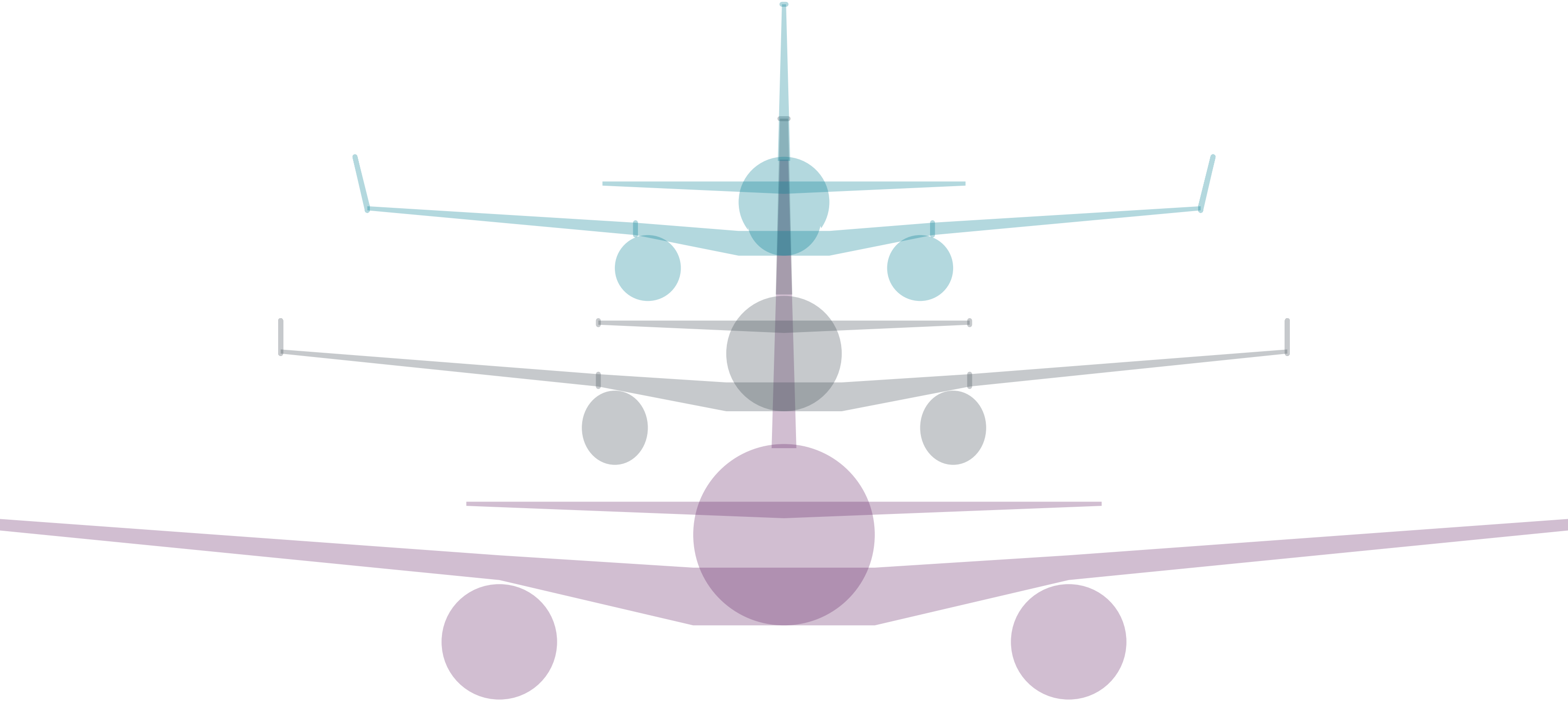

COST ASSESSMENT OF NEAR AND MID-TERM TECHNOLOGIES TO IMPROVE NEW AIRCRAFT FUEL EFFICIENCY

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EXECUTIVE SUMMARY

The aviation sector is one of the fastest-growing sources of greenhouse gas (GHG) emissions globally, with carbon dioxide (CO_2) emissions from international aviation projected to triple by 2050 compared with today's levels. Nonetheless, the aviation industry is lagging fuel-efficiency goals set by the International Civil Aviation Organization (ICAO) for new aircraft types in the 2020 and 2030 time frames by more than a decade.

This report provides a comprehensive cost assessment of near-term (2024) and mid-term (2034) fuel-efficiency technologies for commercial aircraft in the United States. It considers the upfront costs and operating savings, the fleet-wide benefits of fully adopting cost-effective technologies, and the potential impacts on ticket prices assuming that fuel savings are passed along to consumers. A performance comparison between the cost-effective fuel-efficiency technologies identified in this study and of aircraft currently under development is also presented, along with a discussion regarding policy options to bridge the gap between what is possible and current market demand for fuel efficiency in new aircraft.

Figure ES-1 depicts the fuel-efficient technologies—advanced engines, improved aerodynamics, and lightweight materials—studied in this report and their general placement on the aircraft. The technologies shown in the figure were grouped into technology packages, ensuring that mutually exclusive technologies were not deployed on the same aircraft. Each package is modeled into the baseline aircraft and "flown" to assess its improved performance.

This study finds that the fuel consumption of new aircraft designs can be reduced by approximately 25% in 2024 and 40% in 2034 compared with today's aircraft by deploying emerging cost-effective technologies providing net savings to operators over a seven-year time frame. The fuel savings of the 2024 cost-effective improvements are roughly double those seen for new aircraft designs being brought to market by manufacturers today in response to market forces alone, which are projected to burn between 9% and 13% less fuel than today's aircraft with similar seating configurations.

Figure ES-2 compares the cost-effective improvements identified in this study for three aircraft types to long-term trends in new design fuel efficiency on a fuel per revenue passenger kilometer (RPK) basis, normalized to the fuel burn of the reference single aisle (SA), small twin aisle (STA), and regional jet (RJ) aircraft (reference = 100). As the figure indicates, fully deploying the cost effective technologies identified in this study on new aircraft designs would more than double the rate of expected fuel burn reductions through 2034, from an average of slightly less than 1% per year from 1980 to 2016 up to 2.2% per year in the coming decades. This gap between market-driven fuel-efficiency improvements and what is estimated to be cost effective given current fuel price projections represents an opportunity for additional CO_2 emission reductions at net savings for airlines and consumers.

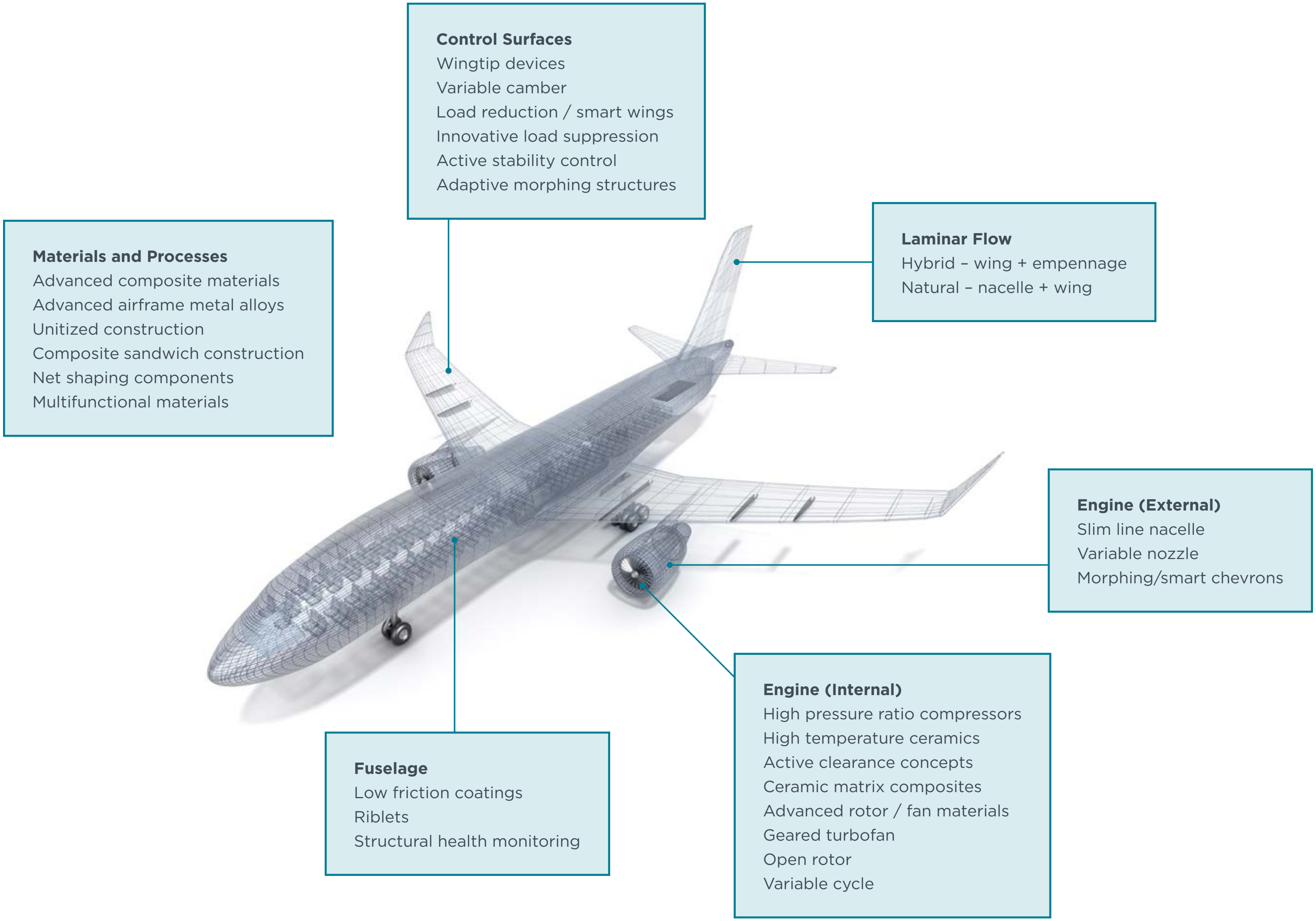

Figure ES-1 Example aircraft fuel-saving technologies assessed

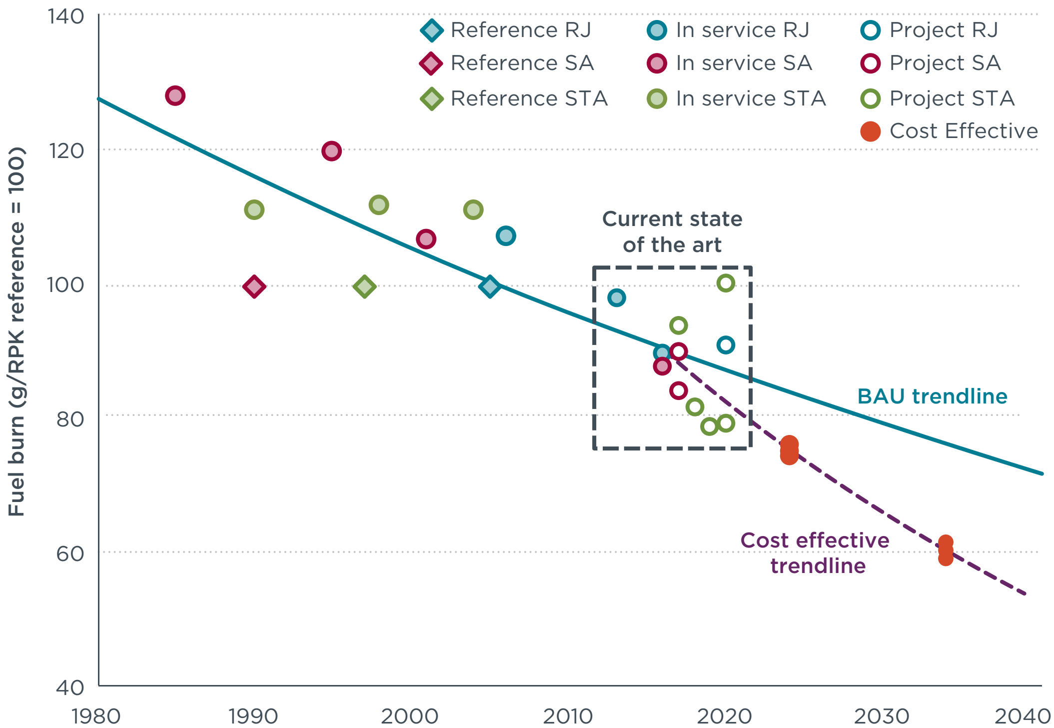

Figure ES-2 Trends in new aircraft fuel burn by entry into service year, 1980 to 2040

Accelerating the adoption of these technologies would provide significant benefits to airlines, consumers, and the environment. For all advanced aircraft modeled, benefits outweighed costs by a factor of three to one, meaning that for each dollar spent to purchase a more advanced aircraft, roughly $3 would be saved in operational costs (fuel plus maintenance) over a 17-year first-owner lifetime. Collectively, as shown in Figure ES-3, U.S. airlines could reduce their fleet-wide fuel spending over the 2025 to 2050 time frame by more than 200 megatonnes of oil equivalent (Mtoe), or 19%, compared with the baseline case through the adoption of cost-effective technologies. If passed along to the consumer, these savings could lower ticket prices by up to $20 for short-haul flights and $105 for long-haul international flights, assuming U.S. Energy Information Administration (EIA) reference fuel price projections. Fleet-wide CO_2 emissions from U.S. airlines could be reduced by 6% in 2030 and 30% in 2050 compared with the base case.

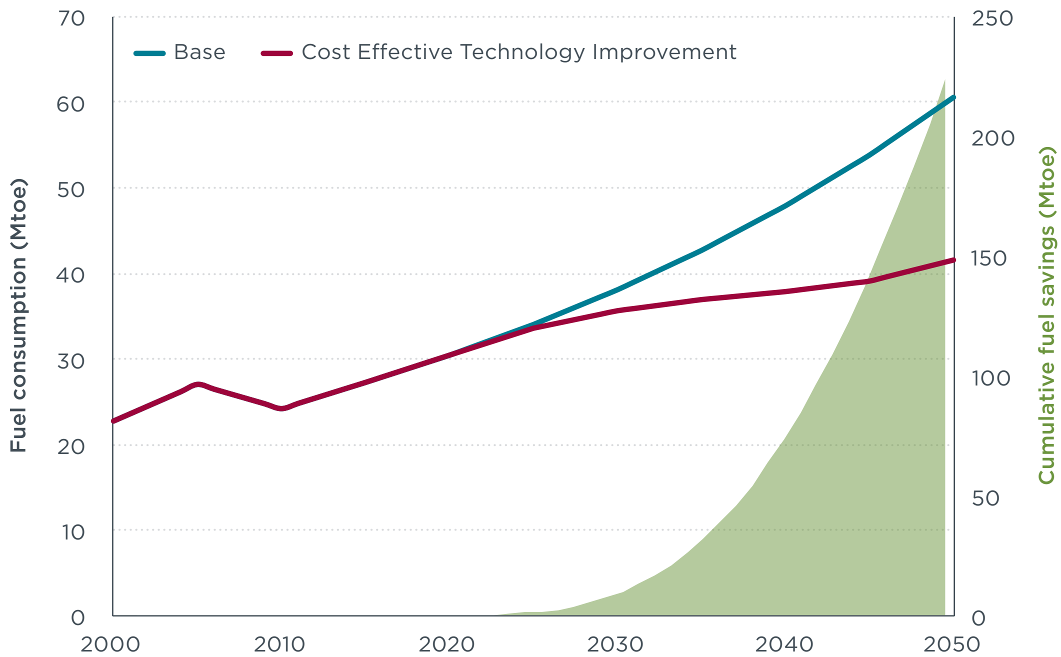

Figure ES-3 Estimated U.S. fleet-wide fuel consumption and savings, 2000 to 2050

These results align with plans to reduce the impact of U.S. aviation on the global climate. The U.S. Aviation Greenhouse Gas Emissions Reduction Plan submitted to ICAO in 2015 details strategies to achieve the aspirational goal of carbon-neutral growth for U.S. commercial aviation by 2020, using 2005 emissions as a baseline. This study suggests that the aircraft and engine technology improvements needed to achieve the U.S. goals can be accomplished in a cost-effective manner.

The substantial gap between the improvements identified in this study and the products being brought to market for delivery highlights the need for public policies to promote aircraft fuel efficiency, including robust performance standards for new aircraft; economic incentives to provide market pull for new technologies by promoting fleet turnover; and research support to defray the costs of maturing new technologies.

1. INTRODUCTION

1.1. AVIATION GREENHOUSE GAS EMISSIONS IN PERSPECTIVE

Aircraft are large, and quickly growing, contributors to carbon dioxide (CO_2) emissions from the transportation sector. Aircraft emit about 3% of global CO_2 emissions, and 10% of total CO_2 emissions from the transportation sector (EIA, 2015). In addition, the aviation sector is one of the fastest-growing sources of greenhouse gas (GHG) emissions globally. The International Civil Aviation Organization[1] (ICAO) projects that CO_2 emissions from international aviation will triple in 2050 compared with today's levels given current trends (ICAO, 2010; ICAO, 2013). Figure 1 summarizes historical (1981 to 2012) and projected (through 2050) trends in global aviation CO_2 emissions, including military and general aviation. During this time, the global fleet is expected to grow from 19,700 commercial passenger aircraft in 2010 to 68,000 in 2050.[2]

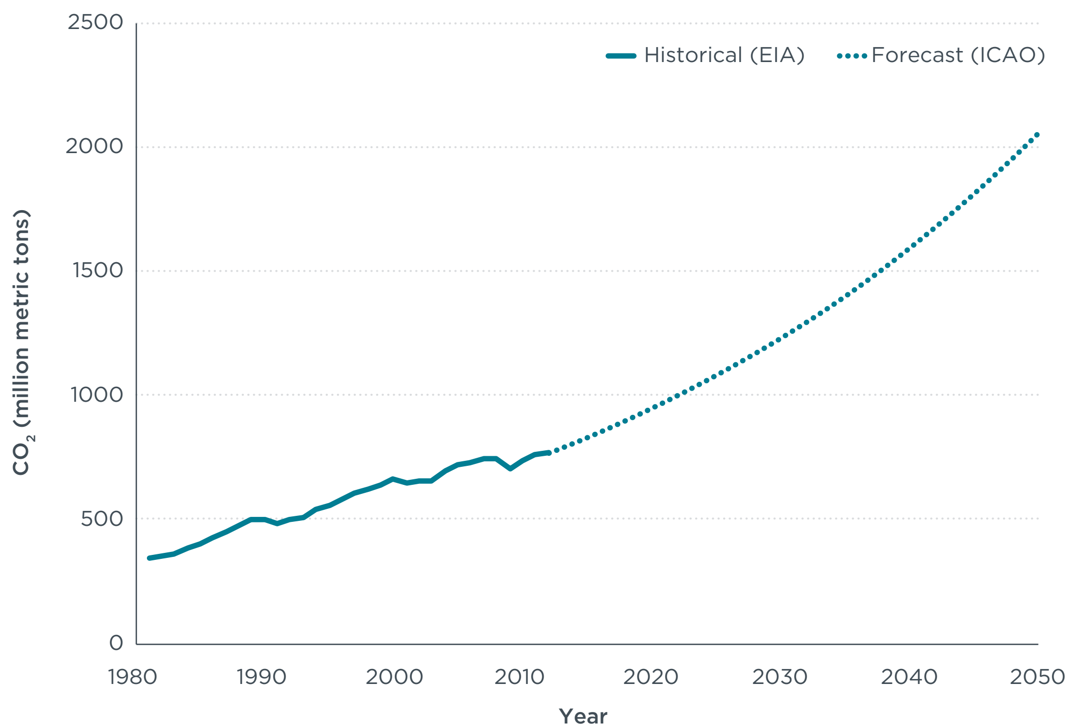

Figure 1 Global CO_2 emissions from aviation, 1981 to 2050 (EIA 2012, ICAO 2010)

CO_2 emissions are directly correlated with fuel consumption, traditionally the largest operating expense for airlines. In theory, airline demand for more fuel-efficient aircraft should provide sufficient market pull for the development and deployment of all achievable fuel-efficient technologies. Evidence suggests that new aircraft and engines developed by manufacturers are less efficient than is technologically possible, although information on the relative costs of further improvements is scarce. For example, it is projected that the aviation industry will miss ICAO's 2020 and 2030 fuel-efficiency goals for new aircraft by more than a decade (Kharina & Rutherford, 2015). The most likely

1 ICAO is the specialized United Nations agency that sets recommended standards and practices for civil aviation worldwide, with specific responsibility to control international greenhouse gas emissions.

2 Based on ICAO projections (ICAO, 2013), extrapolated to 2050.

driver of this shortfall is the trend toward re-engined aircraft, rather than clean sheet designs, that fail to deploy new aerodynamic and material technologies and, relatedly, the continued expansion of capability (payload and especially range), which diverts some technology gains away from fuel efficiency (ICCT, 2016).

Cost-effectiveness analyses, which are typically used to set performance standards for new vehicles, assessing the costs and benefits of fuel-saving technologies are abundantly available for other modes of transportation. Analyses of light-duty (e.g., EPA, 2009; EPA, 2013) and heavy-duty vehicles (e.g., Mezler et.al, 2015) are in particular broadly available. In contrast, economic assessments of fuel efficiency for commercial aircraft are rare. This report aims to address this gap. While the findings of this study are generalizable worldwide, this report focuses on the costs and benefits for U.S. airlines and consumers, reflecting both the importance of the U.S. aviation sector and the expectation that new policies to promote aircraft fuel efficiency, notably a CO_2 emission standard for new aircraft, will be adopted first there.

1.2. POLITICAL AND REGULATORY CONTEXT

1.2.1. International: CO_2 standard and global market-based measure

The 1997 Kyoto Protocol, which included targets and timetables for reducing GHG emissions to specific levels for countries, did not establish binding targets for international aviation and shipping. However, it was agreed that GHG emissions from international aviation should be “limited” or “reduced” by developed countries working through ICAO. Twelve years later, in 2009, ICAO started work to establish the world’s first CO_2, or efficiency, standard for new aircraft. The standard was completed in February 2016, and ICAO contracting states are expected to implement it under national legislation starting in 2020. The CO_2 standard is part of ICAO’s basket of measures to achieve two main goals for aviation: an annual 2% average fleet-wide fuel efficiency improvement until 2020 and an aspirational 2% improvement per annum from 2021 to 2050, and to achieve carbon neutral growth from 2020 (ICAO, 2010b). Separately, airlines have established a goal to reduce sector-wide net emissions of 50% below 2005 levels by 2050 (International Air Transport Association [IATA], 2013b).

As part of efforts to reduce emissions, the European Union (EU) adopted the European Union Emissions Trading System (EU ETS) in 2005 as a major part of the European transport policy, with inclusion of aviation starting in 2012. This triggered negative reactions from the airline industry and non-EU countries, notably the United States, China, and India. For example, in the United States the European Union Emissions Trading Scheme Prohibition Act of 2011 allowed the U.S. Secretary of Transport to prohibit U.S. carriers from participating in the EU ETS. With this lack of agreement on international aviation, the EU ETS requirements were suspended for flights to and from non-EU countries between 2013 and 2016 to allow time for negotiation on a global market-based measure applied to aviation within ICAO.

1.2.2. U.S. federal actions

Since the 1970s, the U.S. Environmental Protection Agency (EPA) has regulated aviation emissions under the Clean Air Act (CAA). Section 231 of the CAA directs that “*The Administrator shall, from time to time, issue proposed emission standards applicable to the emission of any air pollutant from any class or classes of aircraft engines which in his judgment causes, or contributes to, air pollution which may reasonably be anticipated to endanger public health or welfare.*” (CAA).

The EPA issued its first aviation emission standard in 1973, regulating smoke, fuel venting, and specified pollutants: hydrocarbon, carbon monoxide, and nitrogen oxides (NOx) (EPA, 1973). In 1997, the EPA amended the regulation to adopt ICAO's emission standards and test procedures (EPA, 1997). In 2011, a federal court ruled that the EPA must consider whether GHGs from aircraft should be regulated under the CAA by conducting an endangerment finding for aviation emissions. In 2015, the EPA proposed that GHG emissions are a danger to public health and welfare, the first step in a process to regulate those emissions from aircraft (EPA, 2015). In August 2016, the EPA finalized the endangerment finding, making its obligation to set an emission standard mandatory. EPA contributed heavily to ICAO's recommended CO_2 standard alongside the Federal Aviation Administration (FAA) and has stated that it will adopt domestic standards "at least as stringent as" those recommended by ICAO (EPA, 2016).

Last year, in June 2015, the FAA submitted a U.S. Aviation Greenhouse Gas Emissions Reduction Plan to ICAO (FAA, 2015a). The document presents U.S. goals and specific efforts and programs to reduce fuel burn and GHG emissions from aircraft. Examples include the FAA's CLEEN (Continuous Lower Energy, Emissions, and Noise) program targets to demonstrate technology that delivers 33% fuel burn reduction in 2015 compared with "current technology." The CLEEN II program aims for a modestly higher target: 40% reductions in fuel burn compared to year 2000 best-in-class in-service aircraft to be matured and entered into product development by 2020. The National Aeronautics and Space Administration (NASA) Environmentally Responsible Aviation (ERA) program targeted a 50% reduction in fuel burn for new subsonic passenger and cargo transport aircraft in 2020, while the NASA Advanced Air Transport Technology (AATT) program aimed for 70% fuel burn reduction for emerging aircraft with entry into service (EIS) dates after 2030.

1.3. RESEARCH BASIS

Mandatory efficiency, $CO_{2,}$ or GHG standards for transportation/mobile sources have been shown to improve vehicle efficiency by accelerating the deployment of new technologies without impacting vehicle manufacturers adversely. In Europe, before the EU-wide mandatory CO_2 regulation was established in 2008, the carbon intensity of new passenger vehicles fell by about 1% per year. After the industry's voluntary target was replaced by the mandatory regulation, the CO_2 reduction rate increased significantly—up to 4% per year (Tietge & Mock, 2014)—from 2008 to 2013. A prominent example of increased technology deployment in this case is an energy-saving transmission system with six or more gears. In 2007, only 30% of new cars in Europe were equipped with the technology. By 2013, almost 70% of new cars in the EU incorporated this technology (Mock, 2014).

In February 2016, ICAO's Committee for Aviation Environmental Protection (CAEP) agreed to the first CO_2 (fuel efficiency) standard for aircraft, the last major transportation mode to be regulated under such standard. ICAO member states are expected to implement the ICAO CO_2 standard starting in 2020 for new designs and in 2023 for types already in production. In contrast to existing fuel-efficiency standards for other modes, however, ICAO's recommended standard is not expected to reduce emissions from aircraft beyond that already expected due to planned investments in fuel efficiency by manufacturers (ICCT, 2016).

A few publicly available studies have analyzed the costs of reducing CO_2 emissions from aircraft. Those studies, which typically apply top-down methodologies, have reached different conclusions about the cost-effectiveness of reducing CO_2 emissions from aircraft via technological means. One study concludes that CO_2 emissions from narrow-body aircraft can be reduced by 2% annually via technology improvement and operational optimization (not taking into account alternative fuels) in a cost-effective manner assuming oil prices remain between $50 and $100 per barrel (Schafer et.al., 2015). Another study, funded by the U.K. Department for Transport, assessed the cost-effectiveness of different policy levers to reduce CO_2 emissions from the U.K. aviation industry, including promoting new aircraft fuel efficiency, operational improvements, support and/or mandates for biofuel use, and, in some cases, behavioral change. That study suggests that promoting aircraft fuel efficiency, either through a CO_2 standard forcing older aircraft types out of production or policies to support the development of new technologies, is the least cost-effective means of controlling emissions while operational improvements are the most cost-effective (Holland, et.al., 2011).

This study was inspired by ICAO's Report of the Independent Experts on the Medium and Long Term Goals for Aviation Fuel Burn Reduction from Technology (ICAO 2010a). The study, conducted by aviation industry experts and leaders, estimated that the fuel consumption of new aircraft designs could be reduced by up to 48% (equivalent to 92% higher fuel efficiency) in 2030 relative to the 2000 baseline if emerging technologies are deployed to conventional airframe designs. What level of technology implementation on future aircraft designs would be cost effective for operators and manufacturers, and under what conditions, was beyond the scope of that study. There is, not surprisingly, little publicly available data regarding the actual cost of developing and manufacturing aircraft equipped with new technologies since the information is considered proprietary by industry. This study aims to address this gap by estimating the costs and benefits of new fuel-efficiency technologies in the United States, an important and representative aviation market. Non-aircraft technologies such as biofuels, operational practices, and efficiencies associated with improved air traffic control are beyond the scope of this work.

1.4. PURPOSE OF THE STUDY

Based on the discussion above, this study has the following goals:

1. To estimate the incremental costs and benefits to operators of purchasing new, more fuel-efficient aircraft in the near- (2024) and mid- (2034) term.
2. To estimate fleet-wide benefits (dollars, tons of oil, and CO_2 saved) of integrating cost-effective technologies into U.S. fleets.
3. To estimate potential benefits to U.S. consumers, in terms of ticket prices, assuming that the cost savings of advanced aircraft are passed along.
4. To compare the cost-effective technologies identified in this study to new aircraft types under development by manufacturers, and to discuss policies to bridge any gap.

1.5. STRUCTURE OF THE REPORT

This report is organized as follows: Section 2 outlines the methodology used in this study. Section 3 presents key findings as well as the driving factors and sensitivity analyses. Section 4 concludes the report with a discussion of policy implications. Further detail on the technology modeling approaches and results can be found in Appendices A and B and the accompanying consultant report (Tecolote, 2015).

2. METHODOLOGY

2.1. OVERVIEW

2.1.1. Contributors

This project was a collaborative effort among three groups: Tecolote Research, Inc., an expert technical advisory group (TAG), and the International Council on Clean Transportation (ICCT).

Tecolote Research, Inc., is a private firm specializing in cost estimations for high-technology acquisition programs, with experience providing cost estimation support to U.S. government agencies since 1973. The Automated Cost Estimating Integrated Tools (ACEIT) and Joint Analysis Cost/Schedule (JACS) tools developed by Tecolote are used by the full range of Department of Defense agencies and organizations, as well as other U.S. government agencies such as NASA, the FAA, and the National Oceanic and Atmospheric Administration (NOAA), among others. For this project, Tecolote was supported by external subject matter experts (SMEs) in conducting detailed technical analysis to support the identification and resulting impact of technologies in the areas of aircraft structural design, configuration, aerodynamics, and propulsion.

The TAG is a blue-ribbon panel of seven experts and industry leaders who contributed comprehensive expertise in all aspects of the study: aircraft fuel-saving technology and design on engines, aerodynamics, and structures, as well as aircraft maintenance and economic assessment. Table 1 lists the membership of the TAG along with their affiliation and chief expertise.

Table 1 Technical Advisory Group members

Member	Affiliation	Chief 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, National Aeronautics and Space Administration (NASA)	Aircraft technology maturation and assessment
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	Aerospace Consultant, Boeing retired	Structures

*Co-authors of ICAO Fuel Burn technology review (ICAO 2010a)

2.1.2. Study phases

The study was divided into three phases:

Phase I identified the three aircraft types included in the study (single aisle, small twin aisle, and regional jet) as well as the baseline aircraft for each type. It also grouped discrete technology improvement packages in two scenario years to qualify the advancements in propulsion, structures, and aerodynamics relevant to improvements in fuel efficiency for each scenario. On the cost side, Phase I defined the cost model data structure and high-level methodologies.

Phase II assessed the aircraft-level efficiency improvements of the technology packages for each EIS year and aircraft class. This included generating and quantifying user factors from the technology packages for performance modeling based on Piano 5[3] default parameters. With those user factors, the fuel burn performance of each aircraft type was quantified with and without technology improvements. A more comprehensive technology cost model was also developed.

Phase III, the final phase of the study, estimated the costs to manufacturers and operators of improved aircraft, focusing on development, integration, acquisition, and maintenance.

Following the completion of Phase III, further analyses was completed by ICCT to estimate the impact of cost-effective technology introduction on U.S. fleet-wide fuel consumption, CO_2 emissions, and ticket prices for consumers.

Table 2 presents the different phases of the study and the main contributor of each task within the phases.

Table 2 Study phases, tasks, and contributors

Phase	Task	Contributor
Phase I	Identifying & quantifying potential improvement from fuel-saving technologies	TAG
	Identifying technology packages by scenario	TAG
	Defining cost model data structure and high-level methodologies	Tecolote
Phase II	Defining Piano user factors for improved aircraft modeling	Tecolote
	Piano modeling for aircraft fuel burn reduction	ICCT
	Defining cost modeling assumptions	Tecolote
Phase III	Comprehensive modeling of recurring and nonrecurring manufacturing costs and operational savings	Tecolote

2.1.3. Main parameters

AIRCRAFT TYPES AND REFERENCE AIRCRAFT

Ideally this study would encompass all commercial passenger aircraft types available in the market but, to limit scope and therefore maximize the quality of the work, this study focuses on the three most representative aircraft types in the fleet today: single aisle (SA), regional jet (RJ), and small twin aisle (STA). There are a few reasons behind this. First, there is more publicly available data on these three aircraft types compared

3 Piano 5 is a commercial aircraft performance model used in this study. More detailed information about this tool is provided in Section 2.3.

with other types (e.g., turboprops, business jets, and large twin aisles). Secondly, more than 50% of global aircraft sales in 2010 and 64% in 2015 were of these three types. Additionally, according to U.S. Department of Transportation (2014) they accounted for more than 77% of revenue passenger kilometers (RPK) flown in the United States[4] and therefore present the largest potential to reduce fuel burn by introduction of more fuel-efficient aircraft. Finally, two of the types, SA and STA, were studied in the ICAO fuel burn technology review in 2010 (ICAO 2010a), providing a benchmark to which results can be compared.

For each aircraft type studied, a reference aircraft was chosen to compare the incremental upfront costs and fuel and maintenance savings of improved aircraft. Representative aircraft were chosen using Ascend Online Fleets based on historical and future sales within each respective class. The chosen reference aircraft and a few chosen parameters are presented in Table 3, while Figure 2 presents a three-view comparison of these aircraft.

Table 3 Select parameters of reference aircraft

Parameter	Reference Aircraft		
	Airbus A320-200	Boeing B777-200ER	Embraer E190AR
Length (m)	37.6	63.7	36.2
Wingspan (m)	33.9 (1)	60.9	28.7 (1)
Max takeoff weight (kg)	77,000	298,000	51,800
Design payload (kg)	13,000	30,000	9,800
Design range (km)	5,320	14,100	4,630
Seat capacity	150-180	314-440	94-114
EIS year	1988	1997	2004

(1)With sharklets/winglets

4 U.S. Department of Transportation, BTS Form 41 Traffic (2014)

Figure 2 Piano 5 reference aircraft 3-view

EIS YEARS

ICAO's CO_2 standard will be implemented for applications for new type certification in 2020. After taking into account the approximately three to five years needed for new type certification, a 2024 EIS year was selected for the near-term scenarios. Furthermore, to keep this study in line with the ICAO fuel burn technology review that has a 10-year lag between scenarios, an EIS year of 2034 was chosen for mid-term scenarios.

SCENARIOS

To provide multiple observation points with varying future technology implementation levels, three technology deployment scenarios of increasing ambition were included for each EIS year. In total, seven technology scenarios were assessed in this study for each aircraft type: the reference scenario and three technology scenarios for each analysis year. Table 4 presents a definition of each scenario.

Table 4 Technology deployment scenarios

Scenario	Definition
Reference	The reference aircraft **without technological improvements**. This is the benchmark scenario, to which all other technology scenarios were compared to evaluate the benefits (fuel and maintenance savings) and costs (technology maturation, development, upfront manufacturing costs) of added technologies.
Evolutionary	A best estimate of real-life aircraft that would be released in the respective EIS (2024 or 2034) year under "**business as usual**" technology improvements.
Moderate	A **modest increase of technology improvements** compared with the Evolutionary scenario, driven by either policy or fiscal factors such as unexpectedly high fuel prices.
Aggressive	Implementation of **all cutting-edge fuel-saving technologies** in development for conventional airframe designs[5], irrespective of whether they are likely to be economically reasonable.

2.2. TECHNOLOGIES ASSESSED

In Phase I of this study, aircraft fuel-saving technologies that are either available today or in some stage of development (i.e., those at TRL[6] 3 and above) at the time of study were evaluated. The exclusion of speculative technologies helped limit modeling uncertainty. For the same reason, technologies that require larger changes in aircraft design and architecture (e.g., blended wing body and truss-braced wings) were excluded. As a consequence, the potential fuel burn reductions for 2034 scenarios assessed in this study can be considered somewhat conservative.

Figure 3 presents some representative technologies and their general placement on an aircraft. Drawing upon the list of technologies, six advanced technology development scenarios were created for each aircraft type: one for each scenario level—Evolutionary, Moderate, and Aggressive—per EIS year. This step included an assessment to ensure that mutually exclusive technologies (e.g., natural laminar flow and hybrid laminar flow) were not integrated into the same structure (e.g., wings/empennage) in the same technology package. The comprehensive list of technologies for each scenario is presented in Appendices A (airframe) and B (engine).

5 Advanced aircraft architectures, such as blended wing body (BWB) and strut-braced wing aircraft, were excluded from this study to limit modeling uncertainty.

6 Technology Readiness Level (TRL) is a scale of technology maturity originally developed by NASA. The lowest levels (TRL 1 to 3) are dedicated to preliminary concept up to proof of concept, TRL 4 and 5 are stages of laboratory and relevant environment demonstration, TRL 6 and 7 are stages of prototype testing, and the latest stages (8 and 9) are implementation of technology into a vehicle and flight testing. Detailed definitions of each TRL can be found at https://esto.nasa.gov/files/trl_definitions.pdf

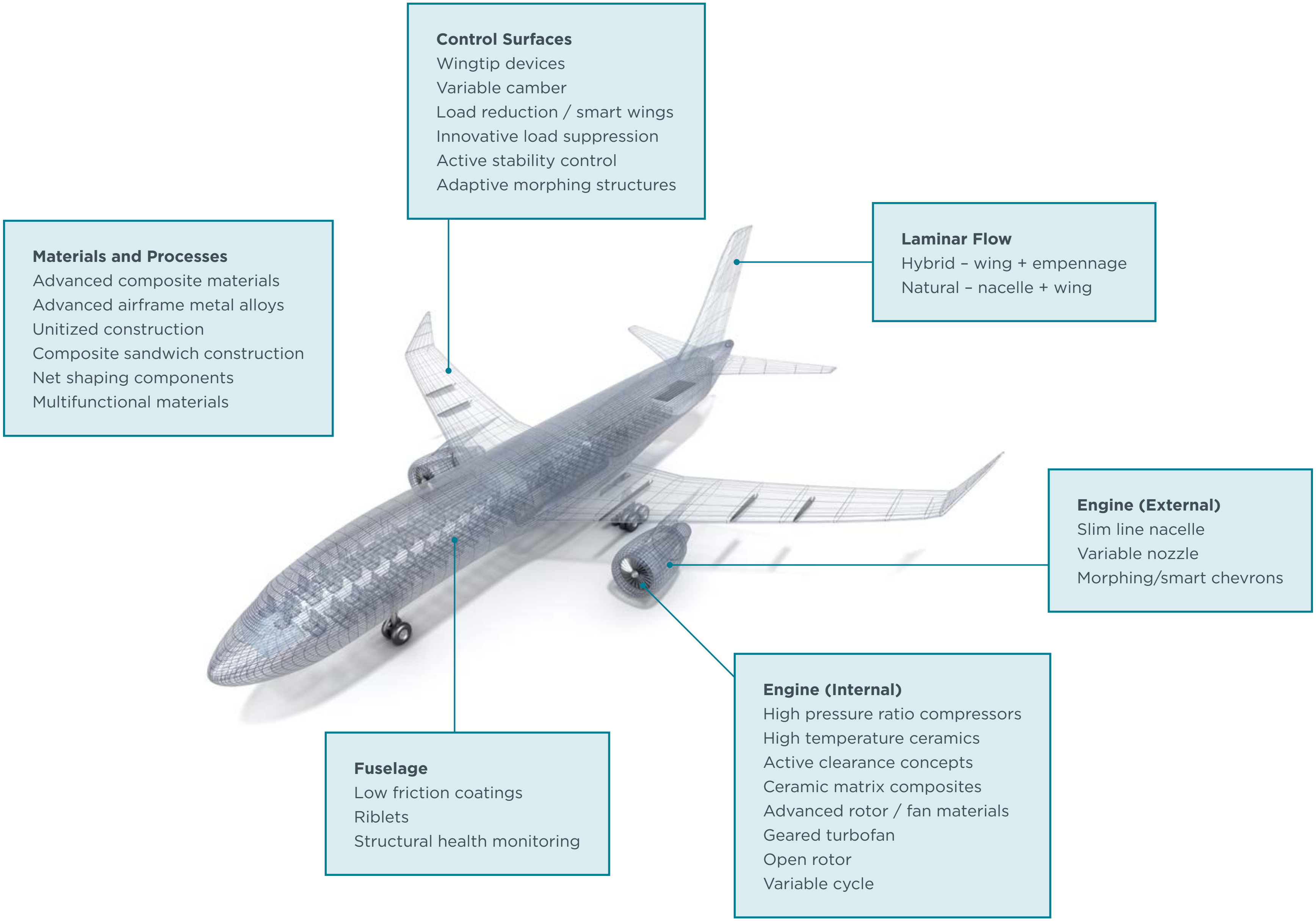

Figure 3 Example aircraft fuel-saving technologies assessed

2.3. FUEL BURN MODELING

Based upon these technology deployment scenarios, the fuel efficiency of the improved aircraft for each aircraft type and EIS year was evaluated. Piano 5, a commercial aircraft performance modeling tool developed by Lyssis, Ltd., was used for aircraft modeling, while the performance modeling for engines was performed using GasTurb 10. A general description of the aircraft and engine technology modeling approaches is provided below, with additional detail presented in Appendix B.

AIRCRAFT TECHNOLOGY MODELING

Piano includes a database of detailed technical and performance data for conventional, commercial, subsonic aircraft certified to civil aviation standards. Assessing the fuel efficiency of aircraft under a given deployment scenario was a multistep process. First, the appropriate aircraft model was identified from the Piano database for each reference aircraft defined in Section 2.1.2. When multiple Piano aircraft are available for the same aircraft type due to variations in maximum takeoff weight (MTOW) or engine, the Ascend fleet database[7] was consulted to determine the most prominent variant based on the global fleet as of April 2013.

Based on the technology deployment scenarios defined in Section 2.2, these baseline aircraft were modified (by changing the appropriate Piano user factors) and resized, while keeping payload and range capability[8] constant, to represent improved aircraft with advanced technologies incorporated. Fuselage size and geometry, number of seats, and operational parameters such as passenger weight, number of crew, etc., were kept constant.

For each of the six advanced technology deployment scenarios (2024 Evolutionary, Moderate, and Aggressive; 2034 Evolutionary, Moderate, and Aggressive) for each aircraft type, a set of Piano user factor multipliers indicating technology impact on the aircraft characteristics and performance were developed by SMEs identified by Tecolote, Ltd. This process resulted in a set of new user factors or performance parameters unique to the improved aircraft.

Based on these user factors, the final improved aircraft was obtained through an optimized resizing process with the objective to minimize fuel burn. The optimization parameters used in this process are MTOW, wing area, aspect ratio, sweep angle, and engine thrust.

ENGINE TECHNOLOGY MODELING

GasTurb, the engine performance modeling software used in this study, is a commercially available program that uses pre-defined engine configurations while permitting input of important parameters, including component geometry. GasTurb was chosen due to its ability to model detailed performance of aircraft engines, which is not possible in Piano.

GasTurb outputs include the engine's specific fuel consumption (SFC), flow, pressure, and temperature values at all major stations within the engine, using nomenclature

7 http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/

8 In this study the R1 point (maximum range at maximum structural payload) is used as the reference point for aircraft resizing.

consistent with current industry standards. Another output used in the latter phases of this study is the engine thrust/weight ratio that, combined with thrust values from Piano, estimates the engine weight used in cost estimation.

FUEL BURN CALCULATION

To estimate fuel burn reductions as a result of technology implementation, each scenario-modified aircraft was "flown" on a set of typical missions for each of the three aircraft types within their payload-range envelope.[9] The matrices were derived based on 2010 payload and mission lengths and frequencies flown by each reference aircraft type from the BTS Form-41 T100 data for U.S. international (inbound and outbound) and domestic flights. Figure 4 shows the combination of stage lengths (flight distance in kilometers, x axis) and payload (in kilograms, y axis) flown by each aircraft type. Combinations in red indicate the most common missions, in terms of stage length and payload, flown within and to or from U.S. airports in 2010.

9 A payload-range envelope is defined by the aircraft capability of carrying the maximum amount of payload authorized under its airworthiness certification over a certain range.

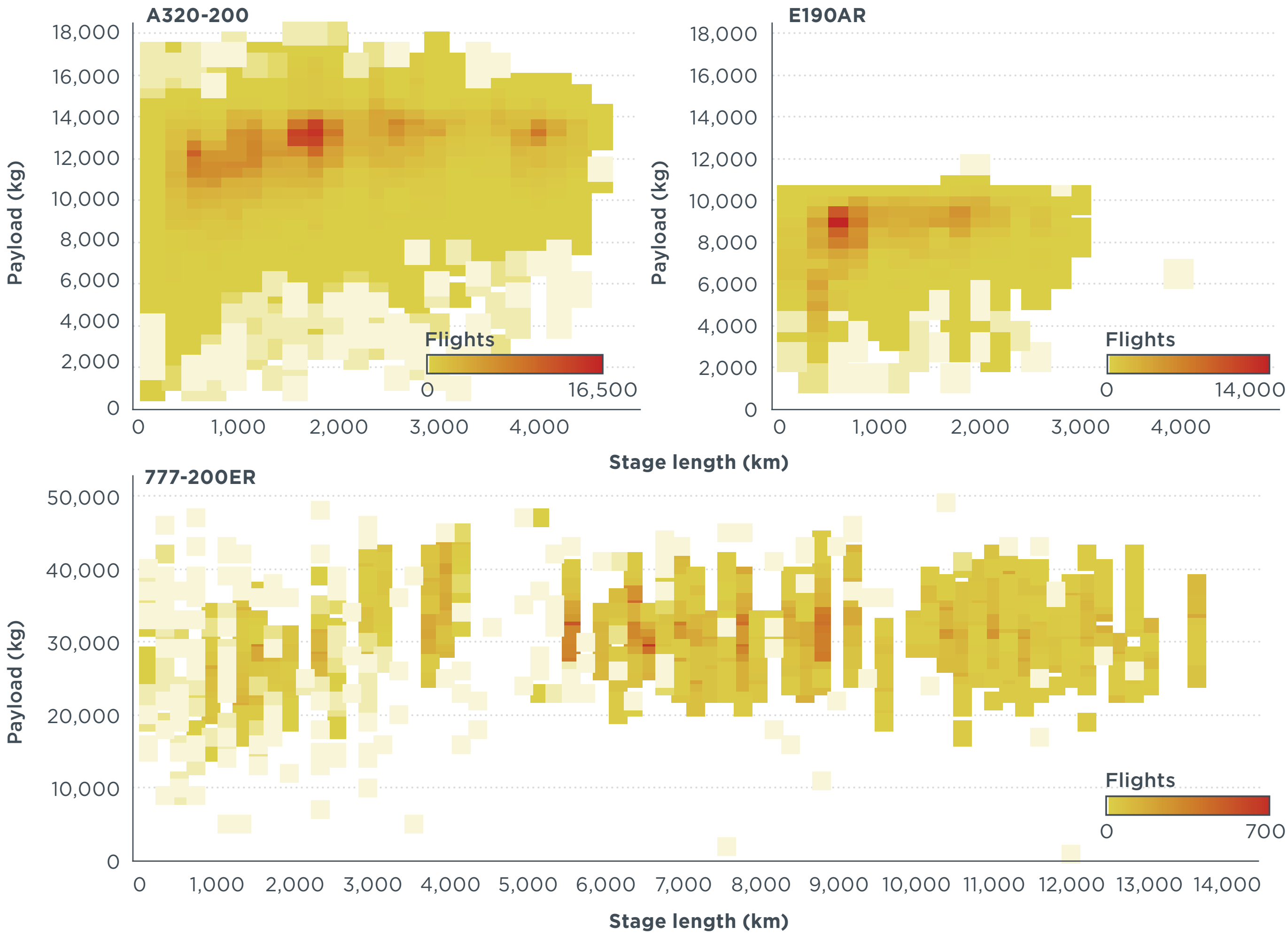

Figure 4 Typical operations by aircraft type used for fuel burn determination

To streamline the modeling process, payloads were divided into 500-kilogram bins, and ranges into 200-kilometer bins. Under each payload-range bin, the aircraft (reference and six technology scenarios) were "flown" at cruise speeds enabling 99% specific air range (SAR), with fuel reserve and allowances set at 370-kilometer diversion distance, 30 minutes holding time, and 5% mission contingency fuel for all aircraft. All flight levels or cruise altitudes from 17,000 feet 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 small twin aisles based upon average taxi times for U.S. operations in 2010 by type.[10] Fuel consumption per mission was weighted based on the frequency of the flight at each payload-range bin, and compared with the reference aircraft fuel consumption calculated using the same methodology.

2.4. MODELING OF FLEET-WIDE SAVINGS

Potential fuel and CO_2 emissions savings from 2024 to 2050 were calculated using ICCT's open source, in-house developed Global Transportation Roadmap Model (referred

10 U.S. Department of Transportation, BTS Form 41 Traffic (2010).

to as the Roadmap model in this report)[11], assuming the improved aircraft in this study are introduced to the U.S. market starting in their respective EIS years. This analysis focuses on the United States due to the availability of robust data on its aircraft fleet and traffic forecast.

ACTIVITY FORECAST

The Roadmap model uses activity forecast in RPKs to project future fuel consumption. Information from 2014 BTS T-100 Segment flights data[12] and FAA Aerospace Forecast 2015-2035 (FAA, 2015b) was used to develop a simple activity forecast for each aircraft type.

First, the shares of activity (in RPK) performed by each aircraft type (SA, RJ, and STA) were calculated based on domestic and international (to and from the United States) traffic data obtained from BTS Form 41. In 2014, SA aircraft accounted for 65% of activities in the United States, while RJs with seat capacity above 90 and STA aircraft accounted for 1%[13] and 11.5% of all U.S. traffic, respectively.

These activity shares were applied to historical activity data in the FAA Aerospace Forecast to obtain projected U.S. activity by aircraft type. According to FAA, the annual activity growth for different markets is different; hence a different method was used to calculate future activity. The FAA reports of 2014-2035 annual activity growth that were most representative of the three aircraft types studied were used:

» **Single Aisle**: The FAA estimates annual activity growth for domestic flights performed by mainline carriers to be 1.9% (FAA 2015b). Since domestic flights performed by mainline air carriers are dominated by the use of SA aircraft, this annual activity growth was used to forecast the growth of SA aircraft in the United States.

» **Small Twin Aisle**: In contrast to SA aircraft, twin aisle aircraft are typically used for international flights to and from the United States. For that reason, the annual activity growth forecast for international scheduled passenger traffic by mainline air carriers (3.7%) was used to project the future activity of STA aircraft.

» **Regional Jets**: The FAA projects that regional carriers will increase their passenger-seat-miles by 2.1% per year, and this value was used to inform the regional jet activity forecast through 2050.

The five-year activity forecast for each aircraft type as calculated using this methodology is presented in Table 5.

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11 The Roadmap model is an Excel-based tool designed to help policymakers see trends, assess emissions and energy-efficiency implications of different policy options, and to conceptualize strategies to reduce GHG emissions and local air pollution. The tool and its documentations can be downloaded from http://www.theicct.org/global-transportation-roadmap-model

12 U.S. Department of Transportation, BTS Form 41 Traffic (2014)

13 RJ aircraft with 90+ seats are responsible for one-third of total RJ RPKs, which represent 11% of U.S. domestic RPKs. While this share is relatively small, larger RJs were selected for analysis in this study due to their prevalence in models under development and their growing importance in the U.S. fleet.

Table 5 Historical and projected activity by aircraft type for commercial aircraft over 90 seats capacity, 2000 to 2050.

	Year	Single aisle	Small twin aisle	Regional jet
Historical (FAA, 2015b)	2000	722	128	11
	2005	859	152	13
	2010	822	145	13
	2015	911	164	14
Projection	2020	1,001	197	16
	2025	1,100	236	17
	2030	1,209	283	19
	2035	1,328	339	21
	2040	1,459	407	24
	2045	1,603	488	26
	2050	1,761	585	29

Units of billion RPK.

SURVIVAL CURVE

In the Roadmap model, the aircraft survival curve characterized by a Weibull distribution function developed by the ICCT (Rutherford, Kharina, & Singh, 2012) was used to inform the percentage of new (improved) aircraft coming into the fleet, both for growth and replacement. Subsequently it is used to calculate the share of vehicle activity (reference vs. parameter).

TRANSITION PERIOD

In the fleet-wide fuel burn analysis, an assumption of a six-year linear transition period was used. This transition period extends from the EIS date of an aircraft until the aircraft is used for all new deliveries of a given year. For example, a 2024 EIS parameter aircraft is assumed to fulfill 14% of new deliveries in its class in 2024, 28% of all new delivery in 2025, and finally 100% of new deliveries in 2029.

2.5. COST MODELING

Cost modeling of the improved aircraft was conducted by Tecolote Research. This section provides a summary of that methodology. For an in-depth description of methodology and assumptions, please refer to the Final Report of the Aviation Fuel Efficiency Technology Assessment (Tecolote, 2015).

The incremental cost assessment of the implemented technologies to reference aircraft was performed on the base of total ownership cost (TOC), which comprises operator capital cost, maintenance cost, and fuel cost over a given operational period. Figure 5 summarizes the cost models used (on the far left column) and the major components of the TOC (far right column). The tools used in the cost estimation analysis and each element of TOC presented in the diagram are discussed in the following subsections.

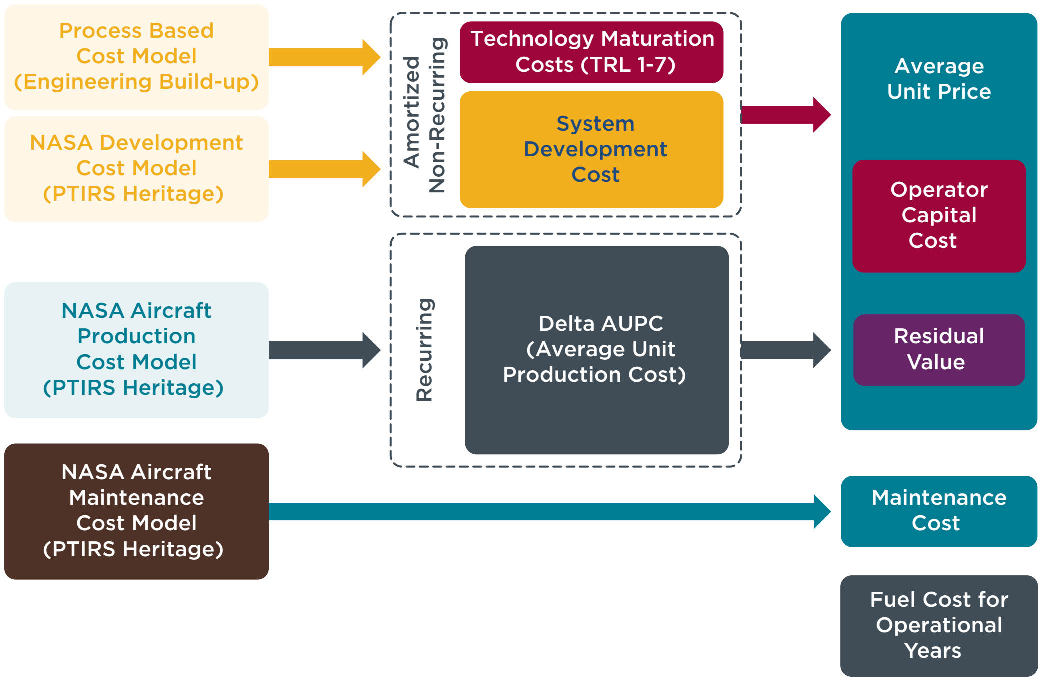

Figure 5 Total ownership cost determination and components (Tecolote, 2015)

2.5.1. Tools used

Three distinct cost estimation tools were used in this study.

PTIRS COST MODEL

The Probabilistic Technology Investment Ranking System (PTIRS) is a "tool that is used to build a business case for incorporating a technology or suite of technologies on a future aircraft."[14] PTIRS was developed for and sponsored by the NASA ERA project. It is a weight-driven model, meaning that costs are computed at the component level based primarily on the weight of the aircraft components. In this study, PTIRS was used to perform analyses of system development, production, and maintenance costs, where all the calculations were ported into the Automated Cost Estimating Integrated Tools (ACEIT) framework.

ACEIT

ACEIT is a suite of software tools/applications that standardize the estimating process to develop, report, and share cost estimates. ACEIT enables analysts to build concise, structured, and robust cost estimates; develop cost estimating relationships (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; basis of estimate (BOE) documentation; cost and schedule uncertainty analysis; statistical analysis; automated reporting, charts, and presentation development; database development, search, and retrieval; and methodology and inflation libraries.[15]

14 https://www.nasa.gov/sites/default/files/files/31_PTIRS_Update2_Tagged.pdf
15 ACEIT functionality, https://www.aceit.com/aceit-suite-home

ACEIT is a productivity tool providing 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.

JACS

JACS[16] is an ACEIT tool that has the capability of integrating cost and schedule analysis, an essential feature in performing technology maturation assessments. In addition, JACS provides the ability to assess cost uncertainty, schedule uncertainty, and risk.

In the study, Tecolote Research analyzed 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 for each task. The data was processed using JACS to generate a joint cost/schedule confidence estimate that includes risk due to uncertainty and the correlation between cost and schedule.

2.5.2. Key parameters in cost analysis

Given the high level of uncertainty involved in cost analysis that looks far into the future, a simulation modeling framework on ACEIT was developed for this study to allow probabilistic calculations using parameters in a range instead of a single deterministic value. Table 6 and Table 7 present the key deterministic and probabilistic parameters used in the cost analysis, respectively. Deterministic values were chosen for the parameters listed in Table 6 to allow apples-to-apples comparison between scenarios and between aircraft types.

A discount rate of 9% was chosen as a baseline case in this study, as an approximation of a reasonable cost of capital for airlines (Tecolote, 2015). This value, which falls on the high range of weighted average cost of capital in the air transport industry range (7% to 9%) according to a 2013 study by IATA (IATA, 2013a), could undervalue future fuel and maintenance savings relative to upfront capital costs. For every aircraft delivery, a manufacturer's profit margin of 20% was integrated into the aircraft unit price, along with technology maturity amortization costs spread over the 10-year production run for each EIS year scenario.

After considering potential time horizons relevant to aircraft investment and purchasing decisions, a seven-year period was chosen to calculate operational (fuel and maintenance) costs (Tecolote, 2015). In comparison, the average first-owner lifetime of an aircraft is 17 years while the average lease period is four to six years, depending on the aircraft type. To calculate aircraft residual value, the average first-owner lifetime of 17 years was used[17] with a depreciation rate of 6%.

16 https://www.aceit.com/aceit-suite-home/product-info/jacs

17 http://www.ascendworldwide.com, data as per April 2014.

Table 6 Basic parameters in cost estimation - deterministic

Parameter	Value
Discount Rate	9%
Profit Margin for Manufacturers	20%
Technology maturation amortization period (years)	10
Production period (years)	10
Operational period (years)	7
First-owner lifetime for residual value estimate (years)	17
Equipment depreciation rate (declining balance)	6%

Given recent fuel price volatility, priority was placed on enabling sensitivity analysis of the fuel price and fuel price increase parameters. Likewise, aircraft market capture, or the share of a given market segment captured by one manufacturer's model, was found to be an important driver of an aircraft type's price and the program's success, since its technology maturity and development costs are amortized across the number of manufactured units. Probabilistic values were chosen for these variables, as summarized in Table 7.

Base fuel price and annual price increase parameters were developed using the 2015 EIA Annual Energy Outlook jet fuel price projection up to year 2040 (EIA, 2015). While market capture (or market share) for each aircraft may and often will change over the years, the market capture parameters used in this study are based on historical market capture of each of the reference aircraft based on Ascend data.

Table 7 Basic parameters in cost estimation - probabilistic

Parameter	Most Likely	Low	High	Probabilistic / Optional
Base fuel price (US dollars per gallon)*	$2.94	—	—	Optional
Annual Fuel Price Increase*	0.97%	-1.23%	3.03%	Probabilistic
Market Capture	SA: 38% TA: 32% RJ: 37%	—	—	Optional
Composite Fraction	Vary By Scenario			Probabilistic
Design Heritage Factors	Vary By Scenario			Probabilistic
Development 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

*Based on EIA Annual Energy Outlook 2015 (EIA, 2015)

Since the cost model used is weight-based, a composite fraction of each aircraft (both reference and improved) had to be determined. Composite materials for aircraft structure are lighter but cost more than conventional aluminum. Unfortunately there is very limited information regarding the composite material fraction in each representative aircraft type. Therefore Tecolote's SMEs used their engineering judgment to determine the composite fraction of each aircraft component for each scenario, and uncertainty factors were built in.

SMEs' expert judgment was also used to estimate design heritage and design and production complexity, as well as maintenance complexity factor and interval adjustment for each scenario.[18] Since the framework cost model is weight-based—meaning that as an aircraft component gets heavier costs increase—and is built upon a database of all-aluminum aircraft, factors were developed to capture the cost effects (positive or negative) of advanced technologies independent of weight. As an example, the more advanced an aircraft component is, the more composite material may be used by weight, which may cost more to develop and produce than its all-metal counterpart. Due to this disconnect, factors like design heritage, design and production complexity, and maintenance complexity factors are needed in order to better estimate costs.

Tecolote Research defined design heritage 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 can be one, which means a completely new design for the component; zero, which means a full reuse of an existing design; or somewhere in between. In addition, to account for uncertainty, design heritage factors for each subsystem of an (improved) aircraft are defined in three values: the most likely, high, and low value. For example, the design heritage factors for the fuselage of SA 2024 aggressive scenario are 0.63 (low), 0.73 (most likely) and 1 (high).[19]

Development complexity is a measure of the complexity of an aircraft component design relative to the reference aircraft. The same principal goes to production and maintenance complexity factors, which aim to indicate how much more difficult, and therefore costly, an aircraft component is to produce and maintain, compared with its reference component.

Finally, maintenance interval adjustment is a parameter to indicate how much more (or less) frequently an improved component will need to receive major maintenance. This parameter affects the maintenance cost calculation of the entire aircraft.

2.5.3. Total ownership cost components

As mentioned in the previous section, the TOC is the sum of operator capital cost, maintenance cost, and fuel cost over a certain operational period, minus the residual value over the first ownership life of the aircraft. Each of these components and a summary of methodology to calculate them are discussed below.

Operator Capital Cost is the estimated cost for an operator to purchase an improved aircraft. It consists of amortized nonrecurring costs and the recurring cost in the form of average unit production cost of the improved aircraft.

- ***Amortized Nonrecurring Costs*** consist of the overall cost to develop, mature, and integrate new technologies into a new aircraft. Lump sum nonrecurring costs are amortized over the total number of aircraft projected for delivery in a 10-year

18 See the following sections of Tecolote, 2015 for additional detail: Design heritage and development complexity (4.4.3); production complexity (4.4.4.1); and maintenance costs, including maintenance complexity factor and interval adjustment (4.4.5.1).

19 See the following sections of Tecolote, 2015 for additional detail: Design heritage (4.4.3.2 and Appendix I).

production run for each EIS period.

- **Maturation Cost**: Maturation cost is the cost required to advance a certain technology from an initial concept (TRL 1) to a marketable product (TRL 9). In this study, Tecolote Research, Inc., with support from its SMEs, calculated maturation costs for each technology based on the current TRL, the EIS year, and whether or not the natural completion schedule (or the time needed to bring the technology to pass TRL 7) needs to be compressed in order for a technology to be available for a given EIS year.[20] The more schedule compression needed, the higher the cost to reflect both the resources needed to complete the process sooner and the risk associated with it. Tecolote used the JACS tool to generate probabilistic cost data for each technology maturation effort.
- **Development Cost**: This is the cost allocated to integrate a matured technology into the development of aircraft design up to producing the first unit. While the PTIRS CER used to estimate the development cost is predominantly based on weight and material type (aluminum vs. composite, for example), two other previously introduced parameters are also important: design heritage and development complexity factor. As previously indicated, design heritage estimates the percentage of a given component being altered due to the inclusion of new technology, with a value that ranges from zero to one. Development complexity identifies the change in difficulty of developing a new aircraft component with new technology relative to the baseline. For example, the (most likely) development complexity factors for SA core engine in the 2024 evolutionary scenario is 1.2, representing 20% higher development costs compared to the SA baseline, all other things being equal.[21]

- ***Recurring Production Cost*** includes all costs incurred in manufacturing and assembling an aircraft to be sold to an operator. It includes manufacturing of all aircraft parts and components, tooling infrastructure, labor, subcontractor costs, as well as overhead and management costs associated with production activities. Three key variables impact production costs: design heritage, production complexity, and overall production quantity. Production complexity factors capture additional (or reduced) costs of an aircraft component with new technology based on a comparison of its production complexity relative to the technology level and production capabilities of the reference aircraft.

In this study, total production cost is calculated by estimating the overall production costs for the specified aircraft deployment scenario for a 10-year production run. The total production quantity was determined for each aircraft type via a two-step analysis: market forecast and market capture assessment. The future market (delivery) forecast was based on Embraer Market Outlook, taking into consideration fleet attrition and fleet growth. Based on 2011-2012 Ascend data and additional comparison with 2015 FAA data, market capture assumptions of 38%, 32%, and 37% were adopted for SA, STA, and RJ, respectively.[22]

20 See section 4.4.2 of Tecolote, 2015 for the detailed methodology used to determine the schedule and cost for new technology maturation.

21 See Appendix J of Tecolote, 2015 for specific development complexity factors by aircraft type and scenario.

22 See Section 2.4.7 of the Tecolote, 2015 for a discussion of how these market capture assumptions were developed.

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 divided by the total production quantity to arrive at an average unit production cost per vehicle.

» **Average Unit Price (AUP)** is the estimated price an operator will pay for an improved aircraft. This value is a summation of the Amortized Nonrecurring Cost and Average Unit Production Cost, with an additional 20% profit margin for the manufacturer. The overall operator investment cost for a specific aircraft is the AUP for all aircraft purchased during a 10-year production period of the aircraft.

Maintenance Costs are calculated based on the expected costs to maintain the advanced airframe and engine maintenance in operation. In this study, maintenance costs are calculated annually over seven operational years, as estimated by Tecolote using Ascend data (Tecolote, 2015). In comparison, the average first-owner lifetime of an aircraft is 17 years. The resulting total of all aircraft annual costs for seven operational years is calculated and provides the total maintenance cost for the respective scenario. Operation costs that encompass landing fees, crew, and passenger support are not included in the analysis as it was assumed that these costs are insensitive to the fuel efficiency of an aircraft.

Fuel Costs are calculated based on the expected annual usage of fuel for the aircraft over seven operational years considered in the study. First, the annual aircraft usage (by hour) is determined by type and age (see Rutherford et al., 2012). From this, the annual fuel consumption by age for the reference aircraft for each type was determined using its average mission fuel burn as modeled in Piano. Hence, the total fuel burn for each reference aircraft can be determined for each operation year parameter (i.e., in this study, seven or 17 years).

Residual Value is the economic value of an aircraft remaining when it is sold to its second owner. Residual value is estimated based upon the depreciation of the aircraft over a period of time based upon a declining balance method, with the residual value calculated as the AUP less the depreciation.

2.6. FLEET-WIDE FUEL SAVINGS AND EMISSION REDUCTIONS

This section describes how fuel burn and CO_2 emission reductions were estimated for new deliveries of improved commercial aircraft with more than 90 seats in the U.S. fleet. The analysis was done using the Roadmap model with the Piano 5 modeling as an input. Fuel burn (and CO_2 emissions) were calculated based on activity (in RPK). For this study, the percentage of activity by type (SA=65% RPK, STA= 11.5%, and RJ [90-120 seats] = 1%) of total activity in the United States, including domestic and international flights, was calculated using 2014 BTS Form-41 data.[23] These values were used to calculate the historical and baseline activity (in RPK) for each type. For activities in 2015 and beyond, average annual growth values from FAA Forecast were used: 1.9%, 3.7%, and 2.1% for SA, STA, and RJ respectively (FAA 2015b).

For the reference case, historical aircraft efficiency values (2000-2010) were taken from previous ICCT work (Rutherford et.al, 2012) for each type, with the calculated average aircraft efficiency value for each type in 2015 adopted as the efficiency baseline. A

23 U.S. Department of Transportation, BTS Form 41 Traffic (2014).

"frozen technology" baseline assuming no aircraft efficiency improvement from 2015 until the improved aircraft EIS date (either 2024 or 2034) was adopted to align the comparison between fleet-wide fuel consumption and emission savings to the study's cost methodology, which assumes no improvements to the reference aircraft in the base case. The transition period in this study was assumed to be six years, as outlined above. For example, an aircraft with EIS date of 2024 will cover 100% of new deliveries in 2029, and an aircraft with EIS date of 2034 will cover 100% of new deliveries in 2039.

2.7. TICKET PRICE SAVINGS ESTIMATION

Depending upon prevailing market conditions, an airline may pass some costs or savings on to customers. This section presents the assumptions used to estimate potential changes in ticket prices as a result of greater investments in fuel-efficient aircraft.

In this calculation, it is assumed that airlines own the aircraft they operate, and that the aircraft is in operation for the entire first-owner lifetime of 17 years. Undiscounted total ownership cost for each aircraft, considering fuel prices and fuel price increase assumptions used in the study (see Table 7), is compared with the total ownership cost of the baseline aircraft, taking into account the potential residual value that the airline may recuperate at the end of the operational time frame.[24] Consistent to the operational parameters used in the cost analysis of this study, 881, 419, and 1,394 flights per year are assigned to SA, STA, and RJ aircraft, respectively (Tecolote, 2015). Aircraft were assumed to operate at 100% load factor over 167, 326, and 100 seats for SA, STA, and RJ, respectively; as a result the potential ticket price reductions estimated may be considered somewhat conservative. The potential carriage of belly freight was not considered in this analysis.

24 See section 2.5.3 for the definition of aircraft residual value.

3. RESULTS AND DISCUSSION

The methods described in Section 2 were used to predict the fuel burn impacts and costs associated with deploying various fuel-saving technologies on EIS 2024 and 2034 aircraft. In this report, fuel consumption results and costs are presented for one representative aircraft, unless otherwise specified. Full details of the cost results can be found in Tecolote's report (Tecolote, 2015).

The first subsection of this section presents the results of the fuel burn reduction achievable using emerging technologies under the six advanced technology scenarios (three for 2024 EIS and three for 2034 EIS) studied. The second subsection presents the cost-effectiveness of the implemented technologies in terms of the relative TOC to the owners/operators of the advanced aircraft by scenario, while the third subsection provides a first order estimate of the effect on ticket prices, assuming all savings attributed to the fuel burn technologies are passed on to consumers. The fourth subsection translates aircraft level fuel burn and CO_2 reductions for the U.S. fleet, and relates these to the country's stated climate protection goals for the aviation sector. The final subsection discusses sensitivity analyses to see how discount rates, fuel prices, and market risk affect the analyses results and, potentially, policy instruments to accelerate aircraft efficiency improvements.

3.1. FUEL BURN

As described in Section 2, estimating the fuel burn impacts of advanced technology scenarios involve several steps: technology identification, technology package assignment by scenario, and modeling the impact of technology application onto a reference aircraft using Piano 5. The results of these analyses are presented in Table 8.

Table 8 Fuel burn by type and scenario

Aircraft type	Reference aircraft	Fuel burn (g fuel/RPK, change from reference in parentheses)						
			2024			2034		
		Ref	Evo	Mod	Agg	Evo	Mod	Agg
Single Aisle	A320-200	20.1	15.0 (-25.7%)	13.2 (-34.2%)	12.1 (-40.0%)	13.2 (-34.2%)	12.0 (-40.4%)	10.9 (-46.1%)
Small Twin Aisle	B777-200ER	23.9	17.3 (-27.3%)	15.9 (-33.3%)	13.7 (-42.5%)	15.8 (-33.7%)	13.3 (-44.1%)	12.7 (-47.0%)
Regional Jet	E190AR	32.6	23.5 (-27.5%)	21.8 (-32.9%)	19.6 (-39.8%)	21.8 (-32.9%)	19.5 (-40.2%)	17.7 (-45.7%)

As shown in Table 8 the implementation of fuel-saving technologies results in significant fuel burn reductions for all technology scenarios and aircraft types.[25] In 2024, the fuel burn of SA aircraft can be reduced from 20 grams of fuel per RPK (reference) to as low as 12 grams (aggressive scenario), a 40% fuel burn reduction, albeit with cost increases due to the need to accelerate technology maturation.[26]

25 Note that the payload/range combinations used to estimate fuel efficiency in Table 9 vary by aircraft type, complicating efforts to compare the fuel efficiency between aircraft types. For example, regional jet aircraft are flown over shorter distances compared to both single aisle and small twin aisle aircraft (see Figure 4). This means that larger fraction of RJ emissions come from the LTO (landing and take-off) cycle, which is more fuel intensive per kilometer flown than the cruise cycle.

26 See section 4.4.2 of Tecolote, 2015 for a detailed discussion regarding technology maturation costs.

Allowing an additional 10 years of technology maturation and development increases the potential fuel burn reduction to 46%.

The potential fuel burn reduction for the three aircraft types vary somewhat due to differences in available technologies along with the types of missions flown, but all fall within the same range. The fuel burn reduction potential for new aircraft designs ranges from 26% to 42% in 2024, and from 33% to 47% in 2034. These values are consistent with the findings of the ICAO Long Term Technology Goal study (ICAO, 2010a) and the NASA ERA project (Nickol & Haller, 2016).

The fuel burn reductions should not be interpreted as a prediction of what a new aircraft in 2024 or 2034 will have, but instead as range of fuel efficiencies that new aircraft designs could have in 2024 or 2034 under various scenarios of technology development and deployment. These scenarios should not be considered comprehensive since they are limited to conventional tube-and-wing aircraft architecture, and do not include alternative architectures such as blended wing body designs that might provide even larger improvements.

Because the fuel burn impacts of individual technology were assessed by integrating the technology on a resized and re-optimized aircraft, comparison can only be done as technology groups (i.e., engines, aerodynamics, and structures) as presented in Figure 6 for SA, STA, and RJ aircraft. Note that the aggregate fuel burn reduction obtained by applying the complete technology package (marked as circles on Figure 6) is typically smaller than the simple sum of fuel burn reduction attributed to the three technology groups. This is due to the fact that fuel burn reductions are generally multiplicative, rather than additive, for the mid and longer stage length flights typical for single and twin aisle aircraft types.

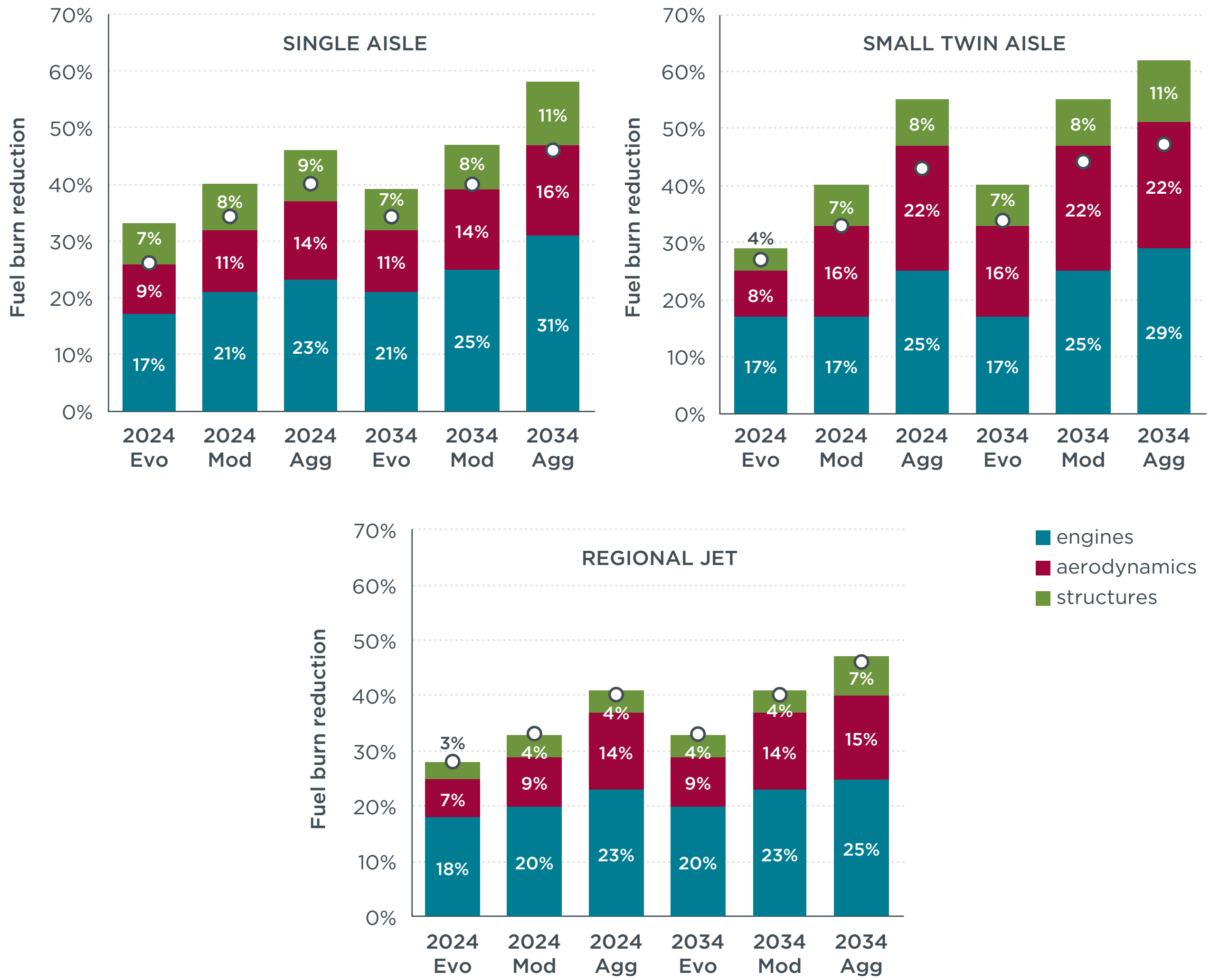

Figure 6 Fuel burn reductions by aircraft type and technology group

As shown in Figure 6, modeled fuel burn reduction for STA aircraft under various scenarios is similar to those modeled for the SA aircraft. In general, rolled-up engine technologies to the engine system (geared turbofan or open rotor) contribute larger fuel burn benefits than aerodynamic or structural technologies only. However, potential impacts of engine technologies rolled up to the engine systems are about the same or less than potential impacts from rolled-up airframe technologies (structures plus aerodynamics).

3.2. COMPARISON WITH EMERGING AIRCRAFT TYPES

While it is difficult to compare the fuel efficiency achieved under the more aggressive scenarios, especially in the latter year, with "real world" aircraft, it is possible to compare the 2024 Evolutionary scenario with the newest-generation aircraft that just entered the market or will enter the market in the next couple of years.

Figure 7 compares the fuel burn performance of the SA and RJ reference aircraft, their direct replacement in the market, and the modeled/improved aircraft under the Evolutionary scenario. Similar to the methodology used in calculating the fuel burn performance seen in Table 8, here all aircraft are modeled in Piano 5 with the same passenger capacity as their replacement type, and then "flown" on the set of missions presented in Figure 4. Note that the Boeing 777-200ER, the study's STA reference aircraft, does not have a direct replacement in the emerging market. Therefore, shown here is its closest type, Boeing 777-300ER, compared with Boeing 777-8X—its upcoming direct successor.

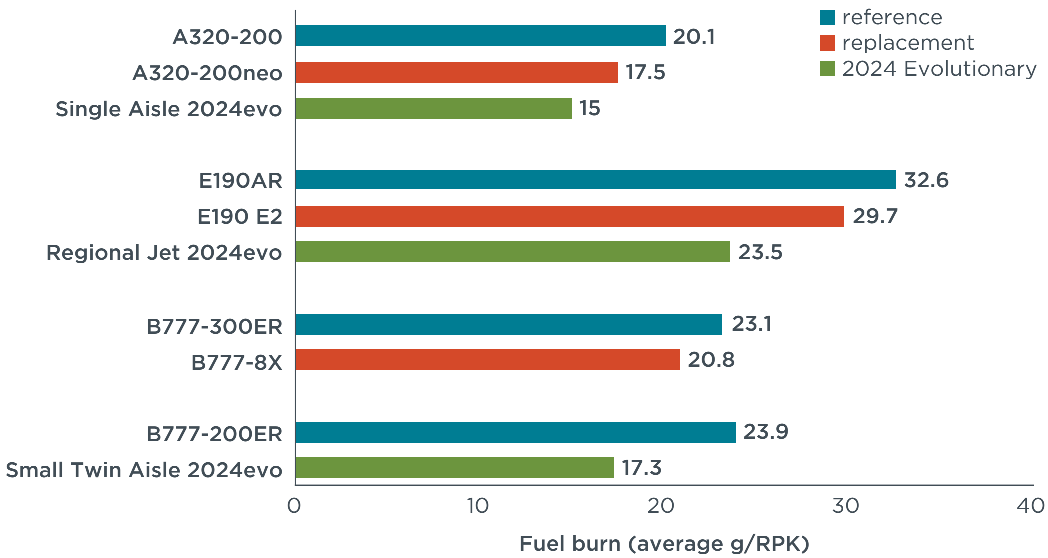

Figure 7 Fuel burn of reference, emerging successor, and 2024 Evolutionary aircraft

These findings, which focus purely on improvements due to fuel efficiency technologies, can be compared to each manufacturer's own estimates of improvement. The Airbus A320neo (EIS 2016), short for A320 new engine option, advertises a 20% fuel savings per seat compared with the current generation A320ceo (current engine option).[27] On the other hand, the upcoming Boeing 737 MAX advertises a 14% reduction in specific fuel consumption compared with the current, somewhat newer, version.[28] The major change in these two aircraft types comes from re-engining, which means there is no significant change in structural and systems design. Re-engining an existing airframe with an advanced engine, rather than developing a new "clean sheet" aircraft, provides cost savings for manufacturers and benefits to airlines in terms of commonality in parts and reduced training requirements for pilots. Comparing these values with subsystem fuel burn reduction as presented in Figure 6, the fuel consumption reduction gained by the two new-generation SA aircraft is on par with the estimated fuel burn reduction in the 2024 Evolutionary scenario from engine technologies alone (see Figure 6), as expected.

The Boeing B777X, an upcoming aircraft family in the STA class, is expected to enter into service in 2020, and it will have a new, larger wing design on top of a new engine developed by General Electric, the GE9X. GE claims that engine will have 10% lower specific fuel consumption than its predecessor (GE90-115B) installed in the B777-300ER.[29]

There are a few new RJ aircraft types in the development pipeline expected to enter into service in the next few years. All of these aircraft claim fuel burn reductions smaller than

27 http://www.airbus.com/presscentre/hot-topics/a320neo/
28 http://www.boeing.com/commercial/737max/#/design-highlights/max-passenger-appeal/
29 http://www.ge.com/stories/aviation-ge9x

the finding of this study. Embraer E2, for example, claims 16% fuel burn reduction per seat from its predecessor[30] while Bombardier CSeries claim to have a 20% fuel reduction over "in production aircraft." This is in contrast to the 2024 Evolutionary case in this study, which suggests a 27.5% reduction from the baseline is possible.

It is clear that the fuel burn reductions seen in the Evolutionary (business as usual) cases are larger than expected for near-term re-engined aircraft. We return to this observation below when considering the relative roles of external pressure (i.e., regulation, oil price, etc.) on aircraft efficiency.

3.3. COST MODELING RESULTS

A key aim of this study was to estimate the costs and benefits of developing and deploying new fuel-efficiency technologies, taking into account technology maturation, aircraft development, production costs, and fuel and maintenance savings, all relative to the non-improved reference aircraft.

Figure 8 presents the total ownership cost change for all aircraft types (SA, STA, and RJ) against the modeled fuel burn reduction obtained for each scenario, compared with their respective reference aircraft as described in Section 2.3. The results shown are based on a 9% discount rate, a 10-year production quantity run, seven years of fuel and maintenance savings, and the residual value of the aircraft after the first-operator lifetime of 17 years. The TOC calculation methodology is presented in brief in Section 2.5.2, and can be found in detail in the associated consultant report (Tecolote, 2015).

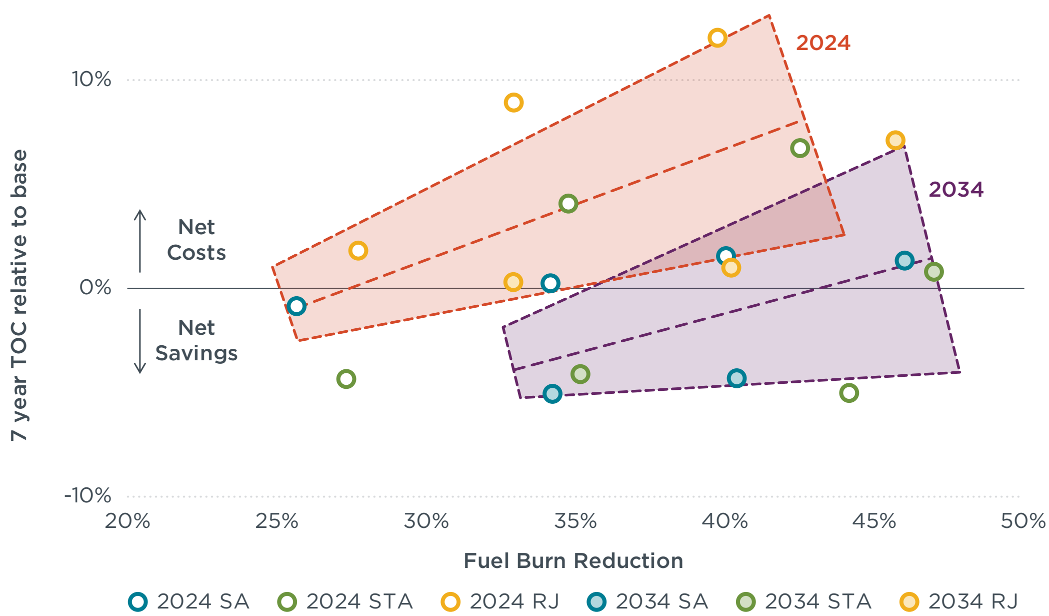

Figure 8 Seven-year total ownership cost change for all aircraft types and deployment scenarios (Tecolote, 2015)

A negative value of TOC in Figure 8 means that the total cost of ownership for the modeled aircraft is lower than the reference aircraft, making the purchase of that aircraft cost effective for airlines over a seven-year time horizon. On the other hand, a

30 http://www.embraercommercialaviation.com/Pages/Ejets-190-E2.aspx

positive TOC value reflects a net cost to the owner/operator over seven years because the resulting aircraft price increase outweighs the fuel and maintenance savings. The shaded areas around both trend lines (2024 and 2034) represent uncertainty in the cost estimation.

The analysis shows that, in 2024, new design aircraft with approximately 25% lower fuel burn are expected to be cost effective for operators; that is, the fuel and maintenance savings for those aircraft offset the increased purchase price of more technologically advanced aircraft. For the 2034 EIS scenarios, fuel burn reductions of around 40% are projected to be cost-effective for operators over a seven-year time horizon. With new aircraft that will be type-certified in the near term having an estimated 9% to 13% fuel burn reduction (see Section 3.2 above) compared with today's aircraft, these results suggest substantial room for additional fuel-efficiency improvements with net savings to operators.

Figure 9 compares the cost-effective improvements identified in this study for three aircraft types to long-term trends in new design fuel efficiency on a fuel per RPK basis, normalized to the fuel burn of the reference aircraft used in this study (reference = 100). Since fuel burn is sensitive to payload and range capability, only aircraft types similar to those analyzed in this study, as defined by having MTOWs or design ranges[31] within 10% of the base aircraft, are included. Blue, red, and green circles denote regional jets, single aisle, and small twin aisle aircraft, respectively, while solid circles represent aircraft already into service and empty circles new types to be introduced in the foreseeable future ("project aircraft").

As the figure indicates, the average fuel burn of new designs, as indicated by their fuel burn at EIS year, fell by about 30% from 1980 to 2016, or a little less than 1% per year. If these trends continue, the fuel burn of new EIS aircraft will fall another 10% through 2034, or about 60% of the potential improvements identified in this study. Put another way, fully deploying the cost effective technologies identified in this study on new aircraft designs would more than double the rate of expected fuel burn reductions through 2034 to 2.2% per year. This gap between market-driven fuel-efficiency improvements and what is estimated to be cost effective given fuel price projections represents an opportunity for additional CO_2 emission reductions at net savings for airlines and consumers.

31 Here, design range is defined as R_{max}, or range at 50% of an aircraft's maximum structural payload, itself calculated as maximum zero fuel weight (MZFW) minus operating empty weight (OEW).

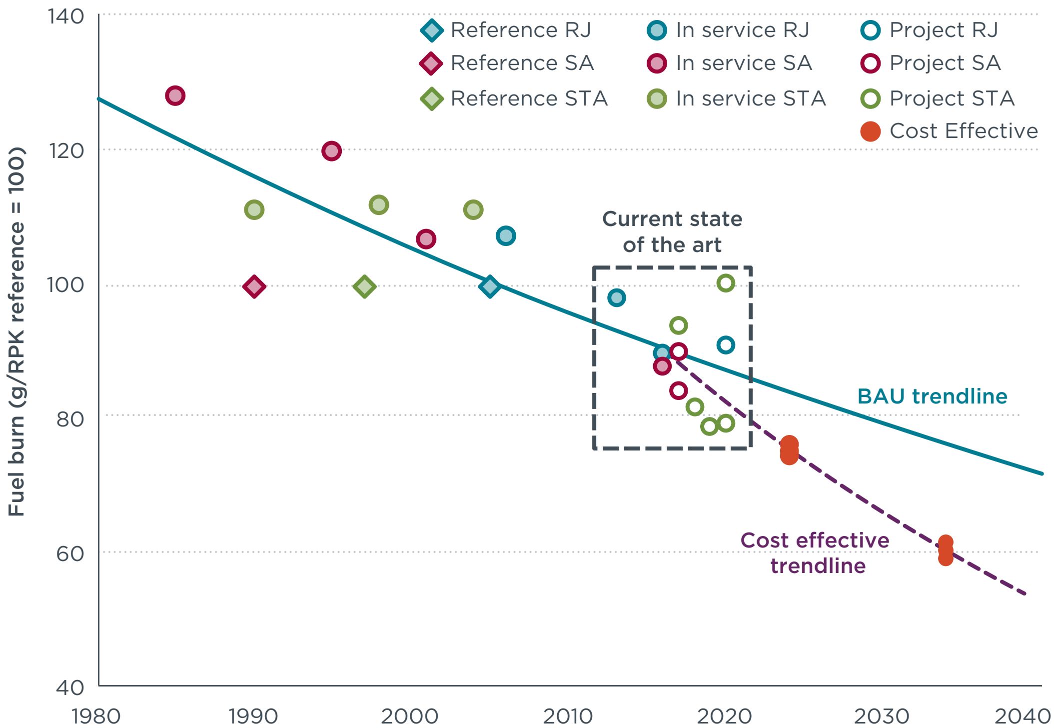

Figure 9 Trends in new aircraft fuel burn by entry into service year, 1980 to 2040

Notably, most airlines that own their aircraft operate them for longer than seven years. Therefore, the benefit these owners would be able to reap over their ownership of the aircraft is greater than what is described above. Table 9 presents the average unit price of the reference aircraft and the improved aircraft by scenario, as well as the comparison of the operational cost incurred across the 17-year first-owner lifetime of the aircraft. The table suggests that, across all scenarios studied, for every additional $1 spent on purchasing a more advanced aircraft, the owner would get roughly $3 in the form of operational cost savings (fuel plus maintenance cost) in return over 17 years, even without taking into account potential residual value of the aircraft in case it is sold to a second owner after this period. As a reminder, this calculation takes into account an assumption of 20% profit margin from the manufacturer.

Table 9 Estimated first-owner lifetime costs for single aisle aircraft

Cost	2024 EIS (million USD)				2034 EIS (million USD)			
	Ref	Evo	Mod	Agg	Ref	Evo	Mod	Agg
Average unit price (AUP)	$29.4	$40.3	$42.9	$44.9	$26.2	$39.5	$40.7	$49.1
Fuel	$111.8	$83.1	$73.5	$67.0	$123.1	$80.9	$73.3	$66.4
Maintenance	$22.6	$17.4	$15.7	$15.6	$22.6	$15.7	$15.6	$15.0
Δ AUP	—	$10.9	$13.5	$15.5	—	$13.3	$14.5	$22.9
Δ fuel + maintenance	—	-$33.9	-$45.1	-$51.7	—	-$49.1	-$56.8	-$64.2
savings/Δ AUP	—	3.09	3.33	3.33	—	3.69	3.90	2.81

3.3. FLEET-WIDE FUEL CONSUMPTION AND CO_2 REDUCTIONS

This section analyzes fuel savings and CO_2 emission reductions from implementing cost-effective fuel burn technologies on aircraft starting in 2024 for the U.S. aircraft fleet. The methodology to calculate fleet-wide fuel savings was presented in Section 2.6.

3.3.1. U.S. fleet-wide fuel savings

Figure 10 compares the fuel consumption of the U.S. fleet (including commercial SA, STA, and RJ with >90 seat capacity aircraft types) with and without the implementation of cost-effective fuel burn technologies (25% in 2024 and 40% in 2034) up to 2050. As seen from Figure 10, the deployment of cost-effective new aircraft technologies could reduce fuel consumption in the United States significantly, with increasing benefits each decade. By 2050, roughly 220 million tons of oil equivalent (Mtoe) for U.S. aviation (~71 billion gallons of jet fuel) could be saved, or more than 20% of total jet fuel consumption from 2025 to 2050, based on the fleet forecast presented in Table 5. This equals $285 billion (2015 dollars) in fuel savings over those 25 years, based on EIA forecast fuel prices (EIA, 2015).

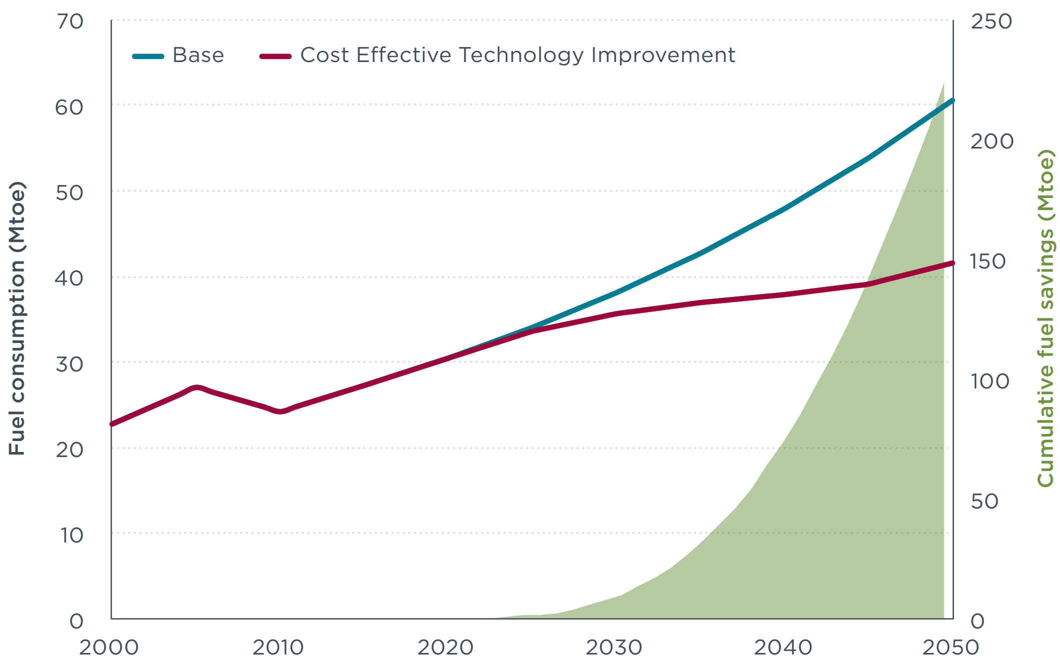

Figure 10 Estimated U.S. fleet-wide fuel consumption and savings, 2000 to 2050

These findings are quite consistent with other assessments. An analysis of the NASA ERA project (Metron, 2015) found that the best new technology scenario could save approximately 20% in fuel compared with the baseline (no technology advancement) in the period from 2025 to 2050. According to their calculation, NASA ERA N+2 best technologies would burn 396 Mtoe less than the No-N+2 case. These larger results are partly because of a more comprehensive calculation of the total U.S. fleet in that study compared to the partial fleet (single aisle, small twin aisle, and larger regional jets) in this study.

3.3.2. U.S. fleet-wide CO_2 emissions

Without technology implementation, and therefore assuming no further technological gains compared with today's aircraft, in 2050 the U.S. aviation industry would emit more than twice its CO_2 emissions in 2005. However, implementing cost-effective fuel efficient technologies (25% and 40% reduction from 2015 aircraft in 2024 in 2034, respectively) would reduce CO_2 emissions by 6% in 2030 and by more than 30% in 2050, reducing roughly 800 million metric tons of CO_2 emissions between 2025 and 2050.

These results are consistent with plans aiming to reduce the impact of U.S. aviation on the global climate. In 2015, the FAA submitted the U.S. Aviation Greenhouse Gas Emissions Reduction Plan (FAA 2015a), which details strategies to achieve the aspirational goal of carbon-neutral growth for U.S. commercial aviation by 2020, using 2005 emissions as a baseline. The plan found that this goal could be met with a combination of aggressive operational and technology improvements[32] plus optimistic alternative fuel deployment pathways. The U.S. Action Plan document does not specify any cost implication of the programs. This study suggests that the aircraft and engine technology improvements needed to achieve the U.S. goals can be accomplished in a cost-effective manner.

3.4. TICKET PRICE IMPACTS

The cost estimation of this study concluded that the implementation of fuel-efficient technologies in future aircraft can save airlines up to 33% in total operational (fuel and maintenance) costs per aircraft every year assuming the aircraft is operated for 17 years. After accounting for the higher initial purchase costs of aircraft, if these savings were passed on to the passengers, on average flight tickets would fall between $9 and $20 for short-haul flights, and $60 and $105 lower for long-haul flights—a not insignificant amount. The breakdown of these airfare savings is presented in Table 10 by aircraft type and scenario. Although this analysis relies upon U.S. operations data, this overall conclusion—that adopting fuel-efficient technologies on new airplanes could provide net savings to consumers—should hold globally as well.

Table 10 Potential airfare savings per passenger by scenario

Aircraft type	2024 EIS			2034 EIS		
	Evo	Mod	Agg	Evo	Mod	Agg
Single Aisle	$11	$15	$17	$17	$20	$21
Small Twin Aisle	$61	$72	$88	$84	$106	$105
Regional Jet	$9	$10	$12	$12	$15	$15

The reality may be more complicated. The situation in 2015, which combined low fuel prices, record airline profits, and still-elevated ticket prices in the United States, suggests a diminished incentive for airlines to voluntarily pass on savings to passengers (Pinsker, 2016; Van Cleave, 2016).

32 The U.S. action plan estimated about 20% life cycle CO_2 reductions from airframe and engine improvements under a moderate improvement scenario, and about 30% life cycle CO_2 emissions impact under aggressive system improvement scenario in 2040.

3.5. SENSITIVITY ANALYSES

This section discusses three sensitivity analyses with potentially strong influences on the results and policy implications: discount rates, fuel prices, and market risk.

3.5.1 Discount rates

Discount rates, which capture the cost of capital for investors and consumers, have a strong effect on how costs are weighed against the benefits and risks of investment. The baseline cost results presented above were calculated using a 9% discount rate—on the high end of the estimated cost of capital for airlines (Tecolote, 2015)—to reflect the private cost of capital for large corporations expecting a high return on investment. A lower discount rate to reflect the social cost of capital, instead of airline cost of capital, could be utilized when analyzing technology costs. The U.S. government recommends an increasing long-term discount rate approach ranging from 2% for three-year periods to 3.5% for 30-year period scenarios (OMB, 2015) for cost-effectiveness analyses. In contrast, the U.K. government recommends declining discount rates over a long period, for the same reason of uncertainties in the future. The discount rates recommended are similar, however, ranging from 3.5% for 0-30 years and 3% for up to 75 years (Treasury, H, 2003).

Tecolote analysis shows that, as a rule of thumb, using a 3% discount rate instead of 9% would shift the fuel burn improvement break-even point over a seven-year period from the base case of 25% in 2024 and 40% in 2034 to 41% and up to 47% in 2024 and 2034, respectively.[33]

3.5.2. Fuel prices

A previous study on historical aircraft fuel efficiency trends related spikes in oil prices to subsequent improvements in average aircraft fuel efficiency after a period of delay (Kharina & Rutherford, 2015). The sharp drop in oil prices starting in September 2014 has the potential to do the opposite by diminishing market incentives for fuel efficiency. Despite several prominent new aircraft types entering the market in the next few years, the pressure to develop and implement fuel-efficiency technologies may diminish as fuel efficiency loses its economic appeal for airlines.

The results of this study are based on the assumption of $2.94/gallon jet fuel price in 2013, with long-term price increases consistent with 2015 EIA projections (EIA, 2015). However, if the same analysis is run based on the 2015 average jet fuel price (approximately $1.50/gallon), different results are seen. Here we investigated the effect of fuel prices on the payback period for aircraft fuel efficiency. Intuitively, the lower the fuel price, the longer it will take operators to recoup the upfront capital costs of improved aircraft via fuel and maintenance savings, leading to less natural technology adoption.

A recent study suggested that current low fuel prices are unlikely to continue in the long term, and that without a push to adopt fuel-savings technology in the transportation sector, prices could rise to $130 a barrel by 2050 (Summerton, P, et. al, 2016). According to the same study, implementation of policies to encourage fuel-efficient transportation would stabilize the market price of oil at between $83 and $87 per barrel from 2030 and

33 See section 5.3.5 of Tecolote, 2015 for a discussion of the sensitivity of technology cost effectiveness to discount rates (i.e., private cost of capital vs. social costs).

2050. Using EIA data to estimate the correlation between crude oil and jet fuel prices[34], this corresponds to stabilized jet fuel prices between 2030 and 2050 of ~$2.40/gallon (in 2013 dollars).

With this fuel price assumption, the effect of low fuel prices on the payback period of advanced aircraft can be considered. Baseline results suggest that the fuel burn on new aircraft designs can be reduced by up to 25% and 40% in 2024 and 2034, respectively, in a cost-effective manner, as estimated on a seven-year operational period (see Section 3.3). Under the equilibrium fuel prices outlined above, the technologies enabling a 25% fuel burn reduction in 2024 EIS aircraft would pay back in eight instead of seven years, a relatively small change. In contrast, a 40% fuel burn reduction for 2034 EIS aircraft would require 11 years, or four years longer than baseline, before payback for the first owner of an aircraft (see Figure 11). From this, it can be concluded that the relative cost of technologies to improve aircraft fuel efficiency is dependent upon fuel prices, with greater elasticity in the mid-term as the range of available technologies expand.

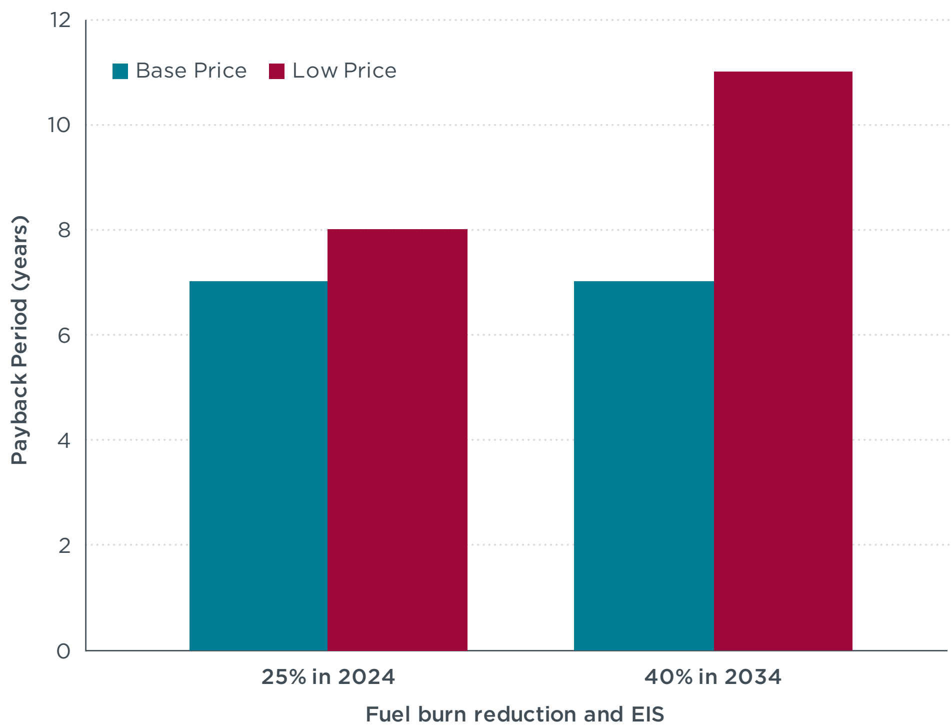

Figure 11 Payback period by fuel burn reduction, EIS year and fuel price scenario

3.5.3. Market risk

For an aircraft manufacturer, the success of an aircraft program is measured not by its environmental performance but rather its profitability, which itself depends on the number of aircraft sold and whether the associated margins are sufficient to recuperate development costs. Changes in market share, either positive or negative, affect cost in at least two ways. First, selling more or fewer aircraft than anticipated changes the price that an aircraft must be sold for to break even given that the nonrecurring costs of

34 https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm (retrieved Jun 2, 2016)

technology maturation and aircraft development are amortized across more (or fewer) aircraft. Secondly, excess or insufficient sales shift a given aircraft type along its learning curve, changing the marginal production cost of each subsequent aircraft.

The cost modeling summarized in Tecolote (2015) found that, across all variables investigated, the TOC of new aircraft are most sensitive to assumptions about the number of aircraft delivered, in terms of market capture. As a rule of thumb, a 20% increase in the number of aircraft delivered reduces TOC by 5% and, vice versa, a 20% reduction in market capture would increase those costs by 5% relative to the reference aircraft. Furthermore, a 50% decrease in market capture would increase total costs by about 13%. Considering that aircraft are multimillion-dollar investments, this equates to significant cost changes for airlines and manufacturers that can impact the commercial viability of entire product lines.

Most recently, the aviation industry has seen the competition for market share intensify, especially in the RJ and SA aircraft markets. While monopoly (or, in this case, duopoly) is generally undesirable, more competition can also mean more development risk for manufacturers, along with a potential disincentive for innovation. A manufacturer investing in new, more efficient aircraft amid substantial uncertainty in market demand and fuel price risks being undercut by competitors selling existing models at lower prices. Transparent and meaningful fuel-efficiency performance standards for new aircraft may help manufacturers manage this investment risk by guaranteeing market demand for new, more efficient products.

4. CONCLUSIONS AND POLICY IMPLICATIONS

The results presented above suggest the following overall conclusions:

1. There is a significant potential to reduce the fuel burn of new commercial aircraft in the near- and mid-term. This study finds that the fuel consumption of new aircraft can be reduced by approximately 25% in 2024 and 40% in 2034 compared with today's aircraft by deploying emerging cost-effective technologies. The latter value, which corresponds to about a 70% increase in fuel efficiency, may be conservative because of the modeling assumptions used and the exclusion of non-conventional airframes like blended wing body or strut-based wings.
2. These improvements dwarf the fuel efficiency of new "project" aircraft designs being brought to market by manufacturers today. Those re-engined designs, which are estimated to burn between 9% and 13% less fuel on a technology basis, will provide only one-half of the near-term cost-effective fuel and emissions reductions identified in this study. This finding suggests that industry's preference for re-engining rather than clean sheet designs results in the underdeployment of key technologies to improve aircraft fuel efficiency, notably airframe improvements that reduce aerodynamic drag and aircraft empty weight.
3. Accelerating the adoption of cost-effective technologies would provide significant benefits to airlines, consumers, and the environment. Airlines could reduce their fuel spending over the 2025 to 2050 time frame by 19% compared with the baseline case; if passed along to the consumer, these savings could lower ticket prices by up to $20 for short-haul flights and $105 for long-haul flights assuming EIA reference fuel price projections. CO_2 emissions could be reduced by 6% in 2030 and 30% in 2050 compared with the base case.
4. Additional efficiency gains beyond the baseline Evolutionary case (seven-year time horizon, 9% discount rate) are possible but will require government support through policies like efficiency standards, carbon pricing, and research support for technology development. Across all scenarios investigated, $1 in upfront investment in fuel efficiency provides about $3 in fuel and maintenance savings over the first-owner lifetime, with additional benefits to the purchasers of used aircraft.
5. Lower fuel prices associated with increased oil supply and/or lower demand have the potential to slow the deployment of fuel-efficient technologies in new aircraft. This effect may be particularly pronounced in the mid-term as the universe of potential technologies expands.

The substantial gap between the cost-effective fuel-efficiency improvements identified in this study and the products being brought to market today holds policy implications, namely the value of public policies to promote aircraft fuel efficiency. Three are considered here: performance standards for new aircraft; economic incentives to reduce emissions from the in-service fleet; and research support to defray the costs of maturing new technologies.

PERFORMANCE STANDARDS

As noted above, performance standards for new vehicles can help promote technologies to reduce vehicle fuel consumption and GHG emissions. A robust, transparent, and properly enforced standard could help mitigate investment risks that manufacturers assume when investing in new technologies. Progress has been made recently to develop aircraft performance standards, although further work is needed. In February 2016, ICAO recommended a CO_2 (fuel efficiency) standard for new aircraft for adoption by its member states. Those standards, which will impose minimum fuel-efficiency targets for new aircraft designs with EIS dates of approximately 2024, will require approximately 30% of the cost-effective near-term technology potential in this study.[35] The results summarized above suggest that substantial benefits could be enjoyed by airlines, consumers, and the environment if agencies such as the EPA strengthen ICAO's recommended standards prior to implementation under domestic legislation.

ECONOMIC INCENTIVES

While performance standards provide the most direct incentive to promote fuel efficiency, economic incentives can likewise help provide demand side pull. Example policies include emissions trading, emission charges, carbon based airport or en route charges, and fuel taxation. As noted above, domestic and intra-European flights are currently subject to carbon pricing under the EU ETS, and ICAO may require that any emissions growth from international flights after 2020 be mitigated (ICAO, 2016), albeit through the use of offsets. Emission charges, or a flat fee per ton of CO_2 emitted, could be collected either on a revenue neutral basis (indexed to CO_2 intensity) or to recover the "full cost" of environmental damages associated with aviation emissions (ICAO 2004). Airport charges such as landing fees and en route charges used to cover the cost of air traffic control are typically responsible for 7% to 9% of an airline's overall cost structure (Doganis, 2002) and could be indexed to aircraft fuel efficiency to reward airlines operating the most efficient planes. Finally, fuel taxes, while levied only sparingly today on jet fuel, could promote new fuel-efficiency improvements by increasing the relative cost of fuel in a predictable manner over time.

RESEARCH SUPPORT

For an aircraft manufacturer, a new aircraft program is a high risk endeavor that requires large upfront research and development expenses. The desire to avoid such risks may have contributed to the shift in manufacturers' approach to developing new products (Ostrower, 2015). Boeing and Airbus, for example, are featuring incremental improvements, in particular re-engines, in new aircraft models entering into service in the next five years, instead of clean sheet designs. On the other hand, government research programs such as the NASA ERA program and the NASA AATT project are developing and demonstrating crucial fuel-efficient technologies applicable to future commercial aircraft. Continued government support for similar projects could alleviate some of the risk and cost burdens for manufacturers, allowing them to pursue more ambitious fuel-efficiency targets for their new products.

35 Overall, ICAO's recommended CO_2 standard is expected to serve predominately as an anti-backsliding measure. The standards will require on average a 4% reduction in the fuel burn of new in-production (InP) aircraft between 2015 and 2028, a level of improvement smaller than that expected due to market forces alone. See ICCT (2016) for details.

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APPENDIX A—TECHNOLOGY PACKAGES

Tables A1 to A3 present aerodynamic and structural technologies included in each scenario package for three aircraft types and the estimated percent technology improvement within the subsystem to which it is applied. For example, percent technology improvements for aerodynamic technologies are presented in drag improvement, while the improvements for structural technologies like lightweight materials indicate percentile weight reductions. Engine technologies, which are not listed here, were treated as direct inputs into engine performance modeling using GasTurb. See Appendix B for a list of engine technologies analyzed during the engine performance modeling.

Table A 1 Improvements for single aisle aircraft by technology group and scenario

Single Aisle		2024			2034		
Technology Group	**Technology**	**Evol.**	**Mod.**	**Aggr.**	**Evol.**	**Mod.**	**Aggr.**
Aerodynamic Efficiency (Viscous) % Improvement in drag, 100% deployment	Natural laminar flow on nacelles	1%	1.25%	1.50%	1.25%	1.50%	1.50%
	Hybrid laminar flow on empennage		2%	2%	2%	2%	2%
	Natural laminar flow on wings			5%		5%	
	Hybrid laminar flow on wing						8%
	Laminar flow coating/riblets			2%		2%	2%
	Low friction paint coating	2%	2%		**2%**		
Aerodynamic Efficiency (Non-viscous) % improvement in drag	Improved aero/transonic design	2%	2%	3%	2%	3%	4%
	Wingtip technologies (for fixed span)	1%	2%	2%	2%	2%	3%
	Variable camber with existing control	1%	1%	1%	1%	1%	1%
	Adaptive compliant trailing edge		1.50%	2%	1.50%	2%	2%
	Active stability control (reduced static)		1%	1%	1%	1%	1%
	Reduction of loads (active smart wing)	1.5%	1.5%	2%	1.5%	2%	3%
	Increased wing span	3%	3%	3%	3%	3%	3%
Structures, Materials and Manufacturing (% weight reduction)	**All composite aircraft**		10%	10%	10%	10%	10%
	All composite fuselage	5%	5%	5%	5%	5%	5%
	All composite wing	3%	3%	3%	3%	3%	3%
	All composite nacelle	1%	1%	1%	1%	1%	1%
	All composite empennage	1%	1%	1%	1%	1%	1%
	Integrated structural health monitoring		1%	2%	1%	2%	3%
	Advanced composite materials (higher strength, stiffness, toughness, damage tolerance, temperature)		2%	3%	2%	3%	4%
	Advanced airframe metal alloy (2000, 7000 series A1 alloy, 3^{rd} gen A1-Li, higher temp, Ti, etc.)	1%	1%	1%	1%	1%	1%
	Advanced Manufacturing Technology						
	Unitized construction (one piece fuselage barrel, wing box, skins, etc.)	3%	3%	4%	3%	4%	5%
	Out-of-autoclave curing composites		1%	1%	1%	1%	1%
	Automated tape laying, automated fiber placement	1%	1%	1%	1%	1%	1%
	5D. Composite sandwich construction		2%	2%	2%	2%	2%
	Net shape components (forgings, castings, extrusions, RTM, RFI elimination of machining and fastening)	1%	1%	1%	1%	1%	1%
	Additive manufacturing (for mass customization of cabin interior structures, depot repairs, etc.)		1%	1%	1%	1%	1%
	3-D Preforms (aero elastically tailored, braided, woven, stitched)						3%
	Bonded joints, innovations in structural joining		1%	1%	1%	1%	3%
	Damage tolerance concepts (3-D woven composites, PRSEUS, crack arrestment features, stitching, z pinning, etc.)		2%	2%	2%	2%	3%
	Adaptive and morphing structures (wings, control surfaces, etc.)						3%
	Advanced metallic joining (Friction Stir Welding, Advanced Welding)	1%	1%	1%	1%	1%	1%
	High temperature materials for Insulation, thermal protection		1%	1%	1%	1%	1%
	High temperature ceramics and coatings for engine components			1%		1%	1%
	Innovative load suppression, and vibration and aeromechanical stability control						1%
	Multifunctional materials and structures (noise cancellation, embedded sensors, signal processing, actuators, antenna, lightning strike, etc.)						1%

Table A 2 Improvements for small twin aisle aircraft by technology group and scenario

Small Twin Aisle		2024			2034		
Technology Group	**Technology**	**Evol.**	**Mod.**	**Aggr.**	**Evol.**	**Mod.**	**Aggr.**
Aerodynamic Efficiency (Viscous) % Improvement in drag, 100% deployment	Natural laminar flow on nacelles	0.25%	0.5%	1%	0.5%	1%	1%
	Hybrid laminar flow on empennage		2%	2%	2%	2%	2%
	Natural laminar flow on wings						
	Hybrid laminar flow on wing			10%		10%	10%
	Laminar flow coating/riblets			2%		2%	2%
	Low friction paint coating	2%	2%		2%		
Aerodynamic Efficiency (Non-viscous) % improvement in drag	Improved aero/transonic design	2%	2%	3%	2%	3%	4%
	Wingtip technologies (for fixed span)	1%	2%	2%	2%	2%	3%
	Variable camber with existing control	1%	1%	1%	1%	1%	1%
	Adaptive compliant trailing edge		1.5%	2%	1.5%	2%	2%
	Active stability control (reduced static)		1%	1%	1%	1%	1%
	Reduction of loads (active smart wing)		1.5%	2%	1.5%	2%	3%
	Increased wing span			8%		8%	8%
Structures, Materials and Manufacturing (% weight reduction)	**All composite aircraft**		10%	10%	10%	10%	10%
	All composite fuselage	5%	5%	5%	5%	5%	5%
	All composite wing	3%	3%	3%	3%	3%	3%
	All composite nacelle	1%	1%	1%	1%	1%	1%
	All composite empennage	1%	1%	1%	1%	1%	1%
	Integrated structural health monitoring		1%	2%	1%	2%	3%
	Advanced composite materials (higher strength, stiffness, toughness, damage tolerance, temperature)		2%	3%	2%	3%	4%
	Advanced airframe metal alloy (2000, 7000 series A1 alloy, 3rd gen A1-Li, higher temp, Ti, etc.)	1%	1%	1%	1%	1%	1%
	Advanced Manufacturing Technology						
	Unitized construction (one piece fuselage barrel, wing box, skins, etc.)	3%	3%	4%	3%	4%	5%
	Out-of-autoclave curing composites		1%	1%	1%	1%	3%
	Automated tape laying, automated fiber placement	1%	1%	1%	1%	1%	1%
	5D. Composite sandwich construction		2%	2%	2%	2%	2%
	Net shape components (forgings, castings, extrusions, RTM, RFI elimination of machining and fastening)	1%	1%	1%	1%	1%	1%
	Additive manufacturing (for mass customization of cabin interior structures, depot repairs, etc.)		1%	1%	1%	1%	2%
	3-D Preforms (aero elastically tailored, braided, woven, stitched)						3%
	Bonded joints, innovations in structural joining		1%	1%	1%	1%	3%
	Damage tolerance concepts (3-D woven composites, PRSEUS, crack arrestment features, stitching, z pinning, etc.)		2%	2%	2%	2%	3%
	Adaptive and morphing structures (wings, control surfaces, etc.)						3%
	Advanced metallic joining (Friction Stir Welding, Advanced Welding)	1%	1%	1%	1%	1%	1%
	High temperature materials for Insulation, thermal protection		1%	1%	1%	1%	1%
	High temperature ceramics and coatings for engine components			1%		1%	1%
	Innovative load suppression, and vibration and aeromechanical stability control						1%
	Multifunctional materials and structures (noise cancellation, embedded sensors, signal processing, actuators, antenna, lightning strike, etc.)						1%

Table A 3 Improvements for regional jet aircraft by technology group and scenario

Regional Jet		2024			2034		
Technology Group	**Technology**	**Evol.**	**Mod.**	**Aggr.**	**Evol.**	**Mod.**	**Aggr.**
Aerodynamic Efficiency (Viscous) % Improvement in drag, 100% deployment	Natural laminar flow on nacelles	1%	1.3%	1.5%	1.3%	1.5%	1.5%
	Hybrid laminar flow on empennage						
	Natural laminar flow on wings			5%		5%	8%
	Hybrid laminar flow on wing						
	Laminar flow coating/riblets			2%		2%	2%
	Low friction paint coating	2%	2%		2%		
Aerodynamic Efficiency (Non-viscous) % improvement in drag	Improved aero/transonic design	2%	2%	3%	2%	3%	4%
	Wingtip technologies (for fixed span)	1%	2%	2%	2%	2%	3%
	Variable camber with existing control						
	Adaptive compliant trailing edge		1.5%	2%	1.5%	2%	2%
	Active stability control (reduced static)						
	Reduction of loads (active smart wing)						
	Increased wing span	1.5%	1.5%	1.5%	1.5	1.5%	1.5%
Structures, Materials and Manufacturing (% weight reduction)	**All composite aircraft**		9.5%	9.5%	9.5%	9.5%	9.5%
	All composite fuselage	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%
	All composite wing	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%
	All composite nacelle	1%	1%	1%	1%	1%	1%
	All composite empennage	1%	1%	1%	1%	1%	1%
	Integrated structural health monitoring						
	Advanced composite materials (higher strength, stiffness, toughness, damage tolerance, temperature)		1.9%	2.9%	1.9%	2.9%	3.8%
	Advanced airframe metal alloy (2000, 7000 series A1 alloy, 3rd gen A1-Li, higher temp, Ti, etc.)	1%	1%	1%	1%	1%	1%
	Advanced Manufacturing Technology						
	Unitized construction (one piece fuselage barrel, wing box, skins, etc.)	2.9%	2.9%	3.8%	2.9%	3.8%	4.8%
	Out-of-autoclave curing composites		1%	1%	1%	1%	2.9%
	Automated tape laying, automated fiber placement	1%	1%	1%	1%	1%	1%
	5D. Composite sandwich construction		1.9%	1.9%	1.9%	1.9%	1.9%
	Net shape components (forgings, castings, extrusions, RTM, RFI elimination of machining and fastening)	1%	1%	1%	1%	1%	1%
	Additive manufacturing (for mass customization of cabin interior structures, depot repairs, etc.)		1%	1%	1%	1%	1.9%
	3-D Preforms (aero elastically tailored, braided, woven, stitched)						2.9%
	Bonded joints, innovations in structural joining		1%	1%	1%	1%	2.9%
	Damage tolerance concepts (3-D woven composites, PRSEUS, crack arrestment features, stitching, z pinning, etc.)		1.9%	1.9%	1.9%	1.9%	2.9%
	Adaptive and morphing structures (wings, control surfaces, etc.)						
	Advanced metallic joining (Friction Stir Welding, Advanced Welding)	1%	1%	1%	1%	1%	1%
	High temperature materials for Insulation, thermal protection		1%	1%	1%	1%	1%
	High temperature ceramics and coatings for engine components			1%		1%	1%
	Innovative load suppression, and vibration and aeromechanical stability control						
	Multifunctional materials and structures (noise cancellation, embedded sensors, signal processing, actuators, antenna, lightning strike, etc.)						1%

APPENDIX B—TECHNOLOGY MODELING METHODS

In this study, aircraft and engine performance modeling was done separately using specialized software. This section summarizes the steps taken to estimate aircraft and engine fuel burn performance with and without the implementation of fuel saving technologies. Expansive detail on the aircraft and engine performance modeling methodology is provided in Tecolote (2015).

AIRCRAFT PERFORMANCE MODELING

This section presents the steps taken in a resizing exercise around technology implementation onto a reference aircraft while maintaining payload and range capabilities. In this study, aircraft performance was modeled using Piano 5, a commercially available software tool developed by Lissys, Ltd.[36] Piano 5 is built around a database of detailed technical and performance data for current conventional, commercial, subsonic aircraft certified to civil aviation standards, allowing for preliminary aircraft design or modification of an existing design, including airline-specific configurations. Further details on Piano capabilities are provided in the Piano user and help files (available at http://www.lissys.demon.co.uk/index2.html).

Piano 5, along with three other aircraft design tools, was used in the ICAO Long Term Technology Goal study to provide modeling data to supplement the independent experts' analysis (ICAO, 2010a). 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[37], PrADO: the Preliminary Design and Optimization Program[38] and EDS: Environmental Design Space[39]). Piano 5 was thus deemed to be a suitable tool to estimate the fuel-efficiency implications of advanced technologies in this study, which overlaps substantially with the LTTG review.

The first step in technology performance modeling is determining the appropriate aircraft model within the Piano database for each reference aircraft defined in Section 2.1.2. When multiple Piano aircraft are available for the same aircraft type due to different MTOW or engine variant, Ascend fleet database[40] was consulted to determine the most prominent variant based on the global fleet as of April 2013. The chosen Piano aircraft used as reference aircraft models are:

- Airbus A320-200 (SA): Airbus A320-214 77t
- Boeing 777-200ER (STA): B777-200 ER (656)g
- Embraer E190AR (RJ): Embraer 190 AR

For each of the six technology deployment scenario (2024 Evolutionary, Moderate, and Aggressive; 2034 Evolutionary, Moderate, and Aggressive) for each aircraft type, a set of Piano user factor multipliers indicating technology impact on the aircraft characteristics and performance were developed, resulting in a set of new user factors or performance

36 http://www.piano.aero/

37 http://adg.stanford.edu/aa241/pass/pass1.html.

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

39 https://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/eds/

40 http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/

parameters unique to the improved aircraft. Out of 34 Piano user factors available, a subset of 14 user factor categories were used in this analysis:

- 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

The technology-based user factors were developed by Tecolote and their SMEs, and the values of the user factors are presented in their report (Tecolote, 2015).

Based on these user factors, these reference aircraft were modified (by changing the appropriate Piano user factors) and resized using Piano's "optimization" function, while keeping payload and range capability[41] constant. The resizing process was done with the objective to minimize fuel burn. The optimization parameters used in this process are MTOW, wing area, aspect ratio, sweep angle, and engine thrust. Parameters that are kept constant are fuselage size and geometry, number of seats, and operational parameters such as passenger weight, number of crew, etc. The result is an improved and resized aircraft with fuel-saving technologies implemented.

Figure B 1 shows a three-view of all 2024 cases for the single aisle aircraft: reference (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 B 2, on the other hand, shows the different payload-range diagram of the different scenarios. While the R1 point (maximum range at maximum payload) was kept constant, with a more aggressive level of technology implementation, the aircraft requires less fuel to operate and therefore gains more range capability with the same design payload (shown as a dot along the colored lines of each technology scenario).

41 In this study the R1 point (maximum range at maximum structural payload) was used as the reference point for aircraft resizing.

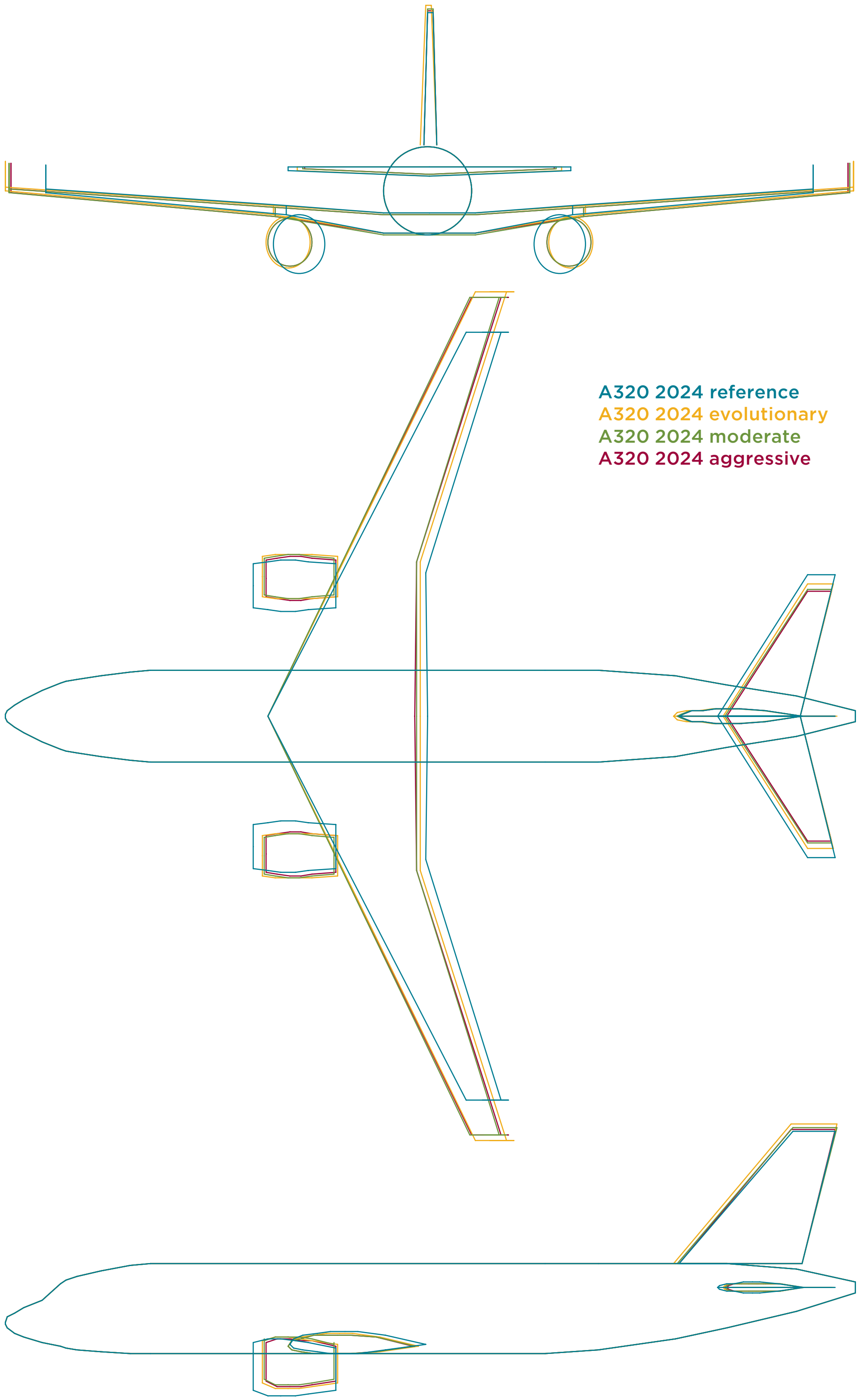

Figure B 1 3-view profile for single aisle 2024 scenarios

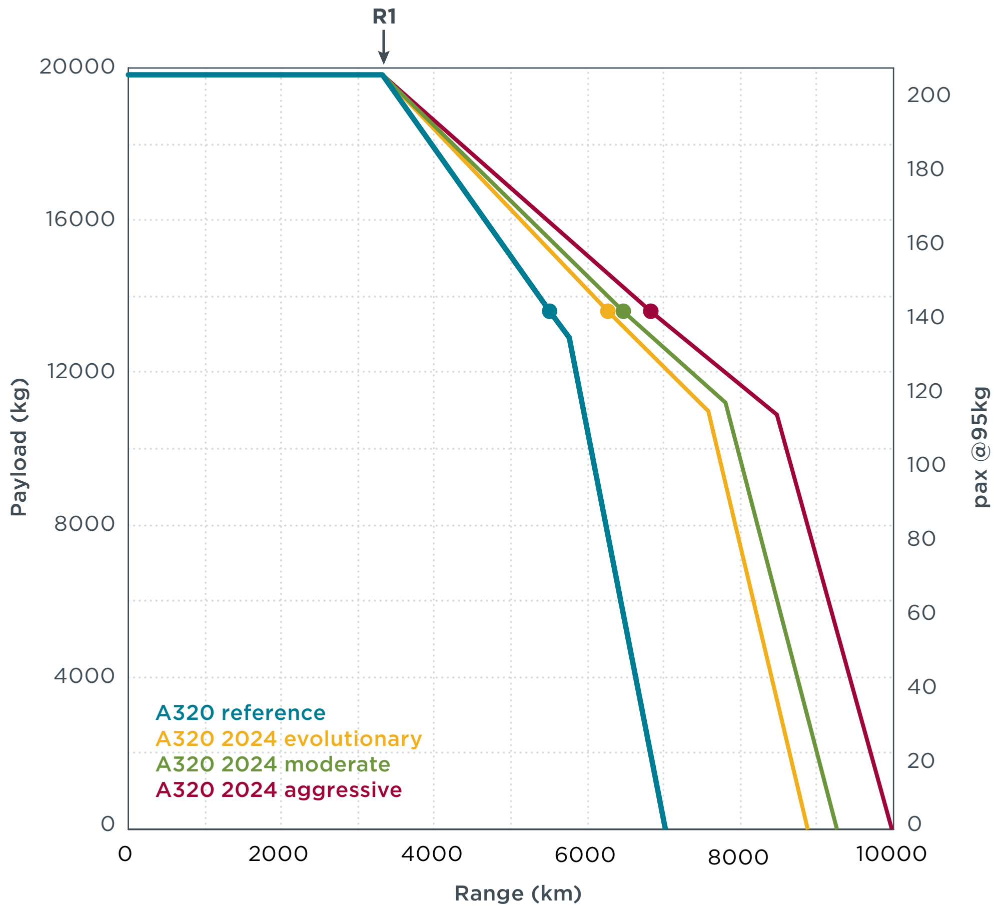

Figure B 2 Payload-range diagram for single aisle 2024 scenarios

Table B1 presents basic parameters of the reference and each optimized aircraft by scenario for SA aircraft. The Piano-estimated mass for the 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.[42]

Table B 1 Single aisle optimized aircraft basic parameters by scenario

Parameter	Reference	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
Wings Aspect Ratio	10.3	12.7	12.9	13.2	13.2	13.2	14.2
MTOW (kg)	77,000	71,500	67,900	66,400	68,300	66,400	62,000
OEW (kg)	42,700	41,000	38,300	37,800	38,900	37,900	34,600

42 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.

ENGINE PERFORMANCE MODELING (TECOLOTE, 2015)

GasTurb, the engine performance modeling software used in this study, is a commercially available program that uses pre-defined engine configurations while permitting input of important parameters, including component geometry. GasTurb was chosen due to its better ability of modeling detailed performance of aircraft engine compared with Piano.

Outputs from this tool include flow, pressure, and temperature values at all major stations within the engine, using nomenclature consistent with current industry standards. Another output used in the latter phases of this study is engine thrust/weight ratio that, combined with thrust values from Piano, resulted in engine weight used in cost estimation. 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). Engine weight estimation methodology will be discussed later in this section.

As with Piano modeling, the first step to engine performance modeling is to determine the reference aircraft. The process was simple since reference engines were chosen based on the most prominent engine installed on the reference aircraft. Table B 2 presents the propulsion configurations for aircraft used in this study as reference aircraft along with their basic parameters.

Table B 2 Engine Reference 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	118,000	378,000	65,000
Fan Diameter—cm	172.7	312.4	117.3
Bypass Ratio	6.0	8.4	4.8
Overall PR	28	39	28.3

The assumptions and ground rules used in modeling improved engine performance for each aircraft type are as follows:

- The reference engines are to 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:
  - Second-generation E-Jet engines for RJ
  - A320neo/737 MAX engines for single aisle
  - 787 and A380 engines for small twin aisle
- 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.)

- 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)

To obtain estimated engine weight parameter as an input in the cost estimation, a weight correlation developed using engine dimensions and corrected flows indicative of dimensions derived from large engine databases were used. A thrust to weight ratio was developed 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.

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. Tables B3, B4, and B5 summarize the calculated engine performance parameters for each aircraft configuration.

Table B 3 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)	15,400	14,400	13,600	14,500	12,900	11,800
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)	2,970	2,890	2,670	2,910	2,540	2,400

Table B 4 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)	21,200	19,000	18,400	18,800	18,000	16,000
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	4.7	4.5	4.4
Per Engine Weight (lbs)	4,610	4,030	4,100	4,000	3,990	3,630

Table B 5 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)	77,300	68,600	66,700	68,800	60,600	57,700
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)	16,100	15,300	14,400	15,300	14,100	12,600