing gear drive
Propulsion (Engines)	
Eng-1	High pressure ratio compressors
Eng-2	Gearbox technologies
Eng-3	Variable nozzles
Eng-4	Active clearance concepts
Eng-5	Composite structures (e.g., on casings)
Eng-6	Ceramic Matrix Composites (CMCs)
Eng-7	Morphing/smart chevrons
Eng-8	Composite nacelles
Eng-9	Slim line nacelles
Eng-10	Advanced rotor/fan materials
Eng-11	Advanced alloys and CMCs in liquid pressure forming (LPF)
Eng-12	Variable cycles

Each of the technology candidates were evaluated to determine their applicability to each aircraft class, the level of maturation required to implement for system development, and impacts to weight, drag, and thrust specific fuel consumption if the technologies were implemented. Engine technologies had to be assessed in an aggregate manner as engine developers do not typically look at infusion of a particular technology but rather at development of a new/modified engine.

The propulsion SMEs evaluated the underlying technologies to define relevant engines that could be developed in the time frame to support fuel efficiency. These engine configurations were modeled using

GasTurb to determine underlying performance characteristics. The resulting engine configurations were reviewed and approved by the TAG.

3.3 Result of Technology Candidate Evaluation

Upon completion of the evaluation of technology candidates, based on their expected availability, technologies were identified for infusion in the 2024 EIS and 2034 EIS periods by aircraft configuration. Although individual technologies were identified for the airframe and structures, the technologies for propulsion were grouped into an overall engine configuration that would be available for a target EIS year.

Table 16 indicates the results of the technology scoping analysis and identifies the viable candidates by category and their potential range of system level improvement. Appendix E shows a lower level breakout by technology on the improvement estimated for each technology candidate

TABLE 16 – TECHNOLOGY CANDIDATES

TECHNOLOGY AREAS	SYSTEM-LEVEL IMPROVEMENTS	TECHNOLOGY CANDIDATES
Aerodynamics (Non-Viscous)	2 – 7%	• Improved transonic design • Wingtip technologies • Variable camber • Increased wing span • Adaptive compliant training edge
Aerodynamics (Viscous)	2 – 10%	• Natural laminar flow on Nacelle, Wings • Hybrid laminar flow on wings and empennage • Laminar flow coating/riblets • Low-friction paint coating
Structures	4 – 22%	• Composite materials • Advanced metal alloys • Advanced structural joining techniques • Structural health monitoring • Net-shaped components • Multifunctional materials and structures
Engines (SFC)	15 – 30%	• Geared turbofan • Advanced turbofan • Open rotor (for SA & RJ)
Aircraft System	1 – 2%	• More electric aircraft • Electric landing-gear drive

Table 17 presents an estimate of fuel burn savings contributed by engine, aerodynamic, and structural technologies for each aircraft type and technology deployment scenario. These values were derived through a series of exercises. First, the impact each technology has on each major subsystem for each scenario was assessed. These benefits were then aggregated by major technology areas (i.e., aerodynamics, structures, and engines), applied to the baseline aircraft via a resizing exercise in Piano, and displayed by aircraft configuration and technology scenario. It is important to note that each improvement value in Table 17 was obtained through a resizing exercise and therefore may have a cascading effect on the fuel burn improvement. The fuel burn improvement values for an aircraft when all technology groups are applied would be smaller than the sum or product of fuel burn improvement from all three technology groups presented below.

TABLE 17 – ESTIMATED FUEL BURN REDUCTION BY AREA BY TYPE AND SCENARIO

	2024			2034		
Technology Area	Evol	Mod	Aggr	Evol	Mod	Aggr
Single Aisle						
Aerodynamics	9%	11%	14%	11%	14%	16%
Structure	7%	8%	9%	7%	8%	11%
Engine	17%	21%	23%	21%	25%	31%
Small Twin Aisle						
Aerodynamics	8%	16%	22%	16%	22%	22%
Structure	4%	7%	8%	7%	8%	11%
Engine	17%	17%	25%	17%	25%	29%
Regional Jet						
Aerodynamics	7%	9%	14%	9%	14%	15%
Structure	3%	4%	4%	4%	4%	7%
Engine	18%	20%	23%	20%	23%	25%

3.4 Technology Packages—Deployment Scenarios

To provide a range of potential technology scenarios, it was determined that three distinct deployment scenarios of increasing ambition would be created. Through this approach, the study provides multiple data points for the incremental cost and cost-effectiveness of technology. To support the economic analysis, the costs of each DS are compared to a non-improved technology scenario based on the continued manufacture of the reference aircraft. The technology deployment scenarios were aircraft class specific and take into consideration the pace of technology development/maturation, the associated costs, the derived performance and emissions benefit, the underlying hurdles for certification on particular technologies, and without requiring major changes to the underlying infrastructure (e.g., airport changes). Each DS was established by the TAG with input from the SMEs. Deployment scenarios were based on technologies deemed achievable the SMEs for adoption in the various EIS years and extreme or exotic technologies were not considered for deployment.

The first deployment scenario is the unimproved reference state, which corresponds to a manufacturer forgoing technology improvements and continuing to manufacture the reference vehicle. This assumes no incremental benefits in fuel burn or maintenance costs for the reference aircraft. Although learning occurs in the maintenance environment, the contribution of maintenance costs to total ownership costs is small, as seen Section 5.3.2. Given the minimal impact and the limited maintenance data available to derive a learning curve, learning was not incorporated into the maintenance calculations.

The second technology deployment scenario, referred to as **EVOLUTIONARY (DS1)**, corresponds to what is expected to be implemented based on the continuation of current industry trends and behavior to introduce new technologies in response to market forces alone. This deployment scenario reflects the industry behavior for the past 20-30 years and is reflective of what the industry views as a fairly aggressive technology introduction. By establishing this scenario more aggressive scenarios can be identified that reflect incremental efforts compared to current-day business as usual trends. Through identifying the cost and performance characteristics of the DS1 technology package, the lower end of fuel burn reduction can be identified for each aircraft type.

The third technology deployment scenario, referred to as **MODERATE (DS2)**, corresponds to an increased technology uptake stimulated by more environmental or regulatory pressure. These are technologies that can be achievable within the time periods, but require increased funding aspects to bring them into the market at an earlier point in time. These are moderate aspects that would not normally unfold due to current market forces but would take into effect due to implementation of regulatory guidelines and targets.

The last deployment scenario, referred to as **AGGRESSIVE (DS3)**, corresponds to incorporation of technologies that are feasible but which may not be cost effective due to the large amount of initial investment required to mature and develop technologies in that timeframe. This DS focuses on the upper end of technology incorporation that is technologically feasible and might become available under increased pressure. Through the analysis of these three technology deployment scenarios, relationships between achieving fuel efficiency, CO_2 reduction, and costs can be determined.

In looking at the EIS analysis years considered for the study, it was identified that there are two potential paths for implementation by the aircraft manufacturers. One path is the creation of derivative aircraft, with the other path being a clean sheet design. A derivative aircraft is one in which the basic design of the vehicle is maintained and incremental design changes are implemented via modifications or replacement of aircraft subsystems. Through implementation of derivative aircraft, significant technology infusion can be incorporated to improve the performance characteristics of an aircraft. A clean sheet design is based on designing and developing an aircraft to meet the desired performance characteristics. This removes the constraints of starting from a prior design and identifying improvements. Clean sheet designs require significant investment and time. In evaluating the EIS time period and the various levels of technology deployment scenarios, it was determined that clean sheet designs would be more likely for the 2034 time period than for the near term analysis year of 2024.

To simplify the modeling process, 2024 EIS scenarios became the basis for the 2034 EIS scenarios with some modification. Given the added timeline, it was determined that technologies considered more aggressive for the 2024 EIS period would be less aggressive for the 2034 EIS period and could conceivably have a higher utilization level. Accordingly, the 2024 EIS Moderate scenario was used as the basis for the 2034 Evolutionary scenario and the 2024 EIS Aggressive scenario is the basis for the 2034 Moderate scenario. This does not mean that the 2034 EIS scenarios are exact duplicates of the 2024 EIS scenarios, but rather have similar technologies deployed, albeit at a higher utilization level. Table 18 indicates the 2024 EIS and 2034 EIS deployment scenarios for the Single Aisle aircraft type. The table identifies which technologies are contained within each deployment scenario.

TABLE 18 – SA TECHNOLOGY DEPLOYMENT SCENARIOS (2024 AND 2034)

		Technology Application – Single Aisle					
		2024			2034		
Evaluated Technology	Code	Evol	Mod	Aggr	Evol	Mod	Aggr
Aerodynamic Efficiency (Viscous)							
Natural laminar flow on nacelles	AV-1	X	X	X	X	X	X
Hybrid laminar flow on empennage	AV-2		X	X	X	X	X
Natural laminar flow on wings	AV-3			X		X	
Hybrid laminar flow on wing	AV-4						X
Laminar flow coating/riblets	AV-5			X		X	X
Low friction paint coating	AV-6	X	X		X		
Aerodynamic Efficiency (Non-Viscous)							
Improved aero/transonic design	ANV-1	X	X	X	X	X	X
Wingtip technologies	ANV-2	X	X	X	X	X	X
Variable camber with existing control surfaces	ANV-3	X	X	X	X	X	X
Adaptive compliant trailing edge	ANV-4		X	X	X	X	X
Active stability control	ANV-5		X	X	X	X	X
Reduction of loads (active smart wings)	ANV-6	X	X	X	X	X	X
Increased wingspan	ANV-7	X	X	X	X	X	X
Structures							
All composite fuselage	S-1	X	X	X	X	X	X
All composite wing	S-2	X	X	X	X	X	X
All composite nacelle	S-3	X	X	X	X	X	X
All composite empennage	S-4	X	X	X	X	X	X
Integrated structural health monitoring	S-5		X	X	X	X	X
Advanced composite materials	S-6		X	X	X	X	X
Advanced airframe metal alloy	S-7	X	X	X	X	X	X
Unitized construction	S-8	X	X	X	X	X	X
Out of autoclave composites	S-9		X	X	X	X	X
Automated tape laying, automated fiber placement	S-10	X	X	X	X	X	X
Composite sandwich construction	S-11		X	X	X	X	X
Net shape components	S-12	X	X	X	X	X	X
Additive manufacturing	S-13		X	X	X	X	X
3-D Preforms	S-14						X
Bonded joints, Innovations in structural joining	S-15		X	X	X	X	X
Damage tolerance concepts	S-16		X	X	X	X	X
Adaptive and morphing structures	S-17						X
Advanced metallic joining	S-18	X	X	X	X	X	X
High temperature materials	S-19		X	X	X	X	X
High temperature ceramics	S-20			X		X	X
Innovative load suppression	S-21						X
Multifunctional materials and structures	S-22						X
Aircraft Systems							
More electric aircraft	Sys-1	X	X	X	X	X	X
Electric landing-gear drive	Sys-2		X	X	X	X	X
Engine Configurations							
Advanced turbofans (non-geared)	E-1	X					
Geared turbofans	E-2		X	X	X	X	
Open rotor	E-3						X

Table 19 indicates the 2024 EIS and 2034 EIS deployment scenarios for the Small Twin Aisle aircraft type.

TABLE 19 – STA TECHNOLOGY DEPLOYMENT SCENARIOS (2024 AND 2034)

		Technology Application – Small Twin Aisle					
		2024			2034		
Evaluated Technology	Code	Evol	Mod	Aggr	Evol	Mod	Aggr
Aerodynamic Efficiency (Viscous)							
Natural laminar flow on nacelles	AV-1	X	X	X	X	X	X
Hybrid laminar flow on empennage	AV-2		X	X	X	X	X
Natural laminar flow on wings	AV-3						
Hybrid laminar flow on wing	AV-4			X		X	X
Laminar flow coating/riblets	AV-5			X		X	X
Low friction paint coating	AV-6	X	X		X		
Aerodynamic Efficiency (Non-Viscous)							
Improved aero/transonic design	ANV-1	X	X	X	X	X	X
Wingtip technologies	ANV-2	X					
Variable camber with existing control surfaces	ANV-3	X	X	X	X	X	X
Adaptive compliant trailing edge	ANV-4		X	X	X	X	X
Active stability control	ANV-5		X	X	X	X	X
Reduction of loads (active smart wings)	ANV-6		X	X	X	X	X
Increased wingspan	ANV-7		X	X	X	X	X
Structures							
All composite fuselage	S-1	X	X	X	X	X	X
All composite wing	S-2	X	X	X	X	X	X
All composite nacelle	S-3	X	X	X	X	X	X
All composite empennage	S-4	X	X	X	X	X	X
Integrated structural health monitoring	S-5		X	X	X	X	X
Advanced composite materials	S-6		X	X	X	X	X
Advanced airframe metal alloy	S-7	X	X	X	X	X	X
Unitized construction	S-8	X	X	X	X	X	X
Out of autoclave	S-9		X	X	X	X	X
Automated tape laying, automated fiber placement	S-10	X	X	X	X	X	X
Composite sandwich construction	S-11		X	X	X	X	X
Net shape components	S-12	X	X	X	X	X	X
Additive manufacturing	S-13		X	X	X	X	X
3-D Preforms	S-14						X
Bonded joints, Innovations in structural joining	S-15		X	X	X	X	X
Damage tolerance concepts	S-16		X	X	X	X	X
Adaptive and morphing structures	S-17						X
Advanced metallic joining	S-18	X	X	X	X	X	X
High temperature materials	S-19		X	X	X	X	X
High temperature ceramics	S-20			X		X	X
Innovative load suppression	S-21						X
Multifunctional materials and structures	S-22						X
Aircraft Systems							
More electric aircraft	Sys-1	X	X	X	X	X	X
Electric landing-gear drive	Sys-2		X	X	X	X	X
Engine Configurations							
Advanced turbofans (non-geared) / Geared turbofans[35]	E-1/ E-2	X	X	X	X	X	X
Open rotor	E-3						

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[35] During identification of the STA engine configuration SME-TAG consensus was not reached on the specific engine architecture; as such the exact engine architecture was left undefined during GasTurb modeling.

Table 20 indicates the 2024 EIS and 2034 EIS deployment scenarios for the Regional Jet aircraft type.

TABLE 20 – RJ TECHNOLOGY DEPLOYMENT SCENARIOS (2024 AND 2034)

		Technology Application – Regional Jet					
		2024			2034		
Evaluated Technology	Code	Evol	Mod	Aggr	Evol	Mod	Aggr
Aerodynamic Efficiency (Viscous)							
Natural laminar flow on nacelles	AV-1	X	X	X	X	X	X
Hybrid laminar flow on empennage	AV-2						
Natural laminar flow on wings	AV-3			X		X	X
Hybrid laminar flow on wing	AV-4						
Laminar flow coating/riblets	AV-5			X		X	X
Low friction paint coating	AV-6	X	X		X		
Aerodynamic Efficiency (Non-Viscous)							
Improved aero/transonic design	ANV-1	X	X	X	X	X	X
Wingtip technologies	ANV-2	X	X	X	X	X	X
Variable camber with existing control surfaces	ANV-3						
Adaptive compliant trailing edge	ANV-4		X	X	X	X	X
Active stability control	ANV-5						
Reduction of loads (active smart wings)	ANV-6						
Increased wingspan	ANV-7	X	X	X	X	X	X
Structures							
All composite fuselage	S-1	X	X	X	X	X	X
All composite wing	S-2	X	X	X	X	X	X
All composite nacelle	S-3	X	X	X	X	X	X
All composite empennage	S-4	X	X	X	X	X	X
Integrated structural health monitoring	S-5						
Advanced composite materials	S-6		X	X	X	X	X
Advanced airframe metal alloy	S-7	X	X	X	X	X	X
Unitized construction	S-8	X	X	X	X	X	X
Out of autoclave	S-9		X	X	X	X	X
Automated tape laying, automated fiber placement	S-10	X	X	X	X	X	X
Composite sandwich construction	S-11		X	X	X	X	X
Net shape components	S-12	X	X	X	X	X	X
Additive Manufacturing	S-13		X	X	X	X	X
3-D Preforms	S-14						X
Bonded joints, Innovations in structural joining	S-15		X	X	X	X	X
Damage tolerance concepts	S-16		X	X	X	X	X
Adaptive and morphing structures	S-17						
Advanced metallic joining	S-18	X	X	X	X	X	X
High Temperature Materials	S-19		X	X	X	X	X
High Temperature ceramics	S-20			X		X	X
Innovative load suppression	S-21						
Multifunctional materials and structures	S-22						X
Aircraft Systems							
More electric aircraft	Sys-1	X	X	X	X	X	X
Electric landing-gear drive	Sys-2		X	X	X	X	X
Engine Configurations							
Advanced turbofans (non-geared)	E-1	X					
Geared turbofans	E-2		X	X	X	X	
Open rotor	E-3						X

3.5 Calculating Aircraft Performance Characteristics

To provide a range of potential technology scenarios, the study developed three distinct deployment scenarios. The costs of each DS were compared to a non-improved technology scenario based on the continued manufacture with no improvement to the reference aircraft. The technology deployment scenarios were aircraft class specific, pace of technology development/maturation, associated costs, derived performance and emissions benefit, underlying hurdles for certification on particular technologies, and without requiring major changes to the underlying infrastructure (e.g., airport changes).

3.5.1 Aircraft Performance Modeling

Piano 5, commercially available software developed by Lissys Ltd[36], is a preliminary aircraft analysis tool that allows for aircraft design or modification of an existing design. The tool is built around a reference database of detailed technical and performance data for conventional, commercial, subsonic aircraft certified to civil standards. In this study, version Piano 5.3 was used to model fuel burn reductions as a result of technology package implementation and to obtain aircraft mass as input to the cost estimation process. Modifications can be achieved through the use of existing plane files representing past, current, and anticipated future aircraft designs with the ability to change several hundred user-defined parameters including geometry and performance characteristics. Piano 5 is built around a reference database of detailed technical and performance data for conventional, commercial, subsonic aircraft certified to civil standards. It has the ability for clean-sheet design or modification of current aircraft through the use of over 250 parameters including geometry and performance characteristics. This section presents the procedures used for a resizing exercise around technology implementation to a baseline aircraft while maintaining payload and range capabilities. Further detail on Piano capabilities can be provided in the Piano user and help files (available at http://www.lissys.demon.co.uk/index2.html).

Piano 5, along with other three aircraft design tools, was used in the ICAO Long Term Technology Goal study to provide modeling data to supplement the Independent Experts' analysis.[37] The resulting fuel burn values from Piano were found to be closely comparable with the other tools used (PASS: the Program for Aircraft Synthesis Studies[38], PrADO: the Preliminary Design and Optimization Program[39] and EDS: Environmental Design Space[40]). Piano 5 was thus deemed to be a suitable tool to estimate the fuel efficiency implications of advanced technologies in this study, which overlap substantially with the LTTG review.

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[36] http://www.piano.aero/

[37] Report of the Independent Experts On Fuel Burn Reduction Technology Goals, CAEP-SG/20101-WP/11, Committee On Aviation Environmental Protection (CAEP) Steering Group Meeting, Toulouse, France, 8-12 Nov 2010. Doc 9963 ENGLISH ISBN 978-92-9231-765-2.

[38] http://adg.stanford.edu/aa241/pass/pass1.html.

[39] See http://www.fzt.haw-hamburg.de/pers/Scholz/arbeiten/TextSalavin.pdf, among others

[40] https://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/eds/

In this study three baseline aircraft chosen from a comprehensive list of Piano aircraft database were resized based on Piano User Factors derived by the SMEs from technology packages applied to each aircraft at different scenarios. The mass estimated for the resized/optimized airframe models were then used in the cost analysis. Engine mass, on the other hand, was calculated based on the (resized) engines thrust and a thrust/weight ratio obtained via GasTurb. This approach was taken because GasTurb provides a more sophisticated representation of engine capabilities and the weight impact of technology adoption, while Piano allows for the precise resizing/optimization of the resulting engine on an airframe along with aerodynamic and structure efficiency improvements.[41] A separate fuel burn modeling exercise was performed for each aircraft type and each technology deployment scenario to obtain the value of fuel burn reduction as a result of technology package implementation.

3.5.1.1 Baseline Aircraft

Table 21 presents the Piano planes used in this study as baseline aircraft by the aircraft type along with their basic parameters. These Piano planes were selected as the most representative based on MTOW and engine type in the current global fleet based on Ascend fleet database among multiple variants of the same aircraft types in the Piano database. The parameters presented in the Table 21 are Piano default values.

TABLE 21 – BASELINE PIANO PLANES AND BASIC PARAMETERS

Aircraft Type	Piano plane name	Baseline Engine Type	MTOW (kg)	Wing span (m)	Design range (km)	Design payload (kg)*
Single Aisle	Airbus A320-200 77t	CFM56-5	77,000	33.91	5,320	29,994
Small Twin Aisle	B777-200 ER (656)g	GE90-94B	297,557	60.94	14,115	63,210
Regional Jet	Embraer 190 AR	GE CF34-10E	51,800	28.72	4,625	21,605

*Parameter kept constant during resizing

3.5.1.2 Piano User Factors

Piano 5 was used in this study to generate reference aircraft mass and estimate mission fuel burn, as well as to develop revised mass and performance characteristics based on incorporation of technologies identified in each deployment scenario. The key parameters needed by Piano 5 to redesign a reference aircraft are an analysis of the relative impact/change on aircraft performance characteristics as represented by approximately 34 user-factor variables. These User Factors (Tables 22, 23, and 24) are multipliers on drag, mass, SFC, structural weight, or take-off performance. Improvements to the aircraft resulting from incorporation of enabling technologies are specified as factor improvements to the reference aircraft through Piano 5's User Factors. Appendix G provides a description of the Piano 5 User Factors.

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[41] Piano 5 engine masses were used directly to model fuel burn reductions as an input into the total ownership cost analysis. Estimated Piano engine masses were generally lower than what were calculated via GasTurb, although with no significant difference (<1%) in the estimated fuel efficiency improvement between those weights.

For modeling the enhanced aircraft, only a subset of the 34 Piano 5 user factors are required to support running the optimized resizing process. This subset consists of 14 key user factors on:

- Wing drag—factor applied to wing zero-lift drag.
- Fuse drag—factor applied to fuselage zero-lift drag.
- Nac drag—factor applied to nacelle zero-lift drag.
- Stab drag—factor applied to stabilizer zero-lift drag.
- Fin drag—factor applied to the fin zero-lift drag.
- Induced drag—factor applied to the wing induced drag.
- Box mass—factor applied to the wing structural mass.
- Flap mass—factor on estimated wing flap mass.
- Fuse mass—factor on estimated fuselage mass.
- Fin mass—factor on estimated vertical tail mass.
- U/c mass—factor on undercarriage mass.
- Takeoff clmax—factor applied to the total CLmax of the aircraft at takeoff flap deflections.
- Landing clmax—factor applied to the total CLmax of the aircraft at landing flap deflections.

For each deployment scenario, impacts to Piano user factors were generated by SMEs as part of their evaluation of the technology packages identified for each reference aircraft and time frame. The process involved the SMES assessing the user factor impact to specific subsystems (e.g., airframe) for each technology identified in the technology deployment scenario, these user factors were then aggregated across all subsystems to determine the overall user factor to be used in Piano. These final numbers used in Piano were a product of all user factor values applied to the subsystems for each combination of technologies judged compatible by the SMEs.[42] From these user factors, Piano 5 was able to run optimization routines with the objective of minimizing fuel-burn by changing the following design variables: MTOW, wing area, reference thrust per engine, aspect ratio, and wing sweep angle. The resulting design provided mass and performance characteristics for the new aircraft. This information was then used to assess the fuel-burn reduction as well as to support calculation of revised production costs based on the mass and level of subsystem changes to the aircraft.

Appendix H contains the user factors developed for each deployment scenario. Each user factor was reviewed during the evaluation process to make sure the level of impact was concurrent with the effects of the technologies employed and that there was incremental improvement with increasing technology level. This evaluation identified that the detailed analysis conducted by the SMEs was credible and reliable.

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[42] Care was taken to avoid the implementation of mutually exclusive technologies (e.g., natural laminar flow and hybrid laminar flow) on the same structure (e.g., wings/empennage).

TABLE 22 – SINGLE AISLE DEPLOYMENT SCENARIO USER FACTORS

Technology Worksheet – Composite UF Comparison	user-factor on wing drag	user-factor on fuse drag	user-factor on NAC drag	user-factor on stab drag	user-factor on fin drag	user-factor on induced drag	user-factor on box mass	user-factor on flap mass	user-factor on fuse mass	user-factor on stab mass	user-factor on fin mass	user-factor on u/c mass	user-factor on takeoff dmax	user-factor on landing dmas
2024														
SA Evolutionary	0.95	0.95	0.91	0.96	0.96	0.97	0.93	0.91	0.89	0.93	0.93	0.99	1.04	1.04
SA Moderate	0.95	0.95	0.90	0.81	0.90	0.96	0.83	0.85	0.83	0.78	0.87	0.98	1.08	1.08
SA Aggressive	0.87	0.87	0.89	0.79	0.89	0.95	0.81	0.83	0.82	0.76	0.85	0.98	1.08	1.08
2034														
SA Evolutionary	0.95	0.95	0.90	0.81	0.90	0.95	0.83	0.85	0.83	0.78	0.87	0.98	1.08	1.08
SA Moderate	0.87	0.86	0.89	0.79	0.89	0.94	0.80	0.83	0.82	0.76	0.85	0.98	1.08	1.08
SA Aggressive	0.86	0.86	0.89	0.79	0.89	0.93	0.68	0.72	0.71	0.65	0.73	0.97	1.08	1.08

TABLE 23 – SMALL TWIN AISLE DEPLOYMENT SCENARIO USER FACTORS

Technology Worksheet – Composite UF Comparison	user-factor on wing drag	user-factor on fuse drag	user-factor on NAC drag	user-factor on stab drag	user-factor on fin drag	user-factor on induced drag	user-factor on box mass	user-factor on flap mass	user-factor on fuse mass	user-factor on stab mass	user-factor on fin mass	user-factor on u/c mass	user-factor on takeoff dmax	user-factor on landing dmas
2024														
SA Evolutionary	0.99	0.95	0.91	0.96	0.96	0.97	0.93	0.91	0.89	0.93	0.93	0.99	1.04	1.04
SA Moderate	0.95	0.95	0.90	0.81	0.90	0.96	0.83	0.85	0.83	0.78	0.87	0.98	1.08	1.08
SA Aggressive	0.87	0.86	0.89	0.79	0.89	0.95	0.81	0.83	0.82	0.76	0.85	0.98	1.08	1.08
2034														
SA Evolutionary	0.95	0.95	0.90	0.81	0.90	0.95	0.83	0.85	0.83	0.78	0.87	0.98	1.08	1.08
SA Moderate	0.87	0.86	0.89	0.79	0.89	0.94	0.80	0.83	0.82	0.76	0.86	0.98	1.08	1.08
SA Aggressive	0.87	0.87	0.90	0.79	0.89	0.93	0.72	0.78	0.76	0.70	0.78	0.97	1.08	1.08

TABLE 24 – REGIONAL JET DEPLOYMENT SCENARIO USER FACTORS

Technology Worksheet – Composite UF Comparison	user-factor on wing drag	user-factor on fuse drag	user-factor on NAC drag	user-factor on stab drag	user-factor on fin drag	user-factor on induced drag	user-factor on box mass	user-factor on flap mass	user-factor on fuse mass	user-factor on stab mass	user-factor on fin mass	user-factor on u/c mass	user-factor on takeoff dmax	user-factor on landing dmas
2024														
SA Evolutionary	0.95	0.95	0.91	0.96	0.96	0.97	0.93	0.91	0.89	0.93	0.93	0.99	1.00	1.00
SA Moderate	0.95	0.95	0.90	0.96	0.96	0.96	0.86	0.85	0.83	0.87	0.87	0.98	1.04	1.04
SA Aggressive	0.87	0.86	0.89	0.89	0.89	0.95	0.84	0.83	0.82	0.85	0.85	0.98	1.04	1.04
2034														
SA Evolutionary	0.95	0.95	0.90	0.96	0.96	0.95	0.86	0.85	0.83	0.87	0.87	0.98	1.04	1.04
SA Moderate	0.87	0.86	0.89	0.89	0.89	0.94	0.84	0.83	0.82	0.85	0.85	0.98	1.04	1.04
SA Aggressive	0.85	0.86	0.89	0.89	0.89	0.93	0.75	0.74	0.73	0.76	0.76	0.97	1.04	1.04

3.5.1.3 Optimized Resizing Process

Piano allows for aircraft resizing based on a baseline aircraft, under several customizable variables and restrictions as well as optimization criteria. For aircraft resizing in this study, default operations-related Piano parameters were used. These parameters include passenger weight, number of seats, number of crews, etc. Furnishing and nacelle weights, both of which change due to certain technologies included in the study, were varied across scenarios based upon SME feedback on the appropriate User Factors.

Baseline aircraft resizing was performed to maintain the payload and range capability (using the R1 point—maximum range at maximum structural payload—as a proxy) as well as the minimum take-off field length of the original aircraft. The fuselage size and geometry, as well as the number of seats, was kept constant to keep the payload capacity constant and exclude the option of reducing fuel burn by increasing seating density. At the same time, several design parameters were rubberized to produce a notional aircraft based on the technology package (and thus Piano user factor) applied with the objective to minimize fuel burn. The rubberized parameters used to optimize aircraft in Piano are MTOW, wing area, aspect ratio, sweep angle, and engine thrust. It is acknowledged that allowing wingspan to grow may have infrastructure impact (i.e., airport compatibility). Therefore, for SA aircraft, care was taken to ensure that the resulting wingspan could still be accommodated in key US airports either by taking advantage of the entire width of a utilized gate or utilizing available adjacent gates.[43] And while all resized RJ aircraft were still within its original design group[44], the wingspan for STA aircraft during resizing were limited to Boeing 777X specification information available at the time of study[45].

Figure 2 shows a 3-view of all 2024 cases for A320 (single aisle) aircraft: baseline (blue), evolutionary (green), moderate (yellow), and aggressive (red). As shown, the wings, empennage, and nacelle sizes differ from one technology scenario to the other while the fuselage size stays the same. Figure 3, on the other hand, shows the different payload-range diagram of the different scenarios. While the R1 point was kept constant, with higher level of technology implementation the aircraft require less fuel to operate and therefore gain more range capability with the same design payload (shown as a dot along the colored lines of each technology scenario).

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[44] Federal Aviation Administration. Document 150/5300-13A - Airport Design. Issued September 28, 2012

[45] http://www.aspireaviation.com/2013/02/14/boeing-777x-787-10-unfazed-by-787-battery-woes/. Retrieved Feb 14, 2013

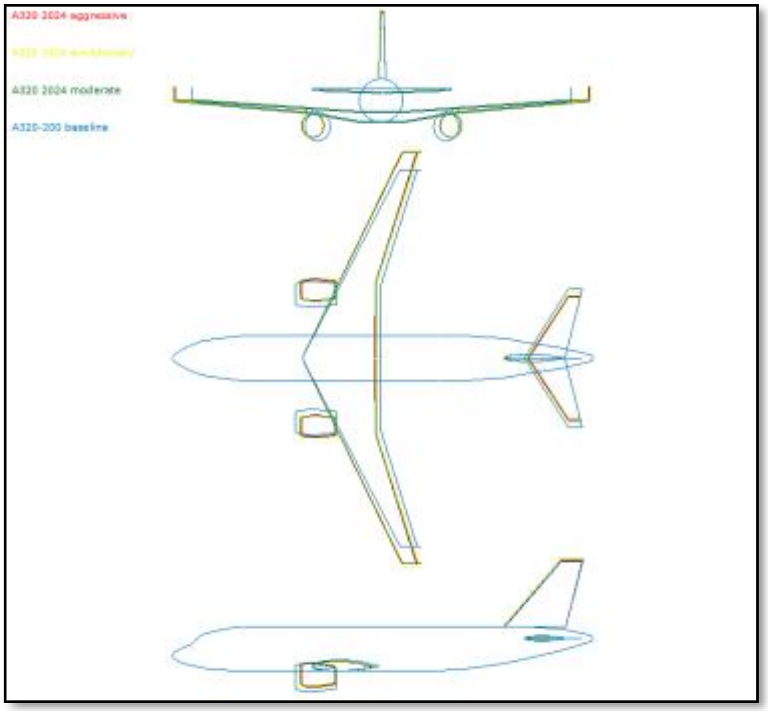

FIGURE 2 – 3-VIEW PROFILE FOR SINGLE AISLE 2024 SCENARIOS

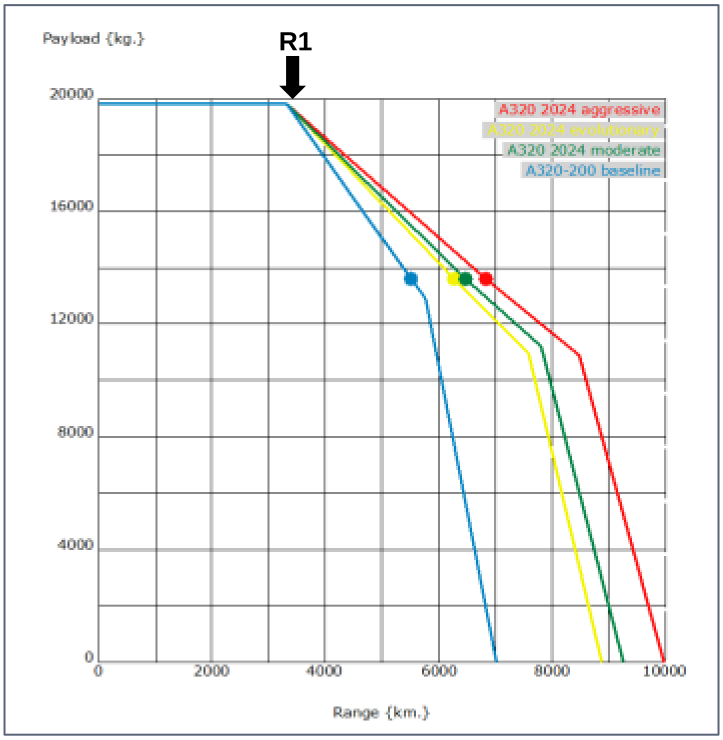

FIGURE 3 – PAYLOAD-RANGE DIAGRAM FOR SINGLE AISLE 2024 SCENARIOS

A detailed review with guidance from the TAG members was performed to make sure the notional aircraft resulted from the resizing process makes sense in terms of design. For example, wing aspect ratio should increase with more aggressive technology scenario due to increase in the use of lightweight materials throughout the airframe and increased laminar flow capabilities in some cases. A review on resulting aircraft weights was also performed to make sure that the resizing process was done properly and that the resulting weight of each new aircraft component was in line with the lightweight structure and technology implemented in each technology deployment case. In general upon technology implementation, less fuel was required, which reduces both weight directly through lower fuel capacity requirements and indirectly by reducing stresses and thus required structural support weight. Since aircraft wings and engines were largely sized for take-off at highest MTOW (other considerations may include climb requirements for example), this weight reduction in turn allows for lowered lift requirement resulting in wing and engine resizing, which in turn has further effect and ultimately a reduction in operating empty weight.

Table 25 provides a snapshot of top level aircraft parameters that were generated from Piano through the resizing process. The values depicted are for the deployment scenarios for the SA aircraft.

TABLE 25 – SINGLE AISLE RESIZED AIRCRAFT BASIC PARAMETERS BY SCENARIO

Parameter	Baseline	2024 Evo	2024 Mod	2024 Agg	2034 Evo	2034 Mod	2034 Agg
Wingspan (m)	33.9	37.5	37.1	37.1	37.8	37.7	38.4
Wing Aspect Ratio	10.3	12.7	12.9	13.2	13.2	13.2	14.2
MTOW (kg)	77,000	71,534	67,888	66,445	68,283	66,449	61,978
OEW (kg)	42,666	41,010	38,307	37,752	38,810	37,906	34,645

3.5.1.4 *Aircraft Mass Estimation*

This study's cost model is weight-based, meaning that the underlying equations require a reliable weight table as a critical input. Aircraft empty weights were obtained for each technology package based on the results of aircraft optimization in Piano 5 using Piano user factors derived from the corresponding technology assessment. Baseline and modified subsystem aircraft weights were estimated by Piano 5, which assumes aluminum structures and applies "semi-empirical preliminary design techniques derived partly from unpublished industrial sources and partly from published texts".[46] Furthermore, for the analysis of probabilistic inputs, a notional range of +/- 3% to 5% was used at the aircraft subsystem level. Figure 4 shows a high-level summary on how the overall MTOW compares across each aircraft class and deployment scenario for the 2024 and 2034 EIS analysis periods.

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[46] PIANO User Guide, Chapter 04. Mass Estimation. Accessible at http://www.piano.aero.

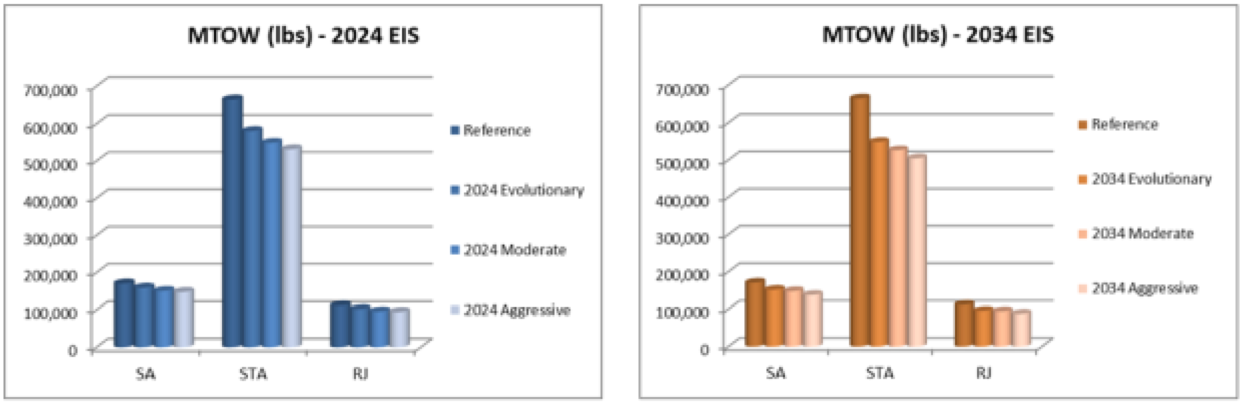

FIGURE 4 – DEPLOYMENT SCENARIO MTOW

3.5.1.5 Fuel Burn Calculation

To calculate fuel burn savings as a result of technology implementation, each scenario-modified aircraft was flown based on a payload-range matrix for each aircraft type (single aisle, small twin aisle, and regional jet). The matrices were derived based on payload and mission lengths flown by each aircraft type in 2010 as obtained from the BTS Form-41 T100 data for international (in- and out-bound) and US domestic flights for select passenger aircraft. To streamline the modeling process payloads were divided into bins of 500 kg, while the ranges were divided into bins of 200 km, as seen in Figure 5. Under each combination of payload-range bin, the aircraft (baseline + 6 technology scenarios) were flown at cruise speeds enabling 99% specific air range (SAR), with fuel reserve and allowances set at 370 km diversion distance, 30 minutes holding time, and 5% mission contingency fuel for all aircraft. All flight levels or cruise altitudes from 17,000 ft. above sea level to each aircraft's service ceiling were made available to accommodate short flight ranges. Taxi times (taxi-in and taxi-out) were set at 12 minutes each way for regional jets and single-aisle aircraft and 15 minutes each way for twin-aisle based upon average taxi times for US operations in 2010 by type. Fuel consumption per mission was weighted based on the frequency of the flight at each payload-range bin, and compared with the baseline aircraft fuel consumption calculated using the same methodology.

A review process with the TAG members were performed to make sure that the modeled fuel burn reductions achieved through each technology implementation scenario were consistent with each EIS date and technology package. One of the parameters used in the review process is comparison between fuel burn savings achieved in this study and the ICAO LTTG review. The graphs in Figure 5 show the comparison of payload to range for the SA, RJ, and STA aircraft.

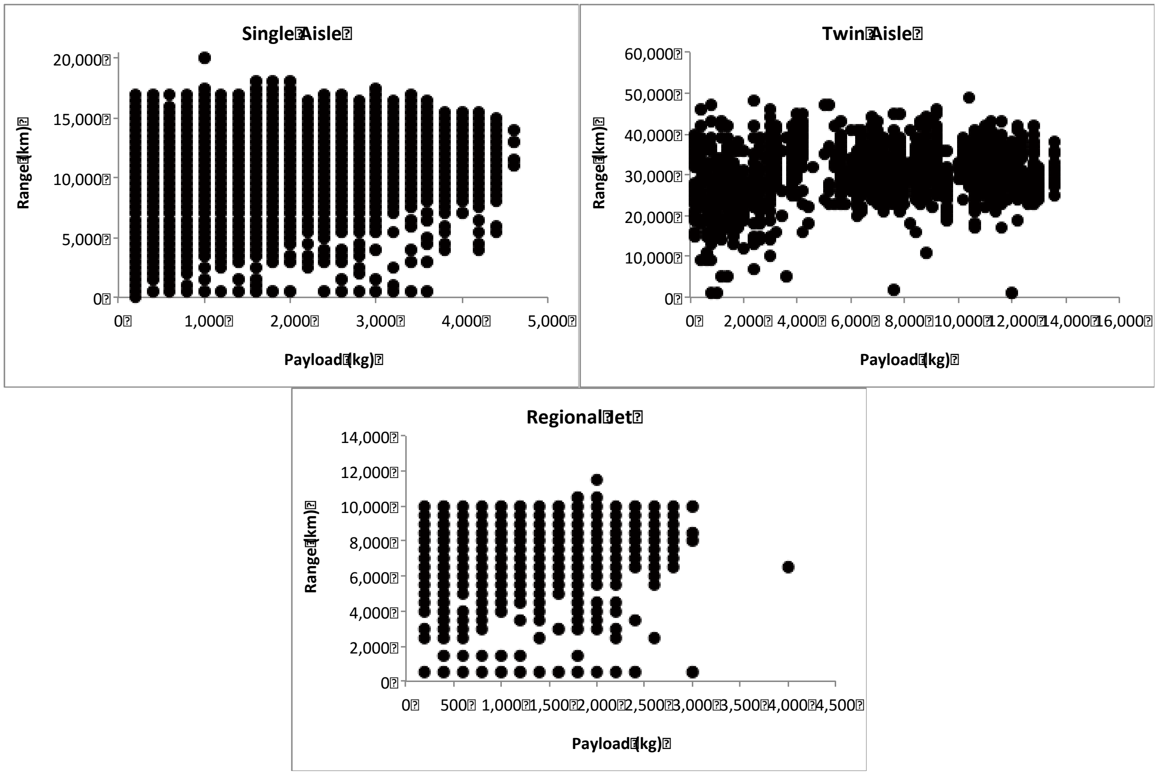

FIGURE 5 – TEST POINTS FOR SINGLE AISLE, TWIN AISLE, AND REGIONAL JET FUEL BURN CALCULATION

An output of the Piano 5 optimization analysis was an estimate of performance characteristics identifying the projected fuel burn of the re-designed aircraft. The TAG and SMEs reviewed the fuel burn reduction with the identified technologies and confirmed that the Piano 5 results were reasonable. Table 26 provides a summary of the fuel-burn reduction assessed for each deployment scenario by aircraft class.

TABLE 26 – FUEL BURN REDUCTION BY TYPE AND SCENARIO

Fuel Burn Reduction	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
SA	25.7%	34.2%	40.0%	34.2%	40.4%	46.1%
STA	27.3%	33.3%	42.5%	33.7%	44.1%	47.0%
RJ	27.5%	32.9%	39.8%	32.9%	40.2%	45.7%

3.5.2 Engine Performance Modeling

Engine design and performance were modeled using GasTurb, a commercially available performance program that uses pre-defined engine configurations while permitting input of all important parameters, including variables that characterize component geometry. This program enables both design and off-design evaluation of thermodynamic cycles. Output from this program provides flow, pressure, and temperature values at all major stations within the engine, using nomenclature consistent with current industry standards. Critical areas are calculated at design conditions and maintained for off-design operation using an iterative numerical solution. GasTurb does not provide weight estimates but it does capture changes in geometry based upon design choice (such as estimating fan diameter and other significant dimensions).

The GasTurb model differs from Piano in that instead of a reference aircraft and the implementation of user factors to conduct a re-design, GasTurb requires specific design parameters to allow modeling of the engine characteristics. The design point interface provides the primary engine modeling parameters required by this study. All results from GasTurb were reviewed by the TAG and deemed reasonable in their values for performance.

3.5.2.1 Baseline Propulsion Configurations

Table 27 presents the propulsion configurations for aircraft used in this study as baseline aircraft along with their basic parameters.

TABLE 27 – ENGINE BASELINE CONFIGURATIONS

	Single Aisle (A320-200) Engine: CFM56-5A3	Small Twin Aisle (B777-200ER) Engine: GE90-85B	Regional Jet (E190) Engine: 1-10-2-4
SLS Thrust – N	117,878	378,099	65,000
Fan Diameter – cm	172.7	312.4	117.3
Bypass Ratio	6	8.4	4.8
Overall PR	28	39	28.3

3.5.2.2 Deployment Scenario Propulsion Configuration Modeling

The propulsion SMEs started the study by evaluating the engine parameters for the new A320neo (New Engine Option) engine, which has an expected EIS date of 2016. There are two engine options for the A320neo, whose engine characteristics are shown in Table 28.

TABLE 28 – SINGLE AISLE A320NEO ENGINE OPTIONS

	Engine: Geared Turbofan	Engine: CFM Leap-1A
SLS Thrust – N	124,550	124,550
Fan Diameter – cm	205.7	198.1
Bypass Ratio	12	10
Overall PR	45	45-50

Review of press releases for the A320neo and Pratt and Whitney's PW1000G suggest that the above fan diameter, BPR, and OPR are reasonable estimates. The thrust shown is consistent with the model of a GTF at 124,550 N scaled to a fan diameter of 205.7 cm. The fan diameter and BPR shown for the CFM International's LEAP-1A are based upon review of press releases for the A320neo and the CFM International's LEAP-1A. The thrust shown is based upon expected similarity between the thrust for a LEAP-1A and a PW1000G. Press releases for the LEAP-1A have spoken of an OPR as high as 50 at the 'top of climb'. Based upon this, an OPR for max cruise is shown as 45-50.

Since fuel burn projections are believed to be similar for the PW1000G and LEAP-1A, it was determined to be reasonable to use data for either as a representative of the engine for this study, in terms of aircraft performance. Differences in projected aircraft performance between the two engine offerings would be small. Fuel burn improvements of 12%[47]to 15%[48] target was obtained from manufacturer press releases and were consistent with the TSFC improvement and weight increase modeled for a GTF by the GasTurb model. Since both these engines are to enter service before 2020 (2015-2016), this performance level was targeted as the performance that may be expected in the Evolutionary scenario, where the choice of available technology is based upon economics rather than any regulatory constraints. This became the baseline for all GasTurb modeling of the engines so that incremental changes could be implemented and TSFC improvement assessed.

Similar data was compiled for the RJ engine model, starting with a baseline engine performance coupled with GTF improvements noted above in the SA configuration. The 2024 Evolutionary engine the SME's used for modeling TSFC improvements for each scenario is shown in Table 29.

TABLE 29 – RJ NOTIONAL ENGINE PERFORMANCE

SLS Thrust – N	77,177
Fan Diameter – cm	142.2
Bypass Ratio	9.4
Overall PR	31.3

The SMEs evaluated several technology improvements from the TAG's technology list, coupled with knowledge of current or future technology programs. This included advancements in GTF architecture and design to support the STA configuration. A ssumptions and ground rules used by the SMEs in modeling notional engine performance are as follows.

- The baseline engine will be similar to modern engines prior to significant growth steps (EIS 2000-2010).
- Growth engine derivative will be similar to modern engines following significant growth (i.e., EIS 2010-2024).
- New engines for 2024 evolutionary scenarios will be similar to planned products being introduced in this time frame.
  - RJ similar to the second generation E-Jet engines.
  - SA similar to A320neo/737 MAX engines.
  - STA similar to 787 and A380 engines.
- Technology considered to include:
  - Architecture (advanced direct drive, GTF, multiple fans, alternative engine mounting for Open Rotor configurations).
  - Materials (Composites, High Temperature Alloys, Advanced Aluminum, etc.).

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[47] GearingUpfortheGTF_ATEM_April-May_2010, Aircraft Technology - Issue 105, p. 86
[48] http://www.cfmaeroengines.com/engines/leap

- Advanced CMC structures, airfoils and seals.
- Turbine Cooling Improvements (including cooled, modulated cooling air).
- Aerodynamics (component efficiency, combustion operation).
- Variable Area Nozzles (optional for 2024, required for 2034).
- Variable Cycle Features.
- Advanced Nacelles (assumed to mitigate impact on weight and drag of higher fans).

Final observations were compiled from the modeling of the three aircraft types. A generic GTF was simulated for a new SA and RJ in the 2024 EIS date. Fan pressure ratio selected for this simulation is near a value where a variable area nozzle would be required (in marginal region). Resulting fan diameter from the GasTurb modeling appeared to be reasonable for use on existing SA aircraft.

A generic GTF was also simulated for new SA and RJ aircraft for the 2034 EIS date; the fan pressure ratio selected would definitely require use of a variable area nozzle or equivalent device. A 10% increase in area at take-off conditions was used for simulation of this engine. A secondary configuration was also considered for the 2034 Aggressive scenario, where a clean sheet aircraft would host new open rotor engines in a tail mount configuration.

The new engine simulated for STA aircraft for the 2024 EIS date was based upon conventional architecture. This was done because engines are currently being developed for this application with conventional architecture, and it is questionable as to whether there would be development of a GTF engine with the required thrust prior to this time period.

Generic fan pressure ratios, coupled with higher BPRs were simulated for the new STA aircraft for the 2034 EIS date, and resulting in fan diameters that may be an issue for installation manufacturers. Application of an engine similar to that simulated may result inner aircraft installation schemes (such as engines mounted atop the wing) or may result in use of multiple fans driven by a single gas generator off a gearbox in the case of an advanced GTF engine. To resolve the increased fan blade diameter, composite material was introduced to reduce weight, which resulted in a larger cowling diameter. This Cowling diameter change causes an impact to the ground clearance. In order to maintain the ground clearance specification the landing gear was lengthened and the SMEs incorporated these impacts to the airframe. This was the only area in which propulsion modeling caused an additional affect to the airframe and structural components.

The final TSFC inputs were captured in the TAG technology list by aircraft configuration and EIS date. The engine performance values and technologies considered for each engine deployment scenario are provided in Appendix D.

3.5.2.3 Engine Mass Estimation

GasTurb does not provide weight estimates, but does capture changes in geometry based upon design choice (such as estimating fan diameter and other significant dimensions). The SMEs used weight correlations that were developed using engine dimensions and corrected flows indicative of dimensions derived from large engine databases to estimate weight for notional engines. Weight estimates were adjusted for technology weight increments for composite cases, composite or lightweight blades, and lightweight low-pressure turbine (LPT) blades. These increments were selected by the SMEs for a given fan or LPT diameter and modified with increasing or decreasing diameter. This provided representative weight estimates that would reflect changes in engine configuration based upon design choice (such as higher bypass ratio), these weight estimates were converted to a thrust to weight ratio to allow calculation of weight parameters based on the engine configuration and assessed thrust performance. Engine mass was calculated based on this GasTurb derived thrust to weight ratio and Piano's assessment of required thrust.

The GasTurb provided performance parameters for the new engine, given the technology infusion, which was used to calculate the engine component weights based on the representative thrust to weight ratio. Table 30, Table 31, and Table 32 provide a summary of calculated engine performance parameters for each aircraft configuration.

Table 30 – Regional Jet Engine Parameters

RJ Engine Parameters	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
Engine Type	Direct Drive (LEAP)	GTF	Improved GTF	GTF	Improved GTF	Open Rotor
Thrust (lbs)	15,417	14,446	13,597	14.537	12,929	11,776
TSFC improvement	15%	15%	20%	15%	20%	30%
BPR	10	12	16	12	16	n/a
Thrust/Weight Ratio	5.2	5	5.1	5	5.1	4.9
Per Engine Weight (lbs)	2,965	2,889	2,666	2,907	2,535	2,403

Table 31 – Single Aisle Engine Parameters

SA Engine Parameters	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
Engine Type	Direct Drive (LEAP)	GTF	Improved GTF	GTF	Improved GTF	Open Rotor
Thrust (lbs)	21,199	18,952	18,433	18,804	17,951	15,990
TSFC improvement	16%	17%	22%	17%	22%`	30%
BPR	10	12	16	12	16	n/a
Thrust/Weight Ratio	4.6	4.7	4.5	4.	4.5	4.4
Per Engine Weight (lbs)	4,608	4,032	4,096	4,001	3,989	3,634

Table 32 – Small Twin Aisle Engine Parameters

STA Engine Parameters	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
Engine Type	Direct Drive (GE90X)	Direct Drive	Direct Drive	Direct Drive	Direct Drive`	Direct Drive
Thrust (lbs)	77,333	68,632	66,669	68,788	60,586	57,747
TSFC improvement	10%	11%	13%	11%	13%	15%
BPR	10	11	13	11	13	15
Thrust/Weight Ratio	4.8	4.5	4.3	4.5	4.3	4.6
Per Engine Weight (lbs)	16,111	15,252	14,375	15,266	14,090	12,554

4 Cost Analysis

This section of the report provides an overview of the process used to estimate costs, the underlying methodologies, the key input parameters, and the flow of the overall cost model.

4.1 General Summary of Cost Modeling Approach

The cost modeling approach encompassed cost model selection, model validation, calculation of total operator cost, and capturing risk and uncertainty. In model selection, PTIRS was used to capture system development, production, and maintenance costs. ACEIT was used as an estimating platform to integrate the various pieces of the cost elements, layout cash flow, and conduct simulations. JACS was used to estimate the technology maturation costs. Model validation was done at three levels—top level PTIRS benchmarking of the results, reference aircraft validation, and single aisle emergent case verification.

There were several components to total operator costs. These costs included the operator capital costs, technology maturation cost, system development cost, production cost, fuel and maintenance cost, and income to operator from residual resale. And taking all the inputs, risk and uncertainty analyses were conducted.

The general flow of the estimating process started with the determination of the technology packages, via the TAG and SME discussion and confirmation dialogue. For each configuration (aircraft type, deployment scenario, and specific technology), technology application matrices were created. Given the applicable technology, the SMEs translated the technology matrices into user factor impacts that became key inputs to the Piano modeling process. The Piano model modified and optimized the reference aircraft based on the technology user factors, which then resulted in new aircraft with distinct weights. The Piano generated weight statements provided the key inputs for aircraft subsystem mass which are the key inputs to the Cost Estimating Relationships in the overall cost model.

For technology maturation cost and system development cost, a process based cost model was used which produced a labor and material buildup cost estimate. For development cost, weight-based CERs were used with all the inputs, adjustments and uncertainty factors, e.g., mass uncertainty, labor hours, uncertainty bounds, development complexity factors, and design heritage factors. Furthermore, the model took into account amortized nonrecurring portion of the operator capital cost.

To account for influence from legacy, or heritage, the SMEs determined design heritage factors that were impacted by the subsystem technologies. Similar process was used for design complexity, production complexity, maintenance intervals, and maintenance complexity.

For production costs, weight-based CERs were used to capture recurring cost. The recurring cost also took the mass statements from the Piano outputs which were based on user factors provided by the SMEs. The recurring cost took into account market forecast, market capture, mass reduction adjustment factor (to address any weight-driven cost estimating relationship (CER) peculiarity), and production complexity factors. To determine the average unit cost, operator capital cost and residual value were taken into consideration.

For maintenance cost, weight and interval duration based CERs were used. The maintenance cost consisted of aircraft/engine maintenance and fuel only. Other operational costs like flight crew, insurance, software maintenance, passenger service, and landing fees were excluded from the analysis. The final cost area was fuel. This was based on a model taking into account the annual fuel price, the forecasted flight hours, and the annual survivability of the aircraft.

A series of crosschecks were conducted, ranging from subjective assessment of reasonableness, to comparison to relative cost ratios (e.g., engine versus airframe costs), to running historical costs in the model to validate replication of published list prices.

4.2 Cost Estimating Model Selection

This study required selection of a cost model that had industry relevance, estimated at the appropriate level for which analysis and mass properties could be generated (e.g., Piano and SME evaluation), allowed calibration for external considerations (e.g., design heritage), and provided transparency to allow understanding of the model equations and the underlying basis. Given the study goals, consideration was obtaining a model that could provide consistent results and provided confidence in the relative accuracy of the cost changes between scenarios. This was of higher priority than finding a model that could estimate a specific scenario with high precision.

Several model platforms were evaluated prior to down-selecting the PTIRS Aircraft Model for system development and production costs and an ABC model for technology maturation. Table 33 shows the tools assessed and a high-level assessment of each model.

TABLE 33 – ASSESSED TOOLS

	ALCCA (GA Tech)	PRICE-H (Price Sys), SEER-H (Galorath)	P-Beat (NASA GRC)	TCM (Boeing)	PTIRS Aircraft Model (NASA)	Activity-Based Process Model (JACS)
Development	X	X	X	X	X	X
Production	X	X	X	X	X	X
O&M	X			X	X	X
Key inputs	Mass, material mass fractions, complexity factors	Mass, material mass fractions, complexity factors	Mass, material mass fractions, complexity factors	Mass, material mass fractions, complexity factors	Mass, material mass fractions, complexity factors	Activity list, effort levels, durations
Calibration	adjust factors	adjust factors		CERs, adjust factors	CERs, adjust factors	
Knowledge base: applicability	Commercial aircraft	Broad base of unnamed components and systems	Space systems, rockets, some Boeing aircraft	Military aircraft	Commercial aircraft, military aircraft	
Transparency	Proprietary	Proprietary	Sensitive	Sensitive	Sensitive	
Methodology	General method and flow is well-documented, no CER VISIBILITY	No public documentation of methods, no CER visibility	Uses process flow and analogy scaling	method, flow, and CERs are documented	Method, flow, and CERs known	

The cost model evaluation consisted not only of identifying relevant and credible cost estimating models for system development, production, and maintenance costs, but also on supporting estimation of technology maturation cost and timelines, calculating fuel costs, allowing for probabilistic simulation, and supporting cash-flow discounting. As a result, several tools were selected: 1) PTIRS for calculation of system development, production, and maintenance costs; 2) JACS for modeling of Technology Maturation; and 3) ACEIT for integrating the results into a probabilistic cash-flow model.

4.2.1 PTIRS Cost Model (System Development, Production, and Maintenance)

The system development, production, and maintenance cost estimation framework utilized the NASA sponsored PTIRS. PTIRS was developed for the NASA ERA Project to support evaluation of infusion of advanced vehicle concepts and technologies that reduce fuel burn, noise and/or emissions. PTIRS contains the underlying cost estimating methodologies for nonrecurring aircraft development costs, recurring costs for aircraft production, as well as annual maintenance costs. PTIRS is a weight-driven model where costs are computed at the component level based primarily on the weights of the aircraft components. Figure 6 shows the PTIRS overall architecture.

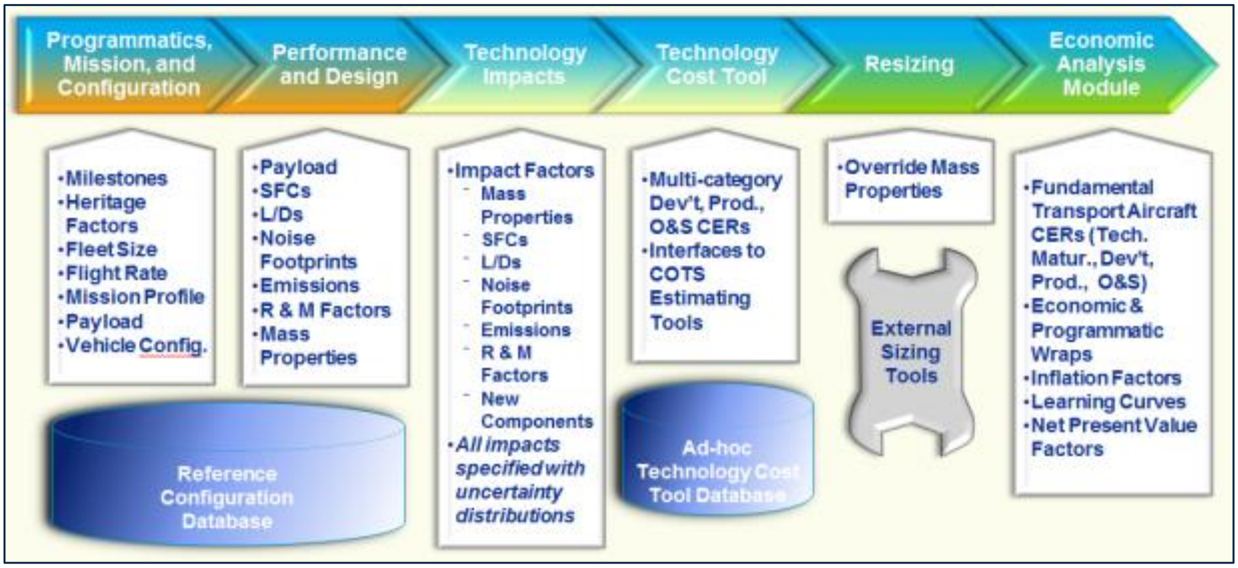

FIGURE 6 – OVERALL ARCHITECTURE OF PTIRS

NASA sponsored the development of PTIRS as a business case model for evaluating emerging technologies in the context of commercial aircraft development, production, and operations. PTIRS is an enabling model that supports promising technologies overcoming the technology gap between research and successful commercialization by reliably quantifying economic benefits of reduced fuel consumption, reduced community noise, and reduced emissions, weighed against research and development costs. The ERA project funded Tecolote to develop PITRS to enable the assessment of the potential impact of applying the ERA N+2 airframe, propulsion and acoustic shielding technologies to 2025 commercial transport vehicle vision systems.

PTIRS produced results through the development of PTIRS cost estimating relationships that are calibrated to reproduce the historical acquisition costs of commercial aircraft and historical operating costs of modern airlines. Benchmarking analysis indicates that with appropriate economic adjustments, PTIRS reproduces published aircraft prices to within +/- 5% and publicly available airline operations costs to within +/- 13%.[49]

PTIRS also provided comprehensive lifecycle cost coverage, addressing all costs from technology maturation through the end of operations. In addition to the government and contractor-borne costs of development, production, and operations, PTIRS addresses the economic impacts of noise and NO_x and CO_2 emissions.

The PTIRS Economic Analysis Module is a complete life cycle cost model for commercial aircraft development, production, and operations. PTIRS Economic Analysis Module development and production CERs are calibrated to reproduce 2012 published prices for commercial transport aircraft — given the reasonable assumptions regarding amortization of development costs, return on investment capital, and manufacturer's pricing mark-ups. Operations CERs in the Economic Analysis Module are derived from airline operations data from the US Department of Transportation's Bureau of Transportation Statistics Form 41 database. PTIRS Technology Cost Tool includes CERs for technologies that are new to commercial aircraft.

PTIRS is a business case model for evaluating emerging technologies in the context of commercial aircraft development, production, and operations. PTIRS allows all inputs to be specified with uncertainty that is described as statistical distributions and uses Monte-Carlo simulation to produce results with statistically described ranges of uncertainty. PTIRS includes a built-in aircraft weight resizing module that allows weight resizing analysis to be moved within the Monte-Carlo iteration loop, ensuring that uncertainty in the sizing inputs is properly reflected in the uncertainty in the economic results.

To advance such technologies, airframe and propulsion contractors are motivated to invest in new technologies—if there is a business case that demonstrates either reduced costs for the contractors or reduced costs for their airline customers. PTIRS helped the ERA Project meet its goal by providing data and information needed to formulate sound business cases that will generate the pull required to carry promising technologies into the market. PTIRS provided data and information for decision makers to have insight into the technologies and their impact to cost and marketability; furthermore, PTIRS also provided oversight perspective to meet NASA HQ and other external stakeholders' interests.

Describing technology impacts in PTIRS is done through a sequence of Excel worksheets. Technology impacts are described in terms of performance impacts, maturation and certification testing requirements, and implementation requirements. PTIRS allows all of these inputs to be specified with uncertainty distributions and uses Monte-Carlo simulation to produce integrated distribution results

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[49] Consultant report delivered to NASA during development of PTIRS framework in April 2014 by Peter Frederic, Tecolote Research Inc. "PITRS Final Report, Appendix N – Support Document for Verification and Validation of PTIRS Model". April 2014.

containing key statistical information, such as mode, mean, standard deviation, and variances. Through this process, the technologist is not hampered by having uncertain input parameters as they can describe the input as a distribution instead of a single input value.

The PTIRS Production CER database contains subsystem-level cost estimates for six Boeing aircraft using on a weight-based parametric cost model. For each aircraft, the PTIRS weight-based parametric cost model was calibrated so that the estimated total cost of the aircraft matched the publish price of the aircraft with adjustments for observed cost of capital and average markdowns.

The PTIRS equations estimates development costs, production costs, and maintenance costs of commercial aircraft and are packaged within an ACE model.

4.2.2 ACEIT Framework (Data Integration, Cash Flow, and Monte-Carlo Simulation)

ACEIT is a US Government (DoD and NASA)-sponsored software tool that standardizes the estimating process to develop, report, and share the cost estimates. ACEIT is a suite of applications built by cost analysts for cost analysis that enables analysts to build concise, structured, and robust cost estimates; develop CERs; conduct what-if analyses; generate management level reports; and prepare extensive basis of estimate documentation. Key ACEIT features include a cost estimate builder, what-if analyses, and Basis of Estimate (BOE) documentation, cost and schedule uncertainty analysis, statistical analysis, automated reporting, charts, and presentation development, database development, search, and retrieval, methodology and inflation libraries.[50,51]

ACEIT is a productivity tool that provided a robust framework for constructing and running cost models. Costs are identified and modeled at the component and activity level and organized within a work breakdown structure (WBS). In addition to the PTIRS equations, ACEIT contains the fuel projection model, forecasted cash flow analysis, discounted cash flow, and Monte-Carlo simulation capability.

4.2.3 JACS Framework (Technology Maturation)

In order to fully estimate both the availability and cost of a matured technology, a fully integrated cost and schedule model is required. Furthermore, this model must incorporate cost uncertainty, schedule uncertainty and risk. The ACEIT tool called JACS was determined to have the appropriate capability to support this analysis capability. JACS requires the user to define a development process and to determine the cost and time required to conduct the process.

The Technology Maturation model is able to do this using methodologies that take Time-Independent (TI)-Costs, Time-Dependent (TD)-Costs and Task Duration estimates for a series of networked tasks; uncertainty for each time and duration; and correlations between tasks and between cost and duration

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[50] ACEIT functionality, https://www.aceit.com/aceit-suite-home

[51] ACEIT mandated for use by US Army for all ACAT 1 programs, https://www.aceit.com/docs/default-source/Compliance-Documentation/army-requires-aceit-for-acat-i-and-acat-ii-cost-estimates-memorandum.pdf?sfvrsn=2

for each task. The data is processed using JACS to generate a joint cost/schedule confidence estimate that includes risk due to uncertainty and the correlation between cost and schedule.

The basic networked model used for this study is based uses the classic systems engineering process mapped to the TRL maturity matrix. Table 34 provides the template outlining the activities and the data for the SMEs to support this analysis. The Technical SME's provide the low and high values for each activity for duration and manpower. The template shows blank values as these are the items the SME's assessed and evaluated for each of the identified technologies and is the basis of the technology maturation cost estimates. Appendix N shows the SME inputs for each of the candidate technologies assessed in the study.

TABLE 34 – TECHNOLOGY MATURATION TEMPLATE

TRI Level	Activity/Milestone	Schedule (Months)			Manpower (FTEs)		
		Low	High	Conf.	Low	High	Conf.
1	Requirements Analysis/Initial Research						
	Requirements Assessment						
	Requirements Allocation						
	Requirements Reconciliation						
2	Evaluation/Optimization of Candidate Architectures						
	Technology Assessment						
	Trade Studies						
	Life-Cycle Cost Evaluations						
	Develop Performance Specifications						
	Determine Unique Manufacturing/Fabrication Needs						
	Design/Develop System Concepts						
	Product Definition						
	Initial Risk Analysis						
	System Requirements Review						
	Evolve Performance Specs into Baseline						
3	Vendor Reviews/Designs						
	Develop Initial Design						
	Aerodynamics						
	Propulsion						
	Controls						
	Mass						
	Structure						
	Rapid Prototyping						
	Conduct Analysis (Modeling and Simulation)						
	Preliminary Design Review						
4	Develop Documentation & Verification Plans						
	Develop Unique Manufacturing/Fabrication Needs						
	Evolve Baseline into Product Specs						
	Develop Design/Initial Drawings						
5	Develop Initial Prototypes						
	Detailed Analysis (Modeling & Simulation)						
	Critical Design Review						
6	Fabricate/Assemble/Code to Product Specs						
	Develop Simulators						
	Develop Test Plans & Verification Options						

TRI Level	Activity/Milestone	Schedule (Months)			Manpower (FTEs)		
		Low	High	Conf.	Low	High	Conf.
7	Individual Test & Evaluation						
	Integrated Test & Evaluation						
	Test Readiness Review						
	Production Readiness Review						

The model contains some assumptions on allocation of costs; correlation of TD- and TI-costs; correlation of cost and schedule within tasks, and uncertainties. These assumptions, including their rationales and/or sources, are discussed below.

TI-costs are those that are not impacted by the duration of the task. If the duration of the task changes, the same total time-independent cost is re-phased over the current duration of the task. Examples include the price of materials and tasks that have a defined length, regardless of outside influences. The TI-costs were determined as a fraction of the SMEs provided cost based on expert opinion. To address uncertainty, a lognormal distribution was used since the tasks will be completed regardless of the schedule. A 20% standard deviation was used to allow for a tighter curve, showing the nature of these tasks.

TD-costs are a function of the duration of the task. The task total cost varies with its duration and is calculated as burn rate multiplied by the duration (in days). These costs typically cover the cost of a standing army, who will continue to work regardless of the length of the task. The TD-costs were determined as a fraction of the SMEs provided cost based on expert opinion. To address uncertainty, a triangular distribution was used, so that the analysis can be consistent with what the SMEs provided. The SMEs assessed the length and estimated number of personnel working on each task (mean). By using these two variables, the low end is 20% of the mean, while the high end is 320% of the mean, which accounts for both the low end of the length and personnel and high end of the length and personnel, respectively.

The duration is simply the amount of time it takes to complete a task. To address uncertainty, a triangular distribution was used, so that the analysis can be consistent with what the SMEs provided. The SMEs assessed the length of each task (mean) and then divided by two to get the low end and multiplied by two to get the high end.

Correlation is a statistical measurement of the relationship between two variables. It is assigned to recognize and model interrelationships between data elements and influence how the values are drawn from those distributions during the simulation. Correlation causes selected elements to move together. Possible correlation values range from -1 to +1. A zero correlation indicates that there is no linear relationship between the variables. A correlation of -1 indicates a perfect negative linear correlation, meaning that as one variable goes up, the other goes down. A correlation of +1 indicates a perfect positive correlation, meaning that both variables move in the same direction together. Correlation between task durations and/or costs in the schedule must be considered since the level of correlation in a model has a profound influence on the results. Correlation was assigned between specific data elements based on expert opinion. The correlation factors are discussed in the following:

- For the TI-costs, a lower correlation factor, 0.4, was used, which equates to an r square value of 0.16. The r square value is equal to the percent of the variation in one variable that is related to the variation of the other variable. In this case, 16% of the variance is related. The rationale behind the lower number for time independent costs is because the tasks are not necessarily tied together, since the tasks will be completed in the same amount of time regardless of when it is completed.
- For the TD-costs, a high correlation factor, 0.6, was used, which equates to an r square value of 0.36 (36% of the variance is related). This correlation applies to every task in the schedule; as if one task slips, there is a likely chance that the rest of the tasks will slip as well.
- For the duration, a higher correlation factor, 0.8, was used, which equates to an r square value of 0.64 (64% of the variance is related). The higher factor was used since the tasks in each TRL are typically handled by the same product team within the manufacturer. If that team slips, there is a good chance that the other tasks will slip as well.

4.3 Cost Model Validation

In assessing the two different states of the world for this analysis, the objective from a cost analysis perspective is to ensure that the relative cost deltas are reasonable and provide consistent results across the scenarios. This requires confidence that the model calculates base costs that are in the region of past/current vehicles. Verification that the model estimates accurately allows us to look at the relative deltas between scenarios to determine the cost effectiveness of the different technology infusion cases. The study objective is not to accurately predict future prices, but to gauge the relative economic deltas between the different scenarios. Model validation was based on assessing how well the equations calculate costs and their reliability to use as relative results.

Three separate analyses were conducted to support verification and validation of the cost equations used. The first were the results from NASA's validation of the PTIRS model. The second was an independent assessment of how well the cost model estimated current list prices for the reference aircraft. The last validation test was developed to identify what a projected NEO configuration would cost and the target cost benefit it would derive compared to the reference aircraft. In all cases, the validation results were positive and indicated that the cost model could effectively be used as the basis for relative cost deltas between the scenarios.

4.3.1 Top-Level PTIRS Benchmark Results

In addition to the formal software testing that has been accomplished by NASA[52], the following analysis was conducted to indicate how the PTIRS cost model performs when trying to estimate configurations for which published prices are available. The acquisition portion of the PTIRS model has been

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[52] Consultant report delivered to NASA upon delivery of PTIRS software application, P. Frederic, "PTIRS IV and V support document v1", 15 April 2014

benchmarked against published prices for the Boeing 737-800 and 777-200LR. We chose these aircraft because we had reliable reference configurations for each in the PTIRS Reference Configuration Database. Table 35 shows the results of this analysis.

In order the translate the costs estimated by PTIRS in equivalent sales prices that PTIRS values could then compare to published prices, a cash flow analysis was required. PTIRS treated the development cost as a line of credit from which debt accrued as development costs were incurred up until the end of development, and then payments were made as production units were sold off. As with any loan, interest accrued at annually on the outstanding balance. The assumed annual interest rate was 10%. Production costs were also effectively funded from this line of credit. Since the total principal plus interest is the amount that must be recovered through sales for the investors to achieve the desired return on investment, the minimum sales price is that total (Acquisition Total Cost with Finance Cost) divided by the sales quantity. For comparison to published prices, which are widely known to be highly inflated, a 25% markup factor was applied.

TABLE 35 – PTIRS BENCHMARK

	737-800	777-200LR
PTIRS Estimates, FY2013$M		
Development	5,942	17,766
Production (1000 units interval)	51,207	164,939
Flight Test Aircraft	6	9
Operational fleet	855	855
Backup aircraft	144	140
Development years	8.6	8.6
Production years	14.9	14.9
Production start to sale lag, years	1.3	1.3
Number of Production Vehicles	1,000	1,000
Present value interest rate	10%	10%
Sales markup	25%	25%
Value of development to end of development	10,354	30,958
Total payments on development to end of production	20,367	60,895
Production at sale	58,142	187,277
Acquisition total cost with finance cost	78,509	248,172
Acquisition unit cost with finance cost	78.2	247.4
Unit cost plus markup	**97.7**	**309.3**
Boeing.com price	**93.8**	**306.5**
PTIRS estimate divided by Boeing.com	**104%**	**101%**

After all of these adjustments, the equivalent prices estimated by PTIRS were 104% and 101% of the published prices for the 737-800 and 777-200LR respectively. This is a strong indicator that the costs estimated by PTIRS are calibrated to the available data used as the basis for price identification. As such, the study team felt that the PTIRS cost model provides a solid and reasonable platform to estimate the relative cost differences within aircraft configurations for the infusion of enhanced technology.

A similar—though somewhat less complicated—analysis exercise was conducted for O&M costs. First, the PTIRS estimated O&M costs for the 737-800 compared, normalized to dollar per hour, to 737-800 actual costs from the Bureau of Transportation Statistics (BTS). American Airlines was chosen for comparison because a quick survey revealed that American's airline operating cost factors represent the middle of the range for US carriers. The result of this comparison is that the PTIRS estimate for 737-800 O&M on a dollars-per-hour basis is 93% of the actual costs found in the BTS database—results appear reasonable. Table 36 shows the results of this analysis.

TABLE 36 – PTIRS O&M COSTS (737-800)

	PTIRS 2013$M	2013$/hr	PTIRS Divided by Actual	Actual 2013$/hr
Assignable Life Cycle (Development, Production, Operations)	350,109	11,036		
Development	5,942	187		
Production	51,207	1,614		
Operations and Maintenance	**292,960**	**9,234**	**93%**	**9,931**
Flight Operations	136,367	4,298	97%	4,440
Flight Crew	23,300	734	90%	817
Fuel and Oil	77,256	2,435	100%	2,438
Insurance	219	7	65%	11
A/B/C/D-Checks and Unscheduled Maintenance	17,169	541	105%	515
Vehicle Level	1,583			
Airframe	2,619	276	83%	334
Propulsion	8,414	265	146%	181
Subsystems	3,281			
Avionics Hardware	384			
Software	888			
Depreciation	18,422	581	88%	659
Passenger Services	34,265	1,080	81%	1,334
Flight-line Servicing	4,743	150	96%	156
Control	4,552	143	97%	148
Landing Fees	5,622	177	82%	216
Other Indirect Costs	107,411	3,386	93%	3,636

Similar analysis was performed for the 777-200LR for O&M costs, as shown in Table 37. The result of this comparison is that the PTIRS estimate for 777-200LR O&M on a dollars per hour basis is 107% of the actual costs found in the BTS database. This also seems reasonable.

TABLE 37 – PTIRS O&M COSTS (777-200LR)

	PTIRS 2013$M	2013$/hr	PTIRS Divided by Actual	Actual 2013$/hr
Assignable Life Cycle (Development, Production, Operations)	1,149,576	24,879		
Development	17,766	384		
Production	164,939	3,570		
Operations and Maintenance	**966,872**	**20,925**	**107%**	**19,538**
Flight Operations	570,141	12,339	112%	10,968
Flight Crew	71,412	1,545	107%	1,450
Fuel and Oil	346,490	7,499	107%	6,980
Insurance	1,051	23	109%	21

	PTIRS 2013$M	2013$/hr	PTIRS Divided by Actual	Actual 2013$/hr
A/B/C/D-Checks and Unscheduled Maintenance	91,958	1,990	133%	1,500
Vehicle Level	10,792			
Airframe	15,039	971	138%	703
Propulsion	47,098	1,019	128%	798
Subsystems	10,122			
Avionics Hardware	940			
Software	7,967			
Depreciation	59,229	1,282	126%	1,017
Passenger Services	42,975	930	81%	1,149
Flight-line Servicing	3,162	68	96%	72
Control	3,035	66	97%	68
Landing Fees	3,748	81	82%	99
Other Indirect Costs	343,811	7,441	104%	7,182

4.3.2 Reference Aircraft Validation

In assessing the two different states of the world in this analysis, the objective from a cost analysis perspective is to ensure that the relative cost deltas across the scenarios are reasonable and consistent. This requires confidence that the model calculates base costs that are in the region of past/current vehicles. Model validation allows us to compare the relative deltas between scenarios to determine the cost effectiveness of the different technology infusion cases. The study objective is not to accurately predict price in the out years, but rather to gauge the relative economic deltas between the different scenarios.

The model validation approach used the process is similar to that developed by the PTIRS team for the ERA project. The validation process used a process of determining average production costs and amortizing development costs over the first 1000 units. In addition, costs for financing and profit were incorporated. These assumptions were affirmed by NASA. The following chart compares the PTIRS cost estimates for the A320, B777, and E190 aircraft using the PTIRS validation method to 2013 list prices. The results show that the underlying model is calibrated well to the vehicles and can be used for delta analysis. Note that the cost results in this validation process should not be used in comparison to the main analysis results as the assumptions are different.

A crosscheck was completed against 2013 list prices[53] (which were 2012 list prices inflated to 2013 dollars) for the three representative aircraft. In order to determine the Present Value, which would provide a figure closest to the list price, the model was normalized for comparison using a defined seven-year development period, a representative 1000 unit production lot for each aircraft type, and standard figures for SLOC and testing hours. Both the nonrecurring and recurring values were adjusted to reflect the Present Value, assuming a discount rate of 10%. The nonrecurring costs were then

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[53] http://www.boeing.com/company/about-bca/#/prices

amortized and allocated to the production units, and then profit, assumed to be 20%, was added, which determined the estimated list price.

This study by design only examined top level labor and material and avoided detail evaluation that led to nuances between labor country, demand, demographics, country economics, etc. which are too uncertain to reasonably forecast. This means that instead of developing labor rates and underlying economic factors (e.g., supply, inflation, etc.) for each category of labor (e.g., welder, engineer, etc.) or by material, a composite was developed to supply the base labor rate.

To calibrate the costs of the reference aircraft it was determined that the labor rates should be adjusted based on the location of the airline manufacturer. Using the US Bureau of Labor Statistics (BLS) August 2013 version of the International Labor Comparisons report, Tecolote was able to determine which labor rates should be used. For the RJ, the E190 is built in Brazil, which has an hourly rate of $11.20. Compared to the US rate of $35.67, this represents labor rate that is 31% that of the US.

For the SA, the A320-200 is manufactured in three different locations— France (112% of US rate), Germany (128%) and China (9%). Using a weighted average, assuming 40% of the production is completed in both France and Germany, and 20% in China, provides a composite labor rate of 90% for Airbus. For the STA, the Boeing 777-200ER is built in the US, so there is no adjustment to the labor rates.

The PTIRS estimated list prices were then compared to publically available list prices obtained in October 2013 from Airbus[54,55], Boeing[56,57], and Embraer[58,59]. Figure 7 shows the comparison between modeled results and list prices for each reference aircraft. The boxes around each point are for illustrative purposes to indicate each aircraft configuration. The results show that the PTIRS model provided realistic values. For the E190, the PTIRS model is estimating a price that is 9% different than the list price. For the A320-200, the model is 8% different, while the B777-200ER is less than 1% different, than their respective list prices.

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[54] http://www.airbus.com/newsevents/news-events-single/detail/new-airbus-aircraft-list-prices-for-2013/

[55] http://en.wikipedia.org/wiki/Airbus_A320_family accessed Sept 2013.

[56] Data provided by NASA on Boeing aircraft prices for use in validation testing of PTIRS Model

[57] http://www.boeing.com/boeing/commercial/prices/index.page accessed September 2013.

[58] http://www.flightglobal.com/news/articles/analysis-lessors-spurn-cseries-overtures-370412/, "ANALYSIS: Lessors spurn CSeries overtures", April 2012

[59] http://en.wikipedia.org/wiki/Embraer_E-Jet_family accessed October 2013

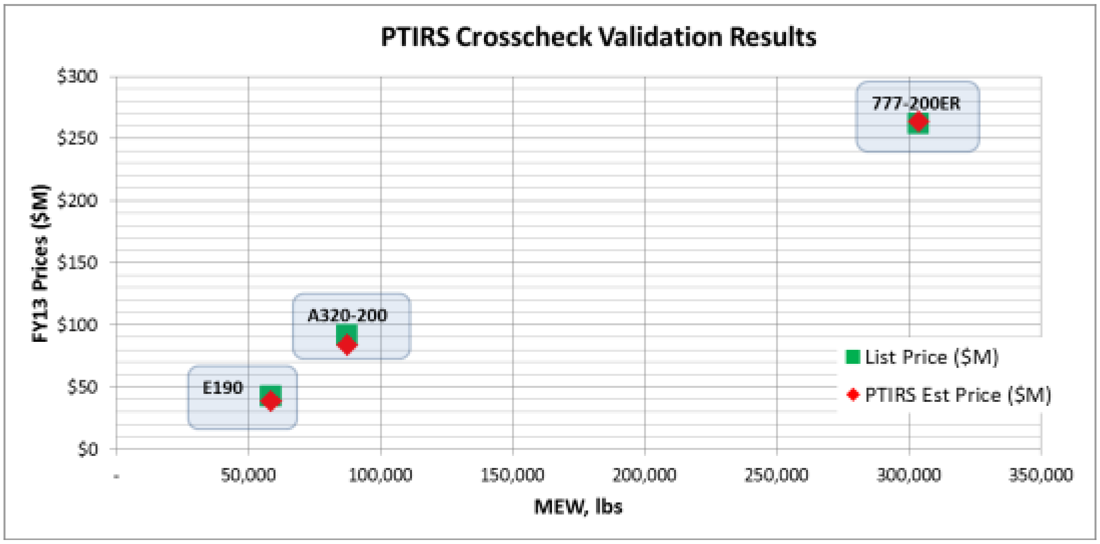

FIGURE 7 – REFERENCE COST CROSSCHECK VALIDATION

4.3.3 Single Aisle Emergent Case Verification

A test case was done to assess if the underlying cost model could effectively model emerging technology infused aircraft currently coming into the market. This case differed from general sensitivity assessments and prior validation cases in that it did not try to assess the impact of input changes to the model results nor try to validate if the model could accurately forecast a list price. This sensitivity case was used to see if the cost model could predict the fuel efficiency and estimated benefit of an emerging aircraft in the current market. This test case was based on assessing the projected cost benefit derived from the A320 New Engine Option (A320neo) as compared to the reference A320-200 Single Aisle case. In essence, a new scenario was created for an A320neo resized for the baseline range and payload capabilities identified in the study. This allowed the validation of a sub-2024 evolutionary improvement to the Single Aisle vehicle.

The A320neo is a recent entry to the market that includes improvements such as a new engine, aerodynamic refinements, large curved winglets (sharklets), and weight savings. This new configuration is expected to result in 15% less fuel consumption per aircraft than the A320-200. As such, this provided a good basis to test the ability of the estimation process and the underlying model(s) to accurately forecast potential costs and benefits of future technologically enhanced aircraft. To be consistent with the rest of the study, the A320neo model aircraft was resized to reflect the capacity and range of the baseline aircraft (A320-200ceo). Further, the cost model was run on the resized Neo aircraft and compared to the Single Aisle scenarios. To conduct the test case, an evaluation of the implemented technologies was conducted similar to the process done for the rest of the study on all technology deployment scenarios. This involved derivation of user factors so that Piano 5 could generate a mass estimate and fuel consumption of the A320neo-like vehicle. In addition, complexity factors for development, production, and maintenance were generated. These parameters were used in the cost model to project benefits derived from an A320neo fleet for a 2024 EIS.

The results in Figure 8 show that an A320 neo-like aircraft can achieve almost a 20% fuel reduction and that the aircraft configuration would be an attractive economic situation for an operator. This attractiveness has been demonstrated by the open purchase orders that Airbus has received. This cost-benefit point is shown in the below graph and indicates that the A320neo follows along the same curve as the 2024 EIS SA scenarios and is at a point where it provides an operator a benefit for the purchase.

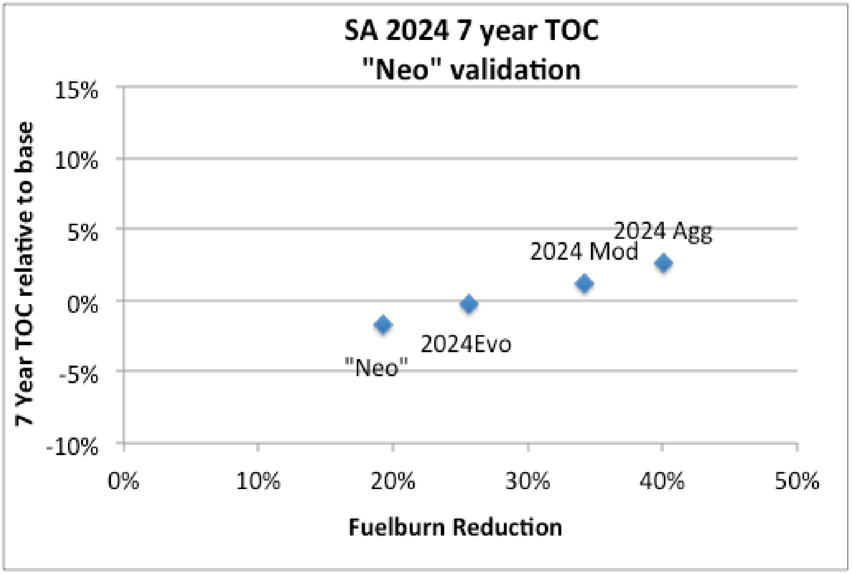

FIGURE 8 – A320 EMERGENT SCENARIO CASE

4.4 Components of Total Operator Cost

The primary output being estimated for the analysis is the total operator cost (TOC). TOC is developed by aggregating the results of several models, creating a cash-flow analysis, and generating discounted cash flows. There are three major sections of the model, with each component having multiple items listed therein. Figure 9 shows the model flow and the major components of the TOC.

The overall analysis is a comparison of TOC for each deployment scenario as compared to a reference case for the 2024 EIS and 2034 EIS time periods. TOC is the overall expected expense for an airline operator to purchase an aircraft, operate for seven years, and resell it to the secondary market after its first owner lifetime. In order to obtain TOC the overall nonrecurring costs for technology maturation and system development must be considered as well as the cost to manufacture the vehicle. In addition to this operator investment for procuring the vehicle, costs for fuel and maintenance must also be considered, as well as estimating the offset due to the residual aircraft value.

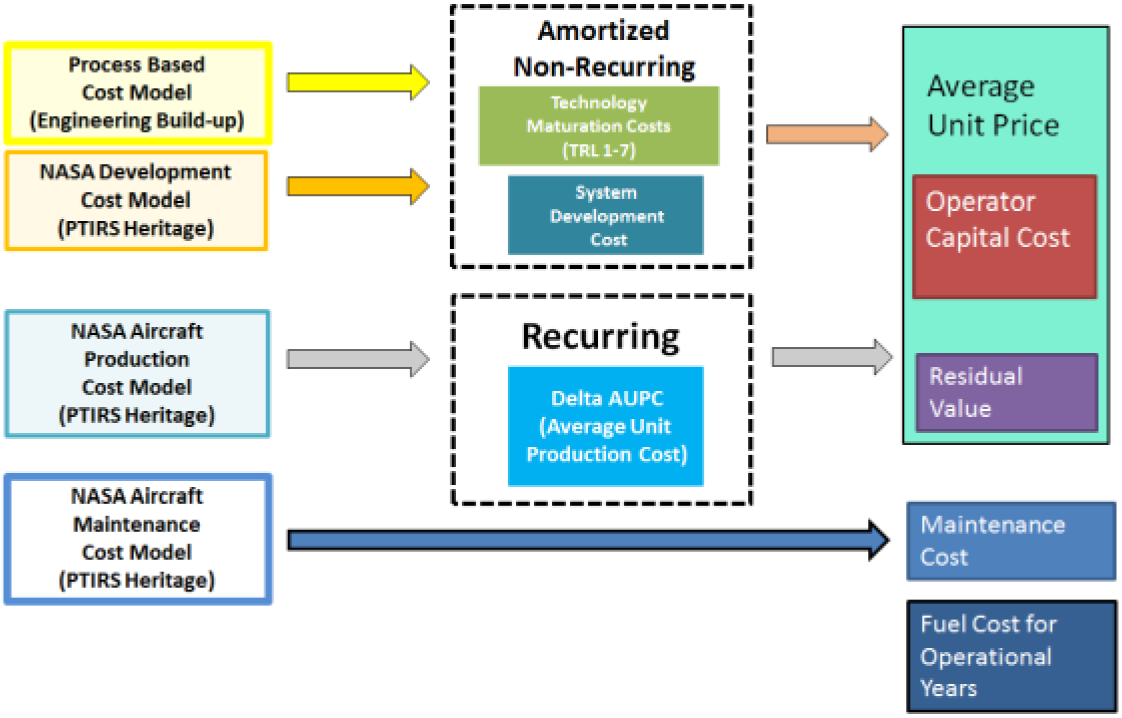

FIGURE 9 –TOTAL OPERATOR COST FLOW

In this study, the **total operator cost** is the sum of operator capital cost, maintenance cost, and fuel cost over seven operational years, less the residual value over 17 years, the estimated first owner lifetime of commercial aircraft. The following section describes the content and components of each item that make up TOC.

TOC = Operator capital cost + Maintenance + Fuel - Residual

Operator capital cost is the estimated investment that will be incurred by operators to procure aircraft of the designated configuration. It consists of the overall price that the manufacturer will charge operators to recover their initial investment, the cost of manufacturing the vehicle, and includes a profit margin. The lower level components of operator capital cost are the overall production quantity, the amortized nonrecurring costs and the average unit price.

Amortized nonrecurring costs consist of the overall cost to develop and mature the technology and the resulting costs for developing the system into a certified aircraft. These costs are estimated within the model and summed to determine the overall manufacturer investment cost for each deployment scenario. The resulting nonrecurring costs are then amortized over the total number of aircraft projected for delivery in a ten-year production run for each EIS period. This resulting value is the cost needed to be added to the production cost to recapture the investment.

Recurring production cost is calculated by estimating the overall production costs for the specified aircraft deployment scenario for a ten-year production run. This cost estimation calculates the overall impact of assuming a learning curve on the production labor inherent to the vehicle. This total production cost is then divided by the total production quantity to arrive at an average unit production cost per vehicle. This value is then used to support calculating the average unit price so that the overall operator capital costs can be calculated.

The **AUP** is the estimated price an operator will pay for the specified aircraft. This value is developed by summing the average unit production cost and the amortized nonrecurring cost and then applying a 20% profit margin. This AUP is then used to forecast the annual investment costs an operator will need to make to procure the aircraft and incorporate them into their fleet. The summation of 10 years of aircraft purchase provides the overall operator investment cost for the specific aircraft.

Maintenance costs are calculated based on the expected annual costs to maintain each aircraft airframe and engine procured. These costs are calculated annually over the number of operational years specified for the analysis. The resulting total of all aircraft annual costs for the number of operational years is calculated and provides the total maintenance cost for the deployment scenario. Operations costs that encompass landing fees, crew, and passenger support are excluded as it was assumed that these costs would be consistent across the scenarios.

Fuel costs are calculated based on the expected annual usage of fuel for the aircraft over the number of operational years considered in the study.

Residual Value is the remaining economic value of an aircraft after it has been used for a certain number of years. The calculation of residual value is based on estimating the depreciation of the aircraft over a period of time and determining the remaining economic value. For this analysis a declining balance method was used. The declining balance method applies the depreciation rate the asset value and each year the asset value is decreased by the prior year's depreciation. Using this method, the depreciation rate stays constant but the actual expense decreases each year due to the declining asset value.

Residual Value = AUC – 17 yrs of depreciation on AUC

4.4.1 Operator Capital Cost

The cost model requires several parameters to support analysis of development, production, and maintenance costs. Cost Estimating Relationships (CERs) use weight as a key parameter and are used to estimate the theoretical first unit cost. To further capture the cost of production and maintenance, additional input parameters and factors were used, such as complexity of the new technology, the level of design (ranging from no modification to clean sheet), to the assumed prior units manufactured of the subsystem. A rigorous evaluation was conducted by SMEs to formulate impacts relative to the reference aircraft design and manufacture for each of these cost model input parameters. The resulting analysis was reviewed by the TAG for reasonableness and the final analysis captures the impact of these input parameters.

Operator capital cost is estimated based on multiplying the AUP estimated for each deployment scenario by the annual forecasted purchase quantities. The AUP is generated based on the input parameters (e.g., mass, complexity factors, design heritage, production quantities, etc.) identified for the aircraft class and the EIS year. To calculate AUP, three major cost items must be estimated: 1) technology maturation cost; 2) system development cost; and 3) total production cost. From the total cost calculations the average production cost is determined and it is summed with the amortized value of the total investment cost (e.g., technology maturation plus system development cost). The amortization is done over the same amount of production quantities as used to generate the analysis.

Regardless of the scenario or cost item, the primary input parameter for estimating costs is to identify the technology being implemented for the scenario. Once this is identified, then all other parameters (e.g., mass, complexity) are generated and applied to the model.

4.4.2 Technology Maturation Cost

Technology maturation cost is the cost associated for technologies to go from an initial concept to a marketable product, based on NASA defined technology readiness levels (TRL).[60] Typically, this is identified as a technology passing TRL 7, which reflects a technology where a prototype has been incorporated into a system and demonstrated in an operational environment. Technology maturation—particularly for new emerging technologies—is often directly funded by government sponsored programs including military and space programs. Much of the technology development and maturation is conducted internally by suppliers of material and subsystems. Aircraft and aircraft engine manufacturers conduct internal technology maturation programs as part of their Independent Research and Development (IR&D) activities. A manufacturer's overall IR&D program is typically conducted as a level-of-effort activity whose resources are split between specific technology programs based on the priorities of the manufacturer.

For this study, there were key assumptions about how technologies were being reused across aircraft types, the interaction between capture share assumption and technology maturation costs, and how technology maturation costs are being handled for engines. These include:

- Technology maturation costs are a lump sum incurred cost amortized individually across each aircraft type they are applied to. If riblets are applied to RJ, SA, and STA aircraft types the mean technology maturation costs for one vendor would be approximately $150 million US (~$50 million per aircraft type) where full tech maturation costs on each aircraft they are applied. This produces a conservative estimate of the overall cost.
- Each vendor is assumed to incur technology maturation costs independently, with total industry costs estimated by dividing the individual vendor costs by the % market capture. For the riblets example, total maturation costs would be larger than $300 million corresponding to an average more than two vendors per aircraft type. If more than one vendor applies the technology then

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[60] John Mankins, "Technology Readiness Levels", NASA Office of Space Access and Technology, April 6, 1995

the industry cost for a two vendor environment would be double the cost of the estimated technology maturation.

- Maturation costs for technologies enabling new engines are wrapped into engine development cost. The assumption is that there is a constant R&D involved in the engine arena with effort geared toward an overall engine instead of individual technology. Since the engine model was derived from PTIRS, an assumption was made that the technology maturation costs were captured primarily in development CERs and in the resulting production cost results. All engine technology maturation costs are captured within the engine development CER.

For each candidate technology, a starting TRL is identified and activities associated with TRL levels lower than the starting TRL are ignored. For the remaining activities, the SMEs provide duration and labor estimates for each activity. To address the uncertainty, low and high estimates for both duration and labor were provided and a probabilistic cost and schedule assessment was conducted.

For the last step in the technology maturation estimating process, the cost estimation team used the JACS tool to generate probabilistic cost data for each technology maturation effort. JACS is a Microsoft Project® add-in that performs a Monte-Carlo simulation and generates cost data based on a network of scheduled activities, resource loading, and uncertainty data. The individual technology maturation activities are loaded into a networked schedule that models the activities identified above along with the durations, resources, and uncertainty information provided by the SMEs. Under the Monte-Carlo simulation, JACS computes cost and duration for each activity using the data provided by the SMEs. These individual components are compiled into an overall cost and duration for each of 2000 replications. Table 38 provides the forecasted cost to mature each identified technology in the study, technologies with costs of zero dollars ($0) indicates that no additional costs are needed to mature the technology to a state reasonable for incorporation.

TABLE 38 – TECHNOLOGY MATURATION COST RESULTS IN MILLIONS OF 2013 USD

Evaluated Technology	Code	Current TRL	Pt Estimate Cost	50th Percentile Cost	Mean Cost	80th Percentile Cost
Aerodynamic efficiency (viscous)						
Natural laminar flow on nacelles	AV-1	9	$0	n/a	n/a	n/a
Hybrid laminar flow on empennage	AV-2	4	$37	$55	$58	$75
Natural laminar flow on wings	AV-3	5	$128	$189	$205	$265
Hybrid laminar flow on wings	AV-4	5	$303	$465	$493	$678
Laminar flow coatings/riblets	AV-5	5	$33	$48	$52	$69
Aerodynamic efficiency (non-viscous)						
Improved aero/transonic design	ANV-1	6	$186	$294	$305	$409
Wingtip technologies (for fixed span)	ANV-2	9	$0	n/a	n/a	n/a
Variable camber with existing control surfaces	ANV-3	6	$79	$124	$133	$180
Adaptive compliant trailing edge	ANV-4	5	$120	$185	$202	$268
Active stability control (reduced static margin)	ANV-5	4	$104	$172	$185	$252
Reduction of loads (active smart wings)	ANV-6	3	$157	$268	$292	$399
Increased wingspan	ANV-7	7	$15	$22	$23	$30
Structures						
All composite aircraft	S-0	9	$0	n/a	n/a	n/a
All composite fuselage	S-1	9	$0	n/a	n/a	n/a

Evaluated Technology	Code	Current TRL	Pt Estimate Cost	50th Percentile Cost	Mean Cost	80th Percentile Cost
All composite wing	S-2	9	$0	n/a	n/a	n/a
All composite nacelle	S-3	8	$0	n/a	n/a	n/a
All composite empennage	S-4	9	$0	n/a	n/a	n/a
Integrated structural health monitoring	S-5	8	$0	n/a	n/a	n/a
Advanced composite materials	S-6	5	$81	$131	$141	$186
Advanced airframe metal alloy	S-7	8	$0	n/a	n/a	n/a
Unitized construction	S-8	8	$0	n/a	n/a	n/a
Out of autoclave curing composite	S-9	5	$60	$93	$100	$133
Automated tape laying, automated fiber placement	S-10	9	$0	n/a	n/a	n/a
Composite sandwich construction	S-11	8	$0	n/a	n/a	n/a
Net shape components	S-12	8	$0	n/a	n/a	n/a
Additive production	S-13	5	$81	$132	$142	$190
3-D preforms	S-14		$60	$94	$102	$136
Bonded joints, innovations in structural joining	S-15	7	$0	n/a	n/a	n/a
Damage tolerance concepts	S-16	7	$0	n/a	n/a	n/a
Adaptive and morphing structures	S-17	5	$128	$204	$227	$321
Advanced metallic joining	S-18	8	$0	n/a	n/a	n/a
High temperature materials for insulation, thermal protection	S-19	7	$0	n/a	n/a	n/a
High temperature ceramics	S-20	6	$137	$219	$243	$334
Innovative load suppression	S-21	6	$150	$243	$258	$351
Multi-functional structures/materials	S-22	5	$128	$202	$225	$304
Aircraft systems			$0	n/a	n/a	n/a
More electric aircraft	Sys-1	9	$0	n/a	n/a	n/a
Electric landing-gear drive	Sys-2	3	$9	$14	$15	$20

In order to determine the schedule and cost for the new technologies, the SMEs provided estimated schedule duration and manpower for each of the tasks identified in each TRL. For each, they provided a low, most likely and high value, which was input into JACS. JACS was then run against 2000 iterations to produce point estimate, 50th percentile, mean and 80th percentile values for both cost and duration. Table 39 details the projected timeline (if started in 2014) to mature the technology. The TRL level indicates where the technology would enter the technology maturation estimation, for example an entry level of TRL 4, means that the technology has to start with the work activities to accomplish TRL 4.

TABLE 39 – TECHNOLOGY MATURATION SCHEDULE RESULTS

Evaluated Technology	Code	Current TRL	Pt Estimate Schedule	50th Percentile Availability	Mean Availability	80th Percentile Availability
Aerodynamic efficiency (viscous)						
Natural laminar flow on nacelles	AV-1	9	available	n/a	n/a	n/a
Hybrid laminar flow on empennage	AV-2	4	27-Nov-19	6-Apr-21	14-Apr-21	11-Oct-22
Natural laminar flow on wings	AV-3	5	17-May-17	23-Mar-18	18-Mar-18	23-Apr-19
Hybrid laminar flow on wings	AV-4	5	27-Nov-19	17-Mar-21	14-Apr-21	8-Nov-22
Laminar flow coatings/riblets	AV-5	5	17-May-17	16-Mar-18	18-Mar-18	12-Feb-19
Aerodynamic efficiency (non-viscous)						
Improved aero/transonic design	ANV-1	6	17-May-17	26-Mar-18	18-Mar-18	8-Mar-19
Wingtip technologies (for fixed span)	ANV-2	9	available	n/a	n/a	n/a

Evaluated Technology	Code	Current TRL	Pt Estimate Schedule	50th Percentile Availability	Mean Availability	80th Percentile Availability
Variable camber with existing control surfaces	ANV-3	6	17-May-17	7-Mar-18	18-Mar-18	11-Mar-19
Adaptive compliant trailing edge	ANV-4	5	17-May-17	26-Feb-18	18-Mar-18	7-May-19
Active stability control (reduced static margin)	ANV-5	4	27-Nov-19	23-Apr-21	14-Apr-21	10-Jan-23
Reduction of loads (active smart wings)	ANV-6	3	11-May-30	20-Oct-33	29-Dec-33	15-Dec-37
Increased wingspan	ANV-7	7	27-Nov-19	23-Feb-21	13-Apr-21	18-Nov-22
Structures						
All composite aircraft	S-0	9	available	n/a	n/a	n/a
All composite fuselage	S-1	9	available	n/a	n/a	n/a
All composite wing	S-2	9	available	n/a	n/a	n/a
All composite nacelle	S-3	8	available	n/a	n/a	n/a
All composite empennage	S-4	9	available	n/a	n/a	n/a
Integrated structural health monitoring	S-5	8	available	n/a	n/a	n/a
Advanced composite materials	S-6	5	9-Aug-22	27-Apr-24	26-Jul-24	27-Nov-26
Advanced airframe metal alloy	S-7	8	available	n/a	n/a	n/a
Unitized construction	S-8	8	available	n/a	n/a	n/a
Out of autoclave curing composite	S-9	5	30-Jul-20	14-Dec-21	7-Feb-22	2-Nov-23
Automated tape laying, automated fiber placement	S-10	9	available	n/a	n/a	n/a
Composite sandwich construction	S-11	8	available	n/a	n/a	n/a
Net shape components	S-12	8	available	n/a	n/a	n/a
Additive production	S-13	5	30-Jul-20	29-Nov-21	7-Feb-22	30-Nov-23
3-D preforms	S-14	????	30-Jul-22	15-Feb-22	23-Feb22	22-Sep23
Bonded joints, innovations in structural joining	S-15	7	available	n/a	n/a	n/a
Damage tolerance concepts	S-16	7	available	n/a	n/a	n/a
Adaptive and morphing structures	S-17	5	9-Aug-22	27-May-24	25-Jul-24	5-Nov-26
Advanced metallic joining	S-18	8	available	n/a	n/a	n/a
High temperature materials for insulation, thermal protection	S-19	7	available	n/a	n/a	n/a
High temperature ceramics	S-20	6	22-Oct-25	10-Jun-28	18-Jun-28	19-Dec-31
Innovative load suppression	S-21	6	20-Nov-32	14-Oct-36	25-Jan-37	22-Mar-42
Multi-functional structures/ materials	S-22	5	9-Aug-22	5-Jun-24	25-Jul-24	18-Nov-26
Aircraft systems						
More electric aircraft	Sys-1	9	available	n/a	n/a	n/a
Electric landing-gear drive	Sys-2	3	27-Nov-19	28-Feb-21	15-Apr-21	19-Sep-22

For each technology and EIS date, an assessment was completed by the SMEs to determine when in the aircraft development cycle the matured technology was required. For the majority of the technologies, the required maturation date was prior to the start of the aircraft development program. For those technologies whose 80th percentile date was past the required date, schedule compression was required. The 80th percentile was used to ensure the dates selected were realistic and encompassed a suitable amount of risk.

To complete the schedule compression, a special risk is added to the schedule, which is tied to all of the tasks that require compression. The schedule duration uncertainty percentages for low, most likely and high are changed to values under 100%, with the severity of the decrease dependent on how much the schedule requires compression. At the same time, the cost uncertainty percentages are increased, based on the concept that, if a company needs to do the work faster, they will hire additional workers, work more overtime, or some combination of the two. These two options will drive costs up through additional manpower costs, overtime costs, and negative learning issues, as new personnel need time for necessary training.

Once the values are updated, the schedule is run against the 2000 iterations of the Monte-Carlo simulation. If the 80th percentile values still do not meet the required date, the process is repeated, with the schedule duration percentages going lower and the cost duration percentages going higher until the required date is met.

The Mathews Curve[61] provides a slope for comparing duration compression against cost increases. Table 40 provides the results for the technologies that required schedule compression in the 2024 EIS timeframe as compared to the values calculated by the Mathews Curve. For example, AV-2 requires 51% schedule compression which requires an additional 51% of the original schedule to complete development which, according to the Mathews Curve will require approximately 20% more of the original cost estimate. Table 41 provides the list of technologies requiring compression for the 2034 EIS timeframe.

TABLE 40 – SCHEDULE COMPRESSION RESULTS 2024 EIS

Included Technologies			
Code	Name	Compression	$ Growth
AV-2	Hybrid laminar flow on empennage	51%	20%
AV-3	Natural laminar flow on wings	25%	15%
AV-4	Hybrid laminar flow on wing	50%	22%
ANV-1	Improved aero/transonic design	25%	16%
ANV-3	Variable camber with existing control surfaces	25%	17%
ANV-4	Adaptive compliant trailing edge	25%	16%
ANV-5	Active stability control (reduce static margin)	50%	24%
ANV-7	Increased wing span	50%	22%
S-6	Advanced composite materials (higher strength, stiffness, toughness, damage tolerance, temperature)	65%	41%
S-9	Out of autoclave curing composites	53%	18%
S-13	Additive production (for mass customization of cabin interior structures, depot repairs, etc.)	60%	34%
S-20	High temperature ceramics and coatings for engine components	80%	47%
Sys-2	Electric landing-gear drive	50%	24%

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[61] "A Model for Evaluation Impact", Paul R. Heather, CCE, AACE Transactions, 1989

TABLE 41- SCHEDULE COMPRESSION RESULTS 2034 EIS

Included Technologies			
Code	Name	Compression	$ Growth
ANV-6	Reduction of loads (active smart wings)	50%	28%
S-21	Innovative load suppression, and vibration and aeromechanical stability control	51%	24%

Table 42 provides the revised cost results from the technology maturation model for schedule compression. Compression indicated that most of the technologies could make the target 2024 and 2034 timelines, except for active smart wings. For this technology, it was determined that some level of technology could be developed for application in the 2024 timeframe but not to the extent originally assessed. It was determined that the full technology application could be made available by the 2034 EIS timeframe.

TABLE 42 – TECHNOLOGY MATURATION COST AND SCHEDULE RESULTS IN MILLIONS OF 2013 USD

Evaluated Technology	Code	Current TRL	2024 Compress?	2034 Compress?	Mean Cost in Millions of 2013 USD	Mean Availability
Aerodynamic efficiency (viscous)						
Natural laminar flow on nacelles	AV-1	9				
Hybrid laminar flow on empennage	AV-2	4	✓		$69.8	8-May-17
Natural laminar flow on wings	AV-3	5	✓		$236.3	16-Jan-17
Hybrid laminar flow on wings	AV-4	5	✓			
Laminar flow coatings/riblets	AV-5	5				
Aerodynamic efficiency (non-viscous)						
Improved aero/transonic design	ANV-1	6	✓		$352.1	16-Jan-17
Wingtip technologies (for fixed span)	ANV-2	9				
Variable camber with existing control surfaces	ANV-3	6	✓		$154.5	14-Jan-17
Adaptive compliant trailing edge	ANV-4	5	✓		$233.9	17-Jan-17
Active stability control (reduced static margin)	ANV-5	4	✓		$230.2	12-May-17
Reduction of loads (active smart wings)	ANV-6	3	✓✓	✓	$374.4	28-Sep-23
Increased wingspan	ANV-7	7	✓		$28.3	12-May-17
Structures						
All composite aircraft	S-0	9				
All composite fuselage	S-1	9				
All composite wing	S-2	9				
All composite nacelle	S-3	8				
All composite empennage	S-4	9				
Integrated structural health monitoring	S-5	8				
Advanced composite materials	S-6	5	✓		$198.9	11-May-17
Advanced airframe metal alloy	S-7	8				
Unitized construction	S-8	8				
Out of autoclave curing composite	S-9	5	✓		$118.2	15-Jul-17
Automated tape laying, automated fiber placement	S-10	9				
Composite sandwich construction	S-11	8				
Net shape components	S-12	8				
Additive production	S-13	5	✓		$190.7	8-Dec-16

Evaluated Technology	Code	Current TRL	2024 Compress?	2034 Compress?	Mean Cost in Millions of 2013 USD	Mean Availability
3-D preforms	S-14					
Bonded joints, innovations in structural joining	S-15	7				
Damage tolerance concepts	S-16	7				
Adaptive and morphing structures	S-17	5				
Advanced metallic joining	S-18	8				
High temperature materials for insulation, thermal protection	S-19	7				
High temperature ceramics	S-20	6	✓		$357.6	23-Jun-16
Innovative load suppression	S-21	6		✓	$321.7	15-Feb-25
Multi-functional structures/ materials	S-22	5				
Aircraft systems						
More electric aircraft	Sys-1	9				
Electric landing-gear drive	Sys-2	3	✓		$18.5	11-May-17

4.4.3 System Development Cost

System development costs capture all of the costs associated with developing and producing the first aircraft. This includes:

- Aircraft design and engineering
- Material and labor required to develop or modify a production line
- Subcontractor costs for engines
- Subcontractor costs for integrating engines
- Subsystems
- Avionics
- Furnishings
- Material and labor to produce the first aircraft
- Subcontractor costs for subsystems, avionics and aircraft furnishing for the first aircraft
- Labor and material required for testing and certifying the aircraft
- Management and overhead costs associated with these activities

4.4.3.1 System Development Cost Model Flow

This study used the PTIRS CERs for estimating system development costs. PTIRS CERs estimate aircraft system development costs predominantly based on the weight and the type of material (alloy versus composite) used to construct the various components of the aircraft. It uses CERs to convert the weights and materials to hours and then to costs associated with system development. To ensure consistency between the technology and cost sides of this study, the WBS is defined at a level consistent with the Piano 5 weight table. This provides a simple and consistent framework to transfer weight data from Piano 5 to the cost model. At each WBS level a CER is used to estimate the cost of a clean sheet design.

Additional cost estimating parameters are multiplied to this CER to adjust for design heritage and development complexity.

Estimating system development costs within the cost model requires multiple inputs and the need to calculate various parts of the model and aggregate them until the total system development cost is generated. The overall flow for the modeling process starts with the SME identification of aggregate Piano user factors. Piano is then used develop a re-sized aircraft and obtain the mass parameters which are used to drive the system development CERs. In addition, the technical SMEs generate composite design heritage and development complexity factors to adjust the CER output. The CERs for PTIRS estimate labor cost, which must be transformed into dollars by multiplying the labor hours by a composite labor rate. Depending on the location of manufacturer the composite labor rate is adjusted to arrive at total cost. Additional cost items for system testing and test hardware units are generated within the model. Figure 10 shows the general flow of the system development cost analysis.

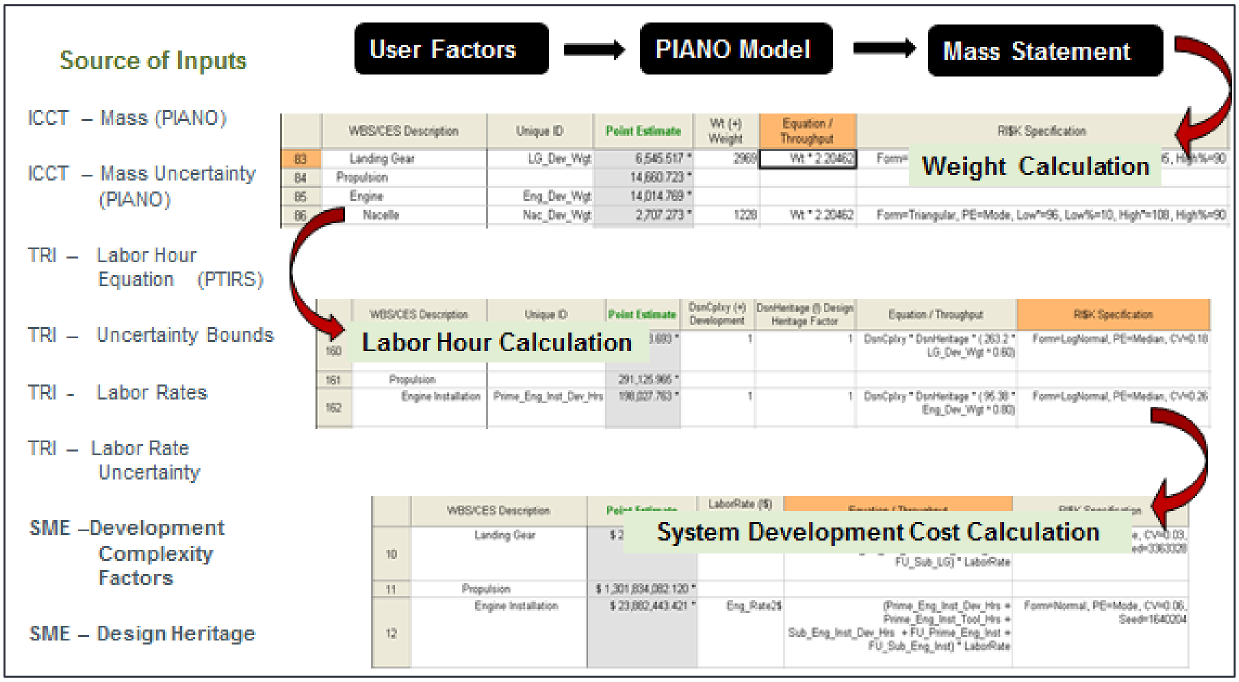

FIGURE 10 – INPUT FLOW FOR SYSTEM DEVELOPMENT COST

For System Development costs, there are four major items estimated by the PTIRS CERs to arrive at the total cost. They are:

1) Design and development engineering hours
2) Tooling
3) Material
4) System testing

The overall lower-level cost WBS for the engineering hours, tooling, and material costs are identified in Table 43.

TABLE 43 – SYSTEM DEVELOPMENT EFFORT WBS

2	Total Development Effort
2.1	Structure
2.1.1	Fuselage Group
2.1.2	Wing Group
2.1.3	Empennage
2.1.4	Landing Gear
2.2	Propulsion
2.2.1	Engine
2.2.2	Fuel System
2.3	Systems
2.3.1	Auxiliary Power Unit
2.3.2	Surface Controls
2.3.3	Hydraulics
2.3.4	Electrical
2.3.5	Furnishings
2.3.6	Air Conditioning
2.3.7	Avionics
2.3.8	Misc. Systems
2.4	Air Vehicle Integration
2.5	Software Development
2.6	SE/PM
2.7	Test
2.8	Support Investment

As identified in the model flow in the Figure 10, two additional cost analysis parameters are required for incorporation into the model to arrive at accurate results. These parameters are design heritage and development complexity.

4.4.3.2 Design Heritage

The underlying CERs in the cost model are structured to estimate system development costs for a clean sheet aircraft. To support the study of derivative aircraft, the model was adapted to include a design heritage factor for aircraft development cost components. Design heritage (or % new)[62] is used as a way of defining the percentage of the component being altered due to the inclusion of new technology to adjust development and production costs. The value of this input can either be zero, which means that it is a full reuse of an existing design; one, which means that it is a completely new design; or a number in between, which captures the percentage change if the change does not result in a new design.

Through implementing a design heritage factor, a cost estimate for modified aircraft can be generated, as the design heritage factor scales the resulting cost for a component to the relative work required for development. To assess design heritage impacts, the technical SMEs reviewed each technology identified for infusion in a deployment scenario and assessed the relative level of modification this

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[62] http://www.nasa.gov/pdf/263676main_2008-NASA-Cost-Handbook-FINAL_v6.pdf, p. 13

would require on each subsystem. Many technologies affected multiple subsystems, and subsystems were affected by multiple technologies. These results were aggregated at the subsystem level to determine the overall design heritage assumption to be used in the cost modeling process. This required additional efforts by the technical SMEs to determine if the combined effect of the technologies resulted in a reasonable value or if individual technology impacts needed to be scaled back to ensure an appropriate aggregate value.

In estimation of development cost, the design heritage is used to adjust the results of the CERs to account for the use of existing design or production. The use of a low and high range for design heritage provides a mechanism to account for uncertainty in the SME's assessments. Production cost CERs are not affected by design heritage factors, but design heritage is used to adjust prior quantities to reflect the fact that the subsystem is further down the learning curve.

Figure 11 provides an example based on the Single Aisle 2024 EIS analysis of design heritage for each of the deployment scenarios. Appendix I contains the design heritage assessment for each deployment scenario.

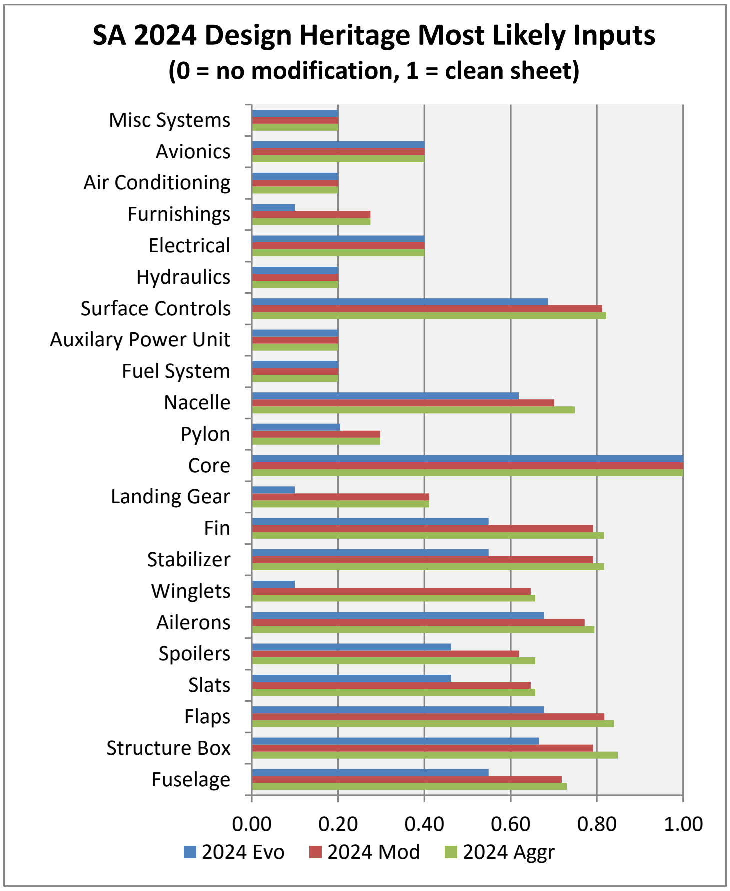


FIGURE 11 – SA DESIGN HERITAGE INPUTS

4.4.3.3 Development Complexity

The study CERs calculate development and production costs for a first-in-class commercial airliner based on current aircraft design standards and technology. Inserting new technology may increase (or decrease) the complexity or difficulty in developing and/or producing particular aircraft components, and hence increase (or decrease) their associated costs relative to the cost computed by the CERs. To address this, the cost equations in the cost model were modified to include both a development complexity factor and a production complexity factor that is applied to the costs at the aircraft component level.

The development complexity factor is a number that identifies the change in difficulty or complexity for developing a new aircraft component with new technology relative to the value computed by the CERs. Its function is to capture additional (or reduced) costs of an aircraft component with new technology based on a comparison of its complexity relative to the reference aircraft design.

The development complexity factor also captures cost changes due to new or modified tooling requirements. A complexity factor of one indicates that for a given component there is either no change in technology, or that a change in technology does not significantly change the development process or production process. In these cases, the existing CER adequately models its costs. A complexity factor greater than one indicates a higher level of complexity and increases the development (or production) cost of the affected subsystem by the identified factor. Similarly, a complexity factor of less than one indicates a lower level of complexity decreasing calculated costs by that factor. It is common for development complexities to be greater than one, with potentially in rare circumstances to be as high as a 10x factor.

The same process of technical SME evaluation and TAG review used in deriving design heritage input assumptions was employed to determine the subsystem level development complexity factors. The SMEs assessed the impact, if any, of the technologies within each development scenario against each of the WBS elements (aircraft subsystems). The SMEs developed a weighting factor spreadsheet that identifies the technologies selected for each component and defines a development impact weighting factor and a production impact weighting for each technology on each component. These were aggregated to develop the overall Development Complexity factor for each aircraft subsystem.

Figure 12 provides an example based on the Single Aisle 2024 EIS analysis of development complexity for each of the deployment scenarios. Appendix J contains the development complexity assessment for each deployment scenario.

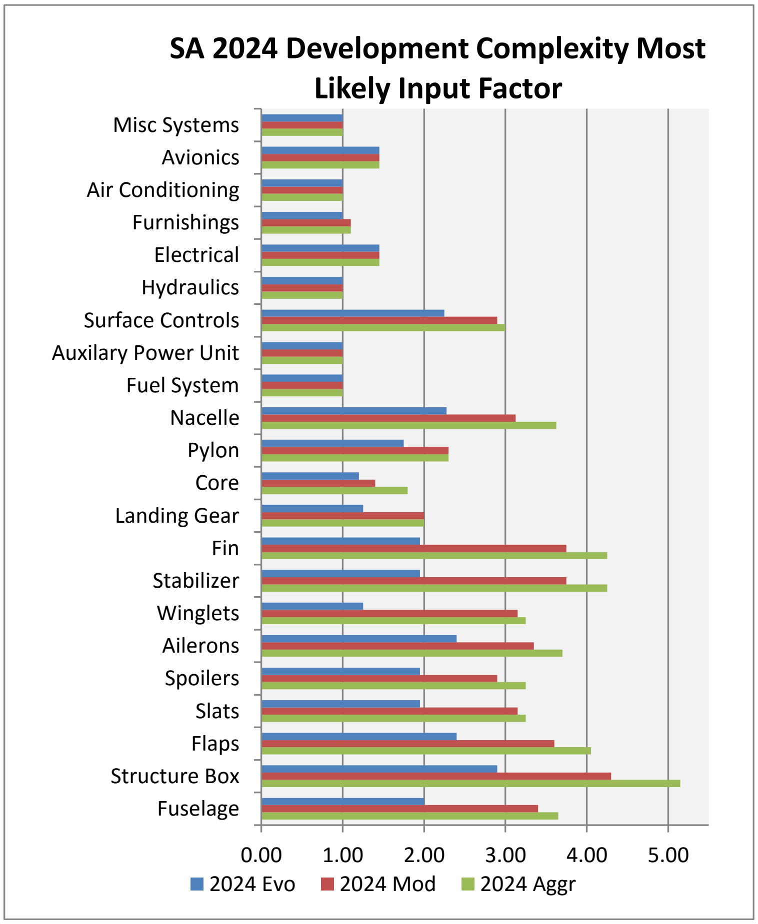


FIGURE 12 – SA DEVELOPMENT COMPLEXITY INPUTS

4.4.4 Production Cost

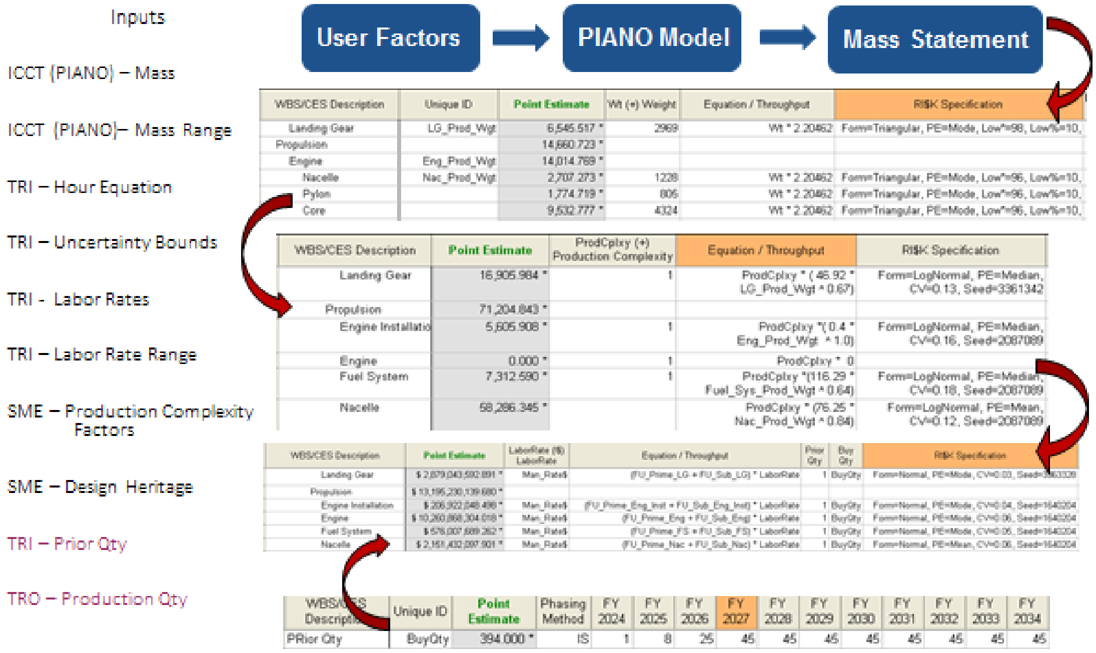
Production costs are all the efforts required in manufacturing and assembling an aircraft so that it can be sold to an operator. The following items are included in production costs:

- Parts and materials for all components required in aircraft
  - Airframe
  - Subsystems
  - Avionics
  - Furnishings
  - Propulsion
- Tooling infrastructure
- All labor required for manufacturing, assembly, and test of the aircraft
- All subcontractor costs
- Management and overhead costs associated with these activities

The total of the production costs for a specific quantity of aircraft is divided by the number of manufactured aircraft to obtain the average unit production cost (AUPC). The AUPC is added with the amortized system development cost to compute the Average Unit Cost (AUC). The amortized system development cost is calculated by taking the total of the nonrecurring costs and dividing it by the total number of aircraft produced. To compute the operator investment cost, a profit margin is applied to this AUC to compute the AUP. The AUP is the base average cost per aircraft for a manufacturer.

To calculate production costs a cost for a specified production unit must be generated. This value is then adjusted to the proper point on the learning curve so that the identified purchase quantities can be estimated. PTIRS CERs are used to calculate the theoretical first unit (TFU) of the production cost for a subsystem. In addition, the design heritage assumption used to separate into new and continuing (reused) production. Design heritage is the portion considered to be new production, starting at the top of the learning curve with prior quantities of zero. The remainder of TFU is assumed to be continuing production and continues down the learning curve based on the prior units built for the reference aircraft.

Similar to system development costs, the flow starts with the analysis by the SMEs to support generation of a mass statement and the indication of variables to adjust the resulting production costs. These variables cover design heritage, production complexity, and overall production quantity. Figure 13 provides a high-level overview of the flow of the production model.



WBS/CES Description	Unique ID	Point Estimate	Wt (+) Weight	Equation / Throughput	RI$K Specification
Landing Gear	LG_Prod_Wgt	6,545.517 *	2969	Wt * 2.20462	Form=Triangular, PE=Mode, Low*=98, Low%=10,
Propulsion		14,660.723 *			
Engine	Eng_Prod_Wgt	14,014.769 *			
Nacelle	Nac_Prod_Wgt	2,707.273 *	1228	Wt * 2.20462	Form=Triangular, PE=Mode, Low*=96, Low%=10,
Pylon		1,774.719 *	806	Wt * 2.20462	Form=Triangular, PE=Mode, Low*=96, Low%=10,
Core		9,532.777 *	4324	Wt * 2.20462	Form=Triangular, PE=Mode, Low*=96, Low%=10,

WBS/CES Description	Point Estimate	ProdCplxy (+) Production Complexity	Equation / Throughput	RI$K Specification
Landing Gear	16,905.984 *	1	ProdCplxy * (46.92 * LG_Prod_Wgt ^ 0.67)	Form=LogNormal, PE=Median, CV=0.13, Seed=3361342
Propulsion	71,204.843 *			
Engine Installatio	5,605.908 *	1	ProdCplxy *(0.4 * Eng_Prod_Wgt ^ 1.0)	Form=LogNormal, PE=Median, CV=0.16, Seed=2087089
Engine	0.000 *	1	ProdCplxy * 0	
Fuel System	7,312.590 *	1	ProdCplxy *(116.29 * Fuel_Sys_Prod_Wgt ^ 0.64)	Form=LogNormal, PE=Median, CV=0.18, Seed=2087089
Nacelle	58,286.345 *		ProdCplxy * (76.25 * Nac_Prod_Wgt ^ 0.84)	Form=LogNormal, PE=Mean, CV=0.12, Seed=2087089

WBS/CES Description	Point Estimate	LaborRate ($) LaborRate	Equation / Throughput	Prior Qty	Buy Qty	RI$K Specification
Landing Gear	$ 2,879,043,592.891 *	Man_Rate$	(FU_Prime_LG + FU_Sub_LG) * LaborRate	1	BuyQty	Form=Normal, PE=Mode, CV=0.03, Seed=[illegible]
Propulsion	$ 13,195,230,139.680 *					
Engine Installation	$ 206,922,048.498 *	Man_Rate$	(FU_Prime_Eng_Inst + FU_Sub_Eng_Inst) * LaborRate	1	BuyQty	Form=Normal, PE=Mode, CV=0.04, Seed=1640204
Engine	$ 10,260,868,304.018 *	Man_Rate$	(FU_Prime_Eng + FU_Sub_Eng) * LaborRate	1	BuyQty	Form=Normal, PE=Mode, CV=0.06, Seed=1640204
Fuel System	$ 576,007,689.262 *	Man_Rate$	(FU_Prime_FS + FU_Sub_FS) * LaborRate	1	BuyQty	Form=Normal, PE=Mode, CV=0.05, Seed=1640204
Nacelle	$ 2,151,432,097.931 *	Man_Rate$	(FU_Prime_Nac + FU_Sub_Nac) * LaborRate	1	BuyQty	Form=Normal, PE=Mean, CV=0.06, Seed=1640204

WBS/CES Description	Unique ID	Point Estimate	Phasing Method	FY 2024	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029	FY 2030	FY 2031	FY 2032	FY 2033	FY 2034
PRior Qty	BuyQty	394.000 *	IS	1	8	25	45	45	45	45	45	45	45	45

FIGURE 13 – MODEL FLOW FOR PRODUCTION COSTS

For production costs, there are three major items estimated by the PTIRS CERs to arrive at the total cost. They are:

1) Production labor hours
2) Material costs
3) Subcontractor costs

The overall lower-level cost WBS for each of the labor, material, and subcontractor costs are identified in the following cost WBS.

Production costs require additional parameters to allow proper calculation of the identified procurement units. The following subsections details some important parameters and concepts used in the model for calculating production costs.

4.4.4.1 Production Complexity

The Production complexity factor captured additional (or reduced) costs of an aircraft component with new technology based on a comparison of its production complexity relative to current standards, technology, and production capabilities.

The same process of technical SME evaluation and TAG review used in deriving design heritage and design complexity input assumptions was employed to determine the subsystem level production complexity factors. The SMEs assessed the impact, if any, of the technologies within each development scenario against each of the WBS elements. The SMEs developed a weighting factor spreadsheet that identifies the technologies selected for each component and defines a production impact weighting for each technology on each component. These were aggregated to develop the overall production complexity factor for each aircraft subsystem. Typically production complexity factors can range from 0.5 to 2.0, with most being in the 0.75 to 1.25 range. Figure 14 provides an example based on the Single Aisle 2024 EIS analysis of production complexity for each of the deployment scenarios. Appendix K contains the production complexity assessment for each deployment scenario.

4.4.4.2 Composite Material Fractions

The applied CERs are sensitive to both weight and the percentage of the composite material used in the component. Over the past 30 years or more, significant advances in structural efficiency have been made through the use of lightweight composite materials. Starting with various non-structural parts such as doors, access panels, radomes, and interior panels, manufacturers have progressed through ailerons, flaps, rudders, etc., to structural boxes in the tail section, to the point where as much as 50% of the structure weight in the Boeing 787 and the Airbus A350 is composite materials.

To set a baseline for the assessment of the impacts from technology on composites, two steps are necessary:

- Establish composite material weight fractions for all subsystems within each reference aircraft.
- Provide a confidence level and uncertainty bounds for each composite weight fraction (high & low).

This proved to be a challenge, as commercial aircraft manufacturers do not typically release this level of detailed information. The data typically released comes from the marketing departments as the manufacturers publicize their technological advances. Brochures and press releases quote a number for the percentage of an aircraft's structural weight generally, and some will include a picture of the aircraft with arrows indicating the parts of the aircraft where these materials are used. In rare cases, a manufacturer may differentiate between the types of composites used in different areas.

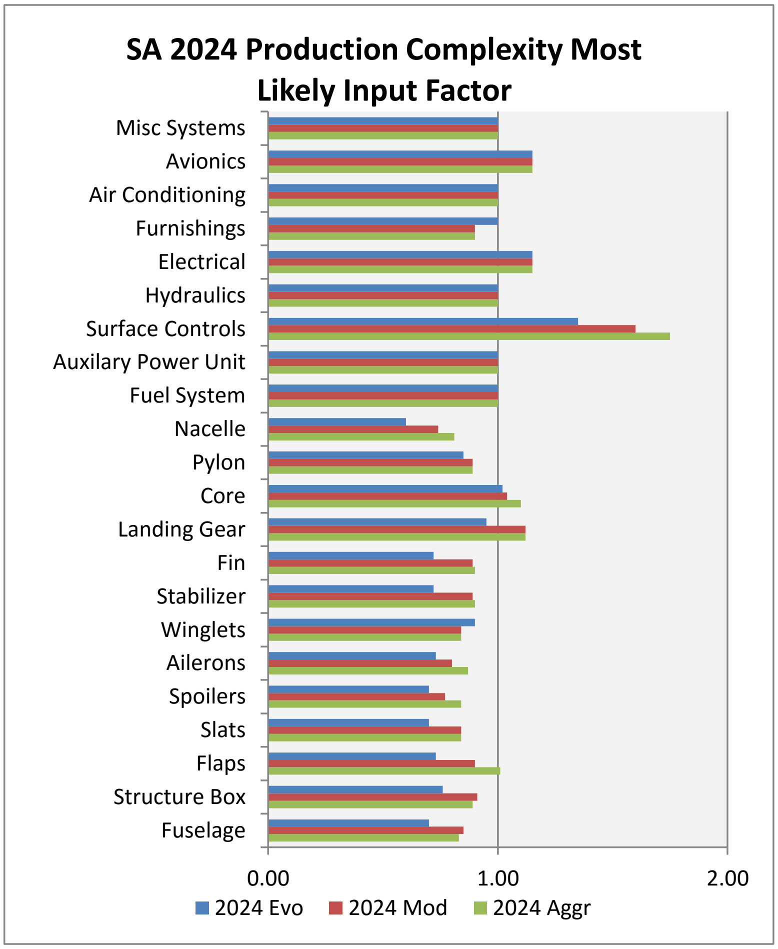


FIGURE 14 – EXAMPLE PRODUCTION COMPLEXITY FACTORS

The study SMEs combined this information with an understanding of aircraft structures in general, physical dimensions, weight distributions, material densities, and past studies of weight reductions achieved by introducing composite materials into older aircraft which have now made their way into text books and industry published papers. These latter sources are listed in the References.

The data sources identified, procedures employed, and the assumptions made to estimate baseline composite fractions are described in the following sections.

Table 44 lists values quoted by various sources for the percentage of aircraft structural weight contributed by composite materials. The entries are listed in order of increasing composite use . The highlighted rows in Table 44 are the two of the reference aircraft for this study.

TABLE 44 – AIRCRAFT COMPOSITE STRUCTURAL WEIGHTS

Aircraft	EIS Year	OEW, lbs	Est Struct Wt, lbs	Percent Composite
767-200	1982	176,650	94,061	4
737-300	1985	69,000	34,272	4
757-200	1983	127,520	66,515	5

Aircraft	EIS Year	OEW, lbs	Est Struct Wt, lbs	Percent Composite
A310-200	1983	176,312	93,870	5
A310-300	1987	183,300	97,823	5
MD-90-30	1994	88,000	44,673	5
MD-83	1986	79,700	40,121	5.8
MD-82	1982	78,000	39,190	6
MD-87	1987	73,300	36,620	6
A300-B4	1984	195,000	104,461	7.5
MD-11	1991	283,975	155,747	7.5
777-200	1995	320,796	178,478	9.2*
A340-300	1993	287,000	157,516	9.8
A330-300	1994	274,000	149,927	10.2
A340-600	2002	392,000	219,929	11.5
A321-200	1994	107,000	55,139	12.7
A320-200	1988	94,061	44,980	14.7
A380-800	2007	628,315	368,660	24.5
787-8	2011	259,500	141,497	50
A350-900	2014	255,100	138,947	53
*Composite fraction quotes for the 777 range from 9.2% to 12+%.				

Piano 5 provides the total structural weight of each of the reference aircraft, so the total composite weight for those aircraft can be calculated where the total composite fraction is known. Table 45 gives the estimated composite weights for the ERJ 190, A320-200, and 777-200ER and indicates where composites are employed on each aircraft. The left side of the table indicates the relevant PIANO 5 WBS.

TABLE 45 – COMPOSITE APPLICATIONS FOR REFERENCE AIRCRAFT

WBS	Aircraft	ERJ 190	A320-200	777-200ER
	EIS Year	2005	1988	1997
	Structure wt, lbs	30,878	44,980	178,478
	Composite %	Not Available	14.7	9.2
	Est. comp. wt, lbs		6,612	16,420
Wing				
flaps	Flaps	X	X	X
spoilers	spoilers, airbrakes	X	X	X
ailerons	Ailerons	X	X	X
winglets	Winglets			
struct box	Fairings	X	X	X
	wing TE panels	X	X	X
	MLG doors	X	X	X
	J-nose (wing inboard LE)			
	center wing box			
	wing ribs			
	outer wing box			

WBS	Aircraft	ERJ 190	A320-200	777-200ER
	EIS Year	2005	1988	1997
	Structure wt, lbs	30,878	44,980	178,478
	Composite %	Not Available	14.7	9.2
	Est. comp. wt, lbs		6,612	16,420
Fuselage				
	radome	X	X	X
	NLG doors	X	X	X
	floor beams	X	X	X
	rear pressure bulkhead			
	keel beam			
	cross beams			
	rear un-press. fuselage			
	upper fuselage skin			
	fuselage skin & frames			
	tail cone	X		
Horizontal Tail Plane				
	elevators	X	X	X
	HTP LE & TE panels		X	X
	HTP box (dry)		X	X
	HTP box (wet)			
Vertical Tail Plane				
	rudder	X	X	X
	fin (VTP box)		X	X
	VTP LE & TE panels	X	X	X
Undercarriage				
Propulsion				
nacelle	nacelles	X	X	X
pylon	pylons	X	X	X

Many of the composite parts such as radomes, fairings, landing gear doors, etc., are below the WBS levels for which weight information is available. This information can be used, and it requires a reasonable estimate of the values for the composite material fraction (CMF) for each individual item, as well as the total weight of the item. The weights of the items that do not contain composites is not necessary, although it would be helpful to know the total weight of those other sub-level items to help bound the unknown weights of the parts of interest. The CMF calculation is the estimation of the weight of the composite materials in each part below a given WBS level, adding them up, and dividing by the total weight at that parent level.

Estimating CMFs involves engineering judgment. There were some data on the weight savings achieved in various parts of the tail sections on the B727, B737, DC-10, and L-1011 aircraft; typical savings were quite consistent across the aircraft at about 26%. With the material densities of aluminum and graphite/epoxy laminate, a corresponding upper limit for the CMF of around 50% can be estimated for the corresponding structural parts. This calculation assumes that the volume of the part remains the same with the composites substituted for aluminum. If the composite replacement requires more material volume, the corresponding CMF would be higher, e.g., 10% extra composite volume would require a CMF of 64% to achieve a 26% weight reduction compared to aluminum.

Other calculations conducted included estimating the weights of some simple composite parts. Aircraft Recovery Manuals and Airport Maintenance Planning documents provided reasonable estimates of the dimensions of radomes for each of the reference aircraft were determined, and weights were calculated assuming a thickness of 0.20 inches for the fiberglass laminate. Radomes were assumed to have a very high composite fraction of 0.90, allowing only for metal reinforcements at attachment points.

Similar calculations were made for landing gear doors. Door areas were estimated from the number of tires on each gear assembly and the tire sizes which would be required to support the weight of each aircraft. Photographs of the landing gear assemblies and doors, and knowledge of how each assembly retracts helped determine the outline of the doors on each aircraft. It was assumed an average thickness of 0.10 inch for the graphite-epoxy door panels to calculate the composite portion of the door weights. A relatively high CMF of 0.80 was assumed for doors with remainder of the total weight being steel for hinges, actuator lugs, and latches.

With these and other applications of engineering judgment, the CMFs were determined, comparing their differences and grouping them by their similarities with respect to the need for metal parts either for structural reasons, or to provide for attachment and/or movement by actuation. Larger, rigid structural elements lend themselves to integrated composite forms with less metal required for attachment to other structural elements. Table 46 provides the assignment of CMF by parts and the description associated with the parts.

TABLE 46 – ASSIGNMENT OF COMPOSITE MATERIAL FRACTIONS (CMF) FOR BASELINE AIRCRAFT

CMF	Parts	Descriptions
0.05	Pylons	Very high load-bearing structure; composite use assumed for fairing only
0.50	Nacelles	Uncertain; place-holder value
0.50	Ailerons, elevators, flaps, rudder, slats, spoilers, airbrakes	Movable surface with high span-to-chord ratio; no. of hinges & actuators increases with length
0.60	Winglets	Stubby, wing-type structure; bending loads at attach point likely to require extra metal
0.75	Cross-beams, full skin & frames, fuselage upper skin, keel beam, rear un-pressurized fuselage, wing center box, wing outer box, wing ribs	Primary load bearing structure
0.80	HTP structure box, LG doors, VTP structure box	Integrated composite structure with mating hardware, hinges, and actuators
0.85	Fairings, floor beams, HTP LE & TE panels, J-nose, rear pressure bulkhead, tail cone, VTP LE & TE panels, wing TE panels	Integrated composite structure with mating hardware
0.90	Radomes	Non-structural cover; electromagnetically transparent; minimal attachment hardware

The parts where the weights were estimated have been divided by that parent-level known weight to estimate a weight fraction which can be used to scale results for future aircraft. Weight fractions for the remaining parts have been chosen to produce part weights which are reasonable in comparison with other similar parts.

Then the composite weights are calculated, starting at the lowest levels, and rolled up to the next level of WBS, calculating the CMFs at each higher level. The resulting CMF at the structure level is then compared with the expected value for the aircraft. If the mismatch is significant, the more uncertain, low-level CMFs are adjusted until a match is achieved. CMFs for the heaviest elements will require the smallest adjustments to close any discrepancies.

A CMF was estimated at the component level for each reference aircraft based on analysis of available data. This established the composite material fraction for each of the reference aircraft. Appendix L provides the detailed calculations conducted to determine the reference aircraft composite material fractions. Table 47 displays the resulting values for each major subsystem by reference aircraft.

TABLE 47 – COMPOSITE MATERIAL FRACTIONS

Composite Material Fraction	RJ: E190	SA: A320-200	STA: 777-200ER
Fuselage	6%	6%	6%
Wing - Structure Box	9%	10%	8%
Wing – Flaps	50%	50%	50%
Wing – Slats	0%	50%	50%
Wing – Spoilers	50%	50%	50%
Wing – Ailerons	50%	50%	50%
Wing – Winglets	0%	60%	0%
Empennage – Stabilizer	72%	72%	72%
Empennage – Fin	72%	72%	72%
Landing Gear	0%	0%	0%
Engine – Core	20%	20%	20%
Engine – Pylon	5%	5%	5%
Engine – Nacelle	50%	50%	50%
TOTAL COMPOSITE FRACTION	**11.6%**	**14.1%**	**12.1%**

4.4.4.3 Learning Curve

Under the concept of learning curve, the cost of manufacturing items decreases as the manufacturer gains experience producing the product. The rate at which the cost decreases as a function of units built defines the learning curve [63]. This means that for a new clean sheet aircraft the first 50 aircraft will be significantly more expensive to produce than the next 50. Figure 15 shows a sample notional learning curve.

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[63] International Cost Estimating and Analysis Association (ICEAA) Cost Estimating Book of Knowledge (CEBok) CEB 06 - Learning Curve Analysis

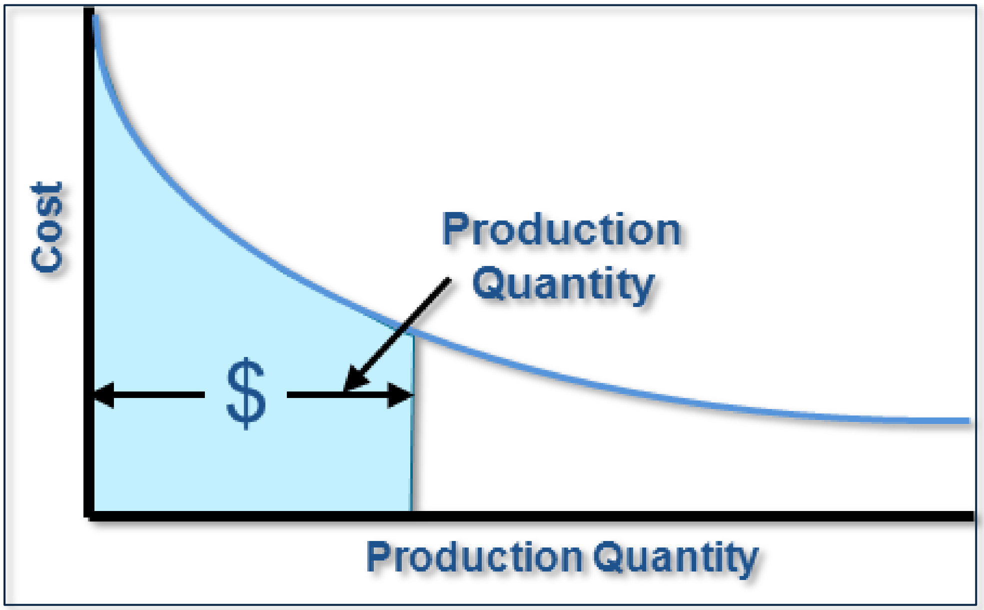

FIGURE 15 – NOTIONAL LEARNING CURVE

A derivative aircraft will also experience decreased cost as a function of units produced, but it will not be as significant as the clean sheet aircraft because some of the individual aircraft components are unchanged and are well down the learning curve. For example, the major design changes for the A320neo are the new engine and the sharklets. The remainder of the aircraft, for the purpose of this example, remains unchanged. Since over 1,700 A320-200 aircraft have been manufactured and delivered (through 2013), an unchanged item like the stabilizer will be much further down the learning curve, and will have a significantly lower production cost than if it was a newly designed component. For the engine and sharklets, the costs will be higher, as the early manufactured units will be near the top of the curve.

Specifying exact learning curves for systems required detailed analysis of the particular system in question. This requires extensive insight into the actual production environment and having actual cost data for the various subsystems in question. As this data was not available for this study, it was determined that for a relative comparison applying a consistent assumption for learning curves would allow for reasonable and comparable costs to be generated. For this study, the learning curves used for all production costs were based on the parameters used by NASA PTIRS model. Table 48 details the learning curves used for each subsystem regardless of the aircraft class, the EIS year, or the technologies infused by the deployment scenarios. [64]

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[64] Learning curve example: at 80% learning curve, every time the quantity is doubled, the cost is 80% of the value, e.g., 1st unit cost is $100, the 2nd unit cost is $80, the 4th unit cost is $64, and the 8th unit cost is $51.

TABLE 48 – LEARNING CURVE SLOPES

Parameter	Value
Composite Structures Learning Curve	80
Conventional Structures Learning Curve	80
Propulsion/Fixed Equipment Learning Curve	90
Avionics Learning Curve	85
Integration/Assembly Learning Curve	80

4.4.4.4 Prior Quantities

Prior quantities are required for the model to determine where on the learning curve slope a given subsystem should begin. Actual buy quantities of the reference aircraft were used for aircraft prior to 2014; while anything from 2014 and beyond used the results of the market forecast and market capture analysis to determine the appropriate prior quantities.

A core aspect of the production cost model is to estimate cost of new versus re-used components. This is achieved by setting prior quantities for all new production components to zero at the start of the production of the new vehicle and continuing down the learning curve for the reused components.

4.4.4.5 Impact of Design Heritage on Production Estimation

The design heritage factor is also used for supporting the estimation of production cost. If in production, there are new design and old design components—costs were calculated by separating cost estimates for the new design from cost estimates for old design components. The design heritage factor is used to determine how the learning curve is applied for each cost element and in determining how the costs for a subsystem are estimated along two separate cost curves.[65]

To accommodate a design heritage that is between zero and one, each component in the model is broken out into new and reuse sections. The new section takes the percentage new and allocates that percentage of the design and production efforts starting at the top of the learning. The reuse section takes the percentage that is reused and allocates that percentage of the design and production efforts further down the learning curve, based on the number of prior aircraft. The sum of these two separate curves (new and reuse of old design) is combined to arrive at the total production cost. An example is shown in Figure 16.

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[65] Separating costs for production items along two curves to capture the benefits of prior manufacture and to estimate the costs of new systems is an internal Tecolote Research best practice that has been used since the late 1980s for a wide range of large systems, ranging from aircraft to spacecraft to ship construction. This practice has been reviewed and accepted by several government agencies (US Air Force, US Marine Corp, US Navy, US Army, and NASA) as a solid approach to estimate manufacturing costs for derivative designs.

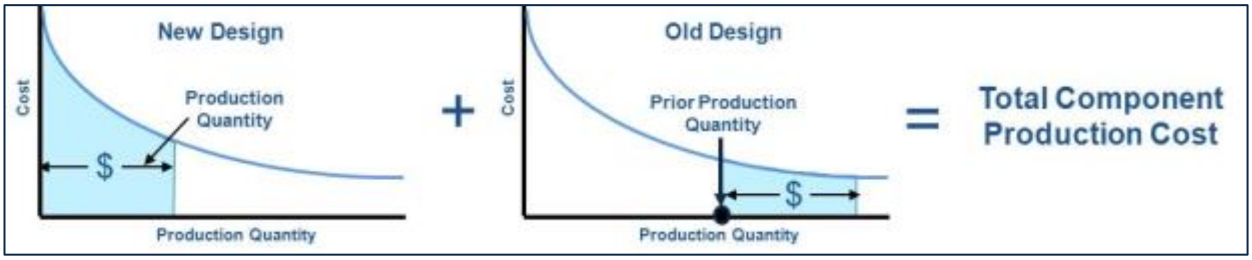

FIGURE 16 – DESIGN HERITAGE FACTOR ILLUSTRATION

4.4.4.6 *Aircraft Production Mass (Weight) Adjustment Factor*

Most parametric cost models strive to find an input parameter as a proxy for size/complexity/etc. that correlates to the overall cost of the system. For major hardware items it has been seen that weight (mass) consistently provides a good proxy. Historically performance has been driven by increasing the size and complexity of a system, which equates to a higher mass and a higher performance value — typically weight scales with increased performance.

Typically, when comparative analysis is assessed between two different states of the world, the primary driver is an increase in performance. For this study, the overall construct is to hold overall payload/range capabilities constant across the scenarios. Consideration and care must be taken when estimating production costs for future systems when performance is held constant and the analyst assumes a continued production component for the modeling. This commonly occurs when technology is infused to allow the designed system to achieve the same performance characteristics (in this case — distance flown and # of passengers) but the overall mass decreases.

In the situation of constant performance, there is potential for the cost results to be skewed if an adjustment factor is not applied. In technology insertion situations, weight is reduced. This causes challenges in production estimation when high prior quantities are involved and from an estimating perspective only a percentage of the improved system is reset to start at the beginning of the learning curve. In this case, since all technology scenarios cause a decrease in mass, without applying a cost adjustment to account for this displacement the overall production costs could be underestimated. This is due to the production cost equations being mainly driven by weight, e.g., cost per pound. Structural CERs are highly sensitive to weight and have a large variation in design heritage.

Tecolote Research developed an adjustment factor, based on prior work with the Air Force Research Laboratory (AFRL) for technology insertion analyses, to counter the effect for continued production, resulting in a shift in the learning curve slope. This is done by adjusting the mass for the reused portion of production costs to be based on the equivalent weight "as if no technology was implemented." Figure 17 shows how this mass adjustment factor adjusts the resulting production costs so that the results are not underestimated.

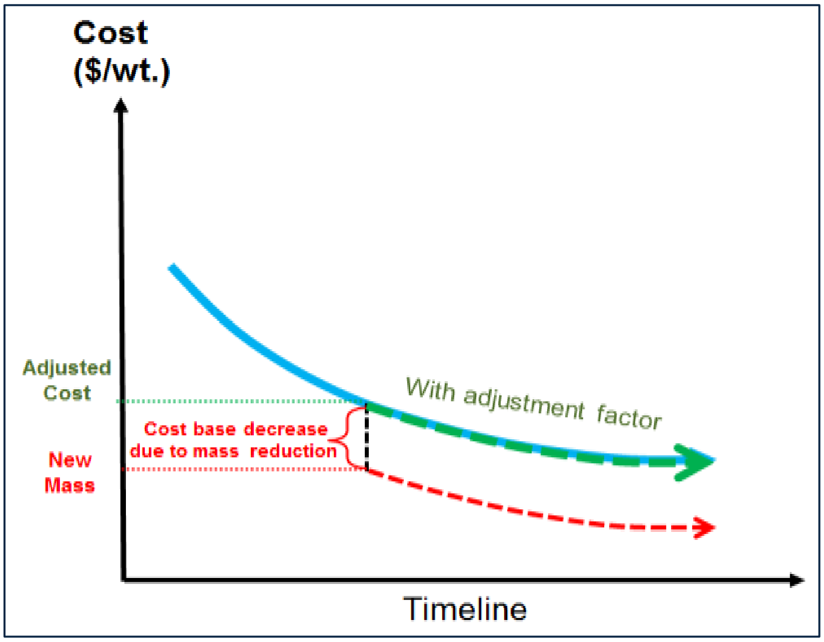

FIGURE 17 – MASS ADJUSTMENT FACTOR ILLUSTRATION

4.4.5 Operator Expense (Maintenance and Fuel Costs)

The second component of total operator cost consists of fuel costs and maintenance costs. These costs are estimated as the annual cost per aircraft for maintenance and fuel and summed over a seven-year operations period. Ongoing operational costs such as flight crew, insurance, software maintenance, passenger services, and landing fees are not included in the model. The underlying methodologies for maintenance and fuel are detailed in the following subsections. Table 49 details the primary drivers to the equations used to estimate operator expense, the *italicized* items are those that are specific to each deployment scenario.

TABLE 49 – MAINTENANCE AND FUEL MODEL INPUTS

Maintenance	Fuel
Year of first purchase	Number of operational years
Number of operational years	*Fuel burn reduction*
Percent of accumulated maintenance cost during operational period	Fuel price
Yearly allocation (%) of accumulated maintenance cost	Fuel price average annual increase
Flight rate	Baseline Fuel consumption
Yearly number of operational aircraft	Yearly flight hours based on age
Average flight duration	Survivability based on age
Engine thrust	Discount %
Manufacture empty weight (MEW)	
Maintenance intervals (D-check, TBO)	
Maintenance complexity (airframe, engine)	
Number of engines	
Discount %	

4.4.5.1 Maintenance Costs

This study estimates annual costs for engine and airframe maintenance based on CERs derived from the Department of Transportation's Bureau of Transportation Statistics Form 41 data[66] covering airline operations from 1991 to 2012. These CERs are also used in the PTIRS model and review of the database allowed identification of the CER drivers, which are listed below.

- Flight Duration (block-to-block time of typical flight). Determined from 2010 BTS data.
- Flight Rate per Year. Determined through the average utilization by hour per year, divided by typical flight duration.
- D-Check, or heavy maintenance visit (HMV), interval. Determined through PTIRS analysis.[67] D-check occurs approximately every five years. It is a check that generally takes the entire airplane apart for inspection and overhaul; if required, the paint may need to be completely removed for further inspection on the fuselage metal skin. D-check can demand up to 50,000 man-hours and it can generally take up to two months to complete, depending on the aircraft and the number of technicians involved. It may require the most space of all maintenance checks, and as such must be performed at a suitable maintenance base.
- Engine Time Between Overhaul. Table 50 provides the data sourced from publicly available information that was used during PTIRS analysis to determine engine time between overhaul.

TABLE 50 – ENGINE TIME (FLIGHT HOURS) BETWEEN OVERHAUL[68]
(DETERMINED FROM AIRCRAFT DATA-SPECIFIC WEBSITE)

Aircraft	Engine TBO, Flight Hours
A330-300	17,500
A300B/C/F-100/200	7,000
A310-300	17,500
A330-200	17,500
737-300	16,000
737-400	16,000
737-500	16,000
737-700	23,000
737-800	23,000
737-900	23,000
747-100	10,000
747-200/300	10,000
747-400	14,000
767-200	17,500
767-300ER	17,500
676-400ER	17,500
777-200ER	15,000
MD-81	9,000
DC-9-10	9,000

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[66] http://www.transtats.bts.gov

[67] Transport Aircraft CERs Probabilistic Technology Investment Ranking System (PTIRS), Tecolote Research Inc., Dec 2012

[68] http://www.airliners.net/aircraft-data/

Aircraft	Engine TBO, Flight Hours
DC-9-30	9,000
DC-9-50	9,000
A318	16,000
A319	16,000
A320-100/200	16,000
747-400F	17,500
747SP	17,500
A300-600/R/CF/RCF	17,500
A310-200C/F	12,000

The costs calculated by the maintenance CERs reflect the average annual cost for maintenance by aircraft. To reflect the increasing cost of maintenance as the aircraft ages, an algorithm from a RAND study[69] was used. The RAND study provided a maintenance cost profile over the given years of aircraft usage where the maintenance costs start out low and it increased as the aircraft aged over time. The RAND algorithm used the premise that, given the total number of aircraft usage years, the percentage increases were spread throughout the given years. This percent increases as the number of operational years increases and goes to a value of 100% at the end of an aircraft's projected operational life (27 years). This portion of maintenance costs are then phased over the operations period (seven years for this study) based on an increasing percentage.

The percentage increase profile was derived by applying the RAND study results. The cumulative value in Base Year FY13 dollars are the same for flat average and Rand profile. In terms of inflated dollars, the Rand profile is greater due to inflation than the flat average. Figure 18 provides the increasing cost profile by year. The Y-axis is the percent of cost as compared to the straight-line method. The chart demonstrates that the estimated initial maintenance costs increase by year and after nine years costs are higher than assuming a flat annual maintenance cost per year.

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[69] Massoud Bazargan and Joseph Hartman, "Aircraft replacement strategy: Model and analysis", Journal of Air Transport Management, 2012, vol. 25, issue C, pages 26-29

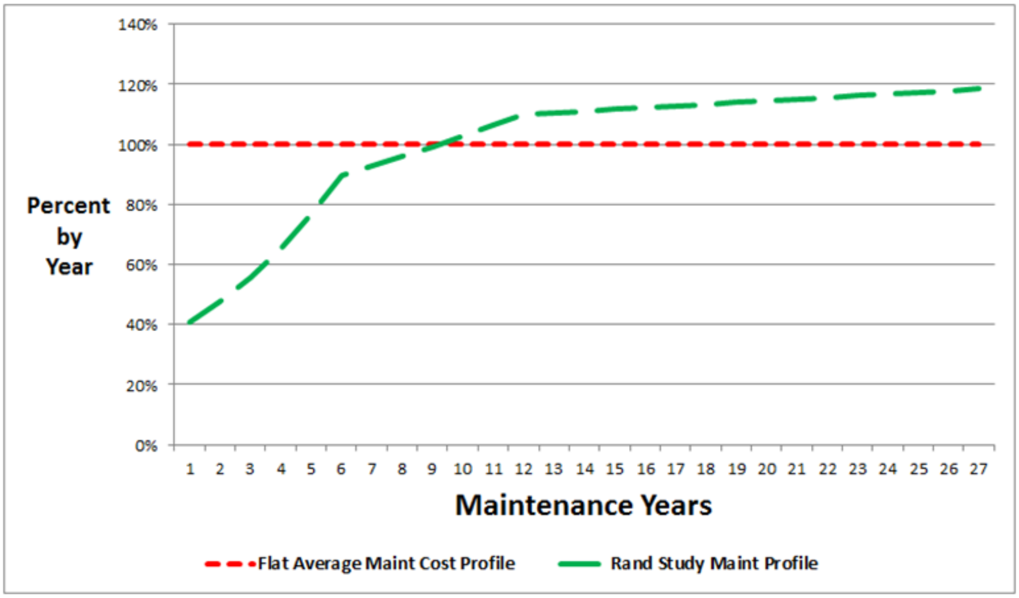

FIGURE 18 – MAINTENANCE COST ANNUAL RAMP-UP EXAMPLE

In addition to a rephrasing of the costs over the period of operational life, two additional adjustments are applied to the maintenance CERs. The first is to adjust the maintenance interval (period between maintenance) to account for the effect of technology infusion on the aircraft. The majority of structural technologies assessed in the study increase the maintenance interval and therefore reduce the O&M cost for the lifetime of the aircraft. The other adjustment is on maintenance complexity. In almost all cases, the technology infusion increases the O&M complexity and therefore increases the aircraft O&M cost. These two drivers act in different directions and the combined effect is seen in the modeling results. These O&M complexity and interval values were developed jointly with SMEs and the TAG and were specified for the airframe and engine respectively. See Appendix F for maintenance assessment of technology candidates.

Maintenance Complexity

The model CERs estimated the annual cost of aircraft and engine maintenance. Similar to development and production costs, the maintenance costs within the cost model can be scaled based on the relative complexity of the maintenance activities associated for the deployment scenarios relative to the reference cost. Maintenance costs for this study were generated at the airframe and engine level. To account for the potential impacts technology has on these areas, Maintenance Complexity factors were developed airframe and engines for each deployment scenario. The assessment of maintenance impacts based on each technology DS was determined by technical SMEs and reviewed by the TAG. In all cases, the technology infused caused an increase in maintenance complexity. For example, in RJ for 2024 Evo, 1.034 indicated 3.4% increase in the timeline between scheduled maintenance, and therefore, it reduced the cost.

For engine maintenance complexity factors, the SME and TAG came to a consensus that no adjustments were required, on the assumption that future engines will be optimized for higher fuel efficiency with no net increase in maintenance complexity. Table 51 contains the maintenance complexity factors used in the study for airframe and engine maintenance.

TABLE 51 – AIRFRAME MAINTENANCE COMPLEXITY FACTORS

Airframe Maintenance Complexity Factor	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
RJ	1.034	1.089	1.092	1.092	1.089	1.089
SA	1.021	1.094	1.097	1.085	1.096	1.100
STA	1.034	1.083	1.098	1.085	1.096	1.100

Maintenance Interval

An additional input parameter to calculating maintenance costs is the maintenance interval. The maintenance interval is specified in terms of the number of hours between major maintenance cycles. for this analysis, the maintenance intervals for the reference case are identified and a scaling factor was developed by the technical SMEs to adjust the time between maintenance activities. The maintenance interval factor works differently than the maintenance complexity factor. Although both are factors, where a value greater than 1.0 increases the value, the effect on costs are different. Whereas an increase in the maintenance complexity factor increases the maintenance cost, an increase in the maintenance interval lengthens the interval time period and thereby reduces the estimated annual costs for engine and airframe maintenance. In almost all technology scenarios, the infused technologies cause an increase to the airframe maintenance interval. Table 52 through Table 55 contain the Maintenance Interval factors used in the study for airframe and engine maintenance.

TABLE 52 – AIRFRAME (D-CHECK) MAINTENANCE INTERVAL ADJUSTMENT FACTORS

Airframe Maintenance Interval Factor	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
RJ	1.46	1.55	1.53	1.55	1.53	1.56
SA	1.46	1.72	1.70	1.72	1.70	1.68
STA	1.46	1.70	1.70	1.70	1.70	1.68

TABLE 53 – ADJUSTED AIRFRAME (D-CHECK) MAINTENANCE INTERVALS

Airframe Maintenance D-Check Interval (Months)	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
RJ	140	149	147	149	147	150
SA	105	124	122	124	122	121
STA	140	163	163	163	163	162

TABLE 54 – ENGINE (TIME BETWEEN OVERHAUL) MAINTENANCE INTERVAL ADJUSTMENT FACTORS

Engine Maintenance Interval Factor	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
RJ	1.00	1.00	1.00	1.00	1.00	0.95
SA	1.00	1.00	1.00	1.00	1.00	0.95
STA	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 55 – ADJUSTED ENGINE (TIME BETWEEN OVERHAUL) MAINTENANCE INTERVALS

Engine Maintenance Interval (Flight Hours Between Overhaul)	2024-Evo	2024-Mod	2024-Agg	2034-Evo	2034-Mod	2034-Agg
RJ	15,000	15,000	15,000	15,000	15,000	14,256
SA	16,000	16,000	16,000	16,000	16,000	15,192
STA	15,000	15,000	15,000	15,000	15,000	15,000

Maintenance Mass Adjustment Factor

Similar to the production cost equations, the maintenance cost equations have mass as a driving parameter. In this study, all technology scenarios cause a decrease in mass. Without a maintenance mass factor adjustment, the maintenance costs will be underestimated since maintenance cost equations are driven by weight, e.g., cost per pound, and they are sensitive to weight.

The mass adjustment factor calibrates the resulting maintenance costs so that the results are not under-estimated. In this case, the adjustment factor was applied to the aircraft MTOW and engine mass which moved the curve back up to the reference case—preventing the maintenance costs from decreasing due to weight reduction driven by technology insertion.

While the principle of adjusting for weight reduction is the same for both production mass adjustment factor and maintenance mass adjustment factor, the application of the principle is slightly different. For the production mass adjustment factor, the factor was applied at the subsystem levels given the availability of a detailed WBS. For maintenance, the factor was applied at the top level since there was no subsystem, or component level breakout.

4.4.5.2 Fuel

Reference fuel costs are calculated based on the expected fuel consumption, the expected flight rate, and the anticipated survivability over the operational years to determine the annual fuel cost per aircraft. Like maintenance costs, these costs are calculated annually over the number of operational years specified for the analysis (seven for the baseline case) and added to arrive at the total fuel cost for the deployment scenario.

Fuel prices were based on fuel prices projections from the Annual Energy Outlook 2015 Report[70] published by the US Energy Information Administration. Given the volatile nature of fuel costs and the historical real cost growth, fuel was estimated at a base price in 2013 and escalated by a growth rate each year to account. The initial fuel price used for the analysis was $2.94 US dollars per gallon.[71] The real fuel price increase was based on the forecast projection and is 0.97% per year.[72]

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[70] http://www.eia.gov/forecasts/aeo/

[71] http://www.eia.gov/petroleum/

[72] http://www.bls.gov/news.release/ximpim.nr0.htm

Given the volatility of fuel prices, this parameter and the ensuing growth rate were modeled as uncertain variables with a range of potential values. For the final results, it was determined to keep fuel costs a deterministic value and to not model them stochastically, while treating the fuel price increase as a probabilistic variable. Table 56 details the assumptions used for fuel cost calculations. Sensitivity analysis was conducted for all aircraft configurations and EIS years based on varying the base annual price increase by +/- 2%, these sensitivity results are discussed in Section 6.3.

TABLE 56 – FUEL PRICE ASSUMPTIONS

Parameter	Value
Fuel price per gallon (US 2013 dollars – 2013$)	$2.94
Real annual price increase (percent per year)	0.97%
Real annual price increase (percent per year) – Low	-1.23%
Real annual price increase (percent per year) - High	3.03%

Estimated fuel savings were estimated using several input parameters for all three aircraft types. The input parameters for fuel are:

- Payload-range matrix and average mission fuel burn by scenario: Generated from BTS data and modeled in Piano over a matrix of missions within the payload-range enveloped for each aircraft. See section 3.5.1.5 for additional details
- Baseline aircraft hourly fuel consumption: calculated from mission fuel burn divided by mission time for each mission in the payload-range matrix, normalized to the mission frequency.
- Survival curve: Addresses the probability of survival of an aircraft as a function of its age. Generated using survivability data[73] of all aircraft delivered between 1950 to 2010 by category (narrow body, wide body).
- Utilization curve: Captures number of hours of aircraft utilization by age by type. Derived from utilization data of all aircraft delivered between 1960s to 2010.[74]
- Fuel price increase: Obtained from US Energy Information Administration's Annual Energy Outlook 2014.[75]

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[73] Rutherford, D., Kharina, A., & Singh, N. (2012, October). Refinement of Projected Aviation Energy Use and Related Characteristics. Consultant report to Argonne National Laboratory

[74] Ibid.

[75] http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf

Figure 19 depicts fuel cost trends for aircraft sold over 10 years and operated for seven years.

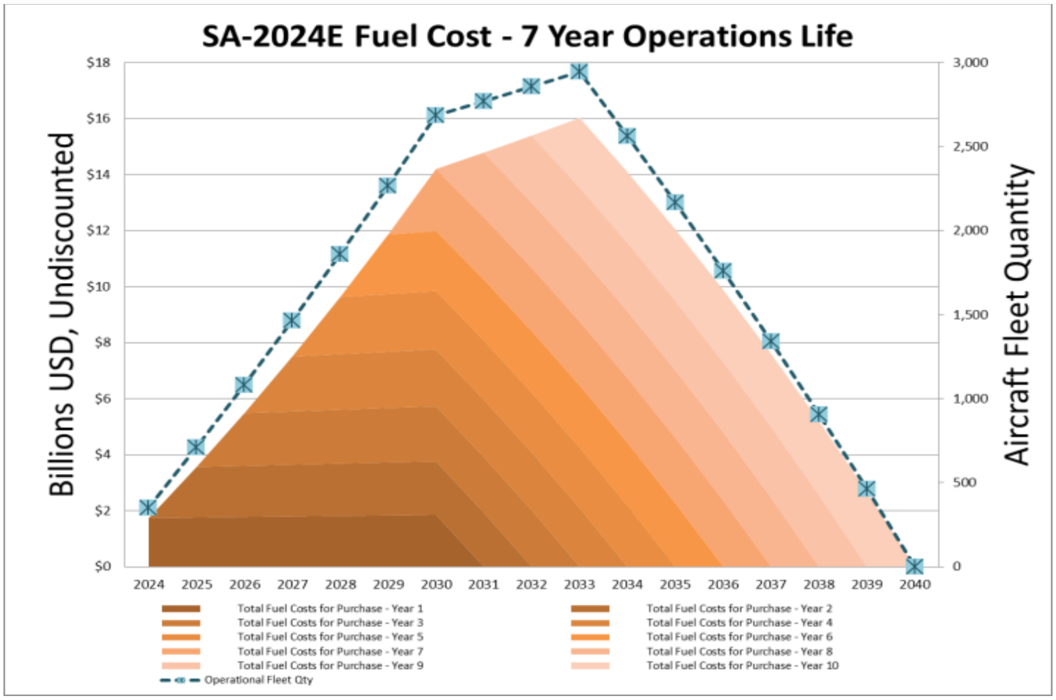

FIGURE 19 – FUEL COST PHASING EXAMPLE

4.4.6 Residual Value (Operator Income from Resale)

The residual cost is the estimated resale value that an operator may obtain upon selling the aircraft after its first owner lifetime based on accumulated depreciation. The declining balance depreciation method was used and it is a technique of accelerated depreciation in which the amount of depreciation that is charged to an asset declines over time—more depreciation is charged during the beginning of the life time and less is charged during the end.

A key parameter in this study was the depreciation technique and depreciation value. The RAND study[76] previously referenced for developing maintenance cost curves used a declining balance method and a 6% depreciation rate.

Additional analysis was obtained from Ascend (November 2012 DVB) and used to calculate the depreciation by aircraft. The rates ranges from 4% to 7% with an average depreciation rate of 6%. It was determined that the RAND study value of 6% and the declining balance methodology were appropriate for use in this analysis. Table 57 provides the assumptions used in the study to calculate residual value.

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[76] Massoud Bazargan and Joseph Hartman, "Aircraft replacement strategy: Model and analysis", Journal of Air Transport Management, 2012, vol. 25, issue C, pages 26-29

TABLE 57 – FIRST OPERATOR YEARS AND DEPRECIATION ASSUMPTIONS

Parameter	Value
Number of years for first Operator (Operator years)	17
Depreciation method	Declining Balance
Annual rate of depreciation	6%

4.5 Risk and Uncertainty Analysis

This analysis covers a time-period up to 30 years in the future. In addition, the analysis is based on the assessment of technical experts on the potential impacts of technologies as well as the use of predictive models to estimate aircraft performance parameters and resulting costs. Although the underlying cost equation methods have been calibrated against publicly available prices and are believed to provide reasonable results, the results have inherent uncertainty as introduced in any attempt to forecast future costs.

Given this uncertainty, a simulation modeling framework was developed to allow calculation of probabilistic results instead of just a single deterministic value. By quantifying the uncertainty in the underlying models and the input parameters, the resulting outputs could be compared to each other through the selection of a specific probability level or the overall expected value, the mean. For the analysis, all results shown and used for the analysis were based on the mean values.

The method for obtaining the probabilistic results was through the use of a Monte-Carlo based simulation model. Monte-Carlo analysis involves multiple running simulations of the model based on a range of possible outcomes for each input and calculation within the model. Random sampling was performed by specifying a distribution range for each uncertain parameter to allow the generation of a range of outcomes. These outcomes could then be evaluated to establish a probability level (confidence measure) for each outcome. In this study, distributions were specified for all input parameters, as well as distributions for the underlying errors in the estimating equations. The distributions were randomly sampled and the underlying equations calculated to obtain the result.

This was done over numerous iterations so that statistics on the outputs could be collected and analyzed. As this was a random process, there will be different results calculated for the mean and the various statistical percentiles based on the number of iterations and the random seeds selected. Given that everything in the model stays consistent, studies[77] [78] [79] [80] have shown that it is possible to see up to

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[77] Joint Agency Cost Schedule Risk and Uncertainty Handbook (JA CSRUH) published by the US Naval Center for Cost Analysis (re: https://www.ncca.navy.mil/tools/csruh/index.cfm)

[78] Morgan, M. Granger., Max Henrion, and Mitchell Small. 1990. Uncertainty, A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. New York: Cambridge University Press.

[79] Garvey, Paul R. 2000. *Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective*, Chapman-Hall/CRC Press, Taylor & Francis Group (UK), Boca Raton, London, New York; ISBN: 0824789660

[80] Smith, Alfred. 2008. "How Many Iterations Are Enough?" Paper presented at SCEA/ISPA Joint Conference & Training Workshop, Industry Hills, CA, June 24-27

a 0.5% delta in probability value results just in the change of the random seed. Additionally, various statistics will have different values between iteration runs with the impact of increasing the number of samples (iterations) decreasing the error. In this study it was found that the error for the mean results between running 500 iterations and 5,000 iterations was less than 0.5% and the error for the standard deviation was less than 1.0%. For all iterations above 500 iterations the error stayed under the 0.5% and 1.0% mark. This indicated a minimum level of 500 iterations for the stable results at the mean. The sampling technique used within the study is Latin-Hypercube sampling[81] and 500 simulations were ran which produced stable mean results. Figure 20 displays the convergence for the mean, the 50% confidence level, 90% confidence level, and standard deviation for the discounted average TOC per aircraft for the Single Aisle 2024 Aggressive and Single Aisle 2034 Aggressive deployment scenarios. The data plotted displays the percent difference from different iteration levels to the result at 10,000 iterations. The SA 2024 Aggressive and SA 2034 Aggressive cases were shown as the aggressive scenarios have the most variability. The convergence results for Regional Jet and Small Twin Aisle behave similarly to the Single Aisle results.

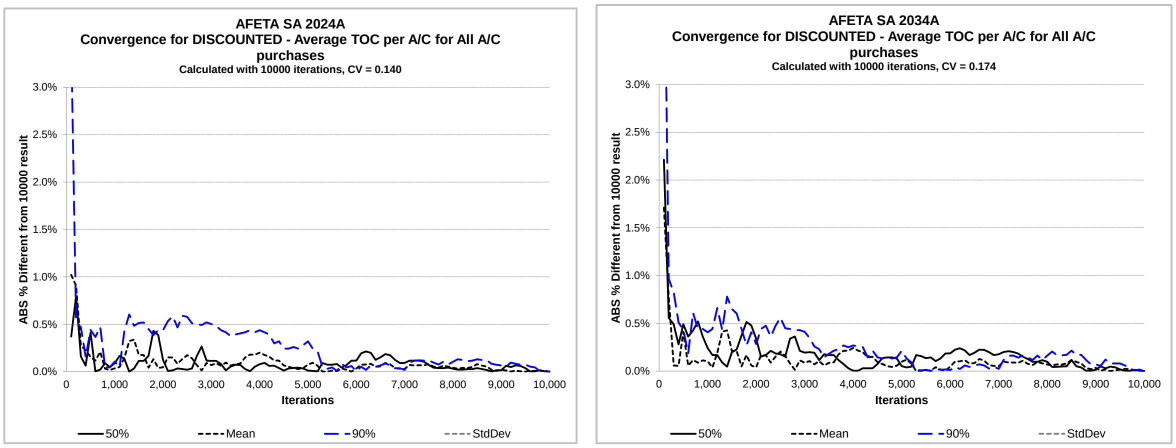

Figure 20 – SA 2024A and SA 2034 Convergence Results for 10,000 Iterations

In the cost model, uncertainty distributions were specified for all equations in the model. The uncertainty distributions used for the underlying CERs come from the fit and predictive statistics of the developed equations. These uncertainties varied from as low as a +/- 5% error to in some rare cases as high as +/- 30% error. Uncertainty distributions were also specified for all mass parameters used in the model. Because the underlying models for Piano are engineering equations, due to actual implementation by a manufacturer the forecasted weight range for a closed system could vary as much as 3% for the subsystems. For engines a distribution range of +/- 5% was used. All adjustment factors were also specified with an uncertainty distribution. These were provided by the SMEs and are detailed in each of the appendices that discuss the design heritage, composite material, design complexity, production complexity, and maintenance complexity variables. The last parameter programmed to have

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[81] http://users.ece.cmu.edu/~xinli/classes/cmu_18660/Lec25.pdf

uncertainty on every model run was the annual real increase in fuel prices. This range was based on 2015 data from the Energy Information Administration (EIA).[82] The uncertainty distributions were established and used for the cost estimating input parameters (i.e., design heritage, design complexity, production complexity, maintenance complexity, and maintenance interval).

Lastly, there were other input parameters dealing with market conditions such as the base fuel price and market capture. Within the model these variables could be treated as uncertain parameters but the main results were run with these parameters as deterministic values. For fuel, the high and low bounds identified for use in the model were derived from AEO's average annual Brent spot crude oil prices forecast scenarios.[83] Table 58 provides a summary of the probabilistic variables used within the cost model.

Table 58 – Probabilistic Parameters

Parameter	Most Likely	Low	High	Probabilistic/Optional
Base fuel price	$2.94	—	—	Optional
Annual fuel price increase	0.97%	-1.23%	3.03%	Probabilistic
Market capture	SA–38%; STA–32%; RJ–37%	—	—	Optional
Aircraft mass	Vary by scenario	+/- 3 or 5%		Probabilistic
Development/Production CERs	Vary by scenario	+/- 10 or 30%		Probabilistic
Maintenance CERs	Vary by scenario	+/- 5 or 15%		Probabilistic
Composite fraction	Vary by scenario			Probabilistic
Design heritage factors	Vary by scenario			Probabilistic
Design complexity factors	Vary by scenario			Probabilistic
Production complexity factors	Vary by scenario			Probabilistic
Maintenance complexity factors	Vary by scenario			Probabilistic
Maintenance interval adjustment	Vary by scenario			Probabilistic

The result of the monte-carlo analysis is a probability distribution for every item in the model. These results provide statistical information (i.e., mean, standard deviation) as well as outcomes by probability level (e.g., 5%, 10%, etc.). The results at the mean (expected value) were used as the point for comparison across all deployment scenarios. A key aspect of the mean is that the values can be summed across and maintain representation as the mean value for the newly formed calculation. Table 59 provides an example of the statistics available for any item within the cost model. The probability levels can be displayed as low as 1% increments.

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[82] Annual Energy Outlook 2015 Report published by the US Energy Information Administration http://www.eia.gov/forecasts/aeo/

[83] ibid.

TABLE 59 – EXAMPLE OF RISK RESULTS FOR SA 2024 AGGRESSIVE DEPLOYMENT SCENARIO

Discounted Costs in Thousands US Dollars ($K)									
Average Cost per Aircraft	**Mean**	**Std Dev**	**CV**	**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
Operator Investment Cost	$13,722	$2,223	0.1620	$8,684	$11,930	$12,935	$13,919	$15,349	$23,552
Operator Expense	$14,030	$3,253	0.2319	$8,106	$11,086	$12,732	$14,361	$16,808	$24,000
Fuel Cost for 7 Years Operations	$10,646	$3,159	0.2967	$5,811	$7,795	$9,373	$10,932	$13,272	$20,489
Maintenance Cost for 7 years Operations	$3,384	$793	0.2345	$1,558	$2,684	$3,108	$3,446	$4,031	$6,595
Operator Income (Residual Value)	$1,107	$179	0.1620	$701	$963	$1,044	$1,123	$1,239	$1,901

In addition to viewing the tabular results of the risk statistics, a visual form can be generated that displays the probability density function (PDF). A PDF shows the percentage of outcomes that occur by each value. This visualization allows identification of central tendency of the results, the overall range of dispersion, and if any skew exists in the results. Skewness is a measure of how symmetrical the probability distribution is about its mean, a distribution with a positive skew indicates that there is a longer tail to the right (higher values) of the mean. Figure 21 provides an example of a PDF graph for the SA 2024 Aggressive deployment scenarios average operator investment discounted cost.

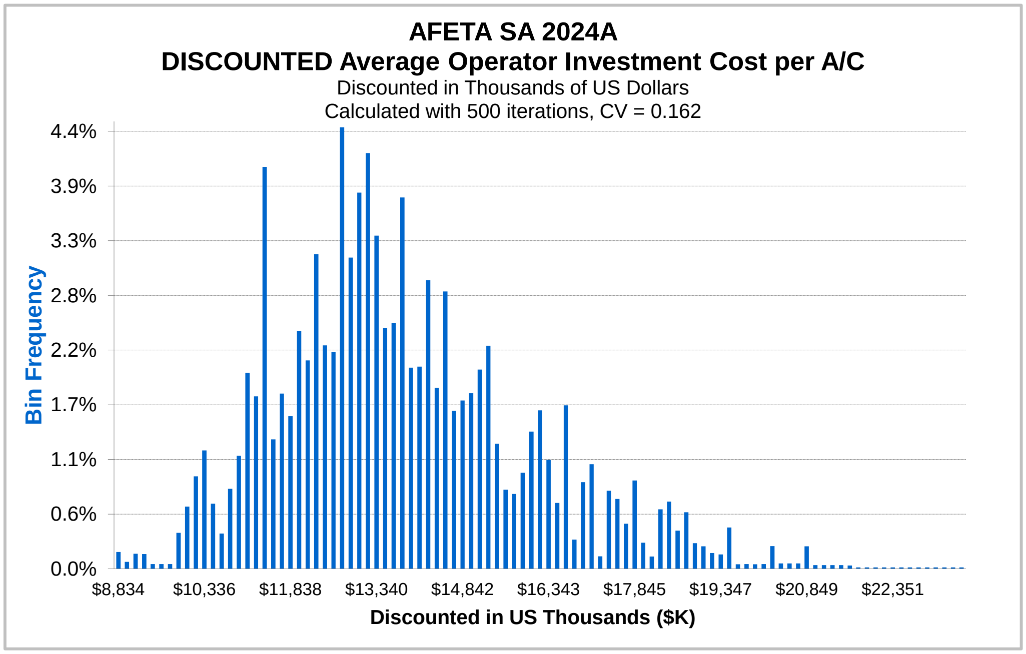


FIGURE 21 – EXAMPLE PROBABILITY DENSITY FUNCTION GRAPH FOR SA 2024 AGGRESSIVE DISCOUNTED OPERATION INVESTMENT COSTS

Model sensitivity analysis is used for determining the most critical variables in a model and to assess what parameters will cause instability within the model. To identify the most critical variables, all the variables are subjected to a fixed deviation and the outcome is analyzed. The variables that have the greatest impact on the outcome of the project are isolated as the key project variables. The actual sensitivity is measured as the impact change to the cost estimate by the change in the input.

For the cost model, sensitivity analysis was conducted with the high and low bounds ranging from +/- 20%. The results showed that the model produces a balanced/stable response with variation of input parameter within this range.

Figure 22 shows the result of the model sensitivity analysis. The results indicated that the majority of input parameters cause less than a +/- 5% change in overall results. The model was shown to be most sensitive to the following input parameters:

- Market capture (buy quantity)
- Fuel price
- Fuel reduction
- Thrust (determines engine weight)
- Non-Engine Subsystem Weights
- Design heritage

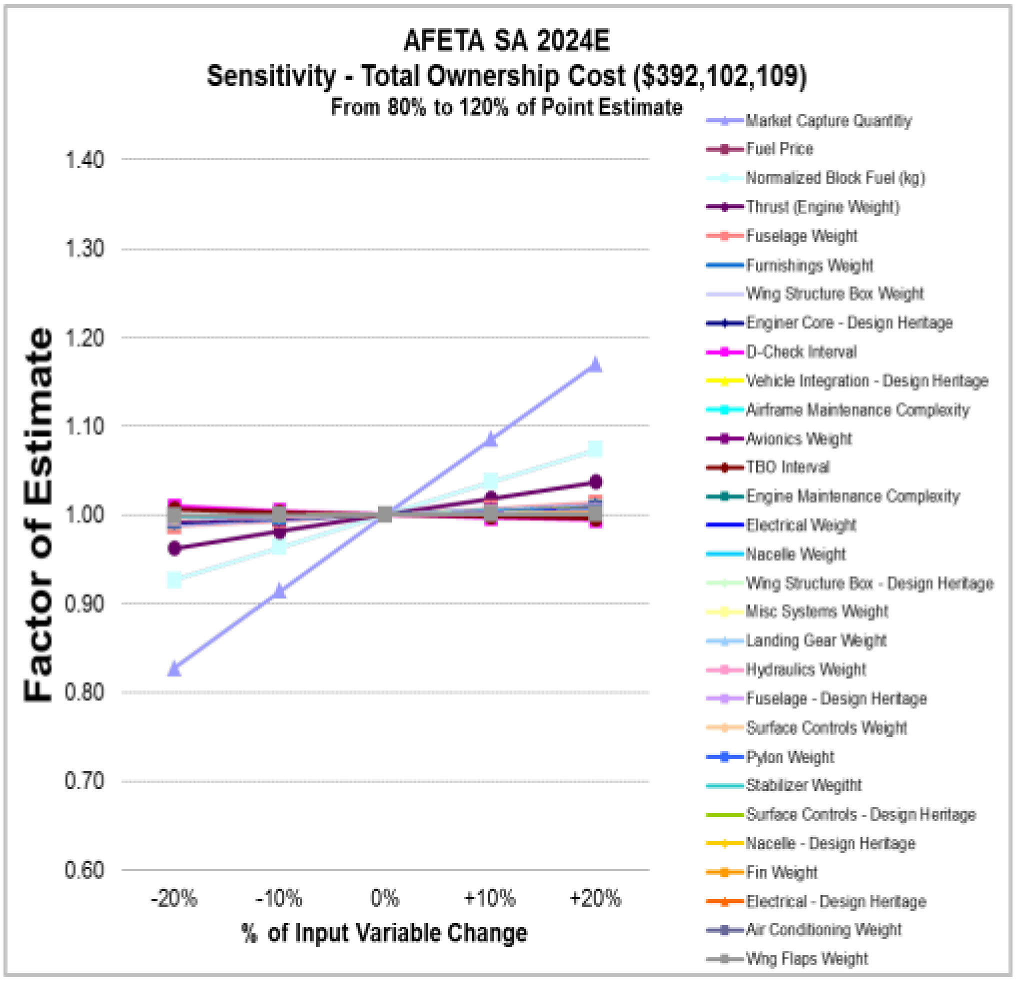


Figure 22 – Cost Model Sensitivity

5 Results

Through the generation of total ownership cost (TOC) and the comparison to reference case the relative costs of each scenario can be determined. For any scenario where the new aircraft TOC is lower, a financial benefit is obtained by an operator for making the investment in the new aircraft compared to the reference aircraft over the determined operational period. If the TOC is higher, then an operator would profit more from purchasing the reference aircraft over the timeframe identified.

By looking at an overall time period of two insertion points, the study results help identify the level of fuel efficiency that provide a monetary incentive to operators based upon market forces alone. Although this study covered a broad range of aircraft, the overall trends and results were similar, and identify those technology deployment scenarios which reduce fuel burn and associated CO_2 emissions while also providing the first operator with net TOC savings over a defined operational timeframe.

The overall TOC distribution consisting of operator capital, fuel, and maintenance—the simple averages of all aircraft, all years, all scenarios in discounted dollars – is provided in Figure 23. The operator cost capital breakout includes residual income when the operator sells the aircraft at the end of the operational years. As the figures show, operator capital cost and fuel cost dominated the TOC—with maintenance accounted for less than 8% depending upon the EIS dates, aircraft, and scenarios.

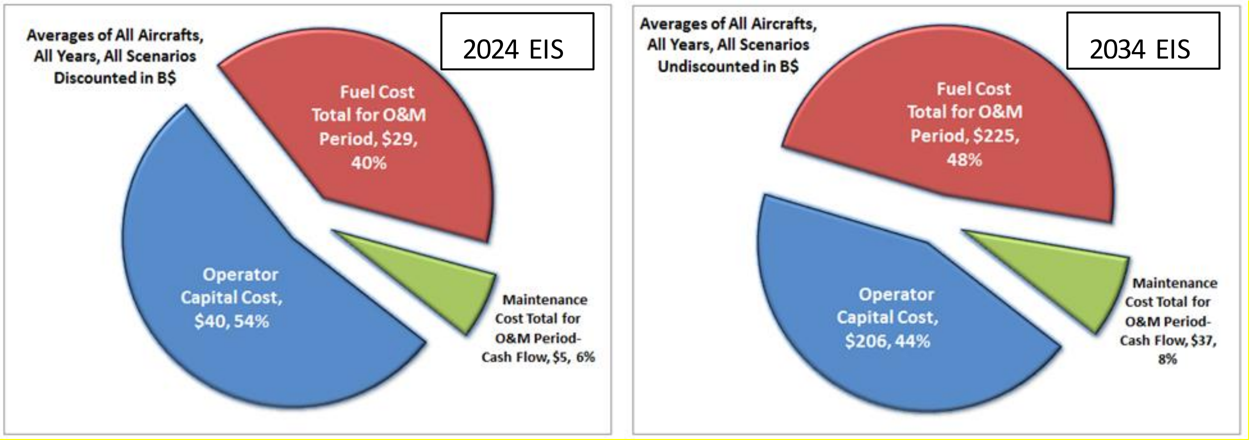


FIGURE 23 – AVERAGE COST DISTRIBUTION OF TOTAL OWNERSHIP COST (TOC)

For SA, in terms of EIS dates, the distribution of costs shown in Figure 24 suggests similar percentages — collectively operator capital and fuel cost were 90% of the TOC.

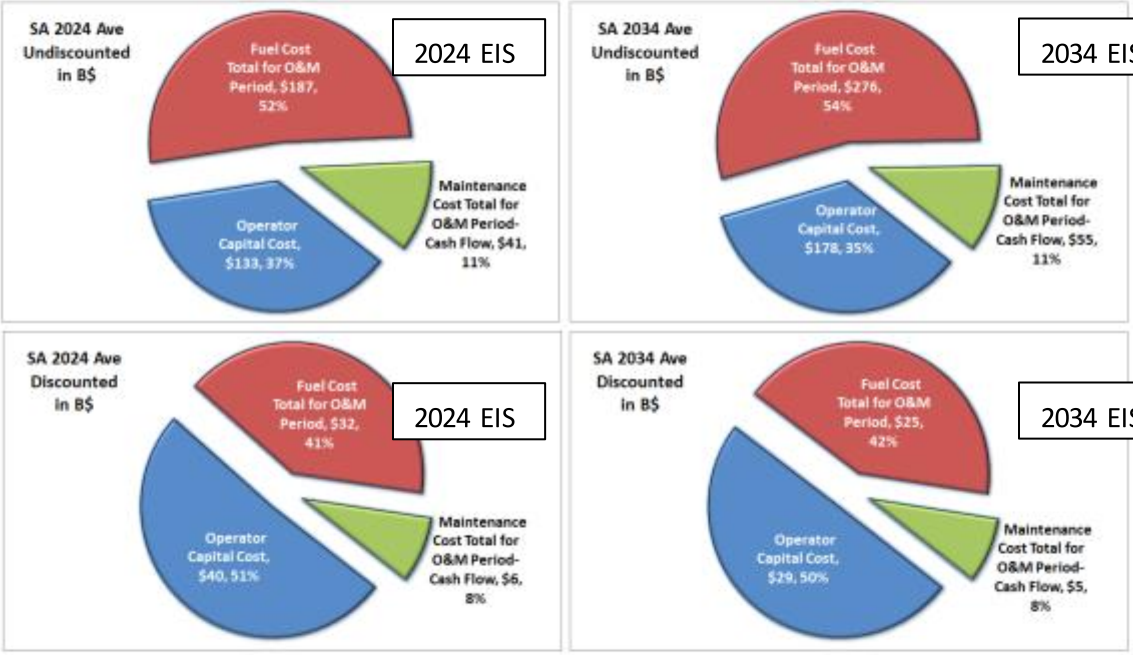


FIGURE 24 – SA AVERAGE COST DISTRIBUTION OF TOTAL OWNERSHIP COST (TOC)

For STA, in Figure 25, the maintenance cost share went down slightly when compared to SA with owner capital cost and fuel costs still dominating the distribution.

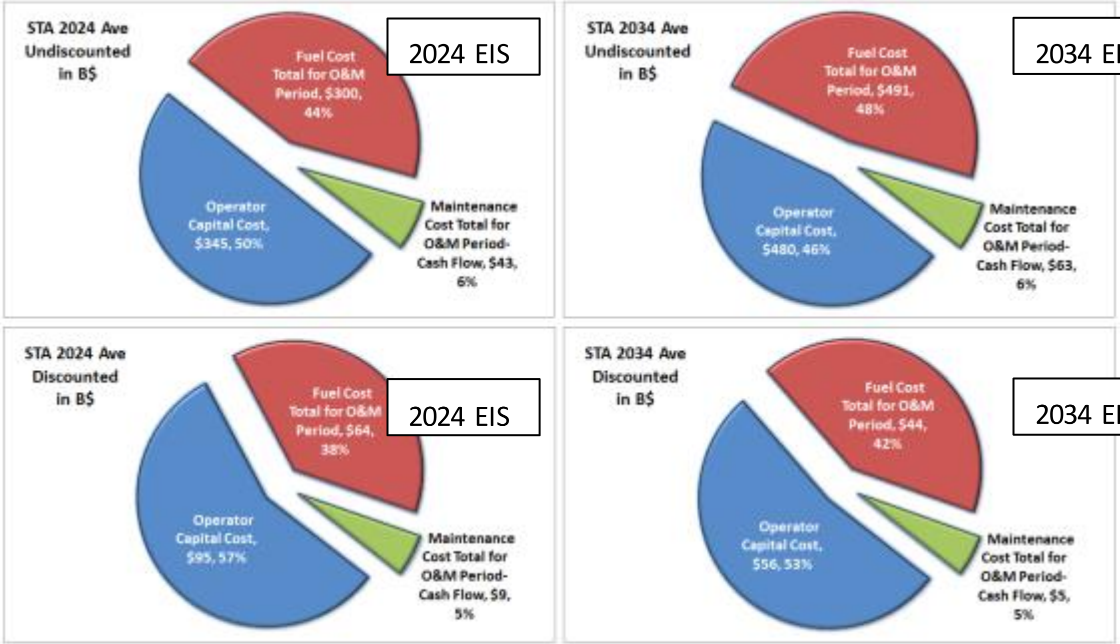


FIGURE 25 – STA AVERAGE COST DISTRIBUTION OF TOTAL OWNERSHIP COST (TOC)

For RJ, the distribution of TOC, in Figure 26, was similar to SA, with a slight change difference in fuel cost.

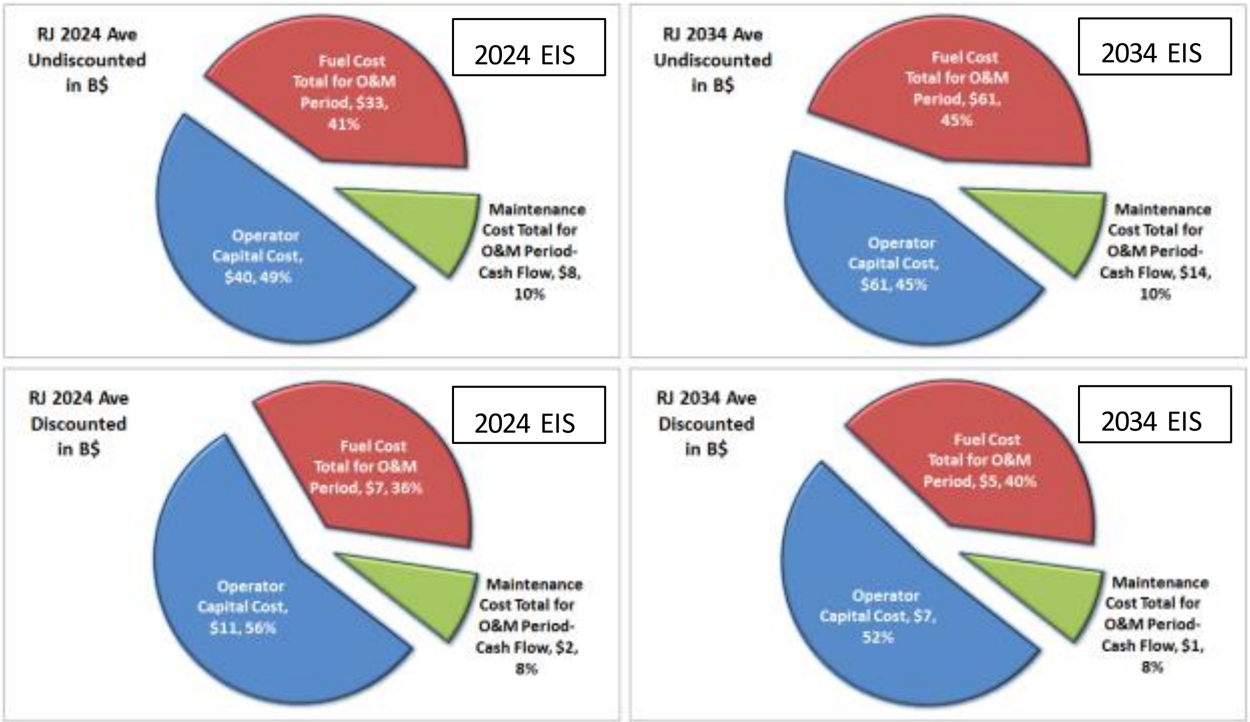


FIGURE 26 – RJ AVERAGE COST DISTRIBUTION OF TOTAL OWNERSHIP COST (TOC)

5.1 2024 EIS Results

The 2024 EIS scenarios provide a near-term look into the level of fuel burn reduction can be expected due to market drivers alone. The data suggests that for all the vehicle classes, fuel reductions below 25% provide net TOC savings to operators. This is currently being seen in the marketplace with the recent purchase order success for the A320-NEO which is advertising a 15% fuel reduction savings.

To provide a comparative basis across scenarios and EIS years, the cost in

Table 60,

Table 61, and

Table 62 are provided in constant (2013) year dollars for each vehicle class. (Supplemental materials in the appendices present results in both non-discounted dollars and EIS inflated dollars, as appropriate.) For example, a 2024 inflated cost of $20 million would correspond to $8 million in discounted 2013 constant year dollars. The following discounted results show the estimated costs in millions of dollars normalized to 2013 US millions of dollars using a 9% discount rate. The tables reflect the breakout of the Total Operator Cost (TOC) by its major components. These components are operator capital costs, operator expenses, and operator income. Total operator expenses consist of fuel cost and maintenance costs for each vehicle procured for an operational period of seven years. Total operator income is the value of the aircraft after 17 years of depreciation (residual value). TOC consists of the operator capital cost, plus operator expenses, less the income from the residual value.

TABLE 60 – RESULTS—SA 2024

Mean—Discounted Costs in BY2013 Millions of USD	SA 2024 Reference	SA 2024E	SA 2024M	SA 2024A
Total Operator cost	**$82,213**	**$81,384**	**$82,336**	**$83,369**
Operator capital cost (AUP)	$33,242	$46,047	$51,452	$55,301
Operator expense	$51,653	$39,053	$35,036	$32,531
Fuel cost total for O&M period	$43,641	$32,438	$28,718	$26,169
Maintenance cost total for O&M period—cash flow	$8,013	$6,615	$6,317	$6,362
Operator income (residual costs)	$2,683	$3,716	$4,153	$4,463
Average TOC per A/C for all A/C purchases	**$20.4**	**$20.2**	**$20.5**	**$20.7**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$8.3	$11.4	$12.8	$13.7
Average operator expense per A/C—over all A/C for number of ops years	$12.8	$9.7	$8.7	$8.1
Average fuel cost per A/C—over all A/C for number of ops years	$10.9	$8.1	$7.1	$6.5
Average maintenance cost per A/C—over all A/C for number of ops years	$2.0	$1.6	$1.6	$1.6
Operator income (residual)—over all A/C for number of ops years	$0.7	$0.9	$1.0	$1.1
Average TOC per A/C for A/C purchased in year 2024	**$29.0**	**$28.9**	**$29.3**	**$29.8**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$12.1	$16.7	$18.7	$20.1
Average operator expense per A/C—over all A/C for number of ops years	$17.9	$13.5	$12.2	$11.3
Average fuel cost per A/C—over all A/C for number of ops years	$15.0	$11.1	$9.9	$9.0
Average maintenance cost per A/C—over all A/C for number of ops years	$2.9	$2.4	$2.3	$2.3
Operator income (residual)—over all A/C for number of ops years	$1.0	$1.3	$1.5	$1.6

TABLE 61 – RESULTS—STA 2024

Mean—Discounted Costs in BY2013 Millions of USD	STA 2024 Reference	STA 2024E	STA 2024M	STA 2024A
Total Operator cost	**$127,765**	**$122,613**	**$133,717**	**$137,200**
Operator capital cost (AUP)	$50,963	$68,574	$85,736	$96,750
Operator expense	$80,916	$59,575	$54,903	$48,262
Fuel cost total for O&M period	$72,164	$52,434	$48,159	$41,463
Maintenance cost total for O&M period—cash flow	$8,752	$7,141	$6,743	$6,798
Operator income (residual costs)	$4,114	$5,536	$6,922	$7,811
Average TOC per A/C for all A/C purchases	**$89.7**	**$86.0**	**$93.8**	**$96.3**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$35.7	$48.1	$60.1	$67.8
Average operator expense per A/C—over all A/C for number of ops years	$56.8	$41.8	$38.5	$33.9
Average fuel cost per A/C—over all A/C for number of ops years	$50.7	$36.8	$33.8	$29.1
Average maintenance cost per A/C—over all A/C for number of ops years	$6.1	$5.0	$4.7	$4.8
Operator income (residual)—over all A/C for number of ops years	$2.9	$3.9	$4.9	$5.5
Average TOC per A/C for A/C purchased in year 2024	**$127.7**	**$123.5**	**$135.2**	**$139.2**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$52.6	$70.7	$88.4	$99.8
Average operator expense per A/C—over all A/C for number of ops years	$79.4	$58.5	$53.9	$47.4

Mean—Discounted Costs in BY2013 Millions of USD	STA 2024 Reference	STA 2024E	STA 2024M	STA 2024A
Average fuel cost per A/C—over all A/C for number of ops years	$70.4	$51.1	$47.0	$40.4
Average maintenance cost per A/C—over all A/C for number of ops years	$9.0	$7.4	$7.0	$7.0
Operator income (residual)—over all A/C for number of ops years	$4.2	$5.7	$7.1	$8.1

TABLE 62 – RESULTS—RJ 2024

Mean—Discounted Costs in BY2013 Millions of USD	RJ 2024 Reference	RJ 2024E	RJ 2024M	RJ 2024A
Total Operator cost	**$14,900**	**$14,862**	**$15,643**	**$16,015**
Operator capital cost (AUP)	$6,271	$8,724	$10,016	$10,983
Operator expense	$9,135	$6,842	$6,435	$5,919
Fuel cost total for O&M period	$7,685	$5,554	$5,153	$4,630
Maintenance cost total for O&M period—cash flow	$1,451	$1,288	$1,283	$1,289
Operator income (residual costs)	$406	$704	$808	$886
Average TOC per A/C for all A/C purchases	**$15.5**	**$15.5**	**$16.3**	**$16.7**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$6.5	$9.1	$10.4	$11.4
Average operator expense per A/C—over all A/C for number of ops years	$9.5	$7.1	$6.7	$6.2
Average fuel cost per A/C—over all A/C for number of ops years	$8.0	$5.8	$5.4	$4.8
Average maintenance cost per A/C—over all A/C for number of ops years	$1.5	$1.3	$1.3	$1.3
Operator income (residual)—over all A/C for number of ops years	$0.5	$0.7	$0.8	$0.9
Average TOC per A/C for A/C purchased in year 2024	**$22.3**	**$22.5**	**$23.7**	**$24.3**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$9.7	$13.5	$15.5	$17.0
Average operator expense per A/C—over all A/C for number of ops years	$13.4	$10.1	$9.5	$8.7
Average fuel cost per A/C—over all A/C for number of ops years	$11.2	$8.1	$7.5	$6.7
Average maintenance cost per A/C—over all A/C for number of ops years	$2.2	$2.0	$2.0	$2.0
Operator income (residual)—over all A/C for number of ops years	$0.8	$1.1	$1.2	$1.4

Average TOC per A/C for all A/C purchases is the TOC divided by the total number of aircraft in service over the full ten year production run. The Average TOC per A/C for first purchase is a similar metric, but it only considers aircraft purchased in the first EIS year. For comparative purposes, the discounted values reflect CY2013 dollars; they are not inflated to future years. The data suggests that for all the vehicle classes, fuel reductions below 25% provide net TOC savings for 2024 EIS aircraft.

5.2 2034 Scenarios

The 2034 EIS scenarios provide a timeframe where significant technology development is possible for new aircraft. The data suggests that for all the vehicle classes, fuel reductions below 40% provide net TOC savings. The data presented in this section and the prior section 5.1 are represented in discounted US dollars. The total operator capital cost for the deployment scenarios between the 2024 EIS and 2034 EIS time periods differ. Table 63, Table 64, and Table 65 shows the comparison by deployment scenario on how operator capital cost for SA, STA, and RJ

TABLE 63 – 2024 VS 2034 SA AVERAGE OPERATOR CAPITAL COST COMPARISON

Mean—Non-Discounted Costs in BY2013 Millions of USD	Reference	Evolutionary	Moderate	Aggressive
2024 SA – Average Operator Capital cost per A/C	$29.8	$41.3	$46.2	$49.6
2034 SA – Average Operator Capital cost per A/C	$26.6	$40.8	$44.3	$51.8

TABLE 64– 2024 VS 2034 STA AVERAGE OPERATOR CAPITAL COST COMPARISON

Mean—Non-Discounted Costs in BY2013 Millions of USD	Reference	Evolutionary	Moderate	Aggressive
2024 STA – Average Operator Capital cost per A/C	$129.9	$174.8	$218.5	$246.6
2034 STA – Average Operator Capital cost per A/C	$114.2	$184.1	$204.3	$232.2

TABLE 65– 2024 VS 2034 RJ AVERAGE OPERATOR CAPITAL COST COMPARISON

Mean—Non-Discounted Costs in BY2013 Millions of USD	Reference	Evolutionary	Moderate	Aggressive
2024 RJ – Average Operator Capital cost per A/C	$23.9	$33.3	$38.2	$41.9
2034 RJ – Average Operator Capital cost per A/C	$20.5	$30.9	$33.3	$38.7

Table 66, Table 67, and Table 68 show the estimated costs in millions of dollars normalized to 2013 value and discounted by 9% per annum. Detailed results for all scenarios and lower level costs are presented in Appendix O.

TABLE 66 – RESULTS—SA 2034

Mean—Discounted Costs in BY2013 Millions of USD	SA 2034 Reference	SA 2034E	SA 2034M	SA 2034A
Total Operator cost	**$49,415**	**$46,825**	**$47,136**	**$49,962**
Operator capital cost (AUP)	$17,035	$26,149	$28,404	$33,160
Operator expense	$33,755	$22,787	$21,025	$19,479
Fuel cost total for O&M period	$29,149	$19,167	$17,368	$15,718
Maintenance cost total for O&M period—cash flow	$4,606	$3,620	$3,657	$3,76
Operator income (residual costs)	$1,375	$2,110	$2,292	$2,676
Average TOC per A/C for all A/C purchases	**$9.0**	**$8.6**	**$8.6**	**$9.1**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$3.1	$4.8	$5.2	$6.1
Average operator expense per A/C—over all A/C for number of ops years	$6.2	$4.2	$3.8	$3.6
Average fuel cost per A/C—over all A/C for number of ops years	$5.3	$3.5	$3.2	$2.9
Average maintenance cost per A/C—over all A/C for number of ops years	$0.8	$0.7	$0.7	$0.7
Operator income (residual)—over all A/C for number of ops years	$0.3	$0.4	$0.4	$0.5
Average TOC per A/C for A/C purchased in year 2034	**$12.7**	**$12.2**	**$12.3**	**$13.1**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$4.5	$7.0	$7.6	$8.8
Average operator expense per A/C—over all A/C for number of ops years	$8.5	$5.8	$5.3	$4.9
Average fuel cost per A/C—over all A/C for number of ops years	$7.3	$4.8	$4.3	$3.9
Average maintenance cost per A/C—over all A/C for number of ops years	$1.2	$1.0	$1.0	$1.0
Operator income (residual)—over all A/C for number of ops years	$0.4	$0.6	$0.6	$0.7

TABLE 67 – RESULTS—STA 2034

Mean—Discounted Costs in BY2013 Millions of USD	STA 2034 Reference	STA 2034E	STA 2034M	STA 2034A
Total Operator cost	**$84,433**	**$81,246**	**$80,338**	**$85,235**
Operator capital cost (AUP)	$28,278	$45,592	$50,574	$57,504
Operator expense	$58,437	$39,335	$33,845	$32,372
Fuel cost total for O&M period	$52,914	$35,075	$29,558	$28,064
Maintenance cost total for O&M period—cash flow	$5,523	$4,259	$4,287	$4,309
Operator income (residual costs)	$2,282	$3,680	$4,082	$4,641
Average TOC per A/C for all A/C purchases	**$39.7**	**$38.2**	**$37.7**	**$40.0**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$13.3	$21.4	$23.7	$27.0
Average operator expense per A/C—over all A/C for number of ops years	$27.5	$18.5	$15.9	$15.2
Average fuel cost per A/C—over all A/C for number of ops years	$24.9	$16.5	$13.9	$13.2
Average maintenance cost per A/C—over all A/C for number of ops years	$2.6	$2.0	$2.0	$2.0
Operator income (residual)—over all A/C for number of ops years	$1.1	$1.7	$1.9	$2.2
Average TOC per A/C for A/C purchased in year 2034	**$56.0**	**$54.6**	**$54.2**	**$57.6**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$19.5	$31.5	$34.9	$39.7
Average operator expense per A/C—over all A/C for number of ops years	$38.1	$25.6	$22.1	$21.1
Average fuel cost per A/C—over all A/C for number of ops years	$34.2	$22.7	$19.1	$18.2
Average maintenance cost per A/C—over all A/C for number of ops years	$3.8	$2.9	$3.0	$3.0
Operator income (residual)—over all A/C for number of ops years	$1.6	$2.5	$2.8	$3.2

Table 68 – Results—RJ 2034

Mean—Discounted Costs in BY2013 Millions of USD	RJ 2034 Reference	RJ 2034E	RJ 2034M	RJ 2034A
Total Operator cost	**$10,868**	**$10,440**	**$10,393**	**$10,986**
Operator capital cost (AUP)	$3,811	$5,743	$6,192	$7,203
Operator expense	$7,364	$5,161	$4,701	$4,364
Fuel cost total for O&M period	$6,335	$4,250	$3,787	$3,438
Maintenance cost total for O&M period—cash flow	$1,029	$911	$914	$927
Operator income (residual costs)	$308	$463	$500	$581
Average TOC per A/C for all A/C purchases	**$6.7**	**$6.5**	**$6.4**	**$6.8**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$2.4	$3.6	$3.8	$4.5
Average operator expense per A/C—over all A/C for number of ops years	$4.6	$3.2	$2.9	$2.7
Average fuel cost per A/C—over all A/C for number of ops years	$3.9	$2.6	$2.4	$2.1
Average maintenance cost per A/C—over all A/C for number of ops years	$0.6	$0.6	$0.6	$0.6
Operator income (residual)—over all A/C for number of ops years	$0.2	$0.3	$0.3	$0.4
Average TOC per A/C for A/C purchased in year 2034	**$9.6**	**$9.3**	**$9.3**	**$9.9**
Average operator capital cost per A/C—over first A/C purchase for number of ops years	$3.5	$5.3	$5.7	$6.6
Average operator expense per A/C—over all A/C for number of ops years	$6.4	$4.5	$4.1	$3.8
Average fuel cost per A/C—over all A/C for number of ops years	$5.5	$3.7	$3.3	$3.0
Average maintenance cost per A/C—over all A/C for number of ops years	$0.9	$0.8	$0.8	$0.9
Operator income (residual)—over all A/C for number of ops years	$0.3	$0.4	$0.5	$0.5

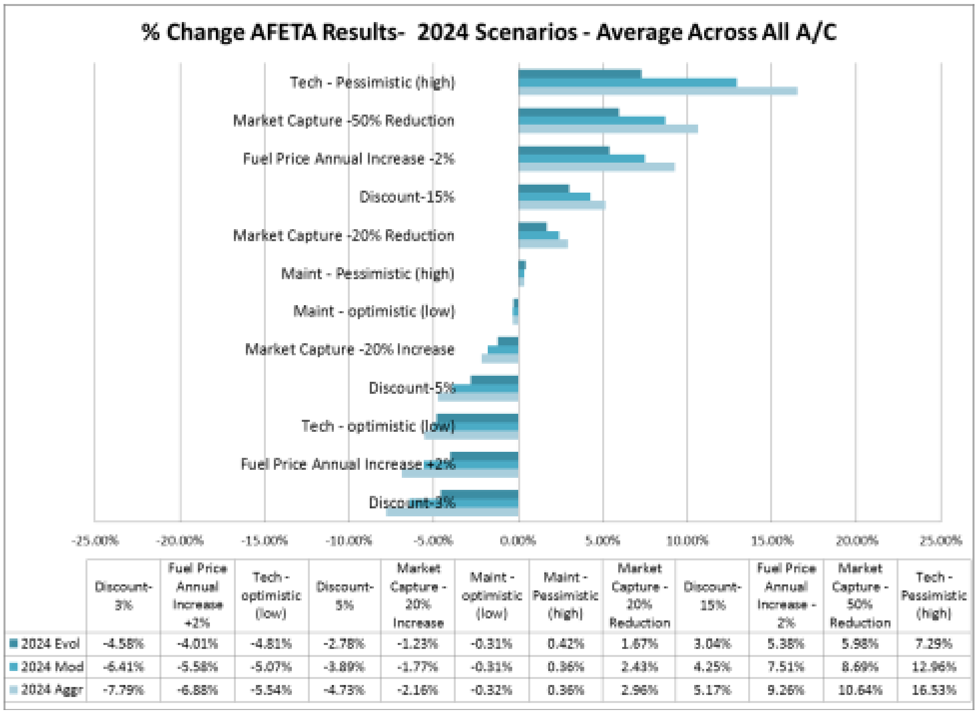
5.3 Sensitivity Analysis

This study contains several key assumptions on driving parameters. These parameters are uncertain and potentially can alter the results of the study. The following section investigates several cases to assess the impact of changing these study assumptions. The areas identified for sensitivity analysis were technical and maintenance parameters, market capture, fuel price increase, discount rate, and years of operations. The results of these sensitivities are detailed in Sections 5.3.1 through 5.3.6.

The sensitivity analyses detailed in this section were generated by re-running all the cost models for each deployment scenario and aircraft class by varying a specific parameter (e.g., market capture percentage). These results of each sensitivity case were then compared to the best base to assess the impact of the sensitivity.

Additionally, we conducted an analysis across all the sensitivity cases to assess which key assumptions have potentially the largest impact to the results of the study. This analysis is shown as a tornado comparing the results of each sensitivity case to the Mean Discounted costs for Average TOC per A/C for all A/C purchases in Table 59, Table 60, and Table 61 for 2024 EIS analysis, and Table 62, Table 63, and Table 64 for 2034 EIS analysis.

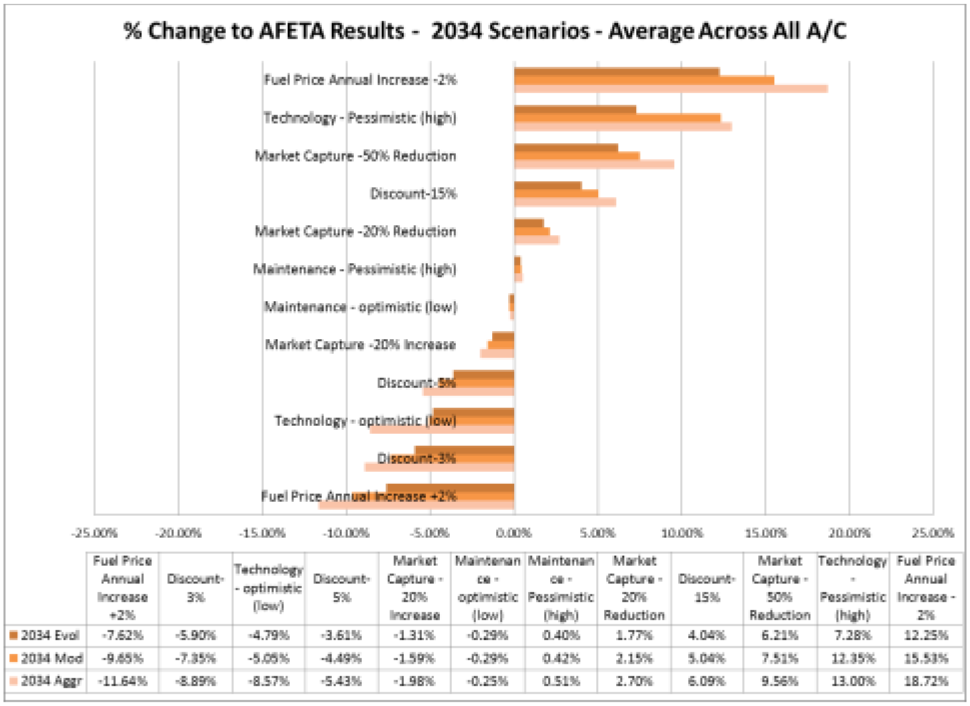
Figure 27 shows for the average impact across all technology scenarios for the 2024 EIS time period on the effect of each scenario. The values in the figure are multipliers to the main results and listed in order from those that cause the largest increase to those that cause the largest decrease.



	Discount-3%	Fuel Price Annual Increase +2%	Tech - optimistic (low)	Discount-5%	Market Capture - 20% Increase	Maint - optimistic (low)	Maint - Pessimistic (high)	Market Capture - 20% Reduction	Discount-15%	Fuel Price Annual Increase - 2%	Market Capture - 50% Reduction	Tech - Pessimistic (high)
2024 Evol	-4.58%	-4.01%	-4.81%	-2.78%	-1.23%	-0.31%	0.42%	1.67%	3.04%	5.38%	5.98%	7.29%
2024 Mod	-6.41%	-5.58%	-5.07%	-3.89%	-1.77%	-0.31%	0.36%	2.43%	4.25%	7.51%	8.69%	12.96%
2024 Aggr	-7.79%	-6.88%	-5.54%	-4.73%	-2.16%	-0.32%	0.36%	2.96%	5.17%	9.26%	10.64%	16.53%

FIGURE 27 – 2024 EIS SENSITIVITY SUMMARY

Figure 28 shows the average impact across all technology scenarios for the 2034 EIS time period.



	Fuel Price Annual Increase +2%	Discount-3%	Technology - optimistic (low)	Discount-5%	Market Capture - 20% Increase	Maintenance - optimistic (low)	Maintenance - Pessimistic (high)	Market Capture - 20% Reduction	Discount-15%	Market Capture - 50% Reduction	Technology - Pessimistic (high)	Fuel Price Annual Increase - 2%
2034 Evol	-7.62%	-5.90%	-4.79%	-3.61%	-1.31%	-0.29%	0.40%	1.77%	4.04%	6.21%	7.28%	12.25%
2034 Mod	-9.65%	-7.35%	-5.05%	-4.49%	-1.59%	-0.29%	0.42%	2.15%	5.04%	7.51%	12.35%	15.53%
2034 Aggr	-11.64%	-8.89%	-8.57%	-5.43%	-1.98%	-0.25%	0.51%	2.70%	6.09%	9.56%	13.00%	18.72%

FIGURE 28 – 2034 EIS SENSITIVITY SUMMARY

Although the ranking of impact differs between the two charts (Figure 25 and Figure 26), the similar items are in the high and low range. The overall analysis suggests that if the technical characteristics of performance are on the low side, or fuel prices decrease over future years, or that the actual market capture is significantly lower than projected for this study, then the cost savings identified in this study for operators will be over-stated.

5.3.1 Technical Parameter Sensitivity

This analysis relies heavily on technical parameters to drive the cost estimating algorithms. These parameter consist of mass, design heritage, design complexity, and production complexity. Ranges for these values were identified by the SMEs and used within the study to bound the results during probabilistic simulation. For this sensitivity analysis the model was run with three cases. The first case is the baseline results with uncertainty on. The second case is with all technical parameters chosen on the high end of the spectrum, meaning the most pessimistic case. The third case is with all technical parameters chosen on the low end of the range, meaning the most optimistic case.

The results for each aircraft configuration show a similar trend for both the 2024 and 2034 EIS periods, in that if the technical parameters are more pessimistic the scenarios are less cost effective. Figure 29 and Figure 30 are grouped by EIS year and show the results for the SA configuration. The sensitivity analysis results for the STA and RJ vehicle configurations can be found in Appendix P. The y-axis in this chart identifies the delta in total ownership cost an operator will incur for the technology scenario as compared to continuing with the reference aircraft. A value of 1.0, means that from an operator perspective moving to a new vehicle will have the same cost as purchasing and operating the reference aircraft. A value greater than 1 means it is more expensive to move to the new aircraft, whereas a value less than 1 indicates a cost benefit.

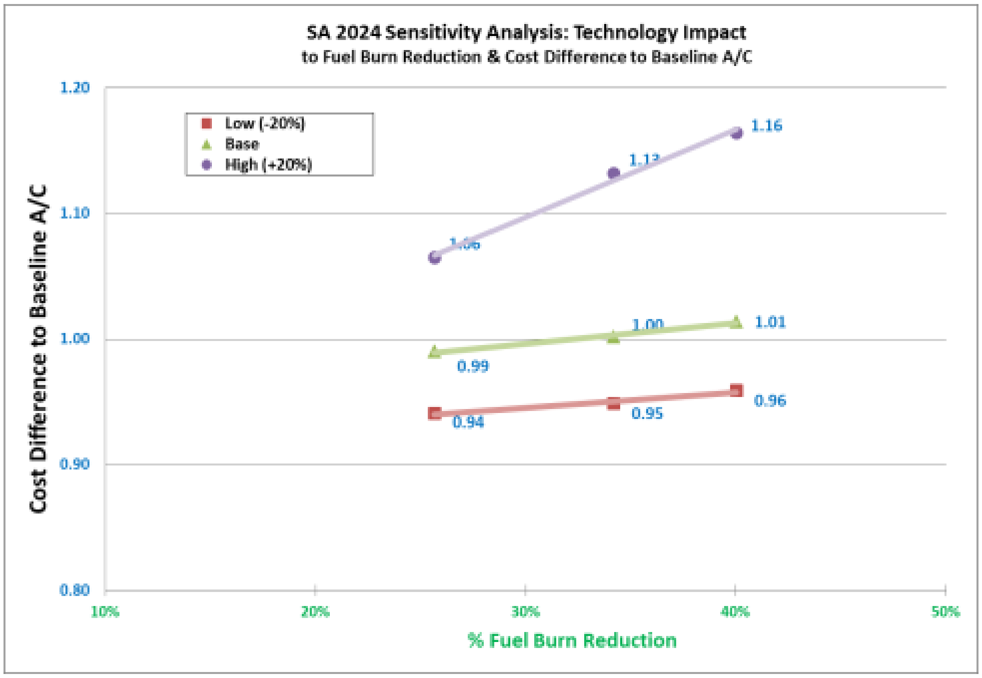


FIGURE 29 – SA 2024 EIS IMPACT OF CHANGE TO TECHNICAL PARAMETERS

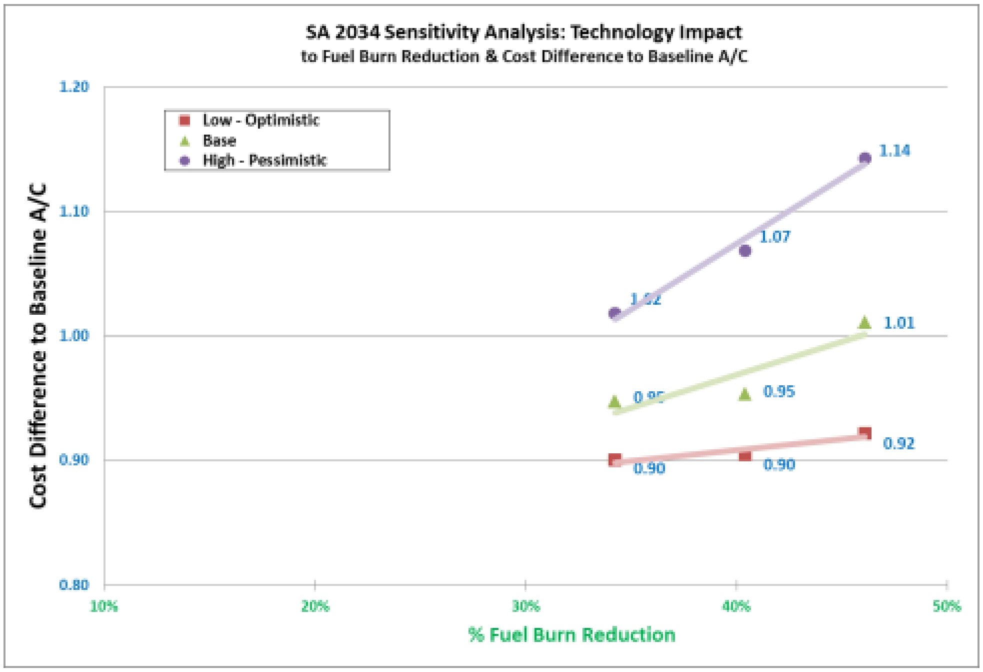


FIGURE 30 – SA 2034 EIS IMPACT OF CHANGE TO TECHNICAL PARAMETERS

5.3.2 Maintenance Parameter Sensitivity

For maintenance costs only four parameters drive the cost over and above the underlying technical characteristics, which were addressed in the technical parameter sensitivity analysis. These parameters are airframe maintenance complexity, airframe maintenance interval, engine complexity, and engine maintenance interval. For this sensitivity analysis the model was run with three cases. The first case is the baseline results with uncertainty on. The second case is the most pessimistic case, which was run with all maintenance parameters chosen to on the bound that drives a higher overall cost. For this case, the maintenance complexity would be the high bound value and maintenance interval would the low range value. The third case, which is the most optimistic case, was run with all technical parameters chosen on the low wind of the range.

The results for each aircraft configuration show a similar trend for both the 2024 and 2034 EIS periods, in that if the maintenance parameters are more pessimistic they scenarios are less cost effective. However, the analysis also shows that the impact of maintenance input is minor in the overall study. Figure 31 and Figure 32 are grouped by EIS year and show the results for the SA configuration. The sensitivity analysis results for the STA and RJ vehicle configurations can be found in Appendix P.

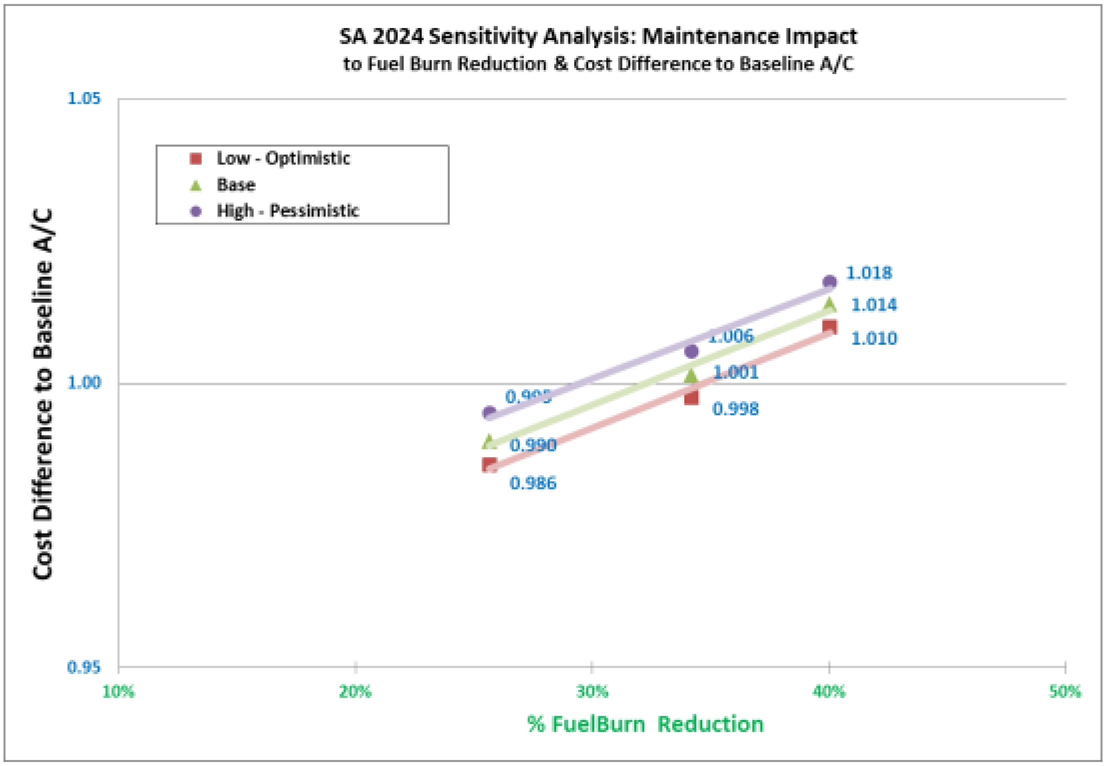


FIGURE 31 – SA 2024 EIS IMPACT OF CHANGE TO MAINTENANCE PARAMETERS

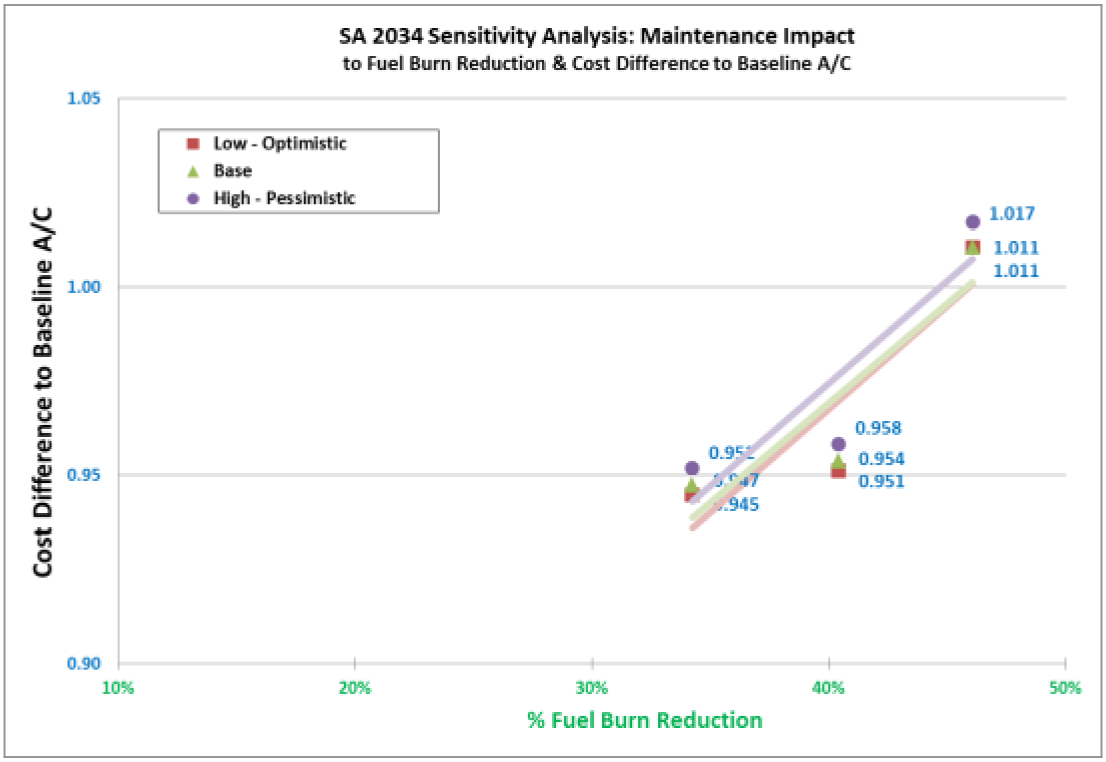


FIGURE 32 – SA 2034 EIS IMPACT OF CHANGE TO MAINTENANCE PARAMETERS

5.3.3 Market Capture Sensitivity

The market capture for each individual vendor is a key parameter of the analysis that influenced the size of the operational fleet which impacts production costs. Given the fact that market capture fluctuates in any given scenario, sensitivities were conducted to see the effects of increased or decreased market capture have on relative cost to the operator from the baseline aircraft, i.e., if the vendor captured x percentage of the market, what is the relative cost difference to the baseline reference aircraft cost? There are three scenarios in this sensitivity—two reductions in market capture—(1) one at a 50% reduction and (2) the other at 20% reduction. The (3) last scenario was to look at a 20% increase in market capture.

Figure 33 and Figure 34 provide the impacts of changing the market capture. The y-axis show the percent change from the baseline which is 1.00. The x-axis is the percent fuel burn reductions by scenarios. For example, in Figure 33, at 40% fuel burn reduction for 2024 Aggressive, if the vendor were only able to capture 50% less than the baseline reference aircraft, the vendor cost will increase by ~13% from the baseline value (1.00).

The graphs for 2024 and 2034 appear to indicate that within +/- 20% change in market capture, the deviation from the baseline reference aircraft cost is within +/- 5%. The significant change happens at the 50% market capture reduction—which showed an ~13% increase from baseline reference aircraft cost.

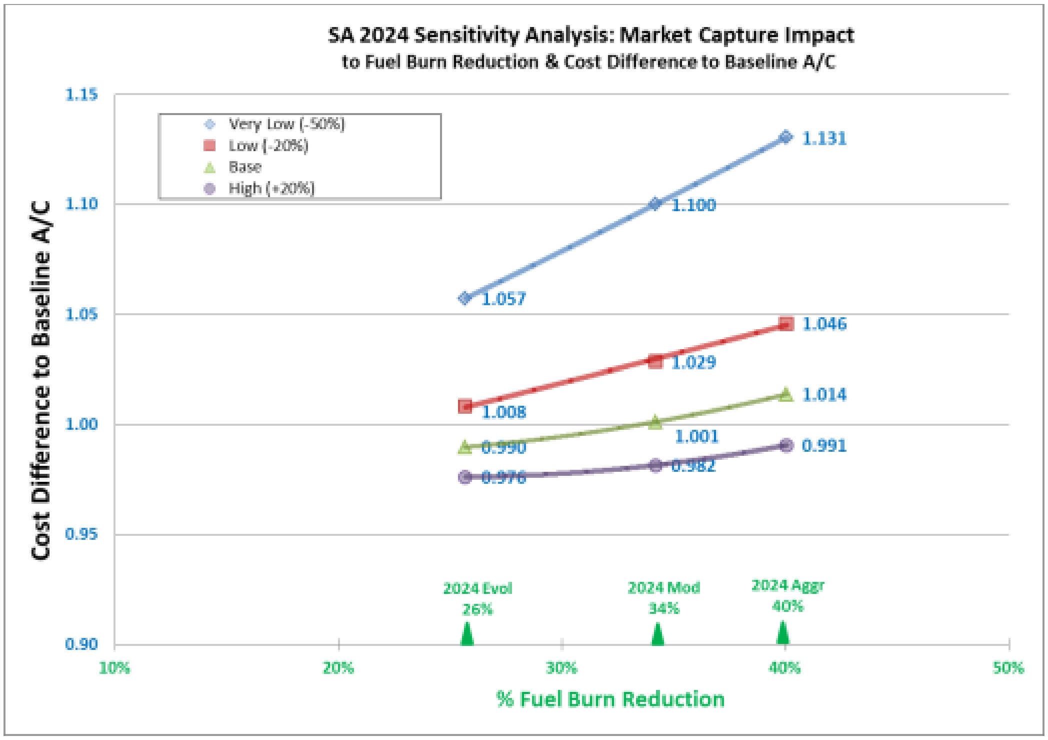


FIGURE 33 – SA 2024 EIS IMPACT OF CHANGE TO MARKET CAPTURE

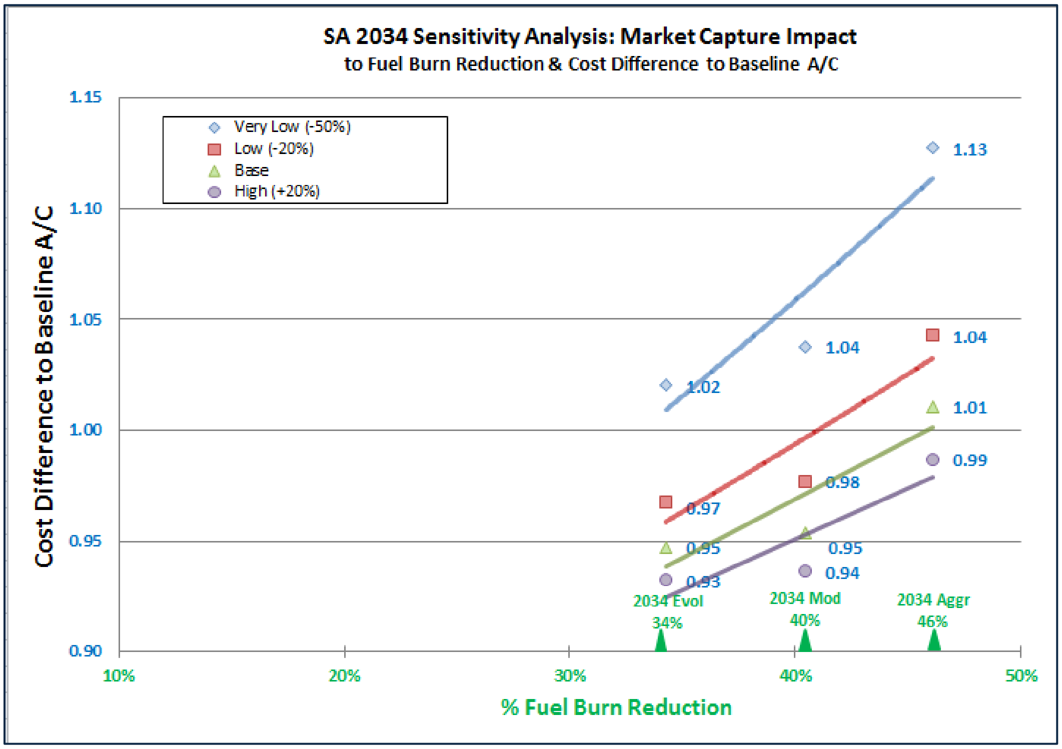


FIGURE 34 – SA 2034 EIS IMPACT OF CHANGE TO MARKET CAPTURE

Change in market capture affects two major cost elements that comprise total ownership costs. The first is the change in average production costs based on the quantity change that affects the level of cost improvement (learning) occurred over the entire production run. As market capture increases, the average production costs will decrease as the effect of learning drives benefits with increased quantities. Conversely, as the market capture decreases the average production cost will increase.

The second component affected by market capture is the amortized system development cost that is added to our estimated price of an aircraft. As the system development cost does not change due to market capture, the amortized amount will increase significantly if the market capture is reduced. This is a linear effect as a 50% reduction in market capture will require the system development cost to be amortized over half the original quantity. In effect this will double to amount of amortized system development cost per aircraft. Displays for the SA 2024 Moderate case the impact on amortized system development cost per aircraft based on the various market capture scenarios. Table 69 displays the impact market capture has on the amortized system development cost. Although the delta per vehicle is small, this does provide a potential barrier for the aircraft manufacturer. In order to bring a fuel efficient aircraft to market, a manufacturer has to make a near-term significant investment and if the market capture targeted is not realized it will have an impact on their initial pricing and resulting profitability. Due to the major investment required, approximately $4.6 billion in discounted dollars, there may be additional hurdles in making the investment to bring the aircraft to the marketplace.

TABLE 69 – SA 2024 MODERATE MARKET CAPTURE IMPACT

SA2024 Moderate	50% Decrease	20% Decrease	Baseline	20% Increase
Single vendor production quantity	2009	3219	4024	4832
System Development Total – Mean Cost – Millions of Discounted US Dollars	$4,671	$4,671	$4,671	$4,671
Amortized System Dev – Mean Cost – Millions of Discounted US Dollars	$2.3	$1.5	$1.2	$1.0

5.3.4 Fuel Price Increase Sensitivity

Another key parameter for the study is the forecasted price of fuel. Given the recent volatility in oil prices, fuel prices have ranged significantly over the past decade. However, the general trend has been an upward increase that is higher than the underlying inflationary rate of the US economy. Currently the base assumption in the model is an approximate 1% per annum real increase in fuel prices. If fuel prices were to increase at a higher rate the study results will show a higher benefit for the aircraft. Conversely, if fuel prices were to decrease the benefit derived from increasing technology would be minimized. A sensitivity analysis was done to show the impact if gas were to deviate +/- 2% around the base assumption. The high range of fuel price was set at a 3% per annum increase and the low range was set to a -1% per annum fuel increase (ongoing fuel price reduction).

Figure 35 and Figure 36 show the sensitivity of the 2024 EIS and 2034 EIS SA scenario results to a change in fuel prices. The results show that a higher fuel price increase rate indicates more aggressive technology investments would be justified.

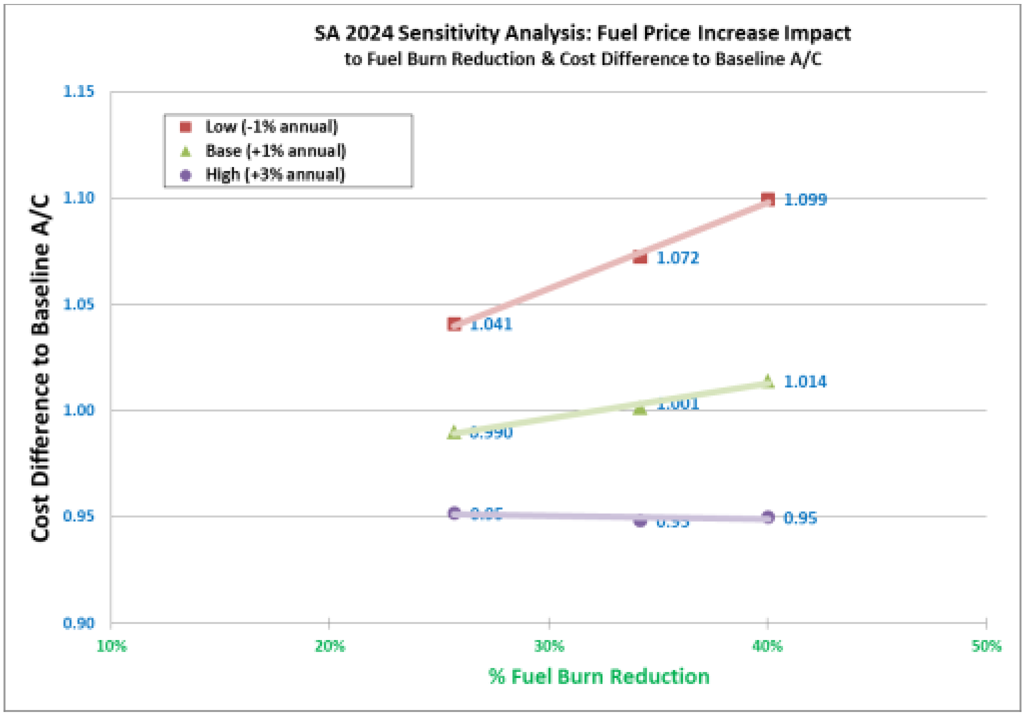


FIGURE 35 – SA 2024 EIS FUEL PRICE INCREASE SENSITIVITY

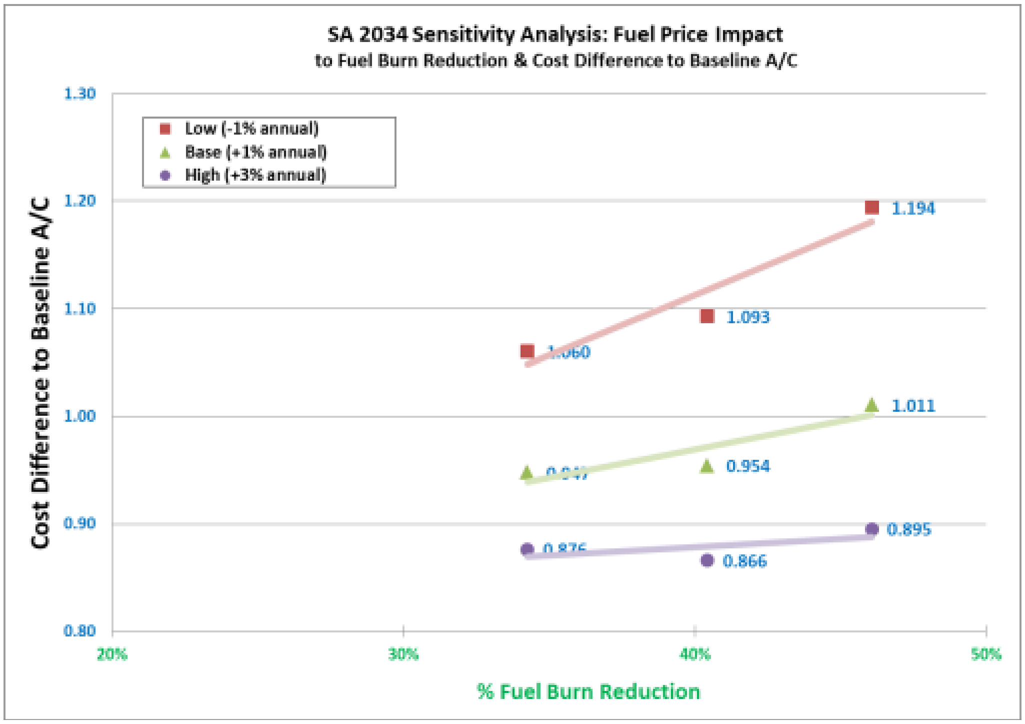


FIGURE 36 – SA 2034 EIS FUEL PRICE INCREASE SENSITIVITY

5.3.5 Discount Rate Sensitivity

A key parameter for the study is the time value of money. Any cost benefit analysis must take this into account and compare different scenarios to a same net present value. A range of discount rates were considered for use in the study. The value of 9% was used in the baseline analysis, reflecting a relatively high capital cost for operators. However in public policy analysis it is common to use a lower discount rate (e.g., 3%) to reflect social costs. In some scenarios where there is a large financial resistance to use available cash, the discount rates can go even higher. The general impact of discounting the results will be that at lower discount more aggressive targets for fuel reduction can be supported, while higher discount rates will lower the efficiency improvements that will provide direct economic benefits for the first aircraft owner.

This analysis looked at the impact of changing discount rates and evaluating a composite weighted value across the aircraft types for each EIS year where a given level of fuel burn reduction is breakeven for an operator over the seven year baseline operational period. These points were calculated for each discount rate sensitivity and plotted on the curve to provide insight into how varying discount rate affects this threshold. Appendix P provides insight into each discount rate sensitivity run for each EIS scenario and aircraft configuration. As the study included only new type aircraft within a certain range of fuel burn reduction (~26% to ~45%), some extrapolation was needed beyond these points. In Figure 37, the shaded regions show the fuel burn reduction areas where the sensitivity results were extrapolated beyond the actual calculations.

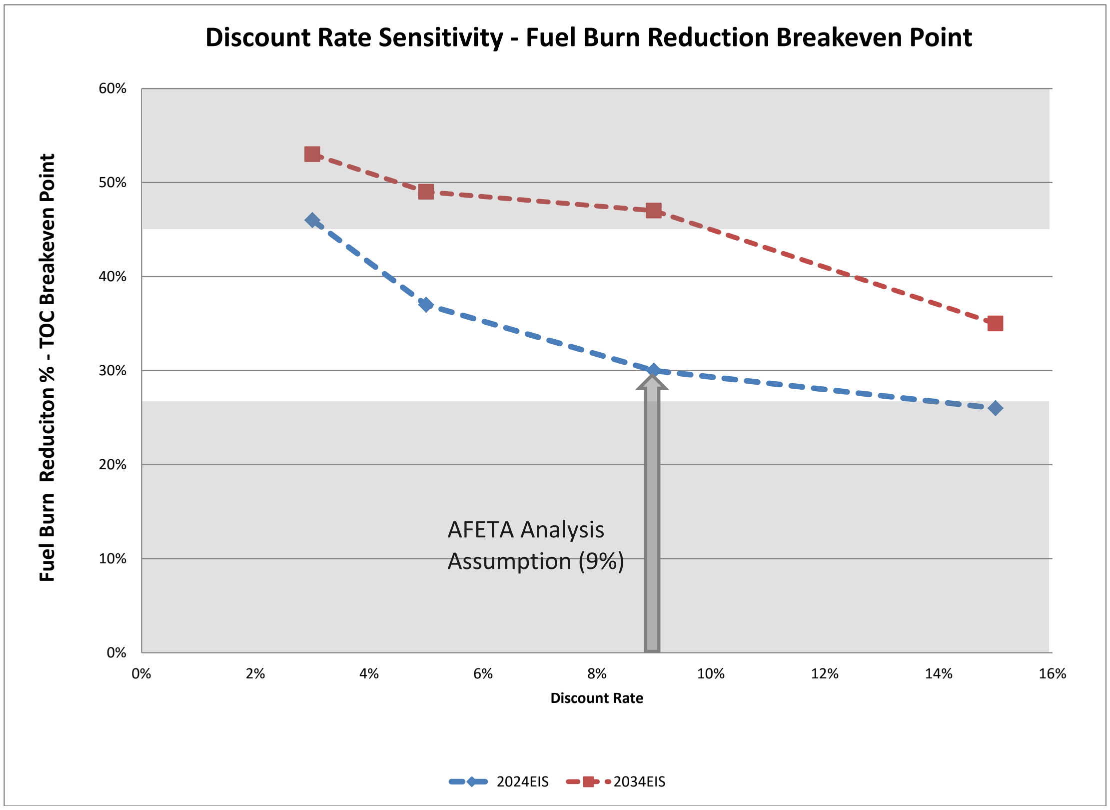


FIGURE 37 – DISCOUNT RATE SENSITIVITY FOR SA AIRCRAFT

This analysis gives insight into how sensitive the breakeven fuel burn reductions are to discounting. The analysis shows that as the discount range is increased a more conservative target for fuel burn reduction is achieved. Consequently a lower discount rate justifies more aggressive stance in fuel efficiency targets can be taken. As a rule of thumb, shifting from 9% discount rate, associated with the cost of capital to airlines, to a 3% discount rate shifts the fuel burn breakeven point by 16% in 2024 and 7% in 2034, depending on aircraft type.

5.3.6 Ownership Years Sensitivity

A key parameter for the study is the number of years for operation per aircraft procured by an operator. The baseline assumption used in this study is to assess ownership costs based on 7 years of operations. This sensitivity assesses the impact of changes to the number of operations years. Several cases were assessed from a 5-year operational period, a 10-year operational period, and a high end of 15 years of operations.

The sensitivity analysis indicates that as the number of years of operations increases, and operator obtains a higher benefit due to the reduction in costs for fuel and maintenance. Figure 38 displays the total ownership cost difference for each technology scenario in the 2024 EIS. This graph illustrates that as the number of years of operations increases the overall benefit to an operator also increases. This indicates that the assumption of seven (7) years used in this study is a conservative value and actual realized benefits may be greater than estimated.

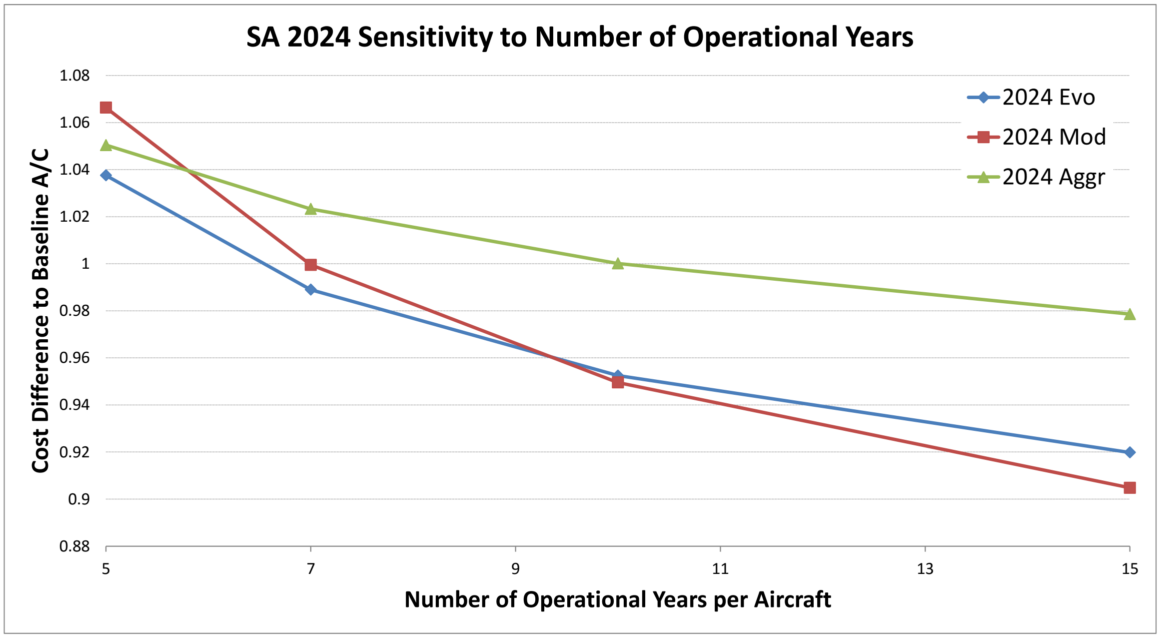


FIGURE 38 – SA 2024 SENSITIVITY TO NUMBER OF OPERATIONAL YEARS

Figure 39 displays the same data, but for the SA 2034 EIS scenarios. This illustrates that the same trend occurs for the 2034 EIS period as the 2024 EIS period, in that the cost benefit increases as the number of operations years increases.

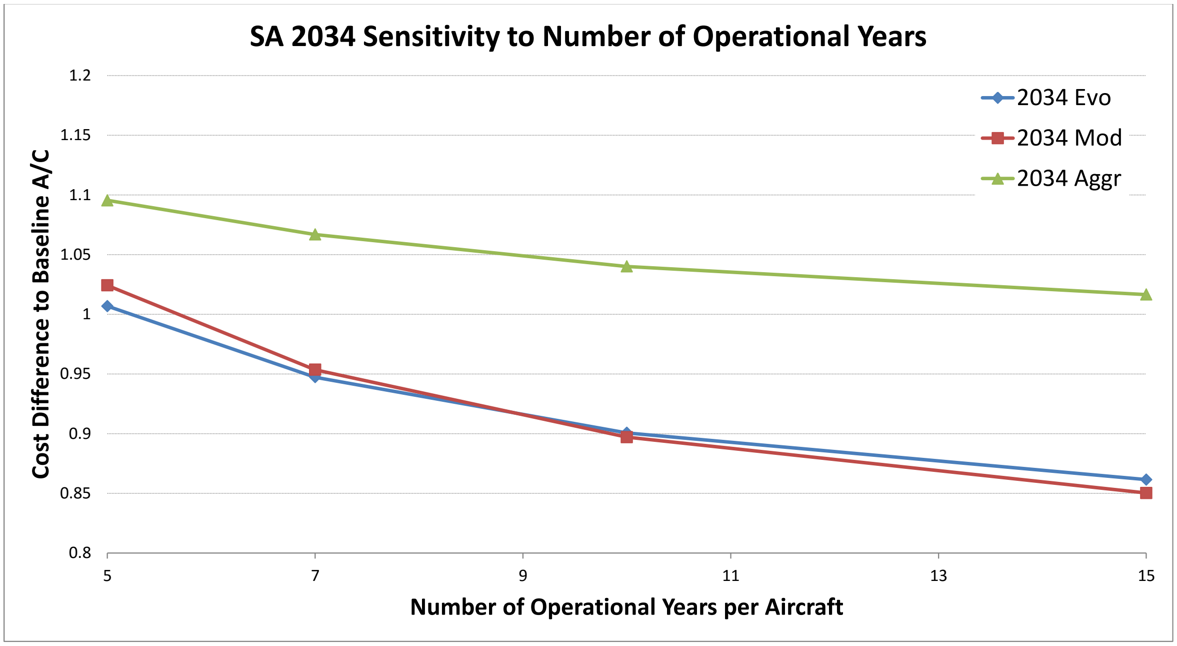


FIGURE 39 - SA 2034 SENSITIVITY TO NUMBER OF OPERATIONAL YEARS

Figure 40 shows the discounted savings in millions of US dollars for the SA 2024 Moderate scenario per years of operations. Illustrated in this graphic is the major impact fuel savings costs has on the overall analysis as the number of operational years increases.

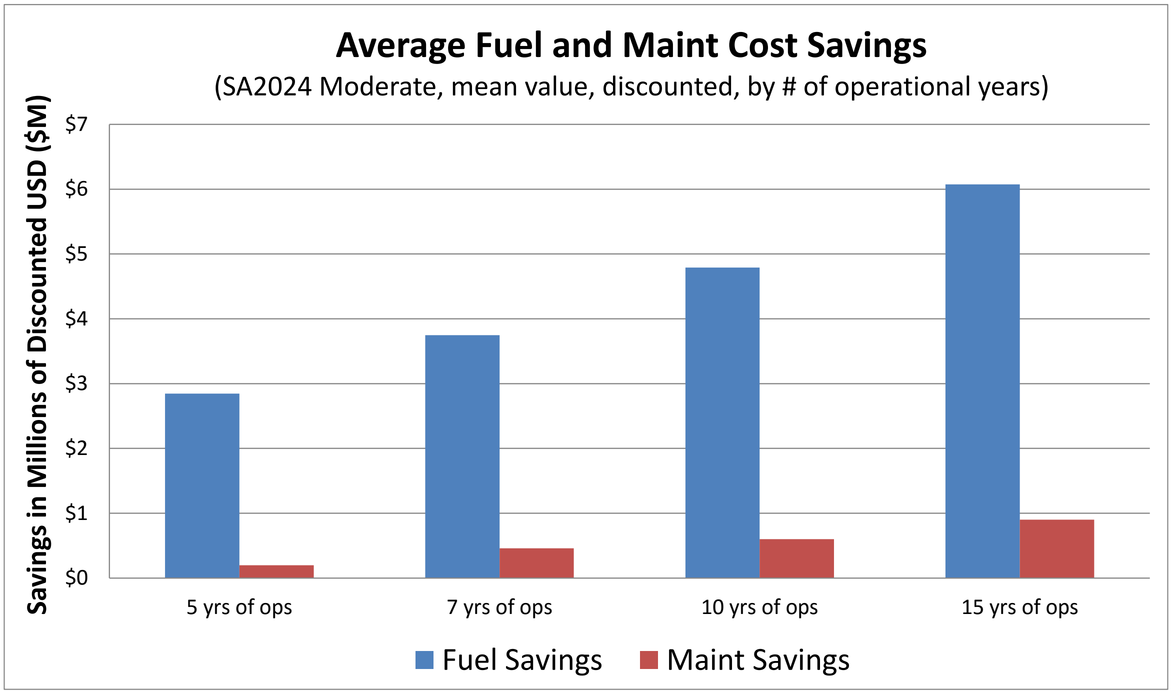


FIGURE 40 – FUEL AND MAINTENANCE SAVINGS FOR SA 2024 MODERATE AS NUMBER OF OPERATIONAL YEARS INCREASES

5.4 Findings

Figure 41 provides an overall summary of the TOC relative benefits for fuel reduction for the various EIS years. The results shown are discounted values at a 9% annum rate, contain overall investment for a ten-year production quantity run, consider seven years of operations for projection of fuel and maintenance costs, and factor in income for the residual value of the aircraft after 17 years of first-operator life. The analysis shows that for the near term EIS, fuel reductions of approximately 25% are expected to provide a reduction in TOC for operators in 2024. For the 2034 EIS it is projected that about a 40% fuel reduction will payback for operators over a seven-year time horizon.

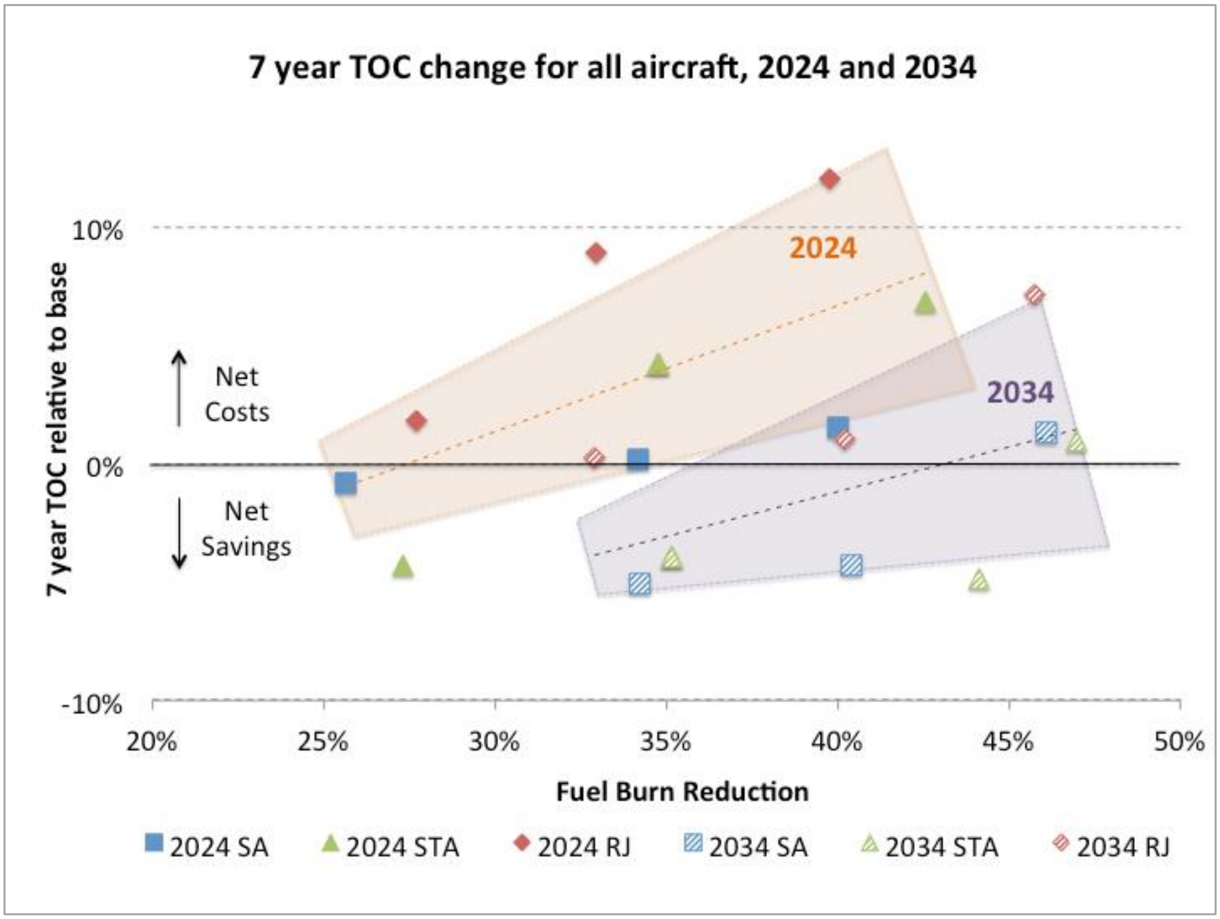


FIGURE 41 – SEVEN-YEAR TOC CHANGE FOR ALL AIRCRAFT

The overall findings of the study are summarized below.

- The fuel burn of new aircraft designs can be reduced by approximately 25% in 2024 and 40% in 2034 in a cost-effective manner, as defined by seven years of operation and a discount rate of 9%. These aircraft would provide net savings to the first operator while reducing fuel burn and associated CO_2 emissions. Additional improvements would become cost-effective by varying assumptions, for example the use of a lower discount rate (3%) to reflect a social cost of capital.
- The development of incrementally more fuel-efficient new aircraft types increases overall manufacturing and development costs while providing savings in fuel and maintenance costs, as seen by the TOC results summarized above. The net TOC change for each EIS year and technology deployment scenarios depends on the relative magnitude of these offsetting factors.
- Among the technology classes, the largest share of fuel burn savings are expected to be attributable to propulsion technologies, followed by aerodynamic improvements and then technologies to reduce structural weight.
- Total Ownership Costs were dominated by operator capital expenditures (51%-57% of TOC) and fuel costs (36%-42%) while maintenance costs played a lesser role in determining the net costs across scenarios (5%-8%).
- The fuel cost analysis used an assumption that fuel prices will increase at 1% per year through the life of the study; if fuel prices were to increase beyond this rate then the TOC savings will increase and larger fuel burn reductions would provide net economic benefits.
- TOC savings increase over time, with substantial fuel and maintenance savings accruing beyond the base seven year operational period used in the study.
- The study was based on implementing currently identified technologies that could be matured in time for deployment, it does not consider aggressive or exotic technologies that may be able to achieve more aggressive reduction.
- Among the various assumptions investigated, the net TOC impacts of advanced aircraft were found to be most sensitive to assumptions about market capture. Where a manufacturer captures less market share than anticipated, operator capital costs increase as the technology maturation and development costs need to amortized over a smaller number of aircraft. The risk of escalating costs and subsequent decrease in product viability may lead to risk adverse manufacturers to introduce products with lower levels of fuel efficiency than predicted based upon deterministic economic factors alone.