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FUEL BURN OF NEW COMMERCIAL JET AIRCRAFT: 1960 TO 2019

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EXECUTIVE SUMMARY

This paper updates a 2015 study by the International Council on Clean Transportation (ICCT) that analyzed the fuel burn of new commercial jet aircraft from 1960 to 2014 (Kharina & Rutherford, 2015) by taking into account new aircraft types and deliveries from 2015 to 2019. One major refinement of this new study is the inclusion of dedicated freighters delivered from 1960 to 2019, and this offers a fuller picture of the commercial jet aircraft market.

Following the methodology used in the prior work, aircraft fuel burn is assessed in this analysis via two indicators: block fuel intensity in grams of fuel per tonne-kilometer and the carbon dioxide (CO_2) metric value (MV) developed by the International Civil Aviation Organization (ICAO). The latter aims to provide a "transport capability neutral" means of regulating aircraft fuel burn.

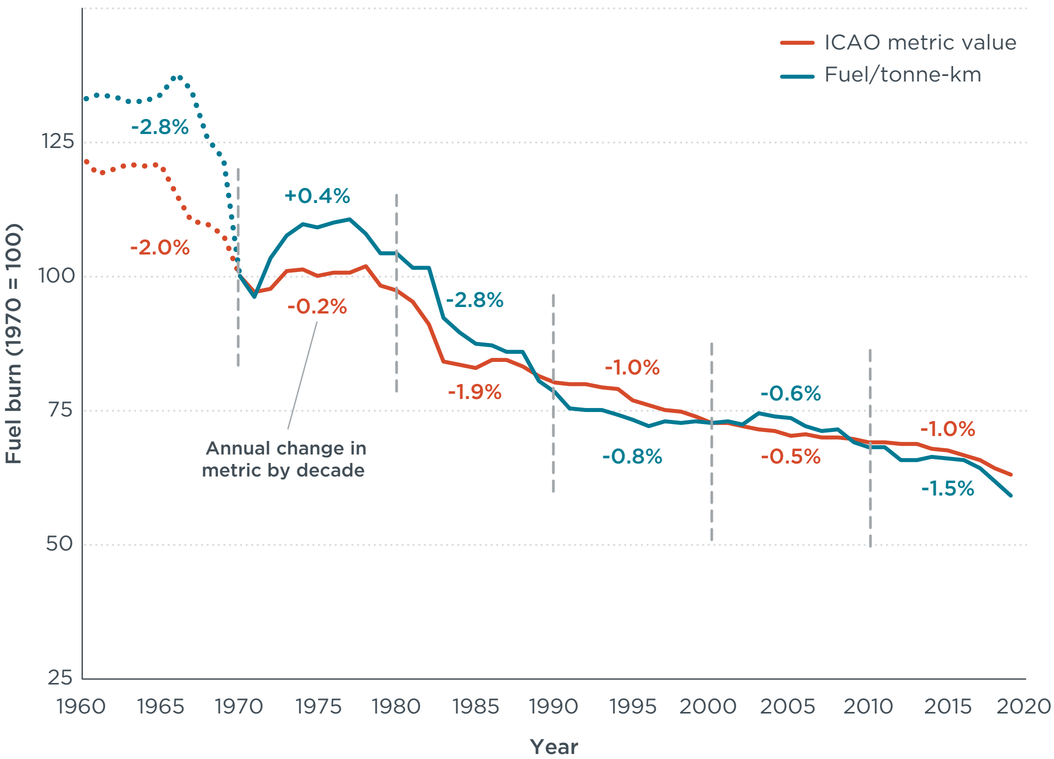

Figure ES-1. Average fuel burn of new commercial jet aircraft, 1960 to 2019 (1970=100)

Figure ES-1 presents the average fuel burn of newly delivered commercial aircraft from 1960 to 2019 in the two metrics with 1970 as the baseline (1970 = 100). The average block fuel intensity of new aircraft decreased 41% from 1970 to 2019, and that is a compound annual reduction rate of 1.0%. When including the prior decade, during which time widebody service was introduced using new aircraft like the Boeing 747 family, the compound annual reduction rate increases to 1.3% per year.

Some time periods saw more drastic reductions in aircraft fuel burn than others. Notably, the block fuel intensity dropped an average of 2.8% each year in the 1980s. That was followed by two decades of more modest improvements at an average rate of less than 1% each year.

The past decade, from 2010 to 2019, has seen a quickening of fuel burn reductions thanks to the introduction of many new fuel-efficient models, including the Airbus A320neo, Boeing 737 MAX, Airbus A350, and Boeing 787 families. Because the only known new aircraft model on the horizon is 777X, fuel burn reduction may slow down again in the upcoming decade.

Over the long run, our analysis shows that fuel burn per tonne-kilometer and ICAO's MV were well correlated. While the two metrics diverge from time to time, that is partially because the block fuel intensity metric is better able to reflect the fuel burn of aircraft types with larger payload carrying capabilities.

Reductions in aircraft fuel burn were also compared with ICAO's aircraft CO_2 emission standard. All new aircraft will need to meet fuel burn targets for their specific sizes in order to be sold globally starting in 2028. Figure ES-2 shows that the average new aircraft delivered in 2016, the year ICAO's standard was finalized, already complied with the 2028 requirements. In 2019, the average new aircraft delivered passed the standard by 6%.

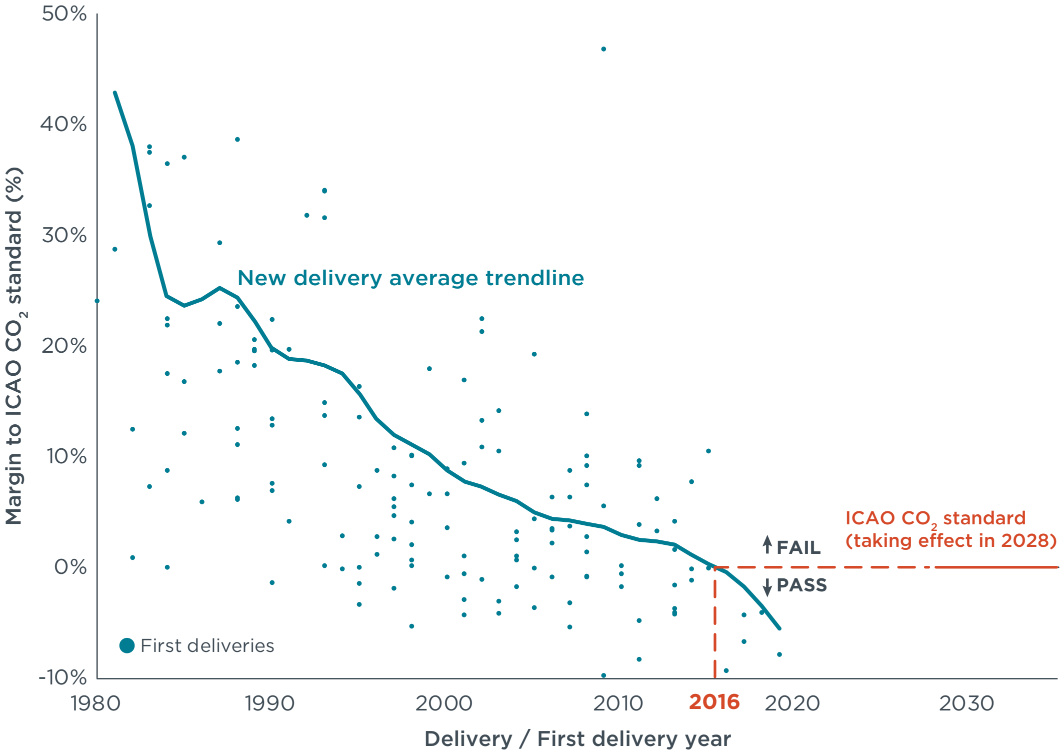

Figure ES-2. Average margin to ICAO's CO_2 standard for new aircraft, 1980 to 2019.

A more stringent CO_2 standard could promote fuel burn reductions above and beyond business as usual, but as this research shows, ICAO's CO_2 standard lags the existing efforts of manufacturers by more than 10 years. This suggests that ICAO should review and tighten its CO_2 standard as quickly as possible. Individual governments, like the United States, should also consider implementing a more stringent domestic standard, such as applying it to in-service, rather than just new, aircraft (Graver & Rutherford, 2019). Future standards for new aircraft will also be needed. Introducing flexibility mechanisms like averaging and banking would allow for more ambitious, cost-effective standards.

1. INTRODUCTION

In many ways, commercial air travel underpins the modern global economy, but this comes with an environmental cost. Jet fuel use is a major contributor to global carbon dioxide (CO_2) emissions, and in 2018, global commercial aviation emitted around 905 million tonnes of CO_2 (International Air Transport Association [IATA], 2019). If commercial aviation were counted as a country, it would rank sixth, after Japan, in terms of CO_2 emissions (Global Carbon Atlas, n.d.). Aviation fuel use and CO_2 emissions from commercial aviation have grown particularly fast of late. They increased by 44% over the past 10 years (Figure 1) and were recently on pace to triple again by 2050 (International Civil Aviation Organization [ICAO], 2019a).

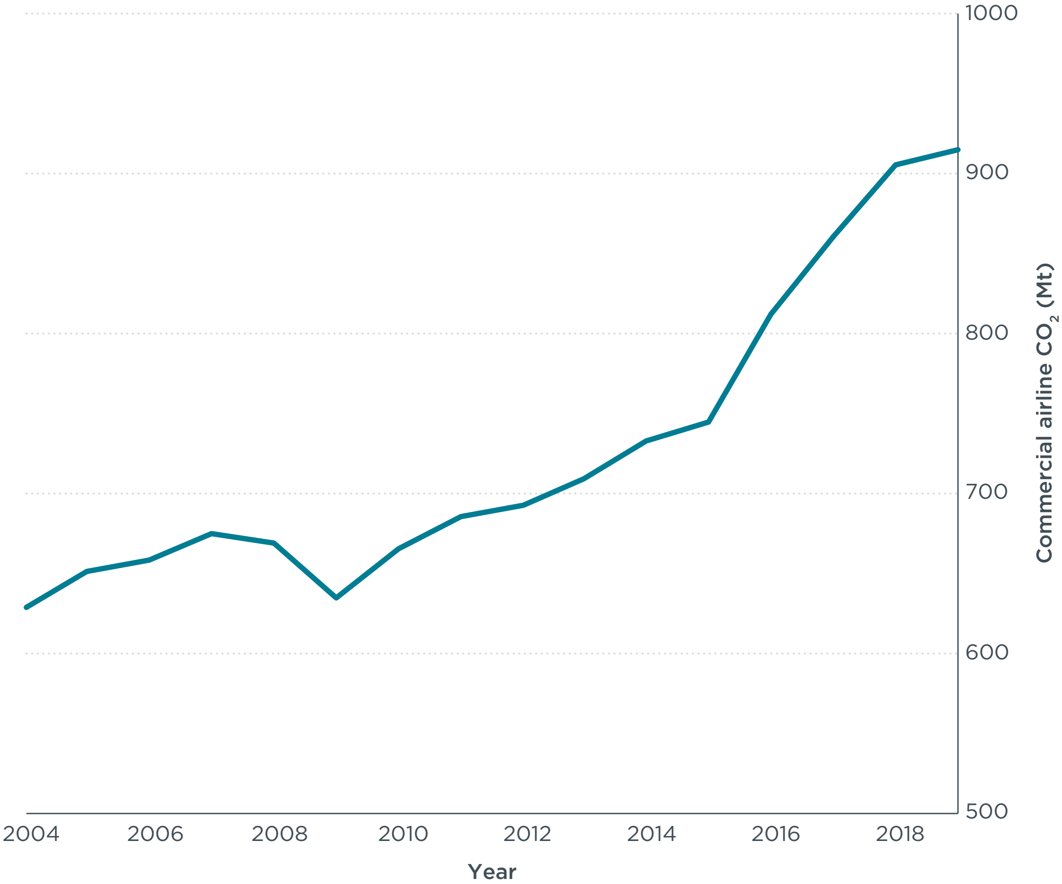

Figure 1. CO_2 emissions from commercial aviation, 2004 to 2019. Source: IATA (2019).

Throughout the history of commercial aviation, aircraft and engine manufacturers have reduced the fuel burn of their products in order to save fuel costs, which typically make up about 25% of airline operating expenses (Airlines for America, n.d.). An airline's fleet composition is a major factor in whether its operational fuel efficiency leads or lags the industry average (Graver & Rutherford, 2018; Zheng & Rutherford, 2019). However, because the growth in demand for both passenger and freight air transport has continued to outpace gains in fuel efficiency, CO_2 emissions from aviation have continued to grow (IATA, 2019).

Recognizing aviation's climate impact, a variety of stakeholders began developing policies to reduce the environmental impact of aviation. In 2012, the European Union began covering CO_2 emissions from domestic and intra-EU flights under its Emissions Trading System (European Commission, 2020). In 2013, the ICAO, the de facto United Nations regulator of civil aviation, established an aspirational climate goal of carbon neutral growth from 2020 onward (ICAO, 2019b). The goal includes an annual 2% fuel efficiency improvement (aspirational from 2020), and ICAO has also started analyzing a long-term climate goal for possible adoption at its 41st Assembly in 2022. Additionally, some airlines, trade associations (Sustainable Aviation, 2020), and civil society organizations (ICAO, 2019c) have proposed mid- and long-term CO_2 reduction targets for aviation.

Perhaps most significantly, in 2016, ICAO's environmental committee finalized the world's first CO_2 emission standard for new aircraft. The agency began work on the standard in 2009. In order for their manufacturers to sell aircraft internationally, individual countries must adopt a domestic standard under their national aviation authorities that is at least as stringent as the ICAO standard. The standard will enter into force for all newly delivered aircraft in 2028. Aircraft models that do not meet the CO_2 emission threshold as a function of their maximum takeoff mass (MTOM) will not be able to operate internationally.[1]

A meaningful aircraft CO_2 standard is critical for managing the impact of commercial aviation on climate change. In July 2020, the U.S. Environmental Protection Agency (EPA) released a proposed aircraft CO_2 standard that closely follows ICAO's standard (EPA, 2020). Other countries and regions, including Canada and the European Union, have already adopted the standard recommended by ICAO. Countries are allowed to adopt more stringent requirements than ICAO's minimum standards and have done so in the past, for example for safety and aircraft noise.

Meanwhile, the COVID-19 pandemic introduces great uncertainty for new aircraft delivery in the coming years. Manufacturers are experiencing historically low deliveries, as more deferrals and order cancellations come in (Isidore, 2020; Hepher & Van Overstraeten, 2020). At the same time, many airlines have decided to retire old, less fuel-efficient aircraft families such as the Airbus A340 and A380, Boeing 747 and 767, and others, earlier than planned (Pallini, 2020). A meaningful CO_2 standard could urge the industry to focus available resources on producing and deploying newer, more fuel-efficient aircraft models.

In 2009, and again in 2015, the International Council on Clean Transportation (ICCT) analyzed improvements in fuel burn of newly delivered aircraft from 1960 for the 20 largest commercial aircraft manufacturers (Rutherford & Zeinali, 2009; Kharina & Rutherford, 2015). The 2015 report found that the average fuel burn of new aircraft fell about 45% from 1968 to 2014, with an annual reduction rate of 1.3%. The rate of efficiency gains fluctuated over time; there was a notably rapid improvement in the 1980s, a flat period from 1995 to 2005, and then a return to the historical average improvement from 2005 to 2014. A sharp increase in fuel prices around 2003 is likely to have been a major contributing factor to this recent trend.

Since 2014, the aviation industry has undergone significant changes that affect the average fuel burn of new aircraft. As airlines and consumers become more aware of the environmental impacts of commercial aviation, some carriers increased their investments in more fuel-efficient aircraft. Two popular re-engined narrowbody aircraft types have been introduced—the Airbus A320neo and Boeing 737 MAX families—to replace older, less-efficient aircraft. The Embraer E-Jet E2 family also entered into service in 2018, and this expanded new, fuel-efficient engine technologies to regional jets. Meanwhile, the introduction of the Airbus A350 and A330neo families, as well as more deliveries of Boeing's 787 Dreamliners, have boosted widebody fuel efficiency.

This paper expands the 2015 study to include new passenger aircraft deliveries from 2015 to 2019, and adds dedicated freighters delivered from 1960 to 2019. While this study follows the same general methodology as used in the 2015 report, the results

1 A regulatory maximum weight of a loaded aircraft at takeoff. A sum of the operating empty weight (OEW), payload carried (passengers and/or freight), plus fuel mass.

are further refined using standardized parameters—cabin sizes, measured in reference geometric factor (RGF), and ICAO metric value (MV) estimations—from representative aircraft models using the Piano aircraft performance model. Recent deliveries are compared to the ICAO CO_2 standard to check its effectiveness. As the reproduced historical trends based on both the fuel/tonne-kilometer and ICAO MV metrics closely align with the trends reported in the 2015 study, this suggests no major change in results for 1960 to 2014 due to the use of different data sources. Hence, the discussion in this report focuses more on the recent fuel efficiency trends from 2015 to 2019.

The rest of this paper is organized as follows. Section 2 explains our methods, and then Section 3 introduces the key trends and compares the trends to ICAO's CO_2 standard. Finally, Section 4 discusses the policy implications and highlights potential areas for further research.

2. METHODS

Here we describe where we obtained the new aircraft delivery statistics and how the two fuel burn metrics were calculated.

2.1 AIRCRAFT DELIVERY DATASET

In the 2015 study, annual deliveries of new commercial jet aircraft from 1960 to 2014 were purchased from Ascend Online Fleets.[2] This data was reanalyzed for this study. From the total of 65,965 aircraft included in the Ascend database, 35,985 passenger aircraft with more than 20 seats were extracted for the 1960–2014 trend analysis.

Deliveries made from 2015 to 2019 were sourced separately from the Airline Monitor Database (Airline Monitor, 2020). These delivery data were compiled on the aircraft series level. When applicable, the total number of deliveries of a specific aircraft series were broken down to MTOM variants based on the delivery patterns from 2010 to 2014.

For dedicated freighters and combination aircraft, deliveries from 1960 to 2014 were compiled from the Ascend database. Deliveries from 2015 to 2019 were based on information publicly disclosed by manufacturers (Boeing, 2020; Airbus, 2020). All of these data sources combined create a full delivery history of both passenger and freight aircraft from 1960 to 2019. Table 1, below, summarizes the manufacturers and aircraft deliveries covered.

Table 1. Top 20 manufacturers by aircraft deliveries, 1960 to 2019

Manufacturer	Number of deliveries	% of total	Relevant types[a]
Boeing	19,440	42.6%	SA, TA, FR
Airbus	12,390	27.1%	SA, TA, FR
McDonnell-Douglas (Boeing)	3,418	7.5%	SA, TA
Embraer	2,756	6.0%	RJ, FR
Canadair (Bombardier)	1,983	4.3%	RJ, FR
Tupolev	1,513	3.3%	SA, FR
Yakovlev	1,023	2.2%	RJ, SA, FR
Fokker	520	1.1%	RJ, SA
Ilyushin	480	1.1%	SA, TA, FR
HS (BAE Systems)	362	0.8%	RJ, SA, FR
Fairchild/Dornier[b]	357	0.8%	RJ
BAC (BAE Systems)[b]	270	0.6%	SA
Aerospatiale[b]	263	0.6%	SA
Lockheed	248	0.5%	TA
Sukhoi	196	0.4%	RJ
Avro (BAE Systems)	167	0.4%	RJ
Convair (General Dynamics)[b]	98	0.2%	SA
Antonov	95	0.2%	RJ, SA, FR
Comac	53	0.1%	RJ
Harbin Embraer Aircraft Industry	41	0.1%	RJ
Total	**45,673**	**100.0%**	**—**

[a] Relevant types include regional jets (RJ), single-aisle passenger jets (SA), twin-aisle passenger jets (TA), and freighters (FR).
[b] Excluded from final analysis due to lack of representative aircraft representations in the Piano database.

2 http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/ascend-online-fleets.html

Piano 5.3, an aircraft performance and emissions model with an extensive database of commercial aircraft designs, was used to model aircraft fuel burn.[3] From 798 distinct aircraft-engine type combinations extracted from the Ascend database, 655 combinations were matched with 161 Piano representative aircraft models based on aircraft type, engine type, and MTOM; this covered 89% of total deliveries from 1960 and 93% of deliveries from 1968. Sixteen new commercial passenger aircraft models delivered from 2015 to 2019 were all successfully matched to representative Piano models. Due to the high uncertainty and low matching rates before 1970, trends prior to 1970 should be treated with caution.

Table 2 summarizes the Piano matching rate for passenger and freighter aircraft. For dedicated freighters, 89% of deliveries from 1960 to 2014 were matched, and 100% of deliveries from 2015 to 2019 were matched. For dedicated freighter types that have no representation in the Piano database, operating empty weight (OEW) adjustments were made to the parent passenger aircraft by subtracting 50 kilograms (kg) per missing seat (ICAO, 2017).

Table 2. Piano model average matching rate for aircraft deliveries by decade

Decade	Passenger aircraft	Dedicated freighters
1960s	32%	71%
1970s	63%	96%
1980s	94%	77%
1990s	97%	88%
2000s	98%	100%
2010s	100%	100%
Total	**91%**	**91%**

2.2 FUEL BURN METRICS

This study follows the same general methodology as used in the 2015 study and evaluates the fuel burn of newly delivered aircraft based on two metrics: a block fuel intensity metric measured in mass of fuel consumed per tonne-kilometer (fuel/tonne-km) and ICAO's CO_2 MV.

Block fuel intensity

The fuel/tonne-km metric is similar to the fuel/passenger-km estimated in the 2015 report, with slight modifications for dedicated freighters. Fuel burn is estimated from the departure gate to arrival gate, and this is also known as "block fuel." In contrast to the MV, the fuel/tonne-km metric accounts for all fuel consumed during taxi, takeoff, cruise, approach, and landing, and credits or penalizes, as appropriate, changes in aircraft capability—i.e., payload capacity and/or range—that impact fuel efficiency.[4]

This paper analyzes the fuel burn of new aircraft delivered independent of operational practices that vary from airline to airline. For this reason, to control for different seat configurations used by airlines on the same type of aircraft, a set of standardized seating densities by aircraft type was used. Global average seating density, or the number of seats divided by estimated reference geometric factor (eRGF), was

3 http://www.piano.aero/

4 The relationship between fuel burn and aircraft capability, in terms of design speed, payload capacity (mass and/or volume), and range, is complex and largely beyond the scope of this work. All things being equal, increasing the design speed and range of aircraft tends to increase its fuel consumed per tonne km of payload transported. Conversely, increasing the amount of payload that can be transported, either in terms of mass (tonnes) or volume (m^3), will tend to lower an aircraft's fuel burn per tonne-km. For this reason, under the block fuel intensity metric, "stretch" aircraft like the A321 tend to have lower fuel burn per unit transported than "shrink" aircraft like the A319.

estimated by aircraft type from the Ascend database (Table 3).[5] The default eRGF of each Piano aircraft was then multiplied by these standardized seating densities to calculate the adjusted seat counts. These eRGF values slightly differ from those gathered from individual manufacturer sources and those used in the 2015 study, but they do not alter the resulting fuel burn trend. The adjusted seat counts were then used to determine the payload modeled and also to adjust the OEW of each matched Piano aircraft model by 50 kg per seat when it differed from the Piano standard seat counts.[6]

Table 3. Average seating density by aircraft type

Type	Seating density (seat/m^2 eRGF)
Regional jet	1.27
Single-aisle	1.48
Twin-aisle	1.05

Airplanes were "flown" using Piano to model their fuel burn over nine payload-range test points. These test points were selected from each aircraft's payload-range diagram to approximate its real-world missions. These points, presented in Table 4, are derived from 2010 global operations (Rutherford, Kharina, & Singh, 2012).

Table 4. Range and load factor assumptions for the block fuel intensity metric

Types[a]	Range (percentage R_{max}[b])			Load factor (percentage of available seats / maximum payload)		
	low	mid	high	low	mid	high
Pax RJ + SA	18%	25%	38%	70%	82%	93%
Pax TA	26%	34%	51%	73%	83%	93%
Freight RJ + SA	20%	28%	43%	42%	49%	56%
Freight TA	39%	51%	76%	43%	49%	55%

[a] Aircraft types include regional jets (RJ), single-aisle (SA), and twin-aisle (TA).
[b] R_{max} = maximum range at 50% maximum structural payload, which is maximum zero fuel weight minus OEW

The payload-range test points of dedicated freighters, also presented in Table 4, were derived for this study based on 2018 global operations (Graver, Zhang, & Rutherford, 2019), with the same scale of low and high bounds of passenger aircraft test points applied to the midpoint. Stage length, or flight distance, was calculated as a percentage of an aircraft's range at 50% maximum structural payload, and payload was estimated as the number of passengers multiplied by 100 kg per passenger including baggage (ICAO, 2019d). No belly freight was assumed for passenger flights.[7]

Aircraft were "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 on the block fuel intensity metric. Taxi-in and taxi-out times were designated as 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. These modeling parameters are summarized in Table 5 below.

5 Reference geometric factor, a close proxy of cabin floor area, was 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 MV.

6 In the few cases where these standardized seat counts would have generated unrealistically high seat counts, Piano defaults were used instead. Examples include older aircraft on which the calculated seat count is higher than the certification allowance (i.e., Boeing 707-320C and Douglas DC-8), and very large aircraft where the discrepancy between calculated and operational (2014) Piano default seat counts exceeds 20% (i.e., Airbus A380-800s).

7 The payload of widebody aircraft will be somewhat underestimated because they commonly carry belly freight; however, this should not impact the overall trend after normalizing to a reference year.

Table 5. Key modeling parameters for the block fuel intensity analysis

Parameter	Description
Range	Operational ranges (% R_{max})
Payload	Operational payloads (% of seats filled or % of maximum payload)
Seating density	Standardized seat counts by aircraft type
Flight levels	Optimal flight level between 270 and aircraft service ceiling
Cruise speed	99% max SAR
Taxi time	Bureau of Transportation Statistics 2010 average by aircraft type (12 min for RJ and SA, 15 min for TA)
Holding time	30 min
Diversion	370 km
Reserve	5% mission fuel

For the average fuel burn of each year, the fuel/tonne-km of each aircraft was weighted by the number of deliveries and estimated block fuel burn in its first year of operation. First year total block fuel was calculated by assuming 3,033 hours of operation per year for SA and RJ, and 4,155 hours of operation for TA (Rutherford et al., 2012). To compare with the ICAO MV, fuel/tonne-km was normalized to the 1970 level (1970=100). The 1970 benchmark was selected based on a coverage threshold and a representativeness screen. For the 1960s, Piano models cover less than 50% of all passenger aircraft delivered in a given year, and this creates a relatively high level of uncertainty. Furthermore, the first widebody aircraft, Boeing's 747-100, entered into service in 1969, and that results in a discontinuity in average fuel burn from earlier years during which only narrowbody aircraft were delivered.

In some cases, the fuel burn of an aircraft type makes small improvements through its production cycle. Since the 2015 study found that new delivery trends are generally insensitive to annual production improvements, the fuel burn of each aircraft type is assumed to be constant throughout its production lifetime in this report.

ICAO's metric value (MV)

The MV was developed within ICAO's Committee on Aviation Environmental Protection as part of the effort to establish a CO_2 emission standard for new airplanes (Rutherford, 2013; ICAO, 2013). One prominent difference from the fuel/tonne-km metric is that MV takes into account only the cruise performance and does not directly evaluate other flight phases such as landing, takeoff, and climb.

The MV is defined as:

$$MV = \frac{\left[{}^{1}\!/_{SAR} \right]_{ave}}{RGF^{0.24}}$$

Here, SAR refers to the maximum specific air range, which represents the cruise fuel consumption rate of an aircraft. RGF, introduced above, is a function of the pressurized fuselage length multiplied by the fuselage width for single-decker aircraft and is a proxy for the amount of usable space in an aircraft. In the calculation, 1/SAR is averaged at three gross weight test points representing a typical aircraft mass at heavy, light, and average combinations of payload and fuel.

Because the MV of an aircraft is sensitive to both its cruise fuel burn and its size, ICAO's standard assigns a fuel burn target (i.e., MV limit) as a function of an aircraft's MTOM. The relative fuel burn of different aircraft therefore needs to be compared against a standard reference line. Figure 2 shows the fuel burn of new aircraft delivered in 2019 compared to the 2028 standard for all new aircraft (blue line) and a separate standard for new types that takes effect around 2024 (red line).[8] Only aircraft types representing more than 1% of 2019 deliveries are shown, and they are distinguished by their entry into service (EIS) year.

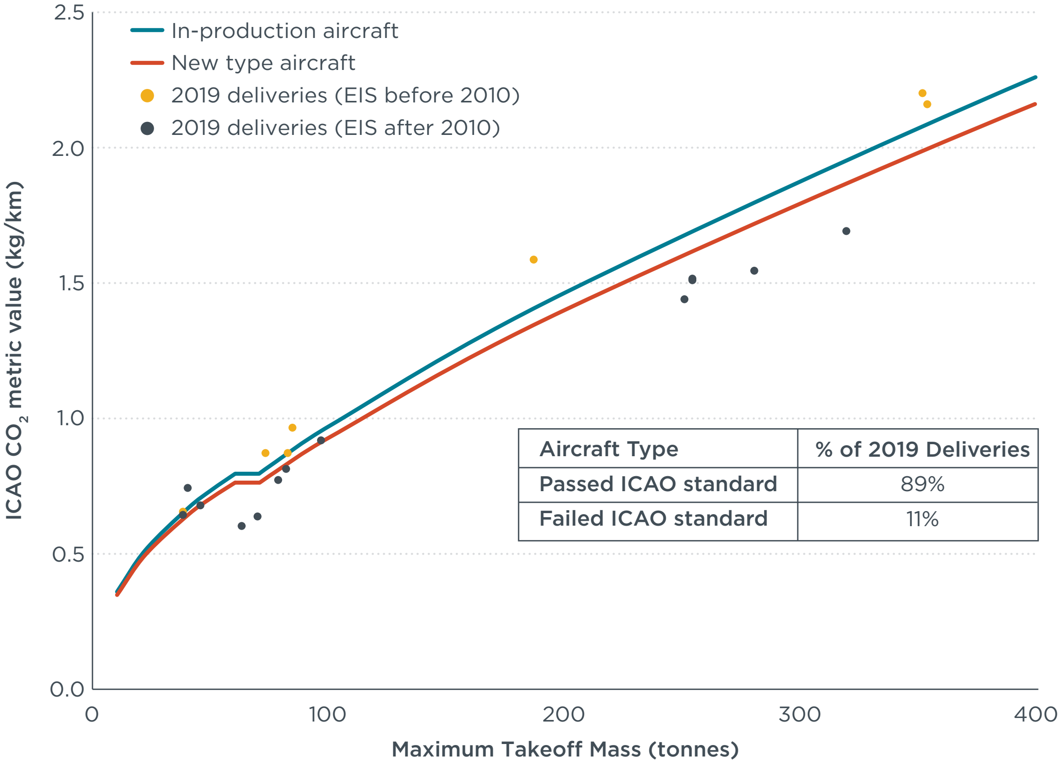

Figure 2. ICAO's CO_2 metric values for new commercial jet aircraft.

As shown, ICAO's standard requires different levels of improvement for different aircraft sizes, with airplane types with gross weight under 60 tonnes having relatively less stringent targets than those over 60 tonnes. This accounts for the fact that fuel efficiency technologies developed for larger narrowbody and widebody commercial jets may not be appropriate for smaller regional and business jets. In accordance with ICAO's certification requirement, each aircraft type's highest MTOM variant was referenced when calculating its exceedance to the standard. As illustrated in the figure, almost 90% of aircraft delivered in 2019 already passed ICAO's 2028 standard, with the exception of five types certified before 2010 and Comac's ARJ21-700.

Finally, the average MV margin of each aircraft type was weighted by its MTOM variants and the number of deliveries in a given year. In order to be compared with the fuel/tonne-km metric, the average margins to the ICAO standard were also normalized to the 1970 level (1970=100).

Note that this study used MVs for each representative aircraft model directly extracted from Piano. These standardized MVs replaced the calculated MVs of "flying" aircraft at 100% maximum SAR at the three individual MTOM test points used in the 2015 study. Furthermore, ICAO finalized its CO_2 standard in 2016, which allows us to use that directly for comparison rather than our own reference line. Despite the difference in sources of reference line and MVs, the fuel efficiency trend measured by MV margins in this study closely aligns with that of the 2015 study.

8 Requirements for "new type" designs start when a manufacturer applies for a new type certificate after January 1, 2020. Since it typically requires about 4 years to complete the type-certification process, that corresponds to an entry into service date in or after 2024.

3. RESULTS

We modeled average new aircraft fuel burn from 1960 to 2019. Key results include the historical trends based on both metrics, the comparison of the two metrics, and the fuel burn of new types delivered each year. We also compare the aircraft fuel burn trend to ICAO's CO_2 standard, to better understand its potential to promote future fuel efficiency gains.

3.1 HISTORICAL TRENDS IN NEW AIRCRAFT FUEL BURN

Figure 3 presents estimated new aircraft fuel burn from 1960 to 2019 based on ICAO's MV (red line) and in terms of fuel/tonne-km (blue line), normalized to the 1970 level (1970 = 100). Improvements before 1970, which are more uncertain and include a large fuel efficiency improvement due to the first introduction of the widebody 747 family, are shown as dotted lines back to 1960.

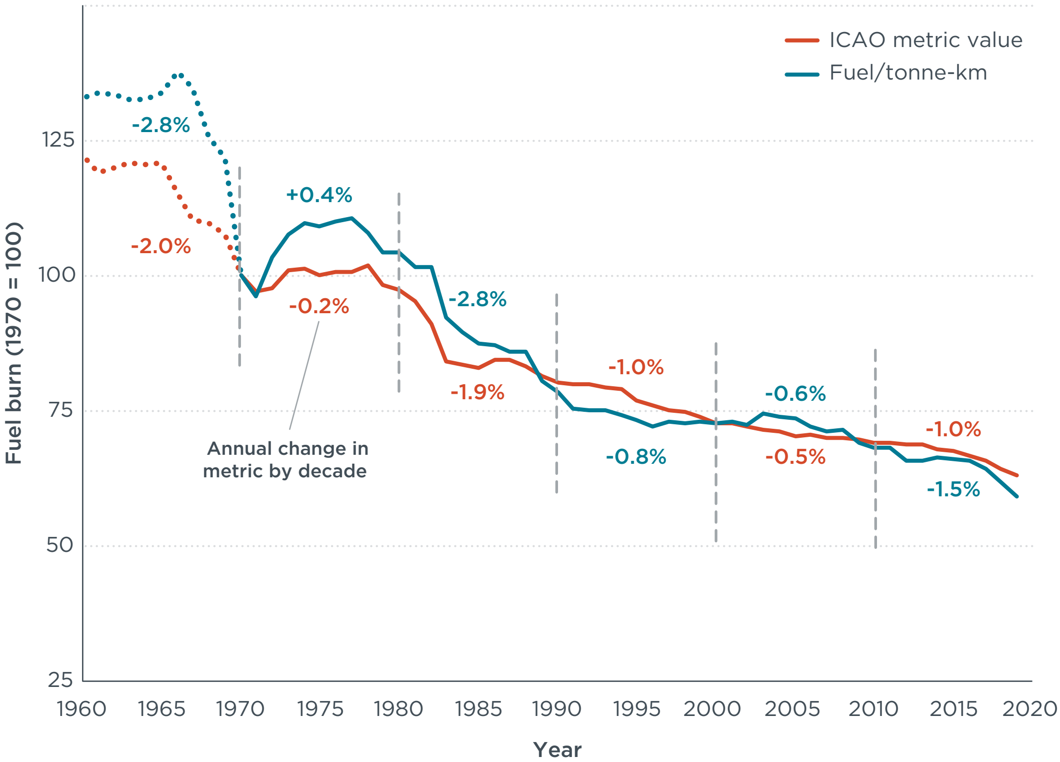

Figure 3. Average fuel burn of new commercial jet aircraft, 1960 to 2019 (1970=100)

The average fuel burn of new jet aircraft fell by about 40% on the block fuel intensity metric from 1970 to 2019, or a compound annual reduction of about 1.0%. For the full period of the study, from 1960 to 2019, annual reductions averaged 1.3% on the block fuel intensity metric and 1.1% on the MV. Despite the changes in data sources and the addition of freighters, the overall trend of fuel burn improvement is consistent with the 2015 study. Results across both metrics were similar after 1970; for this reason, and to simplify further analysis, we predominately present results using the MV in subsequent sections.

There is no perfect reference year for this analysis. The average fuel burn of new deliveries decreased sharply at the very beginning of the 1970s, but later bounced back through 1980. The initial reduction can largely be attributed to the introduction of the first modern widebody aircraft, the Boeing 747 family, starting in 1969 (Kharina & Rutherford, 2015). The 747-100 alone comprised almost 40% of deliveries in 1970. The use of high bypass turbofan engines plus its very large payload capacity helped the 747 aircraft to lead in fuel efficiency at that time. The fuel burn reduction curve flattened later in the 1970s as market share of the 747 dropped and stabilized around 10%. The volatility of average fuel burn in the early years was also a result of fewer aircraft types available in the market.

Aircraft fuel burn decreased rapidly during the 1980s, with average fuel burn falling 2.7% per year on the block fuel intensity metric. That was followed by slower fuel burn reductions in the 1990s and the 2000s. The rapid improvements of the 1980s were a result of introducing new, more fuel-efficient narrowbody and small widebody aircraft like the Boeing 757 and 767 families, and the Airbus A320 family, which used high bypass ratio engines. Fuel burn reductions stagnated from 1990 to 2005 on the fuel/tonne-km metric, with an almost flat curve. This flat period coincides with the continued delivery of older narrowbody and widebody types that were introduced in the 1980s and 1990s—e.g., the Boeing 737 Next Generation, Airbus A320, Boeing 777, and Airbus A330—and relatively few new types and engines.

The rate of fuel burn reduction picked up again around 2010, at 1% to 1.5% per year, depending on the metric. As a point of comparison, a comprehensive technology assessment found that the rate of fuel burn improvement for new aircraft could be accelerated up to 2.2% annually through 2034 via the adoption of cost-effective technologies (Kharina, Rutherford, & Zeinali, 2016; Elliott, 2016).

This trend of fuel burn improvements continued through 2019 due to the introduction of new, more fuel-efficient aircraft models. “Clean sheet” widebody aircraft entered into service, including Boeing’s 787 in 2010 and Airbus’s A350-900 in 2015, as did re-engined narrowbody jets like the A320neo in 2016 and 737 MAX in 2017.[9] Comac’s ARJ 21 and Embraer’s E-Jet E2 were also introduced in recent years. These aircraft-level improvements are reflected in improved airline fuel efficiency in recent years (Graver & Rutherford, 2018; Zheng & Rutherford, 2019).

In most time periods, MV improved more regularly than block fuel intensity did. The two metrics tended to diverge more when block fuel intensity improved rapidly, as in the 1980s, and converge more during flatter periods. This suggests that the block fuel intensity metric could be more sensitive to production patterns in a given year, while the ICAO MV shows steadier “technology only” improvements. An in-depth comparison of the two metrics is below.

3.2 METRIC COMPARISON

As explained above, the two metrics used in this study, fuel/tonne-km and ICAO MV, measure slightly different aspects of aircraft fuel burn. The largest difference between the two lies in whether to take into account the sensitivity of aircraft fuel burn to “transport capabilities” like payload, range, and speed.

The block fuel intensity metric rewards changes in aircraft capability that reduce the fuel burn per unit payload, and these include reduced range and increased payload capability. Conversely, the ICAO MV aims to reward only aircraft technology, not capability, and be transport capability neutral. This means that the MV is relatively insensitive to aircraft design changes that impact aircraft capability and also to the use of lightweight materials.[10] In other words, under the ICAO CO_2 standard, an aircraft’s fuel burn is only sensitive to its cruise fuel burn performance and relative mass, measured by MTOM.

9 Since this study focuses solely on new deliveries, the suspension of 737 MAX operations in 2019 does not affect the aircraft fuel efficiency trend analyzed.

10 The MV’s under-crediting of lightweighting is linked to the use of MTOM as a scaling factor to assign regulatory targets to individual aircraft types. All things held constant, a lighter airframe will burn less fuel than a heavy airframe, but will be required to meet a more stringent CO_2 intensity target because of its reduced MTOM. These effects partially cancel out.

Structural efficiency can be measured by OEW per unit RGF, which approximates the mass of the aircraft per unit floor area. A high value indicates a heavy (structurally inefficient) aircraft, and a low value indicates a relatively lightweight aircraft. Figure 4 plots the trend of structural efficiency from 1970 to 2019, which helps explain several trends seen in Figure 3.

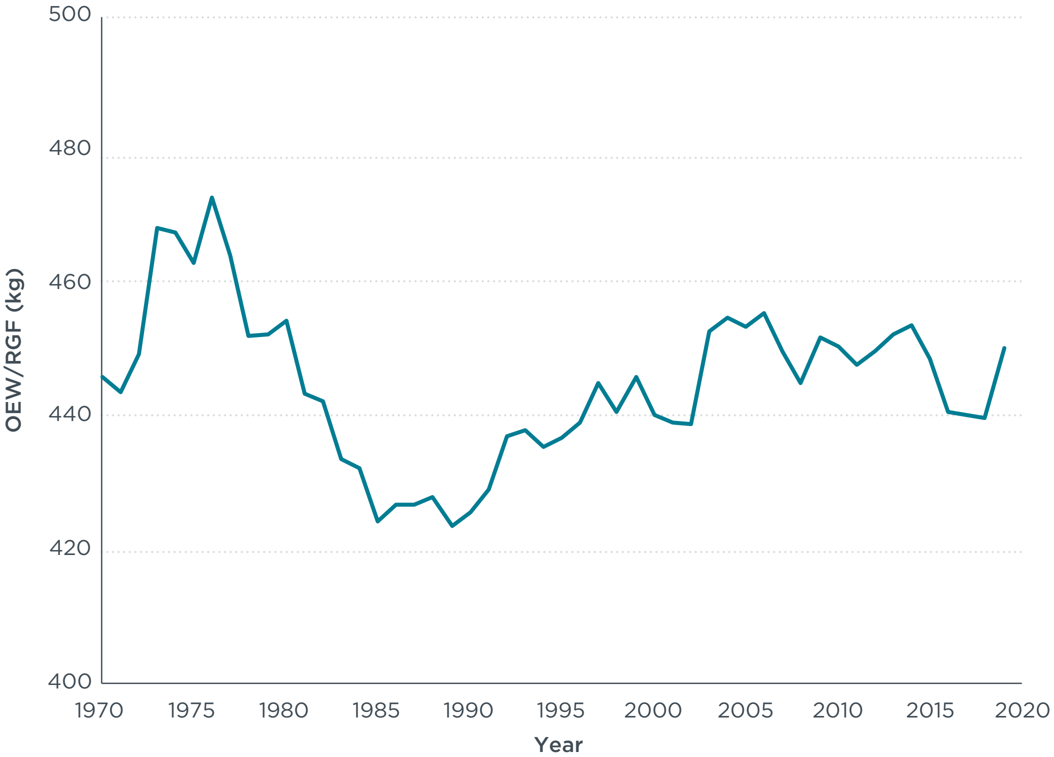

Figure 4. Trend in structural efficiency for new aircraft, as measured by OEW per unit RGF, 1970 to 2019.

First, the sharp increase in block fuel intensity from 1971 to 1975, with relatively little change in the MV, coincided with a sharp degradation in structural efficiency over the same period. This is linked to the sudden shift in sales from the newer 747-100 back to older narrowbody aircraft.

Subsequently, structural efficiency improved rapidly from 1975 to 1988. This coincided with a period when fuel/tonne-km improved more rapidly than the MV, and ultimately took the lead in reduction rates when normalized to 1970. This trend corresponds to the introduction of a cohort of new aircraft types with improved payload carrying capacity, including stretch variants like the Boeing 737-300 instead of the smaller 737-200; more capable derivative aircraft like the McDonnell Douglas MD-80 and Airbus A310 instead of the Douglas DC 9-34 and Airbus A300, respectively; and Boeing's introduction of the fuel-efficient 757 and 767 families. This illustrates how the fuel/tonne-km metric reflected the structural efficiency improvements during that period while the ICAO MV likely did not.

The average OEW per unit RGF then increased in the 1990s, indicating poorer average structural efficiency. This trend coincided with a decrease in stretch aircraft deliveries from 1990 to 2005 (Table 6).[11] Structural efficiency then remained relatively stable from the mid 2000s onward; during this period, the delivery of stretch designs increased and accounted for more than 25% of total new deliveries.

11 Stretch aircraft refers to variants of an existing aircraft type designed with a slightly larger fuselage, such as Airbus A321, A330-300, Boeing 737-900, 777-300, Embraer 190, and others.

Table 6. Share of stretch aircraft and regional jet deliveries by five-year intervals, 1985 to 2019.

Aircraft class	Share of total new deliveries						
	1985–1989	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019
Stretch aircraft	13%	22%	21%	12%	25%	30%	35%
Regional jet	4%	4%	16%	29%	20%	12%	10%

Table 6 also highlights a countercyclical trend of increases in the delivery of regional jets from 1995 to 2009. Since regional jets overlap with less fuel-efficient business jets in terms of size, they qualify for ICAO's weaker reference line below 60 tonnes MTOM. Accordingly, an increase in regional jet deliveries corresponds to disproportionately better fleetwide performance on the MV basis, even though block fuel intensity increases relative to larger aircraft classes.

A sensitivity analysis was conducted to test the effect of stretch aircraft and regional jets on both fuel burn metrics since 1987. The x-axis in Figure 5 shows the annual average MV over time, while the y-axis shows the average block fuel intensity for the same year. As above, both values are normalized to the 1970 average. The main trend in Figure 3 is shown in a solid blue line, while the same trend after excluding stretch aircraft and regional jets are shown as dotted red and green lines, respectively. The dashed black line at a 45-degree angle demonstrates the ideal case where improvement on one metric correlates perfectly with the other.

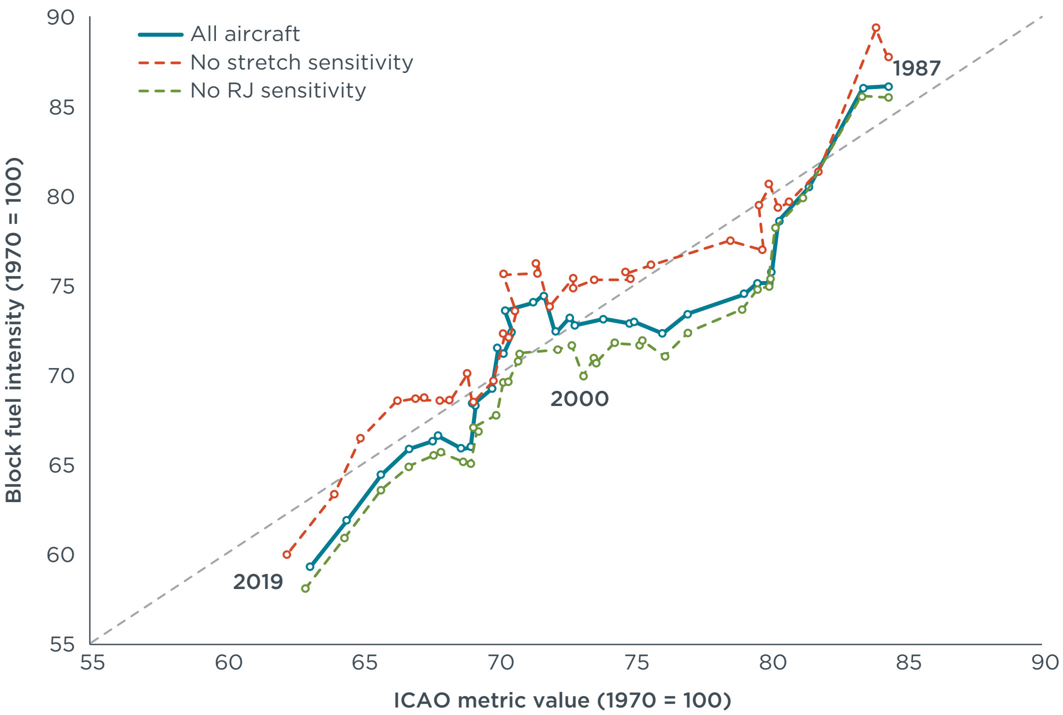

Figure 5. ICAO MV versus block fuel intensity, 1987 to 2019 (1970=100).

As shown, the MV and block fuel intensity metrics are well correlated, and generally follow the black dashed line with periodic deviations. The differences between the blue line and the dotted red line illustrate that stretch aircraft consistently boosted the improvement on the block fuel intensity metric but had minimal impact on the average MV. This occurs because stretched designs can extend the payload transport capability of the original model, and this usually outweighs the fuel burn penalty from increased mass. The gaps between the two metrics in the 1990s and 2010s can be mostly attributed to the stretch aircraft delivered.

The two metrics also behave differently when it comes to regional jets, as shown by the differences between the blue line and the dotted green line. Regional jets tend to perform worse on fuel/tonne-km than larger jet aircraft, but many of them perform well on ICAO MV. This can be explained by the fact that the ICAO reference line for aircraft with MTOM lighter than 60 tonnes is more lenient than that for aircraft heavier than 60 tonnes. The sensitivity analysis of regional jets shows that the average fuel/tonne-km would be lower and more closely aligned with the MV trend in the late 1990s and the 2000s without the regional jets delivered in those years. The rest of the fuel/tonne-km and MV trends remain relatively insensitive to regional jets, as their delivery share was lower in those time periods.

3.3 AVERAGE VERSUS NEW TYPE FUEL BURN

Several studies, including Penner et al. (1999) and Peeters and Middel (2007), assessed technological improvements by plotting the fuel/tonne-km of new types by EIS year. In order to better visualize the impact of new aircraft types on average fuel burn, Figure 6 is a bubble chart of aircraft types by EIS plotted against the MV trend shown in Figure 3. Each bubble represents a single aircraft variant with its MV normalized to the 1970 value (y-axis), plotted against its first delivery year (x-axis), and the size of each bubble represents its MTOM multiplied by the number of aircraft delivered for the first three delivery years for a given type. This approximates the fuel burn of the first three years of deliveries for a new aircraft type.

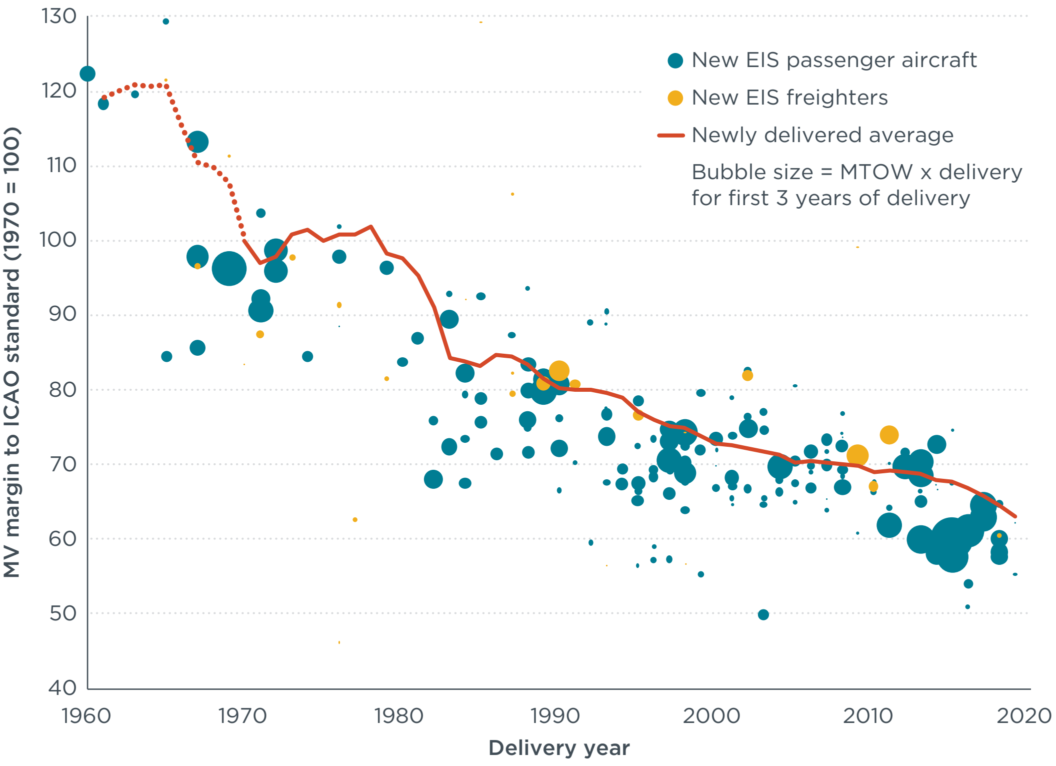

Figure 6. Normalized ICAO MV for commercial jet aircraft, newly delivered average and by entry into service year, 1960 to 2019.

Several trends can be seen in Figure 6. First, there is significant variation in metric values of different aircraft types introduced in a given year. For example, of the nine new aircraft variants introduced in 1998, the most fuel efficient, the Embraer ERJ145, outperformed the ICAO standard by 16%, and the least fuel efficient, the Tupolev Tu-204, exceeded the standard by 10%. Notably, from the 1980s to the early 2010s, there have always been newly introduced aircraft types with fuel burn higher than the in-production average. Since 2015, however, there have been fewer new types delivered, and all have had fuel burn lower than the average. This reflects ongoing airframer consolidation and the widespread diffusion of existing fuel efficiency technologies.

In addition, freighters (yellow bubbles) generally exhibited higher than average fuel burn than passenger aircraft (blue bubbles) when they entered into service, because they were usually introduced several years after the passenger version of the same aircraft type. For instance, the first deliveries of both the Boeing 777-200 and the Airbus A330-200 freighters were made more than 10 years after the passenger versions entered into service. While the passenger versions were leaders in fuel burn performance at the time of EIS, the freighter versions demonstrated fuel burn around the new delivery average. Nevertheless, some freighters were introduced in the same year as the passenger counterpart, such as in the cases of the Boeing 747, McDonnell Douglas MD-11, Douglas DC-10, and others. As new passenger aircraft models are introduced, earlier development and delivery of freighter versions can help improve the average fuel burn of the in-service fleet. Promoting the fuel burn reduction of dedicated freighters is important, because converted freighters will naturally be older and less fuel-efficient models, and there are limited options for reducing their fuel burn.

3.4 COMPARISON TO ICAO'S CO_2 STANDARD

The ICAO CO_2 standard will be phased in over time. It will apply to new designs entering into service starting around 2024 and to all new commercial and business aircraft produced from 2028 onward. An aircraft CO_2 standard directly rewards aircraft and engine manufacturers that develop and market more fuel-efficient aircraft and engines, more so than other policies aimed at pricing or offsetting greenhouse gas emissions from the in-service fleet. Understanding the performance of newly delivered aircraft in recent years in relation to the ICAO CO_2 standard can help evaluate the effectiveness of the standard, as currently structured, in promoting aircraft fuel burn reduction when it takes effect.

Figure 7 shows the average margin in terms of percent difference of newly delivered aircraft to the ICAO standard. Since the standard targets in-production rather than in-service aircraft, new EIS aircraft each year (blue dots) were also added for reference.

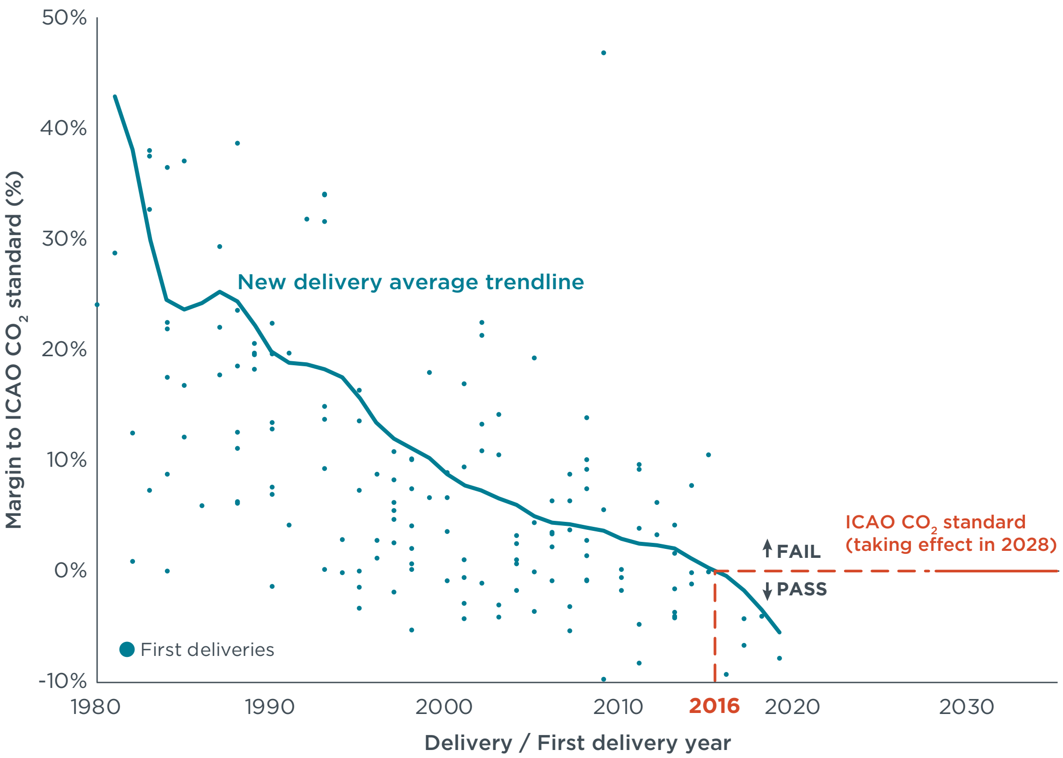

Figure 7. Average margin to ICAO's CO_2 standard for new aircraft, 1980 to 2019

Figure 7 puts the ICAO CO_2 standard into perspective. As shown by the red dashed line, the average new aircraft delivered in 2016, the year the standard was finalized, was already more fuel efficient than the standard. Moreover, in 2019, the average new aircraft delivered passed the standard by 6%. Some new types that entered into service in recent years pass the standard by significant margins, notably the Airbus A330-900neo at -15%, the Embraer E195-E2 at -18%, and the Bombardier CS100 at -25%. This illustrates how the CO_2 standard at its current stringency is unlikely to promote additional fuel burn reductions beyond what industry has already accomplished.

Stricter aircraft emission standards would encourage further innovation and adoption of fuel efficiency technologies. A timely adoption of a more stringent standard will be particularly relevant for new narrowbody aircraft development, as major manufacturers introduced re-engined narrowbody models in the late 2010s and are likely looking to create clean-sheet designs in the next round of development. Certain flexibilities in design, for example allowing manufacturers to meet the standard on average across all aircraft delivered in a year (averaging) or over time (banking), could also support more stringent targets. This can be seen by the fact that about 10% of aircraft delivered in 2019 failed the standard despite the average aircraft complying by a significant margin.

While the neutrality of MV to aircraft's transport capability makes it suitable for standard setting, it also comes with certain biases. Figure 8 plots the average margin of new EIS aircraft since 2000 to ICAO's CO_2 standard versus block fuel intensity.

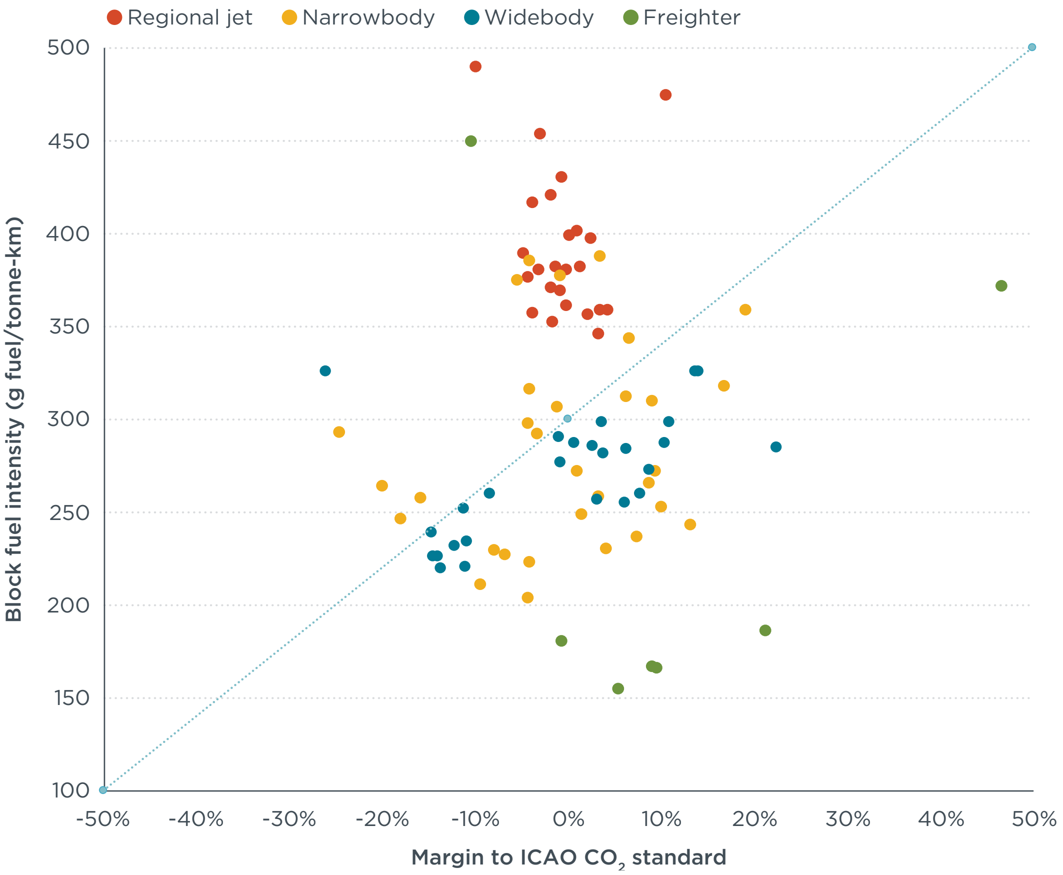

Figure 8. Margin to ICAO's CO_2 standard versus block fuel intensity of new aircraft by type for EIS 2000 to 2020 planes.

Regional jets (red dots) are generally more fuel intensive than narrowbody and widebody aircraft, but they nevertheless perform well on ICAO MV. This is because regional jets fall into a similar MTOM range as business jets, which are usually less fuel-efficient, and this MTOM group has a weaker ICAO reference line. The high fuel burn of regional jets is therefore masked by their margin to a lenient reference line. Indeed, previous ICCT research has shown that regional aircraft burn 60% more fuel than narrowbody and widebody jets per passenger-km (Graver, 2020). The clustering of regional jets around the ICAO reference line, moreover, highlights that fewer new designs have entered into service in recent years.[12]

On the other hand, the two fuel burn metrics correlate well for narrowbody and widebody aircraft, especially the latter. This is likely because widebody is the aircraft class with the longest cruise time compared to landing and take-off. This can be seen by the diagonal scatter of the data where, as an aircraft's margin to the standard increases, its modeled block fuel intensity also falls. Therefore, the ICAO standard better reflects actual in-service fuel burn for these larger jet aircraft.

12 Note that two new types manufactured by Embraer and Bombardier, the E-Jet E2 family and CSeries (now the A220), respectively, are classified as narrowbody aircraft in this work due to their large size.

4. CONCLUSIONS AND FUTURE WORK

This study highlights that average aircraft fuel burn, after stagnating from 1990 to 2005, decreased at a faster pace beginning in the late 2000s, and this continued through the 2010s. The rapid fuel burn reduction during the 1980s and in the most recent decade can be largely attributed to the introduction of various new, more fuel-efficient narrowbody and widebody aircraft.

However, as total CO_2 emissions from commercial aviation have increased alongside this reduction trend, it is important to consider whether the ICAO's CO_2 emissions standard that takes effect in 2028 is stringent enough to provide incentives for additional fuel burn reductions. According to this report, this is not the case. Moreover, research suggests that manufacturers could do even better. A comprehensive technology assessment found that the rate of fuel burn improvement for new aircraft could be accelerated up to 2.2% annually through 2034 if cost-effective technologies were adopted (Kharina, Rutherford, & Zeinali, 2016; Elliott, 2016).

The next few decades will be pivotal for managing the climate impact of aviation and, therefore, the fuel burn performance of the coming generation of aircraft. A meaningful CO_2 standard can be a critical lever for promoting fuel burn technology innovation and adoption beyond business as usual. Our analysis highlights that the current ICAO standard needs to be tightened in order to provide such incentives. Meanwhile, national governments should consider implementing more stringent domestic fuel efficiency standards, including ones that apply to in-service, rather than just new, aircraft (Graver & Rutherford, 2019).

Our analysis highlights in particular the value of incorporating flexibility mechanisms like averaging and banking into future standards. Pass/fail efficiency standards, such as those proposed by ICAO, require each individual aircraft type manufactured to pass minimum requirements in a given year. This kind of pass/fail design provides strong incentives for policymakers to set those standards around the worst, as opposed to the best, aircraft on the market. This can be seen from the fact that even though the average aircraft delivered in 2019 passed ICAO's standard by 6%, the least fuel-efficient 10% of aircraft delivered in 2019 still failed. If manufacturers were provided with flexible means to comply, either within their product mix (averaging) or over time (banking), more stringent standards could be established based upon emerging technologies.

Moreover, because the ICAO standard is designed to be transport capability neutral, its MV metric does not reward structural efficiency as evidently as a block fuel intensity metric does. Besides tightening the standard, additional measures could be considered to promote structural efficiency, in particular with regard to promoting the use of lightweight materials and efficient aircraft design. Differentiated landing fees based on the fuel burn of in-service aircraft are one potential incentive (Kharina & Rutherford, 2019). ICAO's segmentation of emission reference lines by MTOM also allows regional jets to be slightly favored by the MV, and this masks their higher fuel burn compared to larger jet aircraft. The large margins to the standard seen for regional jets suggests that their requirements could be strengthened in the next round of standard setting.

This update has highlighted further areas of possible refinement. Future research could expand this study to include general aviation aircraft, notably turboprops and business jets. A wider coverage of aircraft types could broaden our understanding of overall aircraft fuel burn trends. Further, a future update reassessing industry's progress towards ICAO's fuel burn technology goals would also be informative.

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