# Airplane Greenhouse Gas Standards

## Technical Support Document (TSD)

EPA United States Environmental Protection Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

United States Environmental Protection Agency

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## List of Acronyms

| | |
|---|---|
| AC | Aircraft |
| AIR | Aerospace Information Report |
| ANPR | Advanced Notice of Proposed Rulemaking |
| APU | Auxiliary Power Unit |
| ASK | Available Seat Kilometers |
| ASTM | American Society for Testing and Materials |
| ATK | Available Ton Kilometers |
| AVL | Asset Value Loss |
| BAU | Business As Usual |
| BGA | Business and General Aviation Airplane |
| BPR | Bypass Ratio |
| CAA | Clean Air Act |
| CAEP | Committee on Aviation Environmental Protection |
| CAT | Airplane Category |
| CBI | Confidential Business Information |
| CFR | Code of Federal Regulations |
| CI | Continuous Improvement |
| CMS | Continuous Modification Status |
| $CH_4$ | Methane |
| $CO_2$ | Carbon Dioxide |
| $CO_2$DB | $CO_2$ Certification Database |
| COD | Common Operations Database |
| DICE | Dynamic Integrated Climate and Economy model |
| DOC | Direct Operating Cost |
| DOT | Department of Transportation |
| ECS | Environmental Control System |
| EIA | Energy Information Administration |
| EIS | Entry Into Service |
| EP | Extended Production |
| EPA | Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FUND | Climate Framework for Uncertainty, Negotiation, and Distribution model |
| G&R | Growth and Replacement |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| HLFC | Hybrid Laminar Flow Control |
| IAM | Integrated Assessment Model |
| ICAO | International Civil Aviation Organization |

| | |
|---|---|
| ICF | ICF International, Inc. |
| InP | In-production |
| IWG | Interagency Working Group |
| M | Millions |
| MTOM | Maximum Takeoff Mass |
| MTOW | Maximum Takeoff Weight |
| NG | Next Generation |
| NHTSA | National Highway Traffic Safety Administration |
| NLF | Natural Laminar Flow |
| NRC | Non-recurring Cost |
| NT | New Type Designs |
| $N_2O$ | Nitrous Oxide |
| OD | Origin-Destination |
| OMB | Office of Management and Budget |
| PAGE | Policy Analysis of the Greenhouse Gas Effect model |
| PIANO | Project Interactive Analysis and Optimization |
| PIP | Performance Improvement Package |
| R&D | Research and Development |
| RC | Retirement Curve |
| RFA | Regulatory Flexibility Act |
| RGF | Reference Geometric Factor |
| RIA | Regulatory Impact Analysis |
| RPM | Revenue Passenger Miles |
| RTM | Revenue Ton Miles |
| SAE | Society of Automotive Engineers |
| SAR | Specific Air Range |
| SBA | Small Business Administration |
| SBFA | Small Business Flexibility Analysis |
| SBREFA | Small Business Regulatory Enforcement Fairness Act |
| SC | Survival Curve |
| SOs | Stringency Options |
| TAF | Terminal Area Forecast |
| TC | Type Certificate |
| TRL | Technology Readiness Level |
| TSD | Technical Support Document |
| TSFC | Thrust Specific Fuel Consumption |

## Executive Summary

The Environmental Protection Agency (EPA) is adopting greenhouse gas (GHG) emission standards and other requirements applicable to greenhouse gas emissions from certain classes of engines used by certain civil subsonic jet airplanes (those with a maximum takeoff mass greater than 5,700 kilograms), as well as larger subsonic propeller-driven airplanes (those powered by turboprop engines with a maximum takeoff mass greater than 8,618 kilograms). These standards are equivalent to the Airplane $CO_2$ Emission Standards adopted by the International Civil Aviation Organization (ICAO) in 2017 and will apply to both new type designs (new type design airplanes) and in-production airplanes, consistent with U.S. efforts to secure the highest practicable degree of uniformity in aviation regulations and standards. The standards will also meet the EPA's obligation under section 231 of the Clean Air Act (CAA) to adopt GHG standards as a result of the 2016 positive endangerment and contribution findings for six well-mixed GHGs emitted by certain classes of airplane engines.

We project no reductions in fuel consumption and GHG emissions associated with the standards. This is because all the potentially affected airplanes currently in production either meet the stringency levels of the standards or will be out of production when the standards will take effect, according to our projected technology responses.

This Technical Support Document (TSD) is generally organized to provide overall background information, methodologies, and data inputs, followed by results of the various technical and economic analyses. A summary of each chapter of the TSD follows.

**Chapter 1:** Industry Characterization. In order to assess the impacts of the GHG standards upon the affected industries, and especially on any small entities, it is important to understand the nature of the industries potentially impacted by the regulations. Further, it is helpful to put the contribution of the potentially impacted industry in context regarding its contribution to the overall mobile source GHG inventories. This chapter provides a general overview of the airplane and airplane engine industries, including some basic information on the companies involved in them. It also provides brief overviews of current and projected future air traffic, as well as the relative contribution of this market to overall mobile source GHG emissions.

**Chapter 2:** Technology and Cost. This chapter presents details of the airplane and airplane engine technologies and technology packages for reducing airplane GHG emissions and fuel burn. The methodologies used for projecting technology usage and resultant improvements in GHG/fuel burn are presented for both the near/mid-term and the long term. Specific airplane and engine technologies and their associated fuel burn improvements are then discussed, followed by the projected costs of these technologies. This information provides the basis for the emissions and cost projections.

**Chapter 3:** Test Procedures. This chapter describes the relevant test procedures, including methodologies for determining GHG emissions based on fuel consumption and the determination of the fuel efficiency metric value, which are used to determine compliance with the regulations. Finally, a description of when changes to an existing airplane design will trigger the need for a new certification is presented.

**Chapter 4:** Airplane Performance Model and Analysis. This chapter describes methodologies, assumptions and data sources used to develop the airplane GHG emissions and fuel burn inventories for the standards and two alternative stringency scenarios that were evaluated. A description of the airplane fleet and how we project it to evolve is first presented, followed by a description of how this fleet evolution is projected to translate into airplane activity. Finally, the methodology is presented for determining individual airplane flight GHG emissions, fuel consumption, and how that data is used in conjunction with airplane activity projections to develop overall emissions inventory projections.

**Chapter 5:** Results of Performance Model Analysis. This chapter describes the results of the analysis using the methodology described in Chapter 4 to determine the impacts of the standards. Included are analyses of the baseline emissions, the impact of the standards, and some sensitivity studies looking specifically at the impacts of some key assumptions.

**Chapter 6:** Analysis of Alternatives. This chapter provides EPA's analysis of two alternatives to the standards. The emissions reductions and costs associated with scenarios of accelerated timing and accelerated timing in conjunction with more stringent regulatory levels are presented.

**Chapter 7:** Regulatory Flexibility Analysis. This chapter describes the EPA's analysis of the small business impacts of the regulations.

For reasons discussed throughout this TSD, the EPA does not project any emissions reductions associated with the GHG regulations.

**Industry Characterization**

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# Chapter 1: Industry Characterization

## 1.1 Introduction

### 1.1.1 Overview

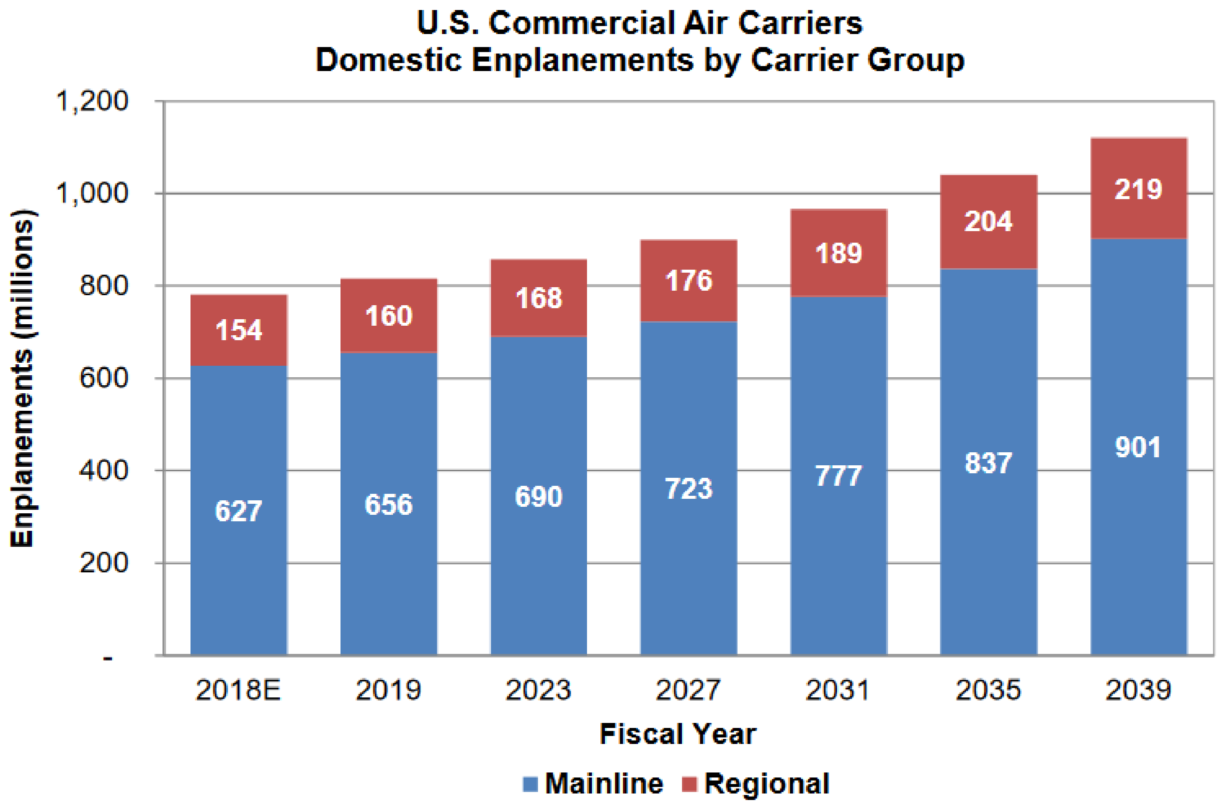
In order to assess the impacts of the regulations upon the affected industries, it is important to understand the nature of the industries potentially affected by the regulations. In general, this includes the manufacturers of subsonic civil jet airplanes with a maximum takeoff mass (MTOM) greater than 5,700 kilograms (kg), the manufacturers of subsonic propeller-driven airplanes (those powered by turboprop engines) with MTOM greater than 8,618 kg, and the manufacturers of engines for these categories of airplanes. A brief description of the airplane and engine development process is presented in section 1.2. A general description of these product categories is contained in section 1.3. An overview of the potentially affected airplane and engine manufacturers is contained in section 1.4.

### 1.1.2 Air Traffic

General information on air traffic in the U.S. was obtained via the Federal Aviation Administration's (FAA) Aerospace Forecast; Fiscal years 2019-2039.[1] This quick overview looks at U.S. air traffic in four general categories – domestic commercial passenger enplanements, international commercial passenger enplanements, cargo traffic (in revenue ton miles) and operation hours for business/general aviation.

Figure 1-1 shows that domestic enplanements totaled over 780 million in 2018. The FAA projects that domestic revenue passenger miles (RPM) will increase between 2019 and 2039 at an average annual rate of 1.9 percent.[i] In contrast, RPMs for international flights are projected to grow at an annual rate of 3.0 percent during this same period, as illustrated in Figure 1-2.

[i] This projection was developed before the COVID-19 pandemic. While the projected level of aircraft operations is affected by the COVID-19 pandemic, aviation is a growth industry that is expected to recuperate over time.




Mainline carriers are defined as those providing service primarily via aircraft with 90 or more seats. Regional carriers are defined as those providing service primarily via aircraft with 89 or less seats and whose routes serve mainly as feeders to the mainline carriers.

**Figure 1-1 Projection of Domestic Passenger Traffic**[2]

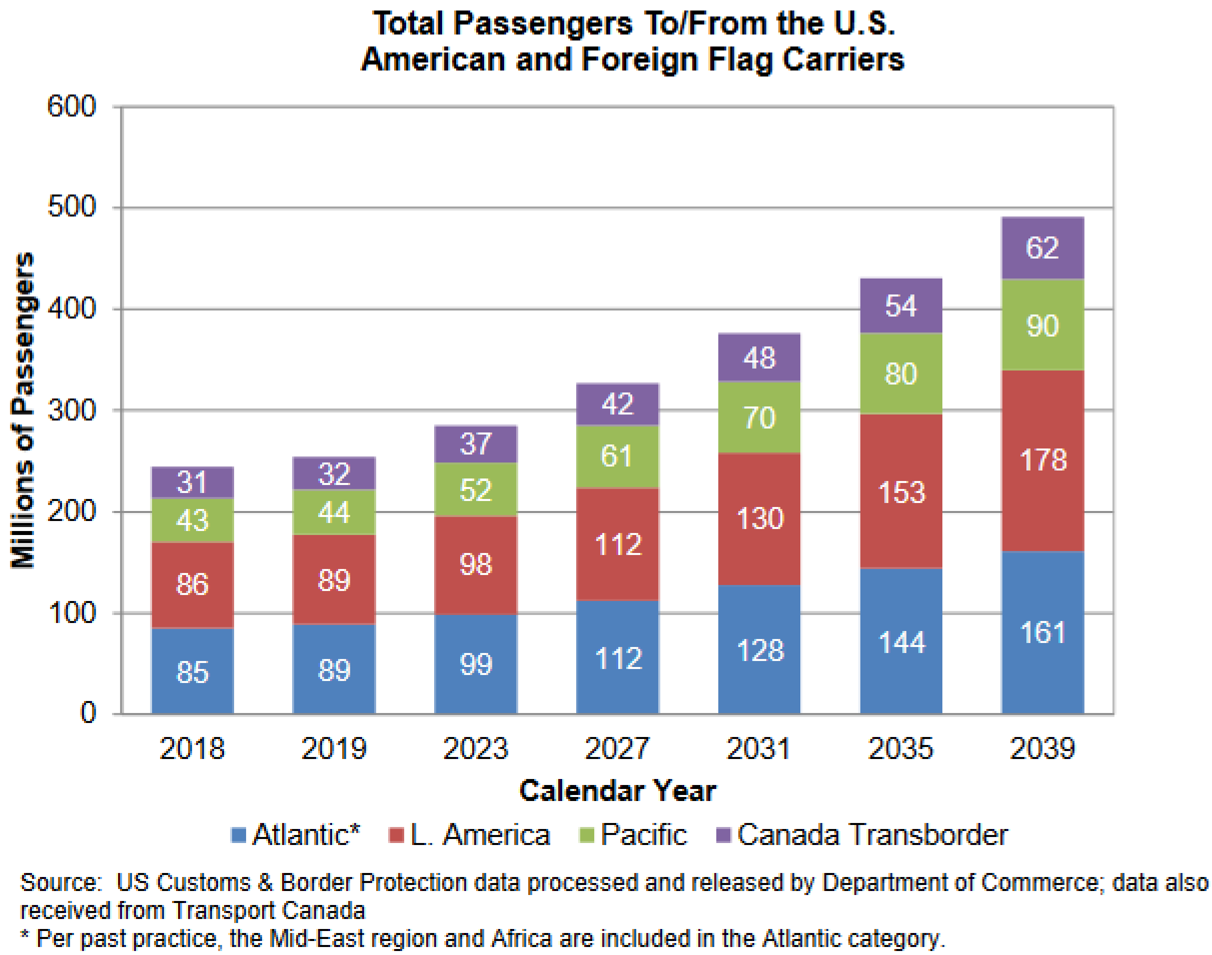



**Figure 1-2 Projections of International Passenger Traffic**[3]

In the business/general aviation sector, fixed wing turbine powered airplanes were projected to operate approximately 8 million hours in 2019. Operating hours in this sector are projected to grow at an annual rate of 2.4 percent through 2039.

U.S. carriers flew 42.8 billion revenue ton miles (RTM) in 2018. Of this, 15.8 billion RTMs were domestic cargo, while 27.0 billion RTMs were international cargo. Of this, approximately 80 percent of cargo is carried by all-cargo carriers, with the remainder carried by passenger carriers. Through 2039, domestic RTM growth is projected at a rate of 1.6 percent annually, with international RTM growth projected at 4.0 percent annually. Overall RTM growth (domestic and international combined) is projected at a rate of 3.3 percent annually.

### 1.1.3 <u>Greenhouse Gas Emissions from Aircraft</u>

The importance of this rulemaking is highlighted by the fact that GHGs from aviation made up over 12 percent of total transportation-related GHG emissions in 2017, as shown in Figure 1-3. Although the aircraft portion of this chart contains three aviation sectors that are not covered by this rule (e.g., military, helicopters, and airplanes operating on aviation gasoline), these three sectors comprised well under one percent of total transportation related GHG emissions in 2017.

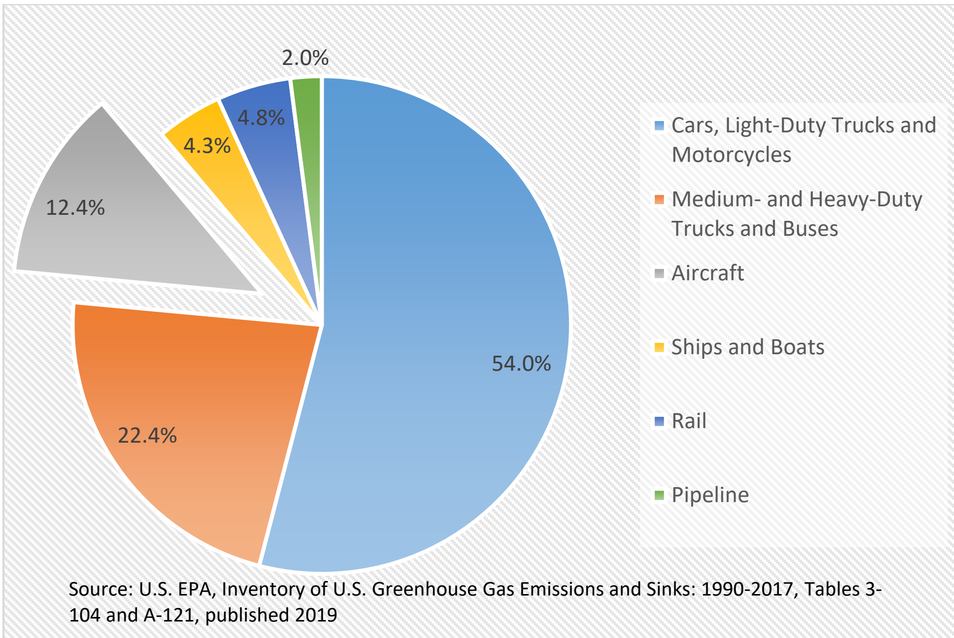



**Figure 1-3 Contribution to GHG Emissions from U.S. Transportation in 2017**

## 1.2 Market Basics

The development of a new airplane from the ground up (i.e., a "clean sheet" design) is a very lengthy and expensive project. As such, completely new airplane designs (known as new type designs) are not introduced very often. The introduction of the Boeing 787, and Airbus A350 and A220 (formerly the Bombardier CSeries) in the last 10 years has marked a relatively active period in the introduction of new type designs in the commercial airplane market.

In contrast to the development of new type designs discussed above, a more common practice is to develop generational updates to existing airplane designs (or redesigns of the airplane). For example, the Boeing 737 was first introduced into commercial operation in 1968. Since that time, it has seen three redesigns – the Classic series in the 1980s, the Next Generation (NG) in the 1990s, and the recent MAX series, introduced in 2017. These generational updates can include any number of improvements/modifications to the previous design, but frequently include new engines, new or redesigned wings, and updated operating systems (or some combination of these modifications). Such updates are not considered new type designs for purposes of certification. Rather, they are considered to be redesigns of an existing design. As such, they are not required to undergo a completely new certification process, but instead go through an amendment certification process of the existing type certificate. Thus, the 737 MAX is covered under an amended version of its original 50 year-old type certificate.

This distinction between new type designs and redesigned versions of existing in-production types is an important one for the purposes of the regulations, which contain different applicability dates and regulatory limits for new type design and in-production airplanes. An in-production airplane is one which received it initial type certificate (TC) prior to the applicability date of the standards for new type designs. Even if an in-production airplane receives a major redesign as described above, it would likely still be considered an in-production airplane for the purposes of the standards applicability.

Engines used on airplanes subject to the standards are generally designed specifically for the airplane type on which they will be used, with precise thrust ratings tailored specifically to an airplane's requirements. The range and payload capacity (as indicated by MTOM) are primary drivers of the engine specifications. Also, it is common for there to be multiple variants of a given airplane type, with different ranges and/or stretched or shortened fuselages. Each of these variants similarly require a variant of the original engine type, with a slightly different required thrust rating. It is common for an airplane manufacturer to offer engines from two (or in some cases, three) different manufacturers on a given airplane type. However, it is also common in the case of some smaller commercial airplanes and especially business jets for a manufacturer to only offer a single engine option.

## 1.3 Product Categories

This section contains a high-level overview of the types of airplanes and engines that are potentially affected by the regulations. ICF performed a detailed industry characterization of these industries for the EPA.[4] This section, and the following section 1.4, contain a brief summary of that report. As described in Section II of that report, ICF draws on a number of sources to develop their industry forecasts, including working directly with the airplane and equipment production industries, attending industry conferences and keeping up with the latest industry news, published articles and papers. ICF synthesizes all of these sources into their own market forecasts, which they then benchmark against global market forecasts done by Boeing and Airbus to assure that their forecasts fall within a reasonable range.

### 1.3.1 <u>Airplanes</u>

Airplanes potentially affected by the regulations can be broadly divided into three main groups - large commercial jets, regional commercial jets, and business and general aviation airplanes. Although there is some overlap among these categories, notably the blurring of the line between the small end of the large commercial jet range and regional commercial jets, these categories serve as a useful way to subdivide the world of potentially affected airplanes for purposes of the cost and emissions analyses contained in later chapters of this document.

In general, the aviation marketplace is an international one. Manufacturers produce and sell their airplanes for use around the world. The global prevalence of international flights (i.e., those that originate in one country and terminate in another) means that airplanes (especially those in the large commercial jet category) are generally designed to operate in the international air transport market. For example, the U.S. flight data which served as the basis for the analyses presented later in this document show that in 2015 almost nine percent of commercial flights originating in the U.S. were to destinations outside of the U.S. Even smaller airplanes with ranges not suitable for international flights are often sold to countries other than a manufacturer's home country.

Finally, while this summary focuses on passenger-carrying airplanes, it is noted that a small number of dedicated freight airplanes are also produced which are subject to the regulations. These tend to be modifications of existing passenger airplane designs rather than airplanes designed exclusively for freight applications.

#### *1.3.1.1 Commercial - Large Jet*

The large commercial jet category consists of a broad range of turbofan-powered airplane types, from single-aisle airplanes seating over 100 people to very large twin-aisle airplanes that can seat well over 500 passengers. The smallest of these are not generally used for transoceanic international flights. Collectively, there were 1,443 large commercial jets manufactured world-wide in 2016, with a total value of $102B. The large commercial jet category can be further divided into four subcategories: small single aisle, small twin aisle, large twin-aisle and large quads.

The small single aisle category consists of airplanes with a single passenger aisle and designed to carry roughly 100-200 passengers at up to six abreast. These airplanes tend to have a range of 60,000 kg to 97,000 kg in MTOM. Examples include the Boeing 737 series and the Airbus A320. As previously mentioned, the line between large commercial jets and regional jets is becoming less clear with the coming introduction of the Airbus A220 (formerly Bombardier CSeries) and the Embraer E2 series. In terms of 2016 production, 72 percent of large commercial jets were small single aisle. However, they only accounted for 45 percent of the total production value.

Small twin-aisle airplanes are wide enough to feature two passenger aisles and can typically carry 230-300 passengers at up to eight abreast. They tend to range from 186,000 kg to 308,000 kg in MTOM. Main examples of small twin-aisle airplanes are the Boeing 787 and the Airbus A330. This subcategory accounted for 10 percent of the 2016 production and 17 percent of the production value.

Large twin-aisle airplanes also feature two passenger aisles but with wider fuselages that can accommodate up to 400 passengers at up to eight abreast and with MTOM from 233,000 kg to around 350,000 kg. An example of a large twin-aisle is the Boeing 777, although the large variants of the Airbus A330 and A350 (small twin-aisles) blur the distinction between small and large twin-aisles. This subcategory accounted for 15 percent of the 2016 production and 30 percent of the production value.

The last subcategory of large commercial jets is the large quad. These airplanes are also twin-aisle, but they are large enough to require four engines (as opposed to the three previously discussed subcategories which are typically powered by two engines). These airplanes can carry as many as 575 passengers in ten-abreast configuration. Examples include the Boeing 747 and the Airbus A380. This subcategory accounted for 3 percent of the 2016 production and accounted for 8 percent of the production value. However, demand for large quad airplanes is declining dramatically for multiple reasons. First, the increasing efficiencies, range and passenger (and payload) capacity of the large twin-aisle airplanes has made them attractive as replacements for large quads. Second, the development of Extended-range Twin-engine Operational Performance Standards (ETOPS) has allowed twin-engine airplanes to safely service routes previously only serviced by airplanes with more than two engines. Finally, the overall growth in the commercial passenger aviation market has resulted in making more city pairs profitable using direct flights with smaller airplanes, thus reducing the demand for large quads to service the “hub and spoke” model of passenger air traffic. Although the future of the large quad market has been the subject of much debate in the aviation world, ICF's 2018 analysis projected that production of large quad airplanes is likely to end altogether by the mid-2020s. As discussed further in Chapter 5 and Chapter 6, since the ICF analysis was completed, Airbus has announced plans to end production of the A380 in 2021.

Total sales of large commercial jets are projected to climb to almost 1,800 units in 2021 but drop back to around 1,600 units in 2026. More significantly, it is expected that the large quad subcategory will shrink dramatically in this time frame.

#### *1.3.1.2 Commercial - Regional Airplane*

The regional commercial airplane category can be divided into two subcategories: the regional jet and the regional turboprop. Regional jets are turbofan-powered jets which typically carry 50-100 passengers with an MTOM in the range of 19,000 kg to 60,700 kg. Examples include the Embraer EJet and the Bombardier CRJ. Regional turboprops are also powered by turbine engines, but the engines' power is instead used to drive a propeller. Regional turboprops tend to be smaller than their jet counterparts, with an MTOM range of 18,600 kg to 30,000 kg and a capacity of around 40 to 80 passengers. Examples include the ATR 42/72 and the Bombardier Q400. While turboprops tend to be more fuel-efficient than their turbofan counterparts, they are also slower and have higher levels of cabin noise which somewhat serves to offset the appeal of that better fuel efficiency.

There were 267 regional commercial airplanes produced in 2016, with a total value of $6.3B. Regional jets accounted for 57 percent of the production volume and 69 percent of the production value. Production of regional airplanes is projected to remain relatively steady through 2026.

#### *1.3.1.3 Business and General Aviation*

The business jet and general aviation market includes a wide range of small, turbofan-powered airplanes designed for business and personal use. These airplanes range from 6,200 kg to 48,000 kg MTOM, with capacities of 6 to 19 passengers. There were 567 business and general aviation airplanes produced in 2016, with a market value of $16.8B. Production of this category of airplanes is expected to steadily grow to well over 800 units in 2026. The main manufacturers in this market include Embraer, Dassault, Gulfstream, Cessna and Bombardier.

### 1.3.2 <u>Airplane Engines</u>

There are two main types of engines potentially affected by the regulations – turbofans and turboprops. While both are turbine engines, they differ in their mode of propulsion. A turbofan engine utilizes the mechanical energy of the turbine to power a ducted fan which provides the majority of the propulsion. However, the air that flows through the turbine itself and exits as combustion exhaust also provides a portion of a turbofan’s propulsion. In contrast, a turboprop utilizes the turbines mechanical energy to power an open propeller, which provides the entirety of turboprop's propulsion. In terms of utilization on airplanes covered by the regulations, turbofans are used across the entire spectrum of airplanes, from the smallest business jets to the largest commercial airplanes. In contrast, turboprops tend to be limited in use to commercial regional airplanes.

There were 5,069 commercial engines produced in 2016 for airplane classes subject to the regulations. Large commercial jet engines accounted for 64 percent, while regional jet engines accounted for 12 percent and business/general aviation engines accounted for the remaining 24 percent. In terms of production value, large commercial airplane engines accounted for 89 percent of the $38B total, with regional airplane at four percent and business/general aviation accounting for the remaining seven percent.

Commercial engine production is driven by airplane production and is expected to grow to 5,817 units in 2026. Most of this growth is expected to be in the business/general aviation sector.

## 1.4 Product Manufacturers

This section contains a brief overview of the manufacturers of products that covered by this rule. Some of this information (i.e., each manufacturer's number of employees) was used in the screening analysis for the Small Business Flexibility Analysis (SBFA) which evaluates the potential impacts of the rule on small entities. That analysis is discussed in Chapter 7.

**Table 1-1 - Airplane Manufacturers**

| Manufacturer | Categories[a] | Main Products | Employee Count[b] |
|---|---|---|---|
| Airbus | Comm | A220, A320, A330, A350, A380 | 136,574 |
| ATR | B/GA | ATR 42, ATR72 | 1,300[c] |
| Boeing | Comm | 737, 747, 767, 777, 787 | 147,683 |
| Bombardier | Comm, B/GA | CRJ, Q400 | 61,900 |
| Cessna | B/GA | Citation | 36,000 |
| COMAC | Comm | ARJ | Unavailable |
| Dassault | B/GA | Falcon | 11,942 |
| Embraer | Comm, B/GA | Legacy, Phenom, ERJ, E2 | 19,357 |
| Gulfstream | B/GA | G150, G280, G450, G550, G650 | 13,313 |
| | | | |
| Irkut | Comm | MS-21 | 10,000 |
| Mitsubishi | Comm | MRJ | 68,247 |
| Pilatus | B/GA | PC-24 | 1,905 |
| Sukhoi | Comm | Superjet | 10,000 |

Comm = commercial, B/GA = business and general aviation

In some cases, the employee count is that of the parent company

ATR is jointly owned by Airbus and Leonardo. Thus, the parent companies have significantly more than the 1,500 employee cutoff used to determine whether a company is a small entity. See Chapter 7.

**Table 1-2 - Airplane Engine Manufacturers**

| Manufacturer | Categories[a] | Main Products[b] | Employee Count |
|---|---|---|---|
| CFM International | Comm | CFM56, LEAP | NA[c] |
| Engine Alliance | Comm | GP7200 | NA[d] |
| GE | Comm, B/GA | GEnx, GE9x, CF6, CF34, Passport | |
| Honeywell | B/GA | HTF7000, TFE731 | 40,000 |
| International Aero | Comm | V2500 | NA[e] |
| Pratt & Whitney | Comm | PW4000, GTF | 35, 104 |
| Pratt & Whitney Canada | B/GA | PW100, PW500, PW800 | 9,200 |
| PowerJet | Comm | SAM146 | NA[f] |
| Rolls-Royce | Comm, B/GA | Trent series, BR700, AE3007 | 49,900 |
| Safran | B/GA | Silvercrest | 15,700 |
| Williams International | B/GA | FJ44 | <1,000 |

a. Comm = commercial, B/GA = business and general aviation

This is not an exhaustive list, and only includes products that are potentially affected by the regulations. It also includes some products which are still under development but nearing commercial introduction.

CFM International is a joint venture between GE and Safran.

Engine Alliance is a joint venture between GE and Pratt & Whitney.

International Aero is a joint venture between Pratt & Whitney, Japanese Aero Engine Corporation and MTU Aero Engines.

PowerJet is a joint venture between Safran and NPO Saturn.

## REFERENCES

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[1] FAA, 2020: *FAA Aerospace Forecast; Fiscal Years 2019-2039*, U.S. Federal Aviation Administration, TC18-0004. Accessed March 18, 2020 at https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/FY2019-39_FAA_Aerospace_Forecast.pdf (last accessed March 20, 2020).
[2] See Reference #1
[3] See Reference #1
[4] ICF, 2018: *Aircraft $CO_2$ Cost and Technology Refresh and Industry Characterization*, Final Report, EPA Contract Number EP-C-16-020, September 30, 2018.

## Technology and Cost

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# Chapter 2: Technology and Cost

As described in section VII of the preamble, the EPA and FAA participated in ICAO/CAEP's analysis that informed the adoption of the international airplane $CO_2$ standards (ICAO Airplane $CO_2$ Emission Standards). A summary of that analysis was published in the report of ICAO/CAEP's tenth meeting,[5] which occurred in February 2016. This summary is useful in giving an overview of the analytical results used by CAEP in deciding on the final standards. However, due to the commercial sensitivity of much of the underlying data used in this ICAO analysis, the ICAO-published report (which is publicly available) provides only limited supporting data for the ICAO analysis. This EPA TSD compares the ICAO analysis to the EPA analysis.

For the purposes of the final GHG standards, the EPA presents an evaluation based on publicly available and independent data. In support of this work, the EPA had an analysis conducted of the technological feasibility and costs of the international Airplane $CO_2$ Emission Standards through a contractor (ICF) study.[6,7] The results developed by the contractor include estimates of technology responses and non-recurring costs for the domestic GHG standards, which are equivalent to the international Airplane $CO_2$ Emission Standards. Technologies and costs needed for airplane types to meet the final GHG standards were analyzed and compared to the improvements that are anticipated to occur in the absence of standards (business as usual improvements).

The ICF study is an update to work performed in support of the 2015 U.S. EPA Aircraft Greenhouse Gas Emissions Advance Notice of Proposed Rulemaking (henceforth the "2015 ANPR").[8] At that time, the EPA contracted with ICF to develop estimates of technology improvements and responses needed to modify in-production airplanes to comply with the international Airplane $CO_2$ Emission Standards. ICF conducted a detailed literature search, performed a number of interviews with industry leaders, and did its own modeling to estimate the cost of making modifications to in-production airplanes.[9] Subsequently, for this rulemaking, the EPA contracted with ICF to update its analysis (herein referred to as the "2018 ICF updated analysis"), which is located in the docket for this rulemaking.[10,ii] It had been three years since the initial 2015 ICF analysis was completed, and with the fast pace of advancing aviation technology the status of $CO_2$ technology improvements has changed in this short time frame.[iii] The 2018 ICF updated analysis was peer-reviewed by multiple independent subject matter

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[ii] The data sources for the 2018 ICF updated analysis are detailed in section II.1.2 of this ICF analysis (or this ICF report), including a description of ICF's broad and thorough aviation market interview program on technology performance, modeling approach and methodology, commercial feasibility, and costs. ICF conducted over 40 interviews with an expansive cross-section of key aviation individuals in the industry – airframe, engine, and systems manufacturers, and airlines -- and in university/research organizations. In addition, ICF leveraged knowledge they had gained through past and ongoing project work on in-depth cost and performance models for aviation.

[iii] The ICAO test procedures for the international airplane $CO_2$ standards measure fuel efficiency (or fuel burn). Only two of the six well-mixed GHGs—$CO_2$ and $N_2O$ are emitted from airplanes. The test procedures for fuel efficiency scale with the limiting of both $CO_2$ and $N_2O$ emissions, as they both can be indexed on a per-unit-of-fuel-burn basis. Therefore, both $CO_2$ and $N_2O$ emissions can be controlled as airplane fuel burn is limited. Since limiting fuel burn is the only means by which airplanes control their GHG emissions, the fuel burn (or fuel efficiency) reasonably serves as a surrogate for controlling both $CO_2$ and $N_2O$.

experts, including experts from academia and other government agencies, as well as an independent technical expert.[11]

## 2.1 Overview

As described in the preamble, ICAO/CAEP traditionally sets standards that are technology-following standards, rather than technology-forcing standards. This means that the international standards reflect a level of emissions performance that is already achieved by some portion of current in-production airplanes. For the international Airplane $CO_2$ Emission Standards, ICAO/CAEP determined in 2012 that all technology responses for its analysis would have to be based on technology that would be in common use by the time the standards were to be decided upon in 2016 or shortly thereafter (ICAO/CAEP's analysis was completed in 2015 for the February 2016 ICAO/CAEP meeting). This generation of technology or technical feasibility was defined within CAEP as "… any technology expected to be demonstrated to be safe and airworthy and proven Technology Readiness Level (TRL) 8 by 2016 or shortly thereafter"[iv] (approximately 2017) -- and "expected to be available for application in the short term over a sufficient range of newly certificated aircraft" (approximately 2020).[12] This means that the analysis that informed the international standards considered the emissions performance of in-production and on-order or in-development[v] airplanes, including types that would first enter into service by about 2020.

In assessing the airplane GHG standards, the 2018 ICF updated analysis, which was completed a few years after the ICAO analysis, uses a different approach for technology responses. ICF based these responses on technology available at TRL8 by 2017 and assumed continuous improvement of fuel efficiency metric values for in-production and in-development (or on-order) airplanes from 2010 to 2040 based on the incorporation of these technologies onto these airplanes over this same timeframe.[vi] Also, ICF considered the end of production of airplanes based on the expected business as usual status of airplanes (with the continuous improvement assumptions). The ICF approach differed from ICAO/CAEP’s analysis for years 2015 to 2020 and diverged even more for years 2021 and after. We believe this approach provides a more up to date assessment compared to ICAO/CAEP’s analysis.[vii] Since ICF used the final effective dates in their analysis of the airplane GHG standards (for new type design airplanes 2020, or 2023 for airplanes with less than 19 seats, and for in-production airplanes 2028), ICF was able to differentiate between airplane GHG technology improvements that would

[iv] TRL is a measure of Technology Readiness Level. CAEP has defined TRL8 as the “actual system completed and ‘flight qualified’ through test and demonstration.” TRL is a scale from 1 to 9, TRL1 is the conceptual principle, and TRL9 is the “actual system ‘flight proven’ on operational flight.” The TRL scale was originally developed by NASA. ICF International, *CO2 Analysis of CO2-Reducing Technologies for Airplanes*, Final Report, EPA Contract Number EP-C-12-011, see page 40, March 17, 2015.

[v] Airplanes that are currently in-development but were anticipated to be in production by about 2020.

[vi] ICF used the terminology, "$CO_2$ metric values," in their updated analysis, consistent with ICAO, when referring to fuel efficiency metric values.

[vii] ICAO/CAEP did not consider continuous improvement of metric value (from 2010 to 2040) for in-production and project (or on-order) airplanes based on incorporating 2016/2017 TRL8 technologies (or 2017 technologies). Instead, ICAO/CAEP considered transition pairs, where project airplanes (or on-order airplanes) would replace their paired in-production airplanes, and these transitions typically represented a step-change in technology and MV improvement.

occur in the absence of the final standards compared to technology improvements/responses that will be needed to comply with the final standards.

To further substantiate the projection of continuous improvement, historically, airplane fuel efficiency has continually improved on an annual basis (for the in-service fleet of airplanes and new jet airplanes). For example, GE stated the following on the annual fuel efficiency improvement of the in-service airplane fleet: "[o]ver the past 30 years, installing more technologically advanced and fuel-efficient GE Aviation and CFM International engine models has equated to the fleet in airline service reducing its fuel burn every year on average by 1 to 1.5%."[13] The 2020 fact sheet issued by the Air Transport Action Group (ATAG), whose members include Airbus, Boeing, the International Air Transport Association (IATA), Airports Council International, (ACI), ATR, CFM International, and Civil Air Navigation Services Organisation (CANSO), stated that airlines have continued to improve their global fuel efficiency between 2009 and 2019 at an average annual rate of 2 percent.[14] Moreover, the ATAG fact sheet indicated that the cumulative fuel efficiency improvement of the in-service fleet was 21 percent between 2009 and 2019, 38 percent between 2000 and 2019, and 54 percent between 1990 and 2019. Also, the 2020 IAE tracking report indicated that the energy intensity of commercial passenger aviation has decreased 2.8 percent per year on average since 2000 (improvements have slackened over time).[15] The 2020 Annual Energy Outlook indicates that the energy use per seat miles available of travel from aircraft is projected to continue to decrease annually for the long term, about 1 percent per annum from 2019 to 2050, because of the economically driven adoption of energy-efficient technology and practices.[16]

For new jet airplanes, ICAO's 2019 CAEP/11 Independent Experts (IE)[17] Review projected that annual reduction rates in fuel burn as follows: single aisle airplanes from 2017 to 2027 is 1.3 percent and from 2017 to 2037 is 1.2 percent -- twin aisle airplanes from 2017 to 2027 is 1 percent and 2017 to 2037 is 1.3 percent. This annual improvement rate represented the independent experts view of challenging, but achievable technology goals for new airplanes. Also, the 2019 ICAO Environmental Report[18] stated that under an optimistic-trends scenario the long-term fuel efficiency improvement per year would be 1.37 percent, and it includes the combined improvements associated with both technology and operations. The individual contributions from technology and operations improvements are .98 percent and .39 percent, respectively. The ICAO Environmental Report stated that the .98 percent technology improvement (fuel efficiency improvement for new jet airplanes) is slightly lower than the 1.3 percent annual improvement cited in the 2019 CAEP/11 IE Review for single aisle airplanes. In addition, the 2020 ICCT white paper[19] for new commercial jet airplanes indicated that from 1960 to 2019, annual fuel burn reductions averaged 1.1 percent (1.1 percent on the ICAO metric value or system, which matches the finalized metric value or system, and 1.3 percent on the block fuel intensity metric). Also, ICCT stated that a comprehensive technology assessment found that the rate of fuel burn improvement for new airplanes could be accelerated up to 2.2 percent per annum through 2034 by the adoption of cost-effective technologies.

ICF projected incremental fuel efficiency improvements or business as usual improvements for newly produced airplanes at 0.25 to 0.5 percent annually (out to 2040), depending on the airplanes size category. This is based on the smoothed continuous improvement forecast. ICF's research revealed that performance improvement packages (PIPs) or technology improvements for individual airplanes occur in step functions and not in continuous improvements per year. However, a reasonable projection of inserting these technologies over the forecast period yielded an annualized 0.25 to 0.5 percent improvement in fuel burn. Ultimately, based on the historical performance improvement described earlier by industry and the other sources, as well as the basket-of-2017-vintage TRL8 technologies available for insertion going forward, this continuous improvement depiction (or business as usual improvement methodology) was reasonable.

## 2.2 Technology Principles

### 2.2.1 Short- and Mid-Term Methodology

ICF analyzed the feasible technological improvements to new in-production airplanes and the potential GHG emission reductions they could generate. For this analysis, ICF created a methodological framework to assess the potential impact of technology introduction on airplane GHG emissions for the years 2015-2029 (short- and mid-term timeframe). Baseline emission rates over the ICAO/CAEP test procedure/cycle, as described in Chapter 3 of the TSD and section III of the preamble, were generated using PIANO data (PIANO is a physics-based airplane performance model).[viii] These emission rates are in units of kilograms of fuel burned per kilometer and are referred to as metric values.

ICF's framework included six steps to estimate annual metric value improvements for technologies that are being or will be applied to in-production airplanes. First, ICF identified the technologies that could reduce GHG emissions of new in-production airplanes. Second, ICF evaluated each technology for the potential GHG reduction and the mechanisms by which this reduction is achieved. Third and fourth, the technologies were passed through technical success probability and commercial success probability screenings, respectively. These first four steps were analyzed by airplane category. Fifth, individual airplane differences were assessed within each airplane category to generate GHG emission reduction projections by technology at the airplane family level (e.g., 737 family). Finally, ICF extended the GHG emission reduction projections by technology to the airplane variant level or airplane model level (e.g., 737-700, 737-800, etc.).

ICF refers to their methodological framework for projection of the metric value improvement or reduction as the expected value methodology. The expected value methodology is a projection of the annual fuel efficiency metric value improvement[ix] from 2015-2029 for all the technologies to be applied to each airplane, or business as usual improvement in the absence of a standard. Figure 2-1 is a flow chart of the expected value methodology (or expected value

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[viii] To generate metric values, the 2015 ICF analysis and 2018 ICF updated analysis used PIANO (Project Interactive Analysis and Optimization) data so that their analyses results can be shared publicly. Metric values developed utilizing PIANO data are similar to ICAO metric values. PIANO is the Aircraft Design and Analysis Software by Dr. Dimitri Simos, Lissys Limited, UK, 1990-present; Available at www.piano.aero (last accessed March 17, 2020). PIANO is a commercially available aircraft design and performance software suite used across the industry and academia.

[ix] Also referred to as the constant annual improvement in fuel efficiency metric value.

technology impact methodology[x]).[xi,xii,20,21] The elements in the flow chart are described in more detail later in this chapter.

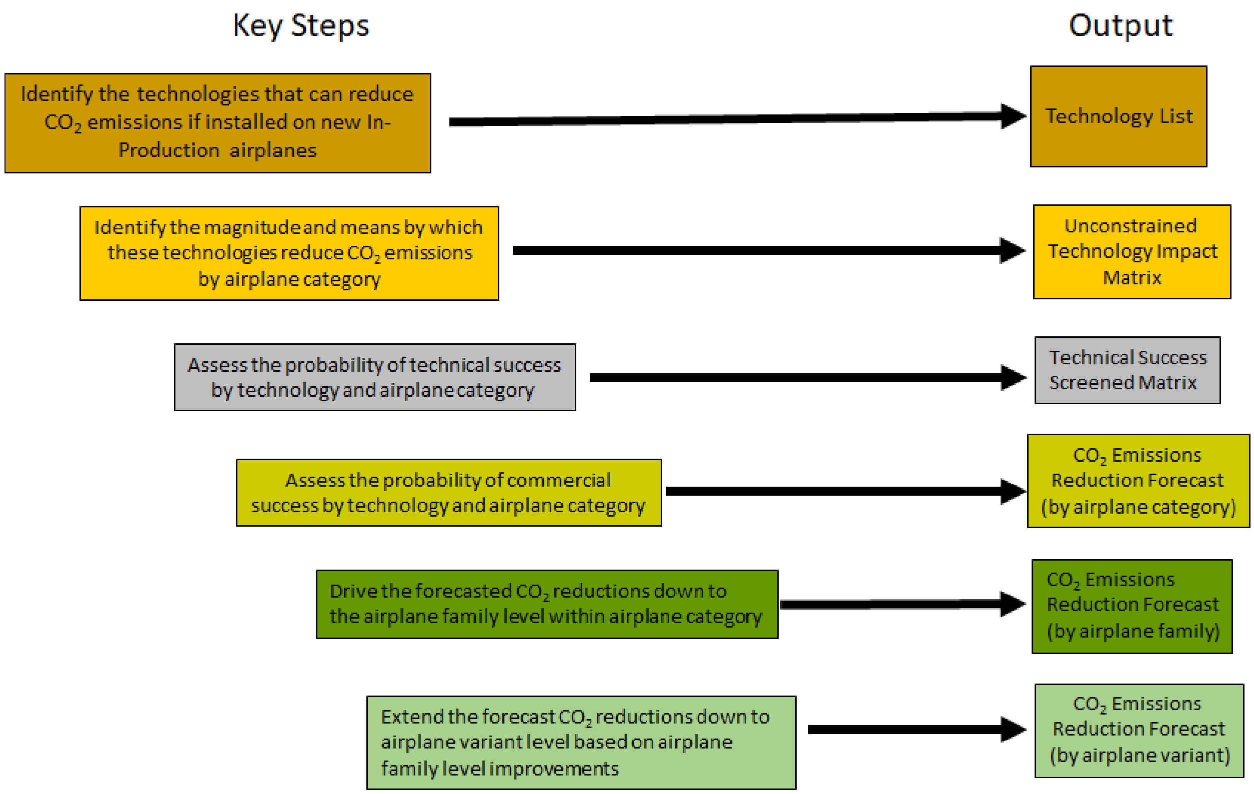


**Figure 2-1.- Expected Value Technology Impact**

As a modification to the 2015 ICF analysis, the 2018 ICF updated analysis extended the metric value improvements at the airplane family level to the more specific airplane variant level. Thus, to estimate whether each airplane variant (e.g., 737-700, 737-800, etc.) complied with the final GHG standard, ICF projected airplane family metric value reductions to a baseline (or base year) metric value of each airplane variant. Equation 2-1 below shows this approach.

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[x] The use of the term, "expected value technology impact methodology," versus "expected value methodology" in the title of Figure 2-1 is to highlight the following: for the short- and mid-term analysis we evaluated each technology and the level or amount of fuel burn and metric value impact (or improvement) the technology contributes to each airplane variant.

[xi] ICF based technology responses on technology that was TRL8 in 2017 -- considering continuous improvements of in-production and project (or on-order) airplane metric values from the incorporation of these technologies in the 2015 to 2029 timeframe (for the short- and mid-term timeframe). Also, in this same time frame, ICF estimated the expected production status of in-production airplanes based on business as usual improvements (or the continuous improvement assumptions). The approach differing compared to ICAO/CAEP's analysis for years 2015 to 2020 and diverging even more for years 2021 and after -- due to ICF including the continuous improvement assumptions).

[xii] Through interviews, prior project work, and extensive literature research, ICF identified the sources of airplane fuel burn improvement. Subsequently, by going through the major systems within an airplane (aerostructures, engines, airframe systems, interior, avionics), ICF then determined the range of magnitude of MV improvements, its applicability to each airplane size category, and other drivers as listed in the diagram (such as probability of technical feasibility, commercial feasibility, etc.).

ICF used this approach to estimate metric values for 125 airplane models, and this approach allows for a comparison of the estimated metric value for each airplane model to the level of the final GHG standards at the time the standards will go into effect. Table 2-1 below provides the results of the analysis of metric value reduction (i.e., fuel efficiency improvement) by airplane variant for the years 2015, 2018, 2020, 2023, and 2028 (the 2015-2029 timeframe) using the short- and mid-term methodology, and 2030 and 2040 (the 2030-2040 timeframe) using the long-term methodology, which is described later in section 2.2.2

**Equation 2-1 Metric Value Reduction**

$$\begin{aligned} \mathit{Metric\ value\ reduction} \\ &= \mathit{Technology\ applicability\ percentage} \\ &* \mathit{commercial\ feasibility\ factor} * \mathit{probability\ of\ technical\ success} \\ &* \mathit{Average\ metric\ value\ benefit\ of\ technology\ by\ airplane\ type} \end{aligned}$$

*where:*

*Technology applicability percentage*[xiii] *= percentage representing the metric value benefit a technology provides for an airplane family (some technologies only realize partial benefits on certain particular airplane families);*

*Commercial feasibility factor = factor representing the probability of commercial success a technology provides for an airplane family;*

*Probability of technical success = factor representing the probability of technical success a technology provides for an airplane family; and,*

*Average metric value benefit of technology by airplane type = absolute metric value reduction of a technology by airplane size category.*[xiv]

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[xiii] For technology applicability percentage, we accounted for partial applicability of an MV reducing technology for an airplane model. Typically, in-development airplanes will have lower baseline metric values (improved or better performing metric values) compared to legacy airplanes, since they have more advanced technologies implemented within the initial launch of the airplane. Consequently, there will be fewer incremental improvements available from future technologies for in-development airplanes. Due to the addition of a number of new in-development airplanes into the analysis, ICF modified the technology applicability matrix from analyzing each technology in a binary manner (i.e. technology can only be fully applicable or fully un-applicable), to a continuous manner so that partial impacts of technologies could be applied to new airplane models (i.e. percentage magnitude of a fuel burn impact will each technology provide).

[xiv] The initial average metric value benefit assessment is conducted at the airplane size category level. Then, we use this airplane size category level assessment for each technology and apply the technology applicability percentage for each in-production airplane variant, which extends the magnitude of metric value benefit from the size category level to the variant level.

As an example, the winglet is assessed to have a 3.5% metric value benefit for widebodies (airplane size category level). We then take this assessment and multiply for the MS-21 airplane, which we assess will only reap 50% of the benefit (variant level) [3.5%*50%]. Another example is the 777X airplane, which we assess will reap none of the benefit (variant level) [3.5%*0%]; because winglets are not applicable to 777X wing design.

**Example calculation #1 of metric value reduction -- advanced wingtip devices for A330 in year 2018:**

Technology applicability percentage of advanced wingtip devices (A330): 100%

Commercial feasibility factor (advanced wingtip devices in 2018): 10%

Probability of technical success (advanced wingtip devices in 2018): 100%

Average metric value benefit of technology by airplane type (large twin aisle): 3.5%

**Equation 2-2: Calculation of Metric Value Reduction – Advanced Wingtip Devices for A330 in 2018**

$$= \ technology\ applicability\ percentage\ of\ advanced\ wingtip\ devices\ (A330)$$
$$*\ commercial\ feasibility\ factor\ (advanced\ wingtip\ devices\ in\ 2018)$$
$$*\ probability\ of\ technical\ success\ (advanced\ wingtip\ devices\ in\ 2018)$$
$$*\ average\ metric\ value\ benefit\ of\ technology\ by\ airplane\ type\ (large\ twin\ aisle)$$

$$= (100\% * 10\% * 100\%) * 3.5\% = 0.35\%$$

This means that 0.35% of MV benefit in A330 in 2018 is attributable to advanced wingtip devices. To obtain the total MV reduction in a particular year, we perform this calculation for all applicable technology and then sum up the results of MV benefit for each technology.

**Example calculation #2 of metric value reduction – adaptive trailing edge for A330 in year 2028:**

Technology applicability percentage of adaptive trailing edge (A330): 100%

Commercial feasibility factor (adaptive trailing edge in 2028): 15%

Probability of technical success (adaptive trailing edge in 2028): 100%

Average metric value benefit of technology by airplane type (large twin aisle): 2.0%

**Equation 2-3: Calculation of Metric Value Reduction – Adaptive Trailing Edge for A330 in 2018**

$$= \ technology\ applicability\ percentage\ of\ adaptive\ trailing\ edge\ (A330)$$
$$*\ commercial\ feasibility\ factor\ (adaptive\ trailing\ edge\ in\ 2028)$$
$$*\ probability\ of\ technical\ success\ (adaptive\ trailing\ edge\ in\ 2028)$$
$$*\ average\ metric\ value\ benefit\ of\ technology\ by\ airplane\ type\ (large\ twin\ aisle)$$

$$= (100\% * 15\% * 100\%) * 2.0\% = 0.3\%$$

This means that 0.3% of MV benefit in A330 in 2028 is attributable to adaptive trailing edge.

In addition, ICF projected which airplane models will end their production prior to the effective date of the final GHG standards. These estimates of production status, at the time the standards will go into effect, further informed the projected response of airplane models to the final standards.

As described earlier in section 2.2.1, the short- and mid-term methodology (2015-2029) is appropriate for the EPA GHG standards because it is from assumptions based on the actual effective dates of the GHG standards. A description of the airplane and engine technologies, which are the primary basis for these assumptions for the short- and mid-term methodology, is provided later in section 2.3.

Table 2-1 - Airplane Metric Value (MV) Forecast/Reduction (PIANO Data)

| Airplane Model | Manufacturer | Market Category | Airplane Type | 2015 MV | 2018 MV | 2020 MV | 2023 MV | 2028 MV | 2030 MV | 2040 MV |
|---|---|---|---|---|---|---|---|---|---|---|
| A380-842 | AIRBUS | Air Transport | Large Quad | 2.9007 | 2.8582 | 2.8220 | 2.7665 | 2.6838 | 2.6495 | 2.5156 |
| A380-861 | AIRBUS | Air Transport | Large Quad | 2.9007 | 2.8582 | 2.8220 | 2.7665 | 2.6838 | 2.6495 | 2.5156 |
| B747-8 | BOEING | Air Transport | Large Quad | 2.5462 | 2.5096 | 2.4783 | 2.4303 | 2.3608 | 2.3317 | 2.2177 |
| B747-8F | BOEING | Air Transport | Large Quad | 2.6503 | 2.6122 | 2.5796 | 2.5296 | 2.4573 | 2.4270 | 2.3084 |
| A330-203 | AIRBUS | Air Transport | Large Twin Aisle | 1.6506 | 1.6264 | 1.6058 | 1.5742 | 1.5272 | 1.5068 | 1.4132 |
| A330-223 | AIRBUS | Air Transport | Large Twin Aisle | 1.6506 | 1.6264 | 1.6058 | 1.5742 | 1.5272 | 1.5068 | 1.4132 |
| A330-243 | AIRBUS | Air Transport | Large Twin Aisle | 1.6506 | 1.6264 | 1.6058 | 1.5742 | 1.5272 | 1.5068 | 1.4132 |
| A330-2F | AIRBUS | Air Transport | Large Twin Aisle | 1.6258 | 1.6020 | 1.5817 | 1.5506 | 1.5042 | 1.4841 | 1.3920 |
| A330-2F | AIRBUS | Air Transport | Large Twin Aisle | 1.6258 | 1.6020 | 1.5817 | 1.5506 | 1.5042 | 1.4841 | 1.3920 |
| A330-303 | AIRBUS | Air Transport | Large Twin Aisle | 1.6169 | 1.5932 | 1.5730 | 1.5421 | 1.4960 | 1.4760 | 1.3844 |
| A330-323 | AIRBUS | Air Transport | Large Twin Aisle | 1.6169 | 1.5932 | 1.5730 | 1.5421 | 1.4960 | 1.4760 | 1.3844 |
| A330-343 | AIRBUS | Air Transport | Large Twin Aisle | 1.6169 | 1.5932 | 1.5730 | 1.5421 | 1.4960 | 1.4760 | 1.3844 |
| B777-200ER | BOEING | Air Transport | Large Twin Aisle | 1.9493 | 1.9257 | 1.9046 | 1.8723 | 1.8265 | 1.8060 | 1.7105 |
| B777-200LR | BOEING | Air Transport | Large Twin Aisle | 2.1836 | 2.1572 | 2.1336 | 2.0974 | 2.0460 | 2.0231 | 1.9161 |
| B777-300ER | BOEING | Air Transport | Large Twin Aisle | 2.1439 | 2.1179 | 2.0948 | 2.0592 | 2.0088 | 1.9863 | 1.8812 |
| B777-2LRF | BOEING | Air Transport | Large Twin Aisle | 2.1846 | 2.1582 | 2.1346 | 2.0983 | 2.0470 | 2.0241 | 1.9170 |
| A350-800 | AIRBUS | Air Transport | Large Twin Aisle | 1.5110 | 1.4897 | 1.4714 | 1.4434 | 1.4029 | 1.3851 | 1.3028 |
| A350-900 | AIRBUS | Air Transport | Large Twin Aisle | 1.6060 | 1.5833 | 1.5639 | 1.5342 | 1.4911 | 1.4722 | 1.3847 |
| A350-1000 | AIRBUS | Air Transport | Large Twin Aisle | 1.7640 | 1.7391 | 1.7178 | 1.6851 | 1.6378 | 1.6171 | 1.5209 |
| A330-800-NEO | AIRBUS | Air Transport | Large Twin Aisle | 1.4700 | 1.4700 | 1.4585 | 1.4406 | 1.4156 | 1.4061 | 1.3632 |
| A330-900-NEO | AIRBUS | Air Transport | Large Twin Aisle | 1.4410 | 1.4410 | 1.4297 | 1.4121 | 1.3877 | 1.3783 | 1.3363 |
| B777-9x | BOEING | Air Transport | Large Twin Aisle | 1.7830 | 1.7830 | 1.7741 | 1.7483 | 1.7125 | 1.6987 | 1.6340 |
| B777-8x | BOEING | Air Transport | Large Twin Aisle | 1.8210 | 1.8210 | 1.8119 | 1.7855 | 1.7490 | 1.7349 | 1.6688 |
| B767-3ER | BOEING | Air Transport | Small Twin Aisle | 1.5695 | 1.5484 | 1.5309 | 1.5039 | 1.4639 | 1.4456 | 1.3588 |
| B767-3ER | BOEING | Air Transport | Small Twin Aisle | 1.5695 | 1.5484 | 1.5309 | 1.5039 | 1.4639 | 1.4456 | 1.3588 |
| B767-3ERF | BOEING | Air Transport | Small Twin Aisle | 1.5854 | 1.5641 | 1.5463 | 1.5191 | 1.4787 | 1.4602 | 1.3725 |
| B787-8 | BOEING | Air Transport | Small Twin Aisle | 1.4102 | 1.3933 | 1.3795 | 1.3581 | 1.3269 | 1.3123 | 1.2408 |
| B787-8 | BOEING | Air Transport | Small Twin Aisle | 1.4102 | 1.3933 | 1.3795 | 1.3581 | 1.3269 | 1.3123 | 1.2408 |
| B787-9 | BOEING | Air Transport | Small Twin Aisle | 1.5105 | 1.4924 | 1.4776 | 1.4547 | 1.4213 | 1.4057 | 1.3291 |
| B787-9 | BOEING | Air Transport | Small Twin Aisle | 1.5105 | 1.4924 | 1.4776 | 1.4547 | 1.4213 | 1.4057 | 1.3291 |

| Airplane Model | Manufacturer | Market Category | Airplane Type | 2015 MV | 2018 MV | 2020 MV | 2023 MV | 2028 MV | 2030 MV | 2040 MV |
|---|---|---|---|---|---|---|---|---|---|---|
| B787-10 | BOEING | Air Transport | Small Twin Aisle | 1.4747 | 1.4571 | 1.4426 | 1.4203 | 1.3876 | 1.3724 | 1.2976 |
| B787-10 | BOEING | Air Transport | Small Twin Aisle | 1.4747 | 1.4571 | 1.4426 | 1.4203 | 1.3876 | 1.3724 | 1.2976 |
| A318-122 | AIRBUS | Air Transport | Single Aisle | 0.8412 | 0.8307 | 0.8224 | 0.8098 | 0.7899 | 0.7804 | 0.7369 |
| A318-112/CJ | AIRBUS | Air Transport | Single Aisle | 0.8412 | 0.8307 | 0.8224 | 0.8098 | 0.7899 | 0.7804 | 0.7369 |
| A319-115 | AIRBUS | Air Transport | Single Aisle | 0.8750 | 0.8640 | 0.8554 | 0.8423 | 0.8216 | 0.8117 | 0.7664 |
| A319-133 | AIRBUS | Air Transport | Single Aisle | 0.8750 | 0.8640 | 0.8554 | 0.8423 | 0.8216 | 0.8117 | 0.7664 |
| A319-115/CJ | AIRBUS | Air Transport | Single Aisle | 0.8968 | 0.8856 | 0.8768 | 0.8633 | 0.8421 | 0.8319 | 0.7856 |
| A319-133/CJ | AIRBUS | Air Transport | Single Aisle | 0.8968 | 0.8856 | 0.8768 | 0.8633 | 0.8421 | 0.8319 | 0.7856 |
| A320-233 | AIRBUS | Air Transport | Single Aisle | 0.8670 | 0.8562 | 0.8477 | 0.8347 | 0.8141 | 0.8043 | 0.7595 |
| A320-214 | AIRBUS | Air Transport | Single Aisle | 0.8670 | 0.8562 | 0.8477 | 0.8347 | 0.8141 | 0.8043 | 0.7595 |
| A321-211 | AIRBUS | Air Transport | Single Aisle | 0.9990 | 0.9865 | 0.9767 | 0.9617 | 0.9380 | 0.9267 | 0.8751 |
| A321-231 | AIRBUS | Air Transport | Single Aisle | 0.9990 | 0.9865 | 0.9767 | 0.9617 | 0.9380 | 0.9267 | 0.8751 |
| B737-700 | BOEING | Air Transport | Single Aisle | 0.8762 | 0.8656 | 0.8573 | 0.8446 | 0.8245 | 0.8148 | 0.7701 |
| B737-700W | BOEING | Air Transport | Single Aisle | 0.8365 | 0.8264 | 0.8185 | 0.8063 | 0.7872 | 0.7779 | 0.7353 |
| B737-700IGW (BBJ) | BOEING | Air Transport | Single Aisle | 0.9110 | 0.9000 | 0.8913 | 0.8781 | 0.8572 | 0.8471 | 0.8007 |
| B737-800 | BOEING | Air Transport | Single Aisle | 0.9308 | 0.9196 | 0.9107 | 0.8972 | 0.8759 | 0.8656 | 0.8181 |
| B737-800W | BOEING | Air Transport | Single Aisle | 0.8911 | 0.8804 | 0.8719 | 0.8589 | 0.8385 | 0.8287 | 0.7832 |
| B737-900ER | BOEING | Air Transport | Single Aisle | 0.9586 | 0.9470 | 0.9379 | 0.9240 | 0.9020 | 0.8914 | 0.8425 |
| B737-900ERW | BOEING | Air Transport | Single Aisle | 0.9586 | 0.9470 | 0.9379 | 0.9240 | 0.9020 | 0.8914 | 0.8425 |
| A319-NEO | AIRBUS | Air Transport | Single Aisle | 0.7262 | 0.7169 | 0.7096 | 0.6983 | 0.6808 | 0.6724 | 0.6339 |
| A319-NEO | AIRBUS | Air Transport | Single Aisle | 0.7262 | 0.7169 | 0.7096 | 0.6983 | 0.6808 | 0.6724 | 0.6339 |
| A320-NEO | AIRBUS | Air Transport | Single Aisle | 0.7272 | 0.7179 | 0.7105 | 0.6992 | 0.6817 | 0.6733 | 0.6348 |
| A320-NEO | AIRBUS | Air Transport | Single Aisle | 0.7272 | 0.7179 | 0.7105 | 0.6992 | 0.6817 | 0.6733 | 0.6348 |
| A321-NEO | AIRBUS | Air Transport | Single Aisle | 0.8557 | 0.8448 | 0.8361 | 0.8228 | 0.8022 | 0.7923 | 0.7469 |
| A321-NEO | AIRBUS | Air Transport | Single Aisle | 0.8557 | 0.8448 | 0.8361 | 0.8228 | 0.8022 | 0.7923 | 0.7469 |
| B737-7 | BOEING | Air Transport | Single Aisle | 0.7290 | 0.7266 | 0.7209 | 0.7121 | 0.6987 | 0.6931 | 0.6688 |
| B737-8 (BBJ) | BOEING | Air Transport | Single Aisle | 0.7817 | 0.7792 | 0.7730 | 0.7635 | 0.7492 | 0.7432 | 0.7171 |
| B737-8 | BOEING | Air Transport | Single Aisle | 0.7817 | 0.7792 | 0.7730 | 0.7635 | 0.7492 | 0.7432 | 0.7171 |
| B737-9 | BOEING | Air Transport | Single Aisle | 0.8247 | 0.8220 | 0.8155 | 0.8055 | 0.7904 | 0.7841 | 0.7566 |
| CS100 | BOMBARDIER | Air Transport | Single Aisle | 0.6550 | 0.6501 | 0.6439 | 0.6346 | 0.6201 | 0.6132 | 0.5816 |

| Airplane Model | Manufacturer | Market Category | Airplane Type | 2015 MV | 2018 MV | 2020 MV | 2023 MV | 2028 MV | 2030 MV | 2040 MV |
|---|---|---|---|---|---|---|---|---|---|---|
| CS300 | BOMBARDIER | Air Transport | Single Aisle | 0.7120 | 0.7066 | 0.7000 | 0.6898 | 0.6741 | 0.6665 | 0.6322 |
| MS-21-300 | IRKUT | Air Transport | Single Aisle | 0.7380 | 0.7380 | 0.7380 | 0.7271 | 0.7103 | 0.7028 | 0.6688 |
| MS-21-300 | IRKUT | Air Transport | Single Aisle | 0.7380 | 0.7380 | 0.7380 | 0.7271 | 0.7103 | 0.7028 | 0.6688 |
| MS-21-200 | IRKUT | Air Transport | Single Aisle | 0.6870 | 0.6870 | 0.6870 | 0.6769 | 0.6612 | 0.6542 | 0.6226 |
| MS-21-200 | IRKUT | Air Transport | Single Aisle | 0.6870 | 0.6870 | 0.6870 | 0.6769 | 0.6612 | 0.6542 | 0.6226 |
| C919ER | COMAC | Air Transport | Single Aisle | 0.7120 | 0.7120 | 0.7082 | 0.6969 | 0.6795 | 0.6711 | 0.6331 |
| CRJ700 | BOMBARDIER | Air Transport | Regional Jet | 0.6144 | 0.6055 | 0.5991 | 0.5894 | 0.5735 | 0.5664 | 0.5339 |
| CRJ900 | BOMBARDIER | Air Transport | Regional Jet | 0.6451 | 0.6357 | 0.6290 | 0.6189 | 0.6021 | 0.5947 | 0.5606 |
| CRJ1000 | BOMBARDIER | Air Transport | Regional Jet | 0.6738 | 0.6640 | 0.6570 | 0.6464 | 0.6290 | 0.6212 | 0.5855 |
| ERJ135-LR | EMBRAER | Air Transport | Regional Jet | 0.4182 | 0.4121 | 0.4078 | 0.4012 | 0.3903 | 0.3855 | 0.3634 |
| ERJ145 | EMBRAER | Air Transport | Regional Jet | 0.4201 | 0.4141 | 0.4097 | 0.4031 | 0.3922 | 0.3873 | 0.3651 |
| ERJ175 | EMBRAER | Air Transport | Regional Jet | 0.6877 | 0.6777 | 0.6706 | 0.6597 | 0.6419 | 0.6340 | 0.5976 |
| ERJ190 | EMBRAER | Air Transport | Regional Jet | 0.7769 | 0.7656 | 0.7575 | 0.7453 | 0.7252 | 0.7162 | 0.6751 |
| ERJ195 | EMBRAER | Air Transport | Regional Jet | 0.7699 | 0.7588 | 0.7508 | 0.7386 | 0.7187 | 0.7098 | 0.6690 |
| RRJ-95 | SUKHOI | Air Transport | Regional Jet | 0.6699 | 0.6602 | 0.6532 | 0.6427 | 0.6254 | 0.6177 | 0.5823 |
| RRJ-95LR | SUKHOI | Air Transport | Regional Jet | 0.7154 | 0.7051 | 0.6977 | 0.6864 | 0.6679 | 0.6597 | 0.6219 |
| MRJ-70 | MITSUBISHI | Air Transport | Regional Jet | 0.5340 | 0.5340 | 0.5340 | 0.5257 | 0.5121 | 0.5060 | 0.4782 |
| MRJ-90 | MITSUBISHI | Air Transport | Regional Jet | 0.5540 | 0.5540 | 0.5540 | 0.5454 | 0.5313 | 0.5250 | 0.4961 |
| ERJ-175 E2 | EMBRAER | Air Transport | Regional Jet | 0.5920 | 0.5892 | 0.5831 | 0.5739 | 0.5588 | 0.5521 | 0.5213 |
| ERJ-190 E2 | EMBRAER | Air Transport | Regional Jet | 0.6040 | 0.6011 | 0.5949 | 0.5856 | 0.5702 | 0.5633 | 0.5318 |
| ERJ-195 E2 | EMBRAER | Air Transport | Regional Jet | 0.6150 | 0.6121 | 0.6058 | 0.5962 | 0.5806 | 0.5736 | 0.5415 |
| ATR42-5 | ATR | Air Transport | Turboprop | 0.3353 | 0.3311 | 0.3280 | 0.3234 | 0.3157 | 0.3125 | 0.3009 |
| ATR72-2 | ATR | Air Transport | Turboprop | 0.3779 | 0.3732 | 0.3697 | 0.3645 | 0.3559 | 0.3522 | 0.3392 |
| Q400 | BOMBARDIER | Air Transport | Turboprop | 0.4960 | 0.4898 | 0.4852 | 0.4783 | 0.4670 | 0.4623 | 0.4451 |
| CL-605 | BOMBARDIER | BGA | Large BGA | 0.4990 | 0.4928 | 0.4878 | 0.4804 | 0.4685 | 0.4633 | 0.4411 |
| CL-850 | BOMBARDIER | BGA | Large BGA | 0.4911 | 0.4849 | 0.4801 | 0.4727 | 0.4610 | 0.4559 | 0.4341 |
| G-5000 | BOMBARDIER | BGA | Large BGA | 0.6428 | 0.6348 | 0.6285 | 0.6188 | 0.6035 | 0.5969 | 0.5683 |
| G-6000 | BOMBARDIER | BGA | Large BGA | 0.6924 | 0.6838 | 0.6770 | 0.6666 | 0.6501 | 0.6429 | 0.6121 |

| Airplane Model | Manufacturer | Market Category | Airplane Type | 2015 MV | 2018 MV | 2020 MV | 2023 MV | 2028 MV | 2030 MV | 2040 MV |
|---|---|---|---|---|---|---|---|---|---|---|
| FAL900LX | DASSAULT-AVIATION | BGA | Large BGA | 0.4712 | 0.4653 | 0.4607 | 0.4536 | 0.4424 | 0.4375 | 0.4166 |
| FAL7X | DASSAULT-AVIATION | BGA | Large BGA | 0.4911 | 0.4849 | 0.4801 | 0.4727 | 0.4610 | 0.4559 | 0.4341 |
| ERJLEG | EMBRAER | BGA | Large BGA | 0.4990 | 0.4928 | 0.4878 | 0.4804 | 0.4685 | 0.4633 | 0.4411 |
| GVI | GULFSTREAM | BGA | Large BGA | 0.5734 | 0.5663 | 0.5607 | 0.5521 | 0.5385 | 0.5326 | 0.5072 |
| GULF5 | GULFSTREAM | BGA | Large BGA | 0.5853 | 0.5780 | 0.5722 | 0.5635 | 0.5495 | 0.5434 | 0.5174 |
| GULF4 | GULFSTREAM | BGA | Large BGA | 0.6419 | 0.6339 | 0.6275 | 0.6179 | 0.6026 | 0.5959 | 0.5674 |
| Global 7000 | BOMBARDIER | BGA | Large BGA | 0.5880 | 0.5880 | 0.5823 | 0.5736 | 0.5597 | 0.5538 | 0.5280 |
| Global 8000 | BOMBARDIER | BGA | Large BGA | 0.5960 | 0.5960 | 0.5930 | 0.5842 | 0.5702 | 0.5641 | 0.5380 |
| Learjet 40XR | BOMBARDIER | BGA | Small BGA | 0.3344 | 0.3305 | 0.3276 | 0.3234 | 0.3165 | 0.3136 | 0.3037 |
| Learjet 45XR | BOMBARDIER | BGA | Small BGA | 0.2947 | 0.2912 | 0.2887 | 0.2850 | 0.2790 | 0.2764 | 0.2676 |
| Learjet 60XR | BOMBARDIER | BGA | Small BGA | 0.3444 | 0.3403 | 0.3374 | 0.3330 | 0.3259 | 0.3229 | 0.3127 |
| CL-300 | BOMBARDIER | BGA | Small BGA | 0.3831 | 0.3785 | 0.3753 | 0.3704 | 0.3626 | 0.3592 | 0.3478 |
| CNA525B | CESSNA | BGA | Small BGA | 0.2421 | 0.2393 | 0.2372 | 0.2341 | 0.2292 | 0.2271 | 0.2199 |
| CNA525C | CESSNA | BGA | Small BGA | 0.2421 | 0.2393 | 0.2372 | 0.2341 | 0.2292 | 0.2271 | 0.2199 |
| CNA560-XLS | CESSNA | BGA | Small BGA | 0.3265 | 0.3226 | 0.3199 | 0.3157 | 0.3090 | 0.3062 | 0.2965 |
| CNA680 | CESSNA | BGA | Small BGA | 0.3865 | 0.3820 | 0.3788 | 0.3739 | 0.3660 | 0.3627 | 0.3513 |
| CNA750 | CESSNA | BGA | Small BGA | 0.4084 | 0.4036 | 0.4002 | 0.3951 | 0.3868 | 0.3833 | 0.3713 |
| FAL2000LX | DASSAULT-AVIATION | BGA | Small BGA | 0.3870 | 0.3824 | 0.3792 | 0.3742 | 0.3663 | 0.3630 | 0.3514 |
| EMB505 | EMBRAER | BGA | Small BGA | 0.2749 | 0.2716 | 0.2693 | 0.2658 | 0.2602 | 0.2578 | 0.2496 |
| G280 | GULFSTREAM | BGA | Small BGA | 0.4426 | 0.4374 | 0.4337 | 0.4280 | 0.4190 | 0.4152 | 0.4021 |
| GULF150 | GULFSTREAM | BGA | Small BGA | 0.3850 | 0.3805 | 0.3772 | 0.3723 | 0.3644 | 0.3611 | 0.3496 |
| Learjet 70 | BOMBARDIER | BGA | Small BGA | 0.3457 | 0.3416 | 0.3387 | 0.3344 | 0.3274 | 0.3244 | 0.3142 |
| Learjet 75 | BOMBARDIER | BGA | Small BGA | 0.3457 | 0.3416 | 0.3387 | 0.3344 | 0.3274 | 0.3244 | 0.3142 |
| CNA680-S | CESSNA | BGA | Small BGA | 0.3865 | 0.3820 | 0.3788 | 0.3739 | 0.3660 | 0.3627 | 0.3513 |
| CNA750-X | CESSNA | BGA | Small BGA | 0.3716 | 0.3672 | 0.3641 | 0.3594 | 0.3519 | 0.3487 | 0.3378 |
| PC-24 | PILATUS | BGA | Small BGA | 0.2930 | 0.2918 | 0.2894 | 0.2857 | 0.2798 | 0.2773 | 0.2687 |

### 2.2.2 Long-Term Methodology

To project metric value improvements for the long-term, years 2030-2040, ICF generated a different methodology compared to the short- and mid-term methodology. The short- and mid-term methodology is based on forecasting metric value improvements due to the implementation of specific existing technologies. ICF projects that in about the 2030 timeframe a new round of technology implementation will begin.[22] For this reason, ICF developed a different method for predicting metric value improvements for the long term. For 2030 or later, ICF used a parametric approach to project annual metric value improvements.[23] This approach included three steps. First, for each airplane type, technical factors were identified that drive fuel burn and metric value improvements in the long-term (i.e., propulsive efficiency, friction drag reduction), and the fuel burn reduction prospect index, which is described below in section 2.2.2.1, was estimated on a scale of 1 to 5 for each technical factor. Second, a long-term market prospect index was generated on a scale of 1 to 5 based on estimates of the amount of potential research and development (R&D) put into various technologies for each airplane type. Third, the long-term market prospect index for each airplane type was combined with its respective fuel burn reduction prospect index to generate an overall index score for their metric value improvements. A low overall index score indicates that the airplane type will have a decelerated annual metric value reduction, and a high overall index score indicates an accelerated annual metric value improvement (relative to an extrapolated short- and mid-term annual metric value improvement).[xv]

As discussed earlier in section 2.1, ICAO/CAEP's analysis did not include a long-term technology assessment for 2030-2040, but instead focused on technology that would have been in operation by 2016/2017 (and considered the emissions performance of in-production and on-order or in-development[xvi] airplanes, including types that would first enter into service by about 2020). ICF's long-term approach is appropriate for the EPA GHG standards because it derives reasonable assumptions based on the best available information for this timeframe.

#### *2.2.2.1 Fuel Burn Reduction Prospect Index*

The fuel burn reduction prospect index is a projected ranking of the feasibility and readiness of technologies (for reducing fuel burn) to be implemented for 2030 and later. For the fuel burn reduction prospect index, the technology factors that mainly contribute to fuel burn were identified.[24] These factors included the following engine and airframe technologies as described below: (Engine) sealing, propulsive efficiency, thermal efficiency, reduced cooling, and reduced power extraction and (Airframe) induced drag reduction and friction drag reduction. A number of these technology factors are described in more detail later in section 2.3. Also, the 2018 ICF updated analysis provides further details on the technology factors.

Sealing: Imperfect air sealing in the engine leads to leaking that diminishes the engine efficiency (especially in the engine compressor) that ultimately increases the fuel burn.

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[xv] Accelerated metric value improvement rate means that the metric value is improving at an accelerated rate (i.e., faster than the historical rate). Decelerated metric value improvement rate means that the metric value is improving at a decelerated rate (i.e., slower than the historical rate).

[xvi] Airplanes that are currently in-development but were anticipated to be in production by about 2020.

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Propulsive efficiency: This is the part of the kinetic energy added to the air that contributes to thrust. (Not to be confused with the overall propulsive efficiency, which is the product of the propulsive efficiency and the thermal efficiency). Increasing bypass ratio is the primary approach to increase propulsive efficiency and thus reduce fuel burn.

Thermal efficiency: This is the efficiency with which the chemical energy of the fuel is converted into mechanical power. The primary approach to increase the thermal efficiency is by increasing the turbine entry temperature.

Reduced cooling: To cool the hotter parts of the engine, bleed air is taken from the engine compressor stage. This leads to a loss that on its own that increases the fuel burn but contributes to improving the thermal efficiency by making it possible to raise the turbine entry temperature.

Reduced power extraction: Bleed air is commonly used for other airplane systems (anti-icing, cabin pressurization, pneumatic actuators, etc.). In addition to power extraction through bleeding air, shaft power may be extracted through electric generators to power airplane systems. The less the power extraction, the less the fuel burn.

Induced drag reduction: This type of drag is induced by the generation of lift. For a given lift, this can be decreased by optimizing the distribution of pressures on the wing through aerodynamic shaping, increasing wingspan, and adding wing tip devices. The lower the induced drag, the lower the fuel burn.

Friction drag reduction: This type of drag is due to mechanical friction of the air with the airplane surface. This can be decreased by reducing the exposed area, improving surface finishing, and through aerodynamic shaping. The lower the friction drag, the lower the fuel burn.

Profile drag reduction: This type of drag is due to flow separation that causes a turbulent wake where energy is dissipated. Profile drag can be decreased by aerodynamic shaping.

The technology factors were each scored on three dimensions that were considered to drive the overall fuel burn reduction effectiveness in the latter end of the forecast years. These three scoring dimensions include the following criteria:

Effectiveness of technology in improving fuel burn;

Likelihood of technology implementation; and

Level of research effort needed.

The scoring dimensions of the effectiveness of technology in improving fuel burn and level of research effort needed were considered the primary drivers in the technical factors because of past experience. These two factors are the most important since the effectiveness of a technology in decreasing fuel burn (or decreasing the metric value) would most incentivize manufacturers to pursue research, while the level of research effort directs how economically feasible a technology is. Thus, heavier weightings were allocated to these two factors (40 percent weighting on each of these factors) compared to likelihood of implementation (20 percent weighting on this factor). The scoring of each of the technical factors on the three dimensions was averaged to develop an overall fuel burn reduction prospect index.

#### *2.2.2.2 Market Driver Index*

Market driver indices for each airplane type[25] were developed based on where the market is projected to shift towards in the latter end of the forecast years. The extent of research and development that manufacturers will carry out was also weighted towards this shift. Engine manufacturers were projected to make more efficient engines that would enable more point-to-point travel, subsequently decreasing the need for large quad airplanes and creating more market demand and more focus on improvements for single aisle and small twin-aisle airplanes. Recent technology developments have been focused on re-engine improvements, and thus, it was anticipated that there would be ample possibilities for an airframe redesign in the next round of technological improvement due in the early 2030s. In addition, it was projected that the number of business jets, turboprops, and regional jet airplanes would grow slightly slower compared to the recent past (or the growth in the number of these airplanes would be relatively stagnant in the outbound years). We expect the highest long-term growth in number of airplanes to occur in the single aisle and small twin aisle airplane categories (the highest near- and mid-term growth is also anticipated in these two airplane categories).[26]

#### *2.2.2.3 Metric Value Improvement Acceleration Index*

The fuel burn reduction prospect index was combined with the market driver index via weighted average for each airplane type to calculate the overall metric value improvement acceleration index.[27] A scoring of 1 was a 60 percent improvement rate relative to extrapolated short/mid-term annual metric value improvement, a scoring of 3 was a continued extrapolated short/mid-term annual metric value improvement, and a scoring of 5 was a 140 percent improvement rate relative to extrapolated short/mid-term annual metric value improvement. Table 2-2 below shows the improvement rates for this assessed index scoring. (A little more weighting was put on the technological factors (or fuel burn reduction prospect index) with a 65 percent scoring weight, compared to market factors (market driver index) with a 35 percent scoring weight, because of past experience. The weighting is reasonable since while fuel burn prospects are the most important factor for manufacturers, the manner in which the overall market is evolving (e.g., more single aisle airplanes) would affect the way manufacturers apportion their research efforts.) Finally, the short/mid-term metric value improvement impact estimates described earlier were extended to the end of the long-term forecast timeframe (2040) and overall metric value improvement acceleration index scoring developed by each airplane type was applied to those estimates.

**Table 2-2 Metric Value Index Scoring**

| MV Acceleration Index Scoring | Improvement rate (relative to extrapolated short/mid-term annual MV improvement) |
|---|---|
| 1 | 60% |
| 2 | 80% |
| 3 | 100% |
| 4 | 120% |
| 5 | 140% |

Figure 2-2 provides the graphical form of the improvement rates for this assessed index scoring, which is in Table 2-2 above. It was extrapolated to cover all scores between 1 and 5. The scoring follows the linear regression of $y = 0.2x + 0.4$ (where x is the scoring, and y is the resulting improvement rate). Figure 2-2 can be utilized to interpret intermediate scores (that are in between 1 and 5) to obtain how much faster or slower the metric value improvement is based on the technical factor scoring of the fuel burn reduction prospect index. 100 percent (or a score of 3) indicates that the pace of metric value improvement will continue at 100 percent of the estimated current rate of reduction (i.e., rate higher than 100% means larger of reduction and rate lower than 100% means vice versa). Furthermore, a score of 3 means that the continuous annual metric value improvement rate for the short- and mid-term methodology remains the same for the long-term methodology or timeframe. A score of 2 means that the continuous annual metric value improvement rate decelerates (or decreases) for the long-term methodology, and a score of 4 means that the rate accelerates (or increases).

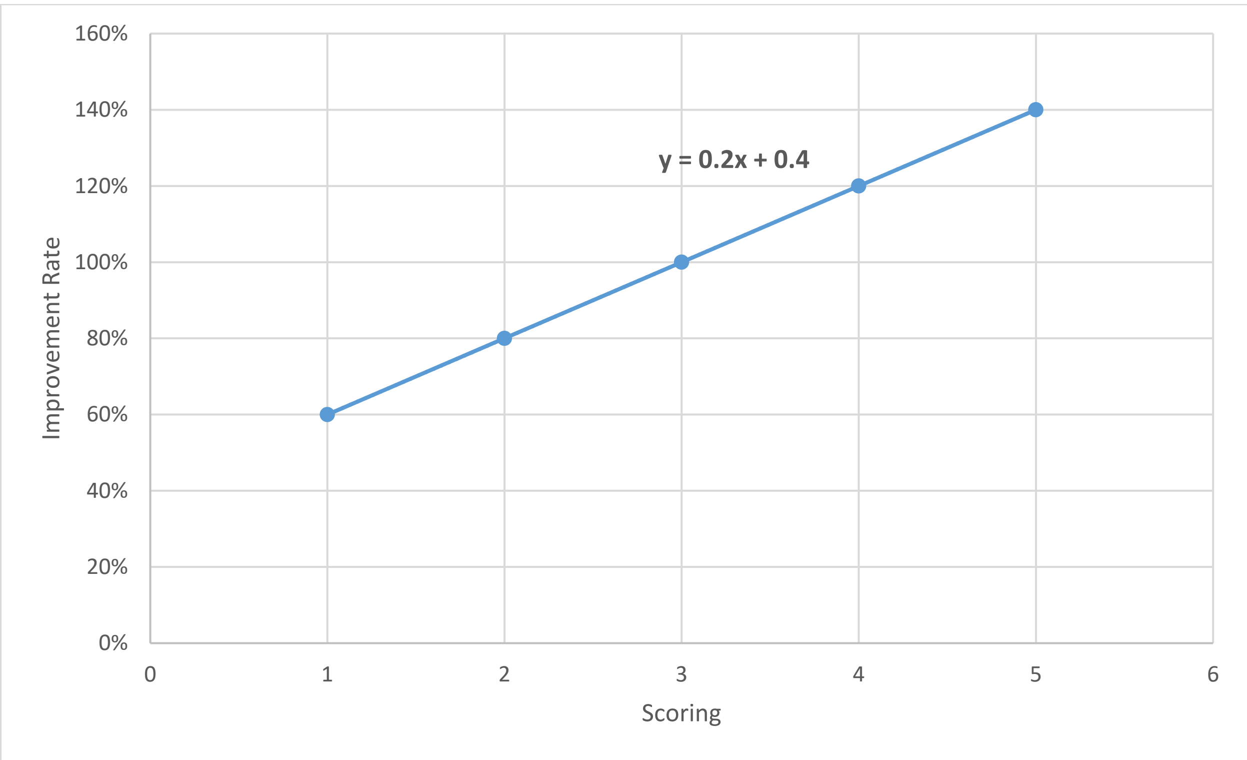


**Figure 2-2 Graphical Form of Metric Value Index Scoring**

### *2.2.2.4 Example for Long-Term Metric Value Forecast*

An example of an overall fuel burn reduction prospect index for a single aisle airplane type is provided below in Table 2-3.[28] Also, examples of fuel burn reduction prospect indexes for the other airplane categories are shown below in Table 2-4.

**Table 2-3 Single Aisle Example for Fuel Burn Reduction Prospect Index**

| Single Aisle Technical Factors: | Effectiveness in reducing fuel burn (1-5) [40%] | Likelihood of implementation in new technology (1-5) [20%] | Level of Research Effort Required (1-5)[xvii] [40%] | Fuel Burn Reduction Prospect Index |
|---|---|---|---|---|
| Weight | N/A | N/A | N/A | N/A |
| Sealing | 1 | 2 | 4 | 2.4 |
| Propulsive efficiency | 3 | 3 | 2 | 2.6 |
| Thermal efficiency | 3 | 3 | 2 | 2.6 |
| Noise reduction | 1 | 2 | 3 | 2 |
| Reduced cooling | 3 | 3 | 3 | 3 |
| Reduced power extraction | 3 | 3 | 3 | 3 |
| Reduced thermal management | 3 | 3 | 3 | 3 |
| Induced drag reduction | 5 | 4 | 1 | 3.2 |
| Friction drag reduction | 5 | 4 | 1 | 3.2 |
| | | | Overall Fuel Burn Reduction Prospect Index: | 2.8 |

For single aisle, it was projected that there will be a new clean sheet design that will have substantial aerodynamics improvement, which will reduce drag, and it will have the latest engine technologies. Thus, there is plenty of potential for the scoring dimensions of fuel burn effectiveness and likelihood of implementation (favorable scoring in these dimensions). However, due to the efforts required, there will be risks related to attaining the improvement. This reasoning led to an overall fuel burn reduction prospect index[xviii] that is a little decelerated from a technical perspective.

[xvii] For Level of Research Effort, 5 is the least amount of effort needed (more favorable) and 1 is the most amount of effort needed (less favorable).

[xviii] As described earlier, the fuel burn reduction prospect index is a projected ranking of the feasibility and readiness of technologies (for reducing fuel burn) to be implemented for 2030 and later. There are three main steps to determine the fuel burn reduction prospect index. First, the technology factors that mainly contribute to fuel burn were identified. These factors included the following engine and airframe technologies as described below: (Engine) sealing, propulsive efficiency, thermal efficiency, reduced cooling, and reduced power extraction and (Airframe) induced drag reduction and friction drag reduction. Second, each of the technology factors were scored on the following three scoring dimensions that will drive the overall fuel burn reduction effectiveness in the outbound forecast years: effectiveness of technology in reducing fuel burn, likelihood of technology implementation, and level of research effort required. Third, the scoring of each of the technical factors on the three dimensions were averaged to derive an overall fuel burn reduction prospect index.

**Table 2-4 Other Airplane Category Examples of Fuel Burn Reduction Prospect Index**

| Technical Factors: | Large Quad | Large Twin Aisle | Small Twin Aisle | Single Aisle | Regional Jet | Turboprop | Large BGA | Small BGA |
|---|---|---|---|---|---|---|---|---|
| Weight | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Sealing | 2.8 | 2.8 | 2.8 | 2.4 | 2.4 | 2.2 | 2.2 | 1.8 |
| Propulsive efficiency | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 1.6 | 1.6 | 1.6 |
| Thermal efficiency | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 1.6 | 1.6 | 1.6 |
| Reduced cooling | 3.4 | 3 | 3 | 3 | 3 | 2.4 | 2.4 | 2.4 |
| Reduced power extraction | 3.4 | 3 | 3 | 3 | 3 | 2.4 | 2.4 | 2 |
| Reduced thermal management | 3.4 | 3 | 3 | 3 | 3 | 2.4 | 2.4 | 2.4 |
| Induced drag reduction | 3.2 | 3.2 | 3.2 | 3.2 | 3.6 | 3 | 3 | 3 |
| Friction drag reduction | 3.2 | 3.2 | 3.2 | 3.2 | 3.6 | 3 | 3 | 3 |
| Profile drag reduction | 2.4 | 2.4 | 2.4 | 2 | 2 | 1.8 | 1.8 | 1.4 |
| **Fuel Burn Reduction Prospect Index** | **3** | **2.9** | **2.9** | **2.8** | **2.9** | **2.3** | **2.3** | **2.1** |

However, we recognized that the single aisle market is expected to be thriving in the long-term based on more point-to-point travel from more fuel-efficient engines, as described earlier. Thus, it is projected that the market driver index for single aisle is quite favorable with a scoring of 5, since manufacturers are anticipated to concentrate their research efforts on this market. Combining the fuel burn reduction prospect index and the market driver index, the resulting metric value improvement acceleration index is 3.56 as provided in Table 2-5 below.

**Table 2-5 Single Aisle Example for Metric Value Improvement Acceleration Index**

| Fuel Burn Reduction Prospect Index [65%] | Market Driver Index [35%] | Metric Value Improvement Acceleration Index |
|---|---|---|
| 2.78 | 5 | 3.56 |

This 3.56 score shows that the single aisle metric value improvement will be accelerated faster compared to an extrapolated short/mid-term metric value improvement rate. With the linear regression that a 1 score represents 60 percent annual metric value decelerated improvement rate and a 5 score represents a 140 percent annual metric value accelerated improvement rate, a score of 3.56 represents that single aisle will annually accelerate at a rate of 111 percent. This annual metric value accelerated improvement rate was integrated into the extrapolated short/mid-term metric value forecast for the appropriate airplane models.

### *2.2.2.5 Long-Term Replacement Airplane Analysis (2030-2040)*

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In addition to the long-term metric value forecast, the potential long-term replacement airplanes[xix] were analyzed according to the following factors: historical airplane design transitions, metric value improvement step-down (metric value improvements of 10-20 percent) per airplane generation, and timing of airplane design transition.[xx,29] Based on these factors, the potential long-term airplane replacements that current/new generation airplanes will transition into were developed for the latter end of the forecast years. The potential airplane replacements were identified as provided below in Table 2-6.[xxi]

**Table 2-6 Long-Term Potential Replacement Airplanes**

| Market Category | Airplane Type | 2030-2040 Replacement | Estimated EIS[a] | MV Improvement Estimate | Uncertainty Band (+/-) |
|---|---|---|---|---|---|
| Air Transport | Large Quad | No direct replacement. | N/A | N/A | N/A |
| Air Transport | Large Twin Aisle | 777X | beyond 2040 | N/A | N/A |
| Air Transport | Small Twin Aisle | Re-wing or re-engine small twin aisle | late 2030 | ~15% | 3% |
| Air Transport | Single Aisle | Clean sheet airplane | early 2030 | ~20% | 4% |
| Air Transport | Regional Jet | Re-wing regional jet | early 2030 | ~10% | 2% |
| Air Transport | Turboprop | Re-wing or re-engine turboprop airplane | early 2030 | ~10% | 2% |
| Air Transport | Freighter | A330neo or 777X freighter | late 2020 | N/A | N/A |
| BGA[b] | Large BGA | Re-wing or re-engine large business jet | early 2030 | ~10% | 2% |
| BGA | Small BGA | Re-wing or re-engine small business jet | early 2030 | ~10% | 2% |

a. Entry into service (EIS)

BGA means business and general aviation airplane.

The detailed results of the long-term replacement and reference airplane assessment is in the Technology Response Database that accompanies the 2018 ICF updated analysis, which is located in the docket for this rulemaking.[xxii] In the Technology Response Database, the long-term replacement airplanes for all in-production and in-development airplane models (models covered by the MTOM thresholds of the final standard) were evaluated, and metric values for

[xix] The term, "replacement airplane," in the long-term methodology means airplane that are projected to replace in-production airplane and current in-development (or on order airplane) that are expected to go out of production in the 2030-2040 timeframe. For some airplane categories, ICF identified specific airplane to replace airplane (e.g., 777X for Large Twin Aisle category), and for most categories ICF identified a generic airplane (e.g., Clean sheet airplane for Single Aisle category and re-wing or re-engine small twin aisle for Small Twin Aisle category).

[xx] Every 15 to 25 years after entry into service, airplane models normally incur major redesigns that are motivated by aerodynamics or engine efficiency improvements that substantially reduce fuel burn. These major re-designs normally generate significant reductions in fuel burn and MV – 10 percent to 20 percent compared to the previous generation they replace, depending on the type of redesign. There are three types of major airplane redesigns: redesigned engines (re-engine), redesigned wings (re-wing), or clean sheet development.

[xxi] This table shows historical examples of major re-design improvements that have been achieved by airplane manufacturers. Clean sheet re-designs have historically produced about 20+ percent, re-wing have historically yielded about 15 to 20 percent, while re-engine have historically accomplished about 10 to 15 percent.

[xxii] ICF, 2018, *Airplane $CO_2$ Cost and Technology Refresh and Industry Characterization*, EPA Contract Number EP-C-16-020, September 30, 2018. Technology Response Database that accompanies this report provides these detailed results of the long-term replacement and reference airplane assessment.

these long-term replacement airplanes were projected based on the available metric values of reference airplanes,[xxiii] which were grouped by airplane type and manufacturer.

Also, uncertainty bands in determining the metric value improvement estimates were provided for the long-term replacement and reference airplane assessment. These uncertainty bands differ by the magnitude of design improvement expected by airplane type. The more challenging the design improvement, the higher the uncertainty band. For example, designing a clean sheet airplane will result in a greater potential metric value improvement, but there are more risks related to attaining the design improvement; therefore, a higher uncertainty band was estimated. In contrast, a re-engine design improvement has less risk related to achieving the improvement, and thus, a lower uncertainty band was estimated.

Table 2-1 above provides the results of the analysis of metric value reduction by airplane variant for the years 2030 and 2040 (the 2030-2040 timeframe) using the long-term methodology and years 2015, 2018, 2020, 2023, and 2028 (the 2015-2029 timeframe) using the short- and mid-term methodology, which is described earlier in section 2.2.1.

## 2.3 Technologies

ICF identified and analyzed about seventy different airframe and engine technologies for fuel burn reductions, as shown in Table 2-7 and Table 2-8. These technologies are mainly for the short- and mid-term methodology, years 2015-2029, since the effective dates for the final standards will be within this time frame: 2020 (or 2023 for airplanes with less than 19 seats) for new type design airplanes and 2028 for in-production airplanes. Further details on these technologies are presented in the appendix of the 2018 ICF updated analysis. Although weight-reducing technologies affect fuel burn in-use, they do not affect the metric value for the final GHG standards.[xxiv] Thus, ICF's assessment of weight-reducing technologies was not included in this rule, which excluded about one-third of the technologies evaluated by ICF for fuel burn reductions. Therefore, based on the methodology described earlier in section 2.2.1, ICF utilized a subset of the about fifty aerodynamic and engine technologies to account for the improvements to the metric value for the final standards (for in-production and in-development airplanes[xxv]).

The 2018 ICF updated analysis considered a number of technologies incorporated on airplanes that had entered service since the initial 2015 analysis. Thus, there are actual service histories to consider now, especially for natural and hybrid laminar flow. Also, the recent completion of some major design changes (i.e., re-engine, re-wing) were assessed.

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[xxiii] Reference airplane means an existing in-production airplane or in-development airplane that is expected to go out of production in 2030-2040 timeframe (and which will have a replacement airplane take its place in the fleet in the long-term).

[xxiv] The metric value does not directly reward weight reduction technologies because such technologies are also used to allow for increases in payload, equipage, and fuel load (this is the case for incorporating weight reduction technologies to in-production airplanes, but it may not be the case for new type design airplanes). Thus, reductions in empty weight can be canceled out or diminished by increases in payload, fuel, or both; and, this varies by operation. Empty weight refers to operating empty weight. It is the basic weight of an airplane including the crew, all fluids necessary for operation such as engine oil, engine coolant, water, unusable fuel and all operator items and equipment required for flight but excluding usable fuel and the payload.

[xxv] Airplanes that are currently in-development but will be in production by the applicability dates. These could be new type design or redesigned airplanes.

**Table 2-7 Airframe and Systems Technologies**

<table>
<tr><th colspan="3">Airframe Technologies</th></tr>
<tr><th>Aerodynamic</th><th>Structural</th><th>Systems</th></tr>
<tr><td>• Adaptive Trailing Edge<br>• Advanced Wingtip Devices<br>• Variable Camber Trailing Edge<br>• Re-Wing (non-retrofittable)<br>• Riblet Coatings<br>• Laminar Flow Control<br>• Natural and Hybrid<br>• Nacelle, Empennage, and Wing<br>• Advanced Configurations (non-retrofittable)<br>• Gap Reductions<br>• Aft Body Redesign<br>• Light Profile</td><td>• Advanced Metals<br>• Increased Composite Application<br>• Advanced Composites (non-retrofittable)<br>• Re-Wing (non-retrofittable)<br>• Advanced Configurations (non-retrofittable)<br>• Titanium Landing Gear<br>• Lightweight Paint / Surface Treatment<br>•</td><td>• Lightweight Lightening Strike Protection<br>• More Electric Systems<br>• On demand Environmental Control Systems<br>• Fuel cell Auxiliary Power Unit (APU)<br>• Light interior<br>• Fly By Wire<br>• Carbon brakes<br>• Zonal Drying<br>• Control Surface<br>•</td></tr>
</table>

**Table 2-8 Engine Technologies**

<table>
<tr><th colspan="3">Engine Technologies</th></tr>
<tr><th>Materials</th><th>Architecture</th><th>Systems</th></tr>
<tr><td>• Titanium Aluminide (TiAl) turbine airfoils<br>• TiAl compressor airfoils<br>• Ceramic-matrix composites (CMC) turbine shrouds/ Outer Air Seal (OAS)<br>• CMC High Pressure Turbine (HPT) blades/ vanes<br>• CMC Low Pressure (LP) blades/ vanes<br>• Organic Matrix Composite (OMC) fan blades<br>• OMC case<br>• CMC exhaust nozzle<br>• Ceramic bearings<br>• Turbine coatings<br>• OMC stator<br>• OMC comp. cases</td><td>• Ultra High By Pass(UHBP) engine (above 10 Bypass Ratio (BPR))<br>• UHBP (above 20 BPR)<br>• Open rotor<br>• Variable cycle<br>• Intercooled compressors<br>• Integrated propulsion system<br>• Lightweight component fab techniques<br>• Reduced hub-tip ratio fan<br>• Fan drive gear<br>• Next gen load sharing architecture</td><td>• Bleedless engines<br>• Electric engine start<br>• High Pressure Compressor (HPC) mod. Clearance control<br>• Turbine mod. Clearance control<br>• Clearance control w/ feedback<br>• High Pressure (HP)/LP power extraction sharing<br>• High eff. Oil/air cooler<br>• Recuperative exhaust</td></tr>
<tr><th>Aerodynamics</th><th>Sealing</th><th>Coating / Cooling</th></tr>
<tr><td>• Next gen engine airfoil designs<br>• Optimized fan root fairing<br>• Scalloped fan exhaust<br>• Low Pressure Ratio (PR) fan<br>• Low drag inlet/nacelle</td><td>• Compressor blisks<br>• Turbine blisks</td><td>• Compressor airfoil coating<br>• Turbine air cooling air cooling<br>• Next gen. turbine airfoil cooling design</td></tr>
</table>

Airframe technologies: The airframe technologies that accounted for the improvements to the metric values from airplanes included aerodynamic technologies that reduce drag. Drag-reducing technologies included advanced wingtip devices, adaptive trailing edge, aft body redesign, laminar flow control (hybrid laminar flow control - empennage), riblet coatings, and environmental control system (ECS) aerodynamics and on-demand ECS scheduling. For the 2018 ICF updated analysis, the technical feasibility projection was increased for riblet coatings due to recent progress on this technology, and the commercial feasibility was mainly decreased for hybrid laminar flow control (empennage) due to the decrease in fuel prices.

Engine technologies: Engine manufacturers target improvements to address thrust specific fuel consumption (TSFC), propulsion system weight reduction, maintenance cost reduction, performance improvement, or system reliability. Though there are a range of improvement drivers that can be embodied (including the use of better materials and optimization in engine architecture), the gas turbine engine technologies that accounted for incremental reductions to the metric values are mainly driven by improvement in airfoil aerodynamics and sealing technologies. Airfoil aerodynamics technologies included next generation engine airfoil designs, and sealing technologies included compressor and turbine blisks[xxvi].[30] For the 2018 ICF updated analysis, the fuel burn reduction impact and commercial feasibility were increased for engine technologies due to recent progress in the technologies listed above. This reflects the observation that engine manufacturers are constantly improving these technologies, and it seems to be a high priority for industry to incorporate such engine technology improvements.

Details on the airframe and engine technologies listed above for metric value improvement are described below in sections 2.3.1 and 2.3.2 and the appendix for Chapter 2. Further details of these technologies are also provided in the 2018 ICF updated analysis (particularly section VII Appendices, Appendix 6, *Technology Profiles*).

### 2.3.1 Airframe Technologies

#### *2.3.1.1 Advanced Wingtip Devices*

Advanced wingtip devices are successful at increasing the lift-to-drag ratio of an airplane, which improves its performance (including takeoff and climb performance) and reduces fuel burn. The annual rate of fuel burn improvement is projected to be 3.5 percent for all the airplane categories. These advanced wingtip devices include winglets (single or split) or span extensions. Enlarging the span or the vertical extent of the wing reduces the lift-induced drag by spreading the vorticity, decreasing the adverse impact that this vorticity has on the remainder of the wing.

There are tradeoffs between extending the wing horizontally compared to installing a winglet. Aerodynamically, a wing horizontal extension is more effective in decreasing the induced drag compared to an equivalent increase in the vertical extent of the wing. The equivalent horizontal extension can be made smaller for the same induced drag reduction, and this further reduces the viscous drag penalty. However, the horizontal extension induces larger bending moments on the wing and thus results in a heavier wing, which makes it more challenging to integrate on a wing that has already been designed.

#### *2.3.1.2 Adaptive Trailing Edge*

[xxvi] Blisks means disks and individual blades are manufactured in one piece – blades are not inserted into disk later – which removes the need for blade roots and disk slots.

The objective of the adaptive trailing edge is to tailor the wing to minimize the drag at different flight conditions. Instead of using hinged surfaces to modify the shape of the wing, morphing the wing (or morphing the trailing edge of the wing) changes the shape of the structure continuously by using piezoelectric materials or by internal mechanisms. (A morphing wing can change its geometric shape during flight to optimize performance.). The outcome is a smooth variation in the shape of the wing with no gaps that would otherwise add to the overall drag.

There are two possibilities to implementing the morphing trailing edge: (a) local morphing on the trailing edge or conventional moving surfaces to augment or replace the conventional adaptive trailing edge technology or (b) replace all control surfaces with morphing. The latter possibility would have the advantage of eliminating the drag from gaps, and it enables a finer control of the spanwise distribution of the trailing edge camber. The annual rate of fuel burn improvement of this technology is projected to range from 0.5 to 2 percent for the various airplane categories. However, the small business and general aviation category is projected to have no fuel burn improvement from this technology (due to technical or economic reasons).

#### *2.3.1.3 Aft Body Redesign*

There are possibilities for aerodynamic improvements on the aft body of numerous contemporary airplanes. The majority of aerodynamic analysis and design effort targets the wings; however, opportunities for drag reduction on non-lifting parts such as the fuselage have also become an emphasis of airplane manufacturers. For example, this technology is on the Boeing 737 MAX.[xxvii]

For in-production airplanes, it is not practical for airplane manufacturers to conduct a major redesign of the aft body, but it is possible to make modifications on the existing shape. The area where the horizontal and vertical tails join the fuselage is especially important for interference drag, and it is an effective area for redesign. The annual rate of fuel burn improvement of this technology is projected to range from 1 to 1.3 percent for the various airplane categories.

#### *2.3.1.4 Hybrid Laminar Flow Control - Empennage*[xxviii]

Skin-friction drag is one of the main sources of drag on an airplane, and it typically accounts for over 50 percent of the total drag at cruise operations. This drag is due to the friction caused by the boundary layer.[xxix] Boundary layers can be either laminar or turbulent, and the former produce less friction and therefore less drag. Laminar boundary layers are also thinner, contributing to a reduction in pressure drag as well. Because of the combination of high speed and scale of commercial transport airplanes, the boundary layers on these airplanes are almost entirely turbulent. It is especially challenging to attain a laminar boundary layer in this flow

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[xxvii] "The tail cone will be extended and the section above the elevator thickened to improve steadiness of air flow. This eliminates the need for vortex generators on the tail. These improvements will result in less drag, giving the airplane better performance." April 11, 2012. Available at http://www.b737.org.uk/737max.htm (last accessed March 17, 2020)

[xxviii] The empennage, commonly called the tail assembly, is the rear section of the airplane. Its primary purpose is to provide stability to the airplane. It includes the horizontal stabilizer and the vertical stabilizer or fin. Available at http://www.pilotfriend.com/training/flight_training/fxd_wing/emp.htm (last accessed March 17, 2020).

[xxix] The boundary layer is a thin layer of air flowing over the surface of an airplane wing or airfoil (as well as other surfaces of the airplane). Available at http://www.pilotfriend.com/training/flight_training/aero/boundary.htm (last accessed March 20, 2020).

regime through passive means, particularly in lifting surfaces that are swept. Even though they begin as laminar at the leading edges, they will quickly transition to turbulent unless the right technology is utilized.

Natural laminar flow (NLF) depends exclusively on the careful design of the aerodynamic shape to delay the transition of the boundary layer from laminar to turbulent as much as possible. The higher the speed and the longer the dimensions, the more difficult it is to attain. Furthermore, wing sweep has an adverse effect. Therefore, NLF is currently not feasible on wings of commercial transports flying at high subsonic speeds.

Yet, recent progress has made it possible to attain NLF for a substantial portion of engine nacelles, as is the case in the Boeing 787. NLF necessitates particularly tight manufacturing tolerances and focus on the paint material and thickness. The Boeing 777X will also have nacelles with NLF.

The boundary layer will ultimately transition from laminar to turbulent when the streamwise distance is long enough. To increase the extent of laminar flow beyond what is possible through passive means of NLF, or to ensure laminar flow with an adverse shape or flight condition, it is possible to use hybrid laminar flow control (HLFC).

HLFC uses suction to delay the transition from laminar to turbulent and, therefore, generate areas with a laminar boundary layer. This technology was tested for the 787-9 vertical tail. Typically, the suction is generated by mechanical means and requires a source of power. The patent filed by Boeing seems to show a system that does not necessitate mechanical power: it sucks the boundary layer in through tiny holes in the skin to a plenum, or hollow chamber, inside the leading edge vertical tail that is then connected to an area of lower pressure elsewhere. This technology decreases the complexity of the system and eliminates the power requirement, making it commercially more viable. The annual rate of fuel burn improvement of this technology is projected to range from 0.3 to 2.5 percent for the various airplane categories.

However, as indicated earlier since the initial 2015 ICF analysis, the commercial feasibility of this technology has reduced -- primarily due to the decreased price of jet fuel. Also, based on Boeing’s continued review of this technology for drag reduction for the 787, we found that because of the current wing shape and several other factors, the technology is not producing as effective a balance of cost and performance as initially expected.

#### *2.3.1.5 Riblet Coatings*

Riblets are a pattern of tiny ridges that are aligned in the direction of the flow. This technology decreases the turbulence at the surface in the direction perpendicular to the flow, decreasing the skin friction drag. Although this is a well understood approach of decreasing skin friction drag, the issues of this technology are the manufacturing cost, the durability in service, and maintenance. With the rising value of decreasing drag, there is a chance that this technology will be deployed early in the next decade. The annual rate of fuel burn improvement of this technology is projected to range from 0.5 to 1.5 percent for the various airplane categories. For the updates to the technologies in the 2018 ICF updated analysis compared to the initial 2015

ICF analysis, Airbus and Lufthansa are already experimenting with shark skin coatings,[xxx] and British Airways has conducted a test trial with riblet coatings on the transatlantic route-dedicated Airbus A318. Thus, as described earlier, for the updates to riblet coatings in the 2018 ICF updated analysis compared to the initial 2015 ICF analysis, the technical feasibility projection was increased for this technology due to this recent progress on this technology.

#### *2.3.1.6 ECS Aerodynamics and On-Demand ECS Scheduling*

The airplane's environmental control system (ECS) provides air supply, thermal control, and cabin pressurization for the crew and passengers. In addition, avionics cooling, smoke detection and fire suppression are normally considered part of an airplane's environmental control system. The Boeing 787 and Airbus A350 both have aerodynamic and power-saving improvements to the ECS system. The inlet and outlet ducts to the system's compressor have been optimized to decrease the pressure drag. Also, on-demand ECS scheduling now enables engines to power the system only when necessary as opposed to powering it for an entire flight. The annual rate of fuel burn improvement of this technology is projected to be 0.6 percent for all the airplane categories.

### 2.3.2 Engine Technologies

Airplane gas turbine engine manufacturers are continually incorporating technologies into engines to address TSFC, performance improvement, or system reliability. Engine technologies include a range of improvements, such as materials (e.g., ceramic matrix composite parts), architecture (e.g., optimizing thermal efficiency versus propulsive efficiency), airfoil aerodynamics, sealing (e.g., blade tip clearances), and cooling (i.e., blade cooling to enable higher operating temperatures). Usually, it is airfoil aerodynamics and sealing technologies that are applied to engines in new in-production airplanes to improve fuel burn, and it is projected that the annual rate of fuel burn improvement of these technologies will be 0.2 percent for all airplane categories (except a 0.1 percent annual rate for turboprops). An airplane gas turbine engine is a highly integrated set of systems that typically limit the number of modifications that can be made to a new engine after entry into service.

Furthermore, engine manufacturers regularly produce performance improvement packages (PIPs) that improve fuel burn, reduce maintenance cost, and/or improve performance -- representative PIPs are shown in Table 2-9. below. A minimum of 0.5 to 1 percent fuel burn improvement (total) is needed to justify the development and certification costs of PIPs. With the numerous new engine developments that occurred recently or are ongoing, technologies developed for new engines (such as LEAP-X and Trent XWB) are being migrated back to prior versions of existing engines (e.g., technology developed for the Trent 1000 and 700EP was incorporated into a PIP for the Trent 900). While PIPs will vary from engine to engine, technologies developed in recent engine programs (e.g., GEnx, Trent 1000/XWB, geared turbofan (GTF), LEAP-X, etc.) will be incorporated into existing engines.

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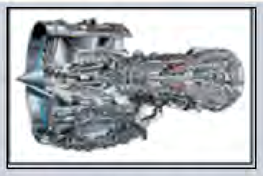
[xxx] Shark skin riblet coatings have a structure like the skin texture of sharks. Available at https://www.travelandleisure.com/airlines-airports/sharkskin-squid-helping-build-planes (last accessed March 17, 2020).

**Table 2-9. Representative Engine Performance Improvement Packages**

| Trent 900 | V2500 | CFM56-5B / -7B |
| --- | --- | --- |
|  |  |  |
| • Introduction of elliptical leading-edge modifications throughout the entire compression system<br>    • Improved high- and intermediate pressure (HP/IP) compressor blades and vanes<br>    • Improved fan and outlet guide vanes<br>• Tweaks to the air management system | • New software for electronic engine control (EEC)<br>• New variable stator vane (VSV) and bleed valve schedules<br>• High Pressure Compressor (HPC)<br>    • Improved airfoil technology<br>    • Improved airfoil surface finish<br>    • Controlled leading edge profile<br>    • Latest design standards<br>• Re-staggered first row of low pressure turbine (LPT) vanes<br>• New materials / coatings, advanced sealing, and airfoil cooling in the high pressure turbine (HPT) | • HPC kit – improved blade aerodynamics<br>• HPT blade kit – low shock airfoil with improved cooling<br>• LPT nozzle kit – improved cooling<br>• Lower NOx combustor |

## 2.4 Technology Application

Based on the short- and mid-term methodology and the resulting expected metric value improvements described above for airplanes (or business as usual improvements to airplane metric values in the absence of a standard), the EPA does not project the final GHG standards will cause manufacturers to make technical improvements to their airplanes that will not have occurred in the absence of the standards. The EPA projects the manufacturers will meet the standards independent of the EPA standards for the following reasons (as was described in section VII.A of the preamble):

Manufacturers have already developed or are developing improved technology in response to the ICAO standards that match the final GHG standards;

ICAO decided on the international Airplane CO2 Emission Standards, which are equivalent to the final GHG standards, based on proven technology by 2016/2017 that was expected to be available over a sufficient range of in-production and on-order airplanes by approximately 2020. Thus, most or nearly all in-production and on-order airplanes already meet the levels of the final standards;

It is likely that those few in-production airplane models that do not meet the levels of the final GHG standards are at the end of their production life and are expected to go out of production in the near term; and

These few in-production airplane models anticipated to go out of production are being replaced or are expected to be replaced by in-development airplane models (airplane models that have recently entered service or will in the next few years) in the near term -- and these in-development models have much improved metric values (which are expected to meet the final standards) compared to the in-production airplane model they are replacing.

Therefore, a technology response will likely not be necessary for airplane models to meet the final standards. This result confirms that the international Airplane $CO_2$ Emission Standards are technology-following standards, and that the EPA's GHG standards as they will apply to in-production and in-development airplane models will also be technology following.

For the same reasons, a technology response is not necessary for new type design airplanes to meet the final GHG standards. The EPA is currently not aware of a specific model of a new type design airplane that is expected to enter service after 2020 (no announcements have been made by airplane manufacturers). Additionally, any new type design airplanes introduced in the future will have an economic incentive to improve their fuel burn or metric value at the level of or less than the final standard.[xxxi]

### 2.4.1 Technology Responses

As described above, the final standards will likely not require a technology response. However, it is informative to describe the different steps in our technology response methodology for the short- and mid-term (for years 2015-2029) in addition to the discussions above on short- and mid-term methods and technologies. First, we determined the difference in metric value of an airplane model compared to the stringency levels of stringency scenarios. Note, Chapter 6 of this TSD describes the three stringency scenarios we analyzed for this rule, and these three scenarios comprise the final standards and two alternatives. Using PIANO metric values[xxxii] and the metric value reduction forecast, we compared the projected metric values for each airplane model to the stringency levels of the scenarios in the year of their effective dates -- to estimate the difference between the expected performance of the airplane model to stringency scenarios. Second, we sorted out from the analysis those airplane models that will end production before an effective date of a stringency scenario. Third, airplane models that met the levels of the stringency scenarios were sorted out next, and thus, the remaining airplane models were those models that did not meet at least one of the stringency scenarios. Chapter 6 of the TSD discusses the airplane models that do not meet the stringency scenarios and the impacts associated with these scenarios.

ICF developed supply curves that provide the projected metric value improvement of a given technology against its estimated non-recurring costs (NRC).[31] NRC is described in detail later in section 2.5. The outcome of the supply curves is a ranking of the incremental technologies by airplane family, from most cost effective to least cost effective. For determining a technical response, it was assumed that a manufacturer will invest in and apply the most cost-effective technologies to start and subsequently continue to the next most cost-effective technology -- to attain the incremental metric value improvements anticipated by the metric value reduction

[xxxi] There will be new type design airplanes in the future, and we expect these airplanes to meet the final standards. This projected outcome would be the baseline status of airplanes, or it would be the business as usual status of airplanes without this rule.

[xxxii] As indicated earlier, baseline metric values were generated using PIANO data.

forecast. When the new technology is implemented, there is expected to be a step change in the metric value reduction - where metric value reductions are achieved all at once (instead of gradually).

For an example, see Figure 2-3 below (MV improvement percentage versus NRC ($million)), which presents business as usual improvements for the Superjet 100 airplane. From the base year to an example effective date of standards (2025), the metric value reduction forecast estimates a given reduction -- 6.25 percent. Yet, to attain that amount of reduction, the manufacturer will need to incorporate Advanced Wingtip Devices and Engine Technologies onto the airplane, for a total of 7.7 percent in metric value reductions. Although the smoothed forecasted reduction shown in the supply curve is 6.25 percent at the example effective date, the actual reductions are greater since the metric value improvement from the technology is fully realized when the technology is incorporated onto the airplane. Representative metric value improvements and their associated non-recurring costs by airplane category are shown in Table 2-10 and Table 2-11 below. Also, the NRC and fuel burn reduction for each technology described earlier in section 2.3 are provided in the technology profiles in the Appendix of this chapter. Also, see the Appendix for examples of supply curves by the different airplane categories.

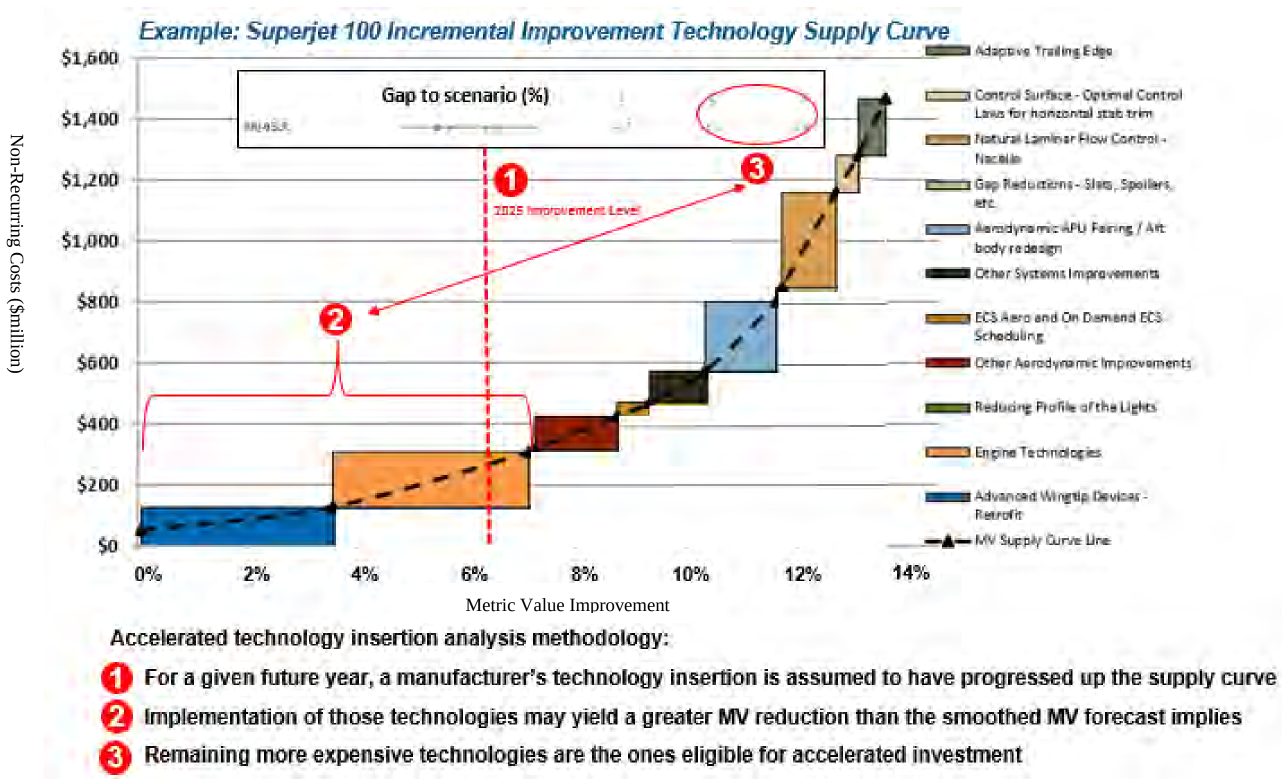



**Figure 2-3. Example Supply Curve**

The approach below was used to develop a projected business as usual metric value improvement in the form of a smoothed forecast for each airplane type that needs a technology response (to comply with a stringency scenario):

1. For a given future year, a manufacturer's technology insertion was assumed to have moved up the supply curve (i.e., technologies with the largest improvement and most economical cost are implemented first). Thus, these most economical technologies will have already been applied by the stringency year and will not be available for future investment.
2. The smoothed forecasted incremental metric value improvement is overlaid by the stringency year on an airplane model's distinct supply-curve. From this overlay, the most economical technologies were identified that already have been applied by the stringency year.
3. The remaining technologies not yet applied are available for accelerated investment when a technology response is necessary. For each in-scope airplane model, these technology responses were assessed using PIANO data.

### 2.4.2 One Percent Additional Design Margin for Technology Response

In the event where a technology response was modeled, we assumed that a manufacturer will need to provide an additional 1 percent design margin beyond the level needed to achieve the standard. This design margin ensures the technology response attains the level of the standard, where in reality fuel burn reductions for a given technology response can be variable.

## 2.5 Estimated Costs

This section provides the elements of the cost analysis for technology improvements, including non-recurring costs (NRC), certification costs, and recurring costs. As described, above, the EPA does not anticipate new technology responses due to the GHG standards, and, consequently, we do not expect any costs (technology costs) from the GHG standards. However, it is informative to describe the characteristics of these different cost elements. While recognizing that the GHG rule does not have NRC, certification costs, or recurring costs, it is informative to describe the elements of these costs (particularly to provide context for the NRC of an alternative described later in Chapter 6).

### 2.5.1 Non-Recurring Costs

Non-recurring cost (NRC) consists of the cost of engineering and integration, testing (flight and ground testing) and tooling, capital equipment, and infrastructure (capital). Engineering and integration costs include the engineering and research and development (R&D) needed to progress a technology from its current technology readiness status to a status where it can be incorporated into a production airframe,[xxxiii] as well as costs for airframe and technology integration. Testing costs include the fixed costs for test instrumentation, infrastructure, and project management and variable costs[xxxiv] associated with the amount of required flight and ground testing. Capital costs include the following: (a) tooling necessary to change the production line to support the fuel burn improvement, (b) modifications to plant, property, and equipment, and (c) other items such as information technology and supply chain systems.

[xxxiii] See description of technology readiness levels (TRLs) earlier in section 2.1.
[xxxiv] Variable costs are flight and ground testing costs that scale with the amount of time used for testing. For example, fuel costs and crew/test engineer salaries scale with the time for flight and ground testing.

As described earlier for the technology improvements and responses, ICF conducted a detailed literature search, conducted a number of interviews with industry leaders, and did its own modeling to estimate the NRC of making modifications to in-production airplanes. The EPA used the information gathered by ICF for assessing the cost of individual technologies, which were used to build up NRC for incremental improvements (a bottom-up approach). These improvements are for 0 to 10 percent improvements in the airplane fuel efficiency metric value, and this magnitude of improvements is typical for in-production airplanes (the focus of our analysis). In the initial 2015 ICF analysis, ICF developed NRC estimates for technology improvements to in-production airplanes, and in the 2018 ICF updated analysis these estimates have been brought up to date. The technologies available to make improvements to airplanes are described earlier in section 2.3.

The methodology for the development of the NRC for in-production airplanes consisted of five steps. First, technologies were categorized either as minor PIPs with 0 to 2 percent (or less than 2 percent) fuel burn improvements or as larger incremental updates with 2 to 10 percent improvements. Minor PIPs were aerodynamic cleanups (e.g., redesigned fairings) and other fuel burn improvements where frequently compliance is attained by analysis and without dedicated flight test airplanes.[xxxv] Large incremental updates were aerodynamic or structural improvements (e.g., winglets) that reduce fuel burn, where compliance includes flight test programs – typically with production airplanes. Second, the components of non-recurring costs were identified (e.g., engineering and integration costs), as described earlier. Third, baseline non-recurring cost component proportions were developed by incremental technology category for single-aisle airplanes. Fourth, the baseline NRC components for a single-aisle airplane were scaled to the other airplane size categories. Fifth, we compiled technology supply curves by airplane model. Appendices A and B of this Chapter 2 and the 2018 ICF updated analysis provide a more detailed description of this NRC methodology for technology improvements and results.[32]

#### *2.5.1.1 Non-Recurring Costs Component Proportions*

For single aisle airplane technologies, the proportions of the various NRC components differ whether it is an airframe or engine technology.[33] Also, for airframe technologies, this proportion varies whether the technology is a minor PIP or a large incremental update. Figure 2-4 below shows the NRC component proportions for the category of single aisle airplanes. Generally, for engine improvements, flight and ground testing is a substantial portion of the NRC. However, for minor airframe PIPs, the NRC is mainly engineering costs. Since minor airframe PIPs typically do not necessitate dedicated flight testing, NRC is focused on the engineering design and analysis required to analytically show compliance for PIPs. Large incremental updates for airframes necessitate a flight test program, and thus, a substantial fraction of the NRC is from this testing.

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[xxxv] Compliance for minor PIPs would typically include only minor ground, wind tunnel, and flight tests (with the analysis).

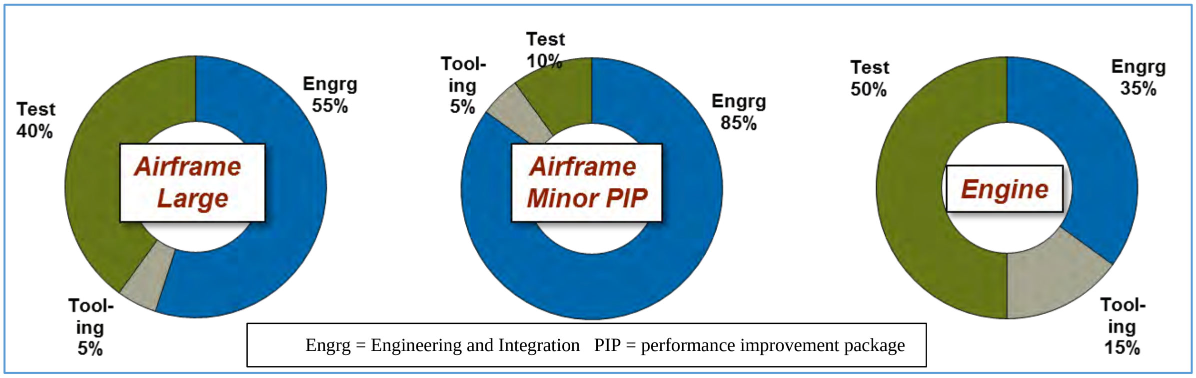


**Figure 2-4. Single Aisle Category Non-Recurring Cost Component Proportions**

### *2.5.1.2 Non-Recurring Cost Scaling Factors*

Non-recurring cost components for metric value improvement scale differently with airplane size -- or maximum takeoff mass; therefore, different scaling factors were used. Engineering and integration costs and capital costs are not strongly correlated with airplane size, and thus, airplane realized sale price was used to scale this component. Flight and ground testing scales with airplane operating costs; therefore, block hour[xxxvi] average operating costs were used to scale with this component. Table 2-10 below shows estimates of these scaling sources.

Engineering and capital scale by 15 percent of the differential in average realized sale price, with the single aisle airplane category as the baseline.[xxxvii] Testing scales with 100 percent of the operating cost differential, using the single aisle airplane category as the baseline. This results in factors that scale the cost components for the baseline of the single aisle airplane category to the other airplane categories, as shown in Table 2-11.[34] Using these scaling factors, NRC was estimated for technologies for each of the airplane categories. (The basic premise is that we believe that the larger the airplane, the more expensive the engineering and integration cost is. Anchoring single aisle airplane as the base index for engineering and integration, as an example, we then extrapolate the small twin aisle engineering and integration cost index by airplane realized price. See example calculation below.)

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[xxxvi] Block hour means the time from when the airplane door closes at departure until the airplane door opens upon arrival (for a given flight).

[xxxvii] To derive the 15 percent scaling factor for engineering and integration costs, we conducted interviews with market experts to confirm the appropriate factors for engineering and integration -- and that engineering and integration cost does not scale linearly with airplane value (or realized sale price).

**Table 2-10 – Non-Recurring Cost Component Scaling Factor Sources**

| Aircraft Category | Average Realized Sale Price | Avg Operating Cost ($/Block Hour) |
|---|---|---|
| Small BGA | $10M | $1,340 |
| Large BGA | $40M | $2,688 |
| Turboprop | $25M | $2,016 |
| Regional Jet | $30M | $2,688 |
| Single Aisle | $45M | $4,538 |
| Small Twin Aisle | $130M | $8,143 |
| Large Twin Aisle | $165M | $10,500 |
| Very Large Aircraft | $195M | $14,449 |

**Table 2-11 – Non-Recurring Cost Component Scaling Factors**

| Aircraft Category | Engineering & Integration Cost | Flight & Ground Test | Tooling, Capital Equipment, & Infrastructure |
|---|---|---|---|
| Small BGA | 0.88 | 0.30 | 0.88 |
| Large BGA | 0.98 | 0.59 | 0.98 |
| Turboprop | 0.93 | 0.44 | 0.93 |
| Regional Jet | 0.95 | 0.59 | 0.95 |
| Single Aisle | 1 | 1.00 | 1 |
| Small Twin Aisle | 1.28 | 1.79 | 1.28 |
| Large Twin Aisle | 1.40 | 2.31 | 1.40 |
| Very Large Aircraft | 1.50 | 3.18 | 1.50 |

Below is an example calculation of the engineering and integration cost.

We assumed a representative realized price of:

- Single aisle: $45M
- Small twin aisle: $130M
- Large twin aisle: $165M

We then scale the engineering and integration cost by 15 percent of the differential[xxxviii] in average realized prices.

- Small twin aisle: 1+15%($130M-$45M)/$45M= 1.28
- Large twin aisle: 1+15%($165M-$45M)/$45M=1.40

For all large incremental updates (2 to 10 percent improvements), it was assumed that there is a minimum $5 million (M) fixed cost, and this fixed cost was used for all incremental upgrades (which meant the same amount of minimum fixed cost regardless of technology or airplane category). This minimum fixed cost is for a manufacturer's overhead of basic program management that comes with any degree of improvement

For an example of the use of the NRC scaling factors by airplane category, see Figure 2-5 below that represents winglets -- which are a large incremental update. For the single aisle airplane baseline, the total NRC is comprised of the following components: 3 percent baseline fixed, 52 percent engineering and integration, 40 percent testing, and 5 percent capital. For this example, an NRC of $173 million was used for the category of single aisle airplanes. With this baseline, the cost component breakdown provided earlier in Table 2-10 separated the total NRC into the different components.[35]

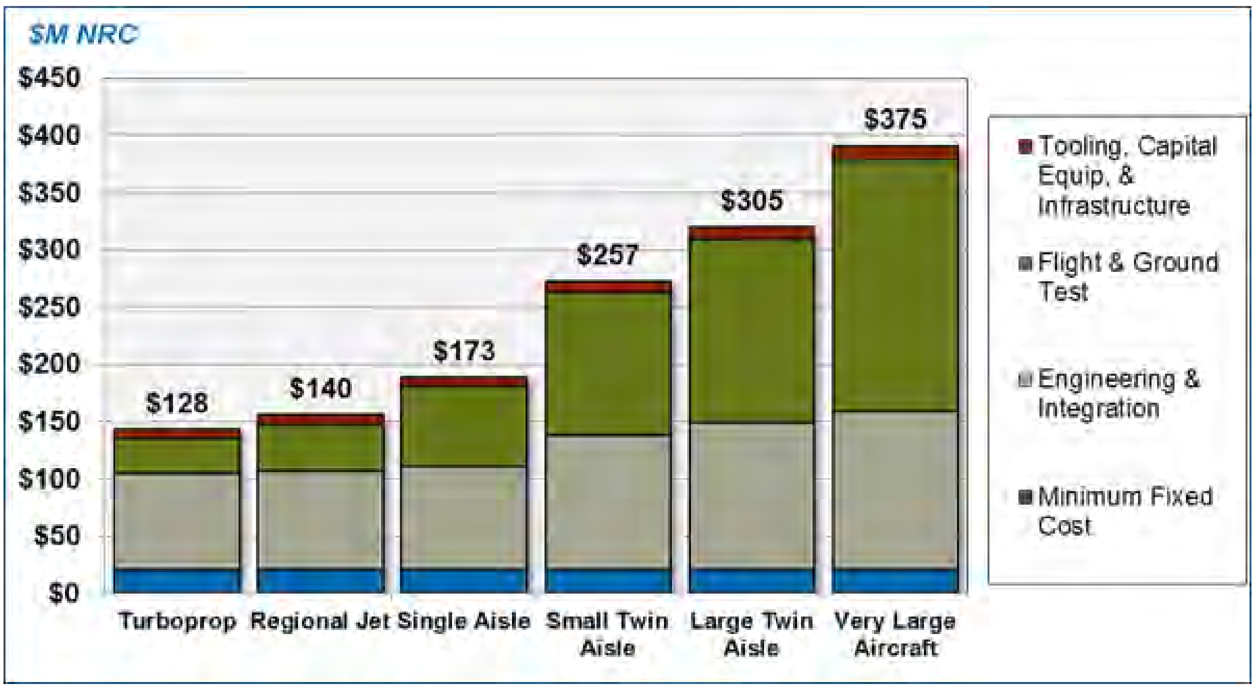


**Figure 2-5. Example Non-Recurring Cost Scaling by Airplane Category - Large Incremental Update**

[xxxviii] The approach of scaling the engineering and integration from the single aisle category to the other airplane categories using the 15% differential in average realized prices was developed by ICF, based on their data sources. As described earlier in this chapter, the data sources for the 2018 ICF updated analysis are detailed in section II.1.2 of this ICF analysis (or this ICF report). These data sources include ICF's broad and thorough market interview program (with key individuals in the aviation industry and university/research organizations), research, and knowledge gained through past work on in-depth aviation cost models.

## 2.5.2 Comparing the EPA NRC to ICAO/CAEP NRC for International Airplane $CO_2$ Emission Standards

As described earlier, ICAO's CAEP conducted an analysis of the international Airplane $CO_2$ Emission Standards, which were agreed to at CAEP in February 2016, and this analysis included an assessment of the NRC. For purposes of showing all the available data on NRC for the standard, we are providing a comparison of the NRC costs in our analysis to the NRC costs in the CAEP analysis. Note that CAEP published a report of their meeting in February 2016, and Appendix C of this meeting report is a summary of the methods and results – for costs and emission reductions -- from the CAEP analysis.[36] Some of the information used in the CAEP analysis is not available in this report and thus to the public, due to commercial sensitivities. Any information from the CAEP analysis that is not in the report of the February 2016 CAEP meeting cannot be shared outside of CAEP, and thus, it will not be provided in this EPA TSD.

As described in the 2015 ANPR, CAEP developed an approach for estimating NRC that was a function of an airplane's MTOM and the required metric value improvement (percent metric value improvement for a technology response), which CAEP termed the Continuous Modification Status (CMS) approach. Based on past practice, industry provided estimates for developing clean sheet designs and redesigns, only including high level information that has been made available to the public. As a result, this was a top-down estimate which included all airplane development costs (type certification, noise, in-flight entertainment, etc.), not just those costs for $CO_2$ improvements.

Since the initial dataset provided by industry only included major changes (or major improvements), the EPA supplemented this dataset with an estimate of $CO_2$-only improvements, which was a bottom-up estimate. These changes are much smaller, on the order of a few percent, and could be applied to in-production airplanes. As described earlier, we contracted with ICF to develop an estimate of the cost to modify in production airplanes to comply with $CO_2$ standards (the initial 2015 ICF analysis).[37] The results from this 2015 ICF peer-reviewed study (for small changes) were then combined with inputs from the industry and the other CAEP participants (for large changes) to develop the $CO_2$ technology response and cost estimation. For the cost estimation, the CAEP combined the two different methodologies to develop the final cost surface.[xxxix] Due to this combination of these methods for CAEP's CMS approach, CAEP indicated that the accuracy of the costs generated by the NRC methodology is representative and considered fit for purpose.

As described above, CAEP's top-down approach in NRC for large changes would be seen in redesigns or new type designs. For redesigns that result in new series of an established model, these types of changes may include redesigned wings, new engine options, longer fuselages, improved aerodynamics, or reduced weight. When making significant design changes to an airplane, many other changes and updates get wrapped into the process that do not affect the $CO_2$ emissions of the airplane, and redesigns may not have been spurred solely by changes to fuel efficiency ($CO_2$ reductions). This confluence of changes led CAEP to agree that it was reasonable to use the full development cost for a new type design or redesign for significant design changes. Total costs for past projects were used to estimate non-recurring cost for the

[xxxix] The two datasets were merged together, and a single cost surface was then generated to calculate the cost to modify any airplane based on the MTOM, and percent metric value change needed.

CAEP analysis. This type of airplane improvement/development program has historically ranged approximately from $1 to $15 billion depending on the size of the airplane and scope of the improvements desired.

As discussed above, CAEP's bottom-up approach was used to model smaller incremental metric value changes to airplane design. CAEP agreed that the above top-down approach is not the best approach for minor changes or incremental improvements, because the significant design efforts include many changes that are not be required for smaller $CO_2$ reductions. The EPA used the information gathered by ICF in their 2015 report to provide input to CAEP on the cost for individual technologies, and the ICF's information was used to build up CAEP's non-recurring costs for these incremental improvements (a bottom-up approach). The technologies available to make incremental improvements to airplanes are wide ranging and airplane specific. Some examples of technologies are described earlier in section 2.3. As an example, in the initial 2015 analysis, ICF estimated that depending on the additive nature of specific technologies and the magnitude improvement required, the cost to incrementally improve the Boeing 767 could range from approximately $230 million to $1.3 billion US dollars (3.5 percent to 11 percent metric value improvement).[38]

CAEP's CMS approach was based on the functional form of the NRC surface as provided in Equation 2-4 below.[39] NRC is measured in billions of US Dollars with a 2010 reference year.[xl] The NRC surface has been calibrated to generate NRC estimates across a broad range of airplane sizes or MTOMs (MTOM is the same as MTOW) and metric value improvements. The method consists of a single cost surface that is a function of metric value improvement and airplane MTOM.

**Equation 2-4 Function of CAEP's NRC Surface**

$$NRC\ (10^9\ \$) = \left( \underbrace{\left(A \cdot e^{(B \cdot x)} + C\right)}_{\text{Reference Airframe NRC}} + \underbrace{\left(A \cdot e^{(B \cdot 0.9)} + C\right) \cdot f(\Delta MV) \cdot \frac{2}{\#\,Engines}}_{\text{Reference Engine NRC}} \right) \cdot \underbrace{\left( \frac{MTOW}{MTOW_{ref}} \right)^D}_{\text{Aircraft Size Scaling}}$$

*Where coefficients and functions; A, B, C, D and f(ΔMV) are defined as follows:*

| NRC Surface Coefficients | | |
|---|---|---|
| **A** | **B** | **C** |
| *0.188902* | *3.247077* | *-0.142274* |

All coefficients are regressed based on metric value improvement data, except for D, which along with f(ΔMV) is represented as a sigmoid function, as shown in Figure 2-6 below. Since boundaries of metric value improvements differ with MTOM (or MTOW), the cost surface is driven by a normalized metric value improvement. The normalized metric value improvement is generated by:[xli]

[xl] CAEP's NRC is measured in billions of US Dollars with a 2010 reference year.

[xli] The Metric Value Improvement Upper and Lower Bounds were airplane specific terms developed by CAEP. These terms were not discussed, nor were data provided on them, in the publicly available Appendix C of the February 2016 CAEP meeting report, and thus, they are not described further in this EPA TSD.

**Equation 2-5 Equation to Calculate ΔMV**

$$\Delta MV = |MV\ Improvement| - MV\ Improvement\ Lower\ Bound$$

**Equation 2-6 Equation to Calculate Normalized MV Improvement**

$$Normalized\ MV\ Improvement = x = \frac{\Delta MV}{MV\ Improvement\ Upper\ Bound - MV\ Improvement\ Lower\ Bound}$$

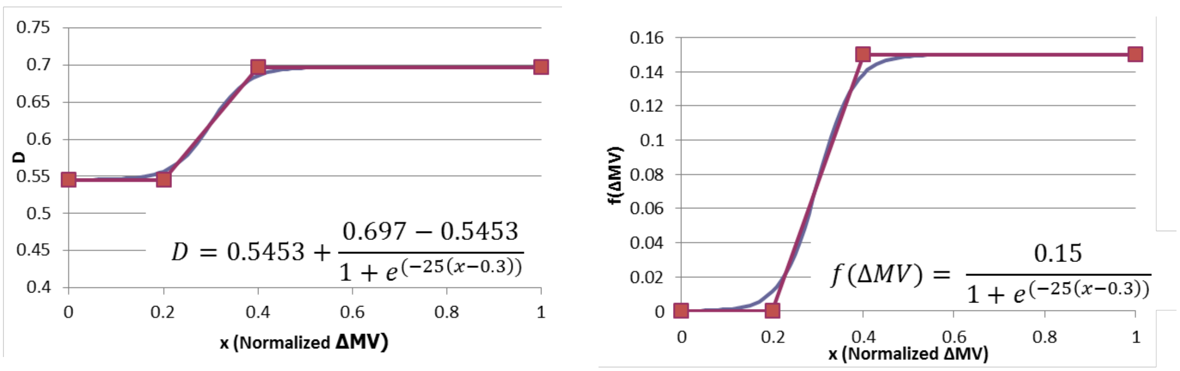


**Figure 2-6. CAEP NRC Surface's Coefficient D (left) and f (ΔMV) (right) Formulation**

Table 2-12 and Table 2-13 below show a comparison of today's NRC results from the EPA analysis (based on 2018 ICF updated analysis) to the results of the ICAO/CAEP's NRC Surface (for the CAEP10 meeting in 2016): NRC ($B) for percent metric value improvement. Table 2-12 and Table 2-13 provide NRC for representative airplanes in each airplane category, ranging from a percent metric value improvement of 3.5 percent to greater than or equal to 10 percent. Note that ICAO/CAEP's NRC are a function of MTOM, and nearly all the representative airplanes and associated airplane categories have different MTOMs, which shows how the ICAO/CAEP NRC changes with MTOM. The results from the ICAO/CAEP NRC surface are on average about 170 percent greater compared to EPA's analysis. Table 2-12 indicates that the results from the CAEP NRC surface are on average about 90 percent greater for small BGA through single aisle airplane categories, and Table 2-13 shows that the CAEP NRC are on average 245 percent greater for small twin aisle through large quad categories.

These results are expected for two reasons. First, CAEP's technology responses were based on technology available in 2016-2017 (or frozen technology 2016-2017) -- compared to the EPA's responses that considered technology available by 2017 and assumed continuous improvement until 2040 based on the incorporation of these technologies onto airplanes. Also, ICF considered the end of production of airplanes based on the expected business as usual status of airplanes. Thus, ICF was able to use the actual effective dates of the final standards in their analysis. Second, the CAEP NRC surface is a combination of the two different methodologies discussed above, top-down and bottom-up approaches, and today's EPA NRC results were only based on the bottom-up approach. Including the top-down approach in the CAEP NRC surface likely adds to the overestimation of the CAEP NRC estimate because it includes all airplane development costs (type certification, noise, in-flight entertainment, etc.), and not just those costs for $CO_2$ improvements.

**Table 2-12 Comparison Results of EPA NRC to CAEP NRC Surface ($ Billions) – Part 1**

| MV% | Small BGA - NRC ($B) | | | Large BGA - NRC ($B) | | | Turboprop - NRC ($B) | | | Regional Jet - NRC ($B) | | | Single Aisle - legacy - NRC ($B) | | | Single Aisle - new gen - NRC ($B) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ICF Cost | ICAO CNA 525B | ICAO FAL 2000LX | ICF Cost | ICAO CL-605 | ICAO Global 8000 | ICF Cost | ICAO ATR 42-5 | ICAO AN 140 | ICF Cost | ICAO CRJ 700 | ICAO ERJ-195 E2 | ICF Cost | ICAO A319-133 | ICAO B737-700 | ICF Cost | ICAO A319-NEO | ICAO B737-7MAX |
| 3.50% | 0.10 | 0.08 | 0.13 | 0.10 | 0.14 | 0.18 | 0.10 | 0.13 | 0.14 | 0.10 | 0.16 | 0.20 | 0.20 | 0.22 | 0.22 | 0.20 | 0.23 | 0.23 |
| 7.10% | 0.20 | 0.23 | 0.45 | 0.30 | 0.48 | 0.70 | 0.20 | 0.44 | 0.48 | 0.30 | 0.59 | 0.82 | 0.40 | 0.92 | 0.90 | 0.40 | 0.95 | 0.95 |
| 7.20% | | 0.23 | 0.46 | | 0.49 | 0.71 | | 0.45 | 0.49 | | 0.61 | 0.84 | | 0.94 | 0.92 | | 0.97 | 0.97 |
| 7.25% | 0.20 | 0.24 | 0.46 | 0.30 | 0.49 | 0.72 | 0.30 | 0.45 | 0.49 | 0.30 | 0.61 | 0.85 | 0.40 | 0.95 | 0.93 | | 0.98 | 0.98 |
| 7.70% | | 0.25 | 0.49 | | 0.53 | 0.78 | | 0.48 | 0.53 | | 0.66 | 0.92 | | 1.04 | 1.02 | | 1.07 | 1.07 |
| 7.73% | | 0.25 | 0.50 | | 0.53 | 0.78 | | 0.48 | 0.53 | | 0.66 | 0.93 | 0.50 | 1.04 | 1.02 | 0.50 | 1.07 | 1.07 |
| 7.85% | | 0.26 | 0.50 | | 0.54 | 0.80 | | 0.49 | 0.54 | | 0.67 | 0.94 | | 1.06 | 1.04 | | 1.10 | 1.10 |
| 7.88% | 0.30 | 0.26 | 0.51 | 0.40 | 0.54 | 0.80 | 0.30 | 0.50 | 0.54 | | 0.68 | 0.95 | | 1.07 | 1.05 | | 1.10 | 1.10 |
| 8.38% | 0.30 | 0.28 | 0.54 | | 0.58 | 0.86 | | 0.53 | 0.58 | | 0.72 | 1.02 | | 1.15 | 1.13 | | 1.19 | 1.19 |
| 8.48% | | 0.28 | 0.55 | | 0.59 | 0.87 | | 0.54 | 0.59 | | 0.73 | 1.04 | | 1.17 | 1.14 | | 1.20 | 1.20 |
| 8.75% | | 0.30 | 0.57 | | 0.61 | 0.91 | | 0.56 | 0.61 | 0.40 | 0.76 | 1.07 | | 1.21 | 1.19 | | 1.25 | 1.25 |
| 9.13% | | 0.31 | 0.60 | | 0.64 | 0.95 | 0.50 | 0.59 | 0.64 | | 0.80 | 1.13 | | 1.27 | 1.24 | | 1.31 | 1.31 |
| 9.20% | | 0.32 | 0.61 | | 0.65 | 0.96 | | 0.59 | 0.65 | | 0.80 | 1.14 | | 1.28 | 1.26 | | 1.32 | 1.32 |
| 9.38% | 0.50 | 0.33 | 0.62 | | 0.66 | 0.98 | | 0.61 | 0.66 | 0.50 | 0.82 | 1.16 | | 1.31 | 1.28 | | 1.35 | 1.35 |
| 9.48% | | 0.33 | 0.63 | | 0.67 | 0.99 | | 0.62 | 0.67 | | 0.83 | 1.18 | 0.80 | 1.33 | 1.30 | 0.80 | 1.37 | 1.37 |
| 9.63% | | 0.34 | 0.65 | | 0.69 | 1.01 | 0.60 | 0.63 | 0.69 | | 0.85 | 1.20 | | 1.35 | 1.32 | | 1.39 | 1.39 |
| 9.88% | 0.60 | 0.35 | 0.67 | | 0.71 | 1.04 | | 0.66 | 0.71 | | 0.87 | 1.23 | | 1.39 | 1.36 | | 1.44 | 1.44 |
| >=10% | 0.80 | 0.36 | 0.68 | 0.60 | 0.72 | 1.06 | 0.70 | 0.67 | 0.72 | 0.60 | 0.89 | 1.25 | 1.00 | 1.41 | 1.38 | 1.00 | 1.46 | 1.46 |

**Table 2-13 Comparison Results of EPA NRC to CAEP NRC Surface ($ Billions) – Part 2**

| MV% | Small Twin Aisle - legacy - NRC ($B) | | Small Twin Aisle - new gen - NRC ($B) | | | Large Twin Aisle - legacy - NRC ($B) | | | Large Twin Aisle - new gen - NRC ($B) | | | Large Quad - NRC ($B) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ICF Cost | ICAO B767-3ER | ICF Cost | ICAO B787-8 | ICAO B787-10 | ICF Cost | ICAO A330-203 | ICAO B777-200ER | ICF Cost | ICAO A330-800-NEO | ICAO B777-8x | ICF Cost | ICAO A380-8 | ICAO B747-8 |
| 3.50% | 0.20 | 0.37 | 0.20 | 0.42 | 0.45 | 0.30 | 0.43 | 0.48 | 0.50 | 0.44 | 0.54 | 0.30 | 0.67 | 0.58 |
| 7.10% | | 1.68 | | 1.98 | 2.12 | | 2.03 | 2.30 | | 2.06 | 2.64 | | 2.80 | 2.37 |
| 7.20% | | 1.72 | | 2.03 | 2.17 | | 2.09 | 2.37 | 1.20 | 2.11 | 2.71 | | 2.88 | 2.44 |
| 7.25% | | 1.75 | | 2.05 | 2.20 | | 2.11 | 2.40 | | 2.14 | 2.75 | | 2.92 | 2.47 |
| 7.70% | 0.70 | 1.92 | 0.70 | 2.27 | 2.43 | 1.00 | 2.34 | 2.65 | | 2.36 | 3.05 | 1.00 | 3.27 | 2.75 |
| 7.73% | | 1.93 | | 2.28 | 2.45 | | 2.35 | 2.67 | | 2.38 | 3.06 | | 3.29 | 2.77 |
| 7.85% | 0.70 | 1.98 | | 2.33 | 2.50 | 1.00 | 2.40 | 2.73 | | 2.43 | 3.14 | 1.10 | 3.37 | 2.84 |
| 7.88% | | 1.99 | | 2.35 | 2.52 | | 2.42 | 2.75 | | 2.44 | 3.15 | | 3.40 | 2.86 |
| 8.38% | | 2.15 | | 2.54 | 2.73 | | 2.62 | 2.98 | | 2.65 | 3.43 | | 3.74 | 3.15 |
| 8.48% | 0.80 | 2.18 | | 2.58 | 2.77 | | 2.66 | 3.03 | | 2.69 | 3.48 | 1.20 | 3.81 | 3.20 |
| 8.75% | | 2.27 | | 2.68 | 2.88 | | 2.76 | 3.15 | | 2.80 | 3.62 | | 3.99 | 3.35 |
| 9.13% | | 2.38 | | 2.82 | 3.03 | | 2.91 | 3.31 | | 2.94 | 3.81 | | 4.24 | 3.56 |
| 9.20% | | 2.41 | | 2.85 | 3.06 | | 2.93 | 3.34 | 1.60 | 2.97 | 3.85 | | 4.29 | 3.60 |
| 9.38% | | 2.46 | | 2.91 | 3.13 | | 3.00 | 3.42 | | 3.04 | 3.93 | | 4.41 | 3.71 |
| 9.48% | | 2.49 | | 2.95 | 3.17 | | 3.04 | 3.46 | | 3.07 | 3.98 | | 4.48 | 3.76 |
| 9.63% | | 2.54 | | 3.00 | 3.23 | | 3.10 | 3.53 | | 3.13 | 4.06 | | 4.58 | 3.85 |
| 9.88% | | 2.62 | | 3.10 | 3.33 | | 3.19 | 3.64 | | 3.23 | 4.19 | | 4.76 | 4.00 |
| >=10% | 1.20 | 2.66 | 1.10 | 3.14 | 3.38 | 1.40 | 3.24 | 3.69 | 2.00 | 3.28 | 4.25 | 1.80 | 4.85 | 4.07 |

### 2.5.3 Certification Costs

After the EPA issues the rulemaking for the GHG standards, the FAA will issue a rulemaking to enforce compliance to these standards, and any potential certification costs for the GHG standards will be attributed to the FAA rulemaking. However, it is informative to discuss certification costs.

As described earlier, manufacturers have already developed or are developing technologies to respond to ICAO standards that are equivalent to the final standards, and they will comply with the ICAO standards in the absence of U.S. regulations. Also, this rulemaking will potentially provide for a cost savings to U.S. manufacturers since it will enable them to domestically certify their airplanes via the subsequent FAA rulemaking instead of having to certify with foreign certification authorities (which will occur without this EPA rulemaking). If the final GHG standards, which match the ICAO standards, are not adopted in the U.S., the U.S. civil airplane manufacturers will have to certify to the ICAO standards at higher costs because they will have to move their entire certification program(s) to a non-U.S. certification authority.[xlii] Thus, there

[xlii] In addition, European authorities charge fees to airplane manufacturers for the certification of their airplanes, but FAA does not charge fees for certification.

are no new certification costs for the final standards.[xliii] However, it is informative to describe the elements of the certification cost, which include obtaining an airplane, preparing an airplane, performing the flight tests, and processing the data to generate a certification test report.

Earlier in section 2.5.1, the testing component of the NRC is described as including fixed costs for test instrumentation, infrastructure, and project management, and this component of the NRC includes different costs (and expected to be greater costs) compared to the testing costs related to only certification discussed in this section. The testing included in certification costs is only for certifying an airplane to the GHG standards, and for an existing in-production airplane that is non-GHG certificated this means that the manufacturers will need to conduct some amount of re-testing and pre- and post-test work to show compliance with the GHG standards. In contrast, the testing component of the NRC includes the full amount of testing to incorporate a technology improvement into an airplane and is not limited to testing only for purposes of certification to GHG standards.

The ICAO certification test procedures to demonstrate compliance with the international Airplane $CO_2$ Emission Standards -- incorporated by reference in this rulemaking -- were based on the existing practices of airplane manufacturers to measure airplane fuel burn and cruise performance.[40] Therefore, manufacturers already have airplane test data (or data from high-speed cruise performance modelling, which they can use to demonstrate compliance with the international Airplane $CO_2$ Emission Standards). In the absence of the standards, the relevant $CO_2$ or fuel burn data will be gathered during the typical or usual airplane testing that the manufacturer regularly conducts for non-GHG standard purposes (e.g., for the overall development of the airplane and to demonstrate its airworthiness). In addition, such data for new type design airplanes, where data has not been collected yet, will be gathered in the absence of a standard. The baseline status for manufacturers is that they likely will have already done the work needed to certify their airplanes in the absence of the final standards. These details further support the rationale above for there being no certification costs for the final standards.

CAEP assessed the certification costs for the international Airplane $CO_2$ Emission Standards. The results of CAEP's assessment of certification costs were not described in the summary of the CAEP analysis,[41] and thus, we are unable to share these CAEP results in this EPA TSD. Nonetheless, the EPA believes there are no certification costs that should be attributed to this rule, for the reasons described earlier in this section. Also, the EPA is not making any attempt to quantify the costs associated with certification by the FAA.

### 2.5.4 Recurring Costs

There will be no recurring costs for the final standards; however, it is informative to describe the components of recurring costs. The components of recurring costs for incorporating technologies that improve fuel burn will include additional maintenance, material, labor, and tooling costs. The EPA analysis shows that airplane fuel efficiency improvements typically result in net cost savings through the reduction in the amount of fuel burned. This makes economic sense because if technologies add significant recurring costs to an airplane, operators (e.g., airlines) will likely reject these technologies.[42]

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[xliii] Due the unprecedented nature of the final airplane emission standards providing cost savings to manufacturers in this manner, we are unable to quantify the amount of these costs savings.

**Technology and Cost**

CAEP's analysis for the international Airplane $CO_2$ Emission Standards included an assessment of the recurring costs.[43] CAEP's recurring costs were described as recurring direct operating costs (DOC) and included the following elements: (a) capital costs (including finance and depreciation), (b) other-DOC (including crew, maintenance landing and route costs) and (c) fuel costs. The results of the CAEP analysis showed the fuel savings from the standards will far outweigh any of the other elements of the recurring costs. Thus, in total the recurring costs ended up being a cost savings.

### 2.5.5 Reporting Costs

The costs of generating a certification test report should not be attributed to this rule. The FAA is expected to promulgate a rule to enforce compliance to these standards subsequent to the EPA final rule of these standards, and any potential costs of the certification will be attributed to this FAA rule.

## 2.6 Airplane Fuel Savings

As described earlier, manufacturers have already developed or are developing technologies to respond to ICAO standards which are equivalent to the standards adopted today. Additionally, they will need to find a way to certify to the ICAO standards even in the absence of U.S. regulations. As a result, all airplane models (in-production and in-development airplane models) are expected to be in compliance with the final standards by the time they will become effective. Therefore, there will be no fuel savings from this rulemaking. Chapter 6 of this TSD discusses the fuel savings from an alternative scenario (Scenario 3) we analyzed, which is different from the final standards (Scenario 1) that match the international standards. (The other alternative scenario (Scenario 2) does not have fuel savings).

CAEP's analysis for the international Airplane $CO_2$ Emission Standards included an assessment of the fuel savings.[xliv] First, CAEP provided results for the cumulative $CO_2$ reductions for different effective dates for the 10 stringency options (SOs) assessed. Chapter 6 provides a description of the 10 CAEP stringency options.[xlv] The international Airplane $CO_2$ Emission Standards that were ultimately adopted by CAEP for in-production airplanes were stringency option 7 (SO7) for in-production airplanes (for airplanes with MTOMs greater than

[xliv] ICAO, 2016: *Tenth Meeting Committee on Aviation Environmental Protection Report*, Doc 10069, CAEP/10, 432 pp, AN/192, Available at: http://www.icao.int/publications/Pages/catalogue.aspx (last accessed July 11, 2018). The ICAO CAEP/10 report is found on page 27 of the English Edition 2018 catalog and is copyright protected; Order No. 10069. The summary of technological feasibility and cost information is located in Appendix C (starting on page 5C-1) of this report. Figure 9 of Appendix C shows the cumulative $CO_2$ reductions for stringency options, and Figure 12 provides the change in cumulative costs (including fuel savings or negative fuel costs) for the stringency options.

[xlv] As described in the 2015 ANPR and later in Chapter 6 (section 6.1.1), for the international Airplane $CO_2$ Emission Standards, CAEP analyzed 10 different SOs for standards of both in-production and new type design airplanes, comparing airplanes with a similar level of technology on the same stringency level. These stringency options were generically referred to numerically from "1" as the least stringent to "10" as the most stringent. The 2015 ANPR described the range of stringency options under consideration at ICAO/CAEP as falling into three categories as follows: (1) $CO_2$ stringency options that could impact only the oldest, least efficient airplanes in-production around the world, (2) middle range $CO_2$ stringency options that could impact many airplanes currently in-production and comprising much of the current operational fleet, and (3) $CO_2$ stringency options that could impact airplanes that have either just entered production or are in final design phase but will be in-production by the time the international Airplane $CO_2$ Emission Standards become effective.

60 tonnes) with an effective date of 2028. Because ICAO analyzed the stringency options relative to a 2016/2017 fixed technology baseline (without continuous improvement and without considering the expected end of production of airplanes), the ICAO analysis reports $CO_2$ reductions and technology costs for the international standard. ICAO's projected $CO_2$ reductions from SO7 with a 2028 effective date are shown in Figure 2-7 below, and the results indicate about 350 Megatonnes (Mt) of $CO_2$ reductions (labeled as 2028-Case-1 and in negative Megatonnes by CAEP in Figure 2-7). These reductions are for SO7 applying to all covered airplanes, even though the international standards that were adopted for airplanes less than or equal to 60 tonnes MTOM are less stringent, SO3. Thus, according to CAEP's approach in their analysis, the $CO_2$ reductions would be less than 350 Mt.

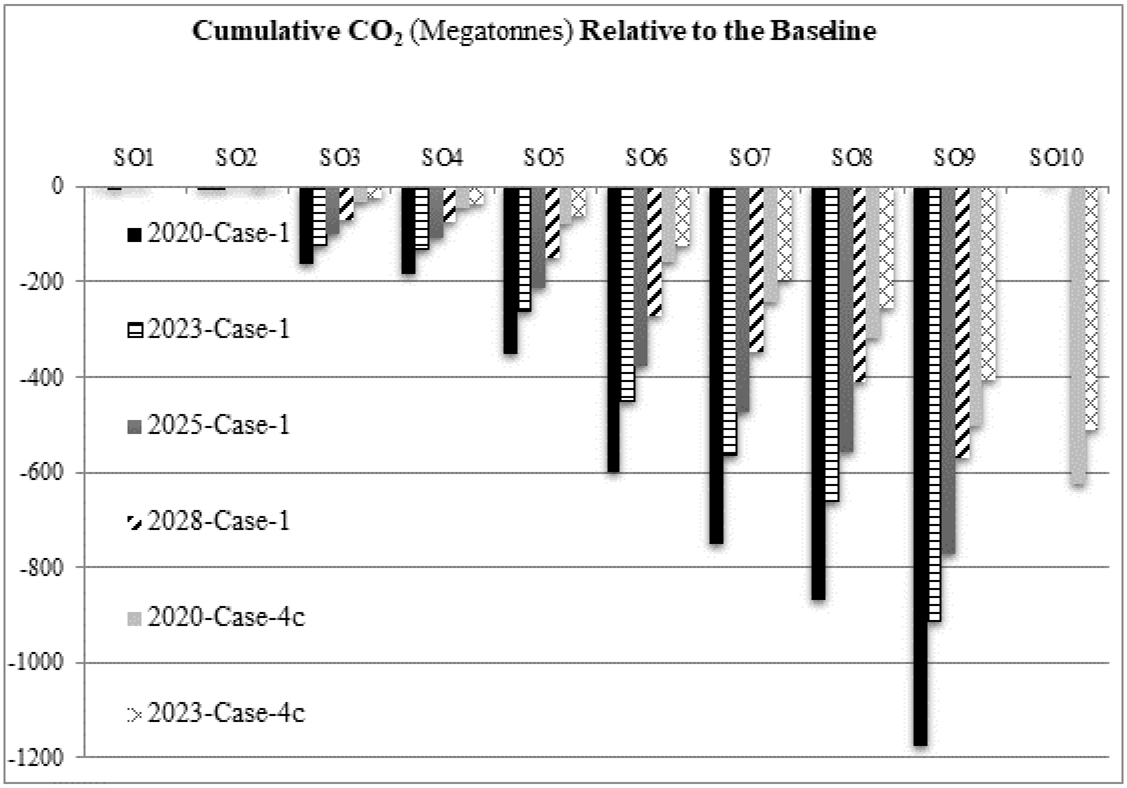


**Figure 2-7. CAEP Cumulative $CO_2$ (Megatonnes) Reductions from the Effective Date to 2040**[xlvi]

[xlvi] ICAO, 2016: *Tenth Meeting Committee on Aviation Environmental Protection Report*, Doc 10069, CAEP/10, 432 pp, AN/192, Available at: http://www.icao.int/publications/Pages/catalogue.aspx (last accessed July 11, 2018). The ICAO CAEP/10 report is found on page 27 of the English Edition 2018 catalog and is copyright protected; Order No. 10069. The summary of technological feasibility and cost information is located in Appendix C (starting on page 5C-1) of this report. On page 5C-13, the cases analyzed by CAEP are defined. Case 1 is also named the new type design and in-production airplane applicability case - full technology response/out of production case. Case 1 is the analysis of the ten SOs at the agreed implementation dates (2020 and 2023; and, subsequently additional sensitivity analyses were conducted for 2025 and 2028), using all technology responses defined by CAEP, and with airplanes assumed to go out of production at the implementation dates if they cannot be made compliant to a stringency option level. Case 4 is also named the new type design-only applicability case - alternative response/production case: Case 4 is the analysis of the ten SOs at the agreed implementation dates for new type design-only applicability using responses informed by

Also, CAEP characterized these fuel savings as negative fuel costs, as shown in Figure 2-8 below. (Note, the 10 stringency options CAEP analyzed are discussed later in Chapter 6 of this TSD.) The results of Figure 2-8 show that the international standards (SO7) for in-production airplanes provided about $125 billion in fuel savings (labeled as 2028-Case-1 and in negative 2010$ billions by CAEP in Figure 2-8).[xlvii] As described earlier, SO3 would apply to airplanes less than or equal to 60 tonnes MTOM, and thus, according to CAEP's approach in their analysis, the fuel savings would be less than $25 billion (in 2010$).

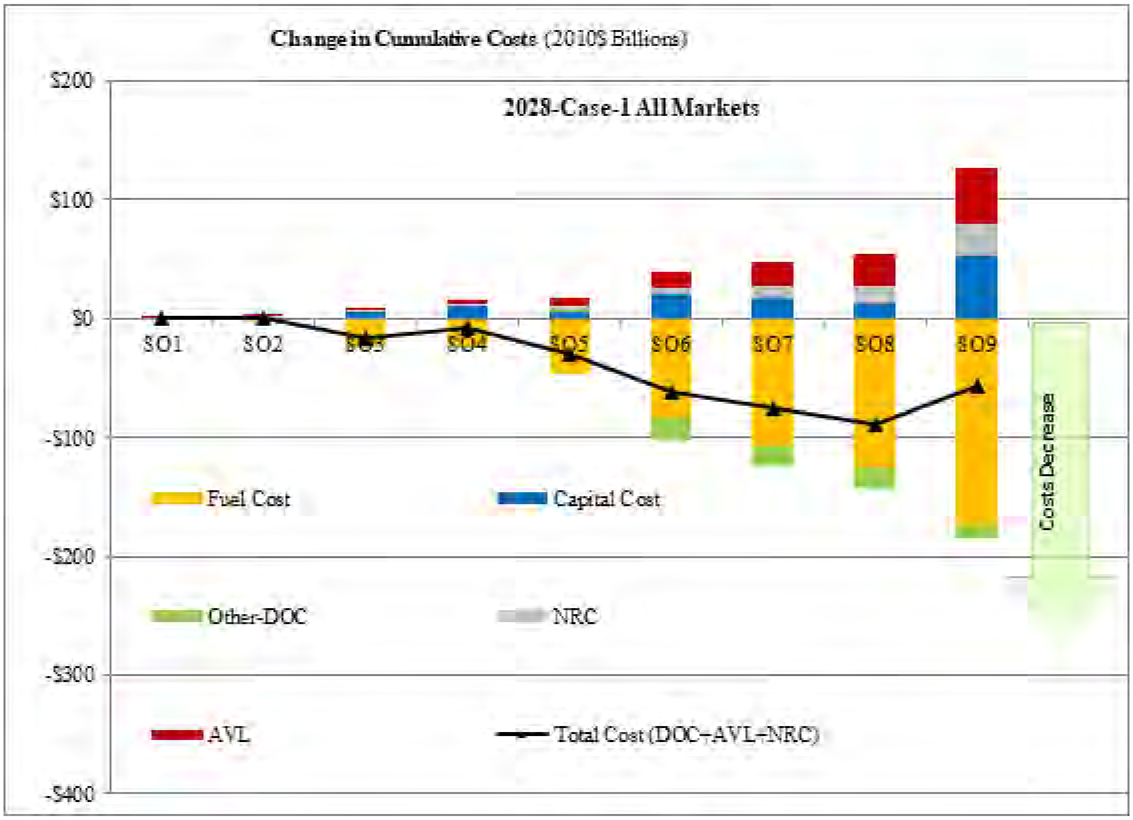


**Figure 2-8. CAEP Change in Cumulative Costs for 2028 Effective Date[xlviii,xlix]**

For Figure 2-8, the yellow bars represent fuel costs, and since these fuel costs are negative, they are fuel savings. AVL means owner /operator asset value loss. Other-DOC includes crew, maintenance landing and route costs.

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market considerations, since manufacturers would not have a legal requirement to bring in-production types to levels under a new type design-only standard. Case 4 is a range of response scenarios from a voluntary response similar to Case 1 to an absence of any response by growth and replacement airplanes. Case 4c is a sub-case of Case 4, and it is the analysis of the top 33 percent most likely airplane families to respond to a SO (for each of the ten SOs). Also, the non-compliant families do not respond in Case 4c, but they remain in production.

[xlvii] CAEP used $3 per gallon of jet fuel in their analysis.

[xlviii] The cumulative costs include Total Recurring Direct Operating Costs (DOC), Manufacturer Non-Recurring Costs (NRC) for Technology Response (TR) and Owner /Operator Asset Value Loss (AVL) from the Implementation Year to 2040. Fuel Costs (or fuel savings) are shown in the yellow colored bars.

[xlix] ICAO/CAEP did not provide cost and cost-effectiveness results for its stringency option 10, and thus, this option was not analyzed by ICAO/CAEP in the manner the other nine stringency options were analyzed.

**Technology and Cost**

The primary difference in the results between the EPA and ICAO analyses is due to the 2016/2017 fixed technology baseline (without continuous improvement and without considering the expected end of production of airplanes) in the CAEP analysis. For a further description of the rationale on the fuel savings difference in the EPA analysis results and CAEP results, see the earlier discussion on costs in this chapter. In addition, refer to Chapter 5 that further discusses the differences between the EPA and CAEP methods and assumptions for modeling emission reductions and fuel savings.[1]

## 2.7 Fuel Prices

The jet fuel price is not central to the EPA analysis, nor will it provide substantially different results. The EPA analysis is based on demonstrated technology by 2017, and the projected business-as-usual incorporation of this technology on airplanes out to 2040 (continuous annual improvement). Also, we estimated the end of production of airplanes based on the expected business as usual status of airplanes. For lower jet fuel prices, older in-production airplanes will likely be flown longer, and fleet renewal will slow.[44] However, as described later in Chapter 5, we have a sensitivity analysis case that shows the results of extending production for some airplanes. Also, in Chapter 5, we discuss a sensitivity analysis case without continuous metric value improvement that shows the effect of less technology application in the fleet. For higher jet fuel prices, there is typically an increase in new airplane (or redesign) launches as well as incremental upgrades. However, there were recently numerous redesigns to airplanes, as well as incremental upgrades, and we believe the prospects for such improvements will be low in the next 10 to 15 years. In any event, these recent improvements and the case of higher fuel prices will only ensure the final standards will have even less effect (due to market forces).

## 2.8 Summary of Benefits and Costs

ICAO intentionally established its standards, which match the final standards, at a level which is technology following to adhere to its definition of technical feasibility that is meant to consider the emissions performance of in-production and in-development airplanes, including types that would first enter into service by about 2020. Independent of the ICAO standards nearly all airplanes produced by U.S. manufacturers will meet the ICAO in-production standards in 2028 due to business-as-usual market forces on continually improving fuel efficiency. The cumulative fuel efficiency improvement of the global airplane fleet was 54 percent between 1990 and 2019, and over 21 percent from 2009 to 2019, which was an average annual rate of 2 percent.[45] Business-as-usual improvements are expected to continue in the future. The manufacturers anticipation of future ICAO standards will be another factor for them to consider in continually improving the fuel efficiency of their airplanes. Thus, all airplanes either meet the stringency levels, are expected to go out of production by the effective dates, or will seek exemptions from the GHG standard. Therefore, there will be no costs and no additional benefits from complying with these final standards – beyond the benefits from maintaining consistency or harmonizing with the international standards and preventing backsliding by ensuring that all new type design and in-production airplanes are at least as fuel efficient as today's airplanes.

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[1] For example, the EPA assumes the Airbus A380 will stop production before 2030, but CAEP assumes it will be in production until 2040.

# Appendix A. – Airframe Technologies

During the evaluation of MV benefit for each technology, ICF determined a range of possibilities of the MV benefit improvement for each technology, because the same technology provides different levels of MV benefit depending on each airplane size category. Subsequently, ICF determined where within the boundary the MV improvement is for each airplane size category. For airplane categories where the technology would not yield much benefit, it was categorized as (-), and ICF determined the benefit to be at lowest boundary of the MV benefit improvement range. On the other hand, where the technology would be most beneficial for the airplane size category, it was categorized as (+), and it was determined the benefit to be at the highest boundary of the MV benefit improvement range. Finally, airplane size categories in between were categorized as (=), for which the average of the minimum value and the maximum value of the MV improvement range was used.

For example, variable camber trailing edge is predicted to produce between 0.5 - 3.0% of MV improvement. For turboprops and regional jets, we do not expect this technology to provide significant benefit; therefore, they were categorized as (-), which means 0.5% MV improvement. For small twin aisle, large twin aisle, and large quad, this technology provides significant benefit due to their sizes; therefore, they were categorized as (+), which means a 3.0% MV improvement. Finally, for single aisle airplane it only provides moderate benefit; therefore, it was categorized as (=), which means the average of a 0.5% MV improvement and a 3.0% MV improvement, and this results in a 1.75% MV improvement.

## Technology and Cost

**Table 2-14 Fuel Burn and Costs Impacts for Advanced Wingtip Devices[46,47]**

| | Sources | Small BGA | Large BGA | Turbo-prop | Regional Jet | Single Aisle | Small Twin | Large Twin | Large Quad |
|---|---|---|---|---|---|---|---|---|---|
| **Fuel Burn** | • Blended winglets achieve 3-5% fuel burn improvements over non-winglet aircraft<br>• New winglet technologies, such as split wingtips and Aviation Partners Boeing "Scimitar" winglets can yield 1-3% improvement compared to current generation winglet technologies<br>• Winglets on 737MAX will offer 1-1.5% fuel burn improvement compared to 737NG blended winglets, depending on results of investigations into natural laminar flow | = | = | = | = | = | = | = | = |
| | | 3.5% | 3.5% | 3.5% | 3.5% | 3.5% | 3.5% | 3.5% | 3.5% |
| | | | | 2015 | 2018 | 2020 | 2023 | 2028 | 2030 |
| | | Commercial Feasibility | | 5% | 10% | 14% | 20% | 30% | 38% |
| | | Technical Feasibility | | 100% | 100% | 100% | 100% | 100% | 100% |
| | | Estimated Total NRC ($M) by Aircraft Category | | | | | | | |
| **Cost Impact** | • Used publicly available pricing and interview input to determine price of current technology winglets<br>• Assumed next-generation winglets will have 10% increased price<br>• NRC estimated based on interview input and some scaling relative to aircraft size<br>• Advanced wingtip device NRC was used as a data point to scale other technology NRCs | $98 | $124 | $111 | $121 | $150 | $222 | $264 | $325 |

**Table 2-15 Fuel Burn and Costs Impacts for Adaptive Trailing Edge**

| | Sources | Small BGA | Large BGA | Turbo-prop | Regional Jet | Single Aisle | Small Twin | Large Twin | Large Quad |
|---|---|---|---|---|---|---|---|---|---|
| **Fuel Burn** | • A full variable camber trailing edge would allow reduced structural weight due to load alleviation, as well as reduced control sizing and more efficient cruise configurations<br>• Scaled benefit from adaptive trailing edge given aircraft manufacturer input and ICF analysis<br>• Fuel burn reduction mechanism: induced drag reduction | X | + | - | - | = | + | + | + |
| | | 0.0% | 2.0% | 0.5% | 0.5% | 1.3% | 2.0% | 2.0% | 2.0% |
| | | | | **2015** | **2018** | **2020** | **2023** | **2028** | **2030** |
| | | Commercial Feasibility | | 0% | 0% | 4% | 10% | 15% | 17% |
| | | Technical Feasibility | | 0% | 0% | 50% | 100% | 100% | 100% |
| | | **Estimated Total NRC ($M) by Aircraft Category** | | | | | | | |
| **Cost Impact** | • Relative scaling "check" to reflect value of increased fuel savings<br>• NRC estimates scaled relatively from known data points on program NRC scale | $148 | $188 | $168 | $184 | $228 | $338 | $401 | $493 |

**Table 2-16 Fuel Burn and Costs Impacts for Aft Body Redesign**

| | Sources | Small BGA | Large BGA | Turbo-prop | Regional Jet | Single Aisle | Small Twin | Large Twin | Large Quad |
|---|---|---|---|---|---|---|---|---|---|
| Fuel Burn | • Fuel burn reduction mechanism: induced drag reduction | - | = | = | = | = | = | = | = |
| | | 1.0% | 1.3% | 1.3% | 1.3% | 1.3% | 1.3% | 1.3% | 1.3% |
| | | | | 2015 | 2018 | 2020 | 2023 | 2028 | 2030 |
| | | Commercial Feasibility | | 9% | 20% | 28% | 40% | 60% | 68% |
| | | Technical Feasibility | | 90% | 100% | 100% | 100% | 100% | 100% |
| | | Estimated Total NRC ($M) by Aircraft Category | | | | | | | |
| Cost Impact | • Significant design and production change for an aircraft program<br>• Cost increase data scaled relatively to other known modification and checked through interview feedback<br>• NRC estimates scaled relatively from known data points on program NRC scale<br>• Significant NRC related to design and changing production process | $184 | $233 | $209 | $228 | $282 | $419 | $496 | $611 |

**Table 2-17 Fuel Burn and Costs Impacts for Hybrid Laminar Flow Control – Empennage**

| | Sources | Small BGA | Large BGA | Turbo-prop | Regional Jet | Single Aisle | Small Twin | Large Twin | Large Quad |
|---|---|---|---|---|---|---|---|---|---|
| Fuel Burn | • Fuel burn reduction mechanism: skin friction drag reduction<br>• Possible issues with practicality (HLFC requires small ports in aircraft skin that may become frequently clogged in practice) | - | - | - | - | = | + | + | + |
| | | 0.3% | 0.3% | 0.3% | 0.3% | 1.4% | 2.5% | 2.5% | 2.5% |
| | | | | 2015 | 2018 | 2020 | 2023 | 2028 | 2030 |
| | | Commercial Feasibility | | 0% | 3% | 6% | 10% | 15% | 17% |
| | | Technical Feasibility | | 0% | 80% | 100% | 100% | 100% | 100% |
| | | Estimated Total NRC ($M) by Aircraft Category | | | | | | | |
| Cost Impact | • NRC estimates scaled relatively from known data points on program NRC scale | $254 | $324 | $289 | $316 | $391 | $580 | $688 | $847 |

**Table 2-18 Fuel Burn and Costs Impacts for Riblet Coatings**

| | Sources | Small BGA | Large BGA | Turbo-prop | Regional Jet | Single Aisle | Small Twin | Large Twin | Large Quad |
|---|---|---|---|---|---|---|---|---|---|
| Fuel Burn | • Not currently in production, but concept validated<br>• Potential issues with increased maintenance and cleaning costs, and practicality in field<br>• Sources for information included publicly available documents, secondary research, and confirmation from airframe manufacturer interview sources (Gubisch)<br>• Fuel burn reduction mechanism: skin friction drag reduction | - | - | - | - | = | + | + | + |
| | | 0.5% | 0.5% | 0.5% | 0.5% | 1.0% | 1.5% | 1.5% | 1.5% |
| | | | | 2015 | 2018 | 2020 | 2023 | 2028 | 2030 |
| | | Commercial Feasibility | | 0% | 5% | 13% | 25% | 35% | 51% |
| | | Technical Feasibility | | 0% | 50% | 80% | 100% | 100% | 100% |
| | | Estimated Total NRC ($M) by Aircraft Category | | | | | | | |
| Cost Impact | • Riblet coatings would primarily affect manufacturing costs, after initial design NRC is performed to validate concept<br>• Estimates from interviews/ICF team consensus<br>• Unknown impact on maintenance costs<br>• NRC estimates scaled relatively from known data points on program NRC scale according to ICF team judgment | $148 | $188 | $168 | $184 | $228 | $338 | $401 | $493 |

**Table 2-19 Fuel Burn and Costs Impacts for ECS Aerodynamics and On-Demand ECS Scheduling**

| | Sources | Small BGA | Large BGA | Turbo-prop | Regional Jet | Single Aisle | Small Twin | Large Twin | Large Quad |
|---|---|---|---|---|---|---|---|---|---|
| Fuel Burn | • Fuel burn reduction mechanism is drag reduction (Thomson) | = | = | = | = | = | = | = | = |
| | | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% | 0.6% |
| | | | | 2015 | 2018 | 2020 | 2023 | 2028 | 2030 |
| | | Commercial Feasibility | | 8% | 20% | 28% | 40% | 60% | 68% |
| | | Technical Feasibility | | 100% | 100% | 100% | 100% | 100% | 100% |
| | | Estimated Total NRC ($M) by Aircraft Category | | | | | | | |
| Cost Impact | • Assumed that refining ECS system would result in minor charges equal to 0.25% of realized aircraft sale price<br>• Changes are mainly from amortized NRC and additional control electronics<br>• NRC estimates scaled relatively from known data points on program NRC scale •NRC is aerodynamics and software design engineering | $40 | $46 | $43 | $45 | $50 | $68 | $77 | $87 |

# Appendix B. – Engine Technologies

**Table 2-20 Fuel Burn and Costs Impacts for Engine Technologies[li, 48, 49]**

| | Sources | Small BGA | Large BGA | Turbo-prop | Regional Jet | Single Aisle | Small Twin | Large Twin | Large Quad |
|---|---|---|---|---|---|---|---|---|---|
| **Fuel Burn** | • Main reduction mechanisms are Airfoil Aerodynamics and Sealing<br>• Engine manufacturers typically do not charge a premium for engine technology improvements<br>• Modeled as a fixed percentage per year, instead of using commercial or technical probability built up from individual technologies | = | = | - | = | = | = | = | = |
| | | 0.2% /yr | 0.2% /yr | 0.1% /yr | 0.2% /yr | 0.2% /yr | 0.2% /yr | 0.2% /yr | 0.2% /yr |
| | | | | **2015** | **2018** | **2020** | **2023** | **2028** | **2030** |
| | | Commercial Feasibility | | N/A | N/A | N/A | N/A | N/A | N/A |
| | | Technical Feasibility | | N/A | N/A | N/A | N/A | N/A | N/A |
| | | **Estimated Total NRC ($M) by Aircraft Category** | | | | | | | |
| **Cost Impact** | • Engine manufacturers typically do not charge a premium for engine technology improvements<br>• $100M of NRC for every 1% improvement (on single aisle-sized engines) for TRL 6+ | $118 | $200 | $115 | $181 | $270 | $503 | $681 | $720 |

[li] TRL6 means system/subsystem or true dimensional test equipment validated in a relevant environment.

ICF International, *CO2 Analysis of CO2-Reducing Technologies for Aircraft*, Final Report, EPA Contract Number EP-C-12-011, see page 40, March 17, 2015.

# Appendix C. – Example Supply Curves by Airplane Category

Metric value improvement percentage versus estimated non-recurring costs ($million):

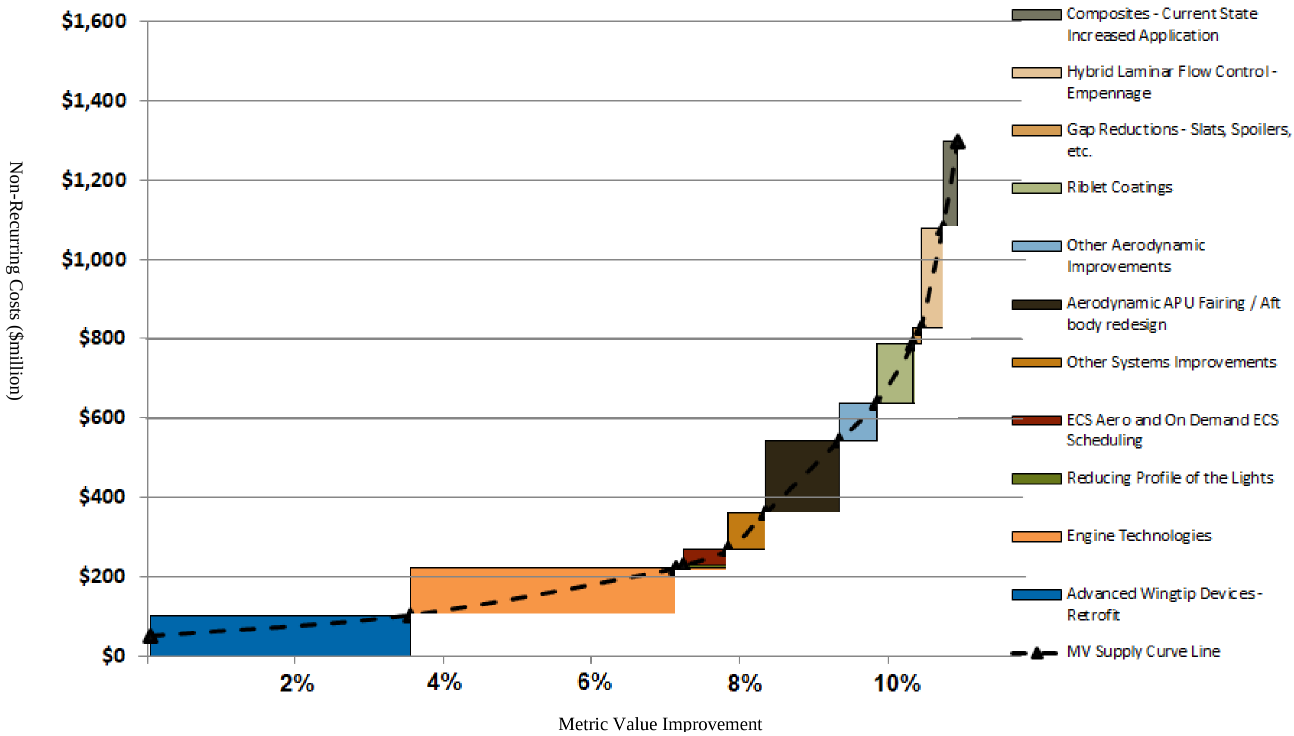


**Figure 2-9 Example Supply Curve for Small BGA**

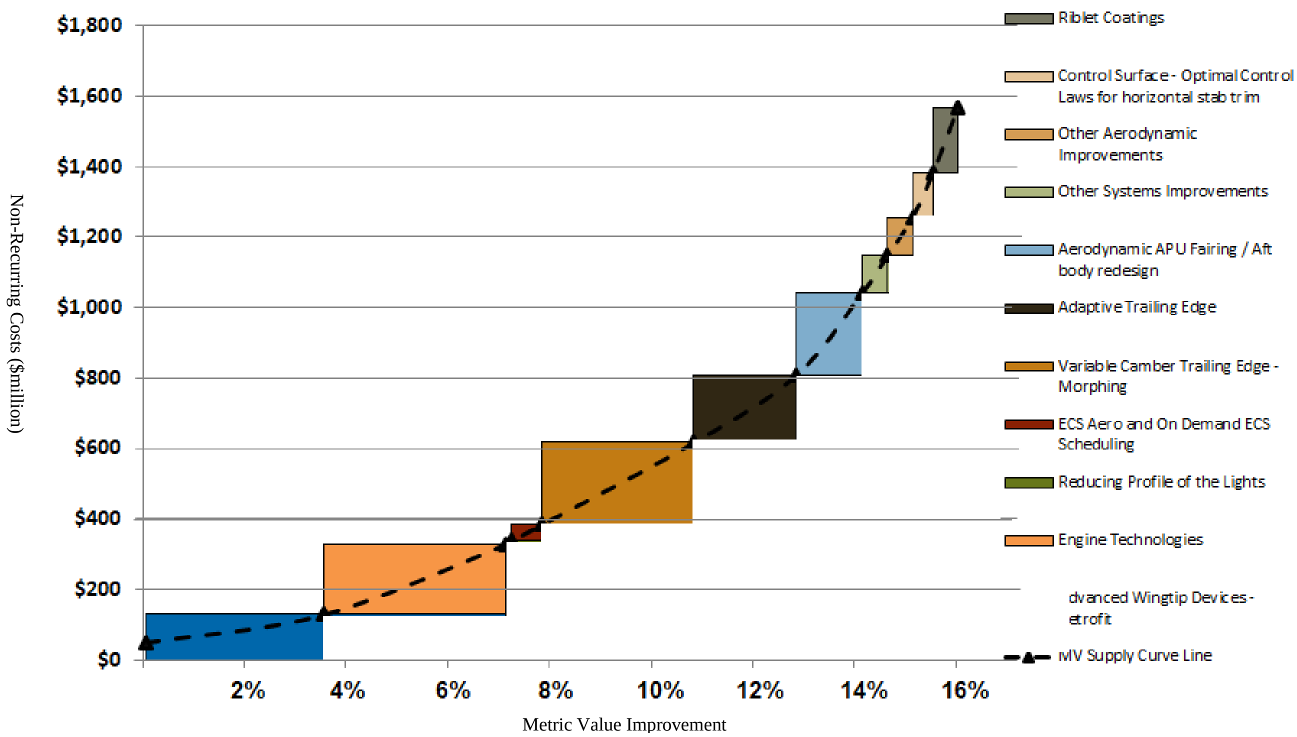


**Figure 2-10 Example Supply Curve for Large BGA**

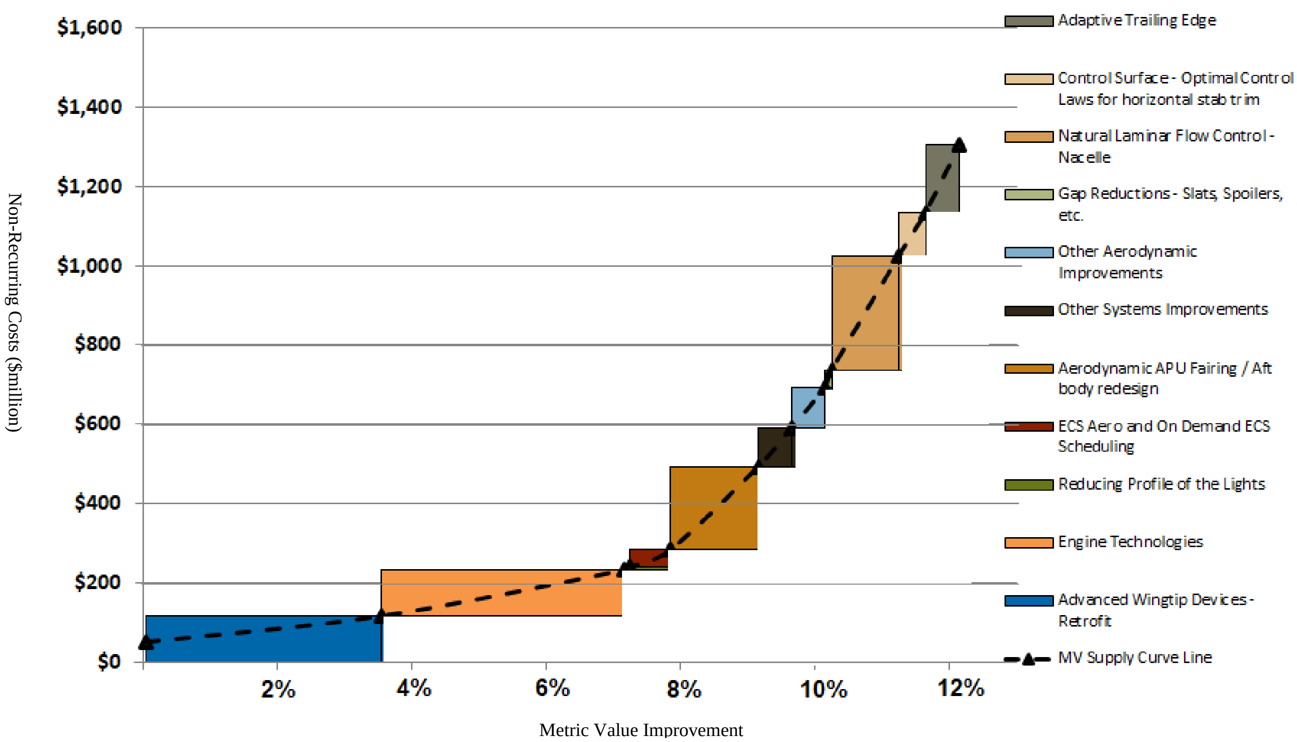


**Figure 2-11 Example Supply Curve for Turboprop**

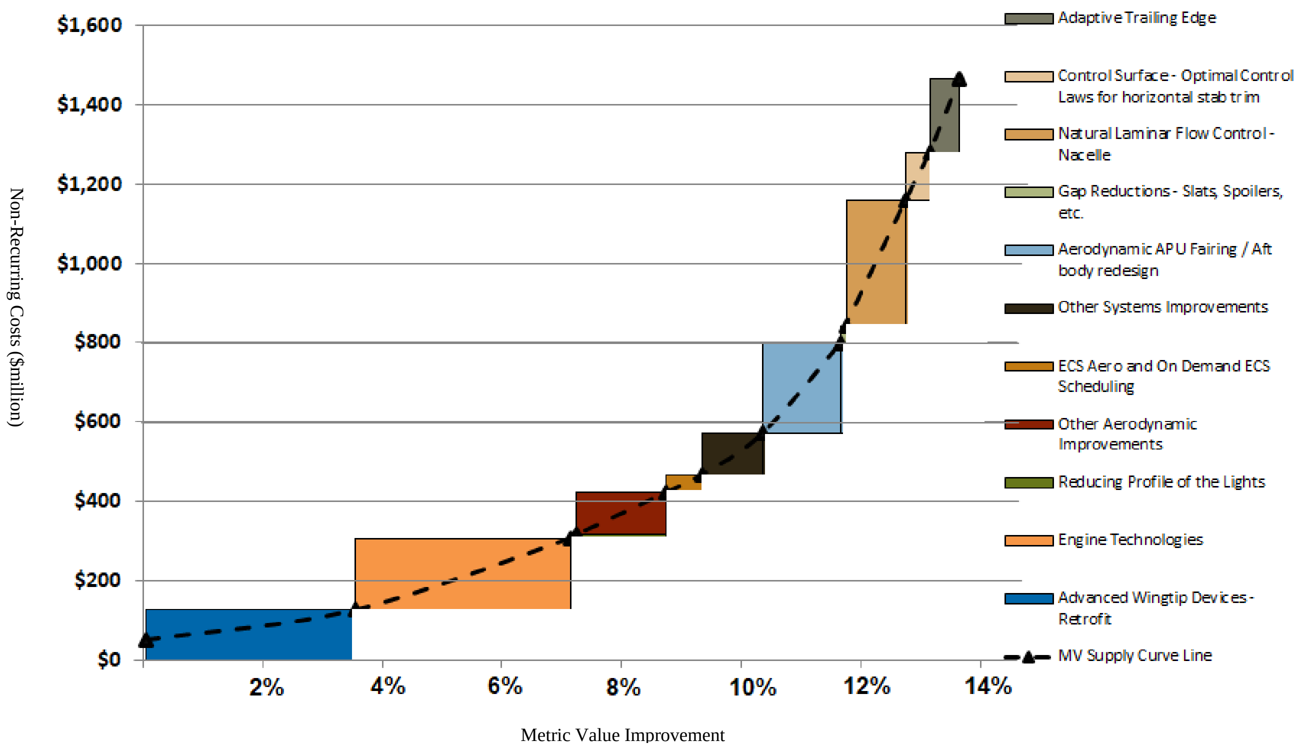


**Figure 2-12 Example Supply Curve for Regional Jet**

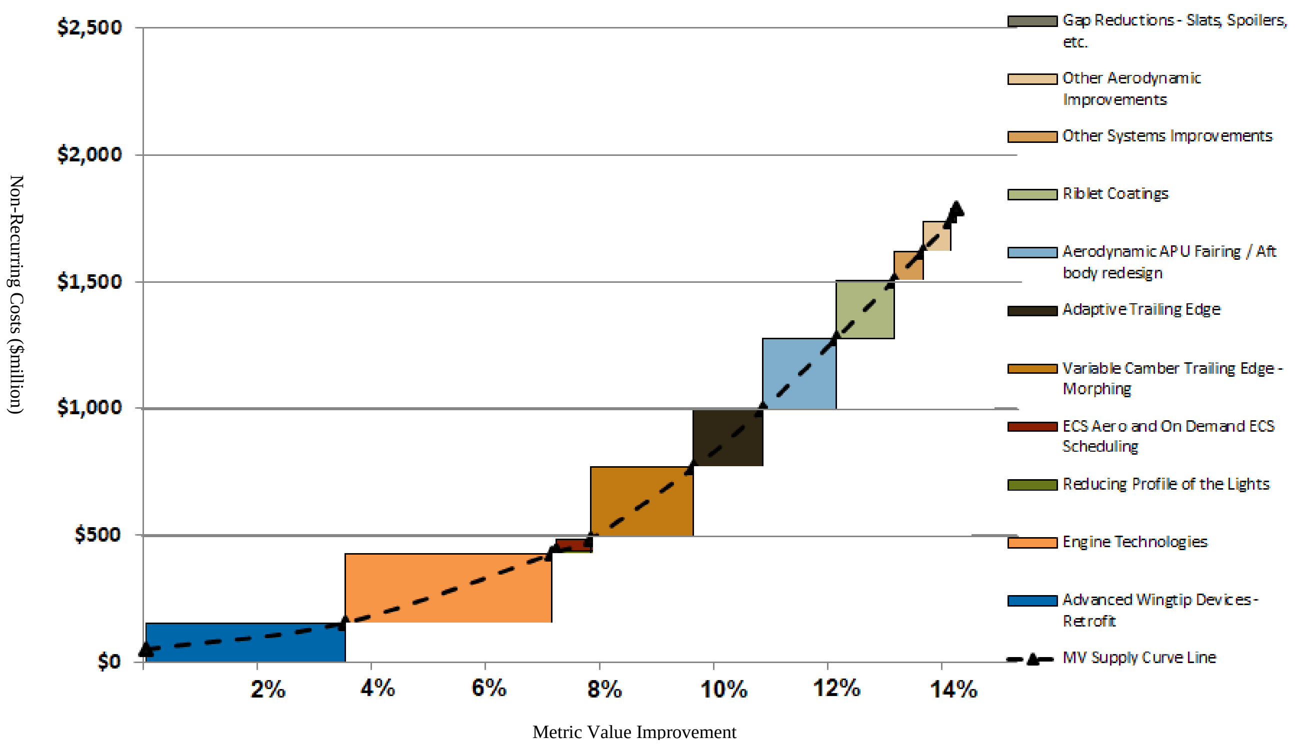


**Figure 2-13 Example Supply Curve for Single Aisle**

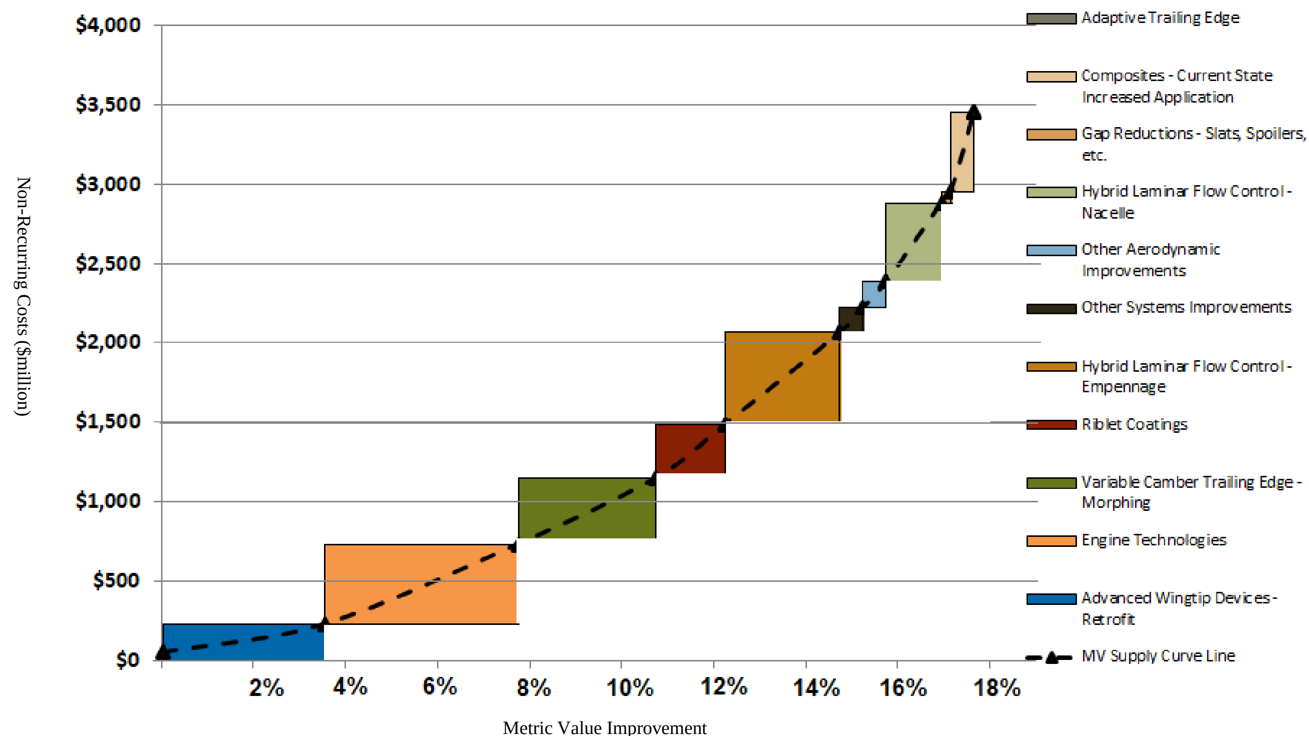


**Figure 2-14 Example Supply Curve for Small Twin Aisle**

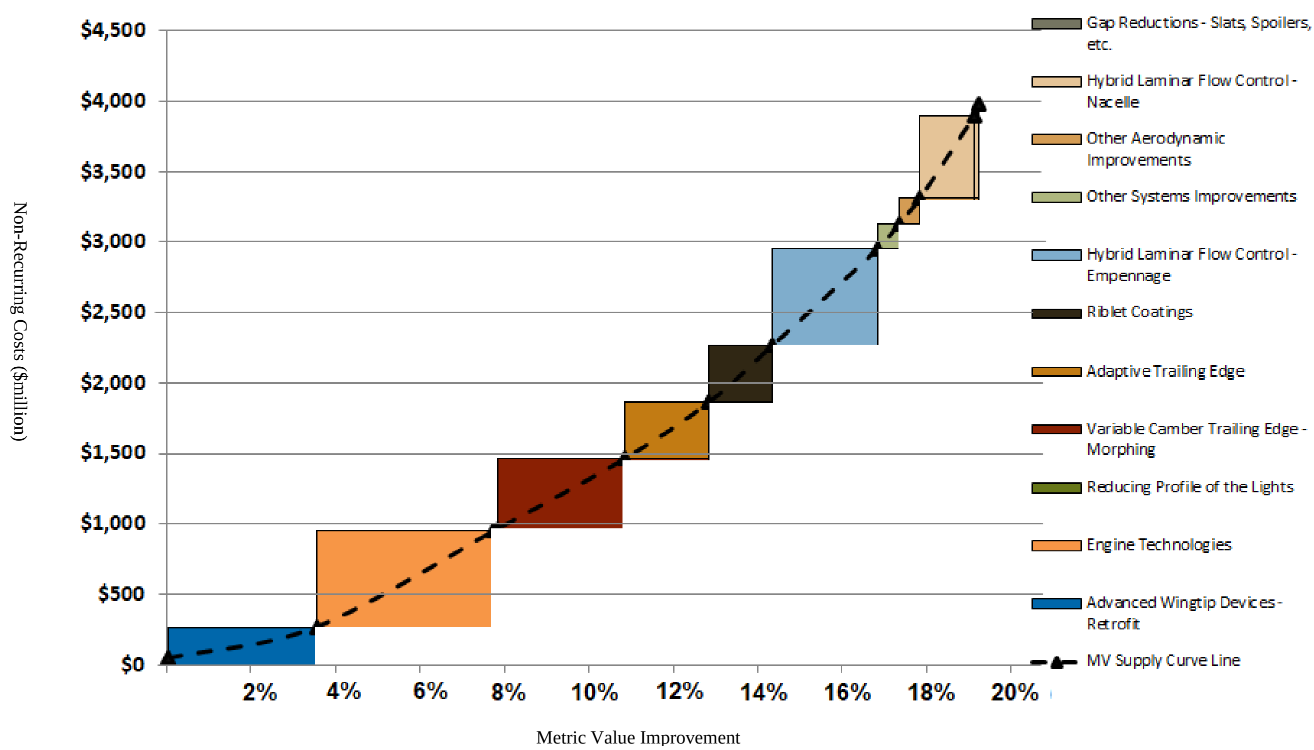


**Figure 2-15 Example Supply Curve for Large Twin Aisle**

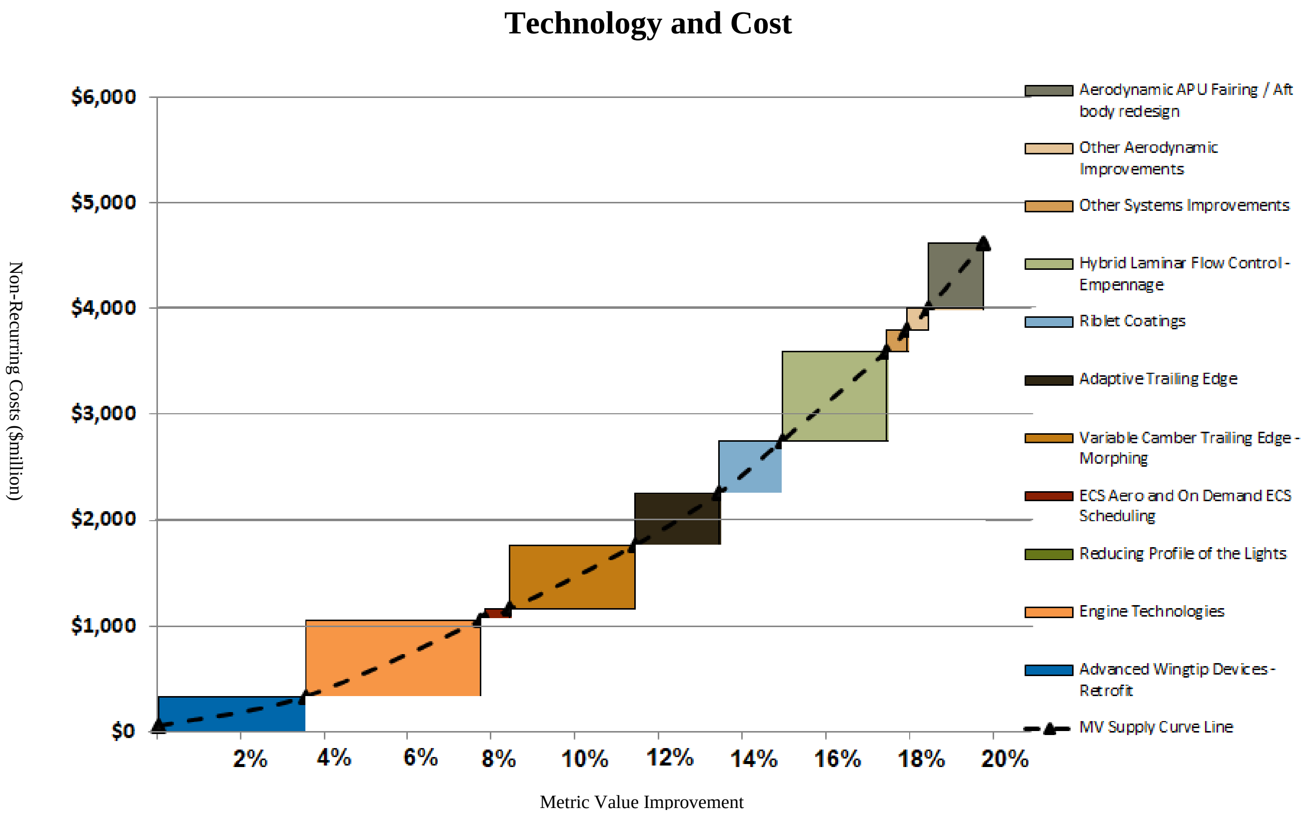


**Figure 2-16 Example Supply Curve for Large Quad**

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[6] ICF, 2018: *Aircraft $CO_2$ Cost and Technology Refresh and Industry Characterization*, Final Report, EPA Contract Number EP-C-16-020, September 30, 2018.
[7] ICF International, 2015: *$CO_2$ Analysis of $CO_2$-Reducing Technologies for Aircraft*, Final Report, EPA Contract Number EP-C-12-011, March 17, 2015.
[8] U.S. EPA, 2015: *Proposed Finding that Greenhouse Gas Emissions from Aircraft Cause or Contribute to Air Pollution that May Reasonably Be Anticipated to Endanger Public Health and Welfare and Advance Notice of Proposed Rulemaking*, 80 FR 37758 (July 1, 2015).
[9] See Reference #7.
[10] See Reference #6.
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[20] See Reference #6.
[21] See Reference #7.
[22] See Reference #6.
[23] See Reference #6.
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[27] See Reference #6.
[28] See Reference #6.
[29] See Reference #6.

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[31] See Reference #6.
[32] See Reference #6.
[33] See Reference #6.
[34] See Reference #6.
[35] See Reference #6.
[36] See Reference #5.
[37] See Reference #7.
[38] See Reference #5.
[39] See Reference #5.
[40] ICAO, 2016: *Tenth Meeting Committee on Aviation Environmental Protection Report*, Doc 10069, CAEP/10, 432 pp, AN/192, Available at: http://www.icao.int/publications/Pages/catalogue.aspx (last accessed March 20, 2020). The ICAO CAEP/10 report is found on page 27 of the English Edition 2020 catalog and is copyright protected; Order No. 10069. The summary of technological feasibility and cost information is located in Appendix C (starting on page 5C-1) of this report.
[41] See Reference #5.
[42] See Reference #6.
[43] See Reference #5.
[44] See Reference #7.
[45] ATAG, 2020: *Tracking Aviation Efficiency, How is the aviation sector performing in its drive to improve fuel efficiency, in line with its short-term goal?* Fact Sheet #3, January 2020. Available at https://aviationbenefits.org/downloads/fact-sheet-3-tracking-aviation-efficiency/ .
[46] See Reference #6.
[47] See Reference #7.
[48] See Reference #6.
[49] See Reference #7.

# Test Procedures

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# Chapter 3: Test Procedures

## 3.1 CAEP Test Procedure Requirements-Overview

Airplane $CO_2$ emissions test procedures were developed at CAEP based on input from manufacturers and regulators. In general, Specific Air Range (SAR) is measured on an engine during flight at three test points. These SAR data represent the distance traveled per unit of fuel burn and are used to determine the international $CO_2$ metric value for the airplane type. Manufacturers' flight test procedures for calculating fuel burn and cruise performance were used as a starting point for development. This input was then standardized to create a consistent procedure for regulatory purposes. Corrections have also been developed to improve data consistency and interoperability of measurements. CAEP has also developed preliminary guidance on equivalent procedures that could be used to meet the requirements. These test procedures and metric are a measure of GHG emissions of airplanes.

## 3.2 Test Procedures for Airplane GHG Emissions Based on the Consumption of Fuel

All flight tests must be conducted in an approved manner to yield the fuel efficiency metric value as described in Section 3.3 below. These procedures shall address the entire flight test and data analysis process from pre-flight actions to post-flight data analysis.

The flight test procedure has been developed based on standard industry practices for determining airplane fuel burn performance. This has been standardized into a regulatory framework.

These test procedures and requirements are described in detail in ICAO Annex 16 Volume III and in ICAO ETM Volume III.

### 3.2.1 <u>Flight Test Method</u>

#### *3.2.1.1 Preflight*

Annex 16 Vol. III §3.2.1 describes the pre-flight procedures that shall be approved by the FAA prior to any certification testing. These requirements include conformity of the airplane to the type design which is to be certificated, procedures to weigh the airplane before and after flight testing, and specifying the fuel used must meet ASTM specification D4809-13 along with when and how to test the fuel.

#### *3.2.1.2 Flight test - A16 §3.2.2*

Flight testing must be conducted in accordance with the requirements outlined in Annex 16 Vol. III Appendix 1 §3.2.2 and §3.2.3. The three test points, described in 3.3.1, must be separated from each other by a minimum of 2 minutes or by a deviation outside of the stability criteria for test points. It is recommended during the collection of SAR data that:

- the airplane should be flown at constant pressure altitude and constant heading;
- the engine thrust/power setting is stable for unaccelerated level flight;
- the airplane is flown as close as practicable to the reference conditions to minimize the magnitude of any corrections;

- there are no changes in trim or engine power/thrust settings, engine stability and handling bleeds, and electrical and mechanical power extraction (including bleed flow). Any changes in the use of aeroplane systems that may affect the SAR measurement should be avoided; and
- movement of on-board personnel is kept to a minimum.

Flight testing should be conducted over a period of not less than 1 minute.

#### *3.2.1.3 Test condition stability*

For SAR measurement data to be valid, the flight test must remain within the tolerances indicated in Annex 16 Vol. III Appendix 1 §3.2.3.

#### *3.2.1.4 Measurement of SAR*

The requirements for measurements and data sampling are described in Annex 16 Vol. III Appendix 1 §4 and ETM Vol. III §3.1.

### 3.2.2 Data Validity

Data validity requirements are described in Annex 16 Vol. III Appendix 1 §6. The 90% confidence interval of the data at the three reference masses shall not exceed 1.5% of the SAR value without approval from the FAA. If clustered data are acquired independently for each of the three gross mass reference points, the minimum sample size acceptable for each of the three gross mass SAR values shall be six. Alternatively, SAR data may be collected over a range of masses. In this case, the minimum sample size shall be 12, and the 90 per cent confidence interval shall be calculated for the mean regression line through the data.

Further information on how to determine data validity is provided in ETM Vol. III §3.3.

#### *3.2.2.1 Reference Conditions & Corrections*

Where the flight test data does not match the reference conditions described in Annex 16 Vol. III §2.5 corrections should be made as described in Annex 16 Vol. III Appendix 1 §5.2. Potential corrections include energy, aeroelastics, altitude, apparent gravity, CG position, power extraction and bleed, deterioration level, fuel spec, Mass Reynolds Number, and Temperature. ETM Vol. III §3.2.2 describes these procedures in detail.

### 3.2.3 Equivalent procedures

Per Annex 16 Vol. III §1.10 equivalent procedures can be used to show compliance to the ICAO Airplane $CO_2$ Emission Standards with the prior approval of the FAA. ETM Vol. III §3.4 provides some initial guidance on procedures that could be used to show compliance with the standard. These must still be approved by the FAA prior to their use.

## 3.3 Determination of the Fuel Efficiency Metric Value

### 3.3.1 Airplane Fuel Efficiency Metric

The metric (shown in Equation 3-1) for the GHG standards (equivalent to ICAO's airplane $CO_2$ emissions metric) uses fuel efficiency as a measure of GHG emissions from airplanes.

**Equation 3-1 – International $CO_2$ Emissions Metric for airplanes**

$$CO_2\ Emissions\ Metric = \left(\frac{1}{SAR}\right)_{avg} \Big/ (RGF)^{0.24}$$

When the international $CO_2$ emissions metric is correlated against airplane mass it has a positive slope. The international Airplane $CO_2$ Emission Standards use MTOM of the airplane as an already certificated reference point to compare airplanes. The $CO_2$ Emissions Evaluation Metric for an airplane is calculated from SAR and a reference geometric factor (RGF) (see Section 3.3.2) using Specific Air Range. It is expressed in units of kilograms of fuel consumed per kilometer.

Specific Air Range (SAR) is a measure of fuel efficiency widely used in the airplane industry. It is a measure of distance traveled per fuel consumed and is calculated using Equation 3-2.

**Equation 3-2 – Equation to calculate Specific Air Range of the airplane**

$$SAR = \frac{TAS}{W_f}$$

*Where:*

*TAS is True air speed and Wf is airplane fuel flow*

For the purposes of the international Airplane $CO_2$ Emission Standards, the inverse of SAR is used to calculate the airplane's metric value. 1/SAR values are calculated at each of the three reference airplane mass test points (per Annex 16 Vol. III §2.3):

a) **high gross mass**: 92 per cent maximum take-off mass (MTOM)

b) **mid gross mass**: simple arithmetic average of high gross mass and low gross mass

c) **low gross mass**: (0.45 × MTOM) + (0.63 × ($MTOM^{0.924}$))

At each of these reference points, the airplane is operated at optimum speed and altitude.

The average of the three inverse SAR points will be used to calculate the airplane $CO_2$ metric value for an individual airplane. The EPA using this same procedure to calculate the fuel efficiency metric value.

### 3.3.2 Reference Geometric Factor

The Reference Geometric Factor (RGF) is a non-dimensional measure of the fuselage size of an airplane normalized by 1 square meter. It represents the usable space in the airplane through the shadow area of the airplane's pressurized passenger compartment. This is defined by Annex 16 Vol. III App. 2. Figure3-1 and Figure3-2 show what is included in RGF.

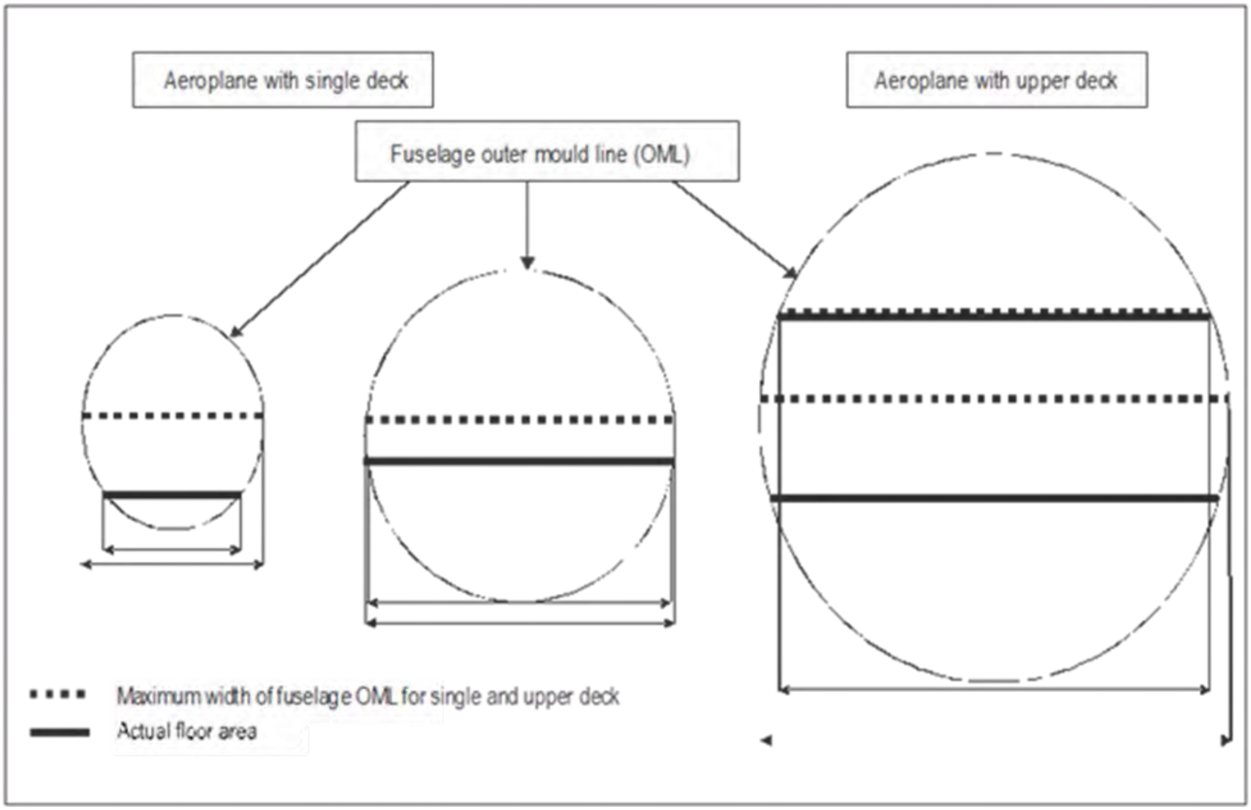


**Figure3-1 – Crossectional View**

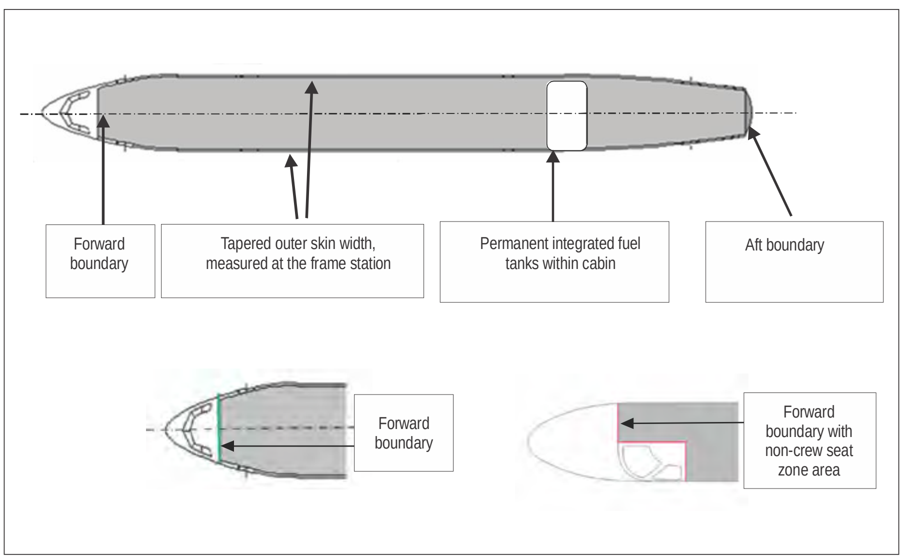


**Figure3-2 – Longitudinal View**

## 3.4 Application of Rules for New Version of an Existing GHG-Certificated Airplane

Under the international $CO_2$ standards, a new version of an existing $CO_2$-certificated airplane is one that incorporates modifications to the type design that increase the MTOM or increase its $CO_2$ Metric Value more than the No-$CO_2$-Change Threshold (described in 3.4.1 below). ICAO's standards provide that once an airplane is $CO_2$ certificated, all subsequent changes to that airplane must meet at least the $CO_2$ emissions regulatory level (or $CO_2$ emissions standard) of the parent airplane. For example, if the parent airplane is certificated to the in-production $CO_2$ emissions level, then all subsequent versions must also meet the in-production $CO_2$ emissions level. This also applies to voluntary certifications under ICAO's standards. If a manufacturer seeks to certificate an in-production airplane type to the level applicable to a new type design, then future versions of that airplane must also meet the same regulatory level. Once certificated, subsequent versions of the airplane may not fall back to a less stringent regulatory $CO_2$ level.

To comport with ICAO's approach, if the FAA finds that a new original type certificate is required for any reason, the airplane will need to comply with the regulatory level applicable to a new type design.

In this action, the EPA is establishing provisions for new versions of existing GHG-certificated airplanes that are to the same as the ICAO requirements for the international Airplane $CO_2$ Emission Standards. These provisions will reduce the certification burden on manufacturers by clearly defining when a new GHG metric value must be established for the airplane.

### 3.4.1 <u>No Fuel Efficiency Change Threshold for GHG-Certificated Airplanes</u>

There are many types of modifications that could be introduced on an airplane design that could cause slight changes in GHG emissions (e.g. changing the fairing on a light,[lii] adding or changing an external antenna, changing the emergency exit door configuration, etc.). To reduce burden on both certification authorities and manufacturers, a set of no $CO_2$ emissions change thresholds was developed for the ICAO Airplane $CO_2$ Emission Standards as to when new metric values will need to be certificated for changes. The EPA is adopting these same thresholds in its GHG rules.

Under this rule, an airplane is considered a modified version of an existing GHG certificated airplane, and therefore must recertify, if it incorporates a change in the type design that either (a) increases its maximum take-off mass, or (b) increases its GHG emissions evaluation metric value by more than the no-fuel efficiency change threshold percentages described below and in Figure 3-3[liii]:

[lii] A fairing is *"a structure on the exterior of an aircraft or boat, for reducing drag."* https://www.dictionary.com/browse/fairing

[liii] Annex 16, Volume III, Part 1, Chapter 1. ICAO, 2017: *Annex 16 Volume III – Environmental Protection - Aeroplane $CO_2$ Emissions, First Edition*, 40 pp. Available at: http://www.icao.int/publications/Pages/catalogue.aspx (last accessed July 15, 2020). The ICAO Annex 16 Volume III is found on page 16 of English Edition 2020 catalog and is copyright protected; Order No. AN 16-3. Also see: ICAO, 2020, Supplement No. 6 – July 2020, *Annex 16 Environmental Protection – Volume III – Aeroplane CO2 Emissions, Amendment 1* (20/7/20). 22pp. Available at: https://www.icao.int/publications/catalogue/cat_2020_sup06_en.pdf (last accessed October 27, 2020). The ICAO Annex 16, Volume III, Amendment 1 is found on page 2 of Supplement No. 6; English Edition, Order No. AN16-3/E/01.

- For airplanes with a MTOM greater than or equal to 5,700 kg, the threshold value decreases linearly from 1.35 to 0.75 percent for an airplane with a MTOM of 60,000 kg.
- For airplanes with a MTOM greater than or equal to 60,000 kg, the threshold value decreases linearly from 0.75 to 0.70 percent for airplanes with a MTOM of 600,000 kg.
- For airplanes with a MTOM greater than or equal to 600,000 kg, the threshold value is 0.70 percent.

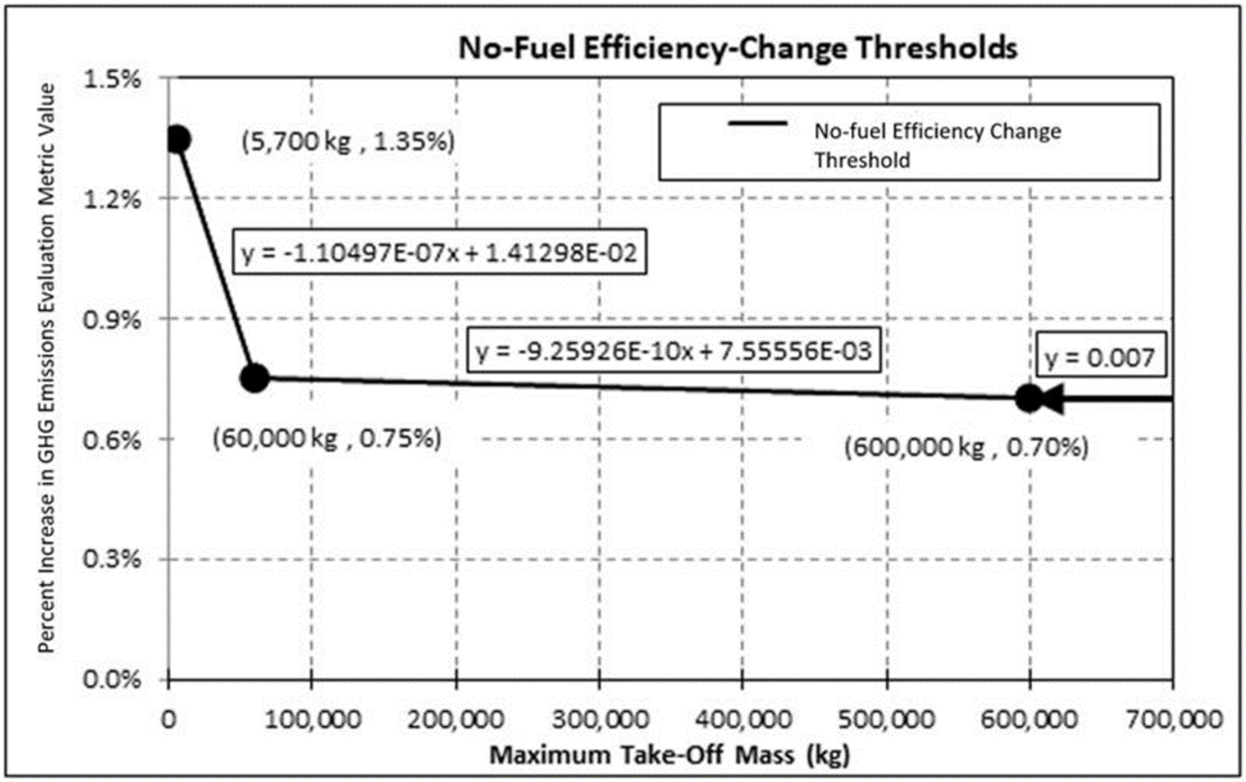


**Figure 3-3 – No Fuel Efficiency Change Thresholds for GHG Certificated Airplanes (ICAO Adopted No $CO_2$ Emissions Change Thresholds)**

The threshold is dependent on airplane size because the potential fuel efficiency changes to an airplane are not constant across all airplanes. For example, a change to the fairing surrounding a wing light, or the addition of an antenna to a small business jet, may have greater impacts on the airplane's metric value than a similar change would on a large twin aisle airplane.

These GHG changes will be assessed on a before-change and after-change basis. If there is a flight test as part of the certification, the metric value (MV) change will be assessed based on the change in calculated metric value of flights with and without the change.

**Test Procedures**

A modified version of an existing GHG certificated airplane will be subject to the same regulatory level as the airplane from which it was modified. A manufacturer may also choose to voluntarily comply with a later or more stringent standard.[liv]

Under this rule, when a change is made to an airplane type that does not exceed the no-change threshold, the fuel efficiency metric value will not change. There will be no method to track these changes to airplane types over time. If an airplane type has, for example, a 10 percent compliance margin under the rule, then a small adverse change less than the threshold may not require the re-evaluation of the airplane metric value. However, if the compliance margin for a type design is less than the No Fuel Efficiency Change threshold and the proposed modification results in a change to the metric value that is less than the no fuel efficiency change threshold, then the airplane retains its original metric value, and the compliance margin to the regulatory limit remains the same. The proposal stated that if the margin to the standard was less than the No Fuel Efficiency Change Threshold that the plane would still be required to demonstrate compliance with the standard. Some commenters pointed out that this language was different than the description adopted by ICAO. To be consistent with ICAO, this language has been corrected.

Under this rule, a manufacturer that introduces modifications that reduce GHG emissions can request voluntary recertification from the FAA. There will be no required tracking or accounting of GHG emissions reductions made to an airplane unless it is voluntarily re-certificated.

The EPA is adopting, as part of the GHG rules, the no-change thresholds for modifications to airplanes discussed above, which are the same as the provisions in the international standard. We believe that these thresholds will maintain the effectiveness of the rule while limiting the burden on manufacturers to comply. The regulations reference specific test and other criteria that were adopted internationally in the ICAO standards setting process.

## 3.5 Changes for non-GHG Certificated Airplane Types

After January 1, 2023, and until January 1, 2028, an applicant that submits a modification to the type design of a non-GHG certificated airplane that increases the Metric Value of the airplane type by greater than 1.5%[lv] will be required to demonstrate that newly produced airplanes comply with the in-production standard. This earlier applicability date for in-production airplane types, January 1, 2023, is the same as that adopted by ICAO and is similarly designed to capture modifications to the type design of non-GHG certificated airplanes newly manufactured (initial airworthiness certificate) prior to the January 1, 2028, production cut-off

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[liv] ETM Vol. III §2.2.3. ICAO, 2018: *Environmental Technical Manual Volume III – Procedures for the $CO_2$ Emissions Certification of Aeroplanes, First Edition, Doc 9501,* 64 pp. Available at: http://www.icao.int/publications/Pages/catalogue.aspx (last accessed July 15, 2020). The ICAO Environmental Technical Manual Volume III is found on page 77 of the English Edition 2020 catalog and is copyright protected; Order No. 9501-3. Also see: *Doc 9501 – Environmental Technical Manual – Volume III – Procedures for the $CO_2$ Emissions Certification of Aeroplanes*, *2nd edition*, 2020.90pp. Available at https://www.icao.int/publications/catalogue/cat_2020_sup06_en.pdf (last accessed October 28, 2020). The ICAO Annex 16, Volume III, 2nd edition is found on page 3 of Supplement No. 6 – July 2020 , English Edition, Order No. 9501 – 3.

[lv] Note that IV.D.1.i, Changes for non-GHG certified Airplane Types, is different than the No GHG Change Threshold described in IV.F.1 below. IV.F.1 applies only to airplanes that have previously been certificated to a GHG rule. IV.D.1.i only applies only to airplane types that have not been certificated for GHG.

date.  The January 1, 2028 production cut-off date was introduced by ICAO as an anti-backsliding measure that gives notice to manufacturers that non-compliant airplanes will not receive airworthiness certification after this date.

An application for certification of a modified airplane type on or after January 1, 2023, will trigger compliance with the in-production GHG emissions limit provided that the airplane's GHG emissions metric value for the modified version to be produced thereafter increases by more than 1.5 percent from the prior version of the airplane type. As with changes to GHG certificated airplane types, introduction of a modification that does not adversely affect the airplane fuel efficiency Metric Value will not require demonstration of compliance with the in-production GHG standards at the time of that change.  Manufacturers may seek to certificate any airplane type to this standard, even if the criteria do not require compliance.

As an example, if a manufacturer chooses to shorten the fuselage of a type certificated airplane, such action will not automatically trigger the requirement to certify to the in-production GHG rule.  The fuselage shortening of a certificated type design would not be expected to adversely affect the metric value, nor would it be expected to increase the certificated MTOM. Manufacturers noted that ICAO included criteria that would require manufactures to recertify if they made “significant” changes to their airplane.  ICAO did not define a “significant change” to a type design.  The EPA did not include this requirement because “significant change” is not a defined term in the certification process.  However, it is expected that manufacturers will likely volunteer to certify to the in-production rule when applying to the FAA for these types of changes, in order to maximize efficiencies in overall airworthiness certification processes (i.e., avoid the need for iterative rounds of certification).This earlier effective date for in-production airplane types is expected to help encourage some earlier compliance for new airplanes.

## REFERENCES

**Airplane Performance Model and Analysis**

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# Chapter 4: Airplane Performance Model and Analysis

## 4.1 Purpose and Scope

This chapter describes methodologies, assumptions and data sources used to develop the airplane emissions and fuel burn inventories for the standards and two alternative stringency scenarios. See chapter 6 for a detailed description of the alternative scenarios. The results of the emissions inventories and stringency analysis are presented in Chapter 5.

The EPA had participated in the Committee on Aviation Environmental Protection (CAEP) to analyze the emission impacts of the ICAO Airplane $CO_2$ Emission Standards. CAEP provided a summary of the results from this analysis in the report of its tenth meeting[50], which occurred in February 2016. However, due to the commercial sensitivity of the data used in the analysis, much of the underlying information is not available to the public. For the U.S. domestic standard, however, we are making our analysis, data sources, and model assumptions transparent to the public so all stakeholders that affected by the standards can understand how the agency derives its decisions. Thus, the EPA has conducted an independent impact analysis based solely on publicly available information and data sources. An EPA report detailing the methodology and results of the emissions inventory analysis[51] was peer-reviewed by multiple independent subject matter experts, including experts from academia and other government agencies, as well as independent technical experts.[52]

The EPA analysis focuses primarily on modeling the U.S. GHG emissions inventory. Because aviation is an international industry, and all major airplane and airplane engine manufacturers sell their products globally, we also model estimated global GHG emissions for reference, but at a much less detailed level for traffic growth and fleet evolution outside of the U.S.

In developing the inputs for our model, we contracted with ICF[11] to conduct an independent airplane/engine technology and cost assessment for the EPA rulemaking analysis. The agency uses this ICF technology and cost forecast as the basis for our impact assessment. We also conducted sensitivity analyses to evaluate the effects of certain model assumptions.

## 4.2 Methodology of the EPA Emissions Inventory and Stringency Analysis

The methodologies the EPA uses to assess the impacts of the standards and alternative stringency scenarios can be summarized in a flow chart shown in Figure 4-1. Essentially, the approach is to develop a baseline emissions inventory which represents the business as usual case in the absence of standards. This baseline inventory was then compared with three “stringency” scenarios, representing the standards and two alternative scenarios.

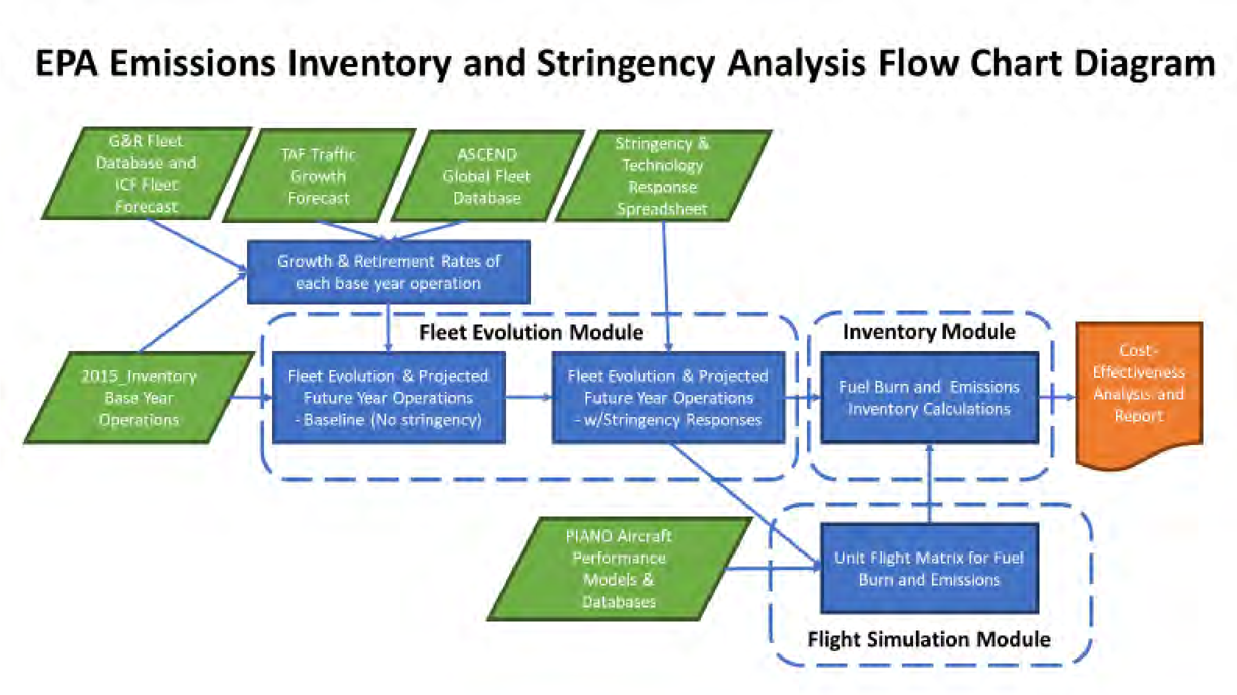


**Figure 4-1 – Regulatory Analysis Flow Chart**

The first step of the EPA analysis is to develop an inventory baseline by evolving the base year operations to future year operations emulating the market driven fleet renewal process without any stringency requirements. This "no stringency" baseline is developed for the analysis period of 2015 to 2040. Our approach to developing the baseline is to estimate the growth and retirement rates of future year operations based on flights with unique route (origin-destination or OD-pair) and airplane combinations in the base year operations. The growth and retirement rates for each of the unique base year operations determine the future year market demand which is then allocated to available airplanes in a Growth and Replacement (G&R) database[53]. The growth and retirement rates over the analysis period are obviously a function of macroeconomic factors like fuel price, materials prices and economic growth. These economic factors are not considered explicitly in our analysis, but they are embedded in the traffic growth forecast and retirement rates data as inputs to the EPA analysis. Together with the residual operations from the base year airplanes, these G&R operations constitute all the operations of in-service fleet for every future year. The same method is applied to define fleet evolution under various stringency scenarios. The only difference is under the stringency scenarios, technology responses need to be taken into consideration. The airplane impacted by a stringency scenario could either be modified to meet the standards or removed from production without a response. Once the flight activities for all analysis scenarios are defined by the fleet evolution module, fuel burn and GHG emissions inventories for the three stringency scenarios are then modeled with a physics-based airplane performance model known as PIANO[54]. The differences between the baseline and the three stringency scenarios are used for assessing the impacts of the stringency scenarios. The computational processes are grouped into three distinct modules as shown in Figure 4-1. More detailed accounts of the methods, assumptions, and data sources used for these three computational modules are given below. The results of the fleet evolution, emissions inventories and stringency analyses are discussed in the next chapter.

## 4.3 Fleet Evolution Model and Data Sources

The EPA fleet evolution model focuses on U.S. aviation, including both domestic and international flights. U.S. international flights are defined as flights originating from the U.S. but landing outside the U.S. Flights originating outside the U.S. are not included in the U.S. inventory. The EPA fleet evolution model is based on FAA' 2015 Inventory Database[55] (2015_Inventory) for base year flight activities and FAA's 2015-2040 Terminal Area Forecast[56] (TAF) for future year traffic growth. Section 4.3.1 describes how the base year operations are mapped into the growth forecast database to determine the future year growth rate. Section 4.3.2 describes how the retirement rates of the base year airplanes are determined from the ASCEND global fleet database. Section 4.3.3 describes how the future market demands are allocated to available airplanes for growth and replacement.

### 4.3.1 Mapping Base Year Operation to the Growth Forecast Database

The FAA 2015 Inventory Database is a comprehensive global flight dataset. Its U.S. based flights have been used as part of the high-fidelity data sources for EPA's official annual GHG and Sinks report since 1990[57]. Globally, the 2015 inventory database contains 39,708,418 flights in which 13,508,800 originated from the U.S. Among the U.S. flights, 1,288,657 are by piston engine airplanes, 341,078 are military operations and 1,393,125 are by small airplanes with maximum zero fuel weight[lvi] less than 6000 lbs. In our analysis, we exclude military, piston engine and small light weight airplanes since they are not covered under this rulemaking. Excluding flights for these three non-covered airplane categories, the database still contains 10.3 million flights, 1,992.2 billion available seat kilometers (ASK) and 341.6 billion available tonne kilometers (ATK) in the modeled 2015 U.S. operations.

Likewise, TAF is a comprehensive traffic growth forecast dataset for commercial operations in both U.S. domestic and U.S. international markets. The 2015-2040 TAF used in this analysis contains growth forecasts for both passenger and freighter markets based on origin-destination airport pair and airplane type. In order to determine the growth rate of a base year operation, the base year operation has to be mapped from the 2015 Inventory Database to a corresponding TAF market defined by market type (passenger or freighter), origin-destination airport pair, and airplane type. There is no unique mapping between these two databases. After some iterations by trial and error and consultation with FAA, we have determined that a two-parameter mapping using USAGE-CODE and SERVICE_TYPE works the best.

The two-parameter mapping from the FAA 2015 Inventory Database to TAF for growth rate type identification is shown Table 4-1. USAGE_CODE and SERVICE_TYPE are parameters in the 2015 Inventory database designed to identify the airplane usage category and the service type of a given flight. Possible USAGE_CODEs are P for passenger, B for business, C for cargo, A for attack/combat, and O for other. Possible SERVICE_TYPEs are C for commercial, G for general aviation, F for freighter, M for military, O for other, and T for air taxi. For this analysis, we filter out SERVICE_TYPEs of M (military), O (other), and T (air taxi) and only keep C

[lvi] The maximum zero fuel weight is the maximum permissible weight of an airplane with no disposable fuel or oil. It is used as a prescreening filter to exclude individual airplane from further analysis in the absence of precise maximum takeoff weight information. Maximum takeoff weight thresholds of 5,700 kg for jet airplanes and 8,618 kg for turboprop airplanes are applied by airplane type to limit the analysis to the subset of airplanes covered by the final GHG standards.

(commercial), G (general aviation), and F (freighter). Likewise, for USAGE_CODE, we filter out A (attack/combat) and O (other) but keep P (passenger), B (business) and C (cargo) for this analysis.

Combinations of the remaining USAGE_CODE and SERVICE_TYPE subdivide the total market into nine sub-market categories as shown in Table 4-1. The size of each sub-market category based on the two-parameter mapping is summarized in Table 4-1 to give a sense of their relative contributions to the overall fleet operations by available seat kilometer (TOTAL_ASK), available tonne kilometer (TOTAL_ATK), and number of operations (2015_OPS). In consultation with FAA, these nine sub-markets are mapped into three growth rate types (under the GR_Map column in Table 4-1) for the purpose of determining their growth rate forecast for future year operations. Again, in GR_Map, G is for general aviation, F is for freighter and P is for passenger. For U.S. passenger (P) and freighter (F) operations, TAF is used to determine the growth rates for U.S. origin-destination (OD) pairs and airplane types from 2015 to 2040.

**Table 4-1 – Two-parameter mapping from 2015 Inventory database to Growth Rate forecast databases**

| USAGE_CODE | SERVICE_TYPE | GR_Map | TOTAL_OPS | TOTAL_ASK | TOTAL_ATK |
|---|---|---|---|---|---|
| B – Business | C – Commercial | G – General | 5.8148E+05 | 4.5898E+09 | 9.8501E+08 |
| B | F – Freight | F – Freight | 6.4350E+03 | 1.4580E+06 | 1.1399E+07 |
| B | G – General | G | 1.3937E+06 | 1.3166E+10 | 2.8144E+09 |
| C – Cargo | C | F | 2.2645E+05 | 2.8492E+10 | 3.7362E+10 |
| C | F | F | 4.7665E+05 | 5.2309E+09 | 6.6587E+10 |
| C | G | G | 9.6400E+03 | 6.1929E+08 | 1.8029E+09 |
| P – Passenger | C | P - Passenger | 2.7432E+07 | 7.0697E+12 | 1.0836E+12 |
| P | F | F | 3.1517E+05 | 8.8414E+10 | 2.6023E+10 |
| P | G | G | 4.1658E+06 | 1.2560E+12 | 2.0427E+11 |

In mapping the base year operations to TAF to determine their corresponding growth rate, if there are exact OD-pair and airplane matches between the two databases, the exact TAF year-on-year growth rates are applied to grow 2015 base year operations to future years. For cases without exact matches, the growth rates of progressively higher-level aggregates will be used to grow the future year operations.[56] For example, if there is no match in exact origin-destination airport pair, the airport pair will be mapped to a route group (either domestic or international), and the growth rate of the route group will be used instead to grow the operation. If there is no match in airplane type (e.g., B737-8 MAX, B777-9X, etc.), the airplane category (e.g., narrow body passenger, wide body freighter, etc.) as defined in the TAF will be used to map the growth rate.

Since general aviation is not covered in TAF, we use the forecasted growth rate of 1.6% for all turboprop operations based on the FAA Aerospace Forecast (Fiscal Year 2017-2037)[58]. For U.S. business jet operations, we use the 3% compound annual growth rate published in the same FAA Aerospace Forecast (Fiscal Year 2017-2037).[58]

For non-U.S. flights, we use an average compound annual growth rate of 4.5% for all passenger operations and 4.2% for all freighter operations based on ICAO long-term traffic forecast for passenger and freighters. [59] For non-U.S. business jet operations, we use the global average growth rate of 5.4% based on Bombardier's Business Aircraft Market Forecast 2016-2025.[60]

Given the classification of the two-parameter mapping table, we have determined that the eighth row of the mapping table (where the USAGE_CODE = "P" and SERVICE_TYPE = "F") is converted freighters which are freighters converted from used passenger airplanes after the end of their passenger services. These converted freighters are not subject to the GHG standards, so they are excluded from all inventory data reported in this TSD.

### 4.3.2 Retirement Rate

The retirement rate of a specific airplane is determined by the age of the airplane and the retirement curve associated with the airplane category. The retirement curve is the cumulative fraction of retirement expected as the airplane ages. It goes from 0 to 1 as the airplane age increases. The retirement curves can be expressed as a Sigmoid or Logistic function in the form of

**Equation 4-1 – Retirement Curve Equation**

$$\boldsymbol{RC}(\boldsymbol{x}) = \mathbf{1}/(\mathbf{1} + \boldsymbol{e}^{\boldsymbol{a}-\boldsymbol{b}\boldsymbol{x}})$$

*where RC is the retirement curve function, a and b are coefficients that change with airplane category and x is the age of the airplane.*

The reason to choose this type of retirement function is because it is a well-behaved function that matches well with historical retirement data of known airplane fleet. Figure 4-2 illustrates the characteristic "S" shape of a historical survival curve, SC(x), where SC(x) = 1 – RC(x). Note that the ratio of the two coefficients in Equation 4-1, i.e., a/b, represents the half-life of the airplane fleet where 50% of the fleet survives and 50% retires. The slope of the retirement curve (or percent retired per year) at half-life is b/4. So, the larger the coefficient b is, the higher the rate of retirement will be at half-life. The retirement curve is also an antisymmetric function with respect to x = a/b and has long tails at both ends of the age distribution (very young and very old airplanes in the fleet).

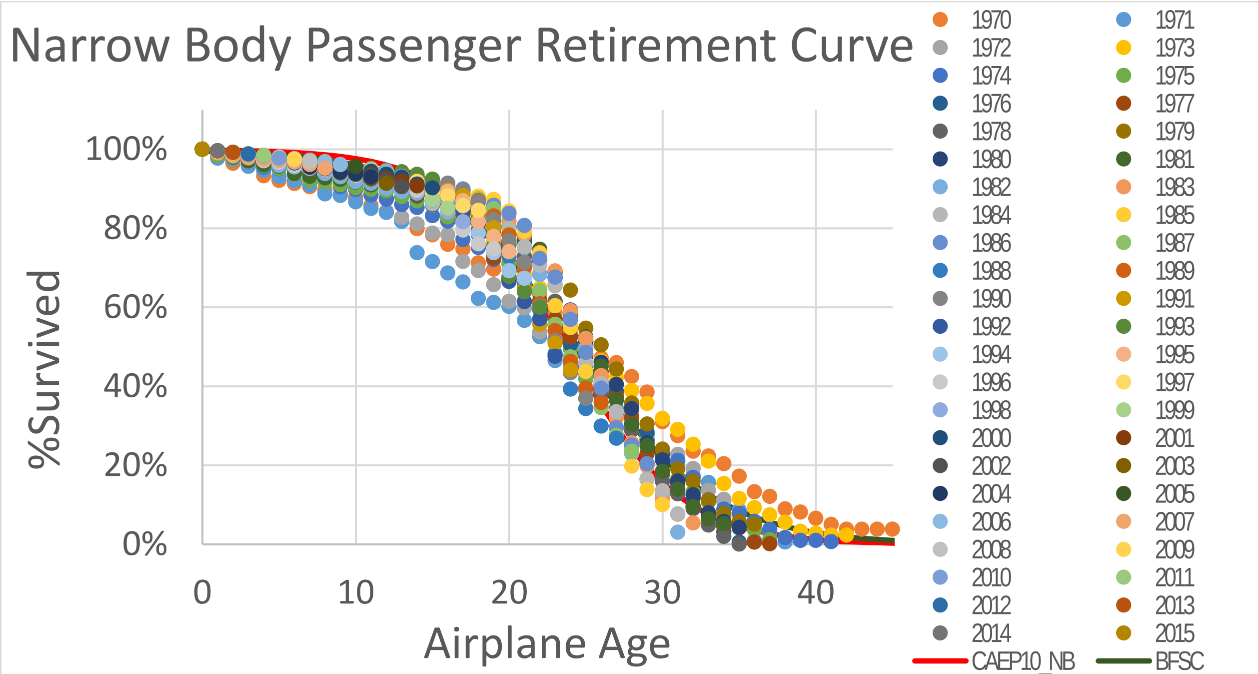


**Figure 4-2 – The Retirement Curve of Narrow–Body Passenger Airplane Based on Ascend[61] fleet data**

Retirement curves of major airplane categories used in this EPA analysis are derived statistically based on data from the FlightGlobal's Fleets Analyzer database[61] (also known as ASCEND Online Fleets Database -- hereinafter "ASCEND"). Table 4-2 lists the numerical values of these coefficients in the retirement curves for major airplane categories. The retirement curves so established are consistent with published literature from Boeing and Avolon in terms of the economic useful life of airplane categories. However, it is recognized from other sectors (e.g., light duty vehicles) that the retirement curves are not necessarily exogenously fixed but rather a function of the relative price of new versus used vehicles; fuel prices; repair costs; etc. Furthermore, when regulations are vintage differentiated (i.e., when new vehicles are subject to stricter requirements than older vintages), it has been shown that the economically useful life of the existing fleet can be extended. The higher cost and sometimes diminished performance of compliant new vehicles makes it economically worthwhile to extend the life of older vehicles that would otherwise have been retired. These extraneous factors, however, are not considered in this analysis.

**Table 4-2 – Retirement Curve coefficients by airplane category**

| Airplane_Category | Description | a | b |
|---|---|---|---|
| BJ | Business Jet | 6.265852341 | 0.150800149 |
| LQ | Large Quad | 5.611526057 | 0.223511259 |
| LQF | Large Quad Freighter | 6.905900732 | 0.205267334 |
| RJ | Regional Jet | 4.752779141 | 0.178659236 |
| SA | Single Aisle | 5.393337195 | 0.222210782 |
| SAF | Single Aisle Freighter | 6.905900732 | 0.205267334 |
| TA | Twin Aisle | 5.611526057 | 0.223511259 |
| TAF | Twin Aisle Freighter | 6.905900732 | 0.205267334 |
| TP | Turboprop | 3.477281304 | 0.103331799 |

For each operation in the base year database (2015 Inventory), if the airplane tail number is known, the retirement rate is based on exact age of the airplane from the ASCEND global fleet database. If the airplane's tail number is not known, the aggregated retirement rate of the next level matching group (e.g., airplane category or airplane 'type' as defined by ASCEND) will be used to calculate the retirement rates for future years.

### 4.3.3 Calculating Future Year Growth and Replacement Market Demands

Combining the growth and retirement rates together, we can determine the total future year market demands for each base year flight. These market demands are then allocated by equal product market share[lvii] to available G&R airplanes competing in the same market segment as the base year flight. The available G&R airplanes for various market segments are based on the technology responses developed by ICF, as described in Chapter 2 of the TSD.[62] The G&R airplanes in each market segment are listed in Table 4-3. ICF technology responses also include detailed information about the entry-into service year and the end-of-production year for each current and future in-production airplane out to 2040.

[lvii] EPA uses equal product market share (for all airplanes present in the G&R database), but attention has been paid to make sure that competing manufacturers have reasonable representative products in the G&R database.

**Table 4-3 – The G&R airplane available in each market segment**

| Market Segment | Description | G&R Airplane |
|---|---|---|
| CBJ | Corporate Jet | A318-112/CJ, A319-133/CJ, B737-700IGW (BBJ), B737-8 (BBJ) |
| FR | Freighter | A330-2F, B747-8F, B767-3ERF, B777-2LRF, TU204-F, AN74-F/PAX, B777-9xF, A330-800-NEOF |
| LBJ | Large Business Jet | G-5000, G-6000, GVI, GULF5, Global 7000, Global 8000 |
| MBJ | Medium Business Jet | CL-605, CL-850, FAL900LX, FAL7X, ERJLEG, GULF4 |
| RJ_1 | Small Regional Jet | CRJ700, ERJ135-LR, ERJ145, MRJ-70 |
| RJ_2 | Medium Regional Jet | CRJ900, ERJ175, AN-148-100E, AN-158, EJ-175 E2 |
| RJ_3 | Large Regional Jet | CRJ1000, ERJ190, ERJ195, RRJ-95, RRJ-95LR, TU334, MRJ-90, ERJ-190 E2, ERJ-195 E2 |
| SA_1 | Small Single Aisle | A318-122, A319-133, B737-700, B737-700W, A319-NEO, B737-7MAX, CS100, CS300, MS-21-200 |
| SA_2 | Medium Single Aisle | A320-233, B737-800, B737-800W, A320-NEO, B737-8MAX, MS-21-300, C919ER |
| SA_3 | Large Single Aisle | A321-211, B737-900ER, B737-900ERW, TU204-300, TU204SM, TU214, A321-NEO, B737-9MAX |
| SBJ_1 | Small Business Jet_1 | CNA515B, CNA515C, EMB505, PC-24 |
| SBJ_2 | Small Business Jet_2 | Learjet 40XR, Learjet 45XR, Learjet 60XR, CNA560-XLS, Learjet 70, Learjet 75 |
| SBJ_3 | Small Business Jet_3 | CNA680, GULF150, CNA680-S |
| SBJ_4 | Small Business Jet_4 | CL-300, CNA750, FAL2000LX, G280, CNA750-X |
| TA_1 | Small Twin Aisle | A330-203, A330-303, B767-3ER, B787-8, A330-800NEO, A330-900-NEO |
| TA_2 | Medium Twin Aisle | A350-800, A350-900, B787-9, B787-10 |
| TA_3 | Large Twin Aisle | B777-200ER, A350-1000, B777-8x |
| TA_4 | Very Large Twin Aisle | A380-842, B747-8, B777-200LR, B777-300ER, B777-9x |
| TP_1 | Small Turboprop | ATR42-5, IL114-100, AN-32P, AN140 |
| TP_2 | Medium Turboprop | ATR72-2 |
| TP_3 | Large Turboprop | Q400 |

We allocate the market demand based on available seat kilometer (ASK) for passenger operations, available tonne kilometer (ATK) for freighter operations and number of operations for business jets. Of course, given the number of seats for passenger airplane, payload capacity for freighters and the great circle distance for each flight, all these can be converted to a common activity measure, i.e., number of operations. The formula for calculating number of operations for out years is given in Equation 4-2.

**Equation 4-2 – Number of Operations Equation**

$$\mathbf{NOP(y)} = \frac{\mathbf{GR(y) + RET(y)}}{\mathbf{N(c,y)}} \boldsymbol{NOP}\mathbf{(2015)}$$

*where* *NOP(y) is number of operations in year y,*

*GR(y) is the growth rate in year y*

*RET(y) is the retirement rate in year y*

*N(c,y) is the number of available airplanes in market segment c and year y*

**Airplane Performance Model and Analysis**

As described in Chapter 2 of this TSD (see Table 2-1), ICF technology responses include continuous improvement in metric value (or fuel efficiency improvement) for all G&R airplanes from 2010[63] to 2040. ICF technology responses also include estimated MV improvements for long-term replacement airplanes (see Table 2-4) beyond the end of production of current in-production and project airplanes. This is meant to establish a baseline where current in-production airplanes are continuously improving and new type design airplanes are introduced periodically to replace airplane models that are going out of production due to market competition. In order to capture these dynamically changing airplane efficiency improvements, our fleet evolution model tracks the market share of every new-in-service airplane entering the fleet each year and applies the annual fuel efficiency improvement via an adjustment factor according to the vintage year of the airplane in the fleet. For stringency analysis, if an airplane fails a stringency limit and needs to improve its MV to comply with the standard, we apply the adjustment factor in the same manner to establish the emissions under the influence of the stringency limit.

## 4.4 Full Flight Simulation with PIANO and Unit Flight Matrix

The purpose of the full flight simulation module is to calculate instantaneous and cumulative fuel burn, flight distance, flight altitude, flight time, and emissions by modeling airplane performance for standardized flight trajectories and operational modes. PIANO[lviii] version 5.4 was used for all the emissions modeling. PIANO is a physics-based airplane performance model used widely by industry, research institutes, non-governmental organizations and government agencies to assess airplane performance metrics such as fuel efficiency and emissions characteristics based on airplane types and engine types. PIANO v5.4 (2017 build) has 591 airplane models (including many project airplanes still under development, e.g., the B777-9X) and 56 engine types in its airplane and engine databases. We use these comprehensive airplane and engine data to model airplane performance for all phases of flight from gate to gate including taxi-out, take-off, climb, cruise, descent, approach, landing, and taxi-in in this analysis.

To simplify the computation, we made the following modeling assumptions: 1) Assume airplanes fly the great circle distance (which is the shortest distance along surface of the earth between two airports) for each origin-destination (OD) pair. 2) Assume still air flights and ignore weather or jet stream effects. 3) Assume no delays in takeoff, landing, en-route, and other flight related operations. 4) Assume a load factor of 75% maximum payload capacity for all flights except for business jet where 50% is assumed. 5) Use the PIANO default reserve fuel rule[lix] for a given airplane type. 6) Assume a one-to-one relationship between metric value improvement and fuel burn improvement for airplanes with better fuel efficiency technology insertions (or technology responses).

When jet fuel is consumed in an engine, the vast majority of the carbon in the fuel reacts with oxygen to form $CO_2$. To convert fuel consumption to $CO_2$ emissions, we used the conversion

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[lviii] PIANO is the Aircraft Design and Analysis Software by Dr. Dimitri Simos, Lissys Limited, UK, 1990-present; Available at www.piano.aero (last accessed March 16, 2020). PIANO is a commercially available airplane design and performance software suite used across the industry and academia.

[lix] For typical medium/long-haul airplanes, the default reserve settings are 200 nm diversion, 30 minutes hold, plus 5% contingency on mission fuel. Depending on airplane types, other reserve rules such as U.S. short-haul, European short-haul, NBAA-IFR or Douglas rules are used as well.

factor of 3.16 kg/kg fuel for $CO_2$ emissions, and to convert to the six well-mixed GHG emissions, we used a slightly higher conversion factor of 3.19 kg/kg fuel for $CO_2$ equivalent emissions. It is important to note that in regard to the six well-mixed GHGs ($CO_2$, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride), only two of these gases -- $CO_2$ and nitrous oxide ($N_2O$) -- are reported (or emitted) for airplanes and airplane engines.[57] The method for calculating $CO_2$ equivalent emissions is based on SAE AIR 5715, entitled Procedures for the Calculation of Airplane Emissions[64] for $N_2O$ emissions, and the EPA publication Emissions Factors for Greenhouse Gas Inventories[65] for the 100-year global warming potential.

Given the flight activities defined by the fleet evolution module in the previous section, we generate a unit flight matrix to summarize all the PIANO outputs of fuel burn, flight distance, flight time, emissions, etc. for all flights uniquely defined by a combination of departure and arrival airports, airplane types, and engine types. This matrix includes millions of flights and forms the basis for all the regulatory scenarios and sensitivity studies. To reduce the computational workload of such a huge task in stringency analysis, we pre-calculate these full flight simulation results and store them in a database of 50 distances and 50 payloads for each airplane and engine combination. The millions of flights in the unit flight matrix are interpolated from the 50x50 flight distance/payload database.

## 4.5 Inventory Modeling and Stringency Analysis

The GHG emissions calculation involves summing the outputs from the first two modules for every flight in the database. This is done globally, and the U.S. portion is segregated from the global dataset. The same calculation is done for the baseline and the GHG standards and two alternative scenarios. When a surrogate airplane is used to model any airplane that is not in the PIANO database or when a technology response is required for any airplane to pass a stringency limit, an adjustment factor is also applied to model the expected performance of the intended airplane and technology responses.

The differences between the GHG standards and alternative scenarios and that of the baseline provide the quantitative measures for the agency to assess the emissions impacts of the GHG standards.

## REFERENCES

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[51] U.S. EPA, 2020: *Technical Report on Aircraft Emissions Inventory and Stringency Analysis*, July 2020.
[52] RTI International and EnDyna, *EPA Technical Report on Aircraft Emissions Inventory and Stringency Analysis: Peer Review*, July 2019, 157pp.
[53] The Growth and Replacement database contains all the available in production and in development airplanes known to the agency for renewing the global in-service fleet in the analysis period of 2015-2040. This G&R database together with technology responses developed by ICF is available in the 2018 ICF Report.
[54] PIANO is the Aircraft Design and Analysis Software by Dr. Dimitri Simos, Lissys Limited, UK, 1990-present; Available at www.piano.aero (last accessed March 18, 2020). PIANO is a commercially available aircraft design and performance software suite used across the industry and academia.
[55] FAA, Inventory Database is developed by the U.S. Federal Aviation Administration (FAA). Commercial airplane jet fuel burn and carbon dioxide ($CO_2$) emissions estimates were included in the U.S. Inventory using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 2000 through 2016 as modeled with the Aviation Environmental Design Tool (AEDT). For this analysis, EPA only uses the operations data from the 2015 Inventory Database to develop the fleet evolution and emissions modeling as described in this document.
[56] FAA, 2015-2040 Terminal Area Forecast, the Terminal Area Forecast (TAF) is the official FAA forecast of aviation activity for U.S. airports. It contains active airports in the National Plan of Integrated Airport Systems (NPIAS) including FAA-towered airports, Federal contract-towered airports, nonfederal towered airports, and non-towered airports. Forecasts are prepared for major users of the National Airspace System including air carrier, air taxi/commuter, general aviation, and military. The forecasts are prepared to meet the budget and planning needs of the FAA and provide information for use by state and local authorities, the aviation industry, and the public.
[57] EPA, 2019: *Inventory of US Greenhouse Gas Emissions and Sinks*, EPA develops an annual report that tracks U.S. greenhouse gas emissions and sinks by source, economic sector, and greenhouse gas going back to 1990. EPA publishes the draft report in February to allow public comment prior to publishing the final report by April 15 of every year. The document is available online at the following EPA website. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (last accessed March 17, 2020)
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[61] FlightGlobal Fleets Analyzer is a subscription based online data platform providing comprehensive and authoritative source of global aircraft fleet data (also known as ASCEND database) for manufacturers, suppliers and MRO providers. https://signin.cirium.com/ (last accessed March 17, 2020)

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[62] ICF, 2018: *Aircraft $CO_2$ Cost and Technology Refresh and Industry Characterization*, Final Report, EPA Contract Number EP-C-16-020, September 30, 2018.
[63] For this analysis with 2015 as the base year, we only use the continuous improvement data from 2015 to 2040.
[64] SAE, 2009: *Procedures for the Calculation of Aircraft Emissions*; AIR 5715, 2009-07. This document can be purchased at SAE website, and is copyright protected, https://www.sae.org/standards/content/air5715/.
[65] EPA, 2014, *Emissions Factors for Greenhouse Gas Inventories*, EPA, last modified 4, April 2014. https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf

# Impacts on Emissions and Fuel Consumption

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# Chapter 5: Impacts on Emissions and Fuel Burn

## 5.1 Executive Summary

EPA analyzed the costs and emissions reductions for the standards and two alternative scenarios. The first alternative scenario (Scenario 2) was for a 5-year pull-ahead (or 5-year earlier effective date) of the in-production standard. The second alternative scenario (Scenario 3) was for a pull-ahead combined with a more stringent level comparable to the new type standard. These alternative scenarios are described in more detail later in section 6.1.2 (of Chapter 6).

The main conclusion of the impact analysis for the airplane GHG emissions rule is that it will result in no costs and no emission reductions. This is because the ICAO standards are technology-following standards and all manufacturers have products that either already meet the standards or have new products under development that will meet the standards by their effective dates. The major effect of the adopted standards is to align with ICAO standards in order to provide a level playing field for U.S. manufacturers and to prevent future airplanes from backsliding or incorporating technologies that will have an adverse effect on GHG emissions.

Of the two alternative stringency scenarios the agency has analyzed, the pull-ahead scenario of the in-production standard also offers no additional benefit but has a much tighter timeline for manufacturers to certify their engines due to the 5-year pull-ahead from the ICAO production cut-off date. The other more stringent scenario (Scenario 3) would only result in modest emission reductions (1.4 Mt of cumulative U.S. $CO_2$ reductions over the period of 2023-2040).[lx] This result is because the only airplane that is impacted by Scenario 3 is the A380. None of the U.S. airlines have the A380 in their fleets, and thus, under Scenario 3 the emissions reduction impacts from both U.S. domestic and international flights are limited.

## 5.2 Introduction

Market forces historically have driven fuel efficiency improvements because fuel efficiency is a major part of the direct operating cost of air carriers, and it influences their airplane purchasing decisions. EPA's Guidelines for Economic Analysis, OMB's A-4, and standard cost-benefit analysis all call for a ceteris paribus[lxi] baseline scenario, against which a policy scenario is compared. From this perspective, a business as usual (BAU) baseline which includes market-driven improvements in the absence of the GHG standards will be the best measure for assessing impact of the standards. In fact, EPA regulatory impact analyses in other sectors all use such BAU baselines to assess the impacts of emission regulations on the regulated sectors.

It is thus important to determine the BAU baseline as accurately as possible by knowledgeable and independent third-party experts. EPA contracted with ICF to conduct such an independent study to develop the best estimates of the BAU improvements for airplanes and engines in detail by airplane models and engine types for the near- and mid- term (2010-2030) and long-term (2030-2040) timeframes, based on technology feasibility and economic viability

[lx] As described later in section 6.4 (of Chapter 6), estimated net benefits (benefits minus costs) range from -$285 million to -$261 million, at 7 and 3 percent discount rates respectively

[lxi] Ceteris paribus means with other conditions remaining the same (all other things being equal).

for each of airplane/engine types. The main analysis results presented in this chapter are based on the fleet evolution and technology responses derived from this ICF study[66].

Inherent in any modeling of future emissions is the uncertainty associated with predictions of the future. The agency has conducted a number of sensitivity studies in an attempt to quantify the effects of certain fleet evolution and technology response parameters, specifically the end-of-production timing and continuous-improvement (which are improvements expected from BAU developments) assumptions. These sensitivity studies provide an estimate of the uncertainties when we vary such parameters one at a time or in combinations.

## 5.3 Fleet Evolution Results and Baseline Emissions

As described in Chapter 4 of the TSD, the EPA fleet evolution model aims to develop future operations of the overall airplane fleet based on the base year operations assuming a fixed network structure (no new routes or time-varying network configurations). We use a very simple market allocation method in which each competing airplane within a market segment is given an equal market share. The market allocation is based on airplane types and their operations measured in available seat kilometer (ASK) or available tonne kilometer (ATK) or number of operations since they directly determine the emissions output. We are not tracking flights and airplane deliveries at individual airplane operator or airline level.

In developing future year operations, all growth and replacement (G&R) operations and residual legacy operations in future years are expressed in fractions of the base year operations in our analysis. The growth and replacement operations come from new airplanes entering into service to fill the market demands from increased air traffic and retirement of in-service fleet in future years. The residual legacy operations are the remaining base year operations expected in future years after retirement of a portion of the base year fleet.

The market allocation method for G&R operations is applied to each individual flight in the base year. Together with the residual operations from the base year, the total fleet operations in any given year are made up of three parts, i.e., growth, retirement and residual operations. This is true at any aggregate levels from individual flight to total global fleet. To illustrate the relationship between base year operations, growth, retirement and residual operations in future years, the overall global fleet growth and replacement operations are depicted as an example in Figure 5-1 where the lower line defines the residual (or remaining) operations while the upper line defines the growth projection. The area between the base year operations (the dashed horizontal line) and the growth line is the growth operations. The area between the base year operations and the residual line is the retirement operations. The area below the residual line is the residual operations from the legacy fleet of the base year. The combined growth and retirement operations in each year will be the total annual market demands that need to be filled by G&R airplanes. The G&R fleet in any future year though is comprised of G&R airplanes entering in service from all previous years. The new enter-into-service airplanes themselves will retire according to their respective retirement curves. Thus, the market share and distribution of operations among the in-service fleet change from year to year, and our fleet evolution model tracks these changes for each G&R airplane type and each enter-into-service year. Thus, we are able to assign proper BAU improvements according to the year a G&R airplane enters into service. Fleet evolution results and baseline emissions all depend on the exact age distribution of the G&R fleet.

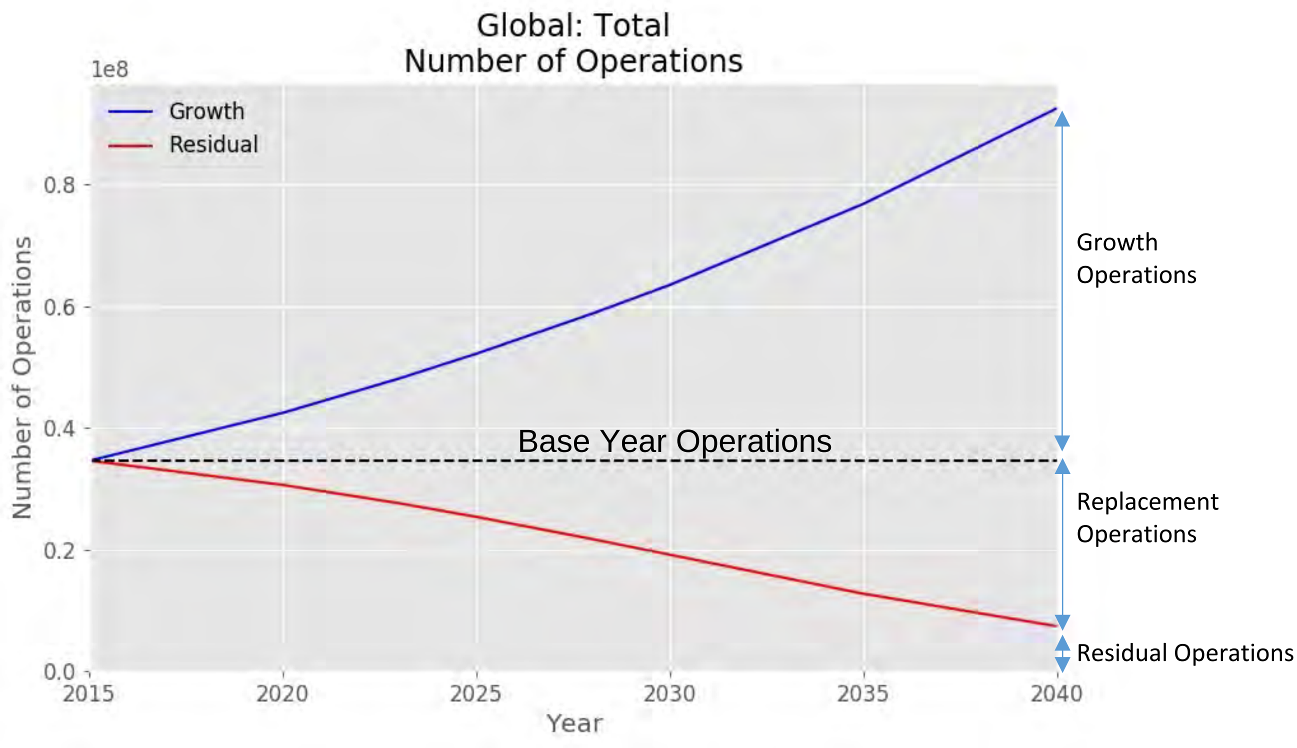


**Figure 5-1 – Global total growth and replacement operations in years 2015-2040**

Fleet Evolution Results

Fleet evolution defines how the future fleet is composed and how future fleet operations are distributed based on the operations of a base year and the market growth forecast from the base year. It is the basis for calculating future year emissions and evaluating the impact of stringency scenarios. The fleet evolution of the EPA analysis is developed independently of the ICAO analysis. Per discussions in section 4.3, it is based on FAA's 2015 inventory database for the base year operations and FAA's 2015-2040 TAF[lxii] for future traffic growth. Since it is developed independently, it is not directly comparable to the ICAO dataset. Nevertheless, we will compare our fleet evolution results with ICAO and TAF data for a consistency check. There is no right or wrong in this comparison, but any outstanding differences may warrant some discussion to ensure that they will not skew the results and affect the policy decisions in an unexplainable manner.

Figure 5-2 compares the EPA fleet evolution results with the ICAO results. The EPA analysis results are close to the ICAO results but differ by up to 10% in the analysis period of 2015-2040. This is expected because there are many fundamental differences between the two analyses.

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[lxii] FAA, 2015-2040 Terminal Area Forecast, the Terminal Area Forecast (TAF) is the official FAA forecast of aviation activity for U.S. airports. It contains active airports in the National Plan of Integrated Airport Systems (NPIAS) including FAA-towered airports, Federal contract-towered airports, nonfederal towered airports, and non-towered airports. Forecasts are prepared for major users of the National Airspace System including air carrier, air taxi/commuter, general aviation, and military. The forecasts are prepared to meet the budget and planning needs of the FAA and provide information for use by state and local authorities, the aviation industry, and the public.

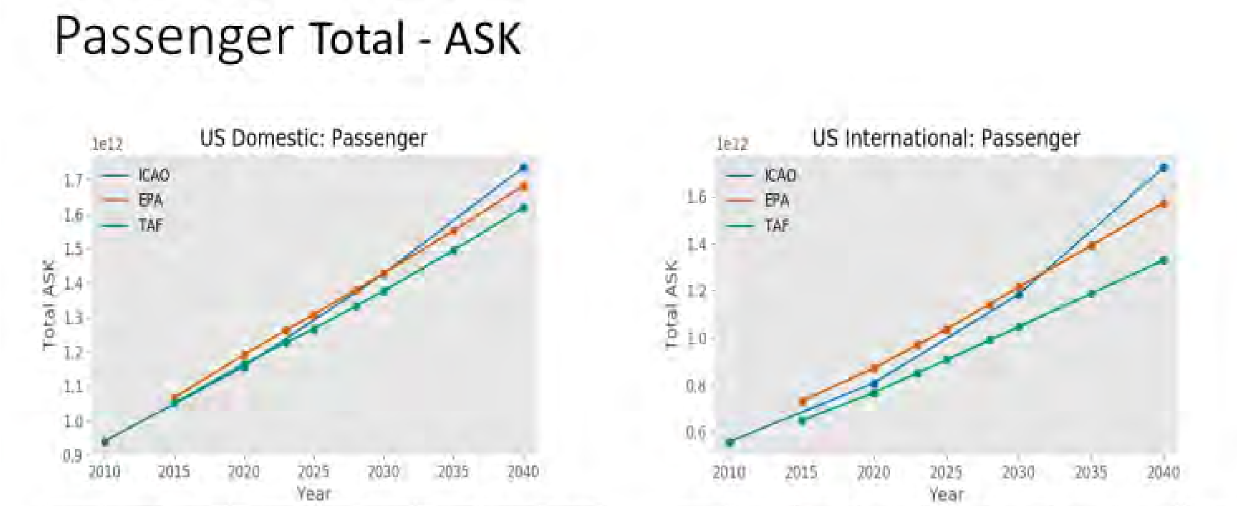
## Impacts on Emissions and Fuel Consumption

First, the EPA fleet evolution for this rule is based on FAA 2015 Inventory Database, while ICAO's fleet evolution is based on 2010 Common Operations Database (COD)[lxiii]. Second, the EPA growth forecast is based on FAA 2015-2040 Terminal Area Forecast (TAF), while the ICAO growth forecast is based on CAEP-FESG[lxiv] consensus traffic forecast and industry-provided fleet forecast for passenger, freight and business jets for 2010-2040. So the two fleet evolution models are based on different data sources in both the base year operation and the growth rate forecast. Coming within 10% differences in a 25-year span is actually quite noteworthy considering the EPA fleet evolution for the U.S. operations is very detailed based on the FAA data while the ICAO model treats all U.S. domestic operation as growing at one uniform growth rate.

We also compare the EPA fleet evolution results with FAA TAF mainly to confirm that the growth rates are consistent between the two since EPA analysis growth rates are sourced from TAF. But because the two databases (2015 Inventory and TAF) are developed and maintained by different groups for different purposes using different data sources, some differences exist in the base year operations, most notably, in the international freight operations. Many operations exist in one database but not in the other and vice versa. Our fleet evolution strategy is to evolve future year fleet operations solely based on FAA 2015 Inventory for the base year operations. So, in cases where the base year operations in TAF are different from those in the 2015 Inventory, the TAF operational data are ignored. TAF is only used to determine the growth rate of the fleet. The challenge for this strategy is in mapping the base year operations correctly onto TAF to find the proper growth rates forecast for the operations in future years. With this strategy, we will always get a unique solution for future year operations with a given mapping of base year operations from 2015 Inventory to TAF, but there is no guarantee that the total operations so derived in any year will be the same as the TAF. By using a two-parameter mapping, we were able to refine the grouping of base year operations and improve the mapping between the two databases. Although some large differences still exist between the two, further reconciliation is beyond the scope of this project. By using the two-parameter mapping, we can also isolate the converted freighter operations and exclude them from stringency analysis because they are not subjected to the GHG standards. This exclusion also makes the EPA analysis freighter results more comparable to ICAO's, but other differences remain as explained later.

[lxiii] Common Operations Database (COD) is a comprehensive global flight database developed and maintained by the Modeling and Database Group (MDG), which is a technical group under ICAO's Committee on Aviation Environmental Protection (CAEP). COD is used for trends analysis of aviation environmental impacts and stringency analysis for ICAO standards.

[lxiv] CAEP-FESG refers to the Forecasting and Economic Analysis Support Group which is the technical group tasked to develop fleet growth forecast and cost effectiveness analyses for ICAO standards.

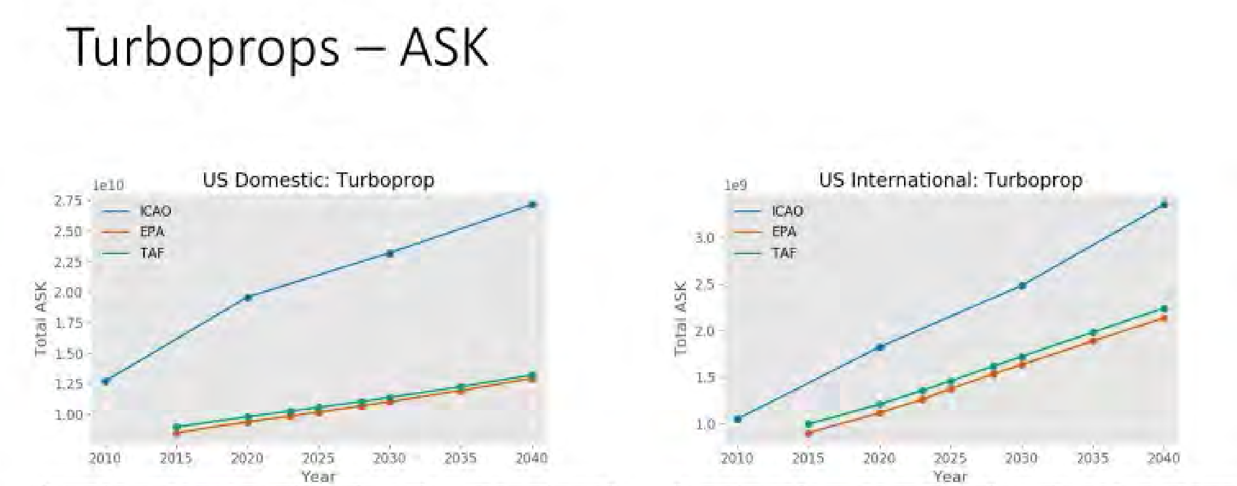



| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 9.40E+11 | | 1.16E+12 | | | | 1.43E+12 | | 1.74E+12 |
| EPA | | 1.07E+12 | 1.19E+12 | 1.26E+12 | 1.31E+12 | 1.38E+12 | 1.43E+12 | 1.55E+12 | 1.68E+12 |
| TAF | | 1.05E+12 | 1.16E+12 | 1.23E+12 | 1.27E+12 | 1.33E+12 | 1.38E+12 | 1.49E+12 | 1.62E+12 |

| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 5.58E+11 | | 8.08E+11 | | | | 1.18E+12 | | 1.72E+12 |
| EPA | | 7.32E+11 | 8.70E+11 | 9.70E+11 | 1.04E+12 | 1.14E+12 | 1.22E+12 | 1.39E+12 | 1.57E+12 |
| TAF | | 6.48E+11 | 7.67E+11 | 8.51E+11 | 9.06E+11 | 9.90E+11 | 1.05E+12 | 1.19E+12 | 1.33E+12 |

**Figure 5-2 – Comparison of U.S. Passenger fleet Available Seat Kilometer of ICAO, EPA and TAF**

The U.S. passenger fleet operations of the three datasets match reasonably well as shown in Figure 5-2. We observe higher growth rate for ICAO in both U.S. domestic and international operations compared to the results from the EPA analysis. The EPA analysis growth rate is between the other two.

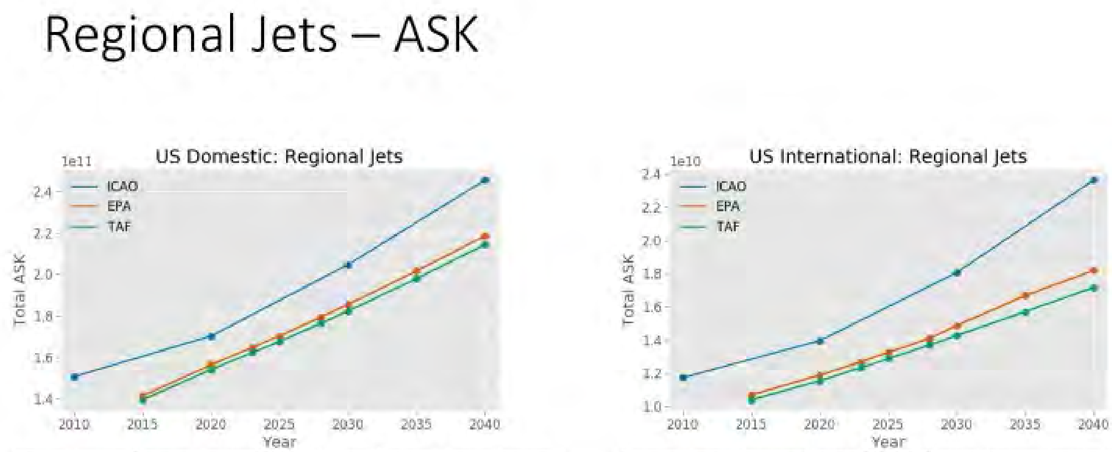



| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 1.27E+10 | | 1.96E+10 | | | | 2.32E+10 | | 2.72E+10 |
| EPA | | 8.48E+09 | 9.37E+09 | 9.85E+09 | 1.02E+10 | 1.07E+10 | 1.10E+10 | 1.19E+10 | 1.29E+10 |
| TAF | | 8.96E+09 | 9.80E+09 | 1.03E+10 | 1.05E+10 | 1.10E+10 | 1.14E+10 | 1.23E+10 | 1.32E+10 |

| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 1.05E+09 | | 1.82E+09 | | | | 2.48E+09 | | 3.35E+09 |
| EPA | | 9.01E+08 | 1.11E+09 | 1.26E+09 | 1.37E+09 | 1.53E+09 | 1.63E+09 | 1.89E+09 | 2.13E+09 |
| TAF | | 9.96E+08 | 1.21E+09 | 1.35E+09 | 1.46E+09 | 1.61E+09 | 1.72E+09 | 1.98E+09 | 2.24E+09 |

**Figure 5-3 – Comparison of U.S. Turboprop fleet Available Seat Kilometer of ICAO, EPA and TAF**

The U.S. turboprop fleet operations of the three datasets match less well as shown in Figure 5-3. The EPA analysis and TAF are reasonably close while ICAO is about 50 to 100 percent higher in ASK. The mismatch is not a major concern for fleet-wide emissions because turboprop emissions are less than 1% of the overall fleet emissions. The mismatch to ICAO data is even less of a concern to U.S. emissions since the ICAO dataset is less detailed and less refined for the U.S. domestic and international operations than the FAA-TAF dataset. Since the EPA fleet evolution results match well with the TAF data, it suggests our fleet evolution results for turboprop are reasonable, and the emissions and stringency analysis will proceed with the EPA fleet evolution results on this basis. We intend to resolve this discrepancy with ICAO in the future.

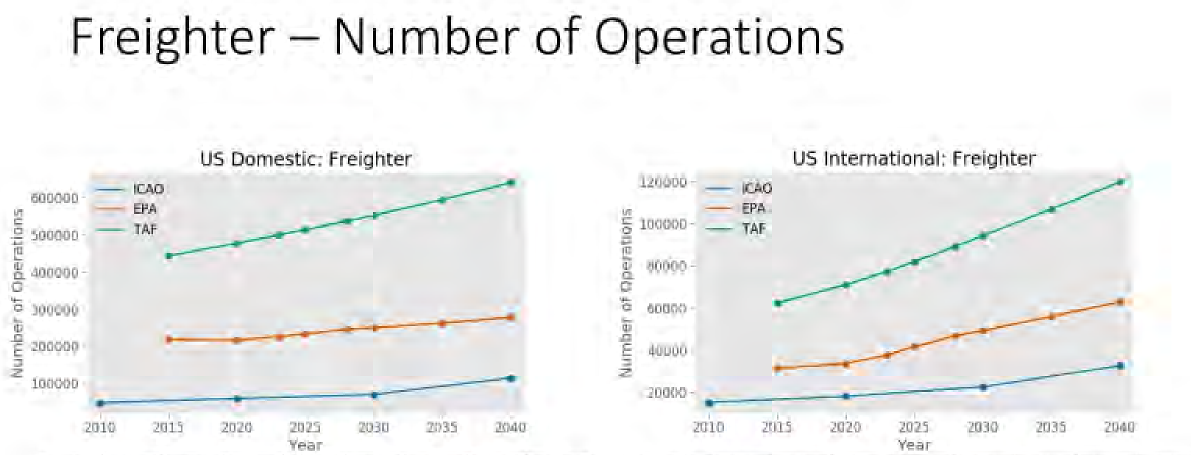



| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 1.51E+11 | | 1.70E+11 | | | | 2.05E+11 | | 2.46E+11 |
| EPA | | 1.41E+11 | 1.56E+11 | 1.65E+11 | 1.70E+11 | 1.79E+11 | 1.85E+11 | 2.02E+11 | 2.19E+11 |
| TAF | | 1.39E+11 | 1.54E+11 | 1.62E+11 | 1.68E+11 | 1.76E+11 | 1.82E+11 | 1.98E+11 | 2.14E+11 |

| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 1.17E+10 | | 1.40E+10 | | | | 1.81E+10 | | 2.36E+10 |
| EPA | | 1.07E+10 | 1.19E+10 | 1.27E+10 | 1.32E+10 | 1.41E+10 | 1.49E+10 | 1.67E+10 | 1.82E+10 |
| TAF | | 1.04E+10 | 1.15E+10 | 1.23E+10 | 1.29E+10 | 1.37E+10 | 1.43E+10 | 1.57E+10 | 1.72E+10 |

**Figure 5-4 – Comparison of U.S. Regional Jet fleet Available Seat Kilometer of ICAO, EPA and TAF**

Similar to turboprop, the U.S. regional jet operations of the three datasets match well between EPA and TAF, but ICAO has about 10% to 30% higher ASK and higher growth rate as shown in Figure 5-4. This mismatch again is less of a concern for fleet-wide emissions because the regional jet emissions are a small fraction of the overall passenger fleet emissions. The mismatch to ICAO data is even less of a concern to U.S. emissions since the ICAO regional jet dataset is less detailed and less refined than TAF for the U.S. domestic and international operations. Given that the EPA fleet evolution results match well with the high-fidelity FAA-TAF dataset, the fleet evolution results for regional jets are fit for purposes of this analysis.

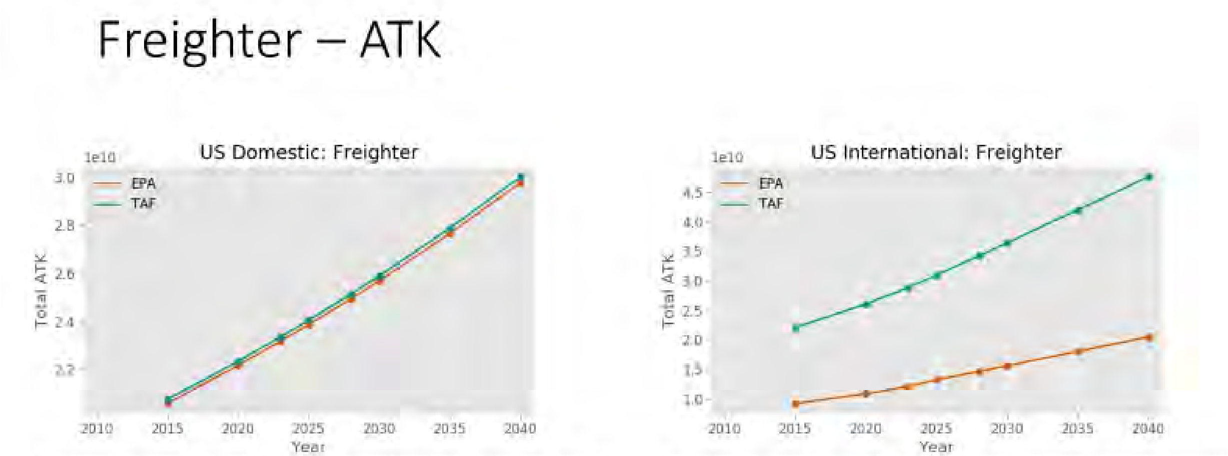



| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 4.84E+04 | | 5.98E+04 | | | | 7.09E+04 | | 1.16E+05 |
| EPA | | 2.19E+05 | 2.17E+05 | 2.26E+05 | 2.34E+05 | 2.46E+05 | 2.50E+05 | 2.63E+05 | 2.79E+05 |
| TAF | | 4.44E+05 | 4.78E+05 | 4.99E+05 | 5.14E+05 | 5.37E+05 | 5.53E+05 | 5.95E+05 | 6.40E+05 |

| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 1.51E+04 | | 1.80E+04 | | | | 2.25E+04 | | 3.26E+04 |
| EPA | | 3.15E+04 | 3.36E+04 | 3.77E+04 | 4.16E+04 | 4.68E+04 | 4.93E+04 | 5.60E+04 | 6.30E+04 |
| TAF | | 6.24E+04 | 7.11E+04 | 7.73E+04 | 8.20E+04 | 8.94E+04 | 9.44E+04 | 1.07E+05 | 1.20E+05 |

**Figure 5-5 – Comparison of U.S. Freighter fleet number of operations for ICAO, EPA and TAF**

Figure 5-5 shows that the three datasets for freighters are quite different in terms of number of operations. To compare fleet evolution results for freighter operations from the three datasets, there are, however, several factors to be considered. These factors are (1) ICAO freighter operations are exclusively from widebody purpose-built freighters while EPA and TAF include smaller freighter types, and (2) between EPA and TAF, TAF has more small airplane operations in its dataset than the EPA analysis, which is based on the FAA 2015 Inventory. Thus, the higher number of operations in Figure 5-5 does not necessarily translate into higher freight capacity in terms of ATK (Available Tonne Kilometer) as shown in Figure 5-6. The ICAO activity dataset we used does not contain payload capacity information, so we can only compare the EPA analysis with TAF for ATK. It is clear from Figure 5-6 that EPA results match TAF results closely for U.S. domestic freighter operations. This close agreement, however, is not observed in the U.S. international freighter operations. In that case, the ATK of TAF is more than twice the ATK of the EPA analysis because possibly many operations present in TAF are missing in FAA 2015 Inventory from which the EPA ATK is derived. Figure 5-7 illustrates some evidence supporting this hypothesis by separating out the operations in TAF with and without origin-destination (OD) pair, aircraft (AC), and airplane category (CAT) matches to the EPA analysis (or FAA 2015 Inventory on which the EPA analysis is based). It is clear from Figure 5-7 that a large part (the top two lines) of TAF U.S. international freight operations has no matching OD/AC or OD/CAT in the EPA analysis. Given our methodology to use FAA 2015 Inventory as the basis to grow future year activities with TAF growth forecast, this discrepancy is not critical to our mission to evolve all FAA 2015 Inventory freighter flights into the future for this EPA analysis. Further reconciliation between TAF and 2015 Inventory is beyond the scope of this project. For the purpose of this analysis, the EPA fleet evolution results will be used exclusively for all the further stringency and impact analysis.




| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| EPA | 2.06E+10 | 2.22E+10 | 2.32E+10 | 2.39E+10 | 2.50E+10 | 2.57E+10 | 2.77E+10 | 2.98E+10 |
| TAF | 2.08E+10 | 2.23E+10 | 2.34E+10 | 2.41E+10 | 2.51E+10 | 2.59E+10 | 2.79E+10 | 3.00E+10 |

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| EPA | 9.23E+09 | 1.09E+10 | 1.21E+10 | 1.32E+10 | 1.47E+10 | 1.56E+10 | 1.80E+10 | 2.05E+10 |
| TAF | 2.21E+10 | 2.60E+10 | 2.89E+10 | 3.09E+10 | 3.42E+10 | 3.64E+10 | 4.20E+10 | 4.76E+10 |

**Figure 5-6 – Comparison of U.S. Freighter fleet Available Tonne Kilometer of ICAO, EPA and TAF**

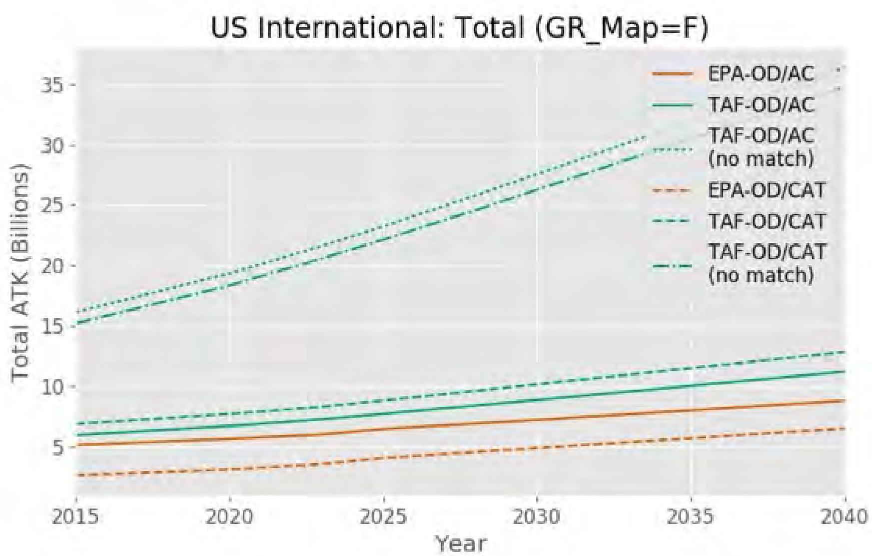
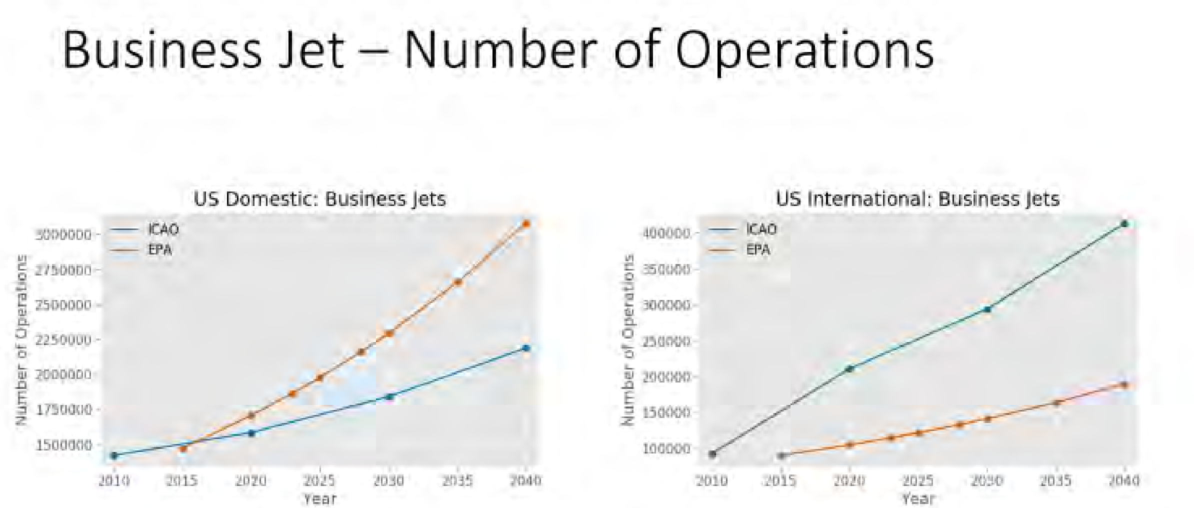



**Figure 5-7 – Total Available Tonne Kilometer of subsets of flights in EPA and TAF with and without match origin-destination pair (OD), aircraft type (AC) and airplane category (CAT)**




| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 1.42E+06 | | 1.58E+06 | | | | 1.84E+06 | | 2.19E+06 |
| EPA | | 1.47E+06 | 1.71E+06 | 1.86E+06 | 1.98E+06 | 2.16E+06 | 2.29E+06 | 2.66E+06 | 3.08E+06 |

| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO | 9.26E+04 | | 2.11E+05 | | | | 2.94E+05 | | 4.13E+05 |
| EPA | | 9.00E+04 | 1.05E+05 | 1.14E+05 | 1.21E+05 | 1.33E+05 | 1.41E+05 | 1.64E+05 | 1.90E+05 |

**Figure 5-8 – Comparison of U.S. Business Jet fleet number of operations for ICAO, EPA and TAF**

The business jet operations of ICAO and EPA analyses have similar 2010/2015 base year operations but different growth rates as shown in Figure 5-8. Comparing to EPA, ICAO appears to underestimate the growth rate of U.S. domestic business jet operations and overestimate that of U.S. international business jet operations. Higher growth rate increases the G&R fleet faster over time, so it tends to amplify the impact of the standards. Conversely, lower growth rate depresses G&R fleet growth and tends to lower the impact of the standards. Nevertheless, the effect of this baseline uncertainty is only secondary since the impact of the stringency scenarios, as measured by the difference from the baseline, are less sensitive to the baseline uncertainty. More importantly, the rank order of stringency scenarios in terms of emission reductions is typically not affected by the uncertainty in baseline. Although the agency recognizes the problem with the general lack of detailed and reliable growth forecast data sources for subcategories like turboprop and business jet, we do not believe that uncertainty in these data alter any conclusion of the analysis.

### *5.3.1.1 Conclusions of the Fleet Evolution Results*

Overall, the EPA fleet evolution results are acceptable with respect to ICAO and TAF for all passenger operations in terms of ASK. For turboprop and regional jet operations, ICAO appears to overestimate the U.S. domestic and U.S. international operations, but the EPA analysis agrees with TAF in all these operations. For freighter operations, the EPA analysis and TAF have many small airplanes included, while ICAO is limited to widebody purpose-built freighters only. The EPA analysis agrees well with TAF in U.S. domestic freighter operations in terms of ATK but contains significantly fewer operations than TAF in U.S. international freighter operations due to differences in the base year datasets. For business jet operations, the EPA analysis and ICAO have similar base year operations but different growth rates, which cause significant differences in out years. In the absence of more reliable data sources for business jet growth forecast, EPA will proceed with the current forecast sources from FAA[58] and Bombardier[60] for the EPA rule analysis. The uncertainty in the baseline forecast is noted but deemed secondary for stringency assessment.

### 5.3.2 Baseline Emissions

The baseline $CO_2$ emissions inventories are estimated in this EPA analysis for 2015, 2020, 2023, 2025, 2028, 2030, 2035, and 2040 using PIANO (the airplane performance model) and the emissions inventory method described in Chapter 4 along with each year's activities data derived from the fleet evolution model. The baseline $CO_2$ emissions for global, U.S. total, U.S. domestic, and U.S. international flights are shown in Figure 5-9 based on outputs from the fleet evolution model.

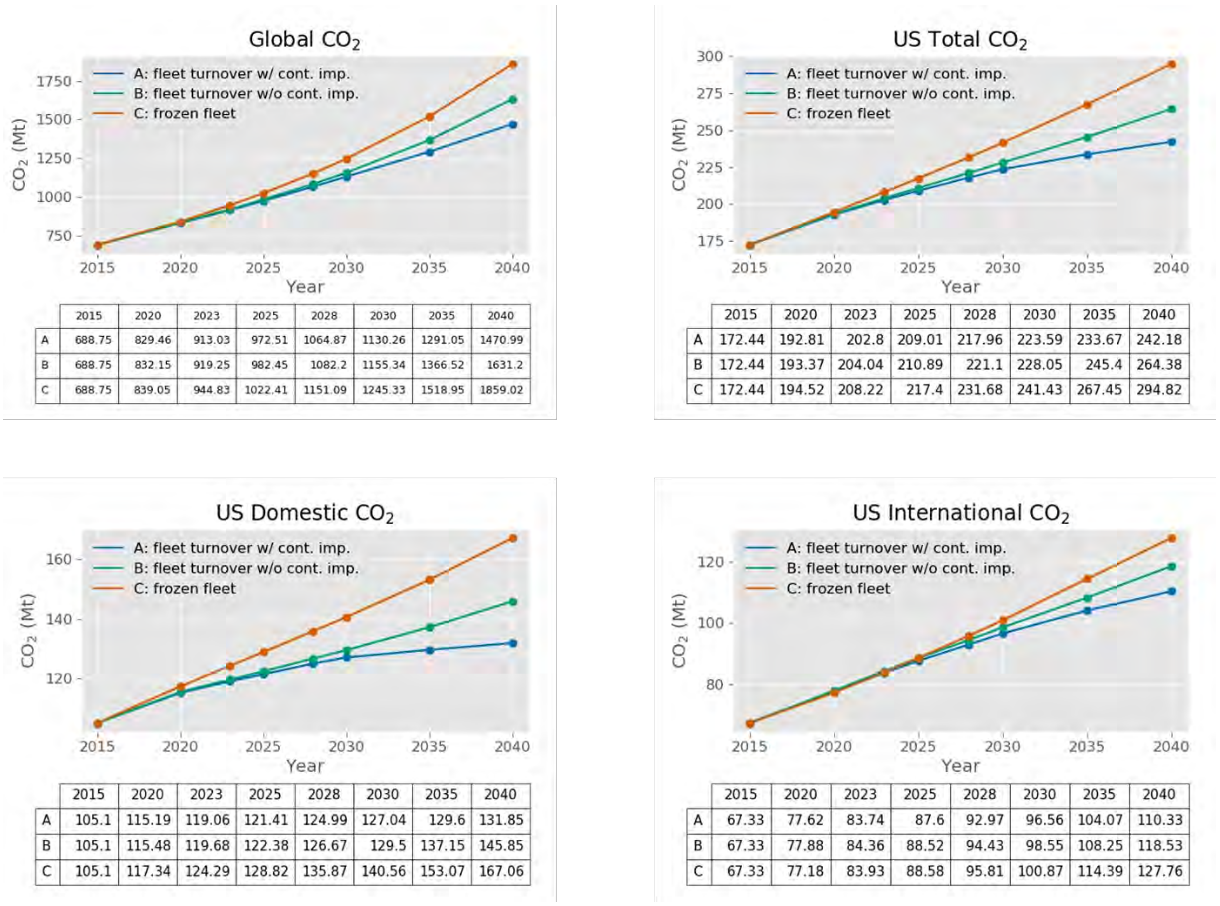
In each of the plots contained in Figure 5-9, there are three baselines plotted. These include the primary analysis (labeled as "A: fleet turnover w/cont. imp.") and two sensitivity scenarios (labeled as "B: fleet turnover w/o cont. imp." and "C: frozen fleet"). The top line is the frozen fleet baseline, which is basically an emission baseline growing at the rate of traffic growth assuming constant fuel efficiency in the fleet (i.e., no fleet evolution). The second line is the no continuous improvement baseline where the fuel efficiency of the fleet benefits from the infusion of newer airplanes from fleet evolution, but the new airplanes entering into the fleet are assumed to be static and not improving over the entire analysis period (2015-2040). The third line is the business as usual baseline where the fleet fuel efficiency benefits from both fleet evolution with new airplanes entering the fleet and business as usual improvement of the new in-production airplanes.

These emissions inventory baselines provide a quantitative measure for the effects of model assumptions on fleet evolution and continuous improvement. The business as usual baseline is the baseline with all market-driven emissions reduction factors incorporated. It is used as the primary baseline for this EPA rule analysis. The other two baselines are useful references for illustrating the effects of fleet evolution and continuous improvement.

Comparing the baselines, the difference between the top two baselines is due to fleet evolution. Even for G&R airplanes without continuous improvement, the powerful effect of fleet renewal is clearly evident in emissions inventories of all markets (global, U.S. domestic and U.S. international). The difference between the bottom two baselines is the effect of continuous improvement since they have identical fleet evolution.

These baselines are established with no stringency inputs; nevertheless, they provide very powerful insights into the drivers for emissions inventories and trends. The difference in global $CO_2$ emissions between the BAU and the frozen fleet baselines in 2040 alone is about 400 Mt, a huge emissions reduction achievable by market force alone.

It is worth noting that the US domestic market is relatively mature with lower growth rate than most international markets. This slower growth rate has obvious consequences in the growth rate of the US domestic $CO_2$ emissions baseline, which is projected with a very slow growth rate by 2040 given the continuous improvement assumptions.




Global $CO_2$ (Mt)

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| A | 688.75 | 829.46 | 913.03 | 972.51 | 1064.87 | 1130.26 | 1291.05 | 1470.99 |
| B | 688.75 | 832.15 | 919.25 | 982.45 | 1082.2 | 1155.34 | 1366.52 | 1631.2 |
| C | 688.75 | 839.05 | 944.83 | 1022.41 | 1151.09 | 1245.33 | 1518.95 | 1859.02 |

US Total $CO_2$ (Mt)

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| A | 172.44 | 192.81 | 202.8 | 209.01 | 217.96 | 223.59 | 233.67 | 242.18 |
| B | 172.44 | 193.37 | 204.04 | 210.89 | 221.1 | 228.05 | 245.4 | 264.38 |
| C | 172.44 | 194.52 | 208.22 | 217.4 | 231.68 | 241.43 | 267.45 | 294.82 |

US Domestic $CO_2$ (Mt)

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| A | 105.1 | 115.19 | 119.06 | 121.41 | 124.99 | 127.04 | 129.6 | 131.85 |
| B | 105.1 | 115.48 | 119.68 | 122.38 | 126.67 | 129.5 | 137.15 | 145.85 |
| C | 105.1 | 117.34 | 124.29 | 128.82 | 135.87 | 140.56 | 153.07 | 167.06 |

US International $CO_2$ (Mt)

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| A | 67.33 | 77.62 | 83.74 | 87.6 | 92.97 | 96.56 | 104.07 | 110.33 |
| B | 67.33 | 77.88 | 84.36 | 88.52 | 94.43 | 98.55 | 108.25 | 118.53 |
| C | 67.33 | 77.18 | 83.93 | 88.58 | 95.81 | 100.87 | 114.39 | 127.76 |

**Figure 5-9 – Range of $CO_2$ emissions baselines with various fleet evolution and continuous improvement assumptions**

### *5.3.2.1 Discussions on baseline modeling*

By modeling fleet evolution variables such as the end-of-production timing and continuous improvements explicitly, the agency believes that the business as usual baseline provides a more accurate assessment of the impacts of the standards on emissions. This comprehensive model can be a powerful tool to understand the effect of these modelled variables.

One might argue that how fast new technology could infuse into the fleet and how much market-driven business as usual improvement can be assumed are all inherently uncertain. But given accurate inputs for fleet evolution and continuous improvement, the baseline inventory can be better assessed for the real-world performance of all fleets (global, domestic or international).

To help develop this baseline, EPA contracted with ICF to conduct an independent analysis to develop a credible fleet evolution and technology response forecast[66]. This ICF analysis considers both near-term and long-term technological feasibility and market viability of available technologies and costs for all the modeled G&R airplanes at individual airplane type and family levels.

**Impacts on Emissions and Fuel Consumption**

Given these fleet evolution and efficiency improvement estimates, the agency believes that the emissions inventory baseline so established provides the best possible representation for the performance of the global and U.S. fleet for assessing the impact of the GHG standards.

It is traditionally assumed that the baseline does not matter for stringency analysis, because as the impact of the stringency is measured from stringency to baseline, the effects of baseline choices tend to cancel out when we consider only the delta of stringency and baseline. It can be shown that this assumption may not be true when some of the fleet evolution assumptions also affect the estimates of emission reductions and, thus, change the output of the impact analysis and potentially influence the policy-making decisions.

In conclusion, using the best possible estimate of a baseline leads to a more accurate assessment of the impact of the standards. The effects of fleet evolution, continuous improvements, and technology responses on emissions inventory and emissions reductions are discussed further in the following sections.

## 5.4 Stringency Analysis of U.S. and Global $CO_2$ Emission Impacts

The EPA main analysis includes three stringency scenarios, the standards and two alternatives. The primary scenario is the GHG standards, which are equivalent to the ICAO Airplane $CO_2$ Emission Standards. The two alternative scenarios are either a pull-ahead scenario at the same stringency level as the ICAO in-production standard (Scenario 2) or a pull-ahead scenario at a higher stringency level comparable to the ICAO new type standard (Scenario 3). See Chapter 6 for a detailed description of the three stringency scenarios, including cost effectiveness discussions for Scenario 3.

Based on the technology response from the ICF technology and cost report[66], there are no reductions projected in fuel consumption and $CO_2$ emissions for both the primary scenario (Scenario 1) and the pull-ahead scenario (Scenario 2). This is because all the airplanes in the G&R fleet either meet the stringency or are out of production when the standards take effect according to our expected technology responses. Thus, under both scenarios 1 and 2, there would be no cost and no benefit (no emission reduction) for the GHG standards.

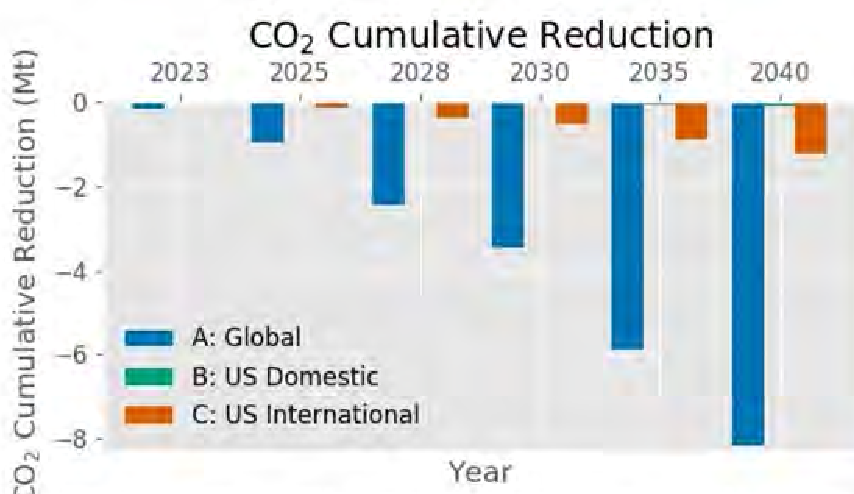
Under Scenario 3, there is one airplane (A380-8) that would be impacted by the stringency. This airplane, however, is projected to go out of production by 2025 according to ICF's end of production forecast. Figure 5-10 shows the global $CO_2$ emissions baseline for A380-8 increases sharply between 2020 and 2025 due to the projected end of production of B747-8 in 2020. After B747-8 ceases production in 2020, A380-8 takes over part of the B747-8's market share, causing the sharp increase of baseline A380-8 emissions. After 2025, A380-8 itself also goes out of production, causing its emissions baseline to decline after 2025 due to normal retirement of the A380 in the in-service fleet. Slightly below the solid baseline, one can see a dashed line for $CO_2$ emissions of A380 under Scenario 3 between 2025 and 2040. It is less visible between 2023 and 2025, but the table below shows a slight decrease in $CO_2$ emissions for Scenario 3 comparing to the A380-8 baseline from 2023 to 2040. The sharp reversal of the A380 baseline emissions inventory is due to the effect of fleet evolution. If we look at the aggregate level of large twin-aisle (TA_4) market segment to which both A380 and B747 belong, the reversal of the emissions baseline disappears. The emissions baseline increases monotonically, but the effects of the stringency is still faintly visible as the rate of increase slows down a little around 2023-2025 due to the technology responses of the A380.


| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 26.89 | 37.59 | 51.55 | 62.92 | 60.81 | 58.74 | 50.76 | 39.35 |
| Scenario 3 | | | 51.39 | 62.42 | 60.31 | 58.25 | 50.28 | 38.91 |

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 147.62 | 177.98 | 197.39 | 210.77 | 228.44 | 241.01 | 275.24 | 316.22 |
| Scenario 3 | | | 197.23 | 210.27 | 227.95 | 240.52 | 274.76 | 315.77 |

**Figure 5-10 – $CO_2$ emissions of A380-8 and market segment TA_4 for the baseline and Scenario 3**

In summary, the total cumulative $CO_2$ emissions reduction under Scenario 3 for all U.S. flights (both U.S. domestic and U.S. international) is 1.36 Mega-tonne (Mt), and the reduction for global flights amounts to 8.16 Mt from 2023 to 2040 as shown below. It is also worth noting that Scenario 3 has a modest impact (1.24 Mt) on U.S. international emissions but only a very small impact (0.12 Mt) on U.S. domestic emissions. This is primarily because none of the U.S. airlines have the A380 in their fleets.




| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| A | -0.16 | -0.98 | -2.47 | -3.46 | -5.88 | -8.16 |
| B | 0.0 | -0.01 | -0.04 | -0.05 | -0.08 | -0.12 |
| C | -0.02 | -0.15 | -0.38 | -0.53 | -0.9 | -1.24 |

**Figure 5-11 – Cumulative reduction of $CO_2$ emissions from 2023 to 2040 for Scenario 3**

## 5.5 Sensitivity Case Studies

As explained previously, the fleet evolution and continuous improvement assumptions have a strong influence on the emissions baseline; likewise these assumptions may also have strong influences on technology responses and subsequently on the emissions reductions. The following sensitivity studies are designed to help look into these influences and put the results of the EPA main analysis in perspective.

Among the three scenarios analyzed for this TSD, only Scenario 3 impacts an airplane and the emission reductions associated with it. The following sensitivity studies will use Scenario 3 to analyze the effects of these model variables and gain insight of their impacts on emissions. We then apply the same concept to Scenarios 1 and 2 and discuss the effects of these variables in a similar manner. Given the evidence from these sensitivity studies, we will summarize and draw conclusions about potential impacts of this rulemaking.

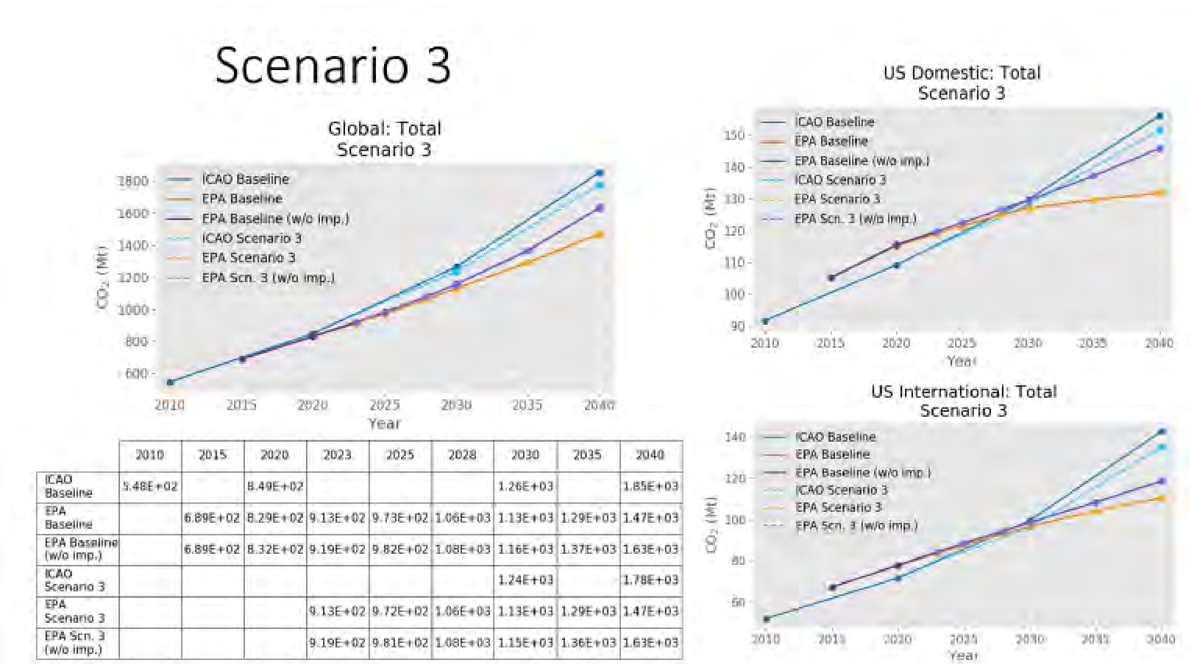
### 5.5.1 Scenario 3 Sensitivity to Continuous Improvement

One of the major stringency analysis assumptions is the continuous improvement of in-production airplanes. We will examine its effect on emissions reductions by turning off the assumption in the EPA main analysis. For reference, we will also compare this analysis with the corresponding ICAO analysis which, although not directly comparable to EPA main analysis as explained in section 5.3.1, is an important reference to show the effects of various assumptions in baseline, fleet evolution, and technology response.

Figure 5-12 shows $CO_2$ emissions of baseline and Scenario 3 for these three cases, i.e., ICAO, EPA analysis with continuous improvements, and EPA analysis without continuous improvements. In the case of U.S. domestic and U.S. international emissions, the ICAO baseline is about 4% lower than the EPA baselines due to differences in the base year datasets (2010 ICAO COD versus 2015 FAA Inventory). This baseline discrepancy, however, does not affect the stringency analysis outcome because the emissions reductions are measured relative to the baseline, and thus they are insensitive to the baseline shift. The emissions reductions, as measured by the differences between the baselines and stringency lines, are what is important for resolving the effects of model assumptions in the three cases.

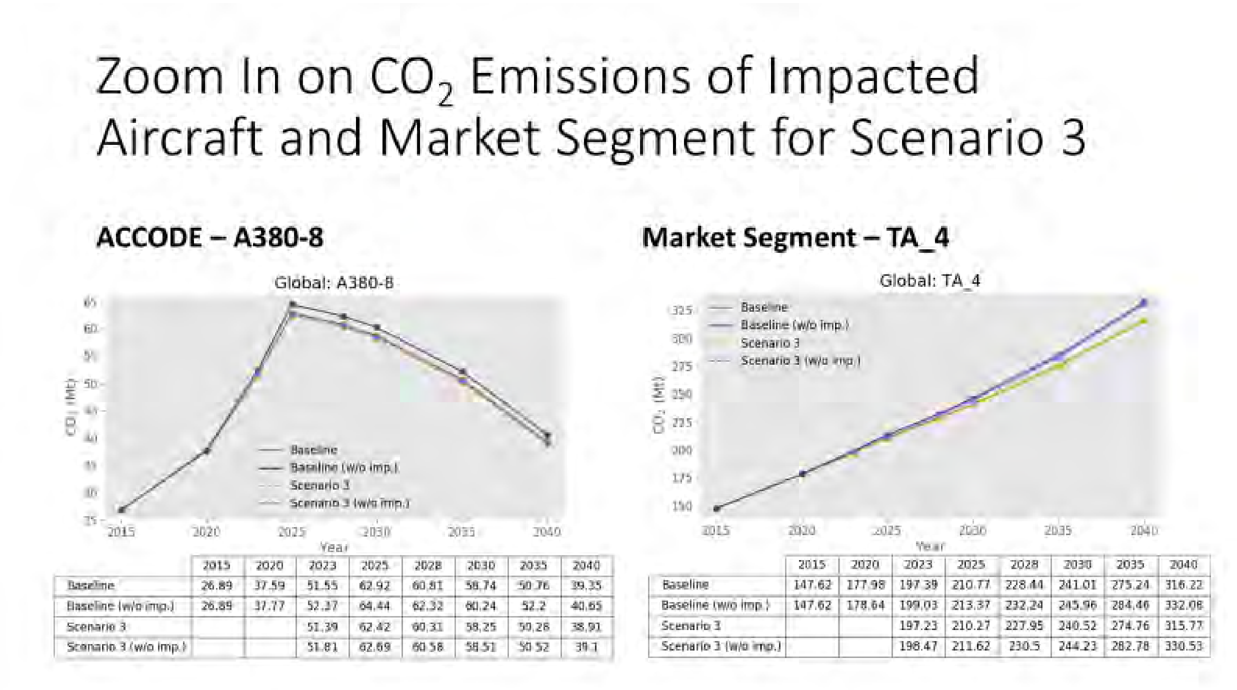
From Figure 5-15, we observe that the emissions reductions increase by more than threefold when continuous improvement is turned off. For example, the cumulative U.S. total emissions reductions from 2023 to 2040 for Scenario 3 increase from 1.36 Mt to 4.78 Mt as shown in the accompanying table in Figure 5-15. These are small compared to the ICAO reduction of 108.99 Mt (38.49 Mt for U.S. Domestic and 70.5 Mt for U.S. International as shown in Figure 5-14) for the same stringency scenario. This is the reason the EPA Scenario 3 (dashed) lines are almost indistinguishable from the baselines in Figure 5-12. Examining the zoom-in graph for the A380 in Figure 5-13, however, shows that there are significant emissions reductions for the no continuous improvement case. This relatively significant amount of reductions for the A380 becomes less significant at the market segment level (the right panel of Figure 5-13). And it is almost invisible at the total fleet level in Figure 5-12 when the aggregate base becomes progressively bigger. Nevertheless, the effect of continuous improvement is significant for the impacted airplane. This result is understandable since the impacted airplane would have to make larger improvement to meet the stringency from a no continuous improvement baseline, while the impact of stringency would be a lot smaller if improvements have been made year over year as assumed by the business as usual baseline. Technically, the two cases achieve the same total improvement, but one attributes the entire amount of improvement to stringency impact while the other attributes the business as usual improvement to market force impact and only the remaining improvement to stringency impact.

It is clear that although the continuous improvement is significant to the impacted airplane, this factor alone cannot explain the huge differences between the emissions reductions of ICAO and EPA analyses. We will examine the other important fleet evolution assumption, i.e., the end of production timing, as a sensitivity study in the next section.




| | 2010 | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|---|
| ICAO Baseline | 5.48E+02 | | 8.49E+02 | | | | 1.26E+03 | | 1.85E+03 |
| EPA Baseline | | 6.89E+02 | 8.29E+02 | 9.13E+02 | 9.73E+02 | 1.06E+03 | 1.13E+03 | 1.29E+03 | 1.47E+03 |
| EPA Baseline (w/o imp.) | | 6.89E+02 | 8.32E+02 | 9.19E+02 | 9.82E+02 | 1.08E+03 | 1.16E+03 | 1.37E+03 | 1.63E+03 |
| ICAO Scenario 3 | | | | | | | 1.24E+03 | | 1.78E+03 |
| EPA Scenario 3 | | | | 9.13E+02 | 9.72E+02 | 1.06E+03 | 1.13E+03 | 1.29E+03 | 1.47E+03 |
| EPA Scn. 3 (w/o imp.) | | | | 9.19E+02 | 9.81E+02 | 1.08E+03 | 1.15E+03 | 1.36E+03 | 1.63E+03 |

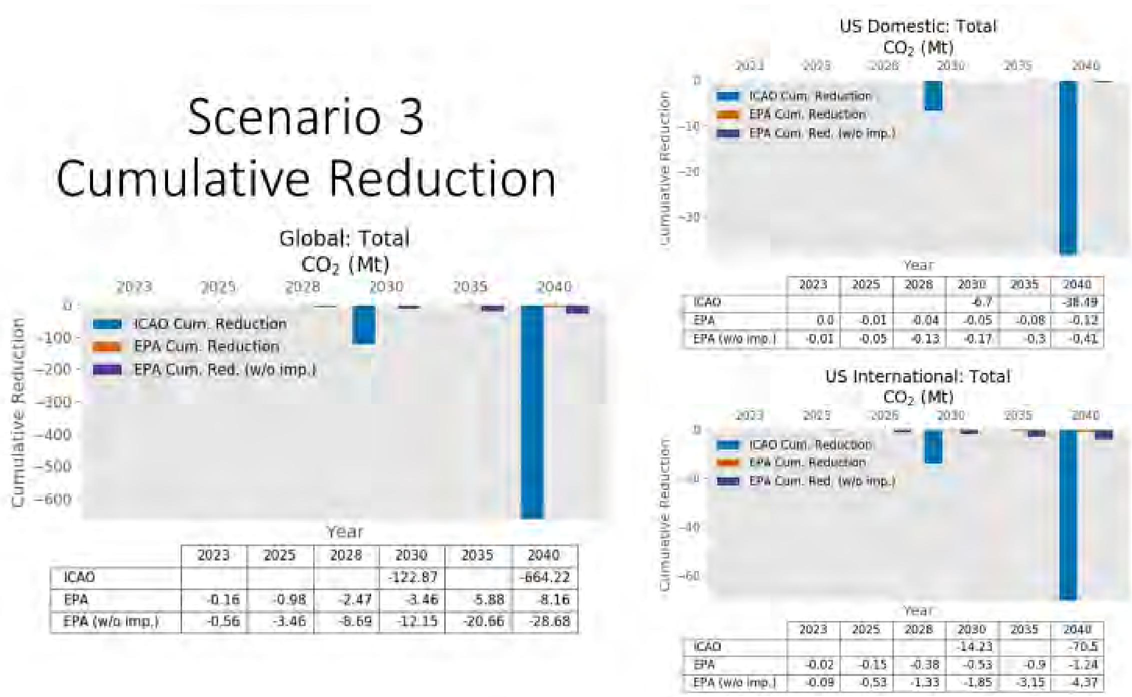
**Figure 5-12 – $CO_2$ Emissions of Baseline and Scenario 3 for ICAO and EPA (w & w/o continuous improvement) Cases**




| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 26.89 | 37.59 | 51.55 | 62.92 | 60.81 | 58.74 | 50.76 | 39.35 |
| Baseline (w/o imp.) | 26.89 | 37.77 | 52.37 | 64.44 | 62.32 | 60.24 | 52.2 | 40.65 |
| Scenario 3 | | | 51.39 | 62.42 | 60.31 | 58.25 | 50.28 | 38.91 |
| Scenario 3 (w/o imp.) | | | 51.81 | 62.69 | 60.58 | 58.51 | 50.52 | 39.1 |

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 147.62 | 177.98 | 197.39 | 210.77 | 228.44 | 241.01 | 275.24 | 316.22 |
| Baseline (w/o imp.) | 147.62 | 178.64 | 199.03 | 213.37 | 232.24 | 245.96 | 284.46 | 332.08 |
| Scenario 3 | | | 197.23 | 210.27 | 227.95 | 240.52 | 274.76 | 315.77 |
| Scenario 3 (w/o imp.) | | | 198.47 | 211.62 | 230.5 | 244.23 | 282.78 | 330.53 |

**Figure 5-13 – Zoom-in Picture of $CO_2$ Emissions of Impacted Airplane A380-8 and Market Segment TA_4 for EPA Scenario 3 with and without Continuous Improvement**

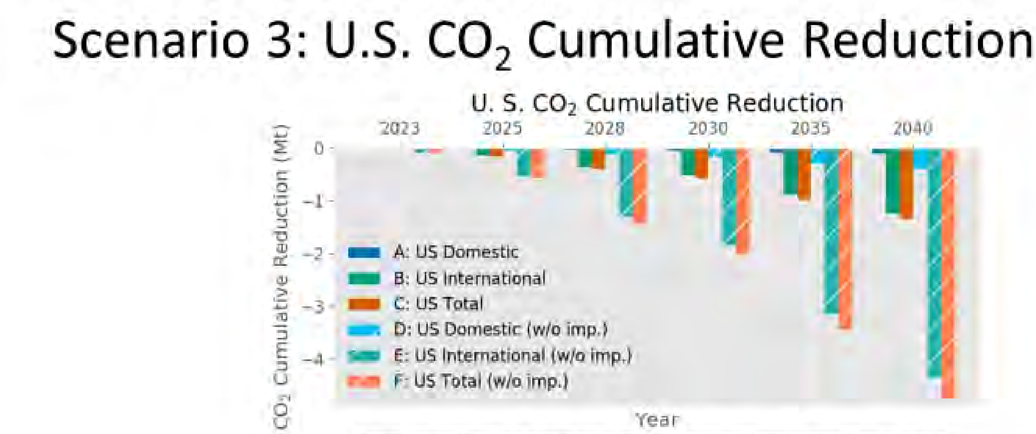



| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| ICAO | | | | -122.87 | | -664.22 |
| EPA | -0.16 | -0.98 | -2.47 | -3.46 | -5.88 | -8.16 |
| EPA (w/o imp.) | -0.56 | -3.46 | -8.69 | -12.15 | -20.66 | -28.68 |

| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| ICAO | | | | -6.7 | | -38.49 |
| EPA | 0.0 | -0.01 | -0.04 | -0.05 | -0.08 | -0.12 |
| EPA (w/o imp.) | -0.01 | -0.05 | -0.13 | -0.17 | -0.3 | -0.41 |

| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| ICAO | | | | -14.23 | | -70.5 |
| EPA | -0.02 | -0.15 | -0.38 | -0.53 | -0.9 | -1.24 |
| EPA (w/o imp.) | -0.09 | -0.53 | -1.33 | -1.85 | -3.15 | -4.37 |

**Figure 5-14 – Cumulative $CO_2$ Reduction of Scenario 3 for ICAO and EPA (w & w/o continuous improvement) cases**




| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| A | 0.0 | -0.01 | -0.04 | -0.05 | -0.08 | -0.12 |
| B | -0.02 | -0.15 | -0.38 | -0.53 | -0.9 | -1.24 |
| C | -0.03 | -0.16 | -0.41 | -0.58 | -0.98 | -1.36 |
| D | -0.01 | -0.05 | -0.13 | -0.17 | -0.3 | -0.41 |
| E | -0.09 | -0.53 | -1.33 | -1.85 | -3.15 | -4.37 |
| F | -0.1 | -0.58 | -1.45 | -2.03 | -3.45 | -4.78 |

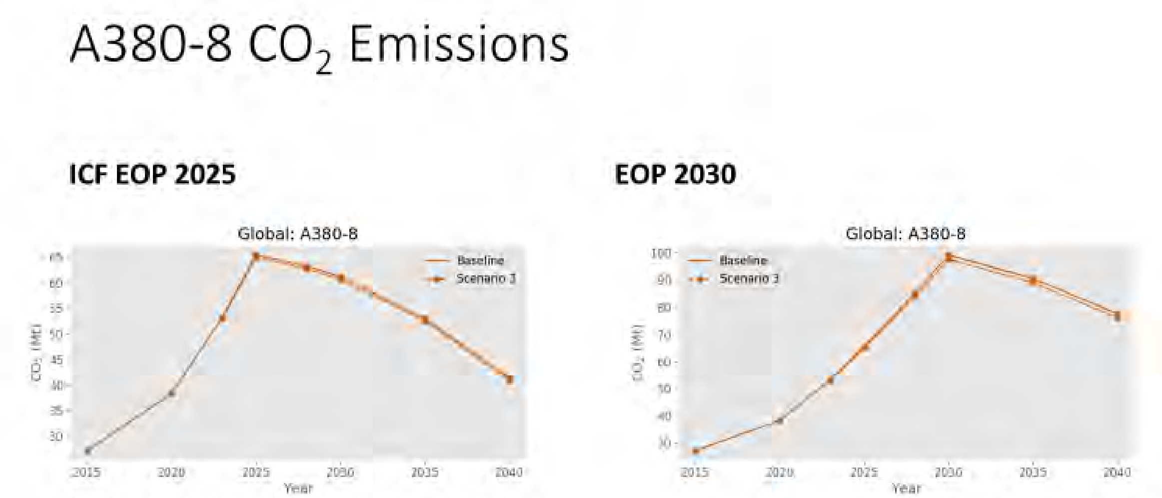
**Figure 5-15 – Cumulative U.S. $CO_2$ Reduction for EPA Scenario 3 with & without Continuous Improvement**

### 5.5.2 Scenario 3 Sensitivity to Extending Production of A380 and B767-3ERF to 2030

Another important fleet evolution variable is the end of production assumption for G&R airplanes. We will examine the effect of this assumption by extending the end of production of both A380-8 and B767-3ERF to 2030 from the EPA main analysis' assumption of 2025 and 2023 respectively for the two airplanes in this sensitivity study. The resulting $CO_2$ emissions from this sensitivity study are shown side by side with the main analysis for A380-8 in Figure 5-16 and for B767-3ERF in Figure 5-17. Note that Scenario 3 starts to impact A380 in 2023 but not the B767-3ERF until 2028, due to the 5-year delay in implementation of the standards for freighters.[lxv] We note that in their comments Boeing, along with Fedex, GE, and the Cargo Airline Association, expressed that there would continue to be a low volume demand for the B767 freighter beyond January 1, 2028. These commenters did not indicate the number of 767F's that would be produced after 2028. The EPA did not change the analysis to adjust the

[lxv] On February 14, 2019, Airbus made an announcement to end A380 production by 2021 after Emirates reduced its A380 order by 39 airplanes and replaced them with A330 and A350. (The Airbus press release is available at: https://www.airbus.com/newsroom/press-releases/en/2019/02/airbus-and-emirates-reach-agreement-on-a380-fleet--sign-new-widebody-orders.html, last accessed on February 10, 2020). The early exit of A380 fits the general trend of reduced demands for large quad engine airplanes presented in this TSD, but the exact timing was not expected at the time when our analysis was completed. This latest A380 production information will affect the modeled results for Scenario 3. Without redoing the whole analysis, we can conclude that the early exit of A380 will nullify its GHG emission reductions from Scenario 3 since it won't be affected by Scenario 3's implementation date. This result, however, is broadly consistent with our prediction of minimum GHG reductions for all scenarios, and it does not alter our conclusion of no cost and no benefits for the primary scenario analyzed in the rule.

baseline to include continued production of the 767F beyond 2030 because insufficient information to characterize this scenario was provided.



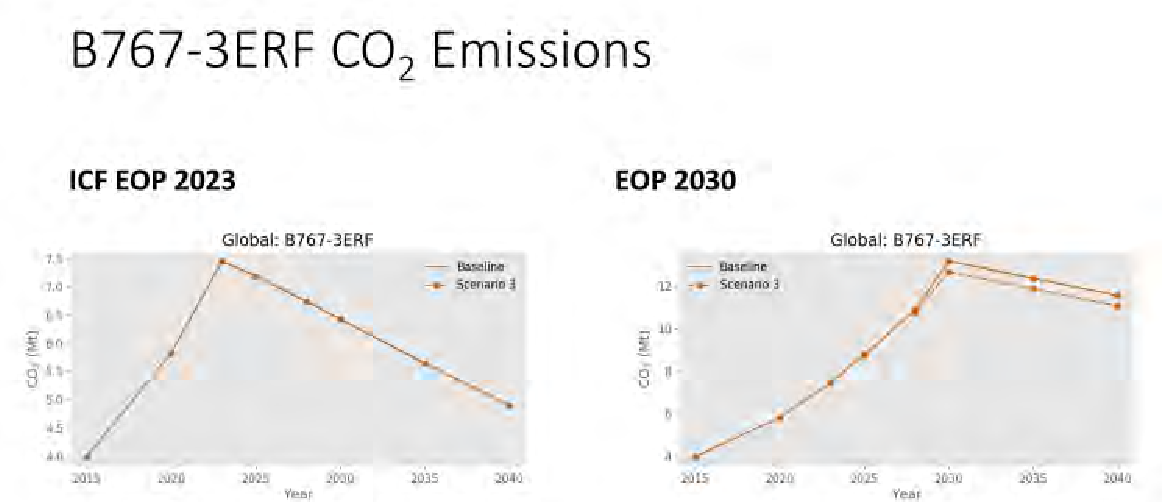

**ICF EOP 2025**

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 27.16 | 38.31 | 53.25 | 65.47 | 63.32 | 61.22 | 53.08 | 41.36 |
| Scenario 3 | | | 53.08 | 64.94 | 62.8 | 60.7 | 52.57 | 40.89 |

**EOP 2030**

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 27.16 | 38.31 | 53.25 | 65.47 | 85.2 | 99.22 | 90.6 | 77.56 |
| Scenario 3 | | | 53.08 | 64.94 | 84.06 | 97.62 | 89.02 | 76.07 |

**Figure 5-16 – $CO_2$ emissions of A380-8 with two different end of production (EOP) assumptions (2025 versus 2030) for EPA baseline and Scenario 3**




**ICF EOP 2023**

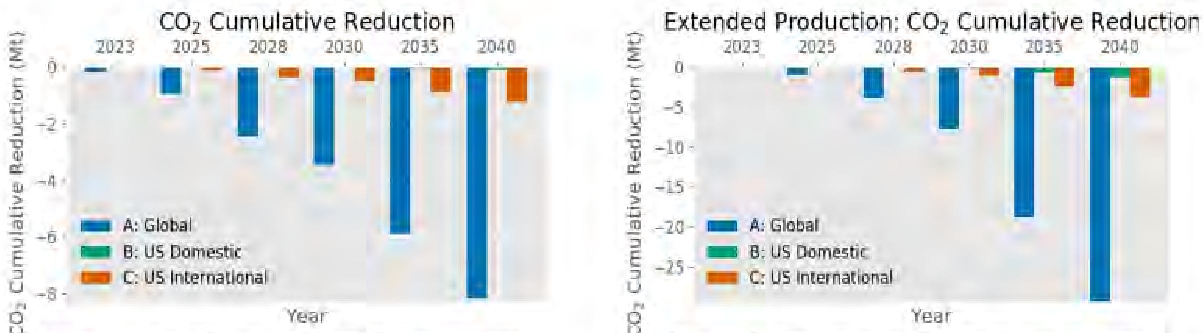
| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 3.99 | 5.83 | 7.45 | 7.19 | 6.74 | 6.42 | 5.64 | 4.89 |
| Scenario 3 | | | 7.45 | 7.19 | 6.74 | 6.42 | 5.64 | 4.89 |

**EOP 2030**

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline | 3.99 | 5.83 | 7.45 | 8.78 | 10.88 | 13.17 | 12.36 | 11.55 |
| Scenario 3 | | | 7.45 | 8.78 | 10.76 | 12.68 | 11.87 | 11.06 |

**Figure 5-17 – $CO_2$ emissions of B767-3ERF with two different end of production assumptions (2023 versus 2030) for EPA baseline and Scenario 3**

It is clear from Figure 5-18 that the cumulative emissions reduction for the extended production case (right panel of Figure 5-18) is more than 3 times that of the main analysis (left panel of Figure 5-18). Extending the end of production forecast thus also has a strong effect on the outcome of the impact analysis (about 3 times in terms of cumulative emissions reductions to 2040).




| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| A | -0.16 | -0.98 | -2.47 | -3.46 | -5.88 | -8.16 |
| B | 0.0 | -0.01 | -0.04 | -0.05 | -0.08 | -0.12 |
| C | -0.02 | -0.15 | -0.38 | -0.53 | -0.9 | -1.24 |

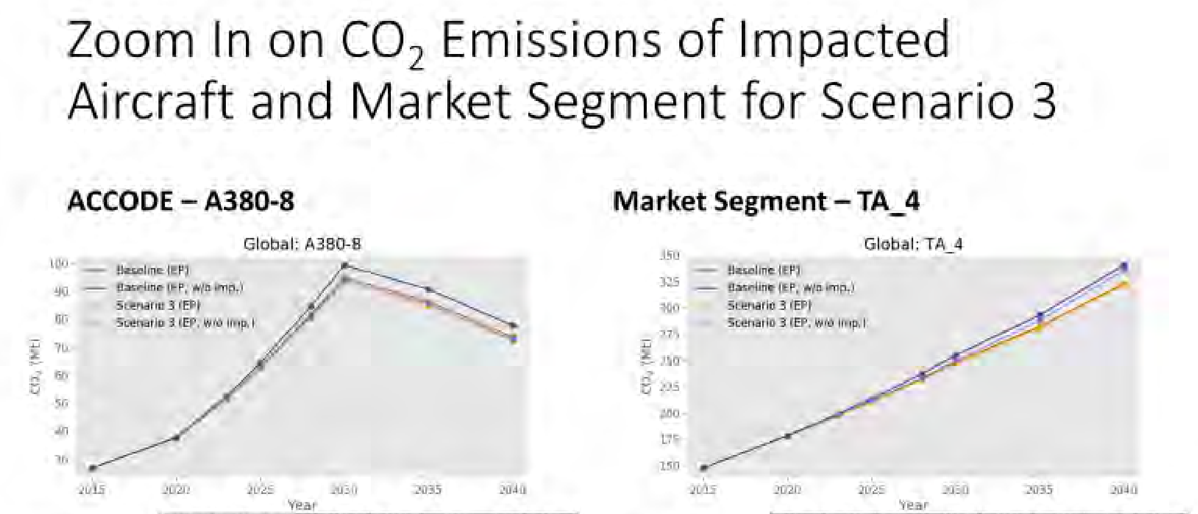
| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| A | -0.16 | -0.98 | -3.96 | -7.86 | -18.72 | -29.3 |
| B | 0.0 | -0.01 | -0.09 | -0.26 | -0.78 | -1.29 |
| C | -0.02 | -0.15 | -0.58 | -1.08 | -2.47 | -3.82 |

**Figure 5-18 – EPA main analysis versus sensitivity study: in cumulative reduction of $CO_2$ emissions from 2023 to 2040 for Scenario 3**

### 5.5.3 Scenario 3 Sensitivity to Combined Effects of Continuous Improvement and Extended Production

Based on the previous two case studies, it is evident that both continuous improvement and extended production have significant impacts on emissions reductions. Furthermore, these two important driving factors are independent variables. Thus, in this section we will assess the combined effects when both extended production and continuous improvement are applied for Scenario 3.

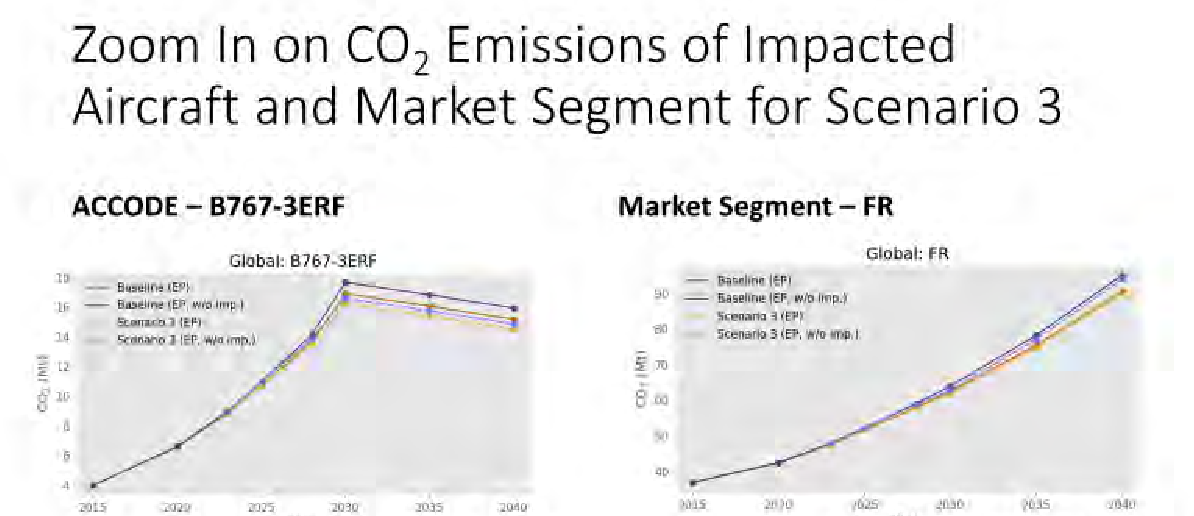
Figure 5-19 to Figure 5-22 detail the results of this sensitivity study. A key finding of this sensitivity study is that the effects of continuous improvement and extended production are largely multiplicative. The two previous sensitivity studies have shown that the extended production and the lack of continuous improvement each produced about 3 times the emissions reductions of the EPA main analysis. As shown in Figure 5-21, the ratio of emissions reduction impact between with and without continuous improvements is again about 3 times (e.g., 29.3 Mt versus 87.34 Mt for the cumulative global $CO_2$ reduction to 2040). The combined effects of extended production and continuous improvement increase the ratio of emissions reductions to more than 10 times (e.g., 87.34 Mt (Figure 5-21) versus 8.16 Mt (Figure 5-14) for the cumulative global $CO_2$ reduction to 2040).




| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline (EP) | 26.89 | 37.59 | 51.55 | 62.92 | 81.48 | 94.76 | 86.3 | 73.66 |
| Baseline (EP, w/o imp.) | 26.89 | 37.77 | 52.37 | 64.44 | 84.52 | 99.18 | 90.64 | 77.76 |
| Scenario 3 (EP) | | | 51.39 | 62.42 | 80.41 | 93.25 | 84.82 | 72.25 |
| Scenario 3 (EP, w/o imp.) | | | 51.81 | 62.69 | 80.74 | 93.87 | 85.41 | 72.79 |

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline (EP) | 147.62 | 177.98 | 197.39 | 210.77 | 232.52 | 248.12 | 282.24 | 322.97 |
| Baseline (EP, w/o imp.) | 147.62 | 178.64 | 199.03 | 213.37 | 237.24 | 254.79 | 293.18 | 340.5 |
| Scenario 3 (EP) | | | 197.23 | 210.27 | 231.45 | 246.61 | 280.76 | 321.56 |
| Scenario 3 (EP, w/o imp.) | | | 198.47 | 211.62 | 233.46 | 249.49 | 287.95 | 335.53 |

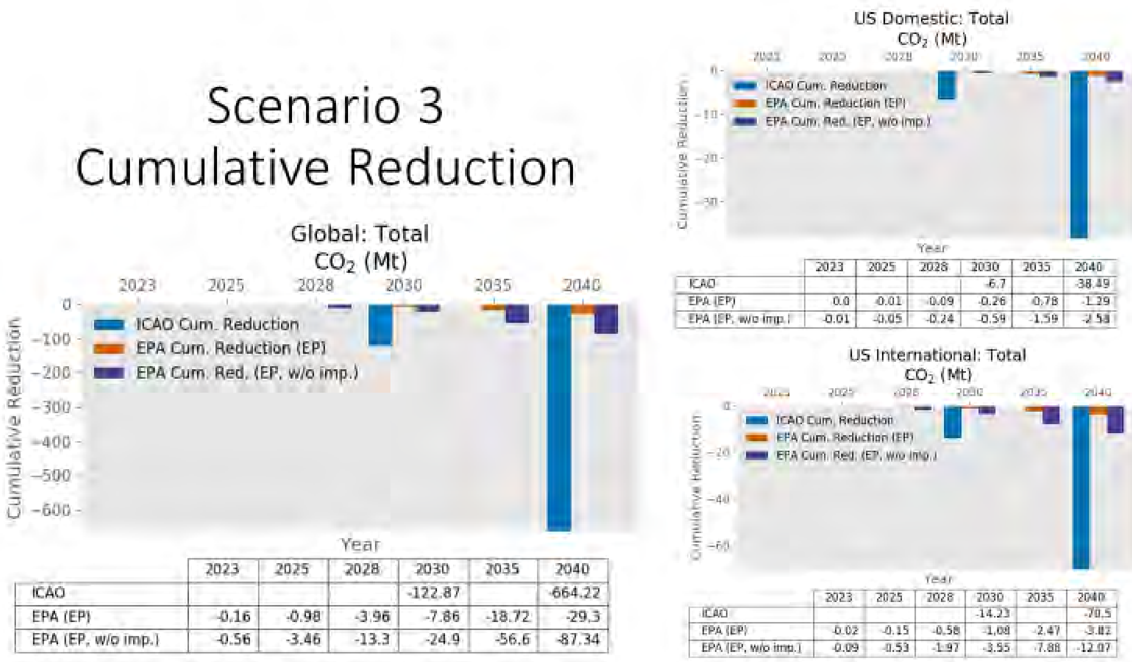
**Figure 5-19 – Zoom-in view of $CO_2$ Emissions of A380-8 and Market Segment TA_4, for Extended Production to 2030, with and without Continuous Improvement**




| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline (EP) | 3.99 | 6.56 | 8.85 | 10.7 | 13.65 | 16.9 | 16.06 | 15.18 |
| Baseline (EP, w/o imp.) | 3.99 | 6.6 | 8.99 | 10.95 | 14.12 | 17.67 | 16.82 | 15.93 |
| Scenario 3 (EP) | | | 8.85 | 10.7 | 13.48 | 16.22 | 15.39 | 14.51 |
| Scenario 3 (EP, w/o imp.) | | | 8.99 | 10.95 | 13.86 | 16.58 | 15.75 | 14.86 |

| | 2015 | 2020 | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|---|
| Baseline (EP) | 36.86 | 42.25 | 47.43 | 51.46 | 57.9 | 62.34 | 75.36 | 90.48 |
| Baseline (EP, w/o imp.) | 36.86 | 42.39 | 47.77 | 52.03 | 58.96 | 63.87 | 78.13 | 95.0 |
| Scenario 3 (EP) | | | 47.43 | 51.46 | 57.73 | 61.66 | 74.69 | 89.81 |
| Scenario 3 (EP, w/o imp.) | | | 47.77 | 52.03 | 58.69 | 62.78 | 77.05 | 93.93 |

**Figure 5-20 – Zoom-in view of $CO_2$ Emissions of B767-3ERF and Market Segment FR, for Extended Production to 2030, with and without Continuous Improvement**




Global: Total $CO_2$ (Mt)

| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| ICAO | | | | -122.87 | | -664.22 |
| EPA (EP) | -0.16 | -0.98 | -3.96 | -7.86 | -18.72 | -29.3 |
| EPA (EP, w/o imp.) | -0.56 | -3.46 | -13.3 | -24.9 | -56.6 | -87.34 |

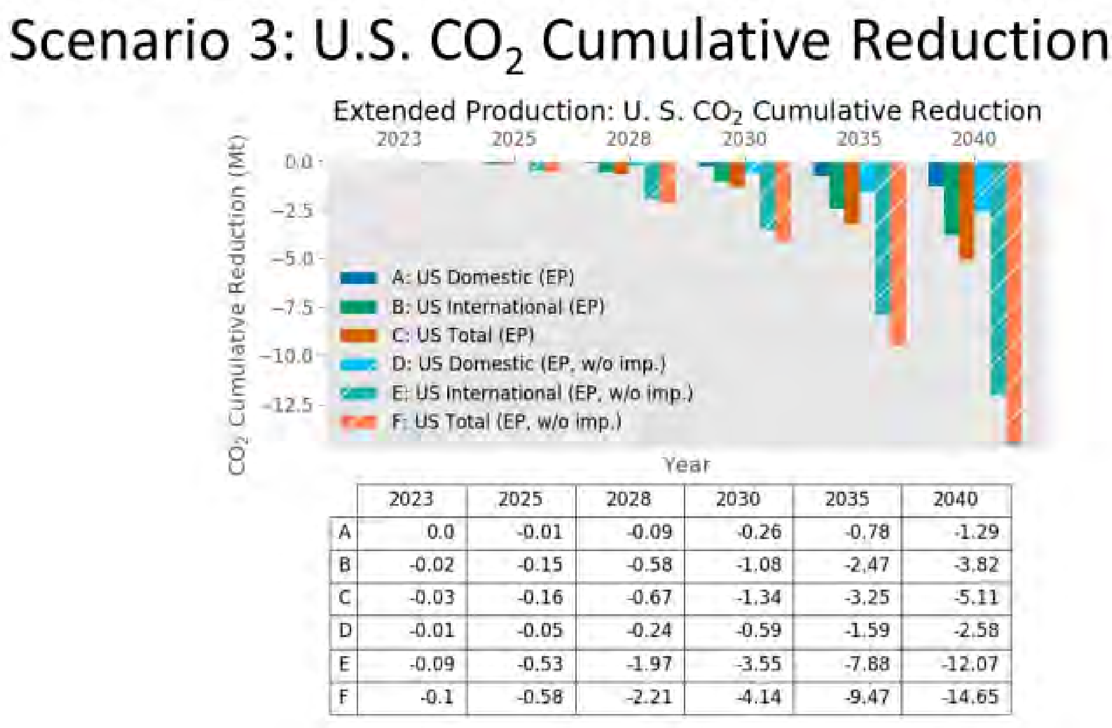
US Domestic: Total $CO_2$ (Mt)

| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| ICAO | | | | -6.7 | | -38.49 |
| EPA (EP) | 0.0 | -0.01 | -0.09 | -0.26 | -0.78 | -1.29 |
| EPA (EP, w/o imp.) | -0.01 | -0.05 | -0.24 | -0.59 | -1.59 | -2.58 |

US International: Total $CO_2$ (Mt)

| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| ICAO | | | | -14.23 | | -70.5 |
| EPA (EP) | -0.02 | -0.15 | -0.58 | -1.08 | -2.47 | -3.82 |
| EPA (EP, w/o imp.) | -0.09 | -0.53 | -1.97 | -3.55 | -7.88 | -12.07 |

**Figure 5-21 – Cumulative $CO_2$ Reduction of Scenario 3 for ICAO and EPA (Sensitivity Study of Extended Production to 2030 for A380 and B767F, with & without continuous improvement)**




| | 2023 | 2025 | 2028 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|
| A | 0.0 | -0.01 | -0.09 | -0.26 | -0.78 | -1.29 |
| B | -0.02 | -0.15 | -0.58 | -1.08 | -2.47 | -3.82 |
| C | -0.03 | -0.16 | -0.67 | -1.34 | -3.25 | -5.11 |
| D | -0.01 | -0.05 | -0.24 | -0.59 | -1.59 | -2.58 |
| E | -0.09 | -0.53 | -1.97 | -3.55 | -7.88 | -12.07 |
| F | -0.1 | -0.58 | -2.21 | -4.14 | -9.47 | -14.65 |

**Figure 5-22 – Cumulative U.S. $CO_2$ Reduction of Scenario 3 for the Sensitivity Study of Extended Production to 2030 for A380 and B767F, with & without continuous improvement**

Extrapolating this finding further, we can clearly see that the projected emissions reductions can be increased even more by extending the production of current in-production airplanes further into the future. ICAO's analysis assumed no end of production for current in-production airplanes. This explains why significantly higher emissions reductions were found in the ICAO analysis compared to the EPA analysis for the same stringency scenario. The key is in fleet evolution, technology response, and baseline assumptions. Thus, it is crucial to establish the best possible estimates for fleet evolution, technology response, and business as usual baseline to provide a more accurate assessment for the costs and benefits of the standards.

### 5.5.4 Similar Sensitivity Studies for Scenarios 1 and 2

In summary, the sensitivity studies for Scenario 3 show that the EPA and ICAO analyses of emissions reductions, although quite different, are results of their respective model assumptions. As we relax the assumptions in the EPA analysis to be more like ICAO's, the results tend toward ICAO results. It will eventually reproduce ICAO results when given the same model assumptions. We also evaluated whether this trend would hold true for Scenarios 1 and 2. We analyzed emissions reductions for Scenarios 1 and 2 under various model assumptions similar to what was done in previous sections for Scenario 3. Like the sensitivity studies for Scenario 3, only A380 and 767-3ERF are considered since they are the only airplanes potentially impacted by the standards and alternative scenarios.

Specifically, without continuous improvement (CI), the A380 would not pass the in-production standards and would need to make about 1% improvements to be compliant and 2% improvements with the 1% design margin. This is true for both Scenarios 1 and 2 since without CI, the metric value margin to the stringency line would not change with time and required improvements would remain the same independent of the standard's effective dates. With CI, A380 would pass the standards in both 2023 and 2028 timeframes and does not require any additional improvement for Scenarios 1 and 2.

On the other hand, 767-3ERF would not pass the in-production standards with or without CI, so its response status is mostly driven by the end of production assumption. In other words, in the normal assumption of end of production in 2023, there would be no need to improve in either Scenarios 1 or 2 with the standards effective date for freighters starting in 2028. In the extended production case, 767-3ERF would have a 3-year window from 2028 to 2030 that it would need to improve to be compliant with the in-production standards.

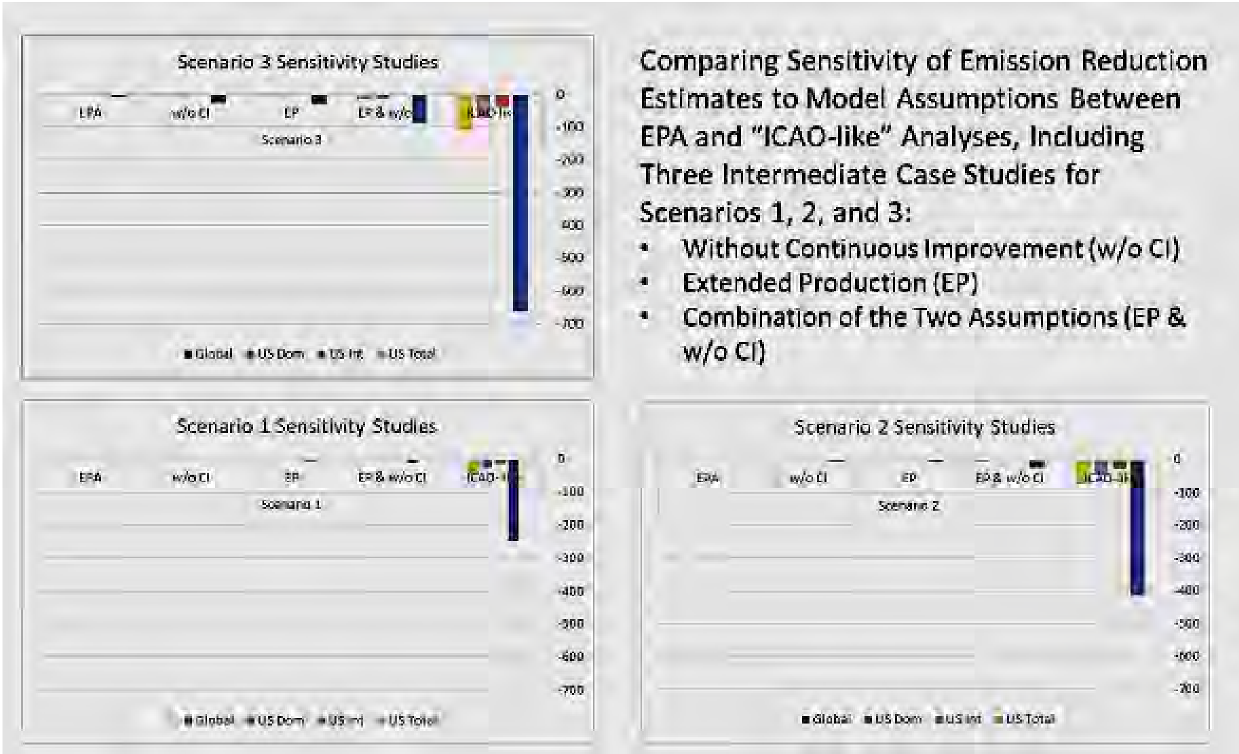



**Figure 5-23 – Summary of Sensitivity to Model Assumptions for Scenarios 1, 2 and 3**

To put the sensitivity studies in context and compare the general trends for all three scenarios, we will examine the five cases in each scenario as shown in Figure 5-23. A brief discussion of the five sensitivity cases is given below.

Case 1 (EPA): For the EPA analysis, both Scenarios 1 and 2 show no emissions reduction, due to the continuous improvement assumption for A380 and the end-of-production assumption (2023) for 767-3ERF.

Case 2 (w/o CI): In the case of without continuous improvement, Scenario 1 would still be no emissions reduction because A380 would be out of production by 2025. Scenario 2, however would produce a small benefit of 2% fuel efficiency improvement from A380 between the pull-ahead schedule of 2023 and the end-of-production year of 2025. The CO2 reduction would be on the order of 6 Mt globally and 1 Mt in U.S. total for Scenario 2.

Case 3 (EP): In the case of extended production (EP) with continuous improvement, the benefit would all come from 767-3ERF since A380 would be compliant with the in-production standards with continuous improvement. Since the pull-ahead schedule is not assumed for freighters, Scenarios 1 and 2 are the same and the estimated CO2 reduction would be on the order of 4 Mt globally and 1 Mt in U.S. total.

Case 4 (EP & w/o CI): In the case of extended production without continuous improvement, Scenario 1 would be benefitted by 3 years of improvement from A380 and 767-3ERF in 2028-2030 and larger improvements required from no continuous improvement baselines. Scenario 2 would be similar except that the A380 benefit would be from the pull-ahead schedule of 2023. The rough estimate of emissions reductions for Scenario 1 would be 14 Mt globally and 3 Mt in U.S. total and for Scenario 2, 24 Mt globally and 4 Mt in U.S. total.

Case 5 (ICAO-like): The ICAO like CO2 reductions have been analyzed previously as 249.75 Mt globally and 45.52 Mt in U.S. total for Scenario 1, and 412.44 Mt globally and 74.82 in U.S. total for Scenario 2.

Given this sensitivity analysis, we can conclude that the technology response and fleet evolution (principally continuous improvement and end of production) assumptions drive the difference between EPA and ICAO analyses. Also, as in Scenario 3, as we modify the continuous improvement (CI) and extended production (EP) assumptions in Scenarios 1 and 2 to be closer to that of the ICAO analysis, the emissions reductions results move progressively closer to ICAO results. These general trends of emissions reductions from EPA analysis to ICAO analysis for Scenarios 1, 2 and 3 are shown in Figure 5-23.

Although uncertainties around these model assumptions exist, the sensitivity studies clearly show that even when we remove the continuous improvement assumption and extend the production of A380 and 767-3ERF to 2030, the emissions reductions for all three scenarios are still quite modest and in all cases are an order of magnitude smaller than that of the ICAO-like analysis. Both assumptions of no improvement for 20 years and extending production of current airplane models indefinitely into the future are highly unlikely to happen in the real world. On the other hand, the business as usual baseline and the independently developed and peer reviewed technology response help estimate the true impact of the standards. In terms of modeling, the agency attributes the business as usual improvements to market competition while ICAO treats them as part of the impacts from the standards. Both are valid with respect to their model assumptions.

In summary, the EPA analysis shows the GHG standards, which match the ICAO Airplane $CO_2$ Emission Standards, have no cost or benefit in Scenarios 1 and 2 but produce a small environmental benefit (1.4 Mt $CO_2$ reductions in the U.S.) in Scenario 3 that is not enough to justify deviating from the international standards. Therefore, the agency is matching the U.S. airplane GHG standards with the ICAO Airplane $CO_2$ Emission Standards. These harmonized standards will enable U.S. airplane and engine manufacturers to compete internationally on a level playing field. Chapter 6 provides further discussions on EPA's rationale for this standard.

## REFERENCES

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[66] ICF, 2018: *Aircraft $CO_2$ Cost and Technology Refresh and Industry Characterization*, Final Report, EPA Contract Number EP-C-16-020, September 30, 2018.

## Analysis of Alternatives

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### Table of Tables



### Table of Equations

# Chapter 6: Analysis of Alternatives

This chapter describes the three scenarios, including the two alternative scenarios, that the EPA analyzed, and it discusses the costs, emission reductions, and benefits of these alternative scenarios. The agency's methodologies for assessing technological feasibility, costs, and emission reductions were described earlier in Chapter 2, Chapter 4, and Chapter 5. The same methodologies were used to analyze the final GHG standards and two alternative scenarios.

## 6.1 Overview

To give context to the alternative scenarios analyzed by the EPA, we will first provide background on the stringency options considered by ICAO/CAEP in developing the international Airplane $CO_2$ Emission Standards. We then describe the alternative scenarios in detail.

### 6.1.1 ICAO/CAEP Stringency Options, International Standards Adopted, and Final Standards

As described in the 2015 ANPR, for the international Airplane $CO_2$ Emission Standards, CAEP analyzed 10 different stringency options (SOs) [lxvi] for standards of both in-production and new type design airplanes, comparing airplanes with a similar level of technology on the same stringency level.[67] These stringency options were generically referred to numerically from "1" as the least stringent to "10" as the most stringent. The 2015 ANPR described the range of stringency options under consideration at ICAO/CAEP as falling into three categories as follows: (1) $CO_2$ stringency options that could impact[lxvii] only the oldest, least efficient airplanes in-production around the world, (2) middle range $CO_2$ stringency options that could impact many airplanes currently in-production and comprising much of the current operational fleet, and (3) $CO_2$ stringency options that could impact airplanes that have either just entered production or are in final design phase but would be in-production by the time the international Airplane $CO_2$ Emission Standards become effective.[1]

In addition, these ten stringency options are described in the report of the CAEP meeting in February 2016.[68] The equation for the ten SOs (or the equation to calculate the SOs' metric values (MVs)) and the accompanying coefficients that determine each of the distinct SOs are provided below in Equation 6-1 and Table 6-1. Equation 6-1 is a second order log curve where the coefficients were derived to match the trends of MVs for airplanes. Table 6-1 shows that there was a kink point at 60,000 kilograms MTOM for each of the ten stringency options. The percentage differences between SOs, which are shown in Table 6-2 below, were not constant because CAEP's intent was for the SOs to affect the full scope of in-production and in-development airplanes as the SOs increased in stringency.[lxviii] The CAEP report indicated that

[lxvi] In this chapter, generally the term, "stringency option" will be used to describe the ten ICAO/CAEP's stringency options, and the term, "stringency level" will be used to describe the final GHG standards, which match the international Airplane $CO_2$ Emission Standards that were agreed to by CAEP in February 2016.

[lxvii] As described in the 2015 ANPR, the airplanes shown in Figures 6-1 and 6-2 are in-production and current in-development. These airplanes could be impacted by in-production standards in that, if they were above the standards, they will need to either implement a technology response or go out of production. For standards for only new type designs, there will be no regulatory requirement for these airplanes to respond.

[lxviii] "In Development" airplanes are the airplanes that were in development by manufacturers at the time of the CAEP cost-effectiveness analysis and the publication of the 2015 ANPR.

the ten SOs provided a convenient analytical space to perform a cost-effectiveness analysis, but these SOs had no particular meaning for the stringencies ultimately agreed upon at CAEP for the international Airplane $CO_2$ Emission Standards.

**Equation 6-1 – Calculation of Metric Values for Ten CAEP Stringency Options**

$$MV = 10^{\left(C0 + C1 * log10(MTOM) + C2 * \left(log10(MTOM)\right)^2\right)}$$

**Table 6-1 –** Coefficients Used in Equation for Ten CAEP Stringency Options

| Coefficients | | SO1 | SO2 | SO3 | SO4 | SO5 | SO6 | SO7 | SO8 | SO9 | SO10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Below 60t | C2 | -0.00129488 | -0.0111115 | -0.0191302 | -0.0233739 | -0.0277861 | -0.0323773 | -0.0371585 | -0.0409071 | -0.0409071 | -0.0409071 |
| | C1 | 0.4623490 | 0.5434880 | 0.6097660 | 0.6448410 | 0.6813100 | 0.7192570 | 0.7587750 | 0.7897580 | 0.7897580 | 0.7897580 |
| | C0 | -2.23839 | -2.42424 | -2.57535 | -2.65507 | -2.73780 | -2.82370 | -2.91298 | -2.98395 | -3.00564 | -3.02627 |
| MTOM at kink point | | 60000 | 60000 | 60000 | 60000 | 60000 | 60000 | 60000 | 60000 | 60000 | 60000 |
| Above 60t | C2 | 0.0593831 | 0.0593831 | 0.0593831 | 0.0593831 | 0.0593831 | 0.0593831 | 0.0593831 | 0.0593831 | 0.0593831 | 0.0593831 |
| | C1 | -0.0205170 | -0.0205170 | -0.0205170 | -0.0205170 | -0.0205170 | -0.0205170 | -0.0205170 | -0.0205170 | -0.0205170 | -0.0205170 |
| | C0 | -1.31651 | -1.33879 | -1.35628 | -1.36529 | -1.37450 | -1.38391 | -1.39353 | -1.40203 | -1.42372 | -1.44435 |

**Table 6-2 – Percentage Differences Between the Ten CAEP Stringency**

| CAEP $CO_2$ Stringency Option | % Difference to SO1 at 60t MTOM | % Difference to Previous SO at 60t MTOM | MV at 60t MTOM |
|---|---|---|---|
| 1 | -- | -- | 0.8734 |
| 2 | -5.0% | -5.0% | 0.8297 |
| 3 | -8.7% | -3.9% | 0.797 |
| 4 | -10.6% | -2.1% | 0.7806 |
| 5 | -12.5% | -2.1% | 0.7642 |
| 6 | -14.4% | -2.1% | 0.7479 |
| 7 | -16.2% | -2.2% | 0.7315 |
| 8 | -17.9% | -1.9% | 0.7173 |
| 9 | -21.9% | -4.9% | 0.6823 |
| 10 | -25.5% | -4.6% | 0.6507 |

At this February 2016 meeting, CAEP agreed on an initial set of international standards to regulate $CO_2$ emissions from airplanes, and the final GHG standards match these international standards. It was agreed that these international standards should apply to both new type design and in-production airplanes. The effective date for the in-production standards were agreed to be later than for the standards for new type designs. This allows manufacturers and certification authorities additional preparation time to accommodate the standards. The standards for smaller and larger new type design and in-production airplanes were agreed to be set at different stringencies to reflect the range of technology being used and the availability of new fuel burn reduction technologies that vary across airplanes of differing size and weight. The final standards and associated effective dates match these provisions for the international standards. Table 6-3 provides a brief overview of the effective dates and stringency levels (SL) of the final standards, which are equivalent to the international standards, including the standards' equations and associated coefficients (as described earlier in Equation 6-1 and Table 6-1). As described earlier, CAEP considered and analyzed 10 different stringency options for standards of both in-production and new type designs (from 1 as the least stringent to 10 as the most stringent). Ultimately, CAEP agreed upon the international Airplane $CO_2$ Emission Standards with a SL8.5 for new type design airplanes greater than about 70,000 kilograms MTOM, which the final standards match for this applicability criteria, and this SL8.5 is between CAEP's SO8 and SO9 (described earlier). There is a difference in the shape of lines for the ten CAEP SOs compared to the final standards. This difference is due to the kink point at 60,000 kilograms MTOM for the ten CAEP SOs versus the horizontal transition between 60,000 and about 70,000 kilograms MTOM for the final standards (which are equivalent to the international standards), as described further below.[lxix]

[lxix] When analyzing stringency options, CAEP determined that there were significant performance differences between large and small airplanes. Airplanes with an MTOM less than 60,000 kilograms are either business jets or regional jets. Due to the physical size of smaller airplanes, there are scaling challenges which limit technology improvements on smaller airplanes compared to larger airplanes. This leads to requiring higher capital costs to implement the technology relative to the sale price of the airplanes. Business jets (generally less than 60,000 kilograms MTOM) tend to operate differently than commercial airplanes by flying at higher altitudes and faster than commercial traffic. Based on these considerations, when developing stringency options for the international standard, ICAO further realized that curve shapes of the data differed for large and small airplanes (on MTOM versus metric value plots). Looking at the dataset, there was originally a gap in the data at 60,000 kilograms. This natural gap allowed a kink point to be established between larger commercial airplanes and smaller business jets and regional jets. The kink point provided flexibility at CAEP to consider standards at appropriate levels for airplanes above and below 60,000 kilograms. (This kink point accommodates a change in slope observed between large and small airplanes.) The flat section of the curve starting at 60,000 kilograms, for the stringency options, is used as a transition to connect the curves for larger and smaller airplanes.

**Table 6-3 – Stringency Levels and Effective Dates for Final GHG Emission Standards**

| | Airplane Weight (MTOM) Thresholds (KG) | New-Type Airplane Maximum Permitted GHG Level | In-Production Airplane Maximum Permitted GHG Level |
|---|---|---|---|
| **Stringency Level** | >5,700 to <60,000 | SL5<br>a | SL3<br>A |
| | Horizontal Transition[lxx]<br>60,000 to ~ 70,000 | SL5-SL8.5[lxxi]<br>c | SL3-SL7[lxxii]<br>D |
| | > ~70,000 | SL8.5<br>e | SL7<br>F |
| **Implementation Date** | Application for a new-type certificate or a change to an existing-type certificate | 2020<br>(2023 for planes with less than 19 seats) | 2023 |
| | Production Cut-Off | n/a | 2028 |

a. Equation of Stringency Level #5: $\boldsymbol{MV = 10^{-2.73780 + (0.681310 * log10(MTOM)) + \left(-0.0277861 * (log10(MTOM))^2\right)}}$

Equation of Stringency Level #3: $\boldsymbol{MV = 10^{-2.57535 + (0.609766 * log10(MTOM)) + \left(-0.0191302 * (log10(MTOM))^2\right)}}$

Equation of New Type transition – 60,000 to 70,395kg: $\boldsymbol{MV = 0.764}$

Equation of In-production transition – 60,000 to 70,107kg: $\boldsymbol{MV = 0.797}$

Equation of Stringency Level #8.5: $\boldsymbol{MV = 10^{-1.412742 + (-0.020517 * log10(MTOM)) + \left(0.0593831 * (log10(MTOM))^2\right)}}$

Equation of Stringency Level #7: $\boldsymbol{MV = 10^{-1.39353 + (-0.020517 * log10(MTOM)) + \left(0.0593831 * (log10(MTOM))^2\right)}}$

Figure 6-1 and Figure 6-2 show a graphical depiction of both the final standards for new type design and in-production airplanes compared against the 10 CAEP stringency options (described earlier) and the $CO_2$ metric values (as of February 2017) of in-production and in-development[lxxiii] airplanes. As described in earlier chapters of this TSD, the airplane metric value data shown were generated by the EPA using a commercially available airplane modeling tool called PIANO (PIANO version 5.4, dated February 2017).[69] Note, a number of the

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[lxx] Stringency lines above and below 60,000 kilograms (MTOM) are connected by a horizontal transition starting at 60,000 kilograms (MTOM) and continuing right (increasing mass) until it intersects with the next level.

[lxxi] The stringency level for the standards starting at 60,000 kilograms maintains the level of SL5 until it intersects the SL8.5 at 70,395 kilograms (MTOM).

[lxxii] The stringency level for the standards starting at 60,000 kilograms maintains the level of SL3 until it intersects SL7 at 70,107 kilograms (MTOM).

[lxxiii] Airplanes that are currently in-development but will be in production by the applicability dates. These could be new type design or significant partial redesigned airplanes.

airplanes currently shown as in-production are expected to go out of production and be replaced by known in-development airplanes prior to both the final GHG standards for new type design and the in-production airplanes going into effect.

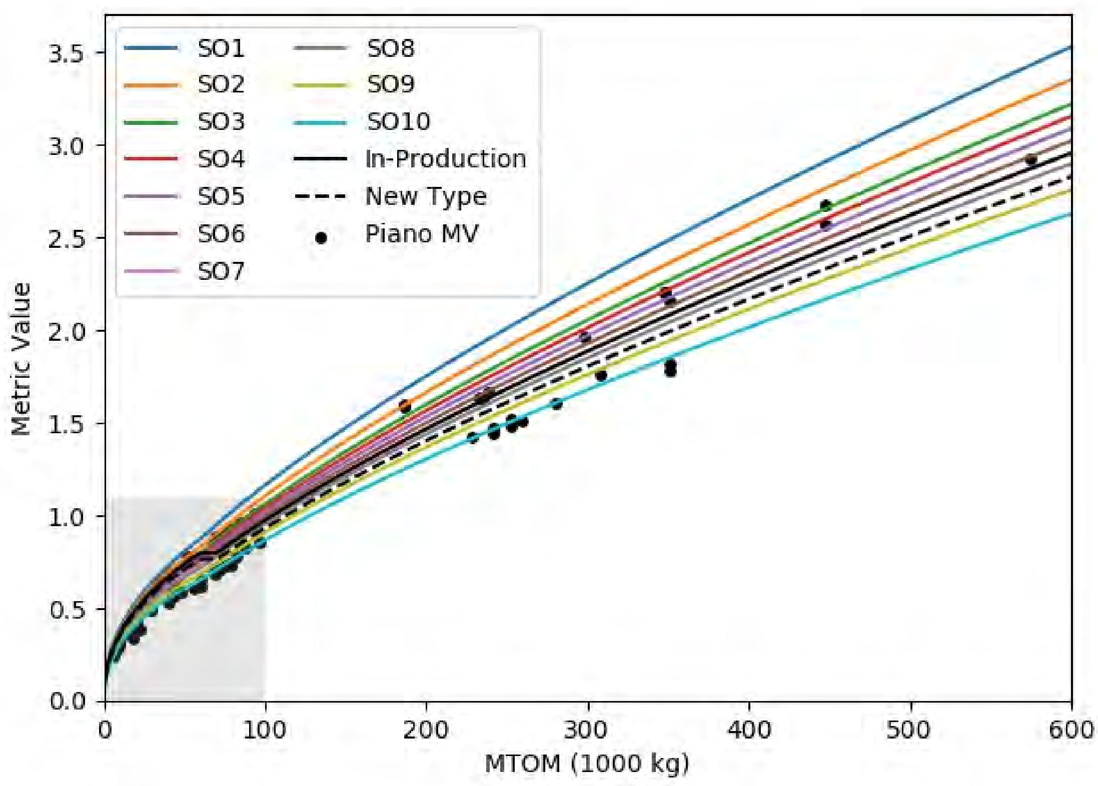


**Figure 6-1 – Final GHG Emission Standards and CAEP's Ten Stringency Options (MTOM in kilograms)[lxxiv]**

[lxxiv] In the legend of Figure 6-1 and Figure 6-2, "In-Production" and "New Type" refer to the graphical depiction of the final standards for in-production and new type design airplanes, and the international standards agreed to at the February 2016 CAEP meeting match these final standards.

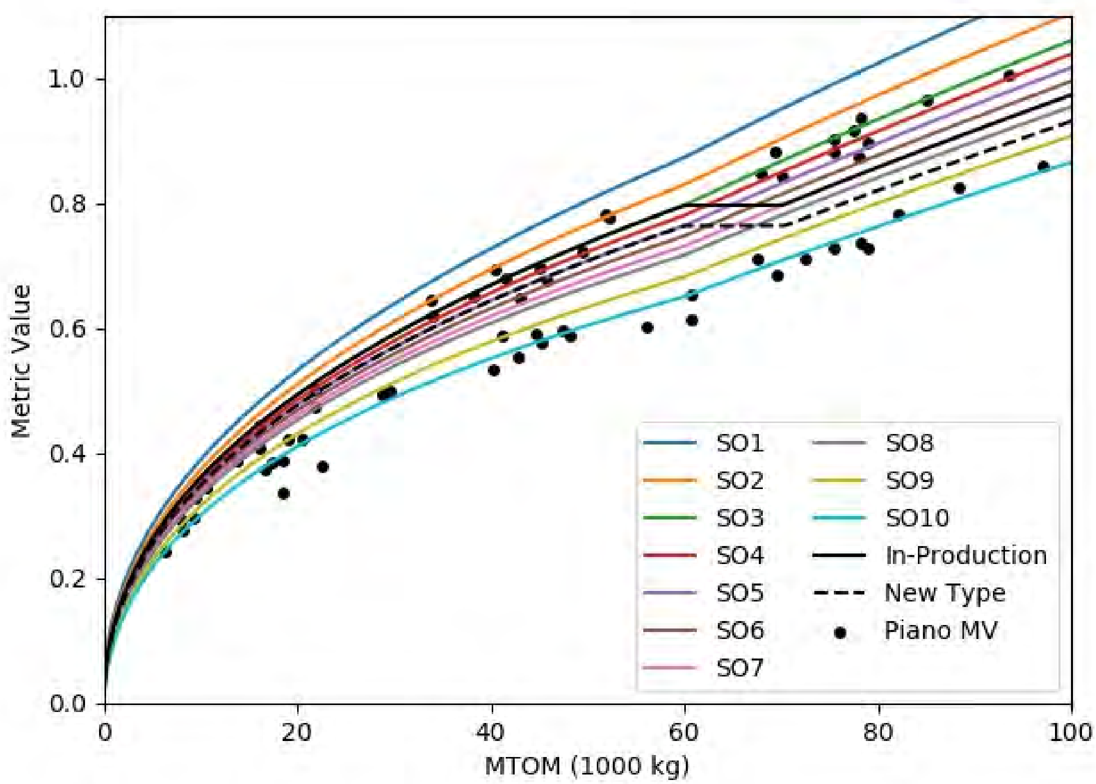


**Figure 6-2 – Final GHG Emission Standards and CAEP's Ten Stringency Options**

**(Zoomed to show <100,000 MTOM in kilograms)**

### 6.1.2 Alternatives Considered in the Context of CAEP Stringency Options, International Standards Adopted, and Final Standards

As discussed earlier, in the EPA consideration of alternative scenarios, the final GHG standards, which match the international standards, are designated as the primary scenario, identified as Scenario 1 (described earlier in Table 6-3). The alternative scenarios considered the earlier implementation dates and more stringent levels (or more stringent options) that CAEP analyzed. The two alternative scenarios, identified as Scenarios 2 and 3, were defined to consider whether moving the implementation date(s) forward (for in-production airplanes) and tightening the stringency (for both in-production and new type designs) would make a meaningful difference.[lxxv] Scenario 2 reflects the earliest implementation date that is practical, and Scenario 3 represents the most stringent option analyzed by CAEP. All three scenarios are summarized below in Table 6-4, and all three scenarios are assessed against the (no regulation)

[lxxv] As described earlier, CAEP analyzed stringency options that were less stringent than the standards ICAO ultimately adopted. As discussed in section II.D. of the Federal Register Notice for this rule, under the Chicago Convention, we are obligated to adopt standards that are at least as stringent as ICAO standards. Thus, the EPA did not analyze any CAEP stringency options that are less stringent than the ICAO standards.

baseline that assumes continuous (2016-2040) annual fuel efficiency improvements and end of production timing (for some in-production airplanes) --as described in Chapter 5. As described earlier, for smaller and larger airplanes, under all three scenarios, the stringencies for new type design and in-production airplanes are assumed to be set at different levels to reflect the range of technology being used and the availability of new fuel burn reduction technologies that vary across airplanes of differing size and MTOM.

**Table 6-4 – Final Rule and Alternative Scenarios**

| Scenario | Option | Description of Stringency and Effective Date |
|---|---|---|
| 1 | Final Rule<br>(see Table 6-3 above) | -<u>New Type</u>: SL8.5, 2020<br>(SL5, 2023 for new type airplanes ≤ 60 tons[lxxvi,lxxvii] & ≤ 19 seats)<br>-<u>In-Production</u>: SL7 (5% less stringent vs. new type), 2028[lxxviii]<br>(SL3, 4% less stringent vs. new type, 2028 also for in-production airplanes ≤ 60 tons and dedicated freighters)<br>(2023 for GHG adverse or significant In-Production type changes) |
| 2 | Pull Ahead Some In-Production<br>Dates | -<u>New Type</u>: Same stringencies and same effective dates for New Type as Scenario 1<br>-<u>In-Production</u>: Differentiate In-Production effective dates and move general effective date to 2023<br>(move in-production airplanes ≤ 60 tons effective date to 2025, but retain 2028 effective date for in-production dedicated freighters) |
| 3 | Pull Ahead Some New Type and In-Production<br>Dates and More Stringent<br>Levels | -<u>New Type</u>: Similar to ICAO SO9, 2.5% more stringent than Scenario 1's SL8.5<br>(Matches ICAO SO6, 2% more stringent than Scenario 1's SL5 and 2020 for airplanes ≤ 60 tons)<br>-<u>In-Production</u>: Similar to ICAO SO8 or SO9[lxxix], 2% to 7% more stringent than Scenario 1's SL7 [lxxx] and move effective date to 2023<br>(Matches ICAO SO5, 3% to 4% more stringent than Scenario 1's SL3 for in-production airplanes ≤60 tons and move effective date to 2025, but retain 2028 effective date for in-production dedicated freighters) |

[lxxvi] In this rulemaking, 60 tons means 60 metric tons, which is equal to 60,000 kilograms (kg). Or, 1 ton means 1 metric ton, which is equal to 1,000 kg.

[lxxvii] For both new type design airplanes and in-production airplanes, the MTOM thresholds for covered airplanes are as follows: greater than 5.7 tons (or 5,700 kilograms) MTOM for subsonic jet airplanes and greater than 8.618 tons (8,618 kilograms) MTOM for turboprop airplanes.

[lxxviii] For Scenarios 1 and 2, the 19-seat differentiation (for airplanes less than or equal to 60 tons MTOM) in effective date only applies to new type design airplanes.

[lxxix] Scenario 3 includes two stringency options, ICAO SO8 and SO9, for in-production airplanes greater than 60 tons MTOM.

[lxxx] For Scenario 3, its more stringent levels also apply to dedicated freighters (including dedicated freighters less than or equal to 60 tons MTOM), but the 2028 in-production effective date is retained for dedicated freighters.

## Analysis of Alternatives

Scenario 2 considers whether an earlier implementation date for the final GHG standards will result in benefits that outweigh the costs. Scenario 2 will have the same stringencies as Scenario 1 (and the final standards, which match the international standards). However, in contrast to Scenario 1 where the standards will only become effective on or after January 1, 2023, for GHG adverse or significant in-production type changes,[lxxxi] Scenario 2 will have this same effective date for most in-production airplanes, which is five years earlier than Scenario 1.[lxxxii] This earlier effective date for Scenario 2 is based on expected improvements to airplanes and changes in their production status in the next five years. For in-production airplanes that are 60 tons or less MTOM, the Scenario 2 effective date is assumed to be moved to 2025, which is three years earlier than Scenario 1. Flexibility is provided for airplanes that are 60 tons or less MTOM because these smaller airplanes have limited technologies available to incorporate in comparison to larger airplanes (mainly larger passenger commercial airplanes), and smaller airplanes have different economic viability of technology development relative to larger airplanes.[lxxxiii] But for dedicated freighters, the Scenario 2 effective date will remain the same as Scenario 1 (January 1, 2028). Flexibility is provided for these dedicated freighters in Scenario 2 because of the unique aspects of the market for commercial air cargo transport -- e.g., the small size of the market for air cargo transport services and the potentially limited business case for making improvements to these airplanes.[lxxxiv]

Scenario 3 considers more stringent standards in addition to an earlier implementation date for new type design airplanes that are 60 tons or less MTOM and 19 seats or less (in maximum passenger seating capacity) and the same earlier effective dates for in-production airplanes considered in Scenario 2. Similar to Scenario 2, Scenario 3 has a January 1, 2023, effective date (five years earlier than Scenario 1) for in-production airplanes in general, a January 1, 2025, effective date for in-production airplanes that are 60 tons or less MTOM, and a January 1, 2028, effective date for in-production airplanes that are dedicated freighters. In addition, Scenario 3 will have more stringent standards for both new type design and in-production airplanes compared to Scenarios 1 and 2. For new type design airplanes greater than 60 tons MTOM, the stringency will be similar to ICAO SO9 and be 2.5 percent stricter compared to Scenario 1's

[lxxxi] Scenario 1's 2028 implementation date for in-production airplanes will be a production cut-off, which means that in-production airplane that do not comply with the final standards after this date will not be allowed enter into service or be built. Also, Scenario 1 has a 2023 implementation date for in-production airplanes with adverse GHG emission changes or significant in-production type changes. This provision means that after 2023, applications to change a type design of a non-GHG certificated airplane that either increase the Metric Value of the airplane, increase the MTOM of the airplane, or significantly change the airplane's GHG emissions (significant decrease in GHG emissions) will be required to comply with the in-production rule. The provision is meant to capture changes to those non-GHG certificated airplanes built prior to the production cut-off date of 2028.

[lxxxii] For Scenario 2, the production cut-off date will be 2023.

[lxxxiii] U.S., United States Position on the ICAO Aeroplane $CO_2$ Emissions Standard, Montréal, Canada, CAEP10 Meeting, February 1-12, 2016, Presented by United States, CAEP/10-WP/59. Available in the docket for this rulemaking, Docket EPA-HQ-OAR-2018-0276.

[lxxxiv] In-production airplanes that are dedicated freighters have developed a unique market segment for the business case of providing air cargo transport services. Demand for new purpose-built freighters is relatively low, therefore they are produced in smaller volumes than their passenger equivalents. Because of the size of the market, manufacturers of dedicated freighters may have a potentially limited business case for making improvements to these airplanes.

ICAO/CAEP, United States Position on the ICAO Aeroplane $CO_2$ Emissions Standard, Tenth Meeting of CAEP, Montréal, Canada, February 1 to 12, 2016, CAEP/10-WP/59.

SL8.5 (and Scenario 2). For new type design airplanes 60 tons or less MTOM, the stringency will match ICAO SO6 and be 2 percent stricter than Scenario 1 and Scenario 2's SL5. For in-production airplanes greater than 60 tons MTOM, we consider a range of stringencies (or two stringencies) as part of Scenario 3. For these in-production airplanes, the stringency will be similar to either ICAO SO8 or SO9 and be 2 to 7 percent stricter (depending on the MTOM) compared to Scenario 1 and Scenario 2's SL7. For in-production airplanes 60 tons or less MTOM, the stringency will match ICAO SO5 and be 3 to 4 percent stricter than Scenario 1 and Scenario 2's SL3.

Scenario 3 reflects the position proposed by the U.S. as an ICAO Member country. However, with U.S. concurrence the tenth meeting of ICAO/CAEP, which occurred in February 2016, did not adopt the U.S. Scenario 3-equivalent position.[lxxxv] For harmonizing with the international standards and providing global consistency of standards, which will ensure all the world's manufacturers need to comply (or certify) to the same standards and no U.S. manufacturer finds itself at a competitive disadvantage, we are finalizing standards that match the ICAO standards (see further rationale for the final standards compared to Scenario 3 later in section 6.4).

Figure 6-3 and Figure 6-4 below show the in-production stringencies for the three scenarios as plots.[lxxxvi] Figure 6-3 shows the scenarios over the entire MTOM range, and Figure 6-4 zooms in on the scenarios below 100 tons MTOM.[lxxxvii] In Figure 6-3 and Figure 6-4, Scenario 1 is red, Scenario 2 is blue, and Scenario 3 is green. The lines for Scenarios 1 and 2 are identical in stringency level, and they only differ in their effective dates. Thus, they overlap in these figures. Scenario 3 is shown as a range in stringency options for in-production airplanes as described above (CAEP SO8 or SO9). Three metric values are plotted for each airplane, corresponding to the values for each scenario's effective date. For the scenarios with different effective dates, the projection of constant annual improvement in fuel efficiency metric value applied for each airplane leads to the difference in metric value for the same airplane -- as described earlier in Chapter 2. Note the metric values for Scenarios 2 and 3 are the same since they have the same effective dates.

The solid red circles represent the metric value each airplane would have at Scenario 1's 2028 in-production applicability date. The open red circles represent the metric value each out of production airplane would have at 2028 (Scenario 1). The solid blue and green circles represent the metric value each airplane would have at Scenario 2 and Scenario 3's 2023 in-production applicability date. The open blue and green circles represent the metric value each out of production airplane would have at 2023 (Scenarios 2 and 3). With fewer baseline improvement

[lxxxv] ICAO/CAEP, United States Position on the ICAO Aeroplane $CO_2$ Emissions Standard, Tenth Meeting of CAEP, Montréal, Canada, February 1 to 12, 2016, CAEP/10-WP/59.

[lxxxvi] The analysis focused on in-production airplanes because, as described in Chapter 2, a technology response is not necessary for new type design airplanes to meet the scenarios.

[lxxxvii] Scenario 1 (and Scenario 2) will have a constant metric value or stringency level for MTOMs between 60 tons and 70.107 tons. For the purposes of presenting Scenario 3 in Figure 6-3 and Figure 6-4, Scenario 3 also has a constant stringency level in this MTOM range. ICF analyzed Scenario 3 with a varying stringency level in this same MTOM range or a kink point at 60 tons MTOM (similar to the ICAO/CAEP SOs), which is consistent with the U.S. position proposed by the U.S. ICAO Member at the tenth meeting of ICAO/CAEP. The results of airplanes affected by Scenario 3 do not change with either having a constant stringency level between 60 tons and 70.107 tons or instead having a kink point at 60 tons MTOM.

years prior to applicability, the 2023 metric values (blue and green circles) would be expected to be higher than the corresponding 2028 values (red circles).

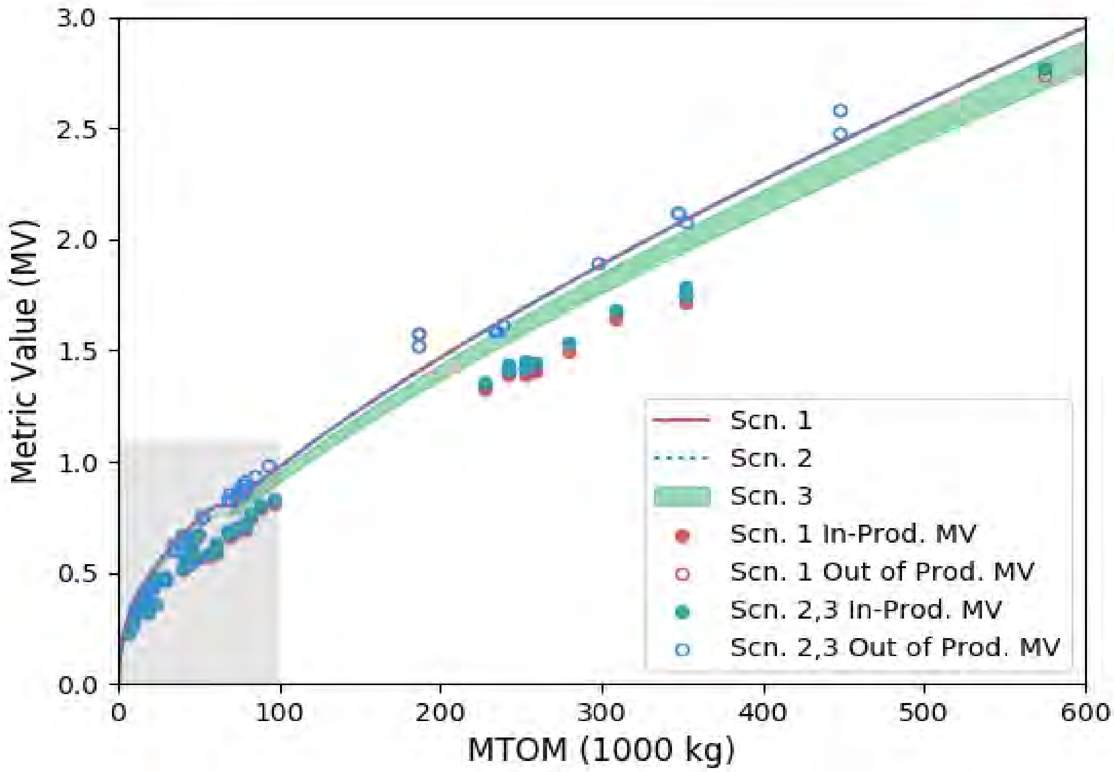


**Figure 6-3 – In-Production Airplane Stringency Lines for the Three**

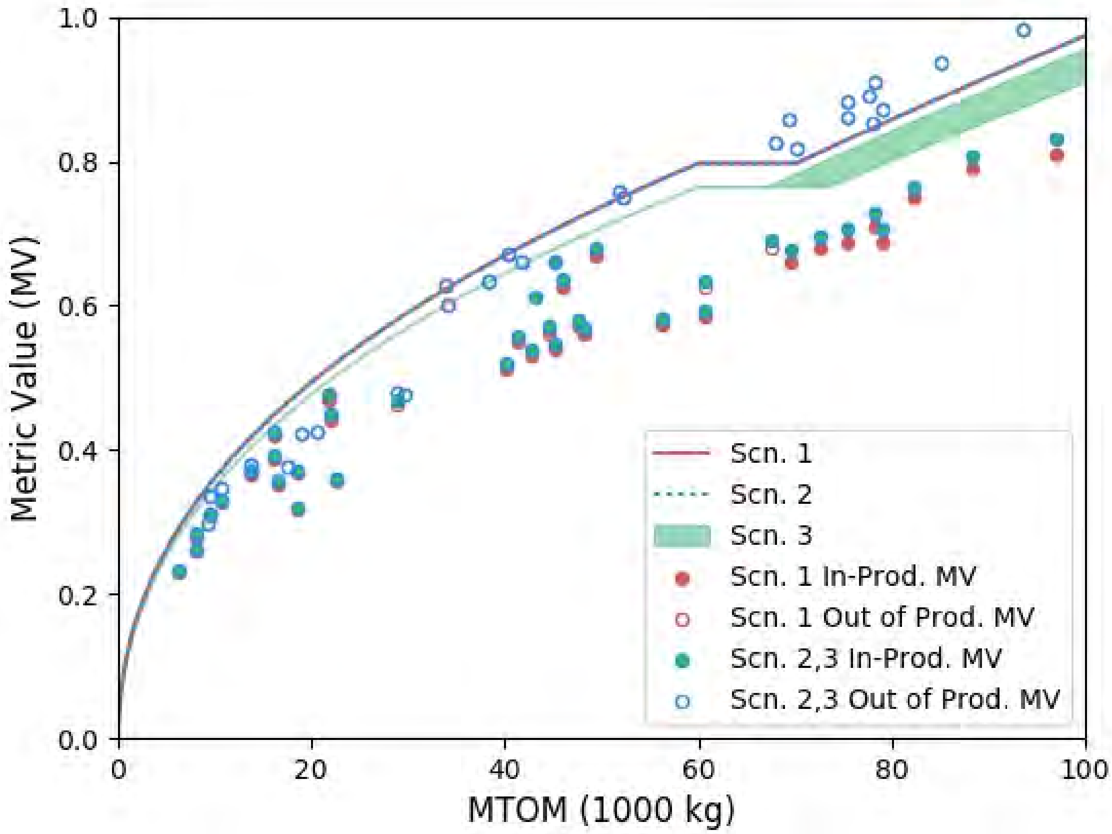


**Figure 6-4 – Detail of In-Production Airplane Stringency Lines for Airplane Below 100 tons MTOM**

## 6.2 GHG Emission Reductions and Costs of Two Alternative Scenarios

The methods used to analyze the GHG costs and emission reductions from the final standards and the two alternative scenarios are described in Chapter 2, Chapter 4, and Chapter 5. Although the final standards (Scenario 1) do not have any costs or emission reductions (based on the rationale provided in the earlier chapters), the effects of the final standards were analyzed using the same methods as the two alternative scenarios.

### 6.2.1 Scenario 2

Scenario 2 would not be expected to result in additional GHG reductions or costs relative to the final standards or Scenario 1. As described earlier in Chapter 2 and Chapter 5 for the final standards (Scenario 1), under Scenario 2 manufacturers comply through already developed or developing technologies to respond to ICAO standards. Moreover, as described in Chapter 2, with the baseline constant annual improvement in fuel efficiency metric value in the absence of rules, all but one airplane model are still expected to be in production and compliant with the 5-year pull ahead associated with Scenario 2. The exception is a single dedicated freighter airplane (Boeing 767-3ERF); however, the 5-year accelerated implementation date will not apply to dedicated freighters for Scenario 2. This provision would mean that the 767-3ERF is not disadvantaged by Scenario 2, and those additional years allow for it to come into compliance given the assumed baseline constant annual improvement in fuel efficiency metric value.[70]

However, it is informative to describe the 767-3ERF's metric value compared with Scenario 2's stringency level but without a five-year delay for dedicated freighters (for a 2023 effective date). The 767-3ERF's metric value would be 7.91 percent greater than Scenario 2 in 2023 (does not meet level of Scenario 2). With a 1 percent design margin,[lxxxviii] as described earlier in Chapter 2, there would need to be an 8.91 percent improvement in the 767-3ERF metric value by 2023 to comply with Scenario 2 (and an 8.91 percent reduction in GHG emissions per 767-3ERF). With this amount of improvement needed for the 767-3ERF to comply with Scenario 2 in 2023 and the 767-3ERF expected to be end production in 2023, the manufacturer would be anticipated to pull forward its final year of production by one year (2022) instead of making the investment for the technology response to comply with Scenario 3. Yet, with the dedicated freighter delay to 2028 in Scenario 2, this pull forward in the end of production for the 767-3ERF would not need to occur. As described above, the 767-3ERF would comply with Scenario 2 based on its expected end of production in 2023 in the absence of a standard, and thus, there would be no emission reductions or costs from Scenario 2 based on the 767-3ERF. In addition, even if we were to change the above expectations, the manufacturer of the 767-3ERF could utilize the exemption provisions described in section V.E of the preamble, which are intended for airplanes at the end of their production life. If Boeing chose to apply for an exemption and it was granted, the 767-3ERF would not need to respond to Scenario 2, and thus, there would be no resultant emission reductions or costs for Scenario 2 from the 767-3ERF.

We note that in their comments on the proposed rulemaking Boeing, along with Fedex, GE, and the Cargo Airline Association, expressed that there would continue to be a low volume demand for the B767 freighter beyond January 1, 2028. These commenters did not indicate the number of 767F's that would be produced after 2028. The EPA did not change the analysis to include continued production of the 767F beyond 2028 because insufficient information to characterize this scenario was provided.

### 6.2.2 Scenario 3

Scenario 3 both accelerates the implementation date by 5 years and increases the stringency. This scenario would be expected to result in additional GHG reductions and costs relative Scenarios 1 and 2. Using the same assumptions applied to the other scenarios, the baseline constant annual improvement in fuel efficiency metric value for each airplane and the delay to 2028 for dedicated freighters, there are limited reductions and costs from Scenario 3. These limited costs and emission reductions are due the impacts on a single airplane model, the Airbus A380.

As described earlier in a Chapter 5 footnote, on February 14, 2019, Airbus made an announcement to end A380 production by 2021 after Emirates airlines reduced its A380 order by

[lxxxviii] The 2018 ICF updated analysis indicated that for those airplanes that do not meet a stringency level, an additional 1 percent design margin above the shortfall would need to be reached. This design margin would ensure the technology addresses the response to the stringency level (actual $CO_2$ reduction for a given technology is variable).

39 airplanes and replaced them with A330s and A350s.[lxxxix] The early exit of A380 will result in no costs and no emission reductions from Scenario 3. However, this EPA analysis of Scenario 3 was conducted prior to Airbus's announcement, so the analysis did not consider the effect of the A380 ending production in 2021. Thus, this analysis results in limited costs and emission reductions for Scenario 3.

#### *6.2.2.1 767-3ERF*

Due to the dedicated freighter 5-year delay in Scenario 3, the 767-3ERF would comply with Scenario 3 for the same reason described above for Scenario 2. However, it is informative to describe the 767-3ERF's metric value compared to the stringency level of Scenario 3. The 767-3ERF's metric value would be 15.7 percent greater than Scenario 3. With a 1 percent design margin, there would need to be a 16.7 percent improvement in the 767-3ERF metric value by 2023 to comply with Scenario 3 (and a 16.7 percent reduction in GHG emissions per 767-3ERF). As with Scenario 2, with this greater amount of improvement (for Scenario 3 compared to Scenario 2) needed for the 767-3ERF to comply with Scenario 3 in 2023 and the 767-3ERF expected to end production in 2023, the manufacturer would be even more likely (versus Scenario 2) to pull forward its final year of production by one year (2022) instead of making the investment to comply with Scenario 3. Yet, with the dedicated freighter delay to 2028 in Scenario 3, this pull forward in the end of production for the 767-3ERF would not be needed. As described above, the 767-3ERF would comply with Scenario 3 based on its expected end of production in 2023 in the absence of a standard, and thus, there would be no emission reductions or costs from Scenario 3 based on the 767-3ERF. In addition, (as with Scenario 2) even if we were to change the above expectations, the 767-3ERF could utilize the exemption provisions described in section V.E of the preamble, which are intended for airplanes at the end of their production life.

As described earlier, we note that in their comments on the proposed rulemaking Boeing, along with Fedex, GE, and the Cargo Airline Association, expressed that there would continue to be a low volume demand for the B767 freighter beyond January 1, 2028. These commenters did not indicate the number of 767F's that would be produced after 2028. The EPA did not change the analysis to include continued production of the 767F beyond 2028 because insufficient information to characterize this scenario was provided.

#### *6.2.2.2 A380*

For Scenario 3, with the baseline constant annual improvement, the 5-year earlier effective date (except dedicated freighters that retain the 2028 effective date), and tighter stringency levels for in-production airplanes, one in-production airplane model would not comply. Further, the impacted airplane model would need a technology response to stay in production after the effect date, and the technology response would lead to GHG reductions and costs (and fuel savings) compared to Scenarios 1 and 2. This airplane model is the Airbus A380-842/A380-861 (herein referred to as the "A380"). The A380 does not comply with the in-production level that is 7 percent more stringent than Scenarios 1 and 2 (Scenario 3 will be similar to the level of ICAO

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[lxxxix] The Airbus press release is available at: https://www.airbus.com/newsroom/press-releases/en/2019/02/airbus-and-emirates-reach-agreement-on-a380-fleet--sign-new-widebody-orders.html, last accessed on February 10, 2020.

SO9 for in-production airplanes greater than 60 tons MTOM and will be effective in 2023). The A380's metric value would be 3.24 percent greater than Scenario 3. With a 1 percent design margin, there would need to be a 4.24 percent improvement in the A380 metric value by 2023 to comply with the Scenario 3 metric value requirement. Applying a constant annual improvement in fuel efficiency metric value would mean 1.71 percent of these reductions would already have been obtained by 2023 (by business as usual technology improvements in the absence of a standard), and the remaining portion of the reductions, 1.53 percent, would be achieved through technology response. With the 1 percent design margin, the technology response would become 2.53 percent. Table 6-5 shows the result of this method for determining the metric value reduction for technology response for the A380.

**Table 6-5 – A380 Scenario 3 – Implementation of Technology Response**

| | No Design Margin | 1% Design Margin |
|---|---|---|
| Percent MV Greater than Scenario 3 | 3.24% | 4.24% |
| Residual Implemented MV Improvement | (1.71%) | (1.71%) |
| Technology Response Improvement Target | 1.53% | 2.53% |
| Technology Response: Adaptive Trailing Edge | 2.00% of A380 baseline MV | 2.00% of A380 baseline MV |
| Technology Response: ECS Aero | N/A | 0.63% of A380 baseline MV |
| Non-Recurring Cost to Implement Technology Response | $493M | $580M |

Based on the supply curve method in the 2018 ICF updated analysis, which is described earlier in Chapter 2, the anticipated technology response (or the most economical technology response) for the A380 would be the adaptive trailing edge and environmental control system (ECS) aerodynamic cleanup and on-demand ECS scheduling, if the 1 percent design margin is necessary (and only adaptive trailing edge if the 1 percent design margin is not needed). These technology responses are described further in Chapter 2. Figure 6-5 provides the supply curve for the technology response of the A380.[4,xc]

[xc] As described in Chapter 2 and earlier in section 6.2.2.2, for a given future year, a manufacturer's technology insertion is assumed to have progressed up the supply curve (i.e. technologies with largest improvement and most economical cost are implemented first). Therefore, these economical technologies would have already been implemented by the stringency year, and they will not be available for future investment. Then, we overlay the smoothed forecasted incremental metric value improvement by the stringency year on the airplane model's discrete supply-curve. From this overlay, ICF identified the most economical technologies that would already have been implemented by the stringency year, and these technologies represent business as usual improvement or continuous metric value improvement by the stringency year – or 2023 improvement level. The red-dashed line in Figure 6-2 shows the continuous metric value improvement by 2023 or the 2023 improvement level. Subsequently, the remaining technologies not yet implemented, which are those technologies that are to the right of the red-dashed line, would be available for the technology response needed to meet Scenario 3.

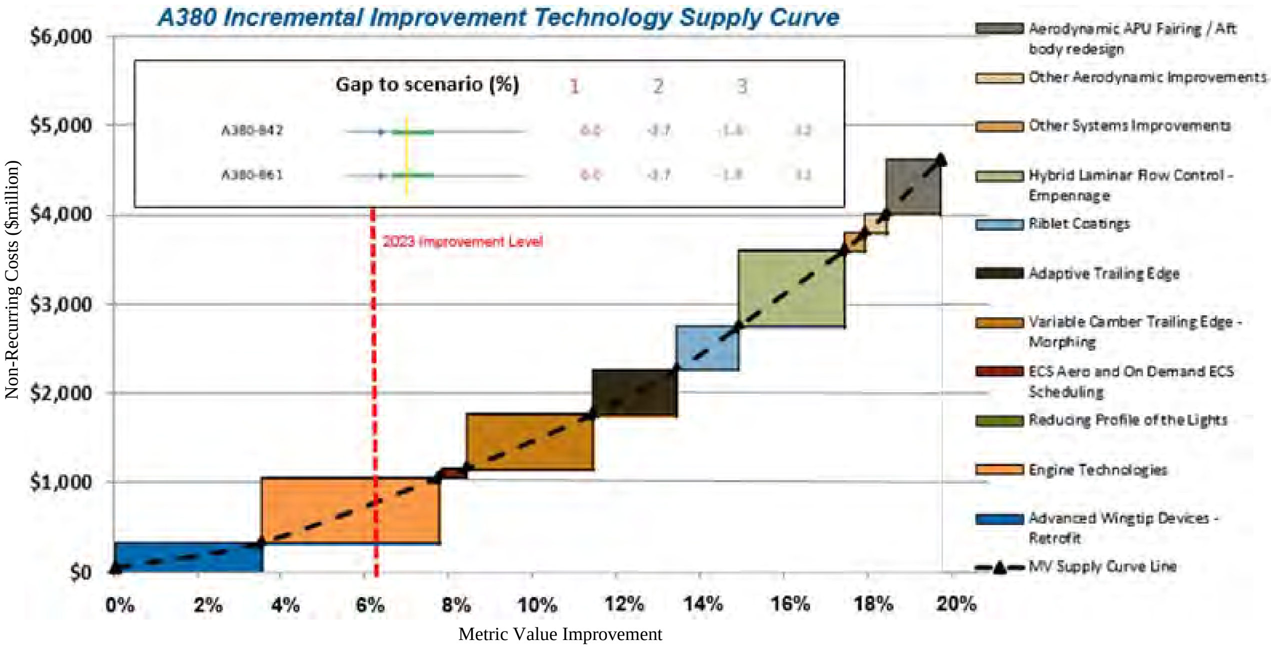


**Figure 6-5 – A380 Incremental Improvement Technology Supply Curve**

#### *6.2.2.2.1 A380's GHG Emission Reductions*

For Scenario 3, we also estimated that the U.S. covered airplane GHG emissions would be reduced in 2030 and 2040 from the anticipated technology response for the A380s built after January 1, 2023 (Scenario 3's effective date for in-production airplanes over 60 tons MTOM). (Note, as described in section III of the preamble, $CO_2$ represents 99 percent of all GHGs emitted from both total U.S. airplanes and U.S. covered airplanes (in megatonnes of $CO_2$ equivalent), and nitrous oxide ($N_2O$) represents 1 percent of GHGs emitted from total airplanes and U.S. covered airplanes.) However, the emissions reductions from such a response would be limited since the 2018 ICF updated analysis projects that the number of A380s that would be built after January 1, 2023, would be about 40 airplanes. The cumulative reductions in U.S. covered airplane GHG emissions for Scenario 3[xci] would be as follows (percentage and absolute reductions): about 0.7 percent and 0.6 Mt $CO_2$ equivalent for 2030 and about 0.8 percent and 1.4 Mt $CO_2$ equivalent for 2040. Further details about the emissions impacts of Scenario 3 are provided in Chapter 5.

#### *6.2.2.2.2 A380's Costs*

Based on the same reasons as discussed earlier in this section there would be limited technology response costs from only the A380 needing to respond to Scenario 3. As described earlier, the technology response for the A380 to comply would be the adaptive trailing edge and

[xci] ICF projected that about 40 A380s would be built globally after January 1, 2023. The cumulative reductions in U.S. covered airplane GHG emissions would be from about 40 A380s receiving a technology response for Scenario 3 from 2023 to 2030. However, as discussed earlier in Chapter 5, we did not connect these cumulative GHG reductions to a specific number of A380s used in the EPA analysis, but instead we connected the reductions to a specific amount of operations.

ECS aerodynamic cleanup and on-demand ECS scheduling. We estimated that the non-recurring cost to apply this technology response to the A380 would be about $415 million and $501 million (in 2015$), at 7 and 3 percent discount rates respectively.[xcii] Chapter 2 provides the details of the cost methodology.

Similar to the earlier discussion in Chapter 2, the 2018 ICF updated analysis indicates that if technologies would add significant recurring costs (recurring operating and maintenance costs) to an airplane and/or an operator (e.g., an air carrier), an air carrier would likely not add these technologies to their airplanes. Thus, the 2018 ICF updated analysis estimates that there would be no recurring costs for the projected technology response of the A380 to Scenario 3.

In addition, for Scenario 3, the A380 could apply to utilize the exemption provisions (described in section V.E of the preamble), which are intended for airplanes at the end of their production life. If Airbus chose to apply for an exemption and it was granted, the A380 would not need to respond to Scenario 3, and thus, there would be no resultant emission reductions or costs for Scenario 3.

#### *6.2.2.3 Monetized Benefits for A380*

We estimate the climate benefits associated with alternative regulatory Scenario 3 using a measure of the domestic social cost of carbon and nitrous oxide (SC-$CO_2$ and SC-$N_2O$). Scenario 3 is the only alternative scenario with potential SC-$CO_2$ and SC-$N_2O$ emission reductions. The social cost of these greenhouse gases is a metric that estimates the monetary value of impacts associated with marginal changes in $CO_2$ emissions in a given year. It includes a wide range of anticipated climate impacts, such as net changes in agricultural productivity and human health, property damage from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning. It is typically used to assess the avoided damages as a result of regulatory actions (i.e., benefits of rulemakings that lead to an incremental reduction in cumulative global $CO_2$ emissions). The SC-$CO_2$ and SC-$N_2O$ estimates used in this TSD focus on the direct impacts of climate change that are anticipated to occur within U.S. borders.

The SC-$CO_2$ and SC-$N_2O$ estimates used in this TSD are interim values developed under E.O. 13783 -- for use in regulatory analyses until an improved estimate of the impacts of climate change to the U.S. can be developed based on the best available science and economics.[xciii] See

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[xcii] We began by using the ICF's estimate for undiscounted non-recurring costs of $580 million for this technology response (of these two technologies together). Subsequently, we allocated a fifth of these NRC costs to each of the five years preceding 2023 since the costs would typically be spent over a five-year period (instead of all in one year). Next, we discounted these annual costs back to 2015 at 7 percent and 3 percent discount rates to calculate the resulting total present value of non-recurring costs of $415 million and $501 million (in 2015$), respectively.

[xciii] Such improved domestic estimates would take into considerations the recent recommendations from the National Academies of Sciences, Engineering, and Medicine for a comprehensive update to the current methodology to ensure that the social cost of greenhouse estimates reflect the best available science. While the Academies' review focused on the methodology to estimate the social cost of carbon (SC-$CO_2$), the recommendations on how to update many of the underlying modeling assumptions also pertain to the SC-$N_2O$ estimates since the framework used to estimate SC-$N_2O$ is the same as that used for SC-$CO_2$. See National Academies of Sciences, Engineering, and Medicine, Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon

the Appendix[71] for additional discussion of E.O. 13783 and an explanation of the modeling steps involved in estimating the domestic estimates used in this TSD.

Table 6-6 and Table 6-7 present the average domestic SC-$CO_2$ and SC-$N_2O$ estimates, respectively, across all the model runs using both 3 and 7 percent discount rates for the years 2015 to 2050. As with the global social cost of greenhouse gas estimates, the domestic estimates increase over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change, and because gross domestic product (GDP) is growing over time and many damage categories are modeled as proportional to gross GDP.

**Table 6-6 – Interim Domestic Social Cost of $CO_2$, 2015-2050 (in 2015$ per metric ton)***

| Year | Discount Rate and Statistic | |
|---|---|---|
| | 3% Average | 7% Average |
| 2015 | $6 | $1 |
| 2020 | 6 | 1 |
| 2025 | 7 | 1 |
| 2030 | 8 | 1 |
| 2035 | 8 | 2 |
| 2040 | 9 | 2 |
| 2045 | 10 | 2 |
| 2050 | 10 | 2 |

* These SC-$CO_2$ values are stated in $/metric ton $CO_2$ and rounded to the nearest dollar. The estimates vary depending on the year of $CO_2$ emissions and are defined in real terms, i.e., adjusted for inflation using the GDP implicit price deflator.

**Table 6-7 – Interim Domestic Social Cost of $N_2O$, 2015-2050 (in 2015$ per metric ton)***

| Year | Discount Rate and Statistic | |
|---|---|---|
| | 3% Average | 7% Average |
| 2015 | $1900 | $310 |
| 2020 | 2100 | 360 |
| 2025 | 2300 | 440 |
| 2030 | 2600 | 510 |
| 2035 | 2800 | 600 |
| 2040 | 3100 | 700 |
| 2045 | 3400 | 810 |
| 2050 | 3700 | 920 |

* These SC-$N_2O$ values are stated in $/metric ton $N_2O$ and rounded to two significant digits. The estimates vary depending on the year of $N_2O$ emissions and are defined in real terms, i.e., adjusted for inflation using the GDP implicit price deflator

The estimates in Table 6-6 and Table 6-7 are used to monetize the domestic climate benefits. Forecasted changes in $CO_2$ and $N_2O$ emissions in a given year, expected as a result of Scenario 3, are multiplied by the SC-$CO_2$ and SC-$N_2O$ estimates, respectively, for that year.

Dioxide, Washington, D.C., January 2017. http://www.nap.edu/catalog/24651/valuing-climate-changes-updating-estimation-of-the-social-cost-of.

Table 6-8 provides annual estimates of SC-$CO_2$ benefits associated with Scenario 3, as well as the total present value of SC-$CO_2$ benefits. Table 6-9 provides annual estimates of the SC-$N_2O$ benefits, as well as the total present value of SC-$N_2O$ benefits. As described earlier, $N_2O$ represents 1 percent of GHGs emitted from U.S. covered airplanes, and therefore contributes a small portion of climate benefits compared to $CO_2$.[xciv] Table 6-10 provides annual estimates of fuel savings, as well as the total present value of fuel savings.

Fuel savings, domestic climate benefits, and total benefits associated with Scenario 3 are presented in Table 6-11 and Table 6-12.[xcv]

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[xciv] Global warming potential (GWP) is a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. It is the accumulated radiative forcing within a specific time horizon, relative to that of the reference gas $CO_2$. GWP-weighted emissions are measured in megatonnes of $CO_2$ equivalent (Mt CO2 Eq.), and GWPs are based upon a 100-year time horizon.
U.S. EPA, 2020: *Inventory of U.S. Greenhouse Gas Emissions and Sinks*: 1990-2018, 733 pp., U.S. EPA Office of Air and Radiation, EPA 430-R-20-002, April 2020. Available at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018 (last accessed June 18, 2020).

[xcv] The airplane GHG emission reductions in the U.S. described earlier in this section for Scenario 3 directly relate to airplane fuel savings in the U.S. For Scenario 3, the EPA approximated the value of airplane fuel burn savings from the reduced demand attributable to improved airplane fuel efficiency, due to the technology response described earlier. To estimate these airplane fuel savings for Scenario 3, we used the average jet fuel price per year (2023 through 2040) from the Annual Energy Outlook 2018. The jet fuel prices were in 2017$, and we converted these jet fuel prices to 2015$.
U.S. Energy Information Administration (EIA), 2018: Annual Energy Outlook 2018, #AEO2018, Table 12 - Petroleum and Other Liquids Prices, Available at www.eia.gov/aeo (last accessed April 11, 2018).

**Table 6-8 – Detailed Domestic $CO_2$-Related Benefits for Scenario 3[xcvi,xcvii,xcviii] (Millions of 2015$)**

| Year | Domestic Reductions $CO_2$ | Domestic Climate Benefits SC-$CO_2$ (3%) | Domestic Climate Benefits SC-$CO_2$ (7%) |
|---|---|---|---|
| 2023[xcix] | 0.03 | $0.19 | $0.03 |
| 2024 | 0.06 | 0.38 | 0.06 |
| 2025 | 0.08 | 0.59 | 0.10 |
| 2026 | 0.08 | 0.60 | 0.10 |
| 2027 | 0.08 | 0.61 | 0.10 |
| 2028 | 0.08 | 0.62 | 0.10 |
| 2029 | 0.08 | 0.63 | 0.11 |
| 2030 | 0.08 | 0.63 | 0.11 |
| 2031 | 0.08 | 0.64 | 0.11 |
| 2032 | 0.08 | 0.65 | 0.12 |
| 2033 | 0.08 | 0.66 | 0.12 |
| 2034 | 0.08 | 0.66 | 0.12 |
| 2035 | 0.08 | 0.67 | 0.13 |
| 2036 | 0.08 | 0.67 | 0.13 |
| 2037 | 0.08 | 0.67 | 0.13 |
| 2038 | 0.07 | 0.67 | 0.13 |
| 2039 | 0.07 | 0.67 | 0.13 |
| 2040 | | 0.67 | 0.13 |
| Total Present Value (3%) | | $6.60 | -- |
| Total Present Value (7%) | | -- | $0.63 |

[xcvi] Estimates are rounded to two significant figures.

[xcvii] The SC-$CO_2$ and SC-$N_2O$ estimates used in this TSD are interim values developed under E.O. 13783 and are based on assumed 3 and 7 percent discount rates used in their estimation. Consistent with OMB Circular A-4 guidance, the present value of the stream of annual climate and fuel savings benefits also use a 3 and 7 percent discount rate.

[xcviii] Global SC-$CO_2$ results are provided in the appendix of this TSD.

[xcix] Since Scenario 3's implementation date for most in-production airplanes will be 2023, this is the first year that benefits will begin to occur.

**Table 6-9 – Detailed Domestic N2O-Related Benefits for Scenario 3[c] (Millions of 2015$)**

| Year | Domestic Climate Benefits SC-$N_2O$ (3%) | Domestic Climate Benefits SC-$N_2O$ (7%) |
|---|---|---|
| 2023 | $0.002 | $0.0003 |
| 2024 | 0.004 | 0.001 |
| 2025 | 0.01 | 0.001 |
| 2026 | 0.01 | 0.001 |
| 2027 | 0.01 | 0.001 |
| 2028 | 0.01 | 0.001 |
| 2029 | 0.01 | 0.001 |
| 2030 | 0.01 | 0.001 |
| 2031 | 0.01 | 0.001 |
| 2032 | 0.01 | 0.001 |
| 2033 | 0.01 | 0.001 |
| 2034 | 0.01 | 0.001 |
| 2035 | 0.01 | 0.002 |
| 2036 | 0.01 | 0.002 |
| 2037 | 0.01 | 0.002 |
| 2038 | 0.01 | 0.002 |
| 2039 | 0.01 | 0.002 |
| 2040 | 0.01 | 0.002 |
| Total Present Value (3%) | $0.1 | -- |
| Total Present Value (7%) | -- | $0.01 |

[c] Global SC-$N_2O$ results are provided in the appendix of this TSD.

**Table 6-10 – Detailed Domestic Fuel Savings for Scenario 3 (Millions of 2015$)**

| Year | Fuel Savings |
|---|---|
| 2023 | $6.8 |
| 2024 | 14 |
| 2025 | 21 |
| 2026 | 21 |
| 2027 | 22 |
| 2028 | 22 |
| 2029 | 22 |
| 2030 | 23 |
| 2031 | 23 |
| 2032 | 23 |
| 2033 | 23 |
| 2034 | 23 |
| 2035 | 23 |
| 2036 | 23 |
| 2037 | 23 |
| 2038 | 23 |
| 2039 | 23 |
| 2040 | 23 |
| Total Present Value (3%) | $230 |
| Total Present Value (7%) | $130 |

**Table 6-11 – Summary of Domestic Climate-Related Benefits and Fuel Savings for Scenario 3[ci]**

**(3% Discount Rate, Millions of 2015$)**

| Year | Domestic Climate Benefits (3%) | Fuel Savings | Total Benefits |
|---|---|---|---|
| | | | Domestic Climate Benefits @ 3% |
| 2023 | $0.2 | $6.8 | $7 |
| 2025 | 0.6 | 21 | 22 |
| 2030 | 0.6 | 23 | 23 |
| 2035 | 0.7 | 23 | 24 |
| 2040 | 0.7 | 23 | 24 |
| Total Present Value (3%) | $6.7 | $230 | $240 |

[ci] Domestic climate benefits in this table includes SC-$CO_2$ and SC-$N_2O$ benefits.

**Table 6-12 – Summary of Domestic Climate-Related Benefits and Fuel Savings for Scenario 3[cii]**

**(7% Discount Rate, Millions of 2015$)**

| Year | Domestic Climate Benefits (7%) | Fuel Savings | Total Benefits |
|---|---|---|---|
| | | | Domestic Climate Benefits @ 7% |
| 2023 | $0.03 | $6.8 | $6.9 |
| 2025 | 0.1 | 21 | 21 |
| 2030 | 0.1 | 23 | 23 |
| 2035 | 0.1 | 23 | 24 |
| 2040 | 0.1 | 23 | 23 |
| Total Present Value (7%) | $0.6 | $130 | $130 |

The limitations and uncertainties associated with the global social cost of greenhouse gas estimates, which were discussed at length in recent rules, likewise apply to the domestic social cost of greenhouse gas estimates presented in this TSD.[ciii] Some uncertainties are captured within the analysis, as discussed in detail in the Appendix, while other areas of uncertainty have not yet been quantified in a way that can be modeled. For example, limitations include the incomplete way in which the integrated assessment models capture catastrophic and non-catastrophic impacts, their incomplete treatment of adaptation and technological change, the incomplete way in which inter-regional and inter-sectoral linkages are modeled, uncertainty in the extrapolation of damages to high temperatures, and inadequate representation of the relationship between the discount rate and uncertainty in economic growth over long time horizons. The science incorporated into these models understandably lags behind the most recent research, and the limited amount of research linking climate impacts to economic damages makes the modeling exercise even more difficult.

These individual limitations and uncertainties do not all work in the same direction in terms of their influence on the estimates. In accordance with guidance in OMB Circular A-4 on the treatment of uncertainty, the Appendix provides a detailed discussion of the ways in which the modeling underlying the development of the social cost of greenhouse gas estimates used in this TSD addressed quantified sources of uncertainty, and presents a sensitivity analysis to show consideration of the uncertainty surrounding discount rates over long time horizons.

In addition to requiring reporting of impacts at a domestic level, OMB Circular A-4 states that when an agency "evaluate[s] a regulation that is likely to have effects beyond the borders of the United States, these effects should be reported separately" (page 15). This guidance is relevant to the valuation of damages from $CO_2$ and other GHGs, given that GHGs contribute to damages around the world independent of the country in which they are emitted. Therefore, in accordance with this guidance in OMB Circular A-4, the Appendix presents the global climate benefits from this rulemaking using global SC-$CO_2$, SC-$CH_4$, and SC-$N_2O$ estimates based on both 3 and 7 percent discount rates. Note EPA did not quantitatively project the full impact of the final action on international trade and the ultimate distribution of compliance costs, so it is not possible to present estimates of global costs resulting from the final action.

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[cii] Domestic climate benefits in this table includes SC-$CO_2$ and SC-$N_2O$ benefits.
[ciii] See e.g., the EPA's 2019 Affordable Clean Energy (ACE) rulemaking (84 FR 32520, July 8, 2019).

## 6.3 Sensitivity Case Studies

As described earlier in Chapter 5, for the three scenarios, we conducted sensitivity studies on the emissions reductions effect of 1) not having continuous annual improvement (continuous improvement was assumed in our main analysis) and 2) having extended production of the A380 and 767-3ERF to 2030 (instead of using the main analysis' assumption of 2025 and 2023, respectively). These sensitivity study criteria are nearer to the assumptions in the ICAO/CAEP analysis.

(As described earlier, we note that in their comments on the proposed rulemaking Boeing, along with Fedex, GE, and the Cargo Airline Association, expressed that there would continue to be a low volume demand for the B767 freighter beyond January 1, 2028. These commenters did not indicate the number of 767F's that would be produced after 2028. The EPA did not change the analysis to include continued production of the 767F beyond 2030 because insufficient information to characterize this scenario was provided.)

### 6.3.1 <u>Emission Reductions for Scenario 3</u>

Under the combined sensitivity studies for Scenario 3, the A380 would not comply with the scenario by its effective dates and therefore would need a technology response of about 4 percent in improvements to the metric value (with the 1% design margin). The 767-3ERF (dedicated freighter) would not meet Scenario 3 with or without continuous annual improvement, and its technology response status would be mostly driven by the end of production assumption (thus needing a technology response of about 17 percent in improvements to the metric value in 2028). The total U.S. $CO_2$ cumulative reductions from the combination of these two sensitivity case studies would be as follows: about 4.2 Mt $CO_2$ equivalent for 2030 and about 15 Mt $CO_2$ equivalent for 2040. As indicated in Chapter 5, these results show that 7 to 11 times greater (or 600 percent to 1000 percent greater) emission reductions for Scenario 3 would occur with the assumptions in the combined sensitivity studies compared to the main analysis (4.2 Mt $CO_2$ equivalent versus 0.6 Mt $CO_2$ equivalent in 2030 and 15 Mt $CO_2$ equivalent versus 1.4 Mt $CO_2$ equivalent in 2040, respectively).

Separate from these combined sensitivity studies, we also analyzed the emission reductions using ICAO/CAEP's assumptions of airplane fleet evolution and airplane operations (used PIANO for airplane $CO_2$ emission rates). Using these same assumptions as ICAO, the total U.S. $CO_2$ cumulative reductions would be about 110 Mt $CO_2$ equivalent for Scenario 3.

### 6.3.2 <u>Emission Reductions for Scenarios 1 and 2</u>

For the combined sensitivity studies of Scenarios 1 and 2, the A380 would not comply with either scenario by their effective dates and therefore would need a technology response of about 2 percent in improvements to the metric value (with the 1% design margin). The 767-3ERF (dedicated freighter) would not meet Scenarios 1 and 2 with or without continuous annual improvement, and its technology response status would be mostly driven by the end of production assumption. For the results of this combined sensitivity study, the total U.S. $CO_2$ cumulative reductions in 2040 would be about 3 Mt $CO_2$ equivalent for Scenario 1 and about 4 Mt $CO_2$ equivalent for Scenario 2.

In the sensitivity case of no continuous annual improvement but no extended production, Scenario 1 would result in no emission reductions because the A380 would be out of production by 2025. However, in this case, Scenario 2 would result in limited emission reductions from the technology response improvement of 2 percent for the A380 due to the 5-year accelerated implementation date (2023). The total U.S. $CO_2$ cumulative reductions in 2040 would be about 1 Mt $CO_2$ equivalent in the U.S.

In the sensitivity case of extended production but with continuous improvement, the emission reductions would result from only the 767-3ERF since the A380 would meet the scenarios. Since the 5-year accelerated implementation date is not adopted for freighters, Scenarios 1 and 2 would have the same emission reductions effect, and the estimated the total U.S. $CO_2$ cumulative reductions in 2040 would be about 1 Mt $CO_2$ equivalent in the U.S.

Separate from these sensitivity studies and using the same assumptions as ICAO/CAEP,[civ] the total U.S. $CO_2$ cumulative reductions would be about 50 Mt $CO_2$ equivalent for Scenario 1 and about 75 Mt $CO_2$ equivalent for Scenario 2.

However, as discussed in Chapter 5 for all three scenarios, we believe that the EPA main analysis assumptions of business as usual improvements in the absence of standards (continuous annual improvement) and the independently developed and peer reviewed technology responses (including expected end of production expectations) are based on more up to date inputs and assumptions, in comparison to these sensitivity studies.

### 6.3.3 Costs for All Three Scenarios

We did not conduct specific sensitivity case studies for costs based on the above criteria for the three scenarios, but a rough approximation of such sensitivity case studies is a comparison of our non-recurring costs (NRC) to ICAO/CAEP analysis' NRC (see Chapter 2 of this TSD, particularly refer to Table 2-12 and

Table 2-13 for a comparison of NRC for a range of percent metric value improvements). We can draw insight from this rough approximation even though the criteria in our sensitivity case studies do not exactly match the assumptions in the ICAO/CAEP analysis. Similar to our sensitivity studies for emissions reductions, the methodology for the ICAO/CAEP's NRC analysis assumed no continuous annual improvement and included extended production of the A380 and 767-3ERF (as well as numerous other airplanes). Thus, it is informative to compare our NRC results to ICAO/CAEP results since they may serve as a general sensitivity analysis of our costs. As with emission reductions from our sensitivity studies, the NRC results from ICAO/CAEP are typically much greater than our NRC results (on average about 170 percent greater for representative airplanes in the various airplane categories). Also, section 2.6 of this TSD describes fuel savings based on our analysis and the ICAO/CAEP analysis, and ICAO/CAEP's results are much greater. The magnitude of these differences is expected. ICAO/CAEP's technology responses were based on technology frozen in 2016-2017 compared to the EPA's responses that considered technologies available in 2017, but with continuous improvement of metric values for in-production and in-development (or on-order) airplanes from 2010 to 2040 based on the incorporation of these technologies onto these airplanes (over this same timeframe). Also, as discussed in Chapter 2, ICAO/CAEP's top-down approach likely included all airplane development costs (type certification, noise, in-flight entertainment, etc.)

[civ] We analyzed the emission reductions using ICAO/CAEP's assumptions of airplane fleet evolution and airplane operations (used PIANO for airplane $CO_2$ emission rates).

instead of only those costs for $CO_2$ improvements. Thus, we believe the assumptions in our cost analysis are based on more up to date inputs and assumptions.

In addition, for the extended production criteria (for the scenarios), manufacturers could apply to use the exemption provisions (described in section V.E of the preamble), which are intended for airplanes at the end of their production life. If manufacturers chose to apply for an exemption and it was granted, the A380 and 767-3ERF would not need to respond, and thus, there would be no resultant emission reductions or costs.

## 6.4 Summary

As described earlier in this TSD, for harmonizing with the international standards and providing global consistency, which would ensure all the world's manufacturers comply (or certify) to the same standards and no U.S. manufacturer finds itself at a competitive disadvantage, the EPA is issuing standards (Scenario 1) that match the international standards. As discussed earlier, according to the EPA analysis, Scenario 2 (accelerated implementation dates) has no costs and benefits, which is the same impact as Scenario 1. Scenario 3 (both accelerated implementation dates and stricter stringency levels) has limited costs, which outweigh the limited benefits. As shown in Table 6-13, for Scenario 3, the present value of non-recurring costs would be about $415 million and $501 million (in 2015$), at 7 and 3 percent discount rates respectively. The present value of total benefits would be about $130 million and $240 million (in 2015$), at 7 and 3 percent discount rates respectively. Estimated net benefits (benefits minus costs) therefore range from -$285 million to -$261 million, at 7 and 3 percent discount rates respectively.

**Table 6-13 – Present Value of Total Benefits, Total Costs, and Net Benefits for Scenario 3**

**(Millions of 2015$)**

| Present Value | 3% Discount Rate | 7% Discount Rate |
|---|---|---|
| Benefits | 240 | 130 |
| Costs | 501 | 415 |
| Net Benefits (benefits minus costs) | -261 | -285 |

# Appendix A.

## A.1 Overview of Methodology Used to Develop Interim Domestic SC-$CO_2$ and SC-$N_2O$ Estimates

E.O. 13783 directed agencies to ensure that estimates of the social cost of greenhouse gases used in regulatory analyses "are based on the best available science and economics" and are consistent with the guidance contained in OMB Circular A-4, "including with respect to the consideration of domestic versus international impacts and the consideration of appropriate discount rates" (E.O. 13783, Section 5(c)). In addition, E.O. 13783 withdrew the technical support documents (TSDs) describing the global social cost of greenhouse gas estimates developed under the prior Administration as no longer representative of government policy. The withdrawn TSDs were developed by an interagency working group (IWG) that included the DOT, EPA and other executive branch entities.

Regarding the two analytical considerations highlighted in E.O. 13783 – how best to consider domestic versus international impacts and appropriate discount rates – current guidance in OMB Circular A-4 is as follows. Circular A-4 states that analysis of economically significant proposed and final regulations "should focus on benefits and costs that accrue to citizens and residents of the United States." We follow this guidance by adopting a domestic perspective in our central analysis. Regarding discount rates, Circular A-4 states that regulatory analyses "should provide estimates of net benefits using both 3 percent and 7 percent." The 7 percent rate is intended to represent the average before-tax rate of return to private capital in the U.S. economy. The 3 percent rate is intended to reflect the rate at which society discounts future consumption, which is particularly relevant if a regulation is expected to affect private consumption directly. EPA follows this guidance by presenting estimates based on both 3 and 7 percent discount rates in the main analysis.

The domestic social cost of greenhouse gas estimates presented in this TSD rely on the same ensemble of three integrated assessment models (IAMs) that were used to develop the IWG global SC-$CO_2$ and SC-$N_2O$ estimates: DICE 2010, FUND 3.8, and PAGE 2009.[cv] The three IAMs translate emissions into changes in atmospheric greenhouse concentrations, atmospheric concentrations into changes in temperature, and changes in temperature into economic damages. The emissions projections used in the models are based on specified socio-economic (GDP and population) pathways. These emissions are translated into atmospheric concentrations, and concentrations are translated into warming based on each model's simplified representation of the climate and a key parameter, equilibrium climate sensitivity. The effect of these Earth system changes is then translated into consumption-equivalent economic damages. As in the IWG exercise, these key inputs were harmonized across the three models: a probability distribution for equilibrium climate sensitivity; five scenarios for economic, population, and emissions growth; and discount rates.[cvi] All other model features were left unchanged. Future

[cv] The full model names are as follows: Dynamic Integrated Climate and Economy (DICE); Climate Framework for Uncertainty, Negotiation, and Distribution (FUND); and Policy Analysis of the Greenhouse Gas Effect (PAGE).

[cvi] In order to develop SC-$CH_4$ and SC-$N_2O$ estimates consistent with the methodology underlying the SC-$CO_2$ estimates also required augmenting the climate model of two of the IAMs to explicitly consider the path of additional radiative forcing from a $CH_4$ or $N_2O$ perturbation, and adding more specificity to the assumptions

damages are discounted using constant discount rates of both 3 and 7 percent, as recommended by OMB Circular A-4.

The domestic share of the global SC-$CO_2$ and SC-$N_2O$—i.e., an approximation of the climate change impacts that occur within U.S. borders[cvii]—is calculated directly in both FUND and PAGE. However, DICE 2010 generates only global estimates. Therefore, the U.S. damages are approximated as 10 percent of the global values from the DICE model runs, based on the results from a regionalized version of the model (RICE 2010) reported in Table 2 of Nordhaus (2017). Although the regional shares reported in Nordhaus (2017) are specific to SC-$CO_2$, they still provide a reasonable interim approach for approximating the U.S. share of marginal damages from emissions of other greenhouse gases.

The steps involved in estimating the social cost of each gas are described below. The three integrated assessment models (FUND, DICE, and PAGE) are run using the harmonized equilibrium climate sensitivity distribution, five socioeconomic and emissions scenarios, and two constant discount rates described above. Because the climate sensitivity parameter is modeled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run is a distribution over the SC-$CO_2$ or SC-$N_2O$ in year t based on a Monte Carlo simulation of 10,000 runs. For each of the IAMs, the basic computational steps for calculating the social cost estimate in a particular year t are the following: 1.) calculate the temperature effects and (consumption-equivalent) damages in each year resulting from the baseline path of emissions; 2.) adjust the model to reflect an additional unit of emissions in year t; 3.) recalculate the temperature effects and damages expected in all years beyond t resulting from this adjusted path of emissions, as in step 1; and 4.) subtract the damages computed in step 1 from those in step 3 in each model period and discount the resulting path of marginal damages back to the year of emissions. In PAGE and FUND step 4 focuses on the damages attributed to the US region in the models. As noted above, DICE does not explicitly include a separate US region in the model and therefore, U.S. damages are approximated in step 4 as 10 percent of the global values based on the results of Nordhaus (2017). This exercise produces 30 separate distributions of the SC-$CO_2$ and SC-$N_2O$ for a given year, the product of 3 models, 2 discount rates, and 5 socioeconomic scenarios. Following the approach used by the IWG, the estimates are equally weighted across models and socioeconomic scenarios in order to consolidate the results into one distribution for each gas for each discount rate.

### A.2-Treatment of Uncertainty in Interim Domestic SC-CO2 and SC-N2O Estimates

There are various sources of uncertainty in the social cost of greenhouse gas estimates used in this analysis. Some uncertainties pertain to aspects of the natural world, such as quantifying the physical effects of greenhouse gas emissions on Earth systems. Other sources of uncertainty are

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regarding post-2100 baseline $CH_4$ and $N_2O$ emissions. See the IWG's summary of its methodology in the docket, document ID number EPA-HQ-OAR-2015-0827-5886, "Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide (August 2016)". See also National Academies (2017) for a detailed discussion of each of these modeling assumptions.

[cvii] Note that inside the U.S. borders is not the same as accruing to U.S. citizens, which may be higher or lower.

associated with current and future human behavior and well-being, such as population and economic growth, GHG emissions, the translation of Earth system changes to economic damages, and the role of adaptation. It is important to note that even in the presence of uncertainty, scientific and economic analysis can provide valuable information to the public and decision makers, though the uncertainty should be acknowledged and when possible taken into account in the analysis (National Academies 2013). OMB Circular A-4 also requires a thorough discussion of key sources of uncertainty in the calculation of benefits and costs, including more rigorous quantitative approaches for higher consequence rules. This section summarizes the sources of uncertainty considered in a quantitative manner in the domestic SC-$CO_2$ and SC-$N_2O$ estimates.

The domestic SC-$CO_2$ and SC-$N_2O$ estimates consider various sources of uncertainty through a combination of a multi-model ensemble, probabilistic analysis, and scenario analysis. We provide a summary of this analysis here; more detailed discussion of each model and the harmonized input assumptions can be found in National Academies (2017). For example, the three IAMs used collectively span a wide range of Earth system and economic outcomes to help reflect the uncertainty in the literature and in the underlying dynamics being modeled. The use of an ensemble of three different models at least partially addresses the fact that no single model includes all of the quantified economic damages. It also helps to reflect structural uncertainty across the models, which stems from uncertainty about the underlying relationships among GHG emissions, Earth systems, and economic damages that are included in the models. Bearing in mind the different limitations of each model and lacking an objective basis upon which to differentially weight the models, the three integrated assessment models are given equal weight in the analysis.

Monte Carlo techniques were used to run the IAMs a large number of times. In each simulation the uncertain parameters are represented by random draws from their defined probability distributions. In all three models the equilibrium climate sensitivity is treated probabilistically based on the probability distribution from Roe and Baker (2007) calibrated to the IPCC AR4 consensus statement about this key parameter.[cviii] The equilibrium climate sensitivity is a key parameter in this analysis because it helps define the strength of the climate response to increasing GHG concentrations in the atmosphere. In addition, the FUND and PAGE models define many of their parameters with probability distributions instead of point estimates. For these two models, the model developers' default probability distributions are maintained for all parameters other than those superseded by the harmonized inputs (i.e., equilibrium climate sensitivity, socioeconomic and emissions scenarios, and discount rates). More information on the uncertain parameters in PAGE and FUND is available upon request.

For the socioeconomic and emissions scenarios, uncertainty is included in the analysis by considering a range of scenarios selected from the Stanford Energy Modeling Forum exercise, EMF-22. Given the dearth of information on the likelihood of a full range of future socioeconomic pathways at the time the original modeling was conducted, and without a basis for assigning differential weights to scenarios, the range of uncertainty was reflected by simply weighting each of the five scenarios equally for the consolidated estimates. To better understand

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[cviii] Specifically, the Roe and Baker distribution for the climate sensitivity parameter was bounded between 0 and 10 with a median of 3 °C and a cumulative probability between 2 and 4.5 °C of two-thirds.

how the results vary across scenarios, results of each model run are available in the docket (Docket ID No. EPA-HQ-OAR-2017-0355, which is for the EPA Affordable Clean Energy (ACE) rulemaking).

The outcome of accounting for various sources of uncertainty using the approaches described above is a frequency distribution of the SC-$CO_2$ and SC-$N_2O$ estimates for emissions occurring in a given year for each discount rate. Unlike the approach taken for consolidating results across models and socioeconomic and emissions scenarios, the SC-$CO_2$ and SC-$N_2O$ estimates are not pooled across different discount rates because the range of discount rates reflects both uncertainty and, at least in part, different policy or value judgements; uncertainty regarding this key assumption is discussed in more detail below. The frequency distributions reflect the uncertainty around the input parameters for which probability distributions were defined, as well as from the multi-model ensemble and socioeconomic and emissions scenarios where probabilities were implied by the equal weighting assumption. It is important to note that the set of SC-$CO_2$ and SC-$N_2O$ estimates obtained from this analysis does not yield a probability distribution that fully characterizes uncertainty about the SC-$CO_2$ and SC-$N_2O$ due to impact categories omitted from the models and sources of uncertainty that have not been fully characterized due to data limitations.

Figure 6-6 and Figure 6-7 present the frequency distribution of the domestic SC-$CO_2$ and SC-$N_2O$ estimates, respectively, for emissions in 2030 for each discount rate. Each distribution represents 150,000 estimates based on 10,000 simulations for each combination of the three models and five socioeconomic and emissions scenarios.[cix] In general, the distributions are skewed to the right and have long right tails, which tend to be longer for lower discount rates. To highlight the difference between the impact of the discount rate and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric representation of quantified variability in the SC-$CO_2$ and SC-$N_2O$ estimates conditioned on each discount rate. The full set of SC-$CO_2$ and SC-$N_2O$ results through 2050 is available as part of the TSD analysis materials.

[cix] Although each distribution in Figure 6-6 and Figure 6-7 is based on the full set of model results (150,000 estimates for each discount rate), for display purposes the horizontal axis is truncated with a small percent of the estimates lying below the lowest bin displayed and above the highest bin displayed, depending on the discount rate.

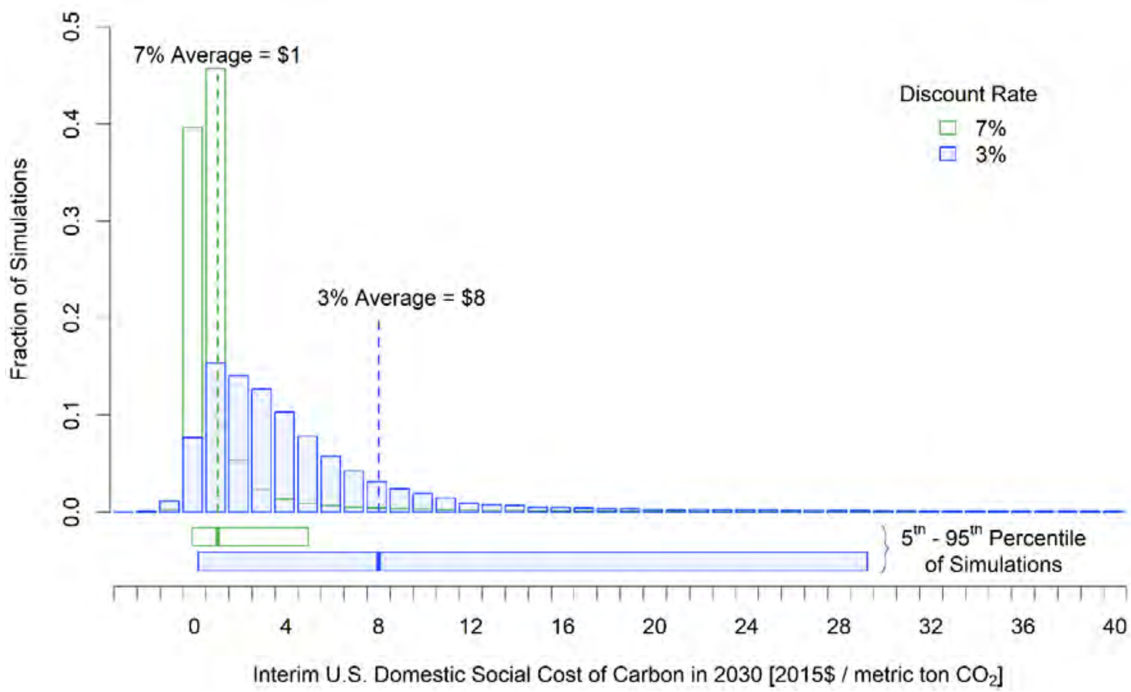


**Figure 6-6 – Frequency Distribution of Interim Domestic SC-$CO_2$ Estimates for 2030 (in 2015$ per metric ton $CO_2$)**

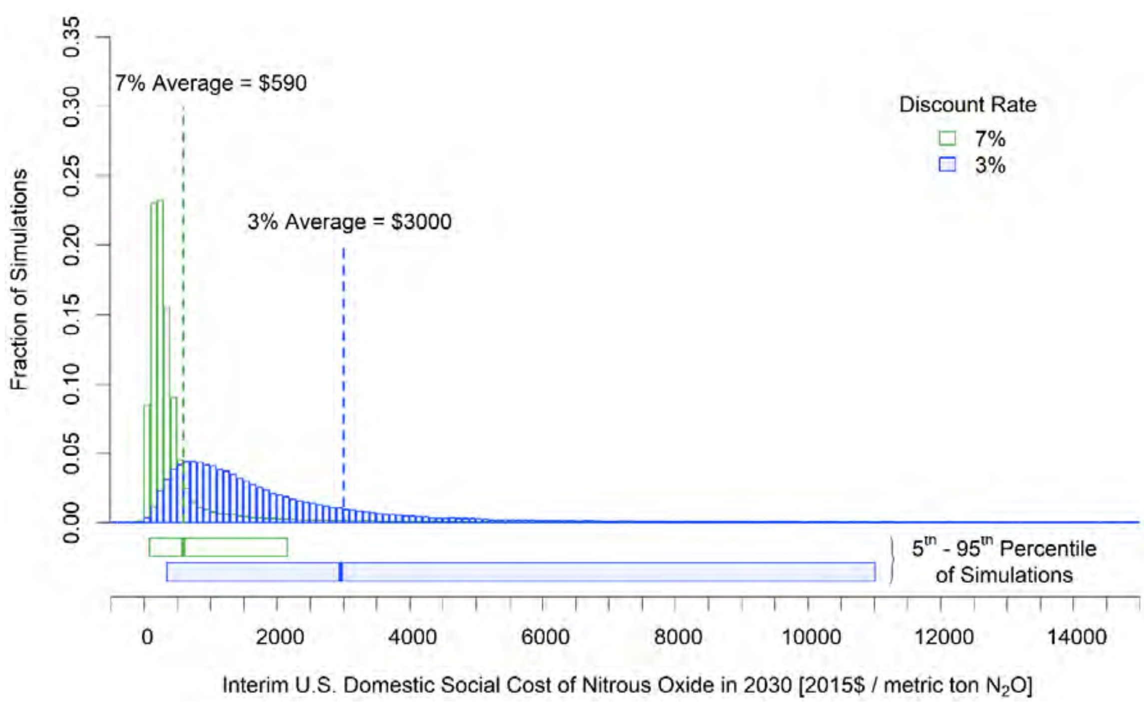


**Figure 6-7 – Frequency Distribution of Interim Domestic SC-$N_2O$ Estimates for 2030 (in 2015$ per metric ton $N_2O$)**

As illustrated by the frequency distributions in Figure 6-6 and Figure 6-7, the assumed discount rate plays a critical role in the ultimate estimate of the social cost of greenhouse gases.

This is because $CO_2$ and $N_2O$ emissions today continue to impact society far out into the future,[cx] so with a higher discount rate, costs that accrue to future generations are weighted less, resulting in a lower estimate. Circular A-4 recommends that costs and benefits be discounted using the rates of 3 percent and 7 percent to reflect the opportunity cost of consumption and capital, respectively. Circular A-4 also recommends quantitative sensitivity analysis of key assumptions[cxi], and offers guidance on what sensitivity analysis can be conducted in cases where a rule will have important intergenerational benefits or costs. To account for ethical considerations of future generations and potential uncertainty in the discount rate over long time horizons, Circular A-4 suggests "further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefit using discount rates of 3 and 7 percent" (page 36) and notes that research from the 1990s suggests intergenerational rates "from 1 to 3 percent per annum" (OMB 2003). We consider the uncertainty in this key assumption by calculating the domestic SC-$CO_2$ and SC-$N_2O$ based on a 2.5 percent discount rate, in addition to the 3 and 7 percent used in the main analysis. Using a 2.5 percent discount rate, the average domestic SC-$CO_2$ and SC-$N_2O$ estimates across all the model runs for emissions occurring in 2030 is $11 per metric ton of $CO_2$ (2015$) and $3,600 per metric ton of $N_2O$, respectively[cxii]; in this case the total domestic climate benefits of Scenario 3 are $0.9 million in 2030 under a 2.5 percent discount rate. The total present value of the domestic climate benefits under a 2.5 percent discount rate is $10 million.

In addition to the approach to accounting for the quantifiable uncertainty described above, the scientific and economics literature has further explored known sources of uncertainty related to estimates of the social cost of carbon and other greenhouse gases. For example, researchers have examined the sensitivity of IAMs and the resulting estimates to different assumptions embedded in the models (see, e.g., Hope 2013, Anthoff and Tol 2013, Nordhaus 2014, and Waldhoff et al. 2011, 2014). However, there remain additional sources of uncertainty that have not been fully characterized and explored due to remaining data limitations. Additional research is needed to expand the quantification of various sources of uncertainty in estimates of the social cost of carbon and other greenhouse gases (e.g., developing explicit probability distributions for more inputs pertaining to climate impacts and their valuation). On the issue of intergenerational discounting, some experts have argued that a declining discount rate is appropriate to analyze impacts that occur far into the future (Arrow et al., 2013). However, additional research and analysis is still needed to develop a methodology for implementing a declining discount rate and to understand the implications of applying these theoretical lessons in practice.

Recognizing the limitations and uncertainties associated with estimating the social cost of greenhouse gases, the research community is continuing to explore opportunities to improve

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[cx] Although the atmospheric lifetime of $CH_4$ is notably shorter than that of $CO_2$ or $N_2O$, the impacts of changes in contemporary $CH_4$ emissions are also expected to occur over long time horizons that cover multiple generations. For more discussion, see document ID number EPA-HQ-OAR-2015-0827-5886, "Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide (August 2016)".

[cxi] "If benefit or cost estimates depend heavily on certain assumptions, you should make those assumptions explicit and carry out sensitivity analyses using plausible alternative assumptions." (OMB 2003, page 42).

[cxii] The estimates are adjusted for inflation using the GDP implicit price deflator. SC-$CO_2$ estimates are rounded to the nearest dollar and SC-$CH_4$ and SC-$N_2O$ estimates are rounded to two significant digits.

estimates of SC-$CO_2$ and other greenhouse gases. Notably, the National Academies of Sciences, Engineering, and Medicine conducted a multi-discipline, multi-year assessment to examine potential approaches, along with their relative merits and challenges, for a comprehensive update to the current methodology. The task was to ensure that the SC-$CO_2$ estimates that are used in Federal analyses reflect the best available science, focusing on issues related to the choice of models and damage functions, climate science modeling assumptions, socioeconomic and emissions scenarios, presentation of uncertainty, and discounting. In January 2017, the Academies released their final report, Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide,[cxiii] and recommended specific criteria for future updates to the SC-$CO_2$ estimates, a modeling framework to satisfy the specified criteria, and both near-term updates and longer-term research needs pertaining to various components of the estimation process (National Academies 2017). Since the framework used to estimate SC-$N_2O$ is the same as that used for SC-$CO_2$, the Academies' recommendations on how to update many of the underlying modeling assumptions also apply to the SC-$N_2O$ estimates.

The 2017 National Academies report also provides recommendations pertaining to discounting, emphasizing the need to more explicitly model the uncertainty surrounding discount rates over long time horizons, its connection to uncertainty in economic growth, and, in turn, to climate damages using a Ramsey-like formula (National Academies 2017). These and other research needs are discussed in detail in the 2017 National Academies' recommendations for a comprehensive update to the current methodology, including a more robust incorporation of uncertainty.

The Academies' report also discussed the challenges in developing domestic SC-$CO_2$ estimates, noting that current integrated assessment models do not model all relevant regional interactions – i.e., how climate change impacts in other regions of the world could affect the United States, through pathways such as global migration, economic destabilization, and political destabilization. The Academies concluded that it "is important to consider what constitutes a domestic impact in the case of a global pollutant that could have international implications that impact the United States. More thoroughly estimating a domestic SC-$CO_2$ therefore needs to consider the potential implications of climate impacts on, and actions by, other countries, which also have impacts on the United States." (National Academies 2017, pg. 12-13). This challenge is equally applicable to the estimation of the domestic SC-$CH_4$ and SC-$N_2O$.

### A.3- Global Climate Benefits

In addition to requiring reporting of impacts at a domestic level, OMB Circular A-4 states that when an agency "evaluate[s] a regulation that is likely to have effects beyond the borders of the United States, these effects should be reported separately" (page 15).[cxiv] This guidance is

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[cxiii] National Academies of Sciences, Engineering, and Medicine. 2017. *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide.* National Academies Press. Washington, DC Available at https://www.nap.edu/catalog/24651/valuing-climate-damages-updating-estimation-of-the-social-cost-of (last accessed March 20, 2020).

[cxiv] While Circular A-4 does not elaborate on this guidance, the basic argument for adopting a domestic only perspective for the central benefit-cost analysis of domestic policies is based on the fact that the authority to regulate extends only, or principally, to a nation's own residents who have consented to adhere to the same set of rules and values for collective decision-making, as well as the assumption that most domestic policies will have negligible effects on the welfare of other countries' residents (EPA 2010; Kopp et al. 1997; Whittington et al.

relevant to the valuation of damages from GHGs, given that most GHGs contribute to damages around the world independent of the country in which they are emitted. Therefore, in this section we present the global climate benefits from this rulemaking using the global SC-$CO_2$ and SC-$N_2O$ estimates – i.e., reflecting quantified impacts occurring in both the U.S. and other countries—corresponding to the model runs that generated the domestic SC-$CO_2$ and SC-$N_2O$ estimates used in the main analysis. The average global SC-$CO_2$ and SC-$N_2O$ estimate across all the model runs for emissions occurring in 2030 are $7/mt$CO_2$ (in 2015 dollars) and $3,500/mt$N_2O$, respectively, using a 7 percent discount rate, and $57/mt$CO_2$ and $21,000/mt$N_2O$ using a 3 percent discount rate.[cxv] The domestic estimates presented above are approximately 15-19 percent and 12-14 percent of the global estimates for the 7 percent and 3 percent discount rates, respectively, depending on the gas. Applying these estimates to the changes in $CO_2$ and $N_2O$ emissions results from Scenario 3 in estimated total global climate benefits of $0.6 million in 2030, using a 7 percent discount rate. The total present value of the global climate benefits using a 7 percent discount rate is $3.5 million. The estimated total global climate benefits are $4.7 million in 2030 using a 3 percent rate. The total present value of the global climate benefits using a 3 percent discount rate is $49 million. Under the sensitivity analysis considered above using a 2.5 percent discount rate, the average global estimates across all the model runs for emissions occurring in 2030 are $82/mt$CO_2$ (in 2015 dollars) and $30,000/mt$N_2O$. The total global climate benefits are estimated to be $6.8 million in 2030 using a 2.5 percent discount rate. The total present value of the global climate benefits using a 2.5 percent discount rate is $77 million. All estimates are reported in 2015 dollars.

1986). In the context of policies that are expected to result in substantial effects outside of U.S. borders, an active literature has emerged discussing how to appropriately treat these impacts for purposes of domestic policymaking (e.g., Gayer and Viscusi 2016, 2017; Anthoff and Tol, 2010; Fraas et al. 2016; Revesz et al. 2017). This discourse has been primarily focused on the regulation of greenhouse gases (GHGs), for which domestic policies may result in impacts outside of U.S. borders due to the global nature of the pollutants.

[cxv] The estimates are adjusted for inflation using the GDP implicit price deflator and then rounded to two significant digits.

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[68] ICAO, 2016: *Report of Tenth Meeting*, Montreal, 1-12 February 2016, Committee on Aviation Environmental Protection, Document 10069, CAEP/10, 432pp, Available for purchase at: http://www.icao.int/publications/Pages/catalogue.aspx (last accessed March 18, 2020). The ICAO CAEP/10 report is found on page 27 of the English Edition 2020 catalog and is copyright protected; Order No. 10069. The summary of the ten stringency options is located in Appendix C (starting on page 5C-1) of this report.
[69] PIANO (Project Interactive Analysis and Optimization), Aircraft Design and Analysis Software by Dr. Dimitri Simos, Lissys Limited, UK, 1990-present; Version 5.4, February 21, 2017. Available at www.piano.aero (last accessed March 18, 2020). This is a commercially available aircraft design and performance software suite used across the industry and academia. This model contains non-manufacturer provided estimates of performance of various aircraft.
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# Chapter 7: Regulatory Flexibility Analysis

This chapter presents our Small Business Flexibility Analysis (SBFA) which evaluates the potential impacts of the rule on small entities. The Regulatory Flexibility Act (RFA), as amended by the Small Business Regulatory Enforcement Fairness Act of 1996 (SBREFA), generally requires an agency to prepare a regulatory flexibility analysis of any rule subject to notice and comment rulemaking requirements under the Administrative Procedure Act or any other statute unless the agency certifies that the rule will not have a significant economic impact on a substantial number of small entities.

## 7.1 Requirements of the Regulatory Flexibility Act

When proposing and promulgating rules subject to notice and comment under the Clean Air Act, we are generally required under the RFA to conduct a regulatory flexibility analysis unless we certify that the requirements of a regulation will not cause a significant impact on a substantial number of small entities. The key elements of the RFA include:

- a description of and, where feasible, an estimate of the number of small entities to which the rule will apply;
- the projected reporting, record keeping, and other compliance requirements of the rule, including an estimate of the classes of small entities which will be subject to the requirements and the type of professional skills necessary for preparation of the report or record;
- an identification to the extent practicable, of all other relevant Federal rules which may duplicate, overlap, or conflict with the rule; and,
- any significant alternatives to the rule which accomplish the stated objectives of applicable statutes and which minimize any significant economic impact of the rule on small entities.

The RFA was amended by SBREFA to ensure that concerns regarding small entities are adequately considered during the development of new regulations that affect them. Although we are not required by the Clean Air Act to provide special treatment to small businesses, the RFA requires us to carefully consider the economic impacts that our rules will have on small entities. Specifically, the RFA requires us to determine, to the extent feasible, our rule's economic impact on small entities, explore regulatory options for reducing any significant economic impact on a substantial number of such entities, and explain our ultimate choice of regulatory approach.

In developing this rule, we concluded that the airplane and airplane engine GHG program does not have a significant impact on a substantial number of small entities. We based this on the fact that the rule does not place any burden on small governmental jurisdictions or small nonprofit organizations. Further, there is only one small business in the group of potentially affected entities - an airplane engine manufacturer. There is no economic burden associated with this rule. Thus, this rule does not place any burden on small entities.

## 7.2 Need for the Rulemaking and Rulemaking Objectives

A detailed discussion on the need for and objectives of this rule is located in the preamble to the rule. The standards in this rule are the equivalent of the ICAO standards, consistent with U.S. efforts to secure the highest practicable degree of uniformity in aviation regulations and standards In addition, EPA is required by Clean Air Act section 231 to propose and promulgate emission standards regulating GHG emissions from the classes of aircraft engines identified in EPA's 2016 final endangerment and cause/contribute findings for those emissions. EPA is meeting the Clean Air Act obligation by adopting GHG standards which are equivalent to the Airplane $CO_2$ Emission Standards adopted by ICAO.

## 7.3 Definition and Description of Small Entities

Small entities include small businesses, small organizations, and small governmental jurisdictions. For the purposes of assessing the impacts of the rule on small entities, a small entity is defined as: (1) a small business that meets the definition for business based on the Small Business Administration's (SBA) size standards (see Table 7-1); (2) a small governmental jurisdiction that is a government of a city, county, town, school district or special district with a population of less than 50,000; and (3) a small organization that is any not-for-profit enterprise which is independently owned and operated and is not dominant in its field. Table 7-1 provides an overview of the primary SBA small business categories potentially affected by this regulation.

**Table 7-1 – Small Business Definitions**

| Industry | Defined as small entity by SBA if: | NAICS Codes[a] |
|---|---|---|
| Manufacturers of new airplane engines | ≤1,500 employees | 336412 |
| Manufacturers of new airplanes | ≤1,500 employees | 336411 |

a. North American Industry Classification System (NAICS)

## 7.4 Summary of Small Entities to Which the Rulemaking Will Apply

The businesses that are potentially affected by this rule are those that manufacture new airplanes and new airplane engines. As outlined in Chapter 1, we performed an industry characterization of potentially affected airplane and airplane engine manufacturers.

The industry characterization was used to determine which airplane and airplane engine manufacturers also meet the SBA definition of a small business under this rule. From the industry characterization, we determined that there is only a single airplane engine manufacturer that meets the definition of a small business. Given the small number of businesses overall that are potentially affected by this rule as well as the relative stability of the commercial aviation market, the EPA is confident that this accounting of the number of potentially affected small businesses is both correct and unlikely to change in the near future.

## 7.5 Related Federal Rules

We are not aware of any area where the regulations directly duplicate or overlap with the existing federal, state, or local regulations; however, one small engine manufacturer is also subject to the airplane engine smoke emissions control requirements. The FAA will follow this with its own rulemaking to incorporate the adopted standards into its certification and compliance framework.

## 7.6 Projected Effects of the Rulemaking on Small Entities

After considering the economic impacts of today's rule on small entities, we do not believe that this action will have a significant economic impact on a substantial number of small entities.

There is no economic burden associated with this rule.

Regulatory Alternatives to Accommodate Small Entities

Given that the EPA does not believe the rule has any impact on even a single small entity, it does not believe there is a need for regulatory alternatives to help minimize such a burden on small entities.

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