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Fuel burn of new commercial jet aircraft: 1960 to 2024

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SUMMARY

In 2022, the International Civil Aviation Organization (ICAO) codified an international goal for aviation to achieve net-zero carbon dioxide (CO_2) emissions in 2050. New, more fuel-efficient aircraft types with lower fuel burn are expected to contribute about one-sixth of emission reductions to the net-zero goal. The world's first fuel efficiency requirements for new aircraft, finalized by ICAO in 2016, took effect for new aircraft types in 2020 and will apply to all newly delivered aircraft, including models certified before 2020, starting in 2028. The effect of the standards on new aircraft fuel burn has not yet been analyzed.

This paper updates a 2020 ICCT study (Zheng & Rutherford, 2020) and analyzes the fuel burn trends from new commercial jet aircraft with data from 2020 to 2024. Aircraft fuel burn is assessed via two indicators: block fuel intensity in grams of fuel per tonne-kilometer and the CO_2 metric value (MV) developed by ICAO. The latter aims to provide a "transport capability neutral" means of regulating fuel burn.

From 1960 to 2024, about 46,000 new commercial jet aircraft were delivered globally, roughly equivalent to the number that manufacturers expect to deliver over the next 20 years. Using block fuel intensity in grams of fuel per tonne-kilometer and ICAO's carbon dioxide MV, the analysis finds that while average block fuel intensity for newly delivered aircraft decreased by 43% from 1970 to 2024, fuel efficiency improvements have stagnated since 2020. While a strong correlation exists between fuel burn per tonne-kilometer and ICAO's MV, differences arise because block fuel intensity better represents fuel burn for planes with larger payload capacity.

As of 2024, the average new aircraft exceeded ICAO's 2028 fuel burn standards by 8%. However, the number of active commercial jet manufacturers has decreased, and the variety of new aircraft types has sharply declined since 2020, limiting potential fuel burn improvements. To incentivize the development of more fuel-efficient aircraft to align with net-zero goals, ICAO member states can consider an in-production CO_2

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standard 15% below the existing 2028 standard at the organization's next Committee on Aviation Environmental Protection meeting.

INTRODUCTION

In 2022, the International Civil Aviation Organization (ICAO) codified an international net-zero carbon dioxide (CO_2) target for 2050. Meeting that ambitious goal will require substantial investments—on the order of $4 trillion for international flights alone—in clean fuels, fuel-efficient planes, and alternative aircraft designs (Mithal & Rutherford, 2023). Countries are now developing plans to meet those goals. National and regional policies, notably in the European Union, are starting to reduce emissions and foster new technologies that will be needed to meet the net-zero challenge.

Technology roadmaps detail the specific measures and technologies needed to meet the 2050 net-zero emissions goal, and based on a consensus technology pathway, fuel efficiency improvements are expected to provide about 30% of needed reductions, second only to clean aviation fuels (International Air Transport Association, 2024). While insufficient to meet net-zero alone, fuel efficiency improvements can help delay the year by which more nascent technologies such as zero-emission planes powered by hydrogen will be needed (Mukhopadhaya & Rutherford, 2022).

Improvements such as adding winglets and engine upgrades may yield slight efficiency increases in current aircraft models, but substantial reductions in fuel burn improvements often arise from entirely new "clean sheet" aircraft designs.[1] Historically, each new generation of aircraft has been approximately 15% better in terms of fuel burn than the aircraft they replaced. In recent years, manufacturers have transitioned to refining existing models with re-engine variants, such as the B737 MAX, A320neo, and A330neo, rather than developing clean sheet designs like the B787 or A350.[2] This trend restricts the application of modern aerodynamic, structural, and engine technology and explains the decrease in the annual rate of fuel efficiency enhancement. By increasing the development of new aircraft models with improved aerodynamics and lightweight materials, the fuel efficiency rate could potentially increase from 1% to 2.2% annually (Kharina, Rutherford, & Zeinali, 2016).

In 2016, ICAO's Committee on Aviation Environmental Protection (CAEP) finalized the world's first fuel efficiency standard for new aircraft at its 10th triennial meeting (CAEP/10). Under the standard, since January 1, 2020 all new-type (NT) certification applications have had to meet minimum fuel efficiency requirements for NT aircraft; starting January 1, 2028, all new in-production (InP) aircraft will have to meet a 4% less stringent standard.[3] Because it can take up to 5 years after an application is submitted for an aircraft to be fully certified, the NT standards can be considered to have fully taken effect at the start of 2025. To date, no aircraft have been certified to the NT standard. ICAO has begun work to update that standard (Lampert, 2022) and aims to agree to increased stringency at the CAEP/13 meeting in February 2025.

The ICCT published its first assessment of fuel burn trends from new aircraft in 2009 (Rutherford & Zeinali, 2009) and the study found that, even in the absence of a CO_2 or fuel efficiency standard, market forces create an incentive for new aircraft designs

1 For example, engine performance improvement packages that include combustor improvements can reduce the fuel burn of aircraft by 2%–3%.

2 Re-engined designs have lower fuel burn because the engines are new. However, as they rely upon an older fuselage, they largely potential fuel-efficiency improvements from advancements in aerodynamic and structural efficiency.

3 The InP aircraft targets are less stringent than the NT standards because a broader range of fuel efficiency technologies can be integrated into NT designs. Aircraft can also be voluntarily certified to the standard; as of the time of this writing, only one aircraft has such been certified; the A330-900 aircraft, which passes the 2028 InP standard by between 9% and 10%.

to have about 15% lower fuel burn than the older designs they replace. Subsequent analysis showed that, over time, the introduction of these NT aircraft reduced the average block fuel (the total fuel required for a given flight) of new aircraft by 1.3% per annum from 1960 to 2019 (Zheng & Rutherford, 2020). Moreover, the average new aircraft delivered in 2019 already passed the ICAO standard by 6% (Zheng & Rutherford, 2020). As ICAO works to update its standard, newer data is needed to understand how much aircraft have improved since the standard was finalized.

Previous analysis of the CO_2 standard focused on the stringency of InP aircraft and not on NT aircraft for several reasons (Rutherford & Kharina, 2017). Because manufacturers choose when to develop a new aircraft type, the NT requirements are best understood as a voluntary requirement triggered at a time of a manufacturer's choosing. Second, a poorly designed NT standard has the potential to impede, rather than promote, new aircraft types with lower fuel burn. This is because if the CO_2 target required exceeds that which can be delivered with available technology, the manufacturer might abandon an NT completely and continue to deliver InP aircraft with higher emissions. Thus, in the long run, a stringent InP standard applied to all newly delivered aircraft is most likely to result in the highest reduction in emissions.

In total, about 46,000 new commercial jet aircraft were delivered from 1960 to 2024. That's about the same number (44,000) that manufacturers expect to deliver over the next 20 years, despite having committed to the 2050 net-zero CO_2 goal (Insinna, 2023). For airlines to achieve net-zero CO_2 emissions in 2050, research has shown that all new aircraft will need to be zero-emission throughout their operational lifetimes starting around 2035 (Kumar & Rutherford, 2024). Fuel efficiency improvements from conventional aircraft will also play a role in the transition, as will the use of alternative fuels, including 100% sustainable aviation fuels (SAF) in all combustion engine aircraft, hydrogen, and some electricity.

This paper assesses how much the average fuel burn of new aircraft has decreased since 2020.

METHODS

The data we analyzed for the annual deliveries of new commercial jet aircraft from 1960 to 2014 were purchased from Ascend Online Fleets.[4] For the trend analysis over this period, 35,985 passenger aircraft with 20 seats or more were extracted from a total of 65,965 aircraft present in the Ascend database. Deliveries from 2015 to 2019 were obtained separately from the Airline Monitor Database (Airline Monitor, 2020), and data from 2020 to 2024 were collected from IBA Insight's Fleet Module (IBA Insight, 2024). Together, these sources provide a comprehensive delivery history of both passenger and freight aircraft from 1960 to 2024.

Actual IBA delivery data was used for aircraft deliveries through July 2024, when this analysis was conducted. Projected deliveries from August to December 2024 were adjusted based on the latest publicly available information from manufacturers. Airbus deliveries were scaled down based on its June 2024 announcement, which indicated 770 expected deliveries for the year (Airbus, 2024b), and Boeing 737 MAX deliveries were scaled down to the monthly delivery rate observed in July 2024 (31 aircraft) to account for ongoing delays in delivery schedules (Boeing, 2024).

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

All delivery data were compiled at the aircraft series level and, when applicable, further categorized by maximum takeoff mass (MTOM) variants based on delivery patterns from 2010 to 2024. The delivery data were further classified into four major aircraft classes:

» *Regional jet*: Aircraft with fewer than 100 seats that are designed for short- to medium-haul flights.[5]

» *Narrowbody*: Also referred to as single-aisle aircraft, these smaller aircraft are commonly used for short-haul domestic and international flights, with passenger capacities ranging from 100 to 300.

» *Widebody*: These large twin-aisle aircraft feature wide fuselages and are built for long-haul travel, transporting large numbers of passengers and goods across great distances.

» *Freighters*: These fixed-wing aircraft are built or modified to transport cargo rather than passengers.[6]

Table 1 summarizes the manufacturers and aircraft deliveries included in the database used for this analysis. Approximately 46,000 new commercial jet aircraft were delivered from 1960 to 2024. As shown, more than three-quarters (78%) of these were built by just two companies, Boeing and Airbus. These manufacturers, along with Douglas (which merged with McDonnell in 1967 and later with Boeing in 1997), have built a variety of aircraft types, including narrowbody, widebody passenger, and freighter. Two other manufacturers, Embraer and Bombardier, held a duopoly on the regional jet market. Together, these five companies delivered almost 95% of all commercial jet aircraft over the period studied.

Table 1
Commercial aircraft deliveries by manufacturer and aircraft class, 1960–2024

<table>
<tr><th rowspan="2">Manufacturer</th><th rowspan="2">Number of deliveries</th><th rowspan="2">% of total</th><th colspan="4">Aircraft classes delivered</th></tr>
<tr><th>Regional jet</th><th>Narrowbody</th><th>Widebody</th><th>Freighter</th></tr>
<tr><td>Boeing</td><td>20,303</td><td>43.6%</td><td rowspan="3"></td><td rowspan="3">✓</td><td rowspan="3">✓</td><td rowspan="3">✓</td></tr>
<tr><td>Airbus</td><td>15,796</td><td>34.0%</td></tr>
<tr><td>Douglas</td><td>2,883</td><td>6.2%</td></tr>
<tr><td>Embraer</td><td>2,760</td><td>5.9%</td><td>✓</td><td>✓</td><td></td><td>✓</td></tr>
<tr><td>Bombardier</td><td>1,812</td><td>3.9%</td><td>✓</td><td></td><td></td><td>✓</td></tr>
<tr><td>Tupolev</td><td>845</td><td>1.8%</td><td></td><td></td><td>✓</td><td>✓</td></tr>
<tr><td>Fokker</td><td>432</td><td>0.9%</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>Ilyushin</td><td>386</td><td>0.8%</td><td></td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>BAe</td><td>370</td><td>0.8%</td><td>✓</td><td></td><td></td><td>✓</td></tr>
<tr><td>Lockheed</td><td>248</td><td>0.5%</td><td></td><td></td><td>✓</td><td></td></tr>
<tr><td>SCAC</td><td>232</td><td>0.5%</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>Comac</td><td>229</td><td>0.5%</td><td>✓</td><td>✓</td><td></td><td></td></tr>
<tr><td>Yakovlev</td><td>178</td><td>0.4%</td><td></td><td></td><td>✓</td><td>✓</td></tr>
<tr><td>Antonov</td><td>48</td><td>0.1%</td><td>✓</td><td>✓</td><td></td><td>✓</td></tr>
<tr><td>Total</td><td>46,522</td><td>100.0%</td><td></td><td></td><td></td><td></td></tr>
</table>

5 The E190/E195 aircraft are classified as narrowbody because their seating capacity of up to 132 passengers exceeds 100 seats.

6 Throughout this document, "freighter" results refer to the combined categories of regional jet, narrowbody, and widebody aircraft used to transport freight.

Piano 5.3, an aircraft performance and emissions model with an extensive database of commercial aircraft designs, was used to model aircraft fuel burn (Lissys Limited, 2020). From the 798 distinct aircraft-engine type combinations extracted from the Ascend database, 655 were matched with 161 representative Piano aircraft models based on aircraft type, engine type, and maximum takeoff mass. This approach covered 89% of deliveries from 1960 and 93% of deliveries from 1968 onward. All 16 new commercial passenger aircraft models delivered from 2015 to 2019 were successfully matched to representative Piano models, as were five aircraft models introduced between 2020 and 2024. Due to high uncertainty and low matching rates before 1970, trends prior to that year should be treated with caution and the results below focus on trends from 1970 onward.

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 2024 were matched. For dedicated freighter types that had no representation in the Piano database, operating empty weight adjustments were made to the parent passenger aircraft by subtracting 50 kg per missing seat (ICAO, 2019).

Table 2
Piano matching rate by aircraft class

<table>
<tr><th>Decade</th><th>Passenger aircraft</th><th>Dedicated freighters</th></tr>
<tr><td>1960s</td><td>32%</td><td>71%</td></tr>
<tr><td>1970s</td><td>63%</td><td>96%</td></tr>
<tr><td>1980s</td><td>94%</td><td>77%</td></tr>
<tr><td>1990s</td><td>97%</td><td>88%</td></tr>
<tr><td>2000s</td><td>98%</td><td rowspan="3">100%</td></tr>
<tr><td>2010s</td><td rowspan="2">100%</td></tr>
<tr><td>2020s</td></tr>
</table>

FUEL BURN METRICS

This study follows the same methodology as our prior study (Zheng & Rutherford, 2020) to evaluate the fuel burn of newly delivered aircraft using two key metrics: block fuel intensity, measured as fuel consumed per tonne-kilometer (fuel/tonne-km), and ICAO's CO_2 metric value (MV). Zheng and Rutherford (2020) found that these two metrics are well correlated, and we present both because they provide somewhat complementary information, as detailed below.

BLOCK FUEL INTENSITY

The fuel/tonne-km metric is comparable to the fuel/passenger-km metric used in Zheng and Rutherford (2020), where fuel burn is calculated from the departure gate to the arrival gate, referred to as block fuel. Unlike the MV, the fuel/tonne-km metric accounts for fuel consumed during all phases of flight, including taxi, takeoff, cruise, approach, and landing. It also adjusts for changes in aircraft capability, such as payload capacity and range, which influence fuel efficiency.[7]

7 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.

This analysis focuses on fuel burn for newly delivered aircraft, independent of airline-specific operational practices. To control for variations in seat configurations across different airlines, standardized seating densities were applied for each aircraft type. Global average seating density, derived from the Ascend database, was calculated by dividing the number of seats by the estimated reference geometric factor (eRGF) for each aircraft type (Table 3).[8] The default eRGF for each Piano aircraft was then multiplied by these standardized seating densities to compute adjusted seat counts. The adjusted seat counts were then used to model payload and to adjust the operating empty weight of each matched Piano aircraft model by 50 kg per seat when it differed from the Piano standard seat counts.[9]

Table 3

Seat density assumptions used in modeling by aircraft class

Class	Seat density
Regional jet	1.27
Narrowbody	1.48
Widebody	1.05

Note: Seat density was derived by dividing the number of seats by the estimated reference geometric factor.

Block fuel was modeled using Piano over nine different payload-range test points selected from each aircraft's payload-range diagram to simulate real-world operations. Passenger aircraft test points, outlined in Table 4, are based on global operations data from 2010 (Rutherford, Kharina, & Singh, 2012). For dedicated freighters, the test points were derived from 2018 global operations data (Graver, Zhang, & Rutherford, 2019), with the same scale of low and high bounds used for passenger aircraft applied to the midpoint.

Table 4

Range and load factors used in block fuel intensity modeling by aircraft class and application

Application	Class	Range (R_{max})[a]			Load factor[b]		
		low	mid	high	low	mid	high
Passengers	**Regional jet + Narrowbody**	18%	25%	39%	70%	82%	93%
	Widebody	26%	34%	51%	73%	83%	93%
Dedicated freight	**Regional jet + Narrowbody**	20%	28%	43%	42%	49%	56%
	Widebody	39%	51%	76%	43%	49%	55%

[a] Maximum range at 50% maximum structural payload, which is maximum zero fuel weight minus operational empty weight
[b] Load factor for passenger aircraft is the percentage of available seats, while for freighters it is the percentage of maximum structural payload

Stage length, or flight distance, was calculated as a percentage of an aircraft's range at 50% of its maximum structural payload. Payload was estimated at 100 kg per passenger (including baggage) per ICAO (2019). Passenger flights assumed no belly

8 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.

9 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 (e.g., 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% (e.g., Airbus A380-800s).

freight. Aircraft were simulated at cruise speeds optimized for 99% specific air range. Fuel reserves and allowances included a 370 km diversion distance, 30 minutes of holding time, and 5% contingency fuel for all aircraft under the block fuel intensity metric. Taxi-in and taxi-out times were based on average 2010 U.S. operations: 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.

Table 5
Key modeling parameters for the block fuel intensity analysis

Parameter	Description
Range	Operational ranges at 50% maximum structural payload
Payload	Operational payloads (percentage of seats filled or percentage of maximum payload)
Seating density	Standardized seat counts by aircraft type
Flight levels	Optimal flight level between 27,000 ft and aircraft service ceiling
Cruise speed	99% max specific air range
Taxi time	U.S. Bureau of Transportation Statistics 2010 average by aircraft type (12 min for regional jet and single-aisle, 15 min for twin-aisle)
Holding time	30 min
Diversion	370 km
Reserve	5% mission fuel

For each year's average fuel burn, the average fuel burn trend was estimated by using the weighted average of each metric of all aircrafts delivered each year. The performance index for the fuel/tonne-km metric was weighted annually according to the number of aircraft delivered and their estimated block fuel consumption during the first year in service. Total block fuel for the first year was calculated assuming 3,033 operating hours annually for short-haul and regional jets and 4,155 hours for long-haul aircraft (Rutherford, Kharina, & Singh, 2012).

To compare with ICAO's MV, fuel/tonne-km was normalized to the 1970 baseline (1970=100). The 1970 benchmark was chosen due to sufficient coverage and representativeness of the data. Coverage for passenger aircraft delivered during the 1960s is below 50% and thus comes with more uncertainty. Moreover, the introduction of the Boeing 747-100 widebody aircraft in 1969 created a noticeable shift in fuel burn averages, as prior years only saw narrowbody aircraft deliveries.

Although some aircraft models improve fuel efficiency slightly over their production cycle, the ICCT's 2020 study found that new delivery trends are generally unaffected by these incremental improvements. Therefore, this paper assumes that the fuel burn of each aircraft type remains constant throughout its production lifespan. The COVID-19 pandemic resulted in considerable interruptions to aircraft deliveries and operations in 2020 and 2021. Although these interruptions may have momentarily influenced the fuel burn trend by shifting the mix of aircraft classes delivered, the results below show that the sector has predominantly reverted to pre-pandemic norms in the subsequent years.

ICAO'S METRIC VALUE

The MV was developed by ICAO's CAEP to create a CO_2 emission standard for new aircraft (Rutherford & Kharina, 2017; ICAO, 2013). Unlike the fuel/tonne-km metric, the MV focuses solely on cruise performance and does not include phases such as takeoff, climb, and landing.

The MV is calculated using the following formula:

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

where SAR (specific air range) represents an aircraft's cruise fuel efficiency and RGF is a proxy for usable space in an aircraft, based on the dimensions of its pressurized fuselage. The specific air range is averaged across three weight test points representing typical payload and fuel conditions at heavy, light, and average combinations.

Because MV is sensitive to both cruise fuel burn and aircraft size, ICAO assigns a fuel burn target (MV limit) based on the aircraft's maximum takeoff mass. Therefore, an aircraft's fuel efficiency is compared with a reference standard.

RESULTS

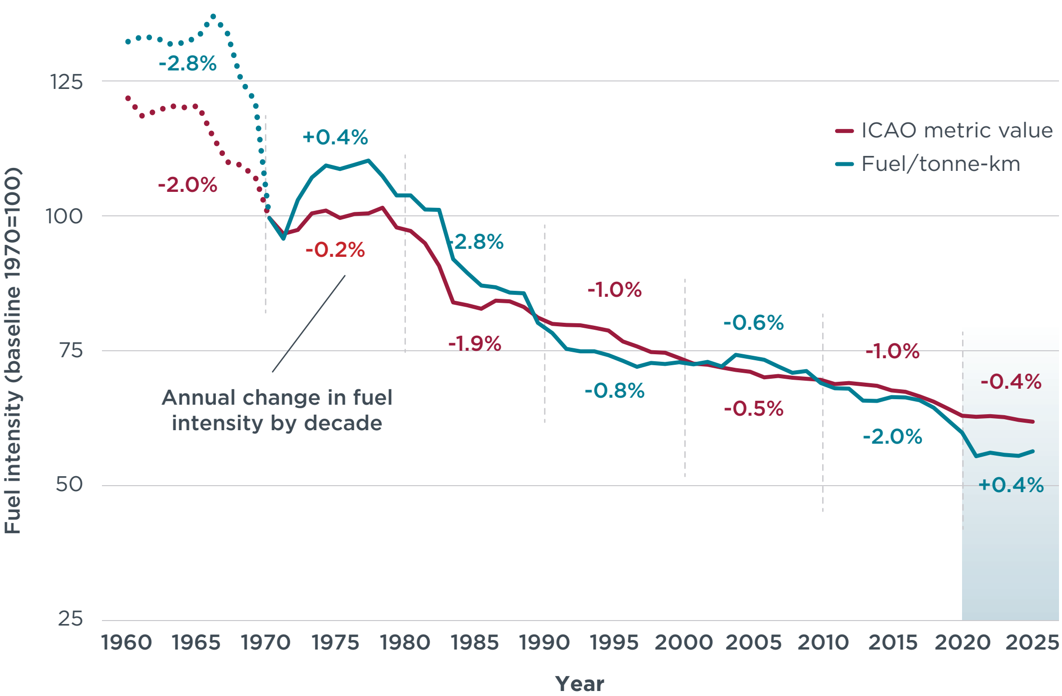
The methodology described above was used to model average new aircraft fuel burn from 1960 to 2024. The primary outcomes highlight historical trends according to both fuel burn metrics, a comparison between the two, and the fuel efficiency of new aircraft delivered each year. Additionally, we compare the fuel burn trends with ICAO's CO_2 standard to assess its potential to encourage further improvements in fuel efficiency.

HISTORICAL TREND OF NEW AIRCRAFT FUEL BURN

Figure 1 illustrates the estimated fuel burn of newly delivered aircraft from 1960 to 2024 using ICAO's MV (red line) and fuel/tonne-km (blue line), both normalized to the 1970 baseline. The dotted lines represent the improvements before 1970, which are more volatile due to a limited number of aircraft types prior to the introduction of the widebody 747 family. The shaded grey area represents the gradual implementation of the ICAO CO_2 standard, which began in 2020.

Figure 1

Fuel burn trends for new commercial jet aircraft, 1960–2024



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From 1970 to 2024, the average fuel burn of newly delivered jet aircraft decreased by about 43%, averaging about 1% reduction annually in terms of the block fuel intensity metric. Over the full study period (1960–2024), the annual reductions averaged 1.4% for block fuel intensity and 1% for ICAO's MV. The ICAO MV, which aims to be "transport capability neutral," is less sensitive to changes in the delivery mix than the block fuel metric, which scores freighters well and regional jets poorly (Zheng & Rutherford, 2020). Accordingly, we present the ICAO MV trends in later sections.

No single reference year is ideal for this analysis, as fuel burn initially dropped in the early 1970s due to the introduction of the Boeing 747 and then fluctuated in the following decade. Fuel burn decreased quickly during the 1980s due to the entry into service of more efficient aircraft like the Boeing 757, 767, and Airbus A320, but stagnated from 1990 to 2005 because of the continued production of older aircraft types. Fuel burn reductions picked up again after 2010 with the introduction of newer models like the Boeing 787, Airbus A350, and re-engine jets like the A320neo and 737 MAX.

The trend in fuel burn reduction continued until 2019 but was disrupted between 2020 and 2024 by the pandemic, which reduced aviation activity and accelerated a shift toward deliveries of narrowbody aircraft and away from widebodies and regional jets (see below). After 2020, almost no reductions in average fuel burn were observed because of a dearth of new, more fuel-efficient aircraft types.

COMPARISON WITH ICAO'S CO_2 STANDARD

The ICAO CO_2 standard is being implemented gradually. It began with applications for new aircraft designs starting in 2020 and derivative aircraft types in 2023; it will be extended to all new commercial and business aircraft produced from 2028 onward. This standard is intended to directly incentivize aircraft and engine manufacturers to develop more fuel-efficient technologies. Analyzing the fuel efficiency of recently delivered aircraft in relation to the CO_2 standard provides insight into how well the standard will promote fuel burn reduction.

Figure 2

Average margin to ICAO's CO_2 standard for new aircraft, 1980–2024

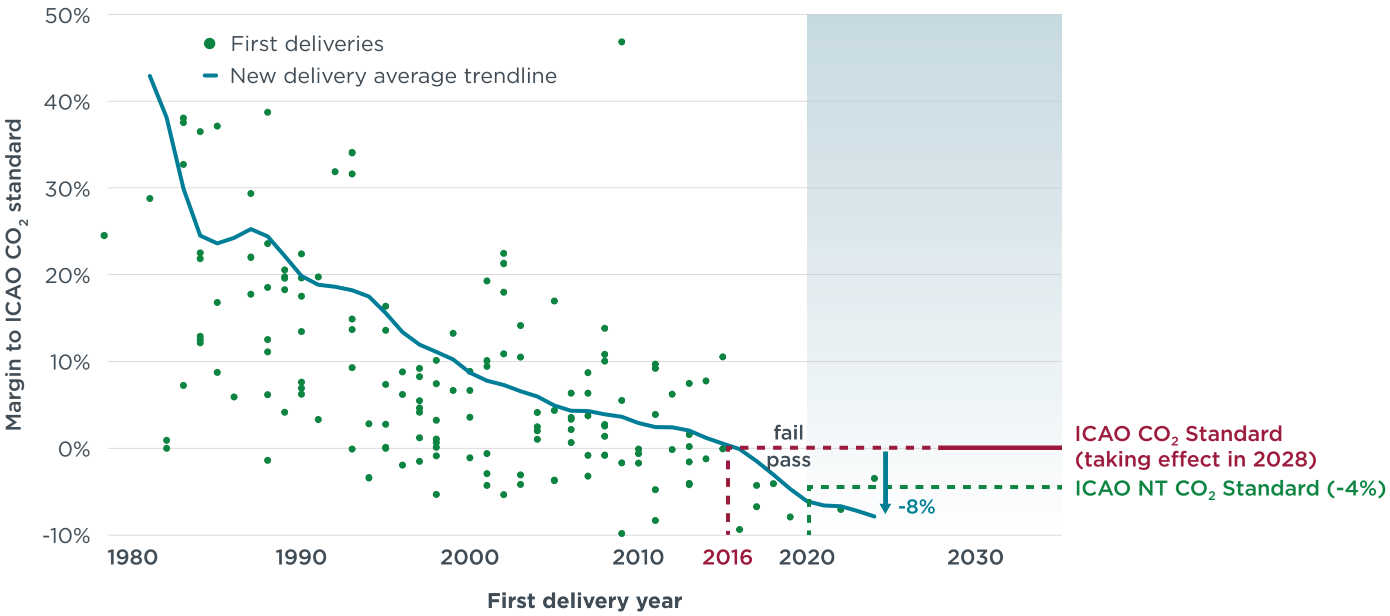

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Figure 2 illustrates the performance of newly delivered aircraft against the ICAO CO_2 standard. By 2016, the average aircraft delivered was already 6% more fuel efficient than the finalized InP standard. The shaded grey area indicates the gradual implementation of the standard starting in 2020, with the stricter NT version that is 4% below the main requirement for new designs aimed at further improving fuel efficiency before full implementation in 2028.

By 2024, new aircraft exceeded the standard by an average of 8%, meaning the emissions were 8% lower than the standard. Certain models surpassed it by large margins, such as the Bombardier CS100 (-25%), Embraer ERJ-135 (-18%), Airbus A350-900 (-17%), and Comac C919 (-12%). However, the new variant of the Airbus A321XLR, set for launch in late 2024, shows only a 3% margin with the 2028 standard.[10] The A321XLR's focus on extended range for medium- to long-haul routes adds weight due to additional fuel capacity and structural reinforcements and thus makes it less efficient than other newer models. This demonstrates the challenge of balancing range capability and emission reductions.

Approximately 5% of passenger aircraft delivered in 2024 did not meet the standard, and this underscores the limitations of the standard in compelling across-the-board improvements. Stricter standards are necessary to encourage more innovation, especially as manufacturers focus on the development of clean sheet narrowbody designs (Insinna, 2023). Flexibility in compliance, such as allowing manufacturers to average emissions across their fleet or over time, could help support more stringent targets.

Figure 3 illustrates how the mix of aircraft deliveries has shifted from 1960 to 2024 in 5-year intervals. It shows that the aircraft market experienced a significant shift in the relative share of aircraft types. Narrowbody aircraft such as the Boeing 737 and 757 and Airbus A320 dominated deliveries throughout this period due to their versatility and efficiency on short- and medium-haul routes. Widebody jets like the Boeing 747, 777, and Airbus A330 grew in the 1970s and maintained a stable market for long-haul flights. Regional jets peaked in the early 2000s with a market share of almost 30% due to models like the Canadair CRJ and Embraer E-Jet and later declined. New freighters, including cargo versions of widebody aircraft, were only 4% of total deliveries across the entire period.[11] By 2024, narrowbody aircraft accounted for nearly 78% of all deliveries.

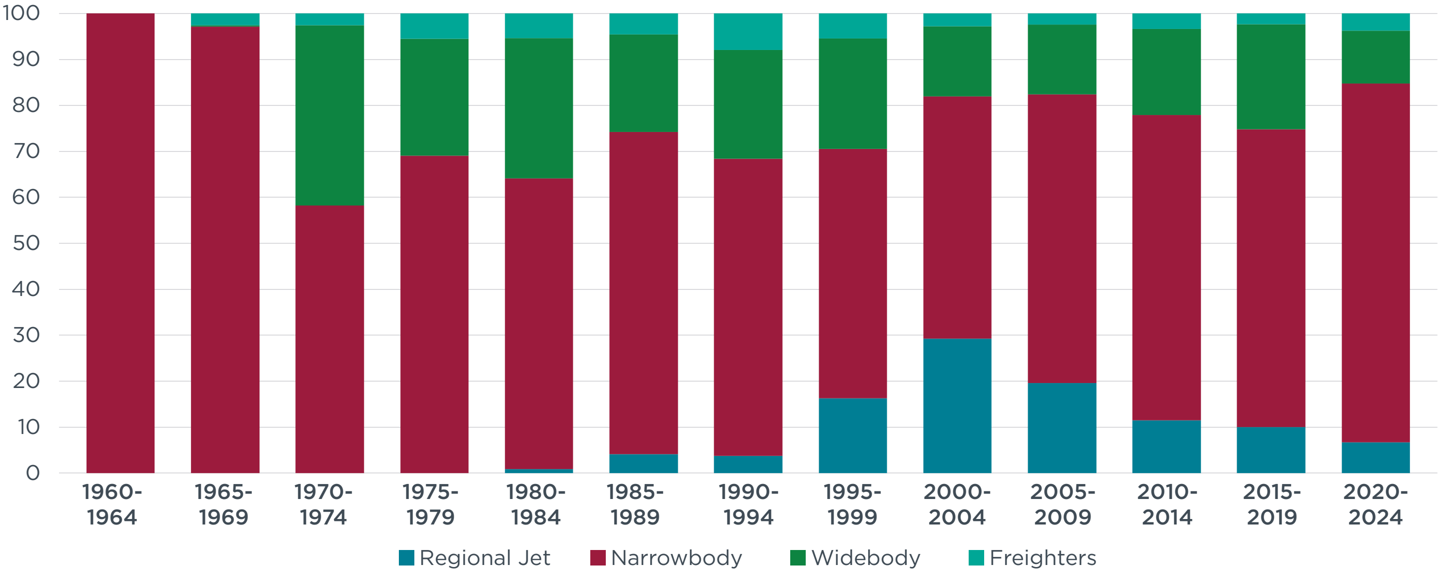
This shift indicates that narrowbody aircraft are significant for future fuel efficiency improvements. It also helps explain the divergence between the block fuel metric, which regional jets score poorly on, and the MV metric, which they score relatively well on, after 2017.

10 That means that the A321XLR would fall short of the NT CO_2 standard that took effect in 2020. However, as a variant of the already certified A321, it was not certified to the NT standard.

11 Passenger-to-freighter conversions, where a widebody or narrowbody passenger aircraft is converted to freighter service after being retired from passenger use, is also an important source of freighters. Because that occurs after a new aircraft is delivered to an airline, these conversions are outside the scope of this work.

Figure 3

Share of new deliveries by aircraft class, 1960–2024



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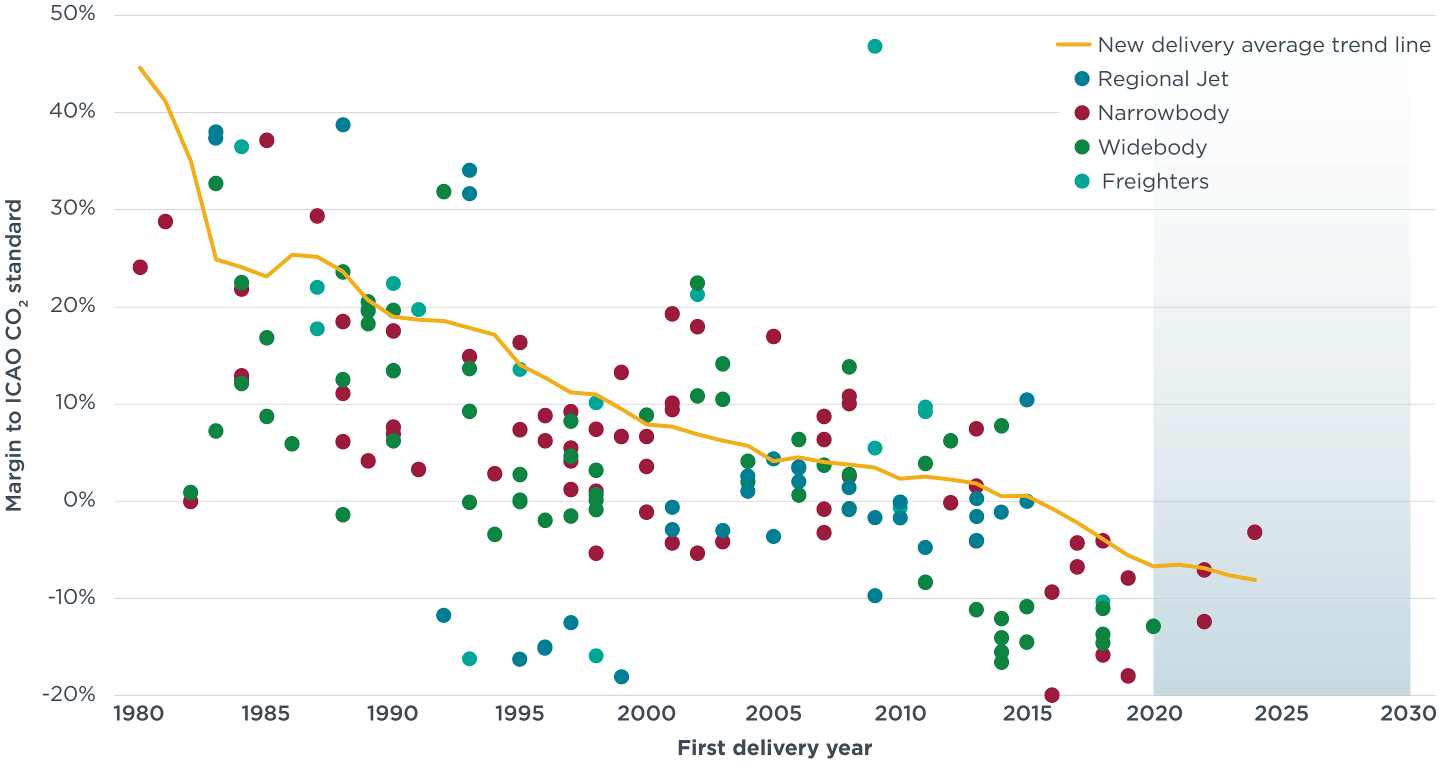
AVERAGE VERSUS NEW TYPE FUEL BURN

The chart in Figure 4 provides a visualization margin relative to the CO_2 standard of different aircraft types, plotted against their entry-into-service year. Each dot represents a specific aircraft variant, with its margin to the ICAO CO_2 standard shown on the y-axis and its first delivery year on the x-axis. The different symbols represent various aircraft types. The trend line illustrates the overall average for new deliveries in terms of CO_2 emissions.

Figure 4

Margin to ICAO CO_2 standard for new types, by aircraft class



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Within a given year, aircraft types show a broad range of MVs and this influences the overall average trend shown by the yellow line. However, certain types contribute more significantly due to a larger number of deliveries or larger size. Initially, regional jets like the BAe 146 exhibited higher fuel burn, but by the 2020s, more efficient models like the Embraer ERJ 170 and ERJ 190 STD began exceeding ICAO's 2028 standard. Although narrowbody types started with higher margins to the standard, they showed greater variability in fuel efficiency over time and by 2020, both narrowbody and regional jet aircraft closely aligned with the ICAO standard, which reflects technological improvements. Likewise, widebody aircraft initially showed higher fuel burn values but improved significantly over time and converged with the standard by the 2010s. Recent widebody models like the Airbus A330neo and A350 outperform the standard and demonstrate up to 13% better fuel efficiency. These advancements in widebody aircraft highlight the industry's progress in optimizing larger, long-haul aircraft for lower fuel burn. Typically introduced after and in service for longer than their passenger counterparts, freighters demonstrated higher fuel burn values but still followed the overall trend. This suggests that additional efforts to promote the fuel efficiency of dedicated freighters is needed.

Historically, new aircraft models show improvements in fuel efficiency, generally surpassing average fleet performance by approximately 10 years. By 2024, the fleet's average fuel efficiency effectively matched the fuel efficiency levels achieved by new models in the late 2010s, reflecting substantial improvements across all categories, especially in accordance with ICAO's 2020 CO_2 regulations. Nevertheless, the limited introduction of new models post-2020 restricts the potential for additional fleet-wide efficiency enhancements. In previous decades, new narrowbody and widebody aircraft types were steadily introduced, and so the recent slowdown in NT development is atypical (Figure 4). This underscores that targeted efforts could encourage the development of new aircraft types to drive continued fuel-efficiency progress. The deceleration in new aircraft types also highlights how policy-driven incentives or innovations are likely to be vital to maintaining and improving fuel-efficiency advancements, particularly for fuel-intensive widebody aircraft crucial for long-haul operations.

Further evidence of the importance of NTs is in Table 6, which summarizes trends in new aircraft manufacturing from 1960 to 2024 in terms of the number of active manufacturers, the number of aircraft delivered, the number of NTs, and the share of deliveries that are NT aircraft in each 5-year period. Annual fuel burn reductions on both the block fuel burn and ICAO MV indicators are shown at far right.

Table 6
Trends in fuel burn and new commercial aircraft manufacturing, 1960–2024

Period	Number of manufacturers	Aircraft delivered	New entry-into-service types	Share of new entry-into-service type deliveries	Annual change in fuel burn	
					Block fuel	Metric value
1960–1964	2	146	3	0%	+0.1%	-0.2%
1965–1969	3	1,342	9	73%	-5.6%	-3.7%
1970–1974	6	1,292	9	34%	+1.8%	0.0%
1975–1979	8	1,610	8	5%	-0.9%	-0.5%
1980–1984	9	2,034	14	22%	-3.4%	-3.1%
1985–1989	10	2,408	21	26%	-2.1%	-0.7%
1990–1994	10	3,803	21	20%	-1.3%	-0.8%
1995–1999	11	3,692	32	42%	-0.2%	-1.1%
2000–2004	9	4,877	24	14%	+0.2%	-0.7%
2005–2009	7	5,125	26	15%	-1.5%	-0.3%
2010–2014	8	6,372	23	18%	-0.5%	-0.4%
2015–2019	8	8,212	17	33%	-3.5%	-1.4%
2020–2024	7	5,609	4	1%	+0.4%	-0.4%
Total or average	**11**	**46,522**	**211**	**—**	**-1.31%**	**-1.04%**

As indicated in the table, the number of active commercial jet aircraft manufacturers increased from 2 to 11 from the early 1960s to the late 1990s, before falling to 7 in 2024. Deliveries increased much more rapidly (56-fold), reaching over 8,200 aircraft delivered in the 5-year period before the pandemic. The number of NTs, meanwhile, peaked in the late 1990s and began to fall afterward. Only four NTs (A330-800neo, Comac C919 B, Comac C919 ER, and A321 XLR) have been brought into service since 2020, and post-2020, almost all (99%) deliveries were of aircraft types that had been certified prior to 2020. The rate of fuel burn reduction for new aircraft varied from 1% to 1.4% per year over the period and has largely stagnated since 2020 due to the low number of NTs.

Beyond the 777X, Boeing has announced its intention to not produce any NTs until the mid-2030's (Chokshi, 2024). Airbus recently certified the A320XLR (Airbus 2024a), an extended range version of the A321neo, but does not plan to certify a successor to the A320neo family until after 2035 (Flottau & Osborne, 2023). Embraer, recognized for its regional jets, has slowed down the rollout of new models and emphasized incremental developments to improve the fuel efficiency in its existing E-Jet (E195-E2, E190-E2, and E175) series (ASD News, 2024). Bombardier, having withdrawn from the commercial aircraft sector, is now prioritizing the reduction of emissions in its current series of long-range business jets (Taylor, 2021). Thus, the trend of fewer NT aircraft and falling fuel burn improvements is likely to continue for the next decade without policy support.

CONCLUSIONS AND POLICY IMPLICATIONS

Improving the fuel burn performance of the coming generation of aircraft will be pivotal for managing the climate impact of aviation and achieving aviation's net-zero emissions goal (Kumar & Rutherford, 2024). This paper highlights a significant reduction in average aircraft fuel burn since the late 1980s, driven primarily by the introduction of more fuel-efficient narrowbody and widebody aircraft. However, we also find that some of the newest and most popular aircraft, including the B787-9, B787-8, A320neo, and A330neo, already exceed ICAO's 2028 CO_2 emission standard by 9%–11%. As the average new aircraft achieved an 8% margin with the standard in 2024, the ICAO Environmental Committee CAEP/13 meeting in February 2025 will need to propose stricter standards that promote new-type (NT) aircraft, if the standards are to further improve the fuel burn of new deliveries.

In particular, as manufacturers have signaled that they do not plan to develop new narrowbody types until the mid-2030s, additional fuel efficiency gains will hinge on encouraging the development of additional NTs across various categories. Research suggests that fuel burn reductions up to 2.2% annually through 2034 are possible if all cost-effective technologies are embraced (Kharina, Rutherford, & Zeinali, 2016). A more ambitious InP standard, on the order of 15% more stringent than the current standard and implemented in 2032, would drive further improvements and promote NT certifications. This is consistent with historical trends, where each new generation of aircraft has typically achieved a 15% reduction in fuel burn compared with the models they replaced (Zheng & Rutherford, 2020).

Policies could help generate demand for NTs. Because ICAO's 2028 standard lags state-of-the-art technology by about a decade, a stronger, technology-forcing standard could be amended to apply to all in-service aircraft through a phaseout (Graver & Rutherford, 2018) that resembles the method used by the U.S. Federal Aviation Administration to enforce the Chapter 2 Noise Phase-Out certification standards for aircraft during the 1990s (United States General Accounting Office, 2001). Additionally, carbon pricing, including emissions trading and a carbon tax, could create additional demand for more fuel-efficient aircraft by raising the operating costs of older aircraft, as could differentiated landing fees based on fuel burn, especially for freighters and older aircraft that tend to have higher emissions.

The findings also highlight the importance of addressing gaps in current standards, particularly for freighters, which lag passenger aircraft in terms of fuel burn reduction due to the limited introduction of NT aircraft. For example, a B767-300F delivered in 2024 shows a 14% increase in the margin with the CO_2 standard. Because ICAO sets pass/fail standards covering all aircraft types as a function of their maximum takeoff mass, the inclusion of freighters in the standard risks diluting the requirements for passenger aircraft with lower fuel burn. To avoid diluting the stringency of future standards, ICAO could consider setting separate requirements for freighters and compliance flexibility mechanisms like averaging and banking. Flexibility mechanisms enable manufacturers to meet more stringent targets without stifling innovation because they can offset less efficient models with more efficient ones.

Future research could expand to include general aviation, turboprops, and business jets, to better understand the contribution of these sectors to overall aviation fuel burn trends. Additionally, it would be beneficial to conduct another update in 5 years, incorporating new data to assess progress and refine strategies for achieving the net-zero CO_2 emissions goal.

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