Technical Report on Aircraft Emissions Inventory and Stringency Analysis

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US EPA Office of Transportation and Air Quality
Assessment and Standards Division

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1 Introduction

Aviation is a major mode of transportation for connecting people and materials given its advantage in speed and long-distance transport capability. Economically, it contributes to more than 5% of U.S. GDP, 10 million U.S. jobs, $1.6 trillion of U.S. economic activities, and $60 billion of U.S. trade balance annually. However, airplanes are also a significant emission source and air traffic is growing fast, globally, at a rate of 4-5% per year[1]. Thus, it is important to assess the airplane emissions inventory and potential environmental impacts.

The first comprehensive global aviation emissions inventory was developed by National Aeronautics and Space Administration (NASA) for 1992[2] and then 1999[3]. Federal Aviation Administration (FAA) in conjunction with Volpe Center of the Department of Transportation subsequently developed a System for Assessing Aviation Global Emissions (SAGE) for 2000-2004[4] inventories and later extended to 2005[5]. Similar European efforts resulted in a global aviation emissions inventories for 2002 and a forecast for 2025[6]. These early works had led to the development of the first International Civil Aviation Organization's (ICAO) Environmental Trends Report in 2010. ICAO has kept this Environmental Trends Report updated every three years ever since, the latest one being the 2019 Environmental Report[7]. Beyond these official global aviation emission inventories, increasingly there are inventories developed by academic and independent initiatives based on diverse data sources and models with varying degree of sophistication, coverage, and timeliness[8] [9] [10] [11].

EPA had worked with the FAA and other stakeholders since 2010 to develop the first-ever international CO_2 standards for airplanes under the auspices of the ICAO's Committee on Aviation Environmental Protection (CAEP). This effort led to the agreement by CAEP on the international CO_2 standards in 2016, and ICAO formally adopted these standards in 2017. The ICAO emissions standards are not self-implementing for individual nations, but these standards must be implemented through domestic regulation.

In 2016, the Environmental Protection Agency (EPA) issued endangerment and contribution findings for aircraft engine greenhouse (GHG) emissions. These findings triggered EPA's duty under section 231 of the Clean Air Act to promulgate emission standards applicable to GHG emissions from the classes of aircraft engines included in the findings. The EPA anticipates moving forward on standards that would be at least as stringent as ICAO's standards.

To inform the U.S. domestic regulation, EPA conducts thorough technical analyses to quantify the impact of the standard. Since much of ICAO regulatory impact analysis and data are proprietary, EPA conducted an independent analysis with publicly available data so all stakeholders would be able to understand how the agency derived its decisions. This report documents the development of EPA's emission inventory analysis including all data sources, methodologies, and model assumptions.

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

In developing the inputs to our model, the agency contracted with ICF to conduct an independent airplane/engine technology analysis of fuel burn improvement for the period of 2010-2040. The agency uses this technology forecast as the basis for our impact assessment. We also conducted sensitivity analyses to evaluate the effects of various model assumptions on our results.

The previous draft of this report (March 2019 version) was peer-reviewed through external letter reviews by multiple independent subject matter experts, including experts from academia and other government agencies, as well as independent technical experts[12]. The report was updated based on the feedback received from the peer reviewers.

2 Methodology of the EPA Emissions Inventory and Stringency Analysis

The methodologies the agency uses to assess the impacts of the proposed standards and alternative stringency scenarios are summarized in the flow chart shown in Figure 1. Essentially, the approach is to compare the emissions inventory of a baseline (business-as-usual case in the absence of standards) with those under various stringency scenarios.

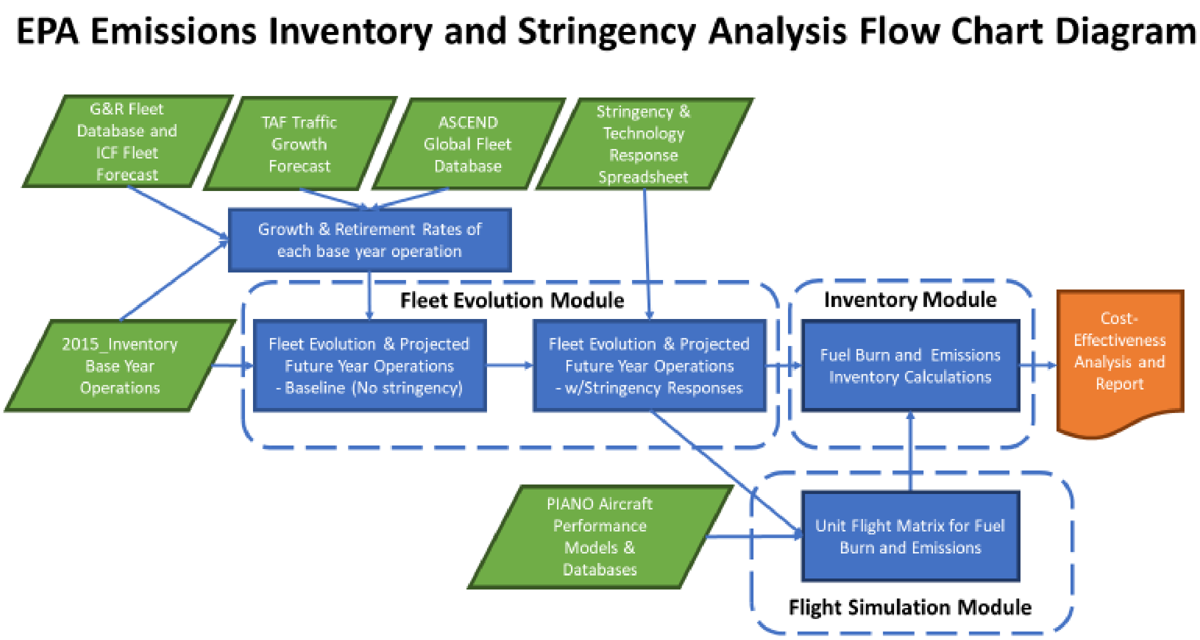

Figure 1 The flow chart diagram for EPA's emissions inventory and stringency analysis

The first step of the EPA emissions inventory and stringency 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 of operations and emissions 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[13].

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 (described in Appendix A) as inputs to the EPA analysis. Together with the residual operations from the base year legacy airplanes, these G&R operations constitute all the operations by the renewed in-service fleet for every future year.

The same method is applied to define fleet evolutions under various stringency scenarios. The only difference is under stringencies, we need to take technology responses into consideration. The airplanes affected by a stringency requirement could either be modified to meet the standard or removed from production without a response.

Once the flight activities for all analysis scenarios are defined by the fleet evolution module, we then compute fuel burn and CO_2 emissions inventories for all the scenarios by simulating these flights with a physics-based airplane performance model known as PIANO[14]. The differences between the baseline and various stringency scenarios are used for assessing the impacts of the stringencies.

The computational processes are grouped into three distinct modules as shown in Figure 1. More detailed accounts of the methods, assumptions and data sources used for these three computational modules are given below.

2.1 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[15] for base year flight activities and FAA's 2015-2040 Terminal Area Forecast[16] (TAF) for future year traffic growth.

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 sources for EPA's official annual GHG and Sinks report since 1990[17]. Globally, the 2015 inventory database contains 39,708,418 flights in which 13,508,800 are originated from the U.S. Among the U.S. flights, 1,288,657 are by piston engine aircraft, 341,078 are military operations and 1,393,125 are by small aircraft with maximum zero fuel weight less than 6000 lbs. In our analysis, we exclude military, piston engine aircraft and small light weight aircraft. Excluding these three aircraft categories that are not subject to the standard, the database still contains 11,624,811 flights, 1,027,296,998 total seats, 1,995,887,786,045 available seat kilometer (ASK) and 36,424,613,164 available tonne kilometer (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 international markets. The 2015-2040 TAF used in this analysis contains growth forecast 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[i] from the 2015 Inventory Database to a corresponding TAF market defined by market type (passenger or freighter), origin-destination airport pair, and

[i] In the absence of a set of keys (primary keys in 2015 Inventory and foreign keys from TAF) that can uniquely identify the relationship between the two databases, a lookup table can be used to "map" the related information from one database to another. The term "mapping" is used here in such context to apply appropriate growth rate category (passenger or freighter) from TAF to the base year operations in 2015 Inventory via a lookup table such as the one proposed in Table 1.

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 is shown in Table 1. USAGE_CODE and SERVICE_TYPE are the parameters in the 2015 Inventory Database designed to identify the airplane usage category and the service type of any given flight operation. They are used to identify the growth rate type (i.e., general aviation, passenger and freighter under the GR_Map column of Table 1). The growth rate type in turn is used to determine which data sources[16,18,19,20] to look up for appropriate growth rate as will be elaborated further below. 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 (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 1. The size of each sub-market category based on the two-parameter mapping is summarized in Table 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 (TOTAL_OPS). In consultation with FAA, these nine sub-markets are mapped into three growth rate types (under the GR_Map column in Table 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 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. 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 U.S. turboprop operations based on FAA Aerospace Forecast (Fiscal Year 2017-2037)[18]. For U.S. business jet operations, we use the 3% CAGR (Compound Annual Growth Rate) forecasted by the FAA Aerospace Forecast (Fiscal Year 2017-2037)[18].

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 freighters based on ICAO long term traffic forecast for passenger and freighters [19]. 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[20]. A summary of all the growth forecast sources and the growth rates used in this report is provided in Appendix C-2 for various market segments.

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 subjected to the GHG standards[ii], so they are excluded from all inventory data reported below.

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

$$R(t) = 1/(1 + e^{a-bt}) \qquad \mathbf{1}$$

where R is the retirement curve function, a and b are coefficients that change with airplane type and t 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 2 illustrates the characteristic “S” shape of a fitted survival function, S(t), where S(t) = 1 – R(t). Note that the ratio of the two coefficients in Equation 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

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[ii] The standards apply to new type and in-production airplanes after the effective dates of the standards, and the standards do not apply to in-use airplanes, which include converted freighters.

respect to the vertical axis, t = a/b and has long tails at both ends of the age distribution (for very young and very old airplanes in the fleet).

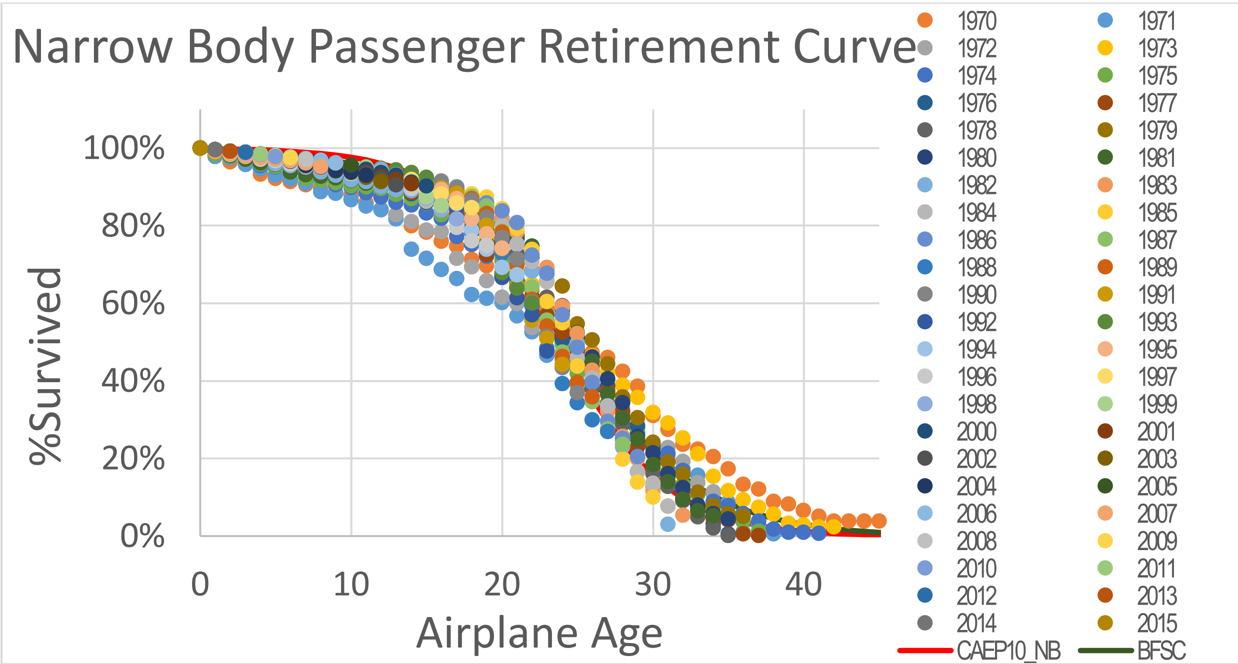

Figure 2 The Retirement Curve of Narrow–Body Passenger Airplane Based on Ascend[21] fleet data

Retirement curves of major airplane categories used in this EPA analysis are derived statistically based on data from the FlightGlobal's Fleets Analyzer database[21] (also known as ASCEND Online Fleets Database -- hereinafter "ASCEND"). Table 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 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 fleet (e.g., airplane category or airplane 'type' as defined by ASCEND) will be used to calculate the retirement rates for future years.

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[iii] 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 documented in an ICF report.[22] 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 airplanes out to 2040. The G&R airplanes in each market segment are listed in Table 3. A detailed mapping of aircraft model identification codes and PIANO aircraft models is provided in Appendix C-1.

Table 3 The G&R airplane available in each market segment

Market Segment	Description	G&R Airplane Type
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

[iii] The 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.

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 ASK for passenger operations, ATK for freighter operations, and number of operations for business jets. Of course, given the number of seats for passenger airplanes, payload capacity for freighters and the great circle distance for each flight, all these parameters can be converted to a common activity measure, i.e., number of operations. The formula for calculating number of operations for any out years is given in Equation 2.

$$\mathrm{NOP(y)} = \frac{\mathrm{GR(y)} + \mathrm{RET(y)}}{\mathrm{N(c,y)}} NOP(2015) \tag{2}$$

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

GR(y) is the year over year growth rate in year y expressed as a fraction of the base year operations

RET(y) is the year over year retirement rate in year y expressed as a fraction of the base year operations

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

ICF technology response includes continuous improvement in metric value[23,iv] (MV) for all G&R airplanes from 2010[v] to 2040. ICF technology responses also include estimated metric value improvements for long-term replacement airplanes 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 improving continuously and new type airplanes are introduced periodically to replace airplane models that are going out of production due to market competition. In order to capture this dynamic changing of airplane efficiency improvements, our fleet evolution model tracks the market share of every new-in-service airplanes entering the fleet each year and applies the annual fuel efficiency improvement -- via an adjustment factor according to the vintage year of the airplanes 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.

2.2 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 version 5.4 was used for all flight simulations. 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., 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 a few modeling assumptions. 1) Assume airplanes fly the great circle distance[vi] (which is the shortest distance along surface of the earth between two

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[iv] The metric value is a certified airplane fuel efficiency value defined by ICAO's Annex 16, Volume III and the Environmental Technical Manual, Volume III. An airplane's metric value is defined as the average of $1/(SAR^* RGF^{0.24})$ evaluated at three test points, where SAR is the Specific Air Range measuring the distance an airplane travels in the cruise phase per unit of fuel consumed and RGF is the Reference Geometry Factor based on a measurement of airplane fuselage size derived from a two-dimensional projection of the fuselage. The three test points are defined by three airplane gross masses, i.e., high, mid and low gross masses. The high gross mass is defined as 0.92*MTOM, where MTOM is the highest maximum take-off mass of all variants in the airplane type design. The low gross mass is defined as $0.45*MTOM + 0.63*MTOM^{0.924}$. The mid gross mass is the average of the high and low gross masses.

[v] For this analysis, with 2015 as the base year, we only use the continuous improvement data from 2015 to 2040.

[vi] Correction for great circle distance (GCD) can be made by an adjustment factor of 4% to 10% at the fleet level or by adding a discrete detour distance for certain length of flights as used in the ICAO carbon calculator to account for the difference between actual flight distance and the great circle distance. Appendix C-4.1 includes a sensitivity study where the emission results are scaled by a constant adjustment factor for a better estimate of the annualized global fleet emissions with realistic flight paths. This adjustment, which raises all emissions by the same factor, does not change any conclusions of our analyses given the constant adjustment factor. Given accurate flight path

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 related flight operations. 4) Assume a load factor of 75%[vii] maximum payload capacity for all flights except for business jet where 50% is assumed. 5) Use the PIANO default reserve fuel rule[viii] 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). Note that additional clarifications to peer reviewers' questions about our model assumptions are provided in Appendix B.

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 factor of 3.16 kg/kg fuel for CO_2 emissions based on ICAO Doc 9889[24] for typical commercial jet fuels. To convert to the six well-mixed GHG emissions, we used 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. The method for calculating CO_2 equivalent emissions is to first calculate N_2O emissions based on SAE AIR 5715, entitled "Procedures for the Calculation of Airplane Emissions"[25], and then to find the conversion factor for N_2O to CO_2 based on the 100-year global warming potential factor from the EPA publication "Emissions Factors for Greenhouse Gas Inventories"[26].

Given the flight activities defined by the fleet evolution module above, 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 of the stringency scenarios and sensitivity studies. To reduce the computational workload of such a huge task in the 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

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data, an accurate adjustment factor can always be established, but it is less important for the stringency analysis. Thus, the GCD assumption is clearly justifiable for the purpose of this report.

[vii] Additional load factors of 85% and 95% has been included as sensitivity studies in Appendix C-4.2. It turns out that an increase of the load factor from 75% to 95% would increase the GHG emission by about 4% at the global fleet level. This result is because load factor is held constant for each of these sensitivity cases and the fleet evolution from the same base year operations and the same growth rate forecast would yield the same fleet operations in all future years independent of the load factor assumption. Since the base year operation is fixed (as input to our model), different load factor assumptions imply different base year RPK/FTK which would then grow to future years at prescribed growth rate independent of the load factor assumption. Hence, the net effect of the load factor assumption under this modeling framework is to increase the aircraft payload and weight resulting in higher emissions for all cases (baseline and stringencies). Similar to the GCD assumption described above, it does not change any conclusions of our analyses except raising emissions for all flights.

[viii] For typical medium/long-haul airplanes, the default reserve settings are for a 200 nautical mile diversion, 30 minutes of hold, plus a 5% contingency on mission fuel. Depending on airplane types, other reserve rules such as U.S. short-haul, European short-haul, and National Business Aviation Association-Instrument Flight Rules (NBAA-IFR) or Douglas rules are used as well.

combination. The millions of flights in the unit flight matrix are interpolated from the 50x50 flight distance/payload database.

2.3 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 all the stringency 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 emissions inventories of various stringency scenarios and that of the baseline provide the quantitative measures for the agency to assess the impacts of the stringency options.

3 Modeling Results for Fleet Evolution, Emission Inventories and Stringency Analyses

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 of all 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 and growth retirement and residual operations in future years, the overall global fleet growth and replacement operations are depicted as an example in Figure 3[ix], 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 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 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. 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 year to year 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.

[ix] Additional charts depicting growth and replacement operations by fleet family are provided in Appendix C-3 for reference.

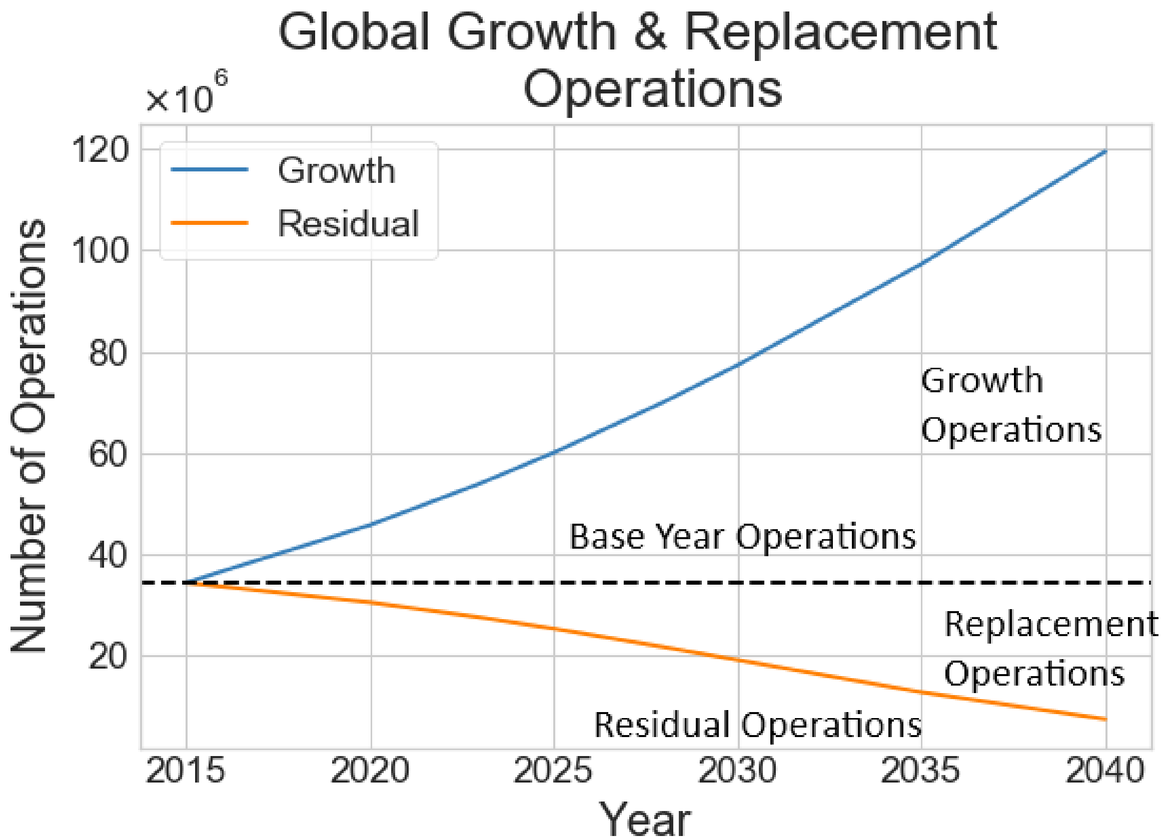


Figure 3 Global total growth and replacement operations in years 2015-2040

3.1 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 2, it is based on FAA's 2015 inventory database for the base year operations and FAA's 2015-2040 TAF 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 are no right or wrong results 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.

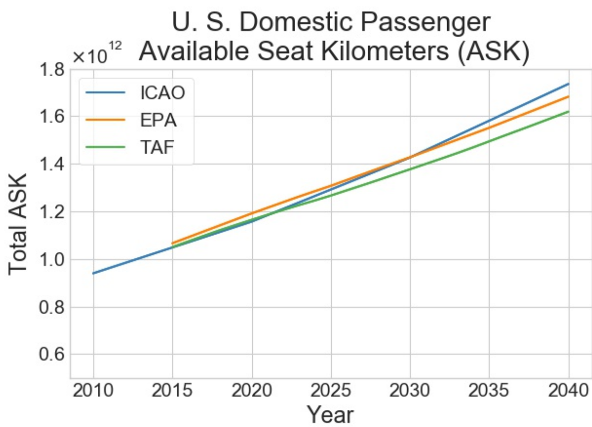
Figure 4 compares the EPA fleet evolution results with ICAO results. The EPA analysis results are close to ICAO results, but differ by up to 10% in the analysis period of 2015-2040. This is expected because there are many fundamental differences between the two analyses. First, the EPA fleet evolution is based on FAA 2015 Inventory Database, while ICAO's fleet evolution is based on 2010 COD (Common Operations Database)[27]. 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[x] consensus traffic forecast and industry provided fleet forecast for passenger, freight and business jets for 2010-2040. Thus, 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 confirms that the two fleet evolution models behave reasonably close to each other at the aggregate level despite the fact that 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 one uniform market.

We also compare the EPA fleet evolution results with FAA TAF mainly to confirm that the growth rates are consistent between the two approaches -- since EPA analysis growth rates are sourced from TAF. 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, and these differences are most notable, in the international freight operations. Many operations exist in one database, but not in the other and vice versa.

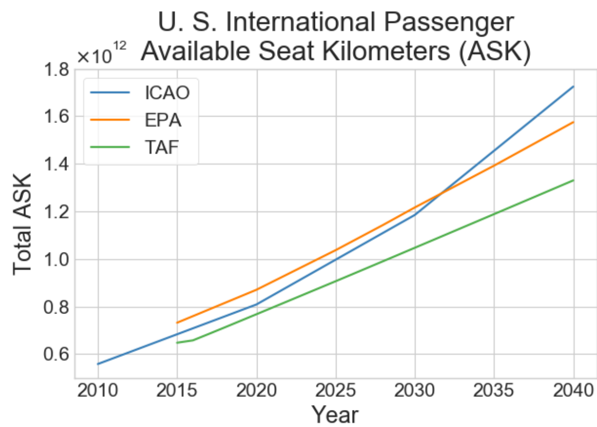
Our fleet evolution strategy is to evolve future year fleet operations solely based on FAA 2015 Inventory for the base year operations. Thus, in cases where the base year operations in TAF are different from those in the 2015 Inventory, the TAF operational data are ignored. TAF is only used to determine 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 corresponding 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 differences still exist between the two databases, 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 the stringency analysis because they would not be subject to the proposed GHG standards. This exclusion also makes the freighter results from the EPA analysis more comparable to ICAO's results, but other differences remain as explained later.

[x] 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.



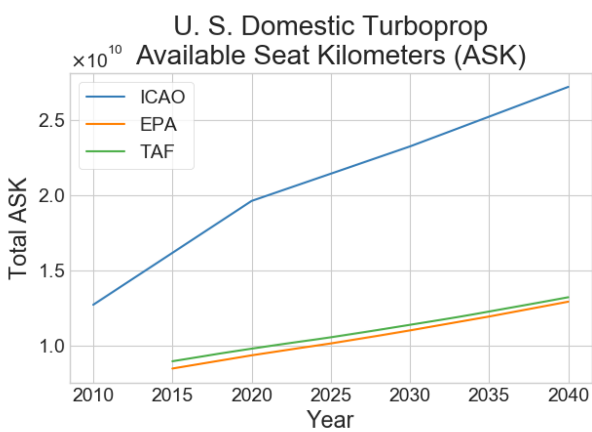
	2010	2015	2020	2030	2040
ICAO	9.40E+11		1.16E+12	1.43E+12	1.74E+12
EPA		1.07E+12	1.19E+12	1.43E+12	1.68E+12
TAF		1.05E+12	1.16E+12	1.38E+12	1.62E+12



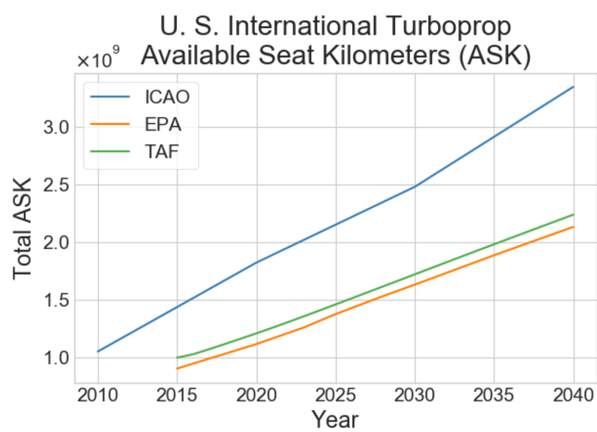
	2010	2015	2020	2030	2040
ICAO	5.58E+11		8.08E+11	1.18E+12	1.72E+12
EPA		7.32E+11	8.70E+11	1.22E+12	1.57E+12
TAF		6.48E+11	7.67E+11	1.05E+12	1.33E+12

Figure 4 Comparison of U.S. Passenger fleet ASK of ICAO, EPA and TAF

The U.S. passenger fleet operations of the three datasets match reasonably well as shown in Figure 4. We observe higher growth rate for ICAO results in both U.S. domestic and international operations compared to the results from the EPA analysis. The EPA analysis growth rate is in between the other two results.



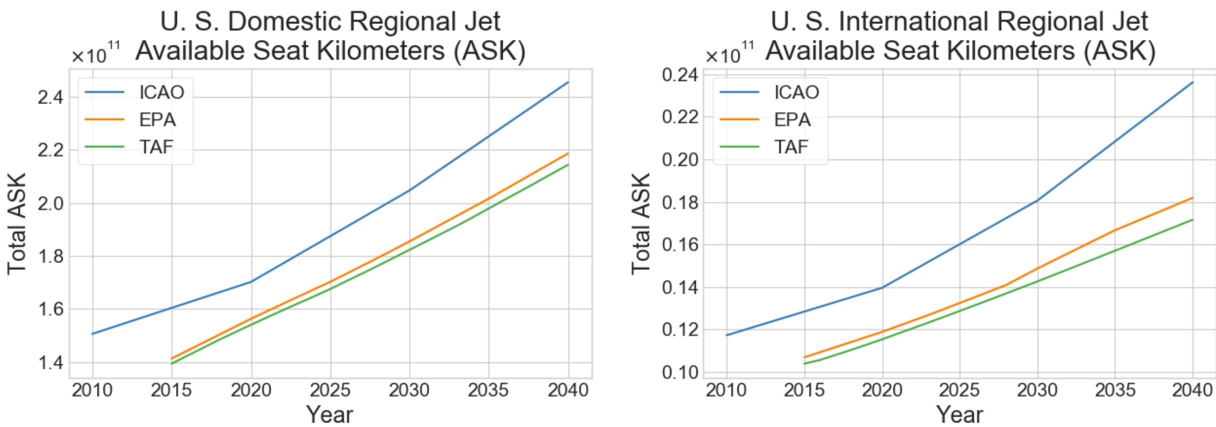
	2010	2015	2020	2030	2040
ICAO	1.27E+10		1.96E+10	2.32E+10	2.72E+10
EPA		8.48E+09	9.35E+09	1.10E+10	1.29E+10
TAF		8.96E+09	9.80E+09	1.14E+10	1.32E+10



	2010	2015	2020	2030	2040
ICAO	1.05E+09		1.82E+09	2.48E+09	3.35E+09
EPA		9.01E+08	1.11E+09	1.63E+09	2.13E+09
TAF		9.96E+08	1.21E+09	1.72E+09	2.24E+09

Figure 5 Comparison of U.S. Turboprop fleet ASK of ICAO, EPA and TAF (note different scale on y-axis)

The U.S. turboprop fleet operations of the three datasets match less well as shown in Figure 5. The EPA analysis and TAF are reasonably close, while ICAO is about 50 to 100 percent higher in ASK. The difference is not a major concern for fleet wide emissions because turboprop emissions are less than 1% of the overall fleet emissions. The difference 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 compared to the FAA-TAF dataset. Since the EPA fleet evolution results matches well with the TAF data, it suggests our fleet evolution results for turboprop are reasonable. Therefore, the emissions and stringency analysis will proceed with the EPA fleet evolution results on this basis and ignore the discrepancy with the ICAO data for now.

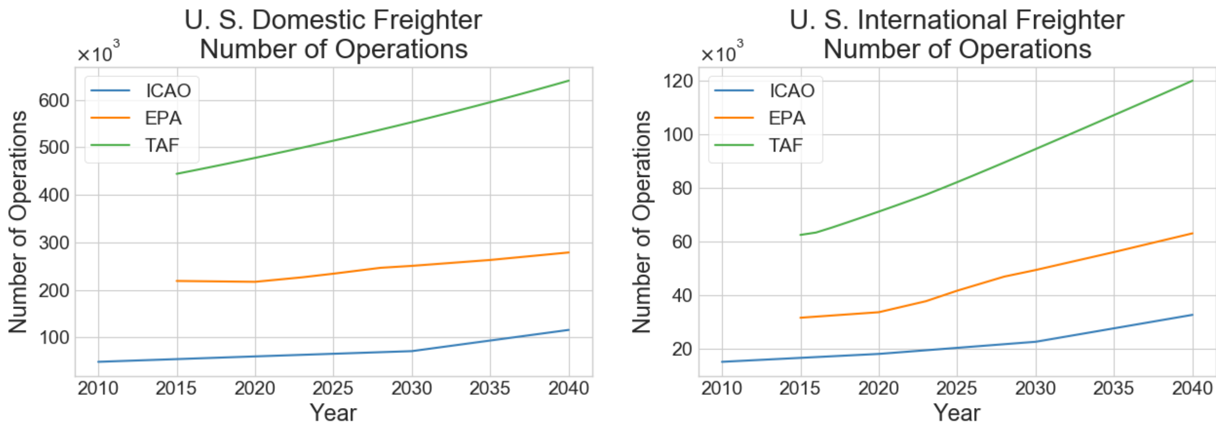


	2010	2015	2020	2030	2040
ICAO	1.51E+11		1.70E+11	2.05E+11	2.46E+11
EPA		1.41E+11	1.56E+11	1.85E+11	2.19E+11
TAF		1.39E+11	1.54E+11	1.82E+11	2.14E+11

	2010	2015	2020	2030	2040
ICAO	1.17E+10		1.40E+10	1.81E+10	2.36E+10
EPA		1.07E+10	1.19E+10	1.49E+10	1.82E+10
TAF		1.04E+10	1.15E+10	1.43E+10	1.72E+10

Figure 6 Comparison of U.S. Regional Jet fleet ASK of ICAO, EPA and TAF (note different scale on y-axis)

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 6. This difference 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 difference 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 purpose of this analysis.



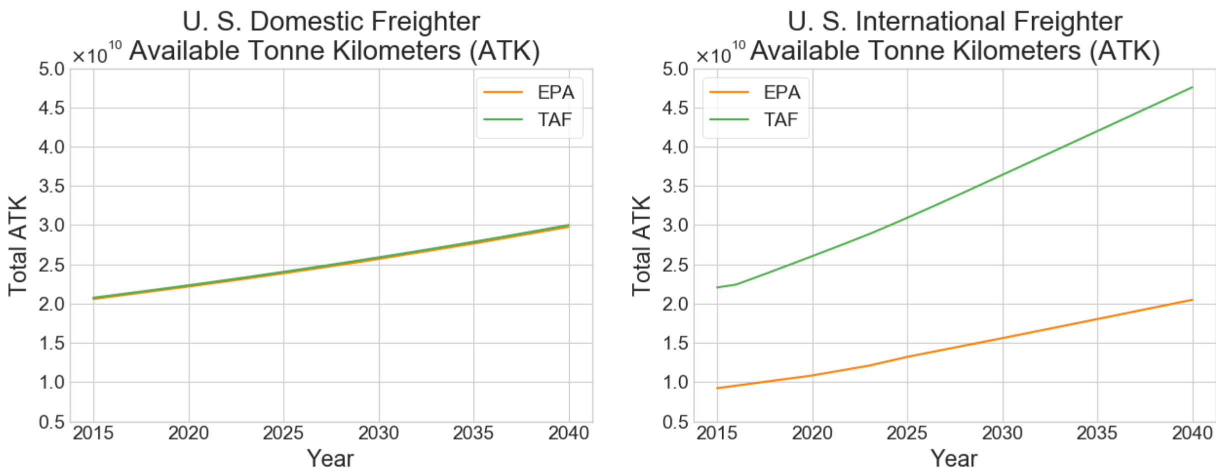
	2010	2015	2020	2030	2040
ICAO	4.84E+04		5.98E+04	7.09E+04	1.16E+05
EPA		2.19E+05	2.17E+05	2.50E+05	2.79E+05
TAF		4.44E+05	4.78E+05	5.53E+05	6.40E+05

	2010	2015	2020	2030	2040
ICAO	1.51E+04		1.80E+04	2.25E+04	3.26E+04
EPA		3.15E+04	3.36E+04	4.93E+04	6.30E+04
TAF		6.24E+04	7.11E+04	9.44E+04	1.20E+05

Figure 7 Comparison of U.S. Freighter fleet number of operations for ICAO, EPA and TAF (note different scale on y-axis)

Figure 7 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 as follows: (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 even 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 7 does not necessarily translate into higher freighter capacity in terms of ATK as shown in Figure 8. The ICAO activity dataset we use does not contain payload capacity information, so we can only compare EPA with TAF for ATK.

It is clear from Figure 8 that the EPA analysis 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 U.S international freighter operations present in TAF are missing in the 2015 Inventory from which the EPA ATK is derived. Figure 9 illustrates some evidence supporting this hypothesis by separating out the operations in TAF with and without origin-destination (OD) pair, airplane (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 9 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 is to use the FAA 2015 Inventory as the basis to grow future year activities with TAF growth forecast, this difference, although notable and maybe worthy of further investigations, does not affect our ability to evolve all future freight operations based solely on freighter flights in the FAA 2015 Inventory. 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	2030	2040
EPA	2.06E+10	2.22E+10	2.57E+10	2.98E+10
TAF	2.08E+10	2.23E+10	2.59E+10	3.00E+10

	2015	2020	2030	2040
EPA	9.23E+09	1.09E+10	1.56E+10	2.05E+10
TAF	2.21E+10	2.60E+10	3.64E+10	4.76E+10

Figure 8 Comparison of U.S. Freighter fleet ATK of EPA and TAF

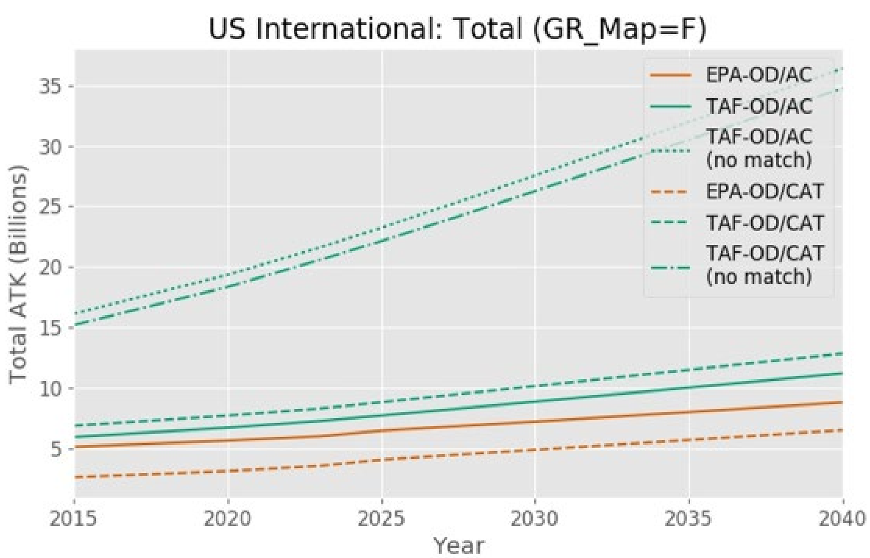
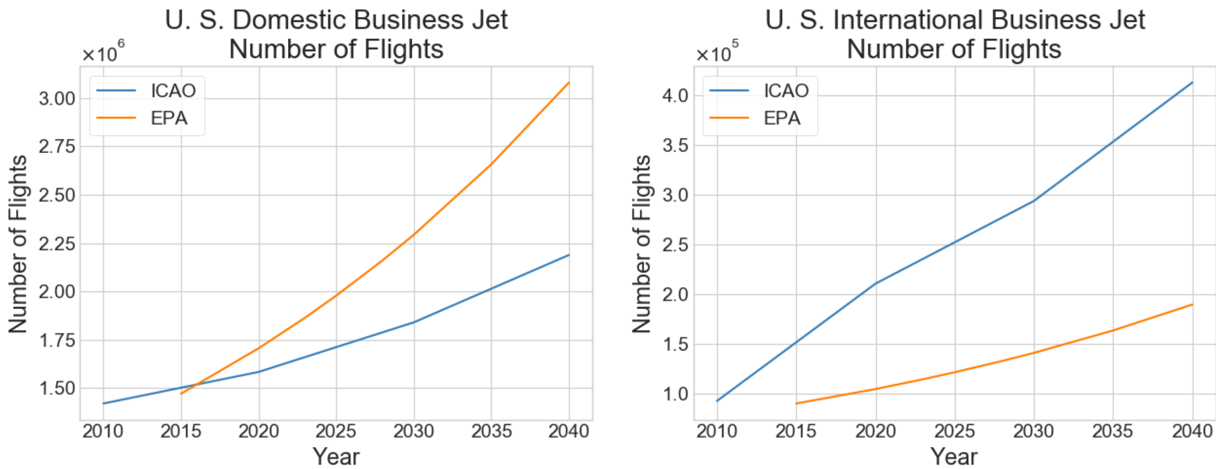


Figure 9 Total ATK of subsets of flights in EPA and TAF with and without match origin-destination pair (OD), airplane type (AC) and airplane category (CAT)



	2010	2015	2020	2030	2040
ICAO	1.42E+06		1.58E+06	1.84E+06	2.19E+06
EPA		1.47E+06	1.71E+06	2.29E+06	3.08E+06

	2010	2015	2020	2030	2040
ICAO	9.26E+04		2.11E+05	2.94E+05	4.13E+05
EPA		9.00E+04	1.05E+05	1.41E+05	1.90E+05

Figure 10 Comparison of U.S. Business Jet fleet number of operations for ICAO and EPA (note different scale on y-axis)

The business jet operations of ICAO and EPA analyses have similar 2010/2015 base year operations, but different growth rates as shown in Figure 10. Comparing to EPA, ICAO appears to underestimate the growth rate of U.S. domestic business jet operations and overestimate the growth rate of U.S. international business jet operations. A higher growth rate of fleet operations increases the G&R fleet faster over time, so it tends to amplify the impact of the standards. Conversely, a lower growth rate of fleet operations 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 stringency impact, as measured by the difference to the baseline, will be 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 the 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 the uncertainty in these data will alter any conclusion of the analysis.

3.1.1 Conclusions of the Fleet Evolution Results

Overall, the EPA fleet evolution results agree quite well with 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 well 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 it 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 absence of more reliable data sources for business jet growth forecast, EPA will proceed with the current forecast sources from FAA and Bombardier for the EPA analysis. The uncertainty in the baseline forecast is noted, but considered to be secondary for the stringency assessment.

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 is described in Section 2 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 11 based on outputs from the fleet evolution model.

In each of the plots contained in Figure 11, there are three baselines plotted. These include the primary analysis (labeled as "CO_2") and two sensitivity scenarios (labeled as "CO_2 without continuous improvement" and "frozen fleet assumption"). 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 is benefitted 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 analysis period (2015-2040). The third line is the business-as-usual (BAU) baseline, where the fleet fuel efficiency would benefit from both fleet evolution with the new airplanes entering the fleet and business-as-usual improvement of the new in-production airplanes.

These emissions inventory baselines thus provide a quantitative measure for the effects of model assumptions on fleet evolution and continuous improvement. The business-as-usual baseline incorporates all market driven emissions reductions factors. It is used as the primary baseline for this EPA 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 two higher baselines in Figure 11 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)[xi]. The difference between the lower two baselines Figure 11 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 emission between the BAU and the frozen fleet baselines in 2040 alone is about 400 Mt, a significant 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

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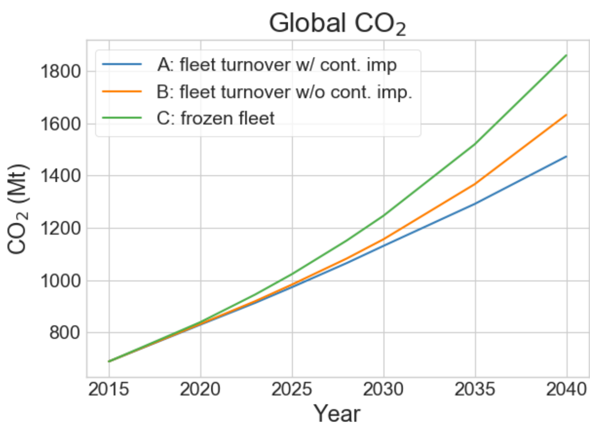
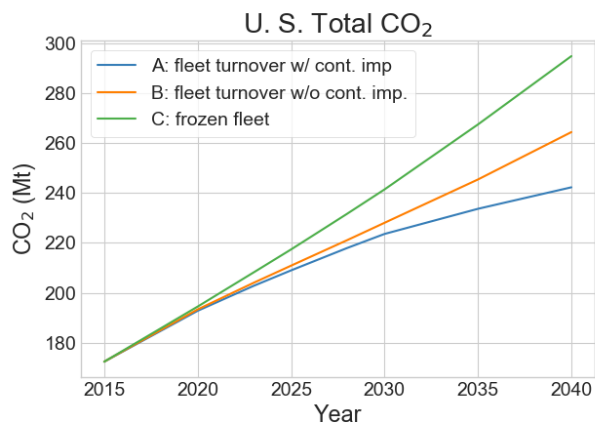
[xi] It may be worth mentioning that the ICAO baseline is in between these two higher baselines since the ICAO baseline includes limited fleet evolution with a short list of transition pairs for which replacement airplanes had been identified at the time of the ICAO CO_2 analysis[23].

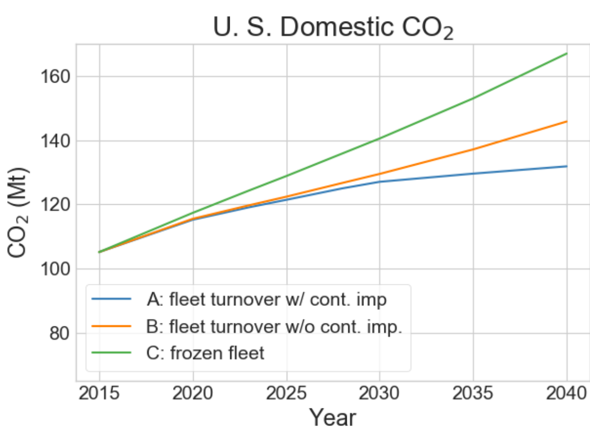
growth rate of the US domestic CO_2 emissions baseline, which is projected with a very slow growth rate by 2040 given the continuous improvement assumptions.



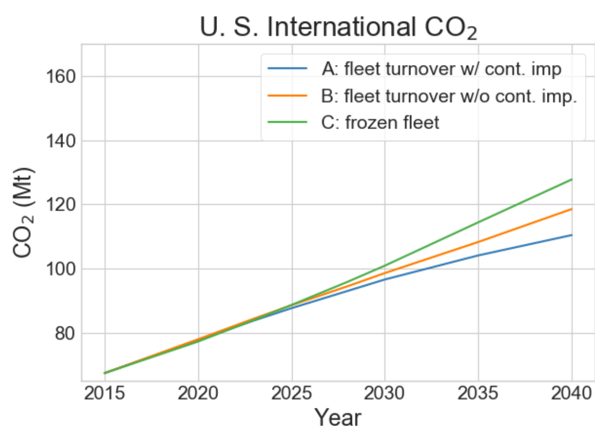
	2015	2020	2030	2040
A	688.75	829.45	1130.21	1471.99
B	688.75	832.14	1155.33	1631.19
C	688.75	838.96	1245.25	1858.95



	2015	2020	2030	2040
A	172.44	192.82	223.59	242.27
B	172.44	193.37	228.05	264.38
C	172.44	194.50	241.42	294.81



	2015	2020	2030	2040
A	105.10	115.19	127.04	131.86
B	105.10	115.48	129.50	145.85
C	105.10	117.33	140.55	167.05



	2015	2020	2030	2040
A	67.34	77.62	96.56	110.41
B	67.34	77.88	98.55	118.53
C	67.34	77.18	100.87	127.76

Figure 11 Range of CO_2 emissions baselines with various fleet evolution and continuous improvement assumptions

3.2.1 Discussions for 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 would provide 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 model variables.

One might argue 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. However, 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, the EPA contracted ICF to conduct an independent analysis to develop a credible fleet evolution and technology response forecast. This forecast considered 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.

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

It is traditionally assumed that the baseline does not matter for stringency analysis, because the impact of the stringency is measured from stringency to baseline, the effects of baseline choices tend to cancel out when the primary objective is just to compare the delta of stringency and baseline. It can be shown that this assumption may not be true when some of the fleet evolution assumptions affect the emission outputs of the baseline and stringency lines differently. As a result, the output of the stringency analysis might be skewed and subsequently influence the policy-making decisions.

In conclusion, using the best possible estimate of a baseline would lead 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.

3.3 Stringency Analysis of U.S. and Global CO_2 Emission Impacts

The EPA main analysis includes three stringency scenarios, the proposed standard and two alternatives. The primary scenario is the proposed standard, which is equivalent to the ICAO CO_2 standard. The two alternative scenarios are a pull-ahead (an earlier implementation of the standard by the timing shown in Table 4) scenario at the same stringency (Scenario 2) and a pull-ahead scenario at a higher stringency (Scenario 3). Table 4 lists the stringency levels and implementation timing of the three stringency scenarios. See ICF Report[22] for more detailed description of these stringency scenarios. Detailed description on the definition of airplane fuel efficiency metric value[iv] and the measurement techniques and test procedures to determine pass or fail status of an airplane against the GHG standards can be found in section V of the 2020 EPA Notice of Proposed Rulemaking for Control of Air Pollution from Airplanes and Airplane Engines: GHG Emission Standards and Test Procedures.

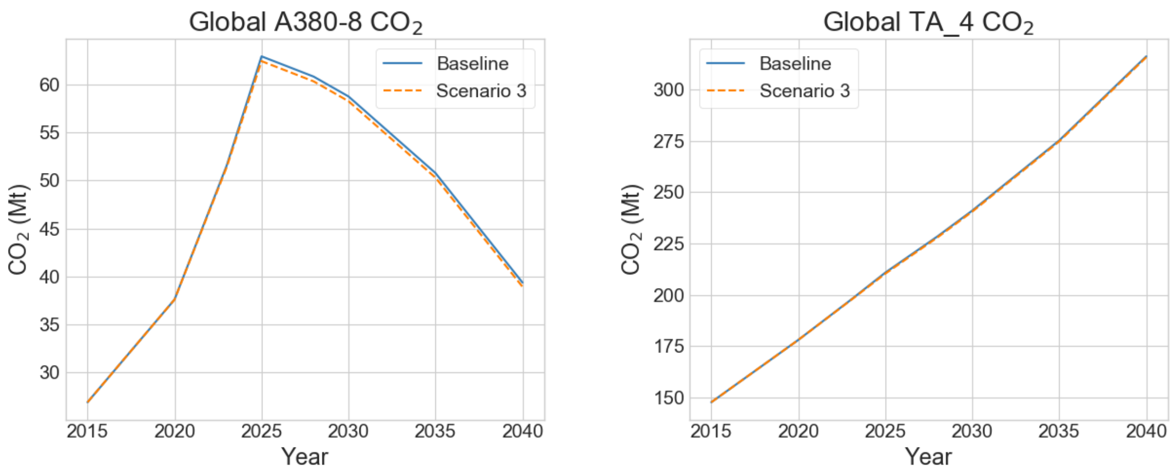
Table 4 The Stringency and Level and Effective Year of the Three Analyzed Scenarios

Airplane Class	Market Segment	Scenario 1: Stringency/Timing	Scenario 2: Stringency/Timing	Scenario 3: Stringency/Timing
<= 60 Tonne	Business Jet Regional Jet Turboprop	ICAO Stringency /2028	ICAO Stringency /2025	Higher Stringency /2025
>60 Tonne	Single Aisle Twin Aisle	ICAO Stringency /2028	ICAO Stringency /2023	Higher Stringency /2023
Freighter	Freighter	ICAO Stringency /2028	ICAO Stringency /2028	Higher Stringency /2028

Based on the technology response from the ICF technology and cost report[22], 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 proposed GHG standards.

Under Scenario 3, there is one airplane, the Airbus A380-8, that will be affected by the stringency. This airplane, however, is projected to go out of production by 2025 according to ICF's end of production forecast.[xii,28] Figure 12 shows the global CO_2 emissions baseline for A380-8 increases sharply between 2020 and 2025 due to the projected end of production of the Boeing 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 slightly visible as the rate of increase slows down a little around 2023-2025 due to the technology responses of the A380.

[xii] Airbus has made an announcement on February 14, 2019 to cease production of A380 in 2021. Since our analysis was finished prior to the announcement, we did not take this latest information into consideration. But, given this latest A380 production information, the projected impact of the GHG standards on A380 would be decreased to zero emissions reductions and costs. According to Airbus, the unfulfilled A380 orders will be replaced by A330NEO and A350. Both of these airplane types meet the ICAO CO_2 standards, and thus, these airplanes will not be affected by the standards.

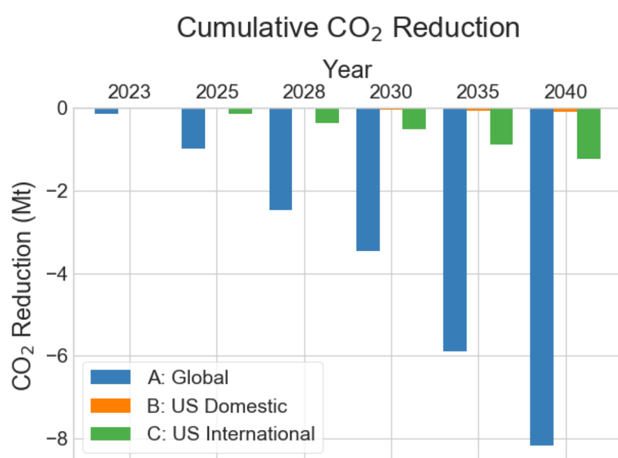


	2015	2020	2030	2040
Baseline	26.89	37.59	58.74	39.35
Scenario 3	26.89	37.59	58.25	38.91

	2015	2020	2030	2040
Baseline	147.62	177.98	241.01	316.16
Scenario 3	147.62	177.98	240.51	315.72

Figure 12 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 8.17 Mt from 2023 to 2040 as shown below in Figure 13. 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	-0.99	-2.47	-3.46	-5.89	-8.17
B	-0.00	-0.01	-0.04	-0.05	-0.08	-0.12
C	-0.02	-0.15	-0.38	-0.53	-0.89	-1.24

Figure 13 Cumulative reduction of CO_2 emissions from 2023 to 2040 for Scenario 3

4 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 look into these influences and put the results of the EPA main analysis in perspective.

Among the three scenarios analyzed for this report, only Scenario 3 impacts an airplane and has 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 tentative conclusions about potential impacts of this proposed rulemaking.

In appendix C-4, more sensitivity studies are presented to evaluate the effects of a few more key model variables. It can be shown from these studies that the effects of these additional variables are significant only to the absolute level of emission inventories, but they are less important for stringency analysis where the primary interest is less in absolute emissions but more in emission reductions relative to a baseline. Further sensitivity analyses and a general uncertainty quantification of the aviation emission model could be an important future research topic.

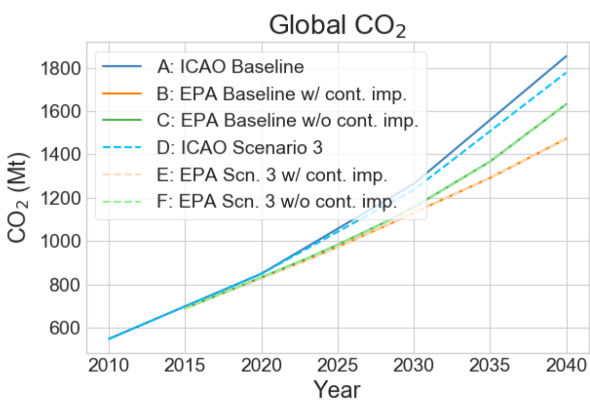
4.1 Scenario 3 Sensitivity to Continuous Improvement

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 these results with the corresponding ICAO analysis which although not directly comparable to EPA main analysis as explained in section 3.1, it is an important reference to show the effects of various assumptions in the baseline, fleet evolution, and technology response.

Figure 14 shows CO_2 emissions of baseline and Scenario 3 for these three cases, i.e., ICAO analysis, 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 insensitive to the baseline shift. The emissions reductions, as measured by the differences between the baselines and stringency lines, are what are important for resolving the effects of model assumptions in the three cases.

From Figure 16, we observe that the emissions reductions increase by more than three-fold when continuous improvement is turned off. For example, the cumulative U.S. total emissions reductions for Scenario 3 increase from 1.36 Mt to 4.77 Mt as shown in the accompanying table in Figure 16. 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 15) for the same stringency scenario. This is the reason the EPA Scenario 3 (dashed) lines are almost undistinguishable from the baselines in Figure 14. Examining the zoom-in graph for the A380 in Figure 17, 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 17). And it is almost invisible at the total fleet level in Figure 14 when the aggregate base becomes progressively larger. 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 improvements to meet the stringency level 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 the 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	2030	2040
A	547.78		848.65	1263.58	1852.91
B		688.75	829.45	1130.21	1471.99
C		688.75	832.14	1155.33	1631.19
D	547.78		848.65	1235.78	1777.24
E		688.75	829.45	1129.72	1471.55
F		688.75	832.14	1153.60	1629.63

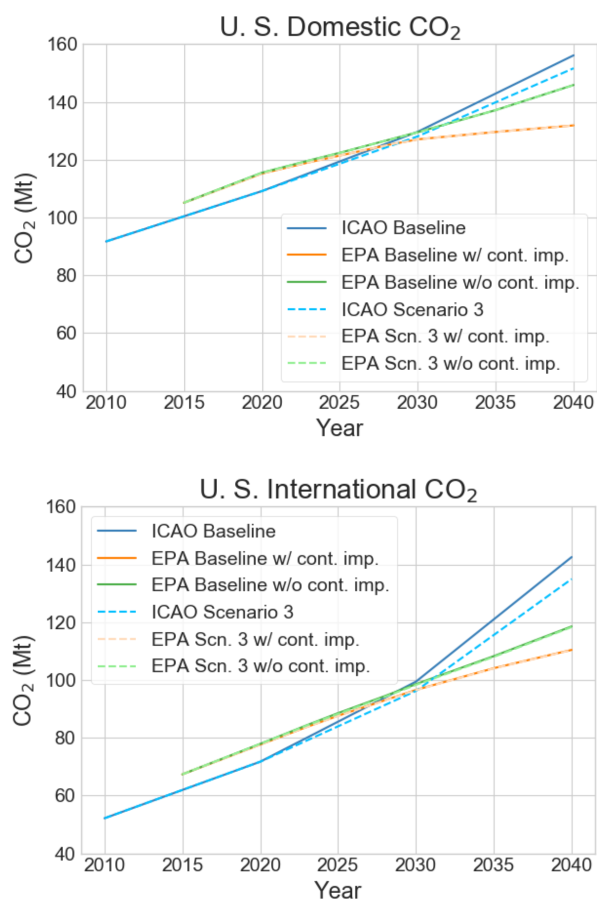
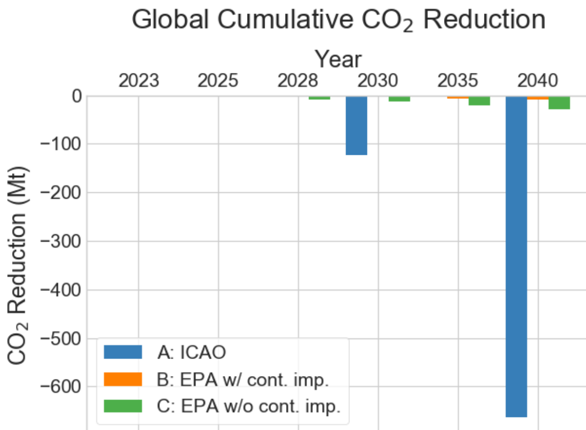
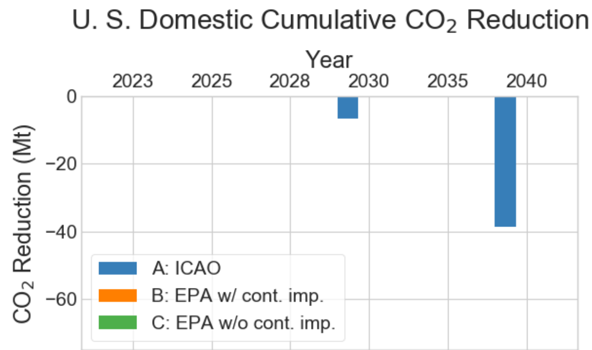


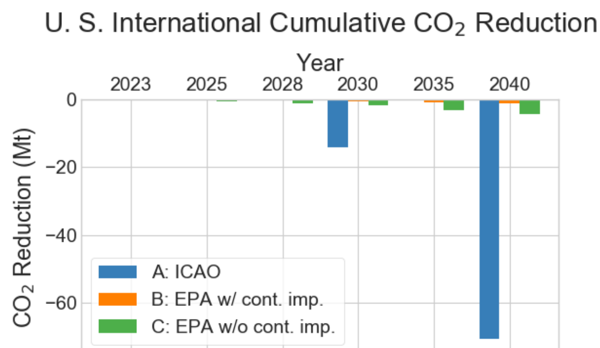
Figure 14 CO_2 Emissions of Baseline and Scenario 3 for ICAO and EPA (w & w/o continuous improvement) Cases



	2023	2025	2028	2030	2035	2040
A				-122.87		-664.22
B	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17
C	-0.56	-3.47	-8.70	-12.18	-20.70	-28.74

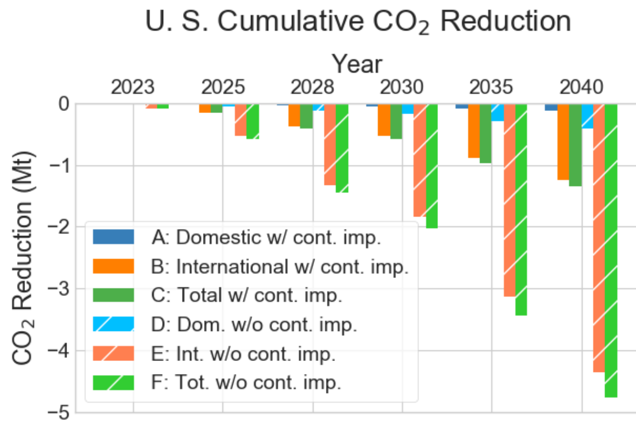


	2023	2025	2028	2030	2035	2040
A				-6.70		-38.49
B	-0.00	-0.01	-0.04	-0.05	-0.08	-0.12
C	-0.01	-0.05	-0.12	-0.17	-0.29	-0.41



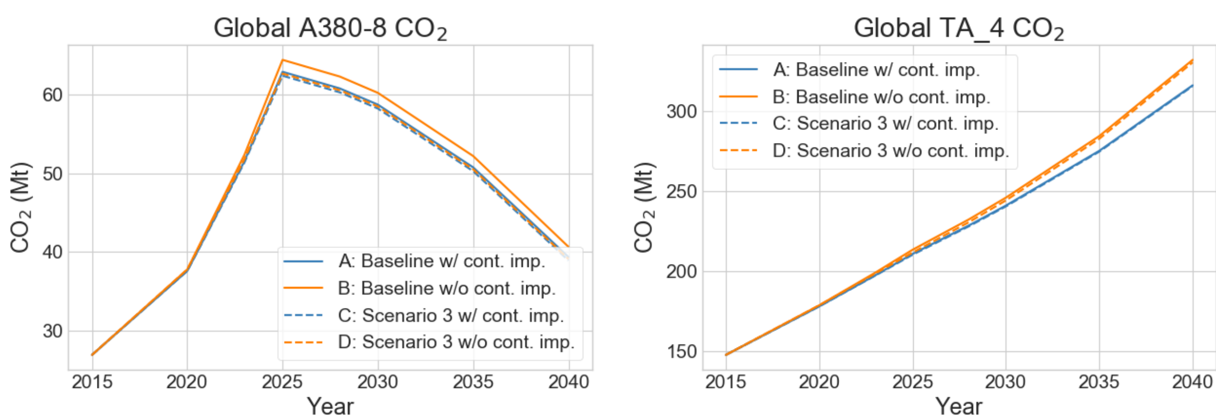
	2023	2025	2028	2030	2035	2040
A				-14.23		-70.50
B	-0.02	-0.15	-0.38	-0.53	-0.89	-1.24
C	-0.09	-0.53	-1.32	-1.85	-3.14	-4.36

Figure 15 Cumulative CO_2 Reduction of Scenario 3 for ICAO and EPA (w & w/o continuous improvement)



	2023	2025	2028	2030	2035	2040
A	-0.00	-0.01	-0.04	-0.05	-0.08	-0.12
B	-0.02	-0.15	-0.38	-0.53	-0.89	-1.24
C	-0.03	-0.16	-0.41	-0.57	-0.98	-1.36
D	-0.01	-0.05	-0.12	-0.17	-0.29	-0.41
E	-0.09	-0.53	-1.32	-1.85	-3.14	-4.36
F	-0.10	-0.58	-1.45	-2.02	-3.43	-4.77

Figure 16 Cumulative U.S. CO_2 Reduction for EPA Scenario 3 with & without Continuous Improvement



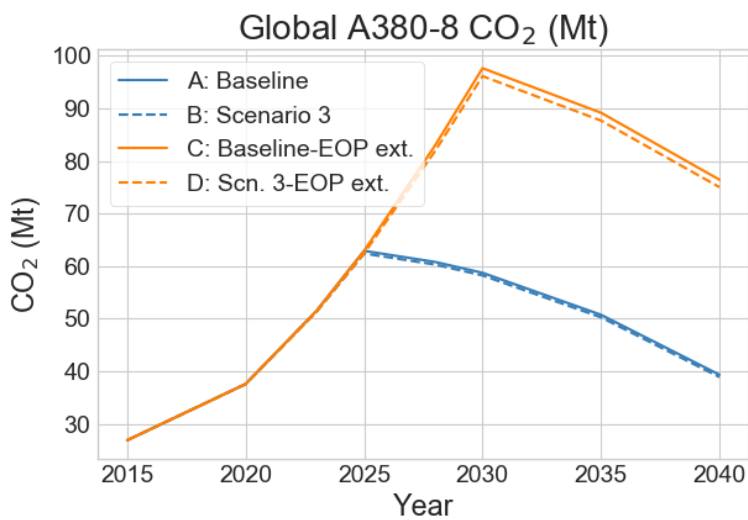
	2015	2020	2030	2040
A	26.89	37.59	58.74	39.35
B	26.89	37.77	60.24	40.65
C	26.89	37.59	58.25	38.91
D	26.89	37.77	58.51	39.09

	2015	2020	2030	2040
A	147.62	177.98	241.01	316.16
B	147.62	178.64	245.96	332.08
C	147.62	177.98	240.51	315.72
D	147.62	178.64	244.22	330.53

Figure 17 Zoom-in Picture of CO_2 Emissions of Affected Airplane A380-8 and Market Segment TA_4 for EPA Scenario 3 with and without Continuous Improvement

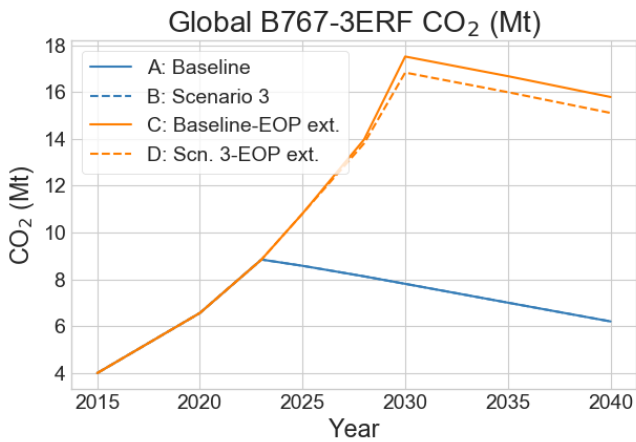
4.2 Scenario 3 Sensitivity to Extending Production of A380 and B767-3ERF to 2030

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 resulted CO_2 emissions from this sensitivity study are shown side by side with the main analysis for A380-8 in Figure 18 and for B767-3ERF in Figure 19. Note, the stringency starts to impact A380 in 2023, but not to B767-3ERF until 2028 due to the 5-year delay in implementation of the standards for freighters.



	2015	2020	2030	2040
A	26.89	37.59	58.74	39.35
B	26.89	37.59	58.25	38.91
C	26.89	37.59	97.67	76.45
D	26.89	37.59	96.16	75.04

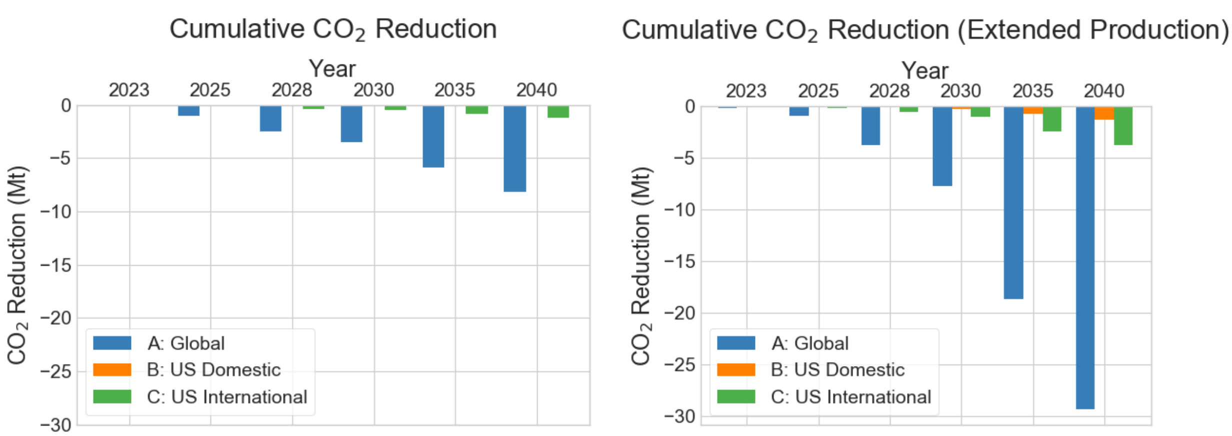
Figure 18 CO_2 emissions of A380-8 with two different end of production assumptions (2025 versus 2030) for EPA baseline and Scenario 3



	2015	2020	2030	2040
A	3.99	6.56	7.81	6.20
B	3.99	6.56	7.81	6.20
C	3.99	6.56	17.52	15.79
D	3.99	6.56	16.83	15.11

Figure 19 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 20 that the cumulative emission reductions for the extended production case (the right panel of Figure 20) are about 3 times that of the main analysis (the left panel of Figure 20). Thus, extending the end of production forecast has a strong effect on the outcome of the impact analysis.



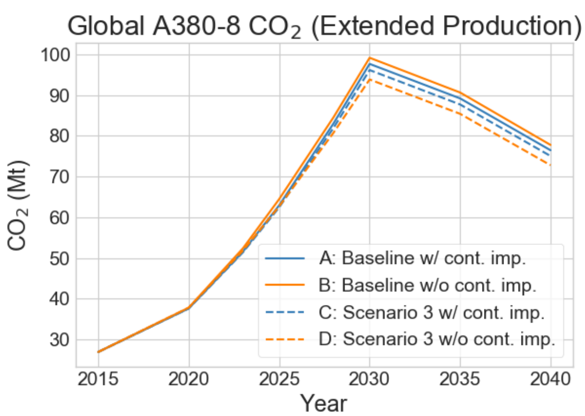
	2023	2025	2028	2030	2035	2040
A	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17
B	-0.00	-0.01	-0.04	-0.05	-0.08	-0.12
C	-0.02	-0.15	-0.38	-0.53	-0.89	-1.24

	2023	2025	2028	2030	2035	2040
A	-0.16	-0.99	-3.81	-7.73	-18.66	-29.30
B	-0.00	-0.01	-0.07	-0.25	-0.77	-1.28
C	-0.02	-0.15	-0.56	-1.07	-2.45	-3.80

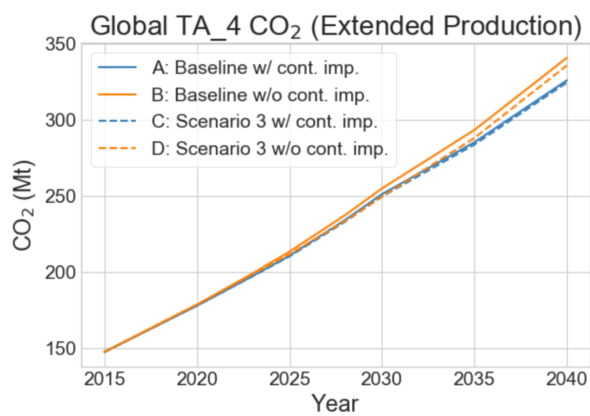
Figure 20 EPA main analysis versus sensitivity study: in cumulative reduction of CO_2 emissions from 2023 to 2040 for Scenario 3

4.3 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 impact 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 21 to Figure 24 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 continuous improvement each produced about 3 times the emissions reductions of the EPA main analysis. As shown in Figure 23, the ratio of emissions reduction impact between with and without continuous improvements is again about 3 times (e.g., 29.3 Mt versus 87.46 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., 87.46 Mt (Figure 23) versus 8.17 Mt (Figure 15) for the cumulative global CO_2 reduction to 2040).

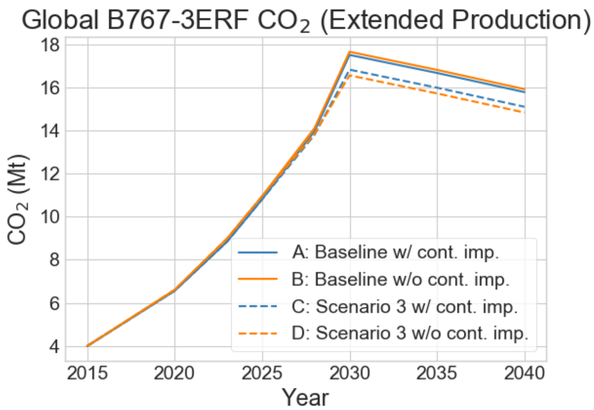


	2015	2020	2030	2040
A	26.89	37.59	97.67	76.45
B	26.89	37.77	99.18	77.76
C	26.89	37.59	96.16	75.04
D	26.89	37.77	93.85	72.77

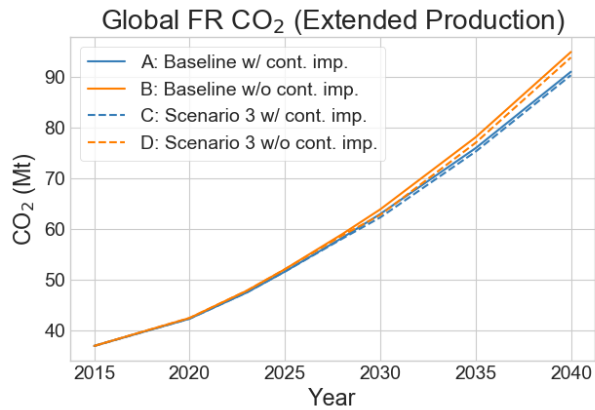


	2015	2020	2030	2040
A	147.62	177.98	251.03	325.72
B	147.62	178.64	254.79	340.50
C	147.62	177.98	249.52	324.30
D	147.62	178.64	249.46	335.52

Figure 21 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

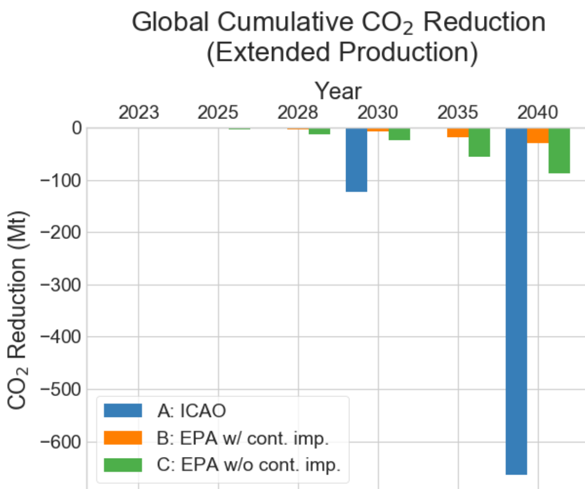


	2015	2020	2030	2040
A	3.99	6.56	17.52	15.79
B	3.99	6.60	17.67	15.93
C	3.99	6.56	16.83	15.11
D	3.99	6.60	16.57	14.84

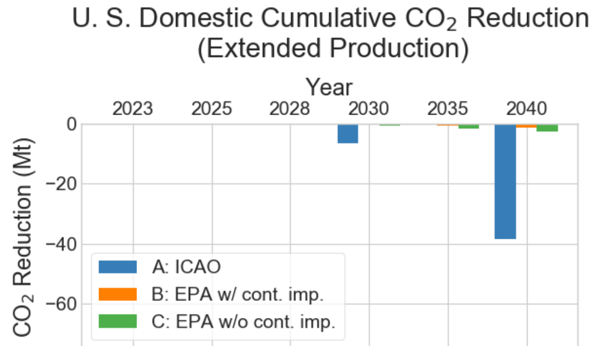


	2015	2020	2030	2040
A	36.86	42.25	62.96	91.09
B	36.86	42.39	63.87	95.00
C	36.86	42.25	62.27	90.41
D	36.86	42.39	62.77	93.91

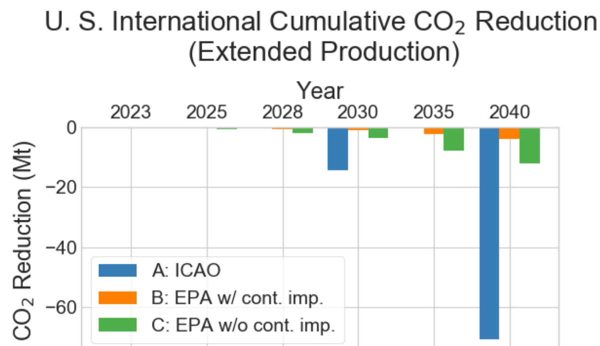
Figure 22 Zoom-in view of CO_2 Emissions of B767-3ERF and Market Segment FR, for Extended Production to 2030, with and without Continuous Improvement



	2023	2025	2028	2030	2035	2040
A				-122.87		-664.22
B	-0.16	-0.99	-3.81	-7.73	-18.66	-29.30
C	-0.56	-3.47	-13.07	-24.74	-56.59	-87.46

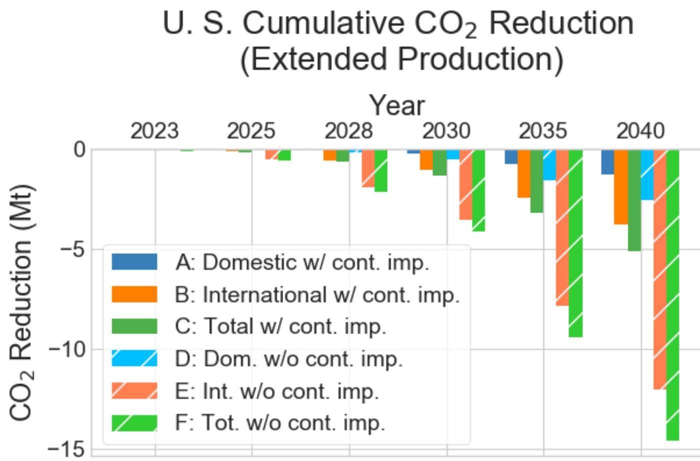


	2023	2025	2028	2030	2035	2040
A				-6.70		-38.49
B	-0.00	-0.01	-0.07	-0.25	-0.77	-1.28
C	-0.01	-0.05	-0.21	-0.56	-1.57	-2.57



	2023	2025	2028	2030	2035	2040
A				-14.23		-70.50
B	-0.02	-0.15	-0.56	-1.07	-2.45	-3.80
C	-0.09	-0.53	-1.94	-3.54	-7.85	-12.02

Figure 23 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	-0.00	-0.01	-0.07	-0.25	-0.77	-1.28
B	-0.02	-0.15	-0.56	-1.07	-2.45	-3.80
C	-0.03	-0.16	-0.63	-1.31	-3.22	-5.08
D	-0.01	-0.05	-0.21	-0.56	-1.57	-2.57
E	-0.09	-0.53	-1.94	-3.54	-7.85	-12.02
F	-0.10	-0.58	-2.15	-4.10	-9.42	-14.59

Figure 24 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 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 the 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.

4.4 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 the result 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 above, only A380 and 767-3ERF are considered since they are the only airplanes potentially impacted by the proposed standards and alternative scenarios.

Specifically, without continuous improvement (CI), the A380 would not pass the proposed in-production standards and would need to make about 1% improvements to be compliant and 2% 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 standards effective dates. With CI, A380 will meet the proposed standard in both the 2023 and 2028 timeframes and does not require any additional improvements for Scenarios 1 and 2.

On the other hand, 767-3ERF would not pass the proposed 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 Scenario 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 proposed in-production standards.

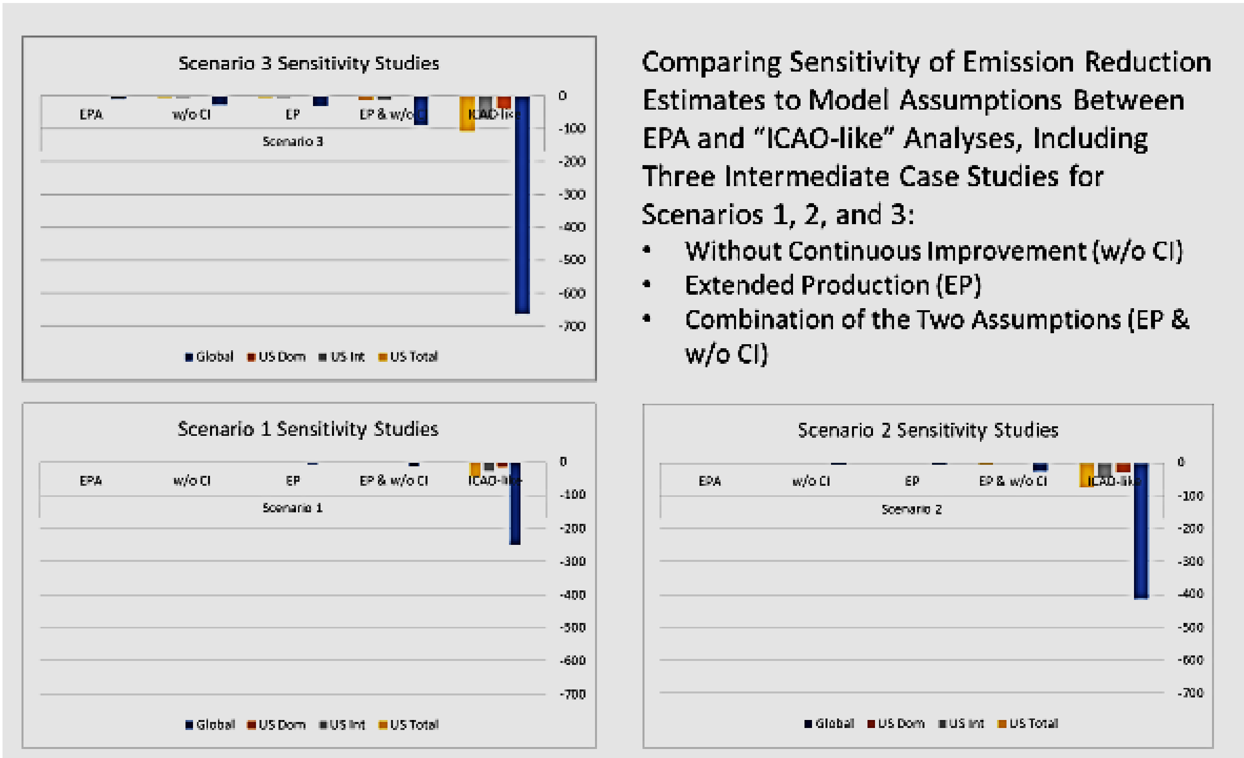


Figure 25 - Summary of Sensitivity to Model Assumptions for Scenarios 1, 2 and 3

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 25. A brief discussion of the five sensitivity cases is given below.

1. 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.

2. 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 CO_2 reductions would be on the order of 6 Mt globally and 1 Mt in U.S. total for Scenario 2.

3. 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 proposed in-production standard with continuous improvement. Since the pull-ahead schedule is not assumed for freighters, Scenarios 1 and 2 are the same and the estimated CO_2 reduction would be in the order of 4 Mt globally and 1 Mt in U.S. total.

4. 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 the 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.

5. Case 5 (ICAO-like): The ICAO like CO_2 reductions have been analyzed previously as 250 Mt globally and 46 Mt in U.S. total for Scenario 1, and 412 Mt globally and 75 Mt in U.S. total for Scenario 2.

Given this qualitative analysis, we conclude that the technology response and fleet evolution (principally continuous improvement and end of production) assumptions drive the difference between the EPA and ICAO analyses. Also similar to 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 the EPA analysis to ICAO analysis for Scenarios 1, 2 and 3 are shown in Figure 25.

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 real world. On the other hand, the business-as-usual baseline and the independently developed and peer reviewed technology response analysis 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 analyses are valid with respect to their model assumptions.

In summary, the EPA analysis shows that the proposed standards, which match the ICAO CO_2 standards, have no cost and 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.

5 Conclusions

1. Aviation emission inventory is significant today and growing rapidly, so improved modeling of airplane emissions is important to quantify future trends and help inform policy decisions. Thus, the EPA has developed a fleet evolution and emissions inventory model designed to use the best data sources available to the agency. For example, in this model, the future year operations are generated from base year operations in FAA 2015 Inventory according to the FAA TAF forecast when there is an exact match of airport pair and airplane type between the base year and forecast databases. When there is not an exact match, the future fleet operations are assigned to grow at the average rate of an aggregate portion of the fleet defined by route group and airplane category (or market segment). This approach allows us to mix and match data sources with different level of details and utilize them to the best level of fidelity afforded by the data sources.
2. The EPA's main analysis is based on ICF technology analysis, which includes forecasts of incremental improvements for all in-production airplanes and near-/mid-term and long-term airplane replacements. This ICF analysis enables improved quantification of emission inventories in the baseline and control scenarios. Using the ICF technology and airplane replacement forecast, the emissions from U.S. domestic flights approach almost carbon neutral growth by 2040, while emissions from U.S. international and global flights continue to grow rapidly.
3. To help inform the U.S. domestic rulemaking by the EPA, the agency has analyzed three stringency scenarios. Only Scenario 3, which is more stringent and with earlier effective dates than the ICAO standards, produces a small emission reduction. The other two scenarios (ICAO standards and ICAO stringency with earlier effective dates) result in no emission reductions based on the ICF continuous improvement and airplane replacement forecast.
4. In developing baseline inventories, it is observed that the fleet evolution assumptions, especially continuous improvement and end of production timing, have significant effects on baseline emissions. For example, the difference in global CO_2 emissions between the business-as-usual baseline and the frozen fleet baseline in 2040 alone is about 400 Mt.
5. Sensitivity studies for quantifying the effects of fleet evolution assumptions show that no continuous improvement and extended end of production timing each increases the cumulative emission reduction by about 3 times for Scenario 3. Their effects are basically multiplicative, and thus, the combined effect of these two factors together is to increase the emission reduction by about 10 times for Scenario 3. An important conclusion from the sensitivity studies is that the results of the regulatory impact analysis depend entirely on the model assumptions. By making these assumptions explicit, their effects can be assessed separately, and the effects of the standards can be clearly identified.

Appendix A Fleet Evolution Modeling Processes

1. Datasets

To model future flight activity and fleet evolution, we started with FAAs 2015 Inventory Database. This dataset consists of detailed flight operations for 2015, which is the base year for our fleet evolution model. Future air traffic growth comes from a few different sources. FAA's Terminal Area Forecast (TAF) contains detailed data on future commercial and cargo flight activity for the U.S. (domestic and international – flights departing form the U.S.) from the years 2015 to 2040. For air traffic growth outside of the U.S. we used the ICAO Long-Term Traffic Forecasts for Passenger and Cargo (July 2016). General aviation growth is based on the FAA Aerospace Forecast Fiscal Years 2017-2037 for activity in the U.S. and on Bombardier's Business Aircraft Market Forecast 2016-2025 for flights outside of the U.S. Retirement rates are based on data from FlightGlobal's Flight Fleets Analyzer (or ASCEND Online Fleets Database). The Growth and Replacement (G&R) fleet provides the basis for the fleet evolution, i.e., a list of specific airplanes that will assume all growth operations after the 2015 base year. This G&R fleet is dynamic with some airplanes going out of production and some new types entering service. ICF provided a thorough analysis of the future airplane market based on the G&R fleet. Their analysis includes end of production (EOP) years for airplanes, technology response to stringency, continuous metric value (MV) improvement forecast, and future long-term improvements to airplanes extending to 2040.

2. Database Filtering

The 2015 Inventory Database is a detailed and comprehensive SQL database that includes many operations for nonregulated airplanes that needed to be filtered out. The filters we applied to the database are listed below along with the SQL command used:

1) No piston engines (only jet and turboprop) – ENGINE_TYPE NOT IN ('P')
2) No military, other, or air taxi operations (only commercial, freighter, and general) – SERVICE_TYPE NOT IN ('M', 'O', 'T')
3) No attack/combat or other usage codes (only passenger, business, cargo/transport) – USAGE_CODE NOT IN ('A', 'O')
4) No military designation codes (only civilian and general) – DESIGNATION_CODE NOT IN ('M')
5) No very small airplanes (Operational Empty Weight (OEW) + MAX_PAYLOAD) ≤ 6,000 lbs.
6) MODEL<>0

Additional filtering had to be applied to the Maximum Takeoff Mass (MTOM). The SQL database did not include MTOM information, so we had to manually map these to different airplanes after the initial SQL filtering was done. Filters applied to MTOM were:

1) MTOM > 8,618 kg for turboprops

2) MTOM > 5,700 kg for jet engines

A few airplanes were additionally filtered out because of the MTOM criteria. These were BAC 1-11 300/400, BAC 1-11-500, Aerospatiale Caravelle-10, Lockheed L-1011-100 Tristar, Lockheed L-1011-500 Tristar, and Lockheed L-188 Electra.

3. Growth Rate Calculation

Growth rates for passenger and freighter flight activity for U.S. domestic and international (departing from the U.S.) come from FAAs TAF. The growth rates were mapped directly where specific origin-destination airport pairs (OD pairs) and airplane matches were found between the 2015 Inventory Database and the TAF. If specific matches were not found between the two databases, growth rates were mapped at progressively higher levels of detail. The order of growth rate mapping is listed below:

1) OD pair/airplane
2) OD pair/airplane category
3) OD pair
4) Route (domestic/international)/airplane
5) Route/airplane type

Growth rates outside of the U.S. came from the ICAO Long-Term Traffic Forecasts for Passenger and Cargo. For passenger operations the compound annual growth rate is 4.5% and for freighter it is 4.2%. U.S. general aviation growth rates from the FAA Aerospace Forecast Fiscal Years 2017-2037 are 1.6% for turboprops and 3% for jet engines. General aviation growth rates outside of the U.S. are 5.4% from Bombardier's Business Aircraft Market Forecast 2016-2025.

These growth rates were applied to operations in the 2015 Inventory Database according to two parameters: usage code and service type. Depending on route (U.S. domestic/international or non-U.S.) and the usage code and service type of the operation, a growth rate was applied to each flight using the one of the data sources discussed above. A table summarizing the different combinations of usage code and service type from the 2015 Inventory Database and the type of growth rate, either passenger, freight, or general, is provided below. The total number of operations, available seat kilometers (ASK), and available tonne kilometers (ATK) for each combination is also provided as a reference to the contribution of each usage code/service type combination.

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

A growth rate, $GR(Y)$, was calculated for each year after 2015 up to 2040.

4. Retirement Rate Calculation

In addition to mapping growth rates, retirement rate calculations are also necessary to model future flight activity. Retirement curves for different airplane categories were calculated using data from FlightGlobal's Flight Fleets Analyzer (or ASCEND Online Fleets Database). These curves were based on the number of airplanes in service given a specific age. The equation for the retirement rate, R, of an airplane given a specific age is

$$R(Age) = \frac{1}{1 + e^{a-b*Age}}$$

where a and b are coefficients based on the airplane category. Coefficients for different airplane categories are given below:

Airplane Category	a	b
Business Jet	6.265852341	0.150800149
Large Quad	5.611526057	0.223511259
Large Quad Freighter	6.905900732	0.205267334
Regional Jet	4.752779141	0.178659236
Single Aisle	5.393337195	0.222210782
Single Aisle Freighter	6.905900732	0.205267334
Twin Aisle	5.611526057	0.223511259
Twin Aisle Freighter	6.905900732	0.205267334
Turboprop	3.477281304	0.103331799

Similar to the growth rate mapping, age and retirement rates were mapped according to varying levels of detail depending on matching data between the 2015 Inventory Database and the ASCEND database. By level of detail, airplane age/retirement rate was mapped by:

1) Tail number – age of airplane
2) Average retirement rate by airplane
3) Average retirement rate by airplane type
4) Average age of airplane

Like the growth rates, a retirement rate, $RET(Y)$, was calculated for each year from 2015 to 2040.

5. Growth and Replacement (G&R) Fleet

The G&R fleet provides the basis for the future fleet. All new operations past 2015 are assigned to an airplane in the G&R fleet. The ICF analysis provides specific end of production (EOP) years, short term airplane replacements, and longer-term metric value (MV) percent improvements for G&R airplanes out to 2040. The G&R fleet includes airplanes that go out of production and new airplane types. Some G&R airplanes are a part of a transition pair, where an older airplane goes out of production and is replaced by a newer version of the same airplane. In these transition pairs, the new airplane enters service once the older airplane goes out of production, as indicated by the EOP year. If a new airplane is not part of a transition pair its entry into service (EIS) year is specifically defined. The G&R fleet is broken down into larger G&R market segments. After an airplane goes out of production it is either replaced by the transition pair or by another airplane within the same market segment.

6. Growth Operations – Market Demand Allocation

Market segments were also mapped to each airplane in the 2015 Inventory Database. The market demand for each segment is then determined by the aggregation of the growth and retirement rates for all airplanes within that segment. The growth and retirement rates are calculated as growth or retirement from the base year, so any of the growth that has survived from years after 2015 and years before the forecast year must be subtracted from the market demand for the forecast year. Survival rate, S, of an airplane with a specific age is just one minus the retirement rate $(1 - R(Age))$ or

$$S(Age) = \frac{e^{a-b*Age}}{1 + e^{a-b*Age}}$$

where, as before, a and b are coefficients based on the airplane category. Taking the market demand and survival of growth after the base year and prior to the forecast year into account then leads to the new in service, NIS, operation in year Y,

$$NIS(Y) = \big(GR(Y) + RET(Y)\big) - \sum_{i=1}^{Y-2015} \big(GR(Y-i) + RET(Y-i)\big) * S(i)$$

where$\big(GR(Y) + RET(Y)\big)$ is the sum of the growth and retirement rates for that year, $\big(GR(Y-i) + RET(Y-i)\big)$ is the sum of the growth and retirement rates for each previous year until the base year (2015), and $S(i)$ is the survival rate of previous years' growth with age i. The first term in the above equation gives the total market demand for a specific year from the base year. The second term is necessary to subtract all the survived growth that occurred after the 2015 base year. For this equation and all equations to follow, Y is a forecast year and must be greater than the base year ($Y > 2015$).

To calculate the number of operations for a new airplane, the growth operations are based on available seat kilometers (ASK) for passenger, available tonne kilometers (ATK) for freighter, and number of operations for general aviation growth. The number of operations, OPS, for a passenger airplane in year Y, is

$$OPS(Y) = \frac{ASK(2015)}{SEATS_{G\&R\,plane} * GCD} * \sum_{i=0}^{Y-2015} \frac{NIS(Y-i) * S(i)}{n_{G\&R\,market\,seg}(Y-i)}$$

where $ASK(2015)$ is the base year ASK for that operation $SEATS_{G\&R\,plane}$ is the number of seats for that specific growth and replacement plane, GCD is the great circle distance between the origin and destination airport (in kilometers) for that specific operation, $NIS(Y-i)$ is new in service operation for year $(Y-i)$, $S(i)$ is the survival rate for airplanes with age i, and $n_{G\&R\,market\,seg}(Y-i)$ is the number of growth and replacement planes still in production in year $(Y-i)$.

Similarly, the equation for the number of growth operations for freighter is

$$OPS(Y) = \frac{ATK(2015)}{MAX\_PAYLOAD_{G\&R\,plane} * GCD} * \sum_{i=0}^{Y-2015} \frac{NIS(Y-i) * S(i)}{n_{G\&R\,market\,seg}(Y-i)}$$

where $ATK(2015)$ is the base year ATK for that operation and $MAX\_PAYLOAD_{G\&R\,plane}$ is the maximum payload for that specific G&R plane. The equation for general aviation growth operations is

$$OPS(Y) = OPS(2015) * \sum_{i=0}^{Y-2015} \frac{NIS(Y-i) * S(i)}{n_{G\&R\,market\,seg}(Y-i)}$$

where $OPS(2015)$ is the number of operations in the base year.

7. Fuel Burn Calculation

To calculate fuel burn, we used a model called PIANO (version 5.4). Each airplane in the 2015 Inventory Database and in the G&R fleet were mapped to a PIANO airplane. To efficiently calculate the total fuel burn for every year, we create a unit flight matrix. This unit flight matrix includes all the different combinations of airplanes and great circle distance (OD pairs) that occur in our baseline (operations from base year 2015 to forecast year 2040). This matrix gives the fuel burn (unit flight fuel burn) for a single flight for these airplane/OD pair combinations. We then multiply the unit flight fuel burn by the total number of operations that were calculated in the above equations to get the total fuel burn.

8. ICF Continuous Metric Value Forecast

After the total fuel burn was calculated for each year in the baseline (2015 to 2040), we applied ICFs MV continuous improvement forecast. The MV continuous improvement forecast was implemented as an adjustment factor to the fuel burn (calculated using PIANO). Because we started with a 2015 base year and the ICF MV forecast started at 2010, we first had to scale the MV continuous improvement values to the base year we used in our analysis, so the adjustment factor, η, for a given year is

$$\eta(Y) = \frac{MV(Y)}{MV(2015)}$$

where $MV(Y)$ is the metric value from the ICF continuous improvement metric value forecast and for year Y and $MV(2015)$ is the metric value in the base year.

If all the airplanes go out of production within a specific market segment for a year after 2015, then the long-term percent improvement provided by ICF is added to this adjustment factor for the airplane remaining in the market segment. Long-term replacement airplanes beyond the project airplanes defined for transition pairs are considered generic. At least one long-term replacement airplane is selected in each market segment to represent the general fleet level efficiency within that market segment in our fleet evolution model. Long-term replacements for airplanes that end production before the final forecast year (2040) are modeled with a MV percent improvement estimate in the Technology Response Database. These long-term improvements are added to the MV continuous improvement forecast of the airplanes that are going out of production. For example, A319-NEO has an EOP year of 2030. The long-term replacement for A319-NEO is a clean sheet airplane, which is estimated to have a MV improvement of about 20 percent. This 20 percent improvement is added to the MV improvement forecast for A319-NEO as a step-change to all subsequent years after the airplane's EOP year (2030). The adjustment factor then becomes

$$\eta(Y) = \frac{MV(Y)}{MV(2015)} * \frac{100 - x}{100}$$

where x is the long-term percent improvement provided by ICF.

The actual adjustment factor we apply to the fuel burn must also include the MVs of the airplanes that were new in service after 2015, but prior to the forecast year. After an airplane enters service, its metric value freezes and does not continue to improve via the MV continuous improvement forecast so the adjustment factor we apply to the fuel burn becomes

$$\eta_{adj}(Y) = \frac{\sum_{i=0}^{Y-2015} NIS(Y-i) * \eta(Y) * S(i)/n_{G\&R\ market\ seg}(Y-i)}{\sum_{i=0}^{Y-2015} NIS(Y-i) * S(i)/n_{G\&R\ market\ seg}(Y-i)}$$

9. Stringency Analysis – Tech Response

For stringency analysis, the adjustment factor is updated further to include the technology response. The only airplane affected by stringency is the A380-8 for stringency Scenario 3. The stringency for this airplane is implemented in the year 2023 and the EOP year for A380-8 is 2025 so for the years 2023 to 2025, the adjustment factor for A380-8 is

$$\eta(Y) = \left(\frac{MV(Y)}{MV(2015)} * \frac{100 - x}{100}\right) - \frac{tr}{100}$$

where x is the long-term percent improvement as before and tr is the percent MV improvement after the accelerated technology insertions. For the A380-8, the tech response MV improvement is 2.63%.

Appendix B QUESTIONS FROM PEER REVIEWERS AND WRITTEN EPA RESPONSES

As indicated earlier, the previous draft of this report was peer-reviewed through external letter reviews by multiple independent subject matter experts (including experts from academia and other government agencies, as well as independent technical experts). The peer review process was facilitated and documented by RTI International and EnDyna, under contract to EPA. This section includes peer reviewer questions that were compiled by the RTI International and EnDyna as part of the peer review process (and which were documented in RTI International and EnDyna's 2019 peer review report)[12].

1) Please provide clarification and/or additional information on how the aircraft performance model, PIANO, was used in the emissions inventory calculation. Specifically to answer the following questions:

1a) Page 11, Paragraph 2[xiii]: For the LTO phases of flight, were PIANO default values assumed or were these modified? If these were modified, can EPA provide details on what assumptions were made? Was a comparison made as to how these values compare to ICAO LTO times?

EPA RESPONSE: All our analysis uses PIANO default values. We only use fuel burn (block fuel) from PIANO to calculate airplane CO_2 emissions. We don't use the LTO time in mode or ICAO LTO data (taxi/idle, takeoff, climbout, and approach modes for altitudes of 3,000 feet and below) to calculate any CO_2 values. We did not compare the information in the PIANO mission tables to ICAO LTO data.

1b) Page 11, Paragraph 2: For certain aircraft types, PIANO data are available for different configurations. What assumptions were made in these cases?

EPA RESPONSE: In cases where more than one PIANO airplane model exists, newer PIANO models are typically chosen for newer airplane types to reflect the latest technologies for that airplane type. For older in-production or in-service airplanes with multiple MTOM variants, typically a larger MTOM version is chosen to cover a wider range of missions. In other cases, we use our best engineering judgement to choose representative airplane types

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[xiii] All page numbers and paragraph numbers in appendix B are referenced to the March 2019 version of the EPA Technical Report on Aircraft Emissions Inventory and Stringency Analysis

(based on the choices available in PIANO). In any case, we keep a unique airplane mapping file for each of our projects, so the mapping is always unique for each project.

1c) Page 12, Paragraph 3: As I understand from the text, PIANO files (and therefore fuel/emission database) were generated for pre-determined 50 distances and 50 payloads. The unit flight matrix, which has aircraft movement information, then used 'interpolated' data from the 50x50 database.

a. Can EPA provide details on the 50x50 database? Specifically, what distances were used? In addition, a constant LF of 75% and 50% were used. Therefore, it is not clear as to why there would be a different payload for each distance (unless there is some misunderstanding here).

EPA RESPONSE: The distances are equally spaced with a typical minimum distance of 200 km, so the 50 distances are equally spaced from 200 km to the maximum range at zero payload for a particular airplane. In terms of payload, we chose 50 values between 2%-100% of maximum payload for that airplane (values are provided at each even % interval – e.g., 2%, 4%, 6%, …, 100%, etc.). For example, for a load factor of 75% we simply interpolate between nearest payload data points of 74% and 76% to get the specified load factor. For the load factor of 50%, we would simply pick the 50% maximum payload from the 50x50 database since it does not require any interpolation.

b. What assumptions were made about the cruise altitudes? If so, could details be provided in terms of the 50x50 database?

EPA RESPONSE: We use PIANO default cruise altitude for the 50x50 database. There were no assumptions made beyond PIANO default about cruise flight levels, we only use the block totals from the mission tables.

c. Can further details on the interpolation method be provided?

EPA RESPONSE: It is simply linear interpolation in both distance and payload.

1d) Page 12, Paragraph 4: How were adjustment factors derived when surrogate aircrafts were used to model aircrafts that were not in the PIANO database?

EPA RESPONSE: In principle, we choose a surrogate airplane from a similar airplane type – such as business jet for a business jet or turboprop for a turboprop. Then we assess the following criteria to best represent the target airplane: equivalent generation of technology and similar range and payload capability or equivalent generation of technology and MTOM. The adjustment factor is only used when we have prior knowledge on the fuel burn performance of the two airplanes in question. For example, when a next generation airplane is expected to be 15% more fuel efficient than the current generation airplane. For a surrogate airplane, we would model it as the next generation airplane with the current generation PIANO model and an adjustment factor of 0.85 to reflect the known fuel efficiency improvement.

2) Regarding the Growth and Replacement strategy (Section 5, p. 45):

2a) What assumptions/protocols were adopted to model the trend for airlines to replace aircraft with larger variants?

EPA RESPONSE: We have made no attempt to model the upgauging effect of airlines in our fleet evolution model other than what is already built in with the larger capacity of project airplanes compared to current in-production airplanes (e.g., B777X vs B777).

2b) How were those assumptions/protocols integrated into the fleet (in Growth and Replacement strategy) to adhere to traffic growth figures for passenger kilometers or ASKs?

EPA RESPONSE: Our fleet evolution model is very simple. It is designed to simply meet the traffic growth forecast at the fleet level in terms of ASK/ATK/NOP (NOP is number of operations) with available G&R airplanes assuming equal market share among these G&R airplanes within each of the predefined market segments. There is no attempt to model real world airline market dynamics or marketing strategies.

2c) Please confirm if passenger kilometers or ASKs were based on calculations on individual aircraft using PIANO, and if so, can more clarification and/or additional information be provided?

EPA RESPONSE: The number of seats information is provided mostly by the flight activity database (2015 Inventory). In case the information is missing, we try to supplement it with other credible sources including ASCEND, PIANO, OEM specifications, etc. The flight distance is based on great circle distance in kilometer.

Appendix C Supplementary Materials

1 ACCODE to PIANO Airplane Mapping

The aircraft code (ACCODE) from the 2015 Inventory Database was mapped to airplanes in PIANO. Table C - 1 gives the ACCODE to PIANO airplane mapping used for this analysis.

Table C - 1 ACCODE to PIANO Airplane Mapping

ACCODE	PIANO_AC
A300B2-2	Airbus A300 B2-200
A300B2K-3	Airbus A300 600R
A300B4-2	Airbus A300 600R
A300B4-6	Airbus A300 600R
A300C4-6	Airbus A300 600F
A300F4-2	Airbus A300 600F
A300F4-6	Airbus A300 600F
A310-2	Airbus A310-200
A310-2F	Airbus A310-200
A310-3	Airbus A310-300
A318-1	Airbus A318-111 68t
A318-1-CJ	Airbus A318-111 68t
A319-1	Airbus A319-131 75t
A319-1-CJ	Airbus A319-131 75t
A319-1X/LR	Airbus A319-131 75t
A319-NEO	A319-271N 75t 1act v16
A320-2	Airbus A320-214 78t SL
A320-NEO	A320-271N 79t 1act v16
A321-1	Airbus A321-231 93t
A321-2	Airbus A321-231 93t
A321-NEO	A321-271N 97t 3act v16
A330-2	Airbus A330-200 238t p
A330-2F	Airbus A330-200F wv0
A330-3	Airbus A330-300 235t r
A330-8NEO	A330-800neo (242t) v14
A330-8NEOF	A330-800neo (242t) v14
A330-9NEO	A330-900neo (242t) v14
A340-2	Airbus A340-200 275t
A340-3	Airbus A340-300 271t
A340-5	Airbus A340-500 380t
A340-6	Airbus A340-600 380t
A350-10	A350-1000 (308t) v15lo
A350-8	A350-800 (259t) v13
A350-9	A350-900ULR (280t)v15
A380-8	A380-800 (575t) v13
AN-158	Antonov An-158
AN124	Antonov An-124-210
AN140	ATR 42-500 (v05)
AN148-100A	Antonov An-148-100A
AN148-100B	Antonov An-148-100B
AN148-100E	Antonov An-148-100E
AN225	Antonov An-225 Mriya
AN24	Dash 8 Series 100
ATP	BAe ATP
ATR42-3	ATR 42-300 (v92)
ATR42-320	ATR 42-300 (v92)
ATR42-4	ATR 42-500 (v05)
ATR42-5	ATR 42-500 (v05)
ATR72-2	ATR 72-500 (v05)
ATR72-5	ATR 72-500 (v05)
AVRORJ85	Avro RJ 85 basic
B707-1	B707-320C degrad
B707-3	B707-320C degrad
B717-2	B717-200 (v00)
B727-1	B727-200A used'80s
B727-2	B727-200A used'80s
B727-2F	B727-200A used'80s
B727-2RE-SUPER27	B727-200A used'80s
B737-1	B737-200 (adv)
B737-2	B737-200 (adv)
B737-2F	B737-200 (adv)
B737-3	B737-300 (option)
B737-3F	B737-300 (option)
B737-4	B737-400 (option)
B737-4F	B737-400 (option)
B737-5	B737-500 (option)
B737-6	B737-600 (145)NG
B737-7	B737-700 (153)NG
B737-7-BBJ	B737-700ER (171p)W
B737-7MAX	A319-271N 75t 1act v16
B737-7W	B737-700 (154)W

ACCODE	PIANO_AC
B737-8	B737-800 (172)NG
B737-8-BBJ2	B737-800 (172)NG
B737-8MAX	B737 MAX-8 (181)v17
B737-8MAX-BBJ	B737 MAX-8 (181)v17
B737-8W	B737-800 (174)W
B737-9	B737-900 (174)NG
B737-9ER	B737-900ER (187a)W
B737-9ERW	B737-900ER (187a)W
B737-9MAX	B737 MAX-9 (194)v17
B747-1	B747-100 (degrad)
B747-2	B747-200B (833)
B747-2F	B747-200F (833)
B747-3	B747-300 (833)
B747-3F	B747-300 (833)
B747-4	B747-400 (875)g
B747-4F	B747-400F (875)
B747-8	B747-8 I (987) v13
B747-8F	B747-8 F (987) v13
B747-SP	B747-SP (degrad)
B757-2	B757-200 (255)2r
B757-2F	B757-200F (255)r
B757-3	B757-300 (273)2r
B767-2	B767-200 (300)v87
B767-2ER	B767-200ER (395)v06
B767-2F	B767-200 (300)v87
B767-3	B767-300 (345)dal
B767-3ER	B767-300ER (412)
B767-3ERF	B767-300F freighter
B767-4	B767-400ER (450)
B767-4ER	B767-400ER (450)
B777-2	B777-200 (545)g

ACCODE	PIANO_AC
B777-2ER	B777-200 ER (656)g'11
B777-2F	B777-200 Freighter
B777-2LR	B777-200 LR (aic)
B777-2LRF	B777-200 Freighter
B777-3	B777-300 (660)
B777-3ER	B777-300 ER (uae2)
B777-8X	B777-8X (775) v15a
B777-9X	B777-9X (775) v15a
B777-9XF	B777-9X (775) v15a
B787-10	B787-10 (557) v13 hi
B787-8	B787-8 (502)boe v14
B787-9	B787-9 (557)boe v16
BAE146-100	BAe 146-100
BAE146-100Q	BAe 146-100
BAE146-200	BAe 146-200
BAE146-200Q	BAe 146-200
BAE146-300	BAe 146-300
BAE146-300Q	BAe 146-300
BAE146-RJ100	Avro RJ-100
BAE146-RJ70	Avro RJ-70
BAE146-RJ85	Avro RJ 85 basic
BEECH400	Raytheon Beechjet 400A
C919ER	Comac C919 B v11
CARAVELLE-12	Douglas DC 9-34
CL-600-2E25-CRJ1000	Canadair CRJ 1000
CL300	Bombardier Challenger 300
CL600	Canadair Challenger 604
CL601	Canadair Challenger 604
CL604	Canadair Challenger 604
CL605	Canadair Challenger 604
CL850	Dassault Falcon 7X

ACCODE	PIANO_AC
CN235-1	ATR 42-500 (v05)
CN235-3	ATR 42-500 (v05)
CNA525B	Cessna CitationJet3
CNA525C	Cessna CitationJet3
CNA550	Cessna CitationJet3
CNA550-S	Cessna CitationJet3
CNA551	Cessna CitationJet3
CNA560	Cessna Citation V
CNA560-XL	Cessna Citation V
CNA560-XLS	Cessna Citation III
CNA650	Cessna Citation III
CNA680	Cessna Sovereign
CNA680-S	Cessna Sovereign
CNA750	Cessna X ce750 orig
CNA750-X	Cessna X ce750 plus
CRJ1	Canadair RJ 100
CRJ1-LR	Canadair RJ 100ER
CRJ1000	Canadair CRJ 1000ER
CRJ2	Canadair CRJ 200LR
CRJ2-ER	Canadair CRJ 200ER
CRJ2-LR	Canadair CRJ 200LR
CRJ4	Canadair CRJ 200LR
CRJ4-LR	Canadair CRJ 200LR
CRJ7	Canadair CRJ 701ER
CRJ7-ER	Canadair CRJ 701ER
CRJ7-LR	Canadair CRJ 701LR
CRJ705-LR	Canadair CRJ 701LR
CRJ9	Canadair CRJ 900LR
CRJ9-ER	Canadair CRJ 900ER

ACCODE	PIANO_AC
CS100	Bombrdr CS100 max v16
CS300	Bombrdr CS300 max v16
CV580	Dash 8 Series Q300
DC10-1	Douglas DC 10-10
DC10-3	Douglas DC 10-30
DC10-3ER	Douglas DC 10-30
DC10-4	Douglas DC 10-30
DC8-6F	Douglas DC 8-55
DC8-7F	Douglas DC 8-55
DC9-1	Douglas DC 9-14
DC9-1F	Douglas DC 9-14
DC9-2	Douglas DC 9-14
DC9-3	Douglas DC 9-34
DC9-5	Douglas DC 9-50 dal
DHC7-1	Dash 8 Series 100
DHC8-1	Dash 8 Series 100
DHC8-2	Dash 8 Series 100
DHC8-3	Dash 8 Series 100
DHC8Q-3	Dash 8 Series Q300
DHC8Q-4	Dash 8 Srs Q400 ehgw
DO328-1	Dornier 328
DO328JET	Dornier 328JET
EMB120	Embraer EMB-120
EMB505	Embraer Phenom 300
EMBLEG	Embraer EMB-145
ERJ135	Embraer EMB-135
ERJ135-ER	Embraer EMB-135
ERJ135-LR	Embraer EMB-135
ERJ140	Embraer EMB-145
ERJ140-LR	Embraer EMB-145
ERJ145	Embraer EMB-145
ERJ145-EP	Embraer EMB-145
ERJ145-ER	Embraer EMB-145
ERJ145-EU	Embraer EMB-145
ERJ145-LR	Embraer EMB-145
ERJ145-LU	Embraer EMB-145
ERJ145-MP	Embraer EMB-145
ERJ145-XR	Embraer EMB-145
ERJ170	Embraer 170 LR
ERJ170-LR	Embraer 170 LR
ERJ175	Embraer 175 AR
ERJ175-E2	Embraer E175-E2 v15
ERJ175-LR	Embraer 175 LR
ERJ190	Embraer 190 AR
ERJ190-E2	Embraer E190-E2 v16
ERJ190-LR	Embraer 190 LR
ERJ195	Embraer 195 AR
ERJ195-E2	Embraer E195-E2 v16
ERJ195-LR	Embraer 195 LR
ERJLEG	Canadair Challenger 604
F27-1	Fokker F50 Srs 100
F27-2	Fokker F50 Srs 100
F27-5	Fokker F50 Srs 100
F27-50	Fokker F50 Srs 100
F27-7	Fokker F50 Srs 100
F28-100	Fokker-F28 Mk4000
F28-3000	Fokker-F28 Mk4000
F28-70	Fokker F70 basic
FAL10	Learjet 45
FAL100	Learjet 45
FAL20-C	Cessna Sovereign
FAL20-D	Cessna Sovereign
FAL20-E	Cessna Sovereign
FAL20-F	Cessna Sovereign
FAL200	Cessna Sovereign
FAL2000	Dassault Falcon 2000
FAL2000EX	Dassault Falcon 2000EX
FAL2000LX	Dassault Falcon 2000EX
FAL50	Dassault Falcon 2000EX
FAL50-EX	Dassault Falcon 2000EX
FAL7X	Dassault Falcon 7X
FAL900	Dassault Falcon 900 EX
FAL900B	Dassault Falcon 900 EX
FAL900C	Dassault Falcon 900 EX
FAL900DX	Dassault Falcon 900 EX
FAL900EX	Dassault Falcon 900 EX
FAL900LX	Dassault Falcon 900 EX
GLOBAL5000	Global Express (v02)
GLOBAL6000	Global Express 6000 v13
GLOBAL7000	Global 7000 prelim v14
GLOBAL8000	Global 8000 prelim v14
GLOBALEXPRESS	Global Express (v02)
GULF1	IAI Galaxy G200
GULF100	IAI 1125 Astra
GULF150	Cessna Sovereign
GULF2	IAI Galaxy G200
GULF2-B	IAI Galaxy G200
GULF200	IAI Galaxy G200
GULF280	IAI Galaxy G200
GULF3	Gulfstream G IV
GULF350	Gulfstream G IV
GULF4	Gulfstream G IV
GULF4-SP	Gulfstream G IV-SP
GULF450	Gulfstream G IV-SP
GULF5	Gulfstream G550
GULF5-SP	Gulfstream G V-SP
GULF550	Gulfstream G550

ACCODE	PIANO_AC
GULF650	Gulfstream G650 v14
H4000	Dassault Falcon 2000EX
HS125-1	Learjet 60
HS125-3	Learjet 60
HS125-4	Learjet 60
HS125-6	Learjet 60
HS125-7	Learjet 60
HS125-8	Learjet 60
HS125-9XP	Learjet 60
HS748-2B	ATR 72-500 (v05)
IAI1121	IAI 1125 Astra
IAI1124	IAI 1125 Astra
IAI1124A	IAI 1125 Astra
IAI1125	IAI 1125 Astra
IAI1126	IAI 1125 Astra
IL114	ATR 72-500 (v05)
IL18	Ilyushin IL-62M
IL62	Ilyushin IL-62M
IL76	Airbus A340-200 275t
IL76-F	Ilyushin IL-96M
IL96	Ilyushin IL-96-400T
IL96-F	Ilyushin IL-96M
J41	Dornier 328JET
JETSTAR-I	Canadair Challenger 604
JETSTAR-II/731	Canadair Challenger 604
LEAR24	Cessna CitationJet3
LEAR24XR	Cessna CitationJet3
LEAR25	Cessna CitationJet3
LEAR28	Cessna CitationJet3
LEAR31	Learjet 31A
LEAR35	Learjet 31A
LEAR36	Learjet 31A
LEAR40	Learjet 55C
LEAR45	Learjet 45
LEAR45XR	Learjet 45
LEAR55	Learjet 55C
LEAR60	Learjet 60
LEAR70	Learjet 60
LEAR75	Learjet 60
MD10-3	Douglas DC 10-30
MD10-F	Douglas DC 10-30
MD11	Douglas MD-11 basic
MD11-ER	Douglas MD-11 option
MD11F	Douglas MD-11F (630)
MD81	Douglas MD-81
MD82	Douglas MD-82-88
MD83	Douglas MD-83 auxcap
MD87	Douglas MD-87
MD88	Douglas MD-88 boe
MD90	Douglas MD-90-30 dal
MRJ70	MRJ 70 LR (v15b)
MRJ90	MRJ 90 LR (v15b)
MS-21-200	Irkut MS-21-200v11
MS-21-300	Irkut MS-21-300v11
MU300	Raytheon Beechjet 400A
PC-24	Pilatus PC-24 SVJ
RRJ-95	Superjet 100-95B v13
RRJ-95LR	Superjet 100-95LR v13
SAAB2000	Saab 2000
SAAB340-A	Saab 340B
SAAB340-B	Saab 340B
SABR40	Learjet 45
SABR60	Learjet 45
SABR65	Learjet 45
SABR75	Learjet 45
SABR80	Learjet 45
SD330	ATR 42-500 (v05)
SD330-1	ATR 42-500 (v05)
SD330-2	ATR 42-500 (v05)
SD360-1	ATR 42-500 (v05)
SD360-2	ATR 42-500 (v05)
SD360-3	ATR 42-500 (v05)
SN601	Cessna CitationJet2
TU134	Tupolev Tu-154M
TU154	Tupolev Tu-154M
TU204	Tupolev Tu-204-300 v05
TU204-F	Tupolev Tu-204-100E v05
TU204-SM	Tupolev Tu-204-220 v03
TU214	Tupolev Tu-204-220 v03
YAK40	Yakovlev Yak-42M (v93)
YAK42	Yakovlev Yak-42M (v93)
YUN7	Antonov An-70T

2 Growth Forecast Numbers and Sources

The table below (Table C - 2) summarizes the data sources and numbers used for projected growth of different markets.

Table C - 2 Growth Forecast Sources by Market

Market	% Growth from 2015-2040	Source
U. S. Passenger	Detailed in TAF	FAA's 2015-2040 Terminal Area Forecast (TAF)[5]
U. S. Freight	Detailed in TAF	FAA's 2015-2040 Terminal Area Forecast[5]
U. S. General Aviation - Turboprop	1.6	FAA Aerospace Forecast (Fiscal Year 2017-2037)[7]
U. S. General Aviation-Jet	3.0	FAA Aerospace Forecast (Fiscal Year 2017-2037)[7]
Non-U. S. Passenger	4.5	ICAO long term traffic forecast for passenger and freighters[8]
Non-U. S. Freight	4.2	ICAO long term traffic forecast for passenger and freighters[8]
Non-U. S. General Aviation	5.4	Bombardier's Business Aircraft Market Forecast 2016-2025[9]

3 Growth and Replacement Operations by Fleet Family

The global growth and replacement operations depicted in Figure 3 of the report can be further broken down by fleet family (Figure C - 1). The following plots show the growth and replacement operations for each fleet family.

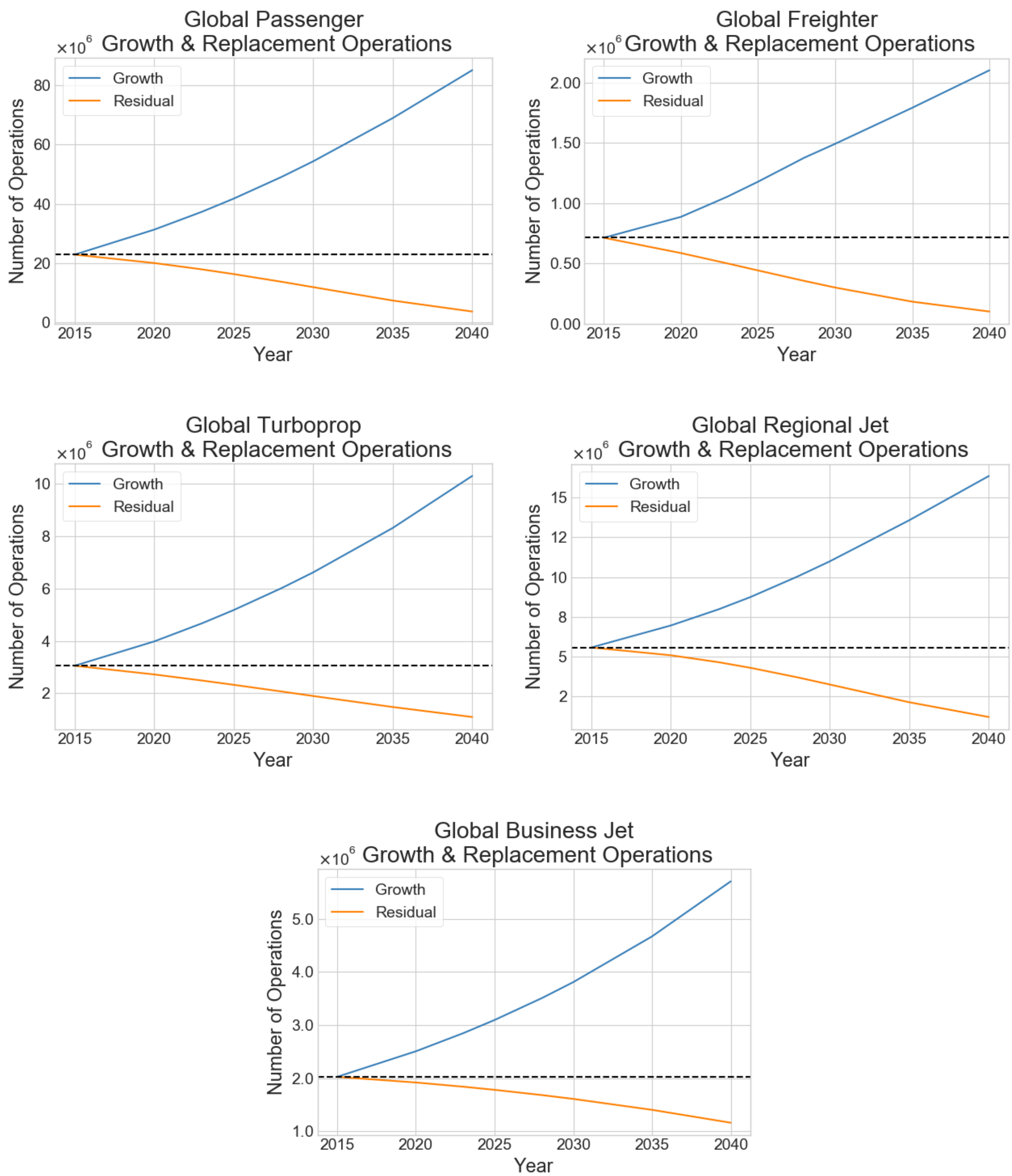


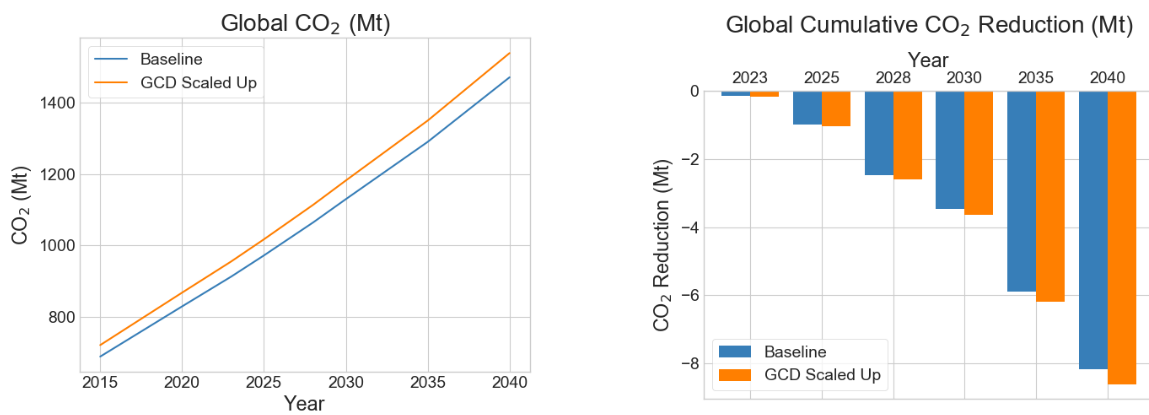
Figure C - 1 Growth and Replacement Curve for Each Fleet Family

4 Further Sensitivity Studies

Several additional sensitivity studies were performed and are summarized in this section.

4.1 Great Circle Distance Scaling

Our analysis uses the great circle distance between origin and destination airports as the flight distance. The great circle distance is not reflective of the actual distance flown. This can be accounted for by applying a factor of 1.49147 to the great circle distance and interpolating PIANO fuel burn to the adjusted distance. The change in global CO_2 emissions and global CO_2 emission reductions for scaling great circle distance up to flight distance is illustrated below in Figure C - 2. Scaling up the great circle distance to approximate actual flight distance gives slightly higher global CO_2 emissions and global CO_2 emission reductions.



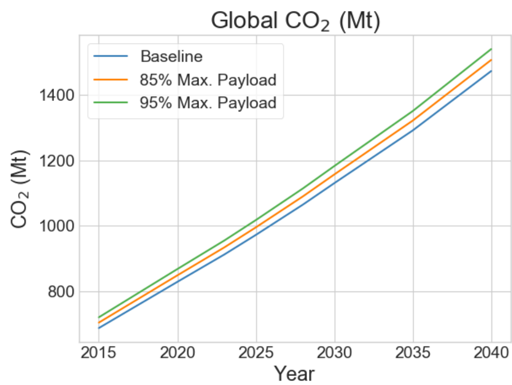
	2015	2020	2030	2040
Baseline	688.75	829.45	1130.21	1471.99
GCD Scaled Up	720.95	868.07	1182.55	1539.91

	2023	2025	2028	2030	2035	2040
Baseline	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17
GCD Scaled Up	-0.17	-1.04	-2.61	-3.65	-6.20	-8.61

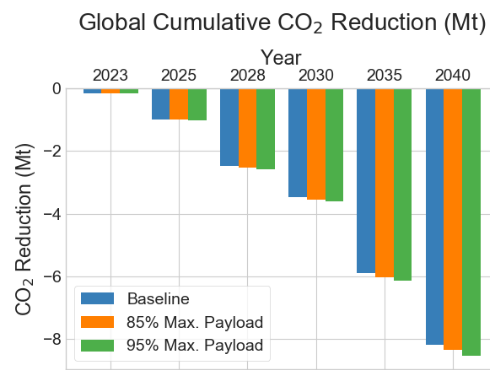
Figure C - 2 Global CO_2 and CO_2 Reduction for Great Circle Distance Scaling Adjustment

4.2 Payload Factor Sensitivity

We assume a 75% maximum payload for passenger and freight operations and 50% for business jet operations. Figure C - 3 illustrates the effect of increasing the payload factor for passenger and freight operations to 85% and 95%. As expected, increasing the payload for passenger and freight operations increases the global CO_2 emissions and global CO_2 emission reductions.



	2015	2020	2030	2040
Baseline	688.75	829.45	1130.21	1471.99
85% Max. Payload	705.34	849.26	1156.71	1505.90
95% Max. Payload	721.52	868.43	1182.33	1538.90

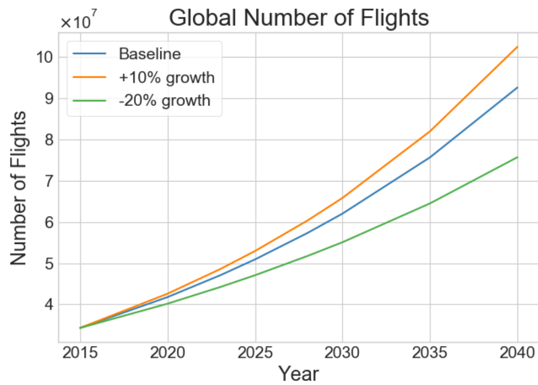


	2023	2025	2028	2030	2035	2040
Baseline	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17
85% Max. Payload	-0.16	-1.01	-2.53	-3.54	-6.01	-8.35
95% Max. Payload	-0.17	-1.03	-2.58	-3.61	-6.14	-8.53

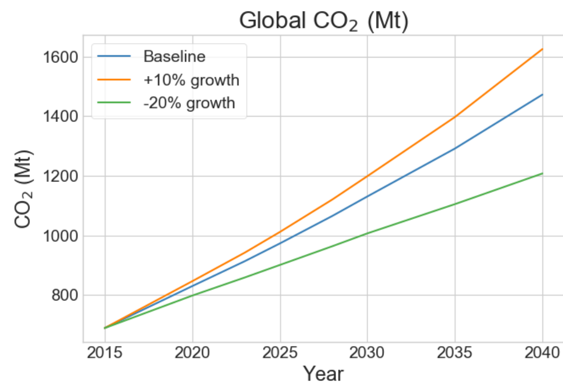
Figure C - 3 Global CO_2 and CO_2 Reduction for Payload Factor Adjustment

4.3 High/Low Growth Traffic Estimates

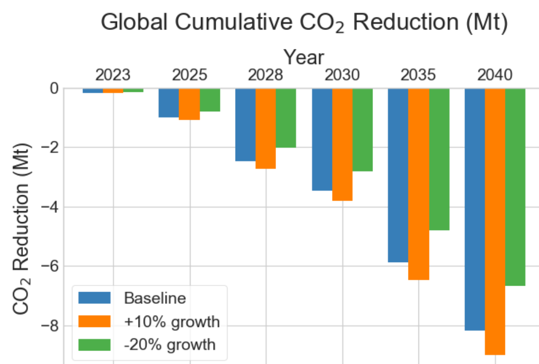
The growth traffic forecasts create another level of uncertainty. To demonstrate the sensitivity of our results to the growth traffic estimate, we scaled the growth forecast up by 10% and down by 20%. The resulting global number of flights, global CO_2 emissions, and global CO_2 emission reductions for this sensitivity study are illustrated in Figure C - 4.



	2015	2020	2030	2040
Baseline	3.43E+07	4.18E+07	6.20E+07	9.26E+07
+10% growth	3.43E+07	4.26E+07	6.58E+07	1.02E+08
-20% growth	3.43E+07	4.02E+07	5.51E+07	7.57E+07



	2015	2020	2030	2040
Baseline	688.75	829.45	1130.21	1471.99
+10% growth	688.75	845.86	1198.29	1624.72
-20% growth	688.75	797.58	1006.34	1207.35

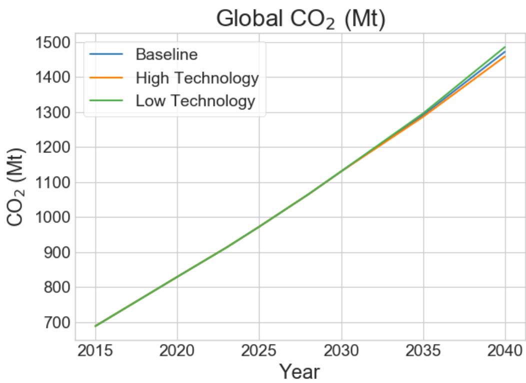


	2023	2025	2028	2030	2035	2040
Baseline	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17
+10% growth	-0.17	-1.09	-2.73	-3.82	-6.49	-9.01
-20% growth	-0.13	-0.80	-2.02	-2.82	-4.80	-6.66

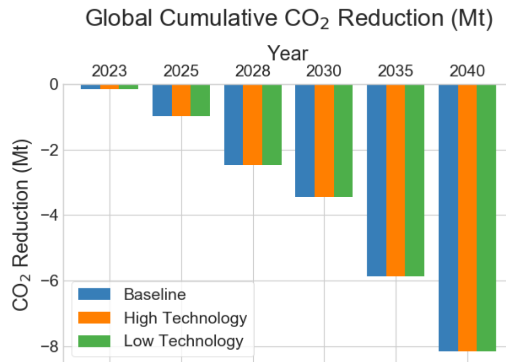
Figure C - 4 Global Number of Flights, CO_2 and CO_2 Reduction for High and Low Growth Traffic Estimates

4.4 High/Low Technology Feasibility

The continuous improvement aspect of this study was provided by ICF as an adjustment factor to the metric value of specific airplanes. ICF also provided uncertainty bands (2-4%) for the long-term (2030-2040) improvement estimates of replacement airplanes. The change in global CO_2 emissions and global CO_2 emission reductions for the high and low uncertainty ranges for the long-term technology feasibilities are presented in Figure C - 5. There is no change in the global CO_2 emission reductions because all the impacted airplanes (A380 and B767F) by stringencies do not have replacement airplanes, thus their technology responses to stringencies are not affected by the high/low technology feasibility. Consequently, the change in CO_2 from this sensitivity only starts after 2030 when the long-term replacement airplanes start entering the fleet and the emission reductions are identical for all three cases (high/medium/low) of technology feasibility.



	2015	2020	2030	2040
Baseline	688.75	829.45	1130.21	1471.99
High Technology	688.75	829.45	1130.07	1458.58
Low Technology	688.75	829.45	1130.36	1485.39



	2023	2025	2028	2030	2035	2040
Baseline	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17
High Technology	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17
Low Technology	-0.16	-0.99	-2.47	-3.46	-5.89	-8.17

Figure C - 5 Global CO_2 and CO_2 Reduction for High and Low Technology Feasibility

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