WHITE PAPER

AUGUST 2015

FUEL EFFICIENCY TRENDS FOR NEW COMMERCIAL JET AIRCRAFT: 1960 TO 2014

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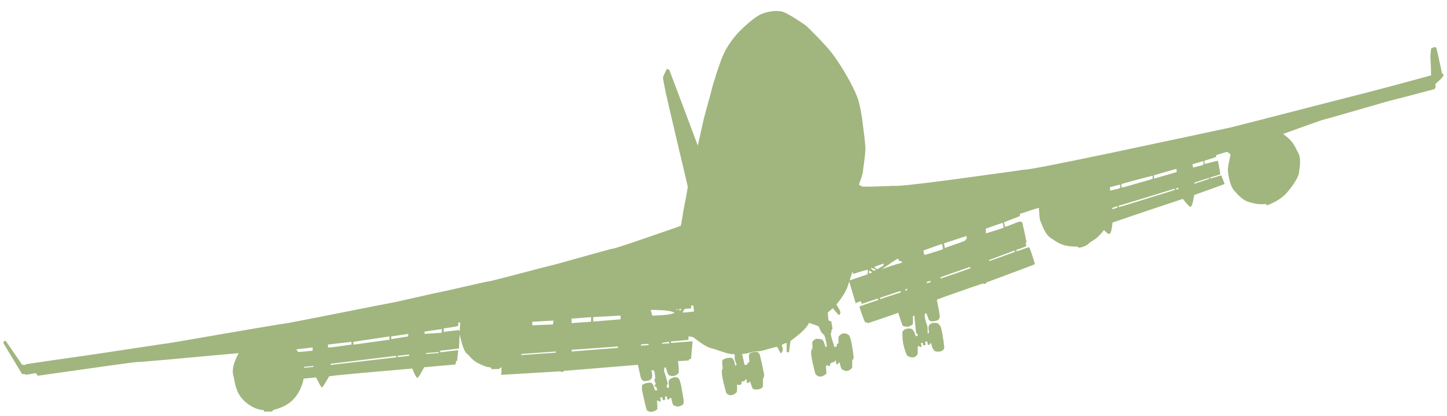

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ACKNOWLEDGEMENTS

The authors thank Paul Peeters, Irene Kwan, Joe Schultz, Fanta Kamakaté, and Guozhen Li for their critical review. This work was completed with the generous support of the ClimateWorks and Oak Foundations.

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EXECUTIVE SUMMARY

This report updates a 2009 study by the International Council on Clean Transportation (ICCT) that analyzed the sales- and activity-weighted fuel efficiency improvement of commercial jet aircraft from 1960 to 2008 (ICCT, 2009), taking into account new aircraft types and deliveries through 2014.

Additional refinements to the 2009 study methodology were made for this study, including the analysis of fuel efficiency trends under the International Civil Aviation Organization's (ICAO) CO_2 standard metric value (MV), replacing the fuel/tonne-kilometer metric used in the previous study. Nine test points (combinations of three payloads and three range test points) were used in this study to obtain a fuel efficiency metric for each aircraft type, as compared to a single test point used in the 2008 study (aircraft design range and payload). Aircraft seating density was standardized by type in order to eliminate the effect of changing (usually increasing) average seat densities over time. As a result of these changes, this study estimates higher average nominal fuel burn values than the 2009 study, while maintaining the overall trend over time relative to the reference year.

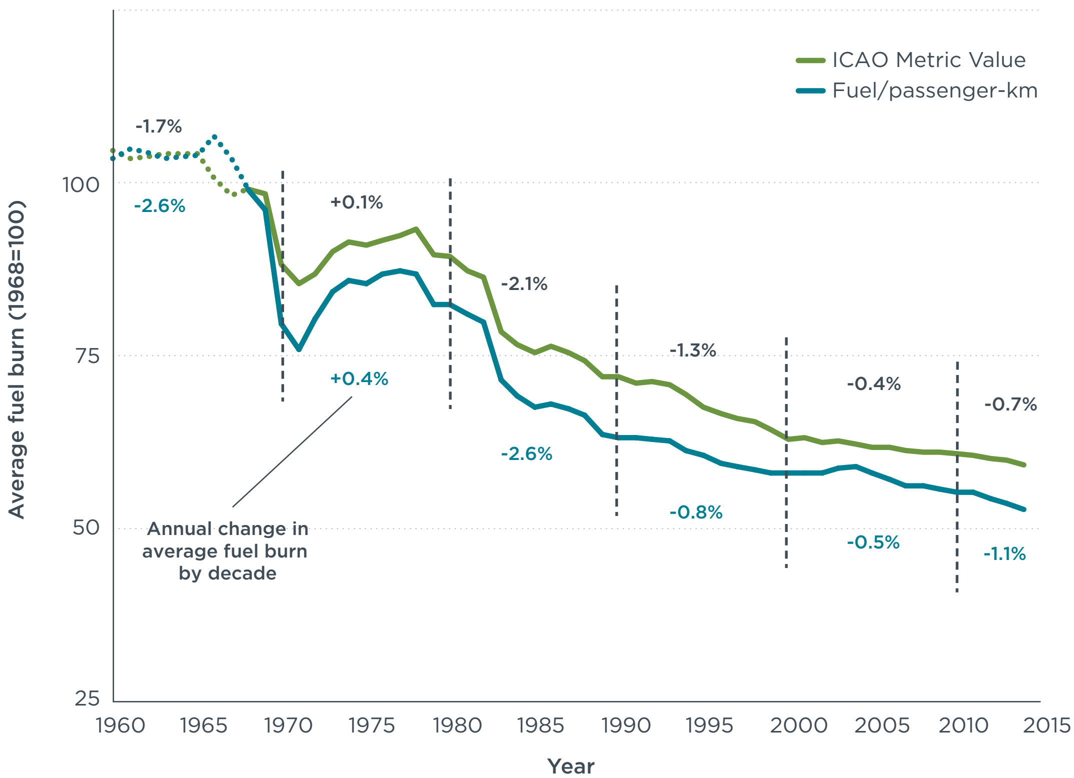

Figure ES-1. Average fuel burn for new commercial jet aircraft, 1960 to 2014 (1968=100)

Figure ES-1 presents historical changes in fuel efficiency for commercial jet aircraft from 1960 to 2014, with the 1968 value as the baseline, using both fuel/passenger-km and ICAO's metric value. The figure shows that the average fuel burn of new aircraft fell approximately 45% from 1968 to 2014, or a compounded annual reduction rate of 1.3%. But the rate of reduction varied significantly. During periods of rapid improvement such as the 1980s, fuel efficiency improved by 2.6% annually due to the aggressive adoption of new technologies and efficient aircraft design principles. In contrast, little net improvement was seen during the 1970s.

Reductions in average aircraft fuel burn slowed noticeably after 1990 and largely halted around 2000. After 2010, average fuel efficiency began to accelerate on both metrics and has now returned to the long-term average improvement of 1.1% per annum on a fuel/passenger-km basis. Acceleration in improvement rate is expected in the foreseeable future due to the introduction of new, more efficient aircraft designs such as the A320neo, 737 MAX, and 777X. Over the long term, fuel efficiency improvements on the fuel/passenger-km and ICAO's cruise fuel metric were found to be comparable. Periodic deviations between the two are partly attributable to the fact that the ICAO metric provides limited crediting for improved structural efficiency (e.g., the use of lightweight materials).

To put the fuel efficiency improvement figures into a policy context, these average fuel burn trends were compared with ICAO's fuel burn technology goals for new types in 2020 and 2030. ICAO estimates the potential for a 40% improvement in fuel efficiency for new single-aisle and small twin-aisle aircraft in 2020 relative to 2000 levels. We compared this goal with a fuel burn trend projection of new single-aisle (SA) and small twin-aisle (STA) aircraft types under ICAO's metric value plotted by the year they enter into service (EIS). Figure ES-2 presents this comparison, showing a 12-year time lag between the projected fuel burn improvement and the time needed to reach ICAO's goals.

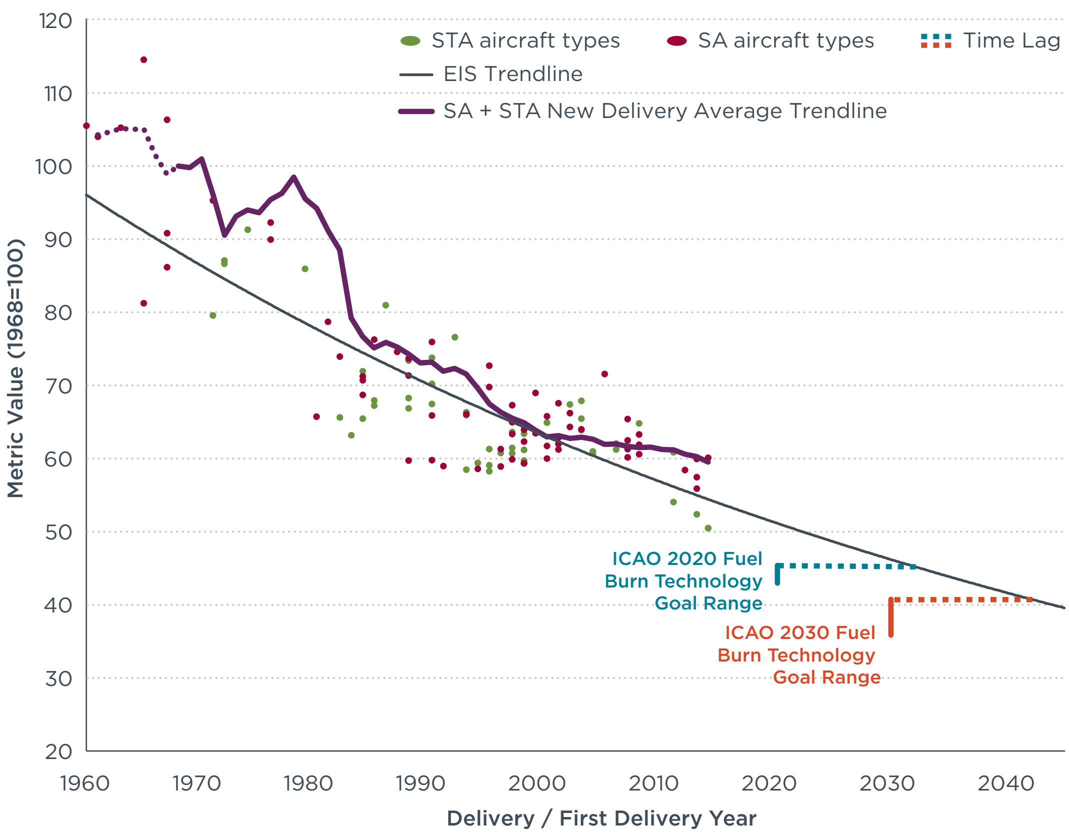

Figure ES-2. New single-aisle and small twin-aisle jet aircraft metric value vs. ICAO fuel burn technology goals

Finally, we compared historical fuel efficiency changes to fuel prices and concluded that continued fuel price volatility, combined with evidence that the industry lags behind the technological potential, highlights the need for a meaningful CO_2 standard to help industry meet its environmental goals.

1. INTRODUCTION

Commercial air travel underpins the modern global economy, but at no small cost to the environment. Aircraft are a major contributor to global climate change. In 2012 commercial aircraft emitted about 700 million metric tons of carbon dioxide (CO_2) worldwide; if commercial aviation was counted as a country, it would rank seventh after Germany in terms of CO_2 emissions. Aviation fuel use and CO_2 emissions, including those attributable to military and general aviation, quadrupled between 1960 and 2006 (Figure 1), and are on pace to triple again by 2050, a time by which many developed countries hope to reduce their emissions by up to 80%.

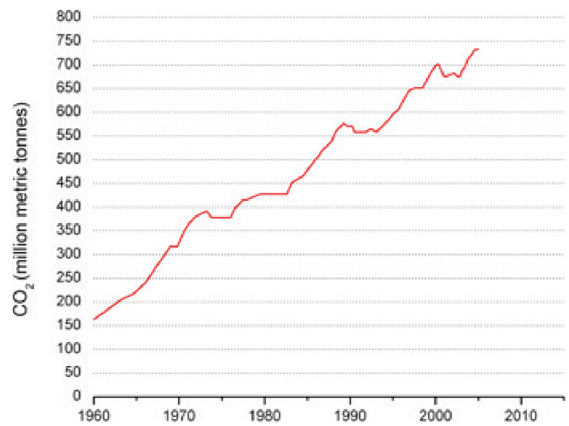

Figure 1. CO_2 emissions from aviation (including military and general aviation), 1960 to 2006 (Lee et al., 2009)

Because fuel is an important contributor to overall airline operating costs, aircraft and engine manufacturers have an incentive to improve the fuel efficiency of their products, thus reducing CO_2 emissions. Historically, new aircraft efficiency improvements have been more than outpaced by increases in travel demand, leading to the emission trends outlined above. Recognizing this threat, the aviation industry has recently begun to develop policies to reduce the climate impact of aviation. In 2010, the 37th Session of the International Civil Aviation Organization (ICAO) Assembly affirmed two main goals for aviation: to achieve an annual 2% average fuel efficiency improvement until 2020 and an aspirational 2% improvement per annum from 2021 to 2050, and to achieve carbon neutral growth from 2020 (ICAO, 2010b).

Beginning in 2009, ICAO, which acts as the de facto regulator for commercial aviation worldwide, started work to establish the world's first CO_2, or efficiency, standard for new aircraft. The standard is expected to be completed in early 2016, after which time it will be implemented by ICAO member states under national legislation.

Other regional and national authorities are likewise working to develop policies to reduce aviation CO_2 emissions. In 2012 the European Union started requiring airlines to reduce or offset CO_2 emissions from flights to and from its airports under its Emissions Trading System (ETS), although under strong opposition from foreign carriers and governments, requirements for international flights that originated or ended outside the EU were suspended pending the development of a global approach by ICAO by 2016. In the U.S., in 2011 in response to a lawsuit filed by environmental groups, a U.S. District Court ruled the U.S. Environmental Protection Agency (EPA) must formally determine whether greenhouse gases from aircraft should be regulated under the Clean Air Act. EPA's finding, which would be the first step in a regulatory process that could impose domestic limits on aviation emissions, was released in June 2015 (EPA, 2015).

In 2009, the International Council on Clean Transportation (ICCT) released a report analyzing trends in new aircraft fuel efficiency from 1960 to 2008 for the 10 largest commercial aircraft manufacturers (ICCT, 2009). The report — the first of its kind to include smaller aircraft types, such as regional jets, and to adopt sales and activity weighting among different types — found that the fuel efficiency of commercial jet aircraft approximately doubled from 1960 to 2008 on both a fuel/passenger-mile and fuel/ton-mile basis. The report also found that the rate of fuel efficiency improvement fluctuated substantially. It identified decades in which the average fuel burn[1] of new aircraft fell by 3% or more annually (1960s and 1980s) and decades where virtually no gains in fuel efficiency were seen (1970s and 2000s). The study explored the drivers of the slowdown in fuel efficiency after 1990, linking them to a lack of new, more efficient aircraft types and the increasing prevalence of regional jets, which are in general less fuel-efficient than larger jet aircraft.

Since 2009, the aviation industry has experienced important changes that impact fuel efficiency. The past six years have seen wild fluctuations in fuel prices, which have generally translated to greater demand for efficient aircraft; relatedly, the market share of regional jets has fallen significantly compared to the prior decade. Second, several new aircraft types were brought to market, notably Boeing's 787-8 and 787-9, with a variety of new technologies designed to improve fuel efficiency. Third, reacting to strong airline demand, aircraft manufacturers have announced a series of new aircraft types — the A320neo, 737 MAX, 777X, A330neo, Embraer E-Jet, and others — that will be brought to market over the next five years. An updated analysis of new aircraft fuel efficiency should help explain and illuminate these trends.

In addition to these industry trends, two policy developments have also occurred that justify an update of the 2009 study. In 2013, ICAO established a new CO_2 certification procedure to evaluate and compare the cruise fuel efficiency of aircraft (ICAO, 2013b). The underlying efficiency metric will serve as the basis for future policies to promote aircraft efficiency, notably ICAO's CO_2 standard. Also, in 2010 ICAO finalized fuel efficiency goals for new aircraft based on a review of engine and airframe technologies that could be brought to market in 2020 and 2030 (ICAO, 2010a). That study, which estimated the fuel efficiency of new aircraft could be improved by up to 40% in 2020 and as much as 90% in 2030 compared to a 2000 technology baseline, provides a means to benchmark the fuel efficiency of newer models compared to the underlying technical potential. Notably, the ICAO 2010 report called attention to the phenomenon of manufacturers using technology gains to increase aircraft capability, rather than to reduce fuel burn while maintaining capability.[2]

This white paper refines and extends the 2009 study to include all commercial jet aircraft deliveries for the full period of 1960 to 2014. While the 2009 study focused on aircraft performance at a single range and payload design point, in practice aircraft are flown carrying different payloads over different ranges. This updated study attempts to capture these variations and make an apples-to-apples comparison between two analyzed metrics: block fuel per passenger-kilometer for representative aircraft operations, and a cruise fuel metric based on ICAO's CO_2 certification procedure. Additional refinements in the study included expanding the analysis from the 10 largest manufacturers (2009) to the 20 largest, and the modeling of fuel burn based

1 The term "fuel burn" can be used to refer to both an absolute quantity (tonnes fuel) or an intensity (fuel/passenger-km). In this study, we use the term "average fuel burn" to refer to the latter intensity measure.

2 "The [Independent Experts] have come to realise that a considerable part of the benefit of improved technology introduced in the past has been used to improve the performance of the new aircraft, mainly range, rather than to reduce fuel burn per [available tonne kilometer]." See ICAO (2010a).

on standardized seating configurations to distinguish changes in fuel efficiency due to aircraft technology/design from those driven by operational parameters controlled by airlines, not manufacturers.

The report is organized as follows. Section 2 outlines the methodology used in this study. Section 3 introduces the key findings along with the drivers of recent changes in new aircraft fuel efficiency. Section 4 discusses the policy implications of this work and outlines next steps for research.

2. METHODOLOGY

2.1 AIRCRAFT DELIVERY DATASET

A database purchased from Ascend Online Fleets[3] covering all deliveries made from January 1, 1960 through August 31, 2014, was used as the source of new aircraft delivered in each year. In total, the database includes 65,965 aircraft.

From the complete Ascend Deliveries database, 35,985 jet aircraft with passenger capacity of more than 20 seats delivered, or projected to be delivered, between January 1, 1960 and December 31, 2014, were isolated. A list of the top 20 manufacturers by aircraft delivery is presented in Table 1.

Table 1. Top 20 manufacturers by aircraft deliveries, 1960 to 2014

Manufacturer	Number of Deliveries	Relevant Types[1]
Boeing	15,054	SA, TA
Airbus	8,522	SA, TA
McDonnell-Douglas (Boeing)	3,152	SA, TA
Embraer	2,265	RJ
Canadair (Bombardier)	1,714	RJ
Tupolev	1,504	SA
Yakovlev	1,010	RJ, SA
Fairchild/Dornier[2]	357	RJ
HS (BAE Systems)	341	RJ, SA
Ilyushin	334	SA, TA
BAC (BAE Systems)[2]	270	SA
Aerospatiale[2]	263	SA
Lockheed	248	TA
Fokker	520	RJ, SA
Avro (BAE Systems)	167	RJ
Convair (General Dynamics)[2]	98	SA
Sukhoi	69	RJ
Antonov	43	RJ, SA
Harbin Embraer Aircraft Industry	41	RJ
Saunders[2]	13	RJ

[1] SA = single-aisle, TA = twin-aisle, RJ = regional jet
[2] Excluded from final analysis due to lack of representative aircraft representations in Piano.

Piano 5.3[4], an aircraft performance and emissions model with an extensive database of commercial aircraft designs, was used to model aircraft fuel burn for both metrics. From 798 distinct aircraft-engine type combinations extracted from the Ascend database, 655 combinations were matched with 161 Piano representative aircraft models based on the aircraft type, engine type, and maximum takeoff weight

3 http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/ascend-online-fleets.html
4 http://www.piano.aero/

(MTOW)[5], covering 89% of total deliveries from 1960, or 93% of deliveries from 1968. Because Piano 5.3 has a more comprehensive database of recent aircraft than historical ones, the matching rate (number of aircraft delivered/number of aircraft matched with a Piano model) for the more recent aircraft types improved relative to the older ones, with 100% of deliveries represented after 2010 (see Table 2). Due to the high uncertainty and low matching rates before 1968, this year was used as a base year to normalize results. Trends prior to 1968 should be treated with caution.

Table 2. Average matching rate (matched aircraft/total deliveries) by decade

Decade	Average Matching Rate
1960s	32%
1970s	63%
1980s	94%
1990s	97%
2000s	98%
2010 and beyond	100%

2.2 METRICS INVESTIGATED

In this study we compare the fuel efficiency of newly delivered aircraft on two metrics, namely fuel per passenger-kilometer and ICAO's metric value (MV). Each is discussed below.

Fuel/passenger-km

The fuel/passenger-km metric is similar to that estimated in the 2009 ICCT report. This metric denotes the amount of fuel burned per passenger-km flown, as measured from the departure gate to arrival gate ("block fuel"). In contrast to the MV, introduced below, this metric includes all fuel consumed for taxi, takeoff, cruise, approach, and landing. While the previous report used aircraft design range and payload as the basis to measure efficiency, this study uses an approximate operational mission that better approximates how aircraft actually are flown in use.

To ensure that this study focuses solely on the fuel efficiency of aircraft as designed by manufacturers, as opposed to airlines in operation, a uniform seat density by type was used to estimate the efficiency of new deliveries. Global 2014 average seat density (number of seats divided by square meters of estimated Reference Geometric Factor[6], or eRGF) by type (regional jet, single-aisle, twin-aisle) was estimated via the Ascend Online Fleets database. The resulting values are summarized in Table 3. These standardized seating densities were used for all Piano aircraft modeled, after adjusting operating empty weight (OEW)[7] by 50 kg per seat when differing from the Piano standard values.[8]

5 A regulatory maximum weight of a loaded aircraft at takeoff

6 Reference geometric factor, a close proxy of cabin floor area, is a parameter developed under ICAO's CO_2 certification requirement to correct for variations in the fuel efficiency of aircraft of different aircraft sizes and applications. See below for information on the derivation and use of RGF in estimating ICAO's MVs.

7 The weight of an aircraft without payload or fuel

8 In a few cases, these standardized seat counts would have generated unrealistically high seat counts, so Piano defaults were used instead. Examples include older aircraft on which the calculated seat count is higher than their certification allowance (B707-320C and Douglas DC-8), as well as very large aircraft where the discrepancy between calculated and operational (2014) Piano default seat counts exceeds 20% (Airbus A380-800s).

Table 3. Average seat density based on 2014 global operational data

Type	Seat Density (seat/m² eRGF)
Regional Jet	1.27
Single-Aisle	1.48
Twin-Aisle	1.05

Airplanes were "flown" using Piano 5.3 to model their fuel efficiency. For fuel/passenger-km metric, nine points within each aircraft's payload-range diagrams were used. These points, presented in Table 4, are derived from 2010 global operations (Rutherford et al., 2012). In both modeling processes for fuel/passenger-km metric and ICAO metric value, aircraft are "flown" at cruise speeds enabling 99% specific air range (SAR). Fuel reserve and allowances were set at 370 km diversion distance, 30 minutes holding time, and 5% mission contingency fuel for all aircraft. Taxi times for both taxi-in and taxi-out are designated by the average taxi times for U.S. operations in 2010 by type, which were 12 minutes each way for regional jets and single-aisle aircraft and 15 minutes each way for twin-aisles.

Table 4. Test points for fuel/passenger-km metric

Types	Range (% R_{max}[1])			Load factor (% available seats)		
	low	mid	high	low	mid	high
RJ + SA	18%	25%	38%	70%	82%	93%
TA	26%	34%	51%	73%	83%	93%

[1] R_{max} = maximum range at 50% maximum payload

The average fuel burn trend was estimated using the weighted average of metric scores for all aircraft delivered each year. For the fuel/passenger-km metric, each delivery year's performance index is weighted by aircraft delivery and annual average fuel burn, calculated using an assumption of 3,033 hours of operation per year for SA and RJ, and 4,155 hours of operation for TA (Rutherford et al., 2012). For comparison with the ICAO cruise metric, the fuel efficiency improvement was normalized to 1968 value (1968 = 100), based on a coverage threshold. Before 1968, Piano models cover less than 50% of all aircraft delivered in a given year, creating a relatively high level of uncertainty.

In this analysis, the fuel burn of each aircraft type is assumed to be constant through its production cycle. A sensitivity analysis, presented in Appendix B, assumes a small annual improvement in aircraft fuel burn to each aircraft type, to assess its effect in overall average fuel efficiency trend.

ICAO's Metric Value

ICAO's metric value (MV) was developed within ICAO's Committee on Aviation Environmental Protection (CAEP) as part of the effort to establish a CO_2 emission standard for new airplanes (ICCT, 2013; ICAO, 2013b). The most prominent difference from the fuel/passenger-km metric is that MV takes into account only the cruise performance and ignores other flight phases of an aircraft such as landing, takeoff, and climb.

MV is a function of an aircraft's size and its SAR, or cruise fuel consumption rate, measured at three equally weighted gross weights. The former value is represented by an aircraft's Reference Geometric Factor (RGF), which is a close approximation of the pressurized floor area of the aircraft. More specifically, ICAO's metric value is defined as:

$$MV = \frac{1/SAR}{RGF^{0.24}}$$

The following steps were taken to estimate the improvement trend on this metric:

1. Aircraft RGF was estimated.
2. Aircraft were "flown" in Piano using ICAO's three SAR points.
3. A reference line was determined for normalizing the results.
4. The margin (in terms of percent difference) of each aircraft type to that reference line was determined.
5. Average values were derived by weighing the value of each aircraft type by its MTOW and the number of aircraft delivered in a given year.

Further detail on each step is provided below.

Estimating aircraft RGF

The aircraft RGF used to calculate ICAO's metric value was estimated from publicly available data using the formula below, which was developed as part of ICAO deliberations on the CO_2 standard:

Estimated RGF (eRGF) = fuselage width x cabin length

The majority of the data are procured from each manufacturer's official website, airport planning documents, and product brochures, www.flightglobal.com, and www.aircraftcompare.com. For aircraft types with more than one cabin floor, top floor RGF was added to the main cabin area.

The highest cruise SAR value at cruise speeds enabling 99% Max SAR for each aircraft type was obtained for each of the three test points based on MTOW. These test points are presented in Table 5. The inverses of these three SAR values (1/SAR) were then averaged and used to calculate the MV.

Table 5. Test points for ICAO's metric value

High	Mid	Low
0.92 x MTOW	Average of High and Low	(0.45 x MTOW)+(0.63 x ($MTOW^{0.924}$))

In practice, the same aircraft type is sold at different MTOW points in the market for various reasons, so the highest MTOW variance available in the market was selected for each type, consistent with ICAO's CO_2 certification requirement.

Development of reference line

Because the MV of each aircraft depends on both its cruise fuel burn performance and its size, the relative cruise efficiency of aircraft can only be compared to a standard reference line. For this study, a reference line for 2014 in-production aircraft, shown in

Figure 2, was determined from a second order log-log regression of cruise metric values of all aircraft types with an entry into service (EIS) 2000 or later on the aircraft MTOW. The reference line is a combination of two separate lines: one drawn to best fit airplane types with gross weight under 55 tons and the other drawn to best fit airplane types with gross weight over 55 tons. Annual average MVs are presented as a percent margin from this reference line, normalized to 1968 and weighted by deliveries in a given year and the MTOW of each representative aircraft type.

Figure 2. Reference line based on aircraft types delivered in 2012 with EIS after 1999

2.3 COMPARISON TO PREVIOUS WORK

This study applies a refined methodology to estimate historical trends in new aircraft fuel efficiency compared to the 2009 ICCT report. Better aircraft delivery data, updated Piano aircraft representations, improved matching of deliveries to Piano aircraft, and refined fuel consumption modeling allow for a better estimation of historical trends. Table 6 summarizes methodological differences between the 2009 study and this 2015 update.

Table 6. Comparison of key parameters and assumptions

Parameter	2009 study	2015 Study
Database	World Jet Inventory	Ascend Online Fleets
Years captured	1960 — 2008	1960 — 2014
Reference year	1960	1968
Metric	Fuel/passenger-km, fuel/ton-km	Fuel/passenger-km, ICAO MV
Software	Piano-X	Piano 5.3
Types included	RJ, SA, and TA jet aircraft.	RJ, SA, and TA jet aircraft
Manufacturers	10 largest	20 largest
Range (where applicable)	Design range (fuel/passenger-km) Maximum range at maximum structural payload (fuel/ton-km)	Operational ranges (% R_{max}, fuel/passenger-km)
Payload	All seats filled (fuel/passenger-km) Maximum structural payload (fuel/ton-km)	Low, mid, high (% MTOW, MV) Operational payloads (% of seats filled, fuel/passenger-km)
Seat density	Default Piano	Standardized seat counts by type
Flight levels	310, 350	Optimal flight level between 270 and aircraft service ceiling
Cruise speed	99% max SAR	99% max SAR
Taxi time	Default Piano	BTS 2010 average by type (SA, RJ, TA)
Holding time	30 min	30 min
Diversion	370 km	370 km
Reserve	5% mission fuel	5% mission fuel

Given these differences in methodology and assumptions, some variation in results is expected across the two studies. Figure 3 summarizes the results of the 2009 study and this update on the metric of grams fuel/passenger-km. Each data point represents the average commercial jet fuel burn at a given year (1968 and 2008 data points are labeled), while the diagonal line serves as a reference of the relative position of each data point. A data point above the reference line means that the average fuel burn value of a given year in this report is higher than the average fuel burn value of the same year in the 2009 report.

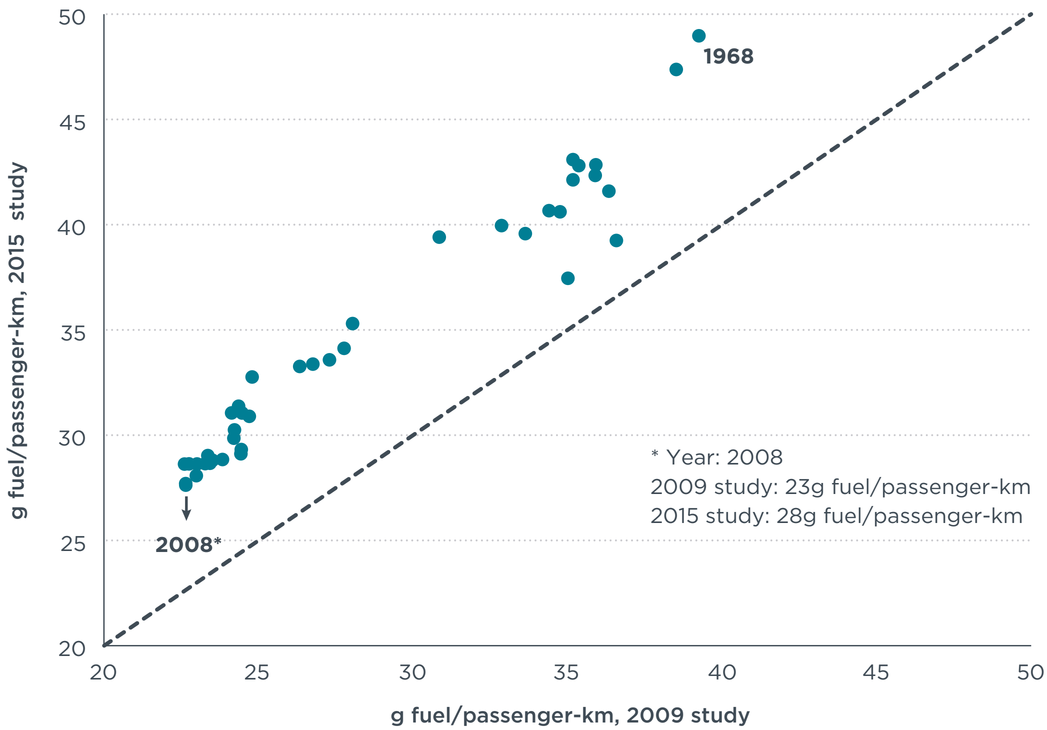

Figure 3. Comparison between 2009 and 2015 results

As illustrated in Figure 3, in general this update generates a higher average fuel burn values for new aircraft than that presented in the 2009 study. This is expected given that the earlier study applied a maximum payload condition of a 100% load factor to evaluate average fuel burn, while this update evaluated aircraft efficiency at lower load factors better representing typical operations. Overall, this study estimates the average fuel burn of new aircraft to be roughly 20% higher than the 2009 report, with a good fit over time. All in all, the curve shapes between the two studies follow each other closely.

3. RESULTS AND DISCUSSION

The methodology outlined above was used to refine estimates of new aircraft fuel efficiency from 1960 to 2014. Key results include the overall historical trend, a comparison of new aircraft efficiency on the two metrics investigated, relating trends in the fuel efficiency of all new aircraft vs. just new types, and an investigation of key drivers, notably fuel costs. We also relate recent improvements to ICAO's fuel burn technology goals in order to draw conclusions about the need for additional policies to promote aircraft efficiency. Each of these results is summarized below.

3.1 HISTORICAL TREND OF NEW AIRCRAFT EFFICIENCY

Figure 4 summarizes the modeled trend in average new aircraft fuel burn from 1960 to 2014 on ICAO's MV (green line) and a fuel/passenger-km metric (blue line), normalized to 1968.

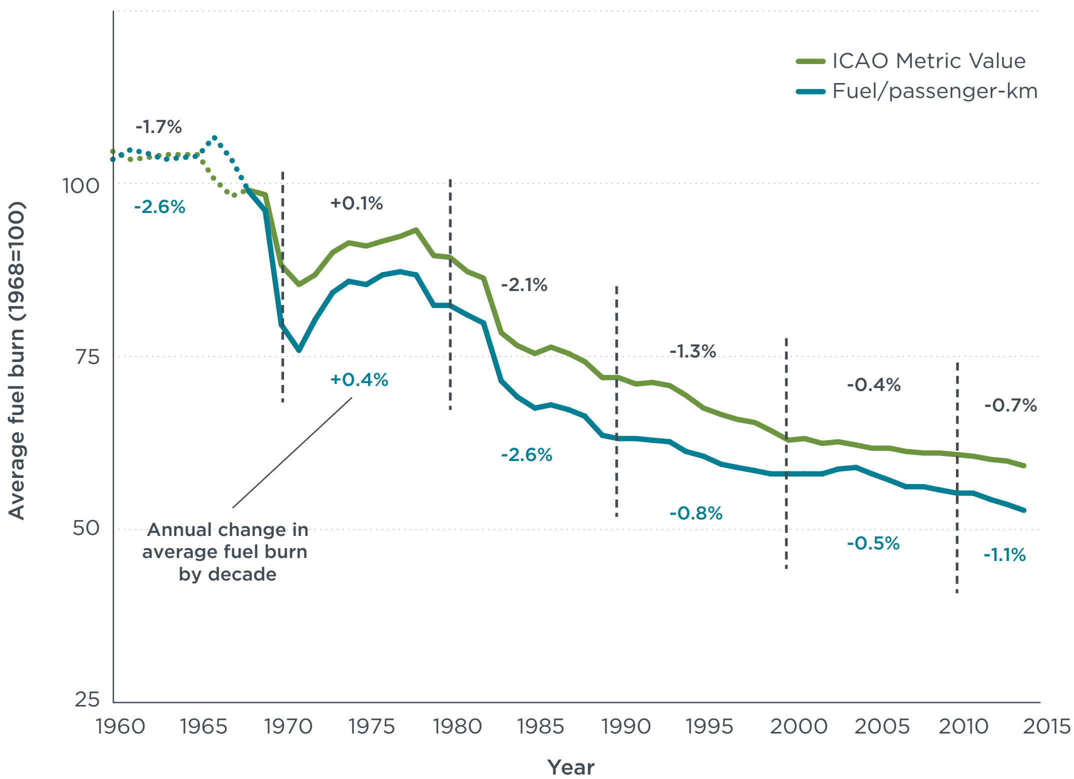

Figure 4. Average fuel burn for new commercial jet aircraft, 1960 to 2014 (1968=100)

Overall, the average fuel burn of new aircraft fell by about 45% from 1968 to 2014, or an annual reduction of about 1.3%. Consistent with the 2009 study, the estimated rate of fuel efficiency improvement varied significantly from decade to decade — reductions were seen as high as 2.6% per year during the 1980s — with fuel efficiency largely flat during the 1970s. Gains began to slow noticeably after 1990, and were flat on a fuel/passenger-km basis by 2000. This finding is consistent with recent evidence that the fuel efficiency of US airlines, whose typical aircraft were delivered during this period, stagnated in 2013.[9]

9 The average age of a U.S. airline's fleets was 13 years in 2013, meaning that the typical aircraft in their fleets was new in 2000, during the period of no fuel efficiency gains. See Kwan & Rutherford (2014) for further details.

The sharp reduction in average fuel burn observed in the early 1970s can be explained by the entry into service of the first modern twin-aisle aircraft, the Boeing 747-100. This aircraft, which entered into service in 1969, and the 747-200, which entered into service in 1971, were the two largest and most fuel-efficient aircraft types delivered between 1965 and 1975. The Boeing 747-100 itself made up 39% of all aircraft deliveries in 1970, and together with the Boeing 747-200 made up 36% of the market in 1971. Combined with their size, the use of the first high bypass turbofan engines in the early 747 models contributed to a large increase in fuel efficiency. In 1972 the delivery of the 747s dropped to 14% of the market, and dropped even further to less than 10% in the following years. This is reflected in Figure 4 as the curve moving back up, as smaller and less fuel-efficient aircraft take over the market. As shown in Figure 4, the fuel efficiency of later years is more stable owing to a larger number of commercial models and relatively consistent delivery patterns.

This analysis suggests that the average fuel burn of new aircraft, after remaining flat for a decade after 1995 and 2005 on a fuel/passenger-km basis, began to fall again in 2005. By 2010, the average fuel burn of new aircraft fell by 1.1% per year on the fuel/passenger-km metric and a somewhat smaller amount (0.7%) on the MV. In total, the average fuel burn of new aircraft dropped by approximately 10% from 2000 to 2014 on a fuel/passenger-km basis. This corresponds to an 11% increase in fuel efficiency, compared to the maximum potential of 40% identified in ICAO's fuel burn review. We return to a discussion of ICAO's technology goals in section 3.5.

3.2 METRIC COMPARISON

Comparing the two metric trends in Figure 4 allows one to evaluate how representative ICAO's cruise metric is of actual operations. The data suggest that over the long term, efficiency improvements measured under ICAO's MV track those under the fuel/passenger-km metric reasonably well, albeit with a gap between the average fuel burn reduction trend between the fuel/passenger-km and the MV of about 5% on a normalized basis. Notably, this divergence changes somewhat over time — for example, between 1990 to 2004 the gap between the fuel/passenger-km and ICAO cruise fuel metrics closes and then widens again.

The most likely driver of this trend relates to the handling of aircraft empty weight under ICAO's MV. In developing its CO_2 certification requirement, ICAO aimed to make the MV "transport capability neutral," meaning that differences in fuel efficiency associated with aircraft capabilities such as range, payload, and speed should not be reflected in the metric. A byproduct of this approach is that the MV cruise metric is largely insensitive to change in aircraft structural efficiency, including the use of lightweight materials and design considerations, such as stretch and shrink aircraft, that lead to more or less improvement in fuel efficiency on a fuel/passenger-km basis.

An analysis of aircraft deliveries between 1975 and 2014 supports the hypothesis that changes in structural efficiency and aircraft capability can explain the gap between the improvement trend on these two metrics. Figure 5 shows trends in aircraft range (red line) and structural efficiency as measured by aircraft empty weight per unit estimated RGF (operating empty weight, or OEW, per unit eRGF, blue line).

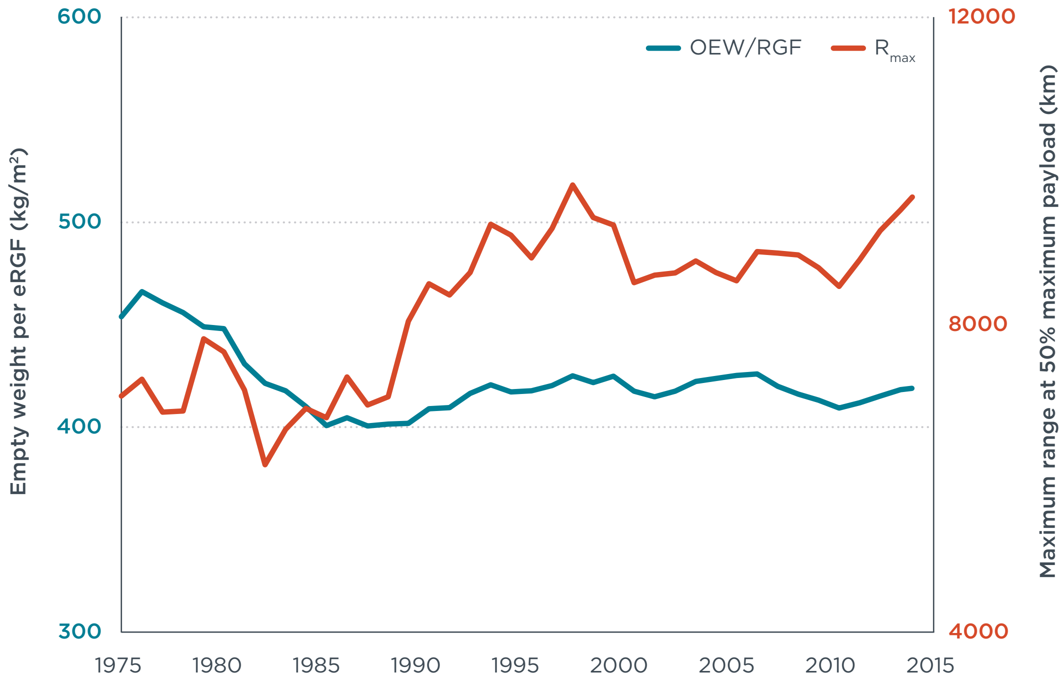

Figure 5. Trends in structural efficiency and range for new aircraft, 1975 to 2014

From 1975 to 1988, both R_{max} range and operating empty weight per unit eRGF fell by approximately 25%, with particularly large reductions during the 1980s. This coincides with a period of a relatively large gap between the two metrics because structural efficiency improvements are reflected on the block fuel burn/passenger-km metric but not the MV. From 1988 to 2014, the trend reversed, with range increasing by 40% while operating empty weight/unit floor area increased modestly, about 6%. Since increasing range boosts aircraft empty weight and degrades fuel efficiency on a common mission, Figure 5 suggests that fuel efficiency gains from technology have been used preferentially to increase aircraft performance, notably range, as noted in ICAO's 2010 fuel efficiency technology review.

3.3 AVERAGE VERSUS NEW TYPE FUEL EFFICIENCY

Several studies (e.g. Penner et al., 1999; Peeters & Middel, 2007) assess aircraft technical progress by plotting the fuel/seat-km at maximum capacity by type over time. Figure 6 plots the average metric value trend presented in Figure 4 with a bubble chart of individual Piano aircraft types. Each bubble in the chart represents a single Piano aircraft with its MV normalized to the 1968 value (y-axis), plotted against its first delivery year (x-axis), while the size of each bubble represents its MTOW multiplied by the number of aircraft delivered for the first three delivery years for a given type.

The chart shows that within a given year, there is a wide range of metric values that influence the average trend, although some types have a larger impact than others due to their larger contribution to overall fuel burn driven by a larger number of deliveries and/or overall size.

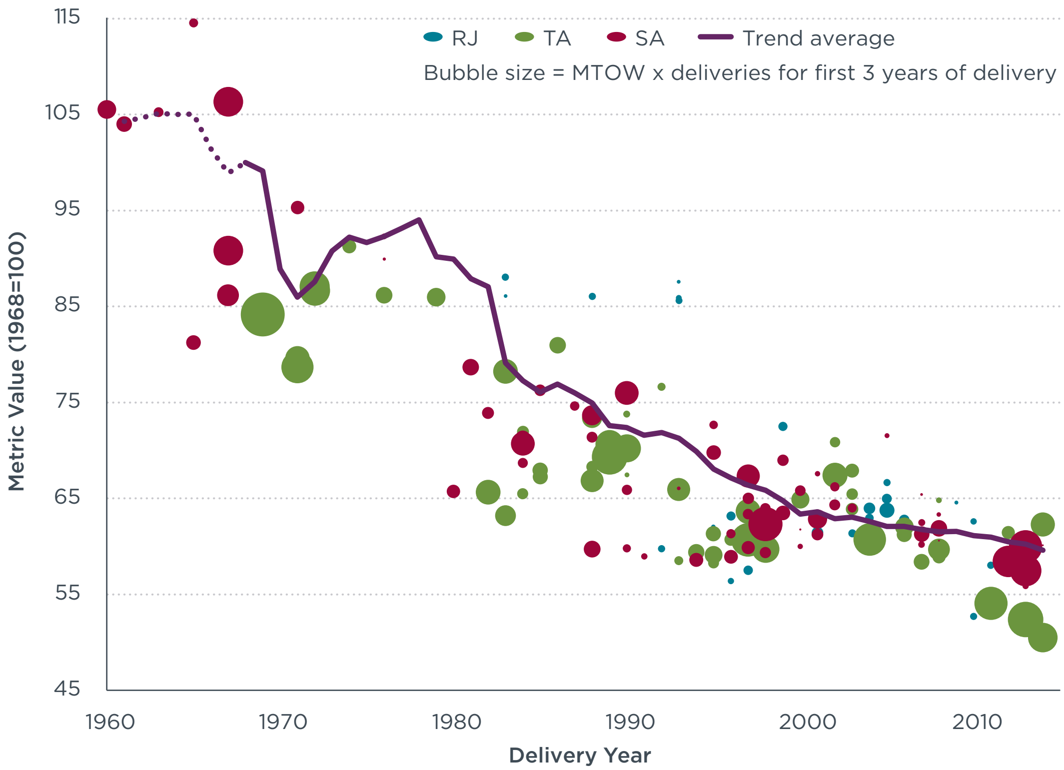

Figure 6. Newly delivered jet commercial aircraft metric value, 1960 to 2014 (normalized to 1968) and individual Piano aircraft type at EIS

3.4 DRIVERS OF NEW AIRCRAFT FUEL EFFICIENCY TRENDS

There are several expected drivers of the recent trends in new aircraft efficiency. One is fuel cost. Figure 7 overlays the trend in real jet fuel prices (EIA, 2015), normalized via the Consumer Price Index to 2015 values, from 1975 to January 2015 over the average fuel burn data (fuel/passenger-km metric) from Figure 4.

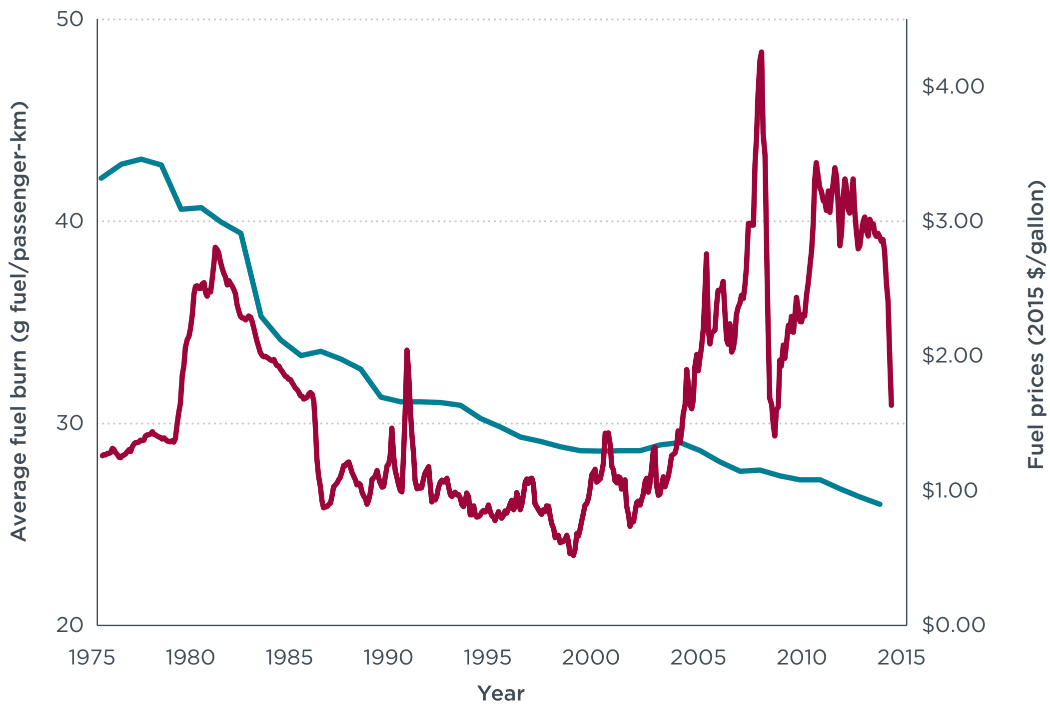

Figure 7. Average fuel burn for new commercial jet aircraft and real jet fuel prices (2015 dollars)

Figure 7 highlights the high volatility of jet fuel prices, especially in the last decade. As demonstrated in the graphic, the sharp increase in jet fuel prices starting in 2003 correlates well with the end of a period of flat efficiency for new aircraft in 2004. At the same time, improvements since 2005 remain relatively modest compared to those seen in the 1980s, when the aviation sector was reacting to both a price spike linked to the 1979 Oil Shock and the 1978 Airline Deregulation Act, which intensified price competition in the U.S. While additional fuel efficiency improvements are expected over the short term as aircraft like the A320neo and 777X enter into service, fuel prices alone may not provide a consistent, long-term motivation for fuel efficiency improvements in the aviation sector.

3.5 COMPARISON TO ICAO'S FUEL EFFICIENCY GOALS

In 2010 ICAO conducted a study to determine medium- and long-term fuel burn technology goals as part of a basket of measures to achieving ICAO's collective global aspirational goals of improving annual fuel efficiency by 2% and stabilizing global CO_2 emissions at 2020 levels. This study, based on single-aisle and small twin-aisle baseline aircraft, reviewed several well-developed propulsion, aerodynamic, and lightweight structure technologies that improve fuel efficiency (see Appendix A). Most of these technologies are not applied in the current aircraft fleet, and only a handful are expected to be applied to new "project" aircraft due to enter the market between 2016 and 2020 (e.g., increased wingspan on the Boeing 777X and geared turbofan engine on the Airbus A320neo, Bombardier CSeries, and others). ICAO set these goals as ranges instead of a deterministic value to account for uncertainties, with a wider range for 2030 compared to 2020.

Figure 8 shows the trend in average newly delivered single-aisle and small twin-aisle aircraft in terms of metric value (normalized to 1968 values) versus the fuel burn technology goals that ICAO established for 2020 and 2030. Metric values and EIS year for new single and small twin-aisle aircraft are indicated by the red and green dots, respectively. Because ICAO's technology goals are set for new aircraft types, they are most comparable to a trend line for new EIS aircraft, which is shown in the black line. Under those goals, in 2020 the metric value of new aircraft types on average could reach between 27% and 31% below the base aircraft values, namely Airbus A320-200, Boeing 737-800, Airbus A330-200, and Boeing 777-200.

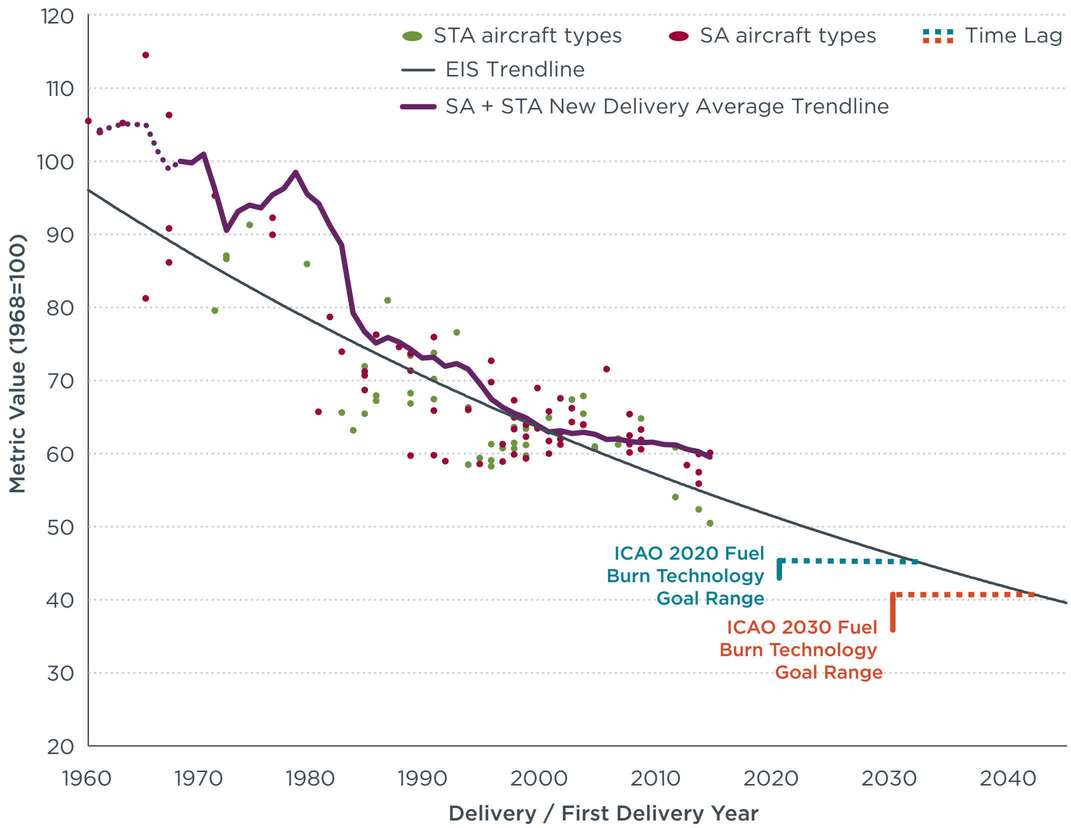

Figure 8. New single-aisle and small twin-aisle jet aircraft metric value vs. ICAO fuel burn technology goals

Figure 8 puts these goals into perspective. Assuming that the historical improvement rate of metric value reduction persists, industry is lagging behind both the 2020 and 2030 ICAO goals by approximately 12 years. Given this trajectory, it appears unlikely that ICAO can achieve its higher-level technology goals without additional policy support.

4. CONCLUSIONS AND NEXT STEPS

This work reconfirms the 2009 study's conclusion that a meaningful CO_2 standard is needed to provide an extra incentive for new technology development and deployment. Despite faster fuel efficiency improvements linked to new aircraft types and higher fuel prices, manufacturers remain 12 years behind ICAO's technology goals. It is also worth noting that, albeit at a slow pace, new aircraft fuel efficiency keeps improving by the year. Any CO_2 emission standard should, therefore, ensure additional emission reductions by taking into account the baseline level of industry improvement in order to avoid setting a standard that would be overtaken by "natural" improvement.

As discussed in the previous section, ICAO's CO_2 emission standard, while rewarding technologies that reduce fuel burn, does not reward structural efficiency as evident from a comparison of ICAO's cruise metric value and the fuel/passenger-km metrics used to measure CO_2 reduction. Even if the adopted standard is stringent enough to incrementally improve fuel efficiency beyond business-as-usual, a supporting measure may be needed to promote structural efficiency, including the use of lightweight materials and efficient aircraft design. Differentiated landing fees based on the fuel efficiency of in-service aircraft is one potential incentive.

Looking forward, further work is needed to comprehensively investigate the degree of correlation between the modeled average fuel burn on the block fuel per passenger-km and ICAO cruise metrics. An expansion of the study to include general aviation aircraft, notably turboprops and business jets, could broaden our understanding of overall industry fuel efficiency trends. A future update will also be necessary to reflect changes linked to project aircraft due to enter into service between 2016 and 2020 — before the earliest application date of ICAO's CO_2 standard. The update will also be useful in reassessing industry's progress toward ICAO's fuel burn technology goals.

APPENDIX A: TECHNOLOGIES REVIEWED BY ICAO FUEL BURN TECHNOLOGY GOALS (ICAO 2010A)

Propulsion

- Advanced Turbofan
- Geared Turbofan
- Open Rotor

Basket of Technologies Which Improve Propulsive Efficiency

- Improved global design through advanced analytical tools
- Optimized components through advanced analytical tools
- Reduced nacelle weights which displace the optimum toward decreased FPR and increased BPR
    - Advanced composites:
        - PMC, phenolic matrix composite
        - MMC, metallic matrix composite
        - CMC, ceramic matrix composite
        - Composite frames
    - Advanced alloys
    - Increased loading
    - Manufacturing technology
- Combined feature functionality
- Integrated installations
- Zero hub fan

Basket of Technologies Which Improve Thermodynamic Efficiency

- Improved materials to allow higher temperature
- Improved compressor and turbine with 3D aerodynamics, blowing and aspiration
- Active tip clearance

Aerodynamic

Basket of Technologies Which Improve Viscous Drag

- Riblets
- Active turbulence control
- Natural laminar flow
- Hybrid laminar flow Control

Basket of Technologies Which Improve Non-Viscous Drag

- Increased wing span (increased aspect ratio)
- Improved aero tools

- Excrescence reduction
- Variable camber with new control surfaces
- Morphing wing

Basket of Technologies Which Improve Weight

- Optimization of geometry through
  - Reduction of loads (active smart wing)
  - New joining processes (removal of riveting) by:
    - Stir welding process
    - Super-plastic forming
    - Diffusion welding
    - Laser beam welding
- Metallic technologies
  - Al-Li
  - Al-Mg-Sc
  - Advanced alloy
- Composites technologies
  - PMC
  - Fluoro-polymers
  - Glare (glass-fibre-reinforced)
  - ARALL (aramid-fibre-reinforced)
  - CentrAl (aluminium-based composite material with alternating high-quality aluminium and composite layers in a fibre metal laminate)
- Multifunctional materials/structures
- Nanotechnologies
- Health monitoring

Other concepts

- Electric landing-gear drive
- More electric aircraft (MEA)
- Fuel cells

APPENDIX B: SENSITIVITY ANALYSIS OF ANNUAL INCREMENTAL IMPROVEMENTS

Over the long term, aircraft average fuel burn trends are largely driven by the introduction of new, more efficient aircraft types (Rutherford & Zeinali, 2009). Within an aircraft type, there are limited means of reducing fuel burn through the introduction of incremental improvements in technology; prominent examples include Performance Improvement Packages (PIPs) that are incorporated into Airbus and Boeing's products over the course of their production lives. Within the Piano model, the fuel efficiencies of representative aircraft are static — that is, they are fixed at a chosen EIS date or operational year for a specific airline configuration. Thus, incremental changes are not always captured by the modeling tools.

Not all aircraft types undergo changes after their entry into service, but to test the robustness of the main findings a sensitivity analysis was performed to test the importance of the static model approach. In this analysis we assume that the average fuel burn of newly delivered aircraft within a given type falls by 0.25% by year after its initial EIS. For example, a new 2001 aircraft of Type Z first delivered in 2000 (let's call it Aircraft Z_{2001}) will burn 0.25% less fuel than a new aircraft of that type delivered the prior year (Aircraft Z_{2000}), while a new aircraft delivered in 2002 (Aircraft Z_{2002}) would burn approximately 0.5% less fuel compared to the initial aircraft. The trend in average fuel burn over time, assuming this natural improvement, is presented in Table B1 relative to the baseline (static model) approach highlighted in Figure 4.

The average fuel burn trend assuming annual improvement on all aircraft types after their EIS dates follows the original trend quite closely, with gaps widening in the 1970s and narrowing back in the 1980s, and again widening in the late 2000. In fact, the annual average fuel burn reduction for the sensitivity analysis between 2010 and 2014 falls to 0.9%, lower than the annual improvement for the trend assuming no annual improvement (1.1%).

It can be concluded, then, that although this analysis did not take into account minor improvements applied to an aircraft over the course of its production cycle, the Piano aircraft database sufficiently represents the aircraft variants available in the market.

Table B1. Sensitivity test for annual improvements within an aircraft type for new aircraft

Assumption of improvement within an aircraft type	Annual average fuel burn reduction in						
	1960s	1970s	1980s	1990s	2000s	2010+	1968 to 2014
No improvement	-2.6%	0.4%	-2.6%	-0.8%	-0.5%	-1.1%	-1.3%
0.25% annual improvement	-2.6%	0.2%	-2.4%	-0.8%	-0.6%	-0.9%	-1.4%

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