OCTOBER 2020

CO_2 EMISSIONS FROM COMMERCIAL AVIATION

2013, 2018, AND 2019

BRANDON GRAVER, PH.D., DAN RUTHERFORD, PH.D., AND SOLA ZHENG

ACKNOWLEDGMENTS

The authors thank Jennifer Callahan and Dale Hall (ICCT), Tim Johnson (Aviation Environment Federation), and Andrew Murphy (Transport & Environment) for their review. This work was conducted with generous support from the Aspen Global Change Institute.

SUPPLEMENTAL DATA

Additional country-specific operations and CO_2 emissions data for 2013, 2018, and 2019 can be found on the ICCT website.

International Council on Clean Transportation
1500 K Street NW, Suite 650,
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

EXECUTIVE SUMMARY

Last year, the International Council on Clean Transportation (ICCT) developed a bottom-up, global aviation inventory to better understand carbon dioxide (CO_2) emissions from commercial aviation in 2018. This report updates the operations and emissions analyses for calendar year 2018 based on improved source data, and includes new analyses for 2013 and 2019. In 2013, the International Civil Aviation Organization (ICAO) requested its technical experts develop a global CO_2 emissions standard for aircraft, and states began to submit voluntary action plans to reduce CO_2 emissions from aviation.

This paper details a global, transparent, and geographically allocated CO_2 inventory for three years of commercial aviation, using operations data from OAG Aviation Worldwide Limited, ICAO, individual airlines, and the Piano aircraft emissions modeling software. Our Global Aviation Carbon Assessment (GACA) model estimated CO_2 emissions from global passenger and cargo operations on par with totals reported by industry (Figure ES-1). In all three analyzed years, passenger flights were responsible for approximately 85% of commercial aviation CO_2 emissions. In 2019, this amounted to 785 million tonnes (Mt) of CO_2. Between 2013 and 2019, passenger transport-related CO_2 emissions increased 33%. Over the same period, the number of flight departures increased 22% and revenue passenger kilometers (RPKs) increased 50%. This means that passenger air traffic increased nearly four times faster than fuel efficiency improved.

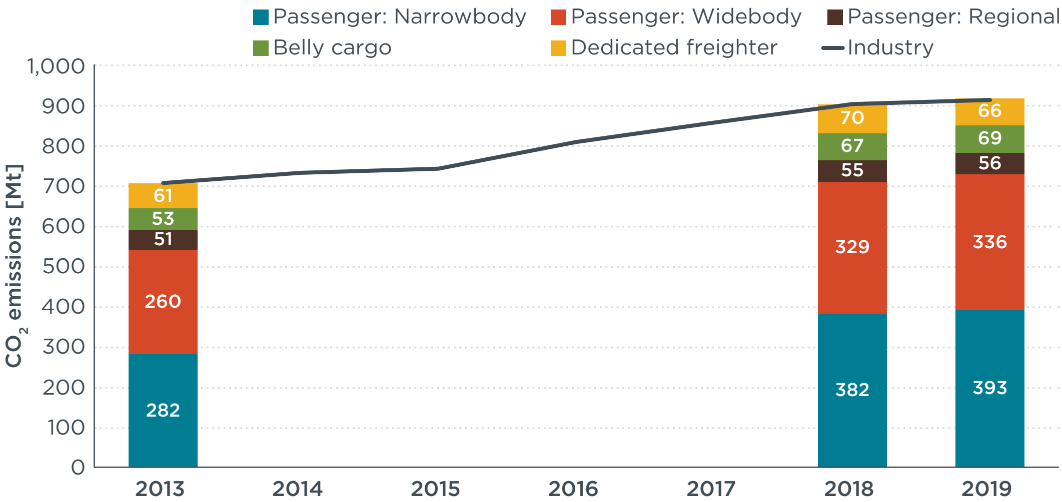

Figure ES-1. CO_2 emissions by operations and aircraft class in the three analyzed years.

The top five departure countries for passenger aviation-related carbon emissions in 2019 are the United States, China, the United Kingdom, Japan, and Germany. Flights departing airports in the United States and its territories emitted 23% of global passenger transport-related CO_2 in 2019, two-thirds of which came from domestic flights. Collectively, the 28 members of the European Union (EU) were second behind the United States, having emitted 19% of the global passenger transport total. When adding China's 13%, these three largest markets were responsible for more than half of all passenger CO_2 emitted in 2019.

ICAO divides the world into six statistical regions. Flights within its Asia/Pacific region emitted the largest share of passenger transport-related CO_2 in 2013, 2018, and 2019. This region accounted for 22% of the global total in 2013, and that increased to 25% in 2018 and 2019. Four out of the top 10 departure countries with the most aviation emissions—China, Japan, India, and Australia—are located in the Asia/Pacific region. Intra-North America flights emitted 16% of global passenger CO_2 emissions in 2019, down from nearly 19% in 2013. Flights within Europe, between both EU and non-EU countries, emitted 14% of the global total in 2019, up from 13% in 2013.

Regarding aircraft class, we found that more than 60% of all passenger flights were operated on narrowbody aircraft in 2019, and these accounted for more than half of all RPKs and passenger CO_2 emissions. On average, global passenger aircraft emitted 90 g CO_2 per RPK in 2019. That is 2% lower than in 2018, and 12% lower than in 2013. Smaller regional aircraft that are used on shorter flights emitted nearly 80% more CO_2 per RPK than the global average for all aircraft. Newer aircraft types like the Airbus A320neo (narrowbody) and Boeing 787-9 (widebody) emit between 30% and 50% less CO_2 per RPK than the most inefficient legacy aircraft.

For the first time, we estimate both absolute emissions and carbon intensity per passenger by both seating class and aircraft class. Premium seating, which is first class and business class, takes up more floor area on an airplane than economy seating and thus can be apportioned a larger share of the fuel burn. In 2019, 179 Mt of CO_2 emissions, or nearly 20% of emissions from commercial aviation, came from passengers in premium seating classes (Figure ES-2). This is more than the emissions associated with the transport of both belly and dedicated freight. Depending on aircraft class, premium seating was found to emit between 2.6 and 4.3 times more CO_2 per RPK than economy seating. Traveling in widebody economy class was found to have the lowest average carbon intensity at about 65 g CO_2 per RPK.

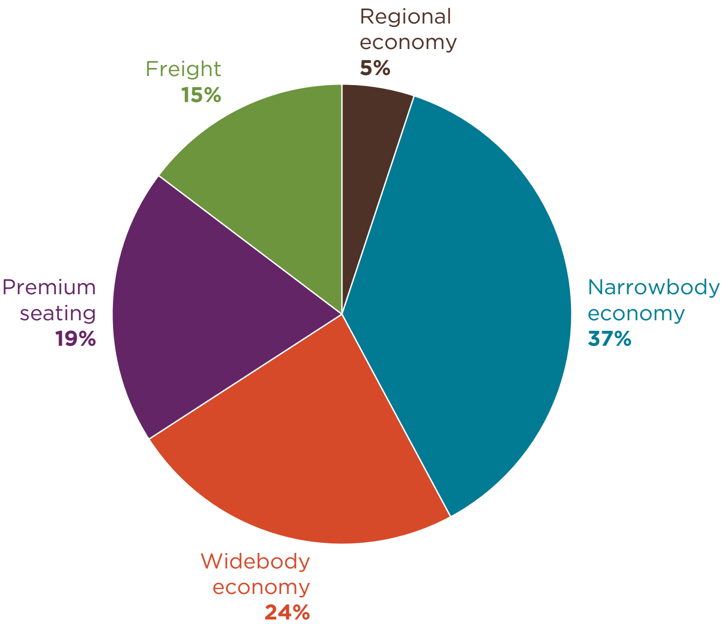

Figure ES-2. CO_2 emissions by operations and aircraft seating class, 2019

This work has three main implications. First, as the United States is both the largest aviation market and a particularly carbon-intensive one in terms of CO_2 per RPK, it should adopt legally binding policies that require additional action to reduce greenhouse gases (GHGs) from aircraft as soon as possible. Second, the significant differences in the carbon intensity of flights strengthens the case for greater emissions disclosure to consumers. Third, efforts to better price carbon emissions from aviation, for example graduating carbon price based upon seating class and distance, could help address both climate change and equity concerns.

TABLE OF CONTENTS

ABBREVIATIONS

ASK	available seat kilometer
ASM	available seat mile
CO_2	carbon dioxide
CTK	cargo tonne kilometer
g	grams
GCD	great circle distance
GHG	greenhouse gas
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
kg	kilograms
km	kilometers
Mt	megatonne (million tonnes)
RPK	revenue passenger kilometer
RTK	revenue tonne kilometer

CONVERSION FACTORS

1 tonne = 1.1023 short tons

1 kilometer = 0.6214 miles

1 tonne-kilometer = 0.6849 ton-miles

1 gallon of jet fuel = 3.785 liters of jet fuel

1 liter of jet fuel = 0.8 kilograms of jet fuel

1 kilogram of jet fuel consumed = 3.16 kilograms of carbon dioxide emissions

1 airline seat = 50 kilograms

1 passenger and checked luggage = 100 kilograms

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION AND BACKGROUND

Aviation emissions are of increasing concern to governments, policymakers, and the flying public. From 2013 to 2018, carbon dioxide (CO_2) emissions from commercial aviation increased about 70% faster than United Nations projections (Graver, Zhang, & Rutherford, 2019), and they were recently on track to triple by 2050, which means they could account for one-quarter of CO_2 emissions from all sectors by then. With the “flying shame” movement and the recent court ruling that the United Kingdom government’s support for expansion at London Heathrow Airport was unlawful on climate grounds (Carrington, 2020), interest in and concerns about greenhouse gas (GHG) emissions from aircraft are at an all-time high.

At the same time, detailed data on aviation emissions remain scarce. While the International Air Transport Association (IATA) releases annual estimates of aviation CO_2 emissions at the global level (IATA, 2020), limited information is available at the level of markets, nations, geography (international vs. domestic), and stage length. In September 2019, the International Council on Clean Transportation (ICCT) released such data for calendar year 2018 (Graver et al., 2019), but data on a single year does not allow for analysis of trends over time. This study aims to address that gap, and introduces several new ways to understand aviation emissions.

One of these relates to premium seating, or seats in first and business class. These seats can be apportioned a larger share of fuel burn, mostly because they take up more floor area on the plane, and thus are more CO_2 intensive per RPK than economy seats (Bofinger & Strand, 2013). While it is understood that premium seating is a larger portion of the total seating in certain markets (Graver, 2018), there have not yet been any attempts to make an assessment of the share of global commercial aviation emissions from premium seating. This paper addresses that gap.

Also, 2019 was a year during which when an increasing number of in-service aircraft were next generation, “re-engined” aircraft. This trend dates back to January 2016 with the arrival of the Airbus A320neo. Indeed, a growing number of aircraft delivered today are equipped with significantly improved engines, either advanced high bypass ratio or geared-turbofan engines. Additionally, 2019 saw the second of two high-profile crashes of Boeing’s 737 MAX family. These crashes ultimately led to the worldwide grounding of the 737 MAX in March 2019 (BBC, 2019). While re-engined aircraft do not deploy the full potential technology benefits of clean-sheet designs (Kharina, Rutherford, & Zeinali, 2016), they are more fuel-efficient than the legacy designs. These new aircraft do not always replace older aircraft, but sometimes expand the global fleet. Greater visibility of the flights, passenger-kilometers traveled, and emissions from such planes is likely to be of general interest.

Separate from these, 2019 was an important year for aircraft emissions from a policy perspective. The first pilot phase of the International Civil Aviation Organization’s (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) will begin in 2021 (Olmer & Rutherford, 2017). Based upon the original agreement, offsetting obligations for each airline are to be established as a function of its emissions growth above a baseline of 2019 and 2020 emissions on covered routes. More recently, though, ICAO’s Council agreed to use calendar year 2019 as the baseline for calculating the offsetting requirements for 2021 to 2023 (Economist, 2020). ICAO will revisit the question of whether 2019 alone should also be used as the baseline for other CORSIA phases at its next Assembly meeting in 2022. The impacts of shifting the baseline are described by Graver (2020) using data developed in this study.

ICAO's decision was spurred by the significant impact of COVID-19 on the airline industry. In response to the pandemic, passenger throughput fell by 90% or more in major markets in March and April 2020 compared with 2019 (U.S. Transportation Safety Administration, 2020). As of July 2020, scheduled flights had fallen by 55% year on year globally and, as a result, IATA projected that CO_2 emissions from aviation will drop by 37% in 2020 and remain 18% below 2019 in 2021 (IATA, 2020).

This paper is arranged as follows. Section 2 outlines our research methods. Section 3 highlights the key findings in terms of absolute CO_2 and carbon intensity by route, country, aircraft type, and seating class. Section 4 summarizes the main conclusions and policy implications of the work, and we close with some thoughts on the direction of future research.

2 METHODS

This study uses the Global Aviation Carbon Assessment (GACA) model introduced in Graver et al. (2019) to estimate fuel burn, CO_2 emissions, and carbon intensity from commercial flights in 2013, 2018, and 2019. GACA merges multiple publicly available data sources to quantify commercial fuel consumption using Piano 5, an aircraft performance and design software from Lissys Ltd.[1] The data obtained concerned airline operations, airports, and capacity, as is detailed below. From that we modeled fuel burn and estimated CO_2 emissions, and then validated the results.

2.1 AIRLINE OPERATIONS DATABASE

Global airline operations data were sourced from OAG Aviation Worldwide Limited. The OAG dataset contained the following variables for passenger and freight airlines: air carrier, aircraft type, departure airport, arrival airport, departures (number of flights), and capacity in available seat miles (ASMs). Operations data for freight air carriers DHL, FedEx, and UPS were not available from OAG due to restrictions put in place by the companies. To compensate, we utilized a public data source (U.S. Department of Transportation [DOT], 2020) to identify the fuel burn associated with these carriers' operations. General and military aviation, which likely accounted for 10% or less of all aviation CO_2 in each of the years analyzed, are beyond the scope of this work.

2.2 GLOBAL AIRPORTS DATABASE

GACA includes a Global Airports Database with geographic information for all airports included in the Airline Operations Database. For each airport, the city, country or territory, latitude, and longitude were recorded from Great Circle Mapper.[2] The latitude and longitude for the departure and arrival airports of each route were used to calculate great circle distance (GCD). To account for variability in actual flight paths due to weather conditions, the GCD of each route was adjusted using ICAO correction factors (ICAO, 2017).

2.3 PAYLOAD ESTIMATION

The mass of passengers and/or freight transported on each flight was estimated differently in GACA for passenger and dedicated freight operations. Payload associated with the transport of passengers and their luggage was estimated using the number of aircraft seats, a passenger load factor, and a default passenger mass of 100 kg including luggage (ICAO, 2019a). If passenger load factors for an airline were not available for purchase (ICAO, 2020b) or published by the airline, an ICAO region-specific passenger load factor was used (ICAO, 2017). Total traffic, in revenue passenger kilometers (RPKs), was estimated by multiplying seat capacity by the passenger load factor.

Payload associated with the transport of freight on a passenger aircraft was estimated using either data purchased from ICAO, specific airline-published data, or an ICAO region-specific passenger-to-freight factor.

For freighter aircraft, if freight carriage data was not available from data purchased from ICAO or published by the airline, an industry average freight load factor of 49% of available mass capacity, in available tonnes, was used.

1 http://www.lissys.demon.co.uk/index2.html
2 http://www.gcmap.com

2.4 FUEL BURN MODELING AND CO_2 ESTIMATION

For each combination of route, airline, and aircraft type, GACA modeled fuel burn using Piano 5 aircraft files, adjusted GCD, and payload, all derived as previously discussed. In cases where a specific aircraft type was not included in Piano 5, a surrogate aircraft was used. Piano default values for operational parameters such as engine thrust, drag, fuel flow, available flight levels, and speed were used. Cruise speeds were set to allow for a 99% maximum specific air range, which is believed to approximate actual airline operations. Fuel reserve values to account for weather, congestion, diversions, and other unforeseen events were based on U.S. Federal Aviation Administration (FAA) Operations Specification B043 (2014). Taxi times were set to 25 minutes, as estimated from block and air time data of U.S. air carriers (U.S. DOT, 2020). We accounted for changes in aircraft weight due to varying seat configurations by adjusting the default number of seats in Piano 5.

For passenger aircraft, fuel burn was apportioned to passenger and freight carriage using the following three equations:

Equation [1]

$$\textit{Total passenger fuel use [kg]} = \left(\frac{\textit{Total passenger weight [kg]}}{\textit{Total weight [kg]}}\right)(\textit{Total fuel use [kg]})$$

Equation [2]

$$\begin{aligned}&\textit{Total passenger weight [kg]}\\&\qquad = (\textit{Number of aircraft seats})(50\ \textit{kg}) + (\textit{Number of passengers})(100\ \textit{kg})\end{aligned}$$

Equation [3]

$$\textit{Total weight [kg]} = \textit{Total passenger weight [kg]} + \textit{Total freight weight [kg]}$$

Thus, total fuel use is proportional to payload mass after taking into account furnishings and service equipment needed for passenger operations. CO_2 emissions were estimated using the accepted constant of 3.16 tonnes of CO_2 emitted from the consumption of one tonne of aviation fuel (ICAO, 2020a).[3]

2.5 SEATING CLASS ALLOCATION

The Airline Operations Database contained the number of seats available for each combination of route, airline, and aircraft type in each of three seating classes: (1) first; (2) business; and (3) economy. Using values from Doganis (2019), passenger load factors for first and business are defaulted to 60% and 75%, respectively. These passenger load factors are similar to the ones used by The World Bank (Bofinger & Strand, 2013) in its estimation of carbon emissions from different seating classes (60% for both first and business) and uses Doganis as a reference. The exception is domestic flights in the United States, where we assumed that the premium passenger cabins are filled to 100% of capacity due to complimentary upgrades for airlines' frequent fliers. The passenger load factor for economy is then back-calculated based upon the overall passenger load factor of a flight and the assumed first and business class load factors.

The allocation of CO_2 emissions to passengers in each seating class in GACA is based on the average percentage of area that each seating class occupies in each aircraft class, including galleys and lavatories, and the average percentage of seats occupied in each seating class. Table 1 outlines how the amount of passenger space on each aircraft class was apportioned to each seating class when the aircraft had multiple seating classes.

3 The non-CO_2 and radiative forcing effects of aviation emissions are not considered in this study.

Table 1. Industry average allocation of passenger space by aircraft and seating class

Aircraft class	Seating configuration	% Passenger space, by seating class		
		First	Business	Economy
Regional	Two classes	29%	—	71%
Narrowbody	Two classes	22%	—	78%
	Two classes	—	25%	75%
Widebody	Two classes	—	32%	68%
	Three classes	16%	30%	54%
Airbus A380 & Boeing 747	Three classes	13%	35%	52%

2.6 VALIDATION

Previous studies established that aircraft performance models tend to underestimate real-world fuel consumption (Graver & Rutherford, 2018a and 2018b; Intergovernmental Panel on Climate Change [IPCC], 1999a). To address this, GACA applies correction factors by aircraft type, in terms of fuel burn per RPK derived from U.S. passenger airlines in Piano 5 and validated by operations and fuel burn data reported to the U.S. DOT. The correction factors ranged from 1.02 to 1.20 by aircraft class, and averaged 9% across all classes. In cases where a specific aircraft type in the Airline Operations Database was not operated by a U.S. passenger airline, the GACA fuel burn correction factor for a comparable aircraft was used.

3 RESULTS AND DISCUSSION

Operations data for 2013 and 2019 were newly evaluated for this report, and 2018 data was reanalyzed using the improved source data. The GACA model was used to estimate CO_2 emissions for all three years. The global operations modeled in this study agreed well with industry estimates.

3.1 TOTAL GLOBAL OPERATIONS AND CO_2 EMISSIONS

More than 39 million flights were included in the Airline Operations Database for 2019 and, of these, more than 98% were flown by passenger aircraft. Our estimate of the total global passenger demand was 8,703 billion RPKs, about 0.3% higher than IATA's published value of 8,680 billion RPKs. The total cargo transported was estimated as 253 billion cargo tonne kilometers (CTKs), within 0.4% of IATA's published value of 254 billion CTKs. GACA-estimated RPKs and CTKs for 2013 and 2018 were also within 1% of industry estimates.

The GACA model estimated that global aviation operations for both passenger and cargo carriage emitted 920 million tonnes (Mt) of CO_2 in 2019, about 0.6% higher than IATA's published value. The reanalysis of 2018 operations data estimated CO_2 emissions of 903 Mt that year, slightly lower than the prior estimate of 918 Mt. This new value is about 0.2% lower than industry's estimate. Comparing 2018 and 2019, emissions increased by about 2%. Our estimate of 2013 emissions is 706 Mt of CO_2, or 0.9% lower than the value published by industry (ATAG, 2020). This means that, based on our analysis, CO_2 increased by about 30% between 2013 and 2019, or an average yearly increase of 4.5%. Emissions from passenger transport increased approximately 33% during this time period, while emissions from freight transport increased about 18%.

Passenger transport accounted for 785 Mt, or 85%, of commercial aviation CO_2 emissions in 2019. Passenger movement in narrowbody aircraft was linked to 43% of total aviation CO_2, transport in widebody jets was linked to 37%, and regional aircraft was linked to 6%. The remaining 15%, 135 Mt, was from freight carriage that was divided between "belly" freight carriage on passenger aircraft, 8%, and dedicated freighter operations, 7%.

In 2013 and 2018, passenger flights were responsible for 84% and 85% of commercial aviation CO_2 emissions, respectively. As illustrated in Figure 1, the breakdown of CO_2 emissions by operation and aircraft class were similar for the three years analyzed.

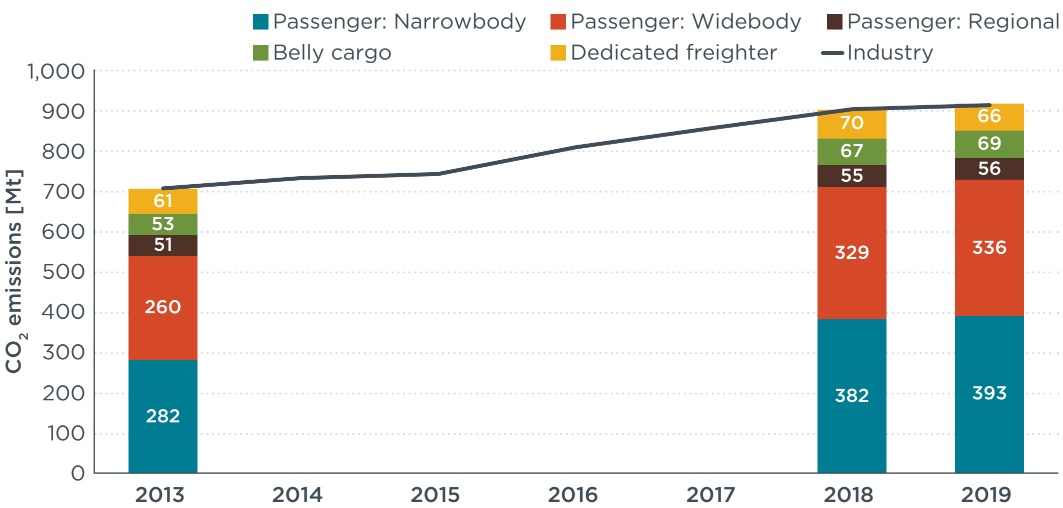

Figure 1. CO_2 emissions by operations and aircraft class, 2013, 2018, and 2019

Given that passenger transport emitted four times as much CO_2 as freight transport in commercial aviation, the focus of the rest of this paper is on passenger transport and aircraft. A more detailed analysis of air freight could be presented in future work.

3.2 CO_2 FROM PASSENGER TRANSPORT

Globally, two-thirds of all flights in 2019 were domestic. Still, these accounted for only approximately one-third of global RPKs and 40% of global passenger transport-related CO_2 emissions, as shown in Figure 2. Operations and emissions from 2013 and 2018 were similar, and the departures, RPKs, and ASKs shown are similar to values published by ICAO (2019b).

Between 2013 and 2019, the total number of flight departures worldwide increased by 23%, RPKs increased 50%, and passenger transport-related CO_2 emissions increased 33%. The average passenger flight distance increased by only 8% over the six-year period, suggesting that RPK growth is due primarily to a rise in the number of passengers. GACA estimates that the number of domestic passengers increased 42% between 2013 and 2019, while the number of international passengers rose 50%.

International operations increased faster than domestic operations over this time period: 47% versus 40% for ASKs and 52% versus 47% for RPKs. CO_2 emissions from international flights increased by 35%, outpacing the 30% increase in emissions from domestic flights.

RPKs correlate well with CO_2 emissions after accounting for improvements in fuel efficiency. That RPKs increased faster than emissions during this time period suggests that fuel efficiency improved.

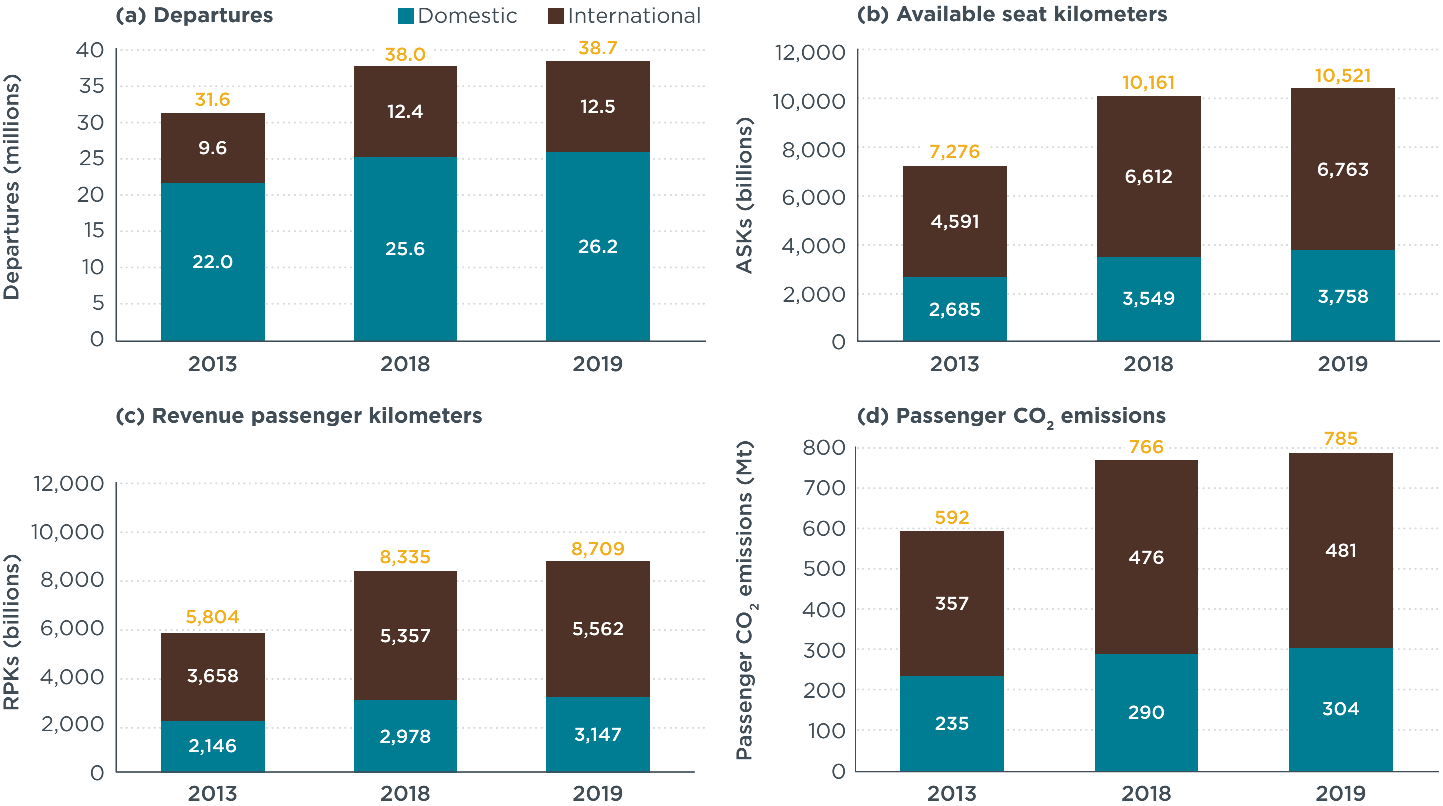

Figure 2. Passenger operations and emissions, 2013, 2018, and 2019

Because the Airline Operations Database includes the departure and arrival airports for every commercial passenger flight, the carbon emissions from passenger air transport can be allocated to specific regions and countries by the departure airport.[4]

Table 2 lists all 21 ICAO route groups, created using ICAO-defined regions.[5] Flights within the Asia/Pacific region emitted the largest share of passenger transport-related CO_2 in 2013, 2018, and 2019. This region accounted for 22% of the global total in 2013, and that share increased to 25% in 2018 and 2019. Four of the 10 countries with the most aviation emissions in 2019—China, Japan, India, and Australia—are in ICAO's Asia/Pacific region. Intra-North America flights (e.g., U.S. domestic, Canada domestic, and transborder flights) emitted 16% of global passenger CO_2 emissions in 2019, down from nearly 19% in 2013. In 2018 and 2019, flights within Europe, between both European Union (EU) and non-EU countries, emitted over 100 Mt of CO_2, or 14% of the global total. This was an increase from 13% in 2013. The Europe – North America route group had the most emissions between separate regions, accounting for 7% of global passenger CO_2 emissions in each year analyzed.

Table 2. Passenger CO_2 emissions by regional route group, 2013, 2018, and 2019

2019 rank	Route group (Not directional specific)	CO_2 emissions [Mt]			Change 2013–2019
		2013	2018	2019	
1	**Intra-Asia/Pacific**	133	194	199	+ 50%
2	**Intra-North America**	110	124	127	+ 16%
3	**Intra-Europe**	79.4	105	107	+ 35%
4	**Europe ↔ North America**	43.2	53.7	56.1	+ 30%
5	**Asia/Pacific ↔ Europe**	39.1	47.1	49.4	+ 26%
6	**Asia/Pacific ↔ North America**	34.5	42.3	44.0	+ 27%
7	**Asia/Pacific ↔ Middle East**	23.3	36.3	34.5	+ 48%
8	**Intra-Latin America/Caribbean**	26.1	30.2	31.0	+ 19%
9	**Europe ↔ Middle East**	17.0	27.0	27.2	+ 61%
10	**Latin America/Caribbean ↔ North America**	20.3	24.0	23.9	+18%
11	**Europe ↔ Latin America/Caribbean**	18.4	22.3	23.6	+ 28%
12	**Africa ↔ Europe**	15.1	17.4	18.0	+ 20%
13	**Middle East ↔ North America**	6.60	9.65	9.94	+ 51%
14	**Intra-Africa**	7.72	9.03	9.37	+ 21%
15	**Intra-Middle East**	7.24	9.71	9.18	+ 27%
16	**Africa ↔ Middle East**	6.09	8.29	8.04	+ 32%
17	**Africa ↔ Asia/Pacific**	2.68	2.91	2.72	+ 2%
18	**Africa ↔ North America**	1.58	2.02	1.98	+ 25%
19	**Asia/Pacific ↔ Latin America/Caribbean**	0.55	0.97	0.89	+ 60%
20	**Latin America/Caribbean ↔ Middle East**	0.72	0.86	0.79	+ 9%
21	**Africa ↔ Latin America/Caribbean**	0.36	0.49	0.48	+ 32%
Total		**592**	**766**	**785**	**+ 33%**

4 The question of how international aviation emissions could be allocated to individual countries has been a topic of international discussion under the United Nations Framework Convention on Climate Change (UNFCCC)'s Subsidiary Body for Scientific and Technical Advice (SBSTA) since 1995. In 1997, SBSTA outlined five options for attributing international aviation emissions to countries for future refinement: (1) no allocation; (2) allocation by fuel sales; (3) allocation by where a plane is registered; (4) allocation by country of departure or destination of an aircraft; or (5) allocation by country of departure or destination of payload (passengers or cargo). See UNFCCC SBSTA (1997), IPCC (199b), and Murphy (2018). The attribution issue remains unsettled. This paper, which assumes no fuel tankering (i.e., excess fuel carriage to take advantage of differences in fuel prices across airports), applies Option (4) to the country of departure of an aircraft.

5 See Appendix for more information on the countries and territories in each ICAO statistical region.

Flights within the regions of Asia/Pacific and Europe saw the largest intra-region increase in passenger emissions since 2013, at 50% and 35%, respectively. Emissions in several regions grew slower than the global average: Middle East, 27%; Africa, 21%; and Latin America/Caribbean, 19%. The smallest growth in passenger emissions for a major market was observed for flights within North America, 16%.

RPKs increased by 50% between 2013 and 2019, while CO_2 intensity decreased by 12%, as shown in Table 3. Carbon intensity of flights, defined as g CO_2 emitted per RPK after correcting for fuel apportioned to belly freight carriage, is the inverse of fuel efficiency.

Table 3. Passenger CO_2 intensity by regional route group, 2013, 2018, and 2019

2019 rank	Route group (Not directional specific)	CO_2 intensity [g CO_2 / RPK]			Change	
		2013	2018	2019	2013–2019	2018–2019
1	**Latin America/Caribbean ↔ North America**	92	83	82	- 11%	- 2%
2	**Europe ↔ Latin America/Caribbean**	94	86	82	- 12%	- 4%
3	**Africa ↔ Europe**	94	88	84	- 11%	- 5%
4	**Asia/Pacific ↔ Latin America/Caribbean**	119	95	85	- 29%	- 11%
5	**Intra-Europe**	99	88	87	- 13%	- 2%
6	**Asia/Pacific ↔ Middle East**	94	94	87	- 8%	- 7%
7	**Europe ↔ Middle East**	94	93	87	- 7%	- 6%
8	**Asia/Pacific ↔ Europe**	102	90	88	- 14%	- 3%
9	**Africa ↔ Asia/Pacific**	108	97	89	- 18%	- 9%
10	**Intra-Asia/Pacific**	100	89	89	- 11%	0%
11	**Europe ↔ North America**	98	90	89	- 9%	- 1%
12	**Africa ↔ Middle East**	99	98	91	- 9%	- 7%
13	**Asia/Pacific ↔ North America**	108	92	93	- 15%	+ 1%
14	**Middle East ↔ North America**	103	98	93	- 10%	- 5%
15	**Latin America/Caribbean ↔ Middle East**	104	104	94	- 10%	- 10%
16	**Africa ↔ Latin America/Caribbean**	107	103	96	- 10%	- 6%
17	**Intra-North America**	109	98	97	- 11%	- 2%
18	**Africa ↔ North America**	111	104	97	- 13%	- 7%
19	**Intra-Latin America/Caribbean**	116	100	98	- 15%	- 2%
20	**Intra-Africa**	127	124	118	- 7%	- 5%
21	**Intra-Middle East**	125	123	118	- 5%	- 4%
Total		**102**	**92**	**90**	**- 12%**	**- 2%**

On average, global aircraft emitted 90 g CO_2 per RPK in 2019. This is 2% lower than in 2018 when using the revised 2018 analysis done for this report, and 12% lower than in 2013. ICAO set an aspirational goal of 2% fuel efficiency improvement annually for international aviation (ICAO, 2020a). While there are domestic operations included in the percent change in passenger CO_2 intensity shown in Table 3, there was an average yearly increase in global fuel efficiency of 2% between 2013 and 2019 and between 2018 to 2019. During the latter period, 18 of 21 route groups, 86% of them, achieved a reduction in CO_2 intensity of 2% or more. Between 2013 and 2019, nine of 21 route groups, 43%, achieved an average 2% per year reduction in CO_2 intensity. The only route group with an increase in estimated CO_2 intensity from 2018 to 2019 was the Asia/Pacific – North America group, which had an increase of 1 g CO_2 per RPK. No improvement in estimated fuel efficiency was observed for intra-Asia flights over the past year.

The least efficient route groups were flights within Africa and within the Middle East. These emitted more than 30% more CO_2 to transport one passenger one kilometer than the global average. This is due primarily to the use of older, fuel-inefficient aircraft and low passenger load factors. However, there were improvements in fuel efficiency for these route groups of 4%–5% from 2018 to 2019, higher than the global average yearly increase in fuel efficiency between 2013 and 2019.

The largest gains in fuel efficiency between 2013 and 2019 were for flights between the Asia/Pacific and Latin America/Caribbean regions. While the sample size of flights in this market is small (fewer than 5,000 flights), the large decrease in CO_2 intensity can be credited to the replacement of Airbus A340 and Boeing 767 aircraft with more fuel-efficient Boeing 787 Dreamliners.

Table 4 lists the 10 countries with the highest carbon emissions from passenger transport by departure in 2019. Overall, flights leaving these countries and their territories accounted for nearly 60% of both CO_2 and RPKs from global commercial aviation passenger transport.

In 2019, flights departing an airport in the United States and its territories supplied nearly 22% of global RPKs, while emitting 23% of global passenger transport-related CO_2. While America's CO_2 emissions increased 19% between 2013 and 2019, its share of global emissions decreased 2 percentage points.[6] Flights departing a U.S. airport had an average CO_2 intensity 6% higher than the global average.

Table 4. Passenger CO_2 emissions in 2019 – top 10 departure countries

Rank	Departure country	CO_2 [Mt]	% of total CO_2	RPKs [billions]	% of total RPKs	CO_2 intensity [g CO_2 / RPK]
1	**United States[a]**	179	23	1,890	22	95
2	**China[b]**	103	13	1,167	13	88
3	**United Kingdom[c]**	31.8	4.1	365	4.2	87
4	**Japan**	25.9	3.3	274	3.1	95
5	**Germany**	23.1	2.9	253	2.9	91
6	**United Arab Emirates**	21.5	2.7	243	2.8	89
7	**India**	21.2	2.7	248	2.9	85
8	**France[d]**	20.6	2.6	237	2.7	87
9	**Spain**	19.8	2.5	249	2.9	79
10	**Australia[e]**	19.5	2.5	217	2.5	90
Rest of the World		319	41	3,567	41	89
Total		**752**	**100**	**8,710**	**100**	**90**

[a] Includes American Samoa, Guam, Johnston Island, Kingman's Reef, Midway, Palmyra, Puerto Rico, Saipan (Mariana Islands), Wake Island, Virgin Islands
[b] Includes Hong Kong SAR and Macau SAR
[c] Includes Anguilla, Bermuda, British Virgin Islands, Cayman Islands, Falkland Islands (Malvinas), Gibraltar, Guernsey, Isle of Man, Montserrat, St. Helena and Ascension, Turks and Caicos Islands
[d] Includes French Guiana, French Polynesia, Guadeloupe, Martinique, Mayotte, New Caledonia, Reunion Island, St. Pierre and Miquelon, Wallis and Futuna Islands
[e] Includes Christmas Island, Coco Islands, Norfolk Island

Not included in Table 3 is the European Union. Collectively, flights departing an airport somewhere in the 28 member states of the European Union in 2019 accounted for 152 Mt CO_2 from passenger transport, or 19% of the global total. This would place the bloc in second, behind the United States. The average CO_2 intensity of flights departing an EU airport was 86 g CO_2 per RPK, 4% lower than the global average. This is an improvement from an average of 98 g CO_2 per RPK in 2013.

6 Country-specific operations and CO_2 emissions data for 2013, 2018, and 2019 can be found on the ICCT website.

The RPKs and emissions from flights departing an airport in China accounted for 13% of the global total in 2019, an increase from 11% in 2013. An increase of over 40 Mt of CO_2 emissions were estimated between 2013 and 2019 for flights departing a Chinese airport. The average CO_2 intensity of flights departing mainland China, Hong Kong, and Macau was 2% higher than the global average.

Figure 3 depicts the 10 airports with the highest carbon emissions from passenger transport by departure in 2019. Overall, these airports accounted for more than 15% of both CO_2 and RPKs from global commercial aviation passenger transport that year. Dubai International Airport, the world's busiest airport by RPKs, had the most CO_2 emissions from passenger transport. The average CO_2 intensity of flights departing Dubai was 2% higher than the global average.

Four of the top 10 airports are in the Asia/Pacific region, three are in Europe, and two are in North America. Singapore Changi Airport had the least carbon-intensive flights of the top 10, with a CO_2 intensity 8% lower than the global average. This could be attributed to the prevalence of low-cost air carriers with newer, more fuel-efficient aircraft making the airport their hub or focus city.

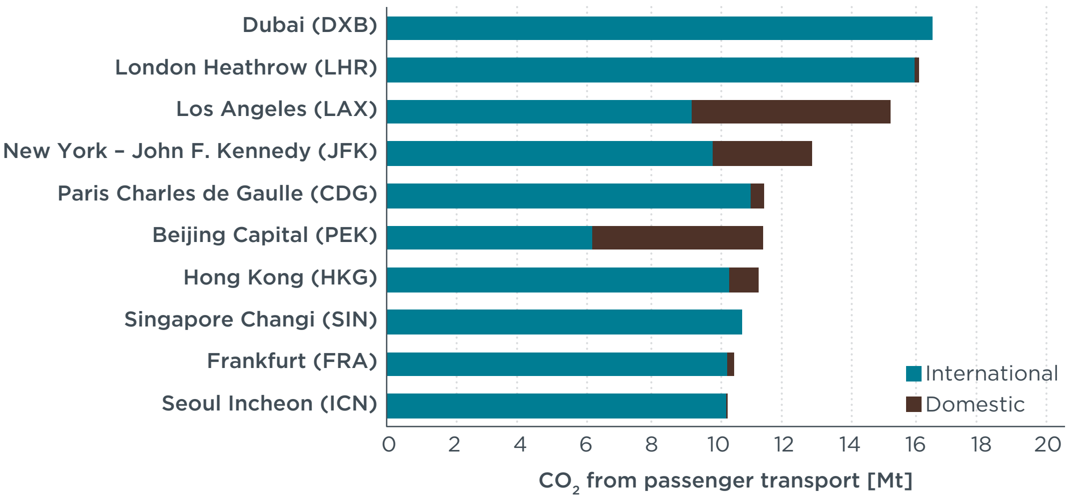

Figure 3. Passenger CO_2 emissions in 2019 – top 10 departure airports

3.2.1 International operations

Approximately 61% of passenger transport CO_2 emissions in 2019 come from international aviation. This is one of the reasons carbon offsetting and reduction efforts have been focused on this market segment.

International flights departing the United States emitted the most CO_2. As shown in Table 5, they accounted for almost 8% of global CO_2 emissions from passenger transport in 2019. Still, only 35% of total emissions from passenger flights departing the United States are from international operations. The average carbon intensity of U.S. flights is the highest among the top 10 countries and 3% higher than the global average. Further, the CO_2 intensity of countries 2 through 10 in Table 5 are all lower than global average of 90 g CO_2 per RPK.

A majority of operations from the United Kingdom (73%), the United Arab Emirates (>99%), Germany (75%), Spain (59%) and France (60%) were international in nature. In 2019, Dubai International Airport and London-Heathrow International Airport led all airports in CO_2 emissions from international operations, as shown in Figure 4.

Table 5. Passenger CO_2 emissions from international operations in 2019 – top 10 departure countries

Rank	Departure country	CO_2 [Mt]	% of total global CO_2	RPKs [billions]	% of total global RPKs	CO_2 intensity [g CO_2 / RPK]
1	**United States**[a]	61.9	7.9	668	7.7	93
2	**China**[b]	34.5	4.4	397	4.6	87
3	**United Kingdom**[c]	30.3	3.9	353	4.1	86
4	**United Arab Emirates**	21.5	2.7	243	2.8	89
5	**Germany**	21.4	2.7	240	2.8	89
6	**Spain**	16.7	2.1	217	2.5	77
7	**Japan**	16.0	2.0	187	2.1	86
8	**France**[d]	15.9	2.0	183	2.1	87
9	**Australia**[e]	12.5	1.6	145	1.7	86
10	**Canada**	11.9	1.5	141	1.6	84

[a] Includes American Samoa, Guam, Johnston Island, Kingman's Reef, Midway, Palmyra, Puerto Rico, Saipan (Mariana Islands), Wake Island, U.S. Virgin Islands
[b] Includes Hong Kong SAR and Macau SAR
[c] Includes Anguilla, Bermuda, British Virgin Islands, Cayman Islands, Falkland Islands (Malvinas), Gibraltar, Guernsey, Isle of Man, Montserrat, St. Helena and Ascension, Turks and Caicos Islands
[d] Includes French Guiana, French Polynesia, Guadeloupe, Martinique, Mayotte, New Caledonia, Reunion Island, St. Pierre and Miquelon, Wallis and Futuna Islands
[e] Includes Christmas Island, Coco Islands, Norfolk Island

Not included in Table 4 is the European Union. If the flights from EU member states were added together, flights departing the EU and arriving at a non-EU country emitted 81.3 Mt CO_2, which would place it at the top of the table. The three departing countries with the most CO_2 emissions from EU to non-EU nations are the United Kingdom, 26% of the EU total, Germany, 18%, and France, 15%.

International flights departing the United States, China, and the European Union emitted 178 Mt CO_2, or 23% of global emissions from passenger air transport in 2019. This is an increase of 32% since 2013. Flights between these "Big 3" emitters in 2019 accounted for nearly 70 Mt CO_2, or approximately 15% of passenger CO_2 emissions from all international flights. This is an increase of 36% since 2013.

Figure 4 highlights the top 10 airports where the most CO_2 emissions come from international passenger operations. All of them are hub airports for major global airlines. Nine of the 10 airports that lead in international CO_2 emissions also lead in total CO_2 emissions. Bangkok International Airport, with 95% of emissions coming from international operations, replaced Beijing Capital International Airport, where 55% of emissions are from international flights. Two of the top 10 airports by international CO_2 are located in the United States.

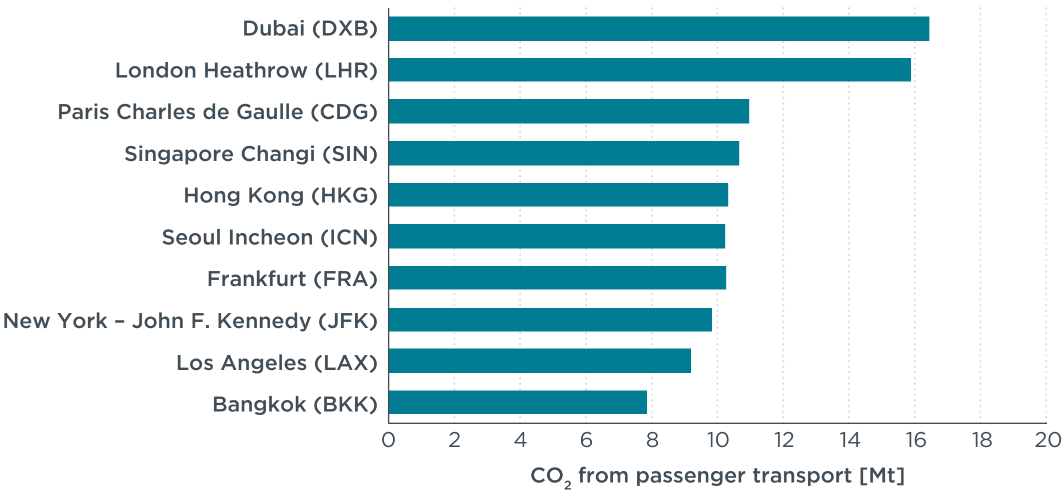

Figure 4. Passenger CO_2 emissions from international operations in 2019 – top 10 departure airports

3.2.2 Domestic operations

Domestic flights emitted 40% of global passenger transport-related CO_2 emissions and made up two-thirds of all departures. Domestic operations accounted for a large majority of flights in a number of countries, including: Brazil, 93%; the United States, 91%; China, 89%; Indonesia, 88%; and Australia, 86%. These are all countries with large total area. Of the 230 nations and territories included in the Airline Operations Database, more than one-third had domestic flights account for 1% or less of total departures.

Table 6 shows the emissions and operations for the top 10 countries based on CO_2 emissions from domestic operations. The United States tops the list, with emissions 71% higher than China, the next largest country. Flights departing and arriving at an airport in a U.S. state or territory accounted for 15% of global passenger CO_2 emissions. The fuel efficiency of these flights is 7% lower than the global average, and 3% lower than all flights departing a U.S. airport. This could be attributed to the prevalence of shorter flights on regional aircraft. (See Section 3.4 for discussion of CO_2 intensity by stage length.)

Flights within mainland China, Hong Kong, and Macau accounted for 9% of both demand and CO_2 from global commercial aviation passenger transport. Air travel within mainland China alone emitted 66 Mt of CO_2 and supplied 747 billion RPKs.

The CO_2 intensity of Japanese domestic flights was 113 g CO_2 per RPK, or 26% more than the global average. The use of widebody aircraft on short flights, an average of 716 km, can explain the large difference.

Table 6. Passenger CO_2 emissions from domestic operations in 2019 – top 10 departure countries

Rank	Departure country	CO_2 [Mt]	% of total global CO_2	RPKs [billions]	% of total global RPKs	CO_2 intensity [g CO_2 / RPK]
1	**United States**[a]	117	15	1,222	14	96
2	**China**[b]	68.4	8.7	770	8.8	89
3	**India**	12.1	1.5	140	1.6	86
4	**Russian Federation**	10.2	1.3	113	1.3	90
5	**Japan**	9.92	1.3	87.5	1.0	113
6	**Brazil**	9.49	1.2	96.4	1.1	98
7	**Indonesia**	8.08	1.0	81.7	0.9	99
8	**Australia**[c]	7.05	0.9	72.2	0.8	98
9	**Canada**	6.28	0.8	62.5	0.7	100
10	**Mexico**	5.51	0.7	57.5	0.7	96

[a] Includes American Samoa, Guam, Johnston Island, Kingman's Reef, Midway, Palmyra, Puerto Rico, Saipan (Mariana Islands), Wake Island, U.S. Virgin Islands
[b] Includes Hong Kong SAR and Macau SAR
[c] Includes Christmas Island, Coco Islands, Norfolk Island

Not included in Table 6 is the European Union, and flights within it emitted 70.2 Mt CO_2. This would make it the second-most emitting region, behind the United States. Domestic flights within each country summed to 15.3 Mt, or 22% of intra-EU flights.

Together the United States and China were responsible for 185 Mt of CO_2 from domestic flights, or over 60% of emissions from global domestic operations in 2019. This is an increase of 31% since 2013 and slightly outpaced the average growth in domestic traffic emissions globally, which was 29% between 2013 and 2019. If flights within the European Union were considered domestic, then operations within the United States, China, and the European Union would account for more than 70% of domestic and regional passenger emissions.[7] Flights within these "Big 3" emitters account for approximately one-third of global emissions from passenger air transport.

Figure 5 highlights the top 10 airports where the most CO_2 emissions come from domestic passenger operations. Nine of the airports are in the United States, with Beijing Capital International Airport in China placing third.

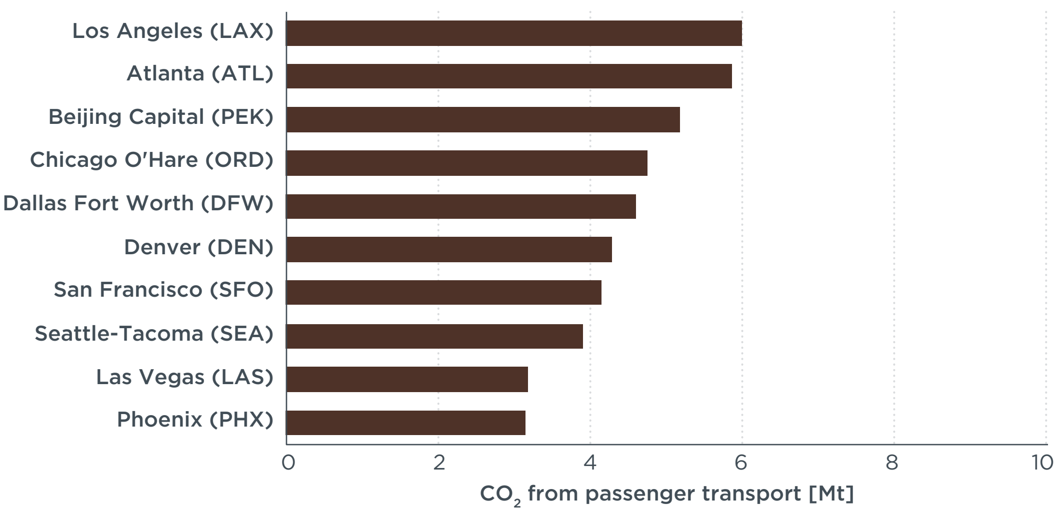

Figure 5. Passenger CO_2 emissions from domestic operations in 2019 – top 10 departure airports

7 Domestic and regional operations CO_2 emissions for 2019 include the 304 Mt from global domestic flights and 54.9 Mt from flights between EU member states.

3.3 PASSENGER CO_2 EMISSIONS AND INTENSITY BY AIRCRAFT CLASS

We also analyzed the total CO_2 and average carbon intensity for each passenger aircraft type included in the Airline Operations Database, and Table 7 summarizes flight operations by aircraft class: regional (turboprops and regional jets), narrowbody, and widebody. More than 60% of all passenger flights were operated on narrowbody aircraft in 2019. These accounted for more than half of all RPKs and passenger CO_2 emissions. On average, narrowbodies and widebodies had similar carbon intensity, but regional aircraft emitted nearly 90% more CO_2 per RPK.

For each passenger transported, the global average flight in 2019 emitted 90 g CO_2 per km, or 124 kg CO_2 over the average flight distance of 1,378 km. The average narrowbody flight of 1,322 km emitted 114 kg of CO_2 per passenger. An average widebody aircraft flight of 4,675 km emitted 416 kg of CO_2 per passenger. Roundtrips would emit twice as much CO_2 over the full itinerary.

Table 7. Passenger CO_2 emissions and intensity by aircraft class, 2013, 2018, and 2019

(a) 2013

Aircraft Class	Departures		RPKs		Avg distance [km]	CO_2		CO_2 intensity [g CO_2/RPK]
	Million	% of total	Billion	% of global total		Mt	% of global total	
Regional	10.8	34	305	5	563	50	9	164
Narrowbody	18.2	58	2,903	50	1,262	275	48	95
Widebody	2.51	8	2,597	45	4,431	241	43	93
Total	**31.6**	**100**	**5,805**	**100**	**1,274**	**566**	**100**	**98**

(b) 2018

Aircraft Class	Departures		RPKs		Avg distance [km]	CO_2		CO_2 intensity [g CO_2/RPK]
	Million	% of total	Billion	% of global total		Mt	% of global total	
Regional	11.0	29	348	4	581	55	7	158
Narrowbody	23.9	63	4,419	53	1,317	382	50	86
Widebody	3.10	8	3,568	43	4,696	329	43	92
Total	**38.0**	**100**	**8,335**	**100**	**1,379**	**766**	**100**	**92**

(c) 2019

Aircraft Class	Departures		RPKs		Avg distance [km]	CO_2		CO_2 intensity [g CO_2/RPK]
	Million	% of total	Billion	% of global total		Mt	% of global total	
Regional	11.2	29	345	4	551	56	7	162
Narrowbody	24.4	63	4,588	53	1,322	393	51	86
Widebody	3.21	8	3,777	43	4,675	336	42	89
Total	**38.8**	**100**	**8,710**	**100**	**1,378**	**785**	**100**	**90**

3.3.1 Regional aircraft

As shown in Table 7, the number of flights flown with a regional aircraft stayed relatively constant between 2013 and 2019 at around 11 million. RPKs completed increased by approximately 13%, while the mass of CO_2 emitted increased by about 9%. This indicates a modest increase in average fuel efficiency of approximately 3% over the time period, or an average of 0.5% per year. The fuel efficiency of narrowbody and widebody aircraft increased four times faster during this time period. This suggests that manufacturers have focused their efficiency improvement efforts on the larger aircraft types that operate a majority of the flights and transport a majority of the passengers.

Table 8 and Figure 6 show the total CO_2 emissions and intensity of the top 10 regional aircraft that operated in 2019, ranked by total emissions. The Embraer E190, which typically has 100 seats, was the highest emitting regional aircraft with nearly 10 Mt CO_2 emitted. That aircraft's total mass of emissions increased by 9% between 2013 and 2019, while the number of departures increased by 11% and the passenger load factor increased by nearly 2%.

The emissions from the top six regional aircraft have all increased since 2013, while those from the smaller Canadair and Embraer regional jets that round out the top 10 have decreased. That the CO_2 intensity of these four aircraft have remained relatively flat over the 6-year period suggests that the drop in CO_2 emissions is due to a decrease in RPKs.

The most fuel efficient of the top 10 regional aircraft are both turboprop aircraft: the De Havilland Dash 8-400 and the ATR 72-600. These two accounted for the most departures by regional aircraft globally with more than 1 million flights each. However, they rank in the middle of the 10 aircraft analyzed because larger regional jets have a higher number of seats and longer flight distances.

Table 8. Passenger CO_2 emissions from the top 10 regional aircraft types, ranked by total emissions, in 2013, 2018, and 2019

2019 rank	Regional aircraft type	Avg seats per flight (2019)	CO_2 emissions [Mt]			Change 2013–2019
			2013	2018	2019	
1	**Embraer E190**	100	8.76	9.69	9.54	+ 9%
2	**Embraer E175**	77	2.53	5.53	6.94	+ 174%
3	**Canadair CRJ900**	80	3.37	6.01	6.40	+ 90%
4	**De Havilland Dash 8-400**	73	2.84	4.14	3.96	+ 40%
5	**Embraer E195**	116	2.50	2.98	3.51	+ 41%
6	**ATR 72-600**	69	2.00	3.45	3.28	+ 64%
7	**Embraer ERJ145**	50	6.07	1.88	3.04	- 50%
8	**Canadair CRJ200**	50	5.75	0.46	2.95	- 49%
9	**Canadair CRJ700**	68	4.07	3.27	2.90	- 29%
10	**Embraer E170**	74	2.68	2.44	2.44	- 9%

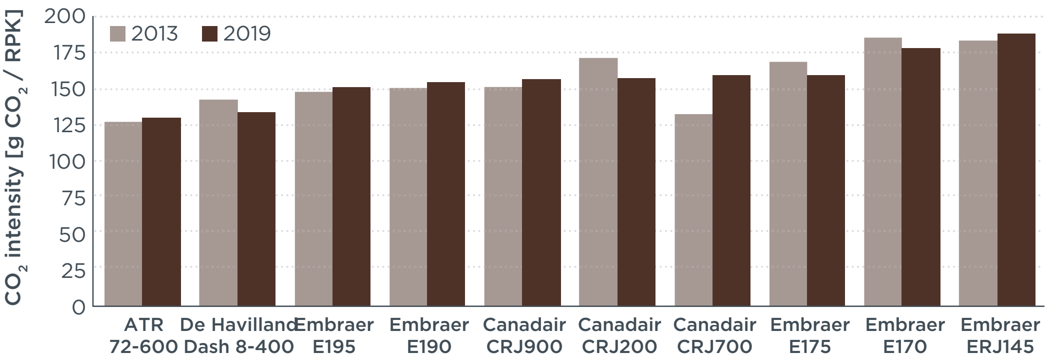

Figure 6. Passenger CO_2 intensity of the 10 highest emitting regional aircraft types, 2013 and 2019

3.3.2 Narrowbody aircraft

The number of flights flown with narrowbody aircraft increased 34% between 2013 and 2019. RPKs completed increased by 58%, while the mass of CO_2 emitted increased by

39%. This indicates an increase in average fuel efficiency of about 12% over the time period, or an average of 2% per year.

The similarly sized Boeing 737-800 and Airbus A320 emitted the most CO_2 among narrowbodies—a combined 59% of the total in 2019, as shown in Table 9, which includes the top 10. The stretch versions of these aircraft, the Airbus A321 and Boeing 737-900, are more fuel-efficient, as shown in Figure 7, and have seen a large increase in emissions since 2013. The new engine variant of the Airbus A320, the Airbus A320neo, has a lower average CO_2 intensity than the older version. Not included in the narrowbody analysis are the MAX versions of the Boeing 737. The number of operations completed by the Boeing 737 MAX 8 and 9 in 2019 were affected by the worldwide grounding of the aircraft starting in March 2019. From the small sample size, the MAX versions are more fuel-efficient than the Boeing 737-800 and -900.

The least fuel efficient of the top 10 narrowbody aircraft are the McDonnell Douglas MD-80 family and Boeing 717-200, as shown in Figure 7. The CO_2 intensities of these two aircraft are twice those of the most prevalent narrowbodies, and similar to regional aircraft. Many of these have been retired early due to COVID-19, as airlines look to save money by flying more efficient aircraft in their fleet.

Table 9. Passenger CO_2 emissions from the top 10 narrowbody aircraft type, ranked by total emissions, in 2013, 2018, and 2019

2019 rank	Narrowbody aircraft type	Avg seats per flight (2019)	CO_2 emissions [Mt] 2013	2018	2019	Change 2013–2019
1	**Boeing 737-800**	174	73.5	113	116	+ 58%
2	**Airbus A320**	169	71.9	109	114	+ 59%
3	**Airbus A321**	196	18.9	45.0	48.4	+ 156%
4	**Airbus A319**	137	28.3	28.8	27.8	- 2%
5	**Boeing 737-700 / -700LR**	140	25.2	20.6	22.7	- 10%
6	**Boeing 737-900 / -900ER**	187	6.73	15.4	16.3	+ 143%
7	**Boeing 757-200**	188	19.0	10.5	10.6	- 44%
8	**Airbus A320neo**	180	—	0.15	3.67	—
9	**McDonnell Douglas MD-80**	151	11.2	5.79	3.40	- 70%
10	**Boeing 717-200**	116	3.34	3.40	3.24	- 3%

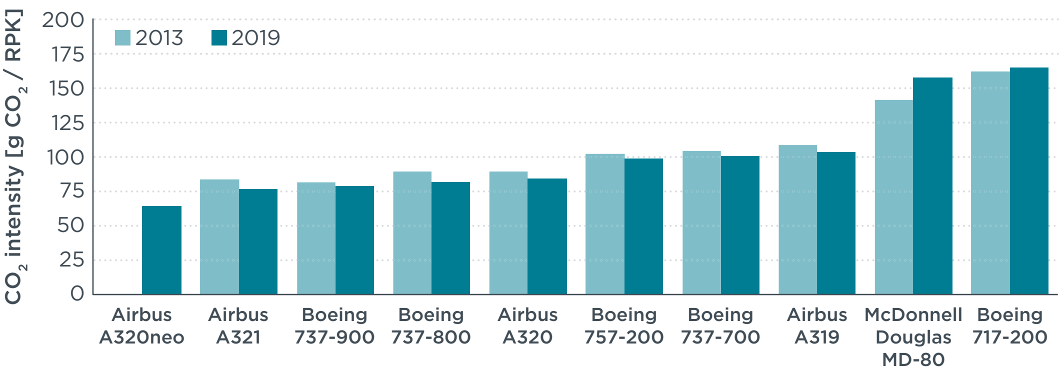

Figure 7. Passenger CO_2 intensity of the top 10 highest emitting narrowbody aircraft types, 2013 and 2019

3.3.3 Widebody aircraft

The number of flights flown with widebody aircraft increased 28% between 2013 and 2019. RPKs completed increased by 45%, while the mass of CO_2 emitted increased by 30%. This indicates an increase in average fuel efficiency of approximately 11% over the time period, or an average of nearly 2% per year.

In Table 10, there are two quad-engine aircraft in the ranking of the top 10 widebody aircraft by total CO_2 emissions: the Airbus A380-800 and Boeing 747-400. These two have the highest CO_2 intensities, in excess of 100 g CO_2 per RPK, compared with other aircraft in the class, as shown in Figure 8. Between 2013 and 2019, total emissions from the A380 increased, while emissions from the 747 decreased. Both trends can be explained by the smaller number of operations and RPKs completed. Due to the reduced demand amidst COVID-19, many airlines have retired these less-efficient aircraft early, so total emissions for the A380 and 747 are thus expected to decrease precipitously in the future.

The three most fuel-efficient widebody aircraft of the top 10 are the Boeing 787 Dreamliner, both the 787-8 and 787-9 variants, and the Airbus A350-900. They became popular amongst airlines over the time period analyzed. Emissions from the Boeing 787-8 increased nearly six-fold, while RPKs increased eight-fold between 2013 and 2019. Meanwhile, the Boeing 787-9 and the Airbus A350-900 entered into service after 2013, in 2014 and 2015, respectively.

Table 10. Passenger CO_2 emissions from the top 10 widebody aircraft types, ranked by total emissions, in 2013, 2018, and 2019

2019 rank	Widebody aircraft type	Avg seats per flight (2019)	CO_2 emissions [Mt]			Change 2013–2019
			2013	2018	2019	
1	**Boeing 777-300 / -300ER**	353	46.2	78.6	77.0	+ 67%
2	**Airbus A330-300**	298	29.1	43.6	40.6	+ 39%
3	**Airbus A380-800**	500	16.2	33.8	34.3	+ 112%
4	**Airbus A330-200**	270	29.5	33.6	33.6	+ 14%
5	**Boeing 777-200 / -200ER / -200LR**	315	38.4	32.0	32.3	- 16%
6	**Boeing 787-9**	284	—	23.7	29.8	—
7	**Boeing 787-8**	257	2.86	18.8	19.3	+ 574%
8	**Airbus A350-900**	302	—	12.7	18.9	—
9	**Boeing 767-300 / -300ER**	246	27.4	17.3	15.9	- 42%
10	**Boeing 747-400**	366	30.9	12.5	11.6	-62%

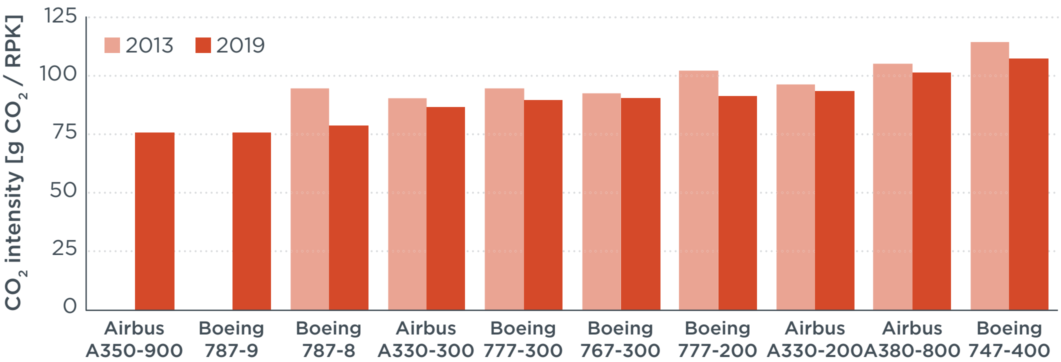

Figure 8. Passenger CO_2 intensity of the top 10 highest emitting widebody aircraft types in 2013 and 2019

3.4 PASSENGER CO_2 EMISSIONS AND INTENSITY BY STAGE LENGTH

Figure 9 shows the distribution of passenger aircraft CO_2 emissions by aircraft class and flight distance in 500 km increments. Approximately one-third of passenger CO_2 emissions occurred on short-haul flights of less than 1,500 km. An additional one-third occurred on medium-haul flights of between 1,500 km and 4,000 km, and the remaining third on long-haul flights of greater than 4,000 km.[8] Regional flights of less than 500 km, roughly the distance where aircraft compete directly with other modes of passenger transport, accounted for about 6% of total passenger CO_2 emissions.

Narrowbodies account for the most CO_2 emissions on flights up to 4,500 km; widebody is the only class flying longer distances.

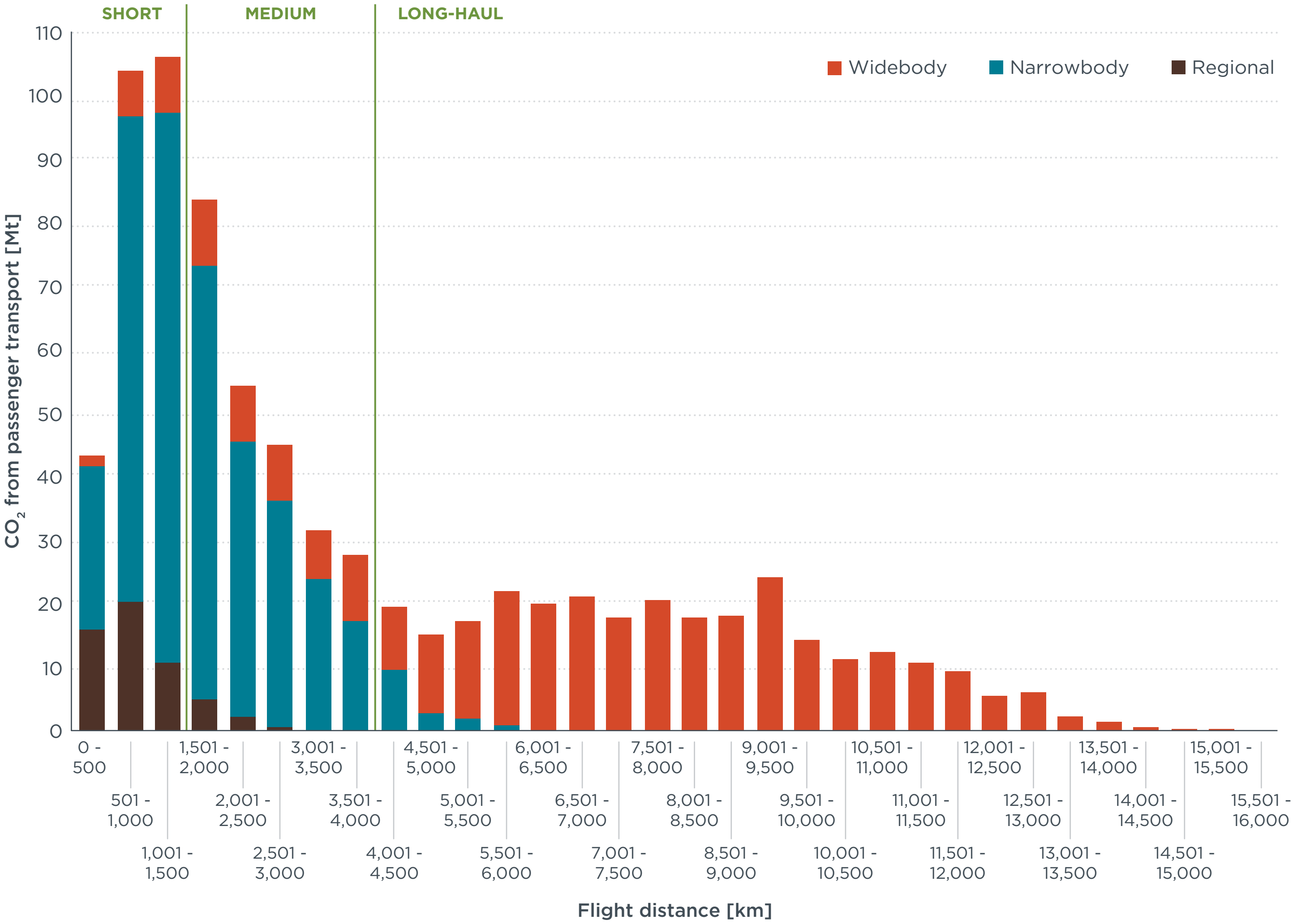

Figure 9. Share of passenger CO_2 emissions in 2019, by stage length and aircraft class

The carbon intensity of medium- and long-haul flights varies between 70 g and 95 g CO_2 per RPK, depending on aircraft class, and this is shown in Figure 10. For flights longer than 5,000 km, the average carbon intensity of all aircraft is the same as the average carbon intensity of the widebodies and is illustrated by the orange line; widebodies are the only aircraft flying this range. The minimum average carbon intensity occurs at about 3,500 km with a slight upward slope as flight length increases.[9]

8 EUROCONTROL's distance definitions for short-, medium-, and long-haul flights were used. See https://www.eurocontrol.int/sites/default/files/2019-07/challenges-of-growth-2018-annex1_0.pdf.

9 This phenomenon, known colloquially as "burning fuel to carry fuel," occurs because longer flights are disproportionately heavy at takeoff due to the extra fuel needed to travel long distances.

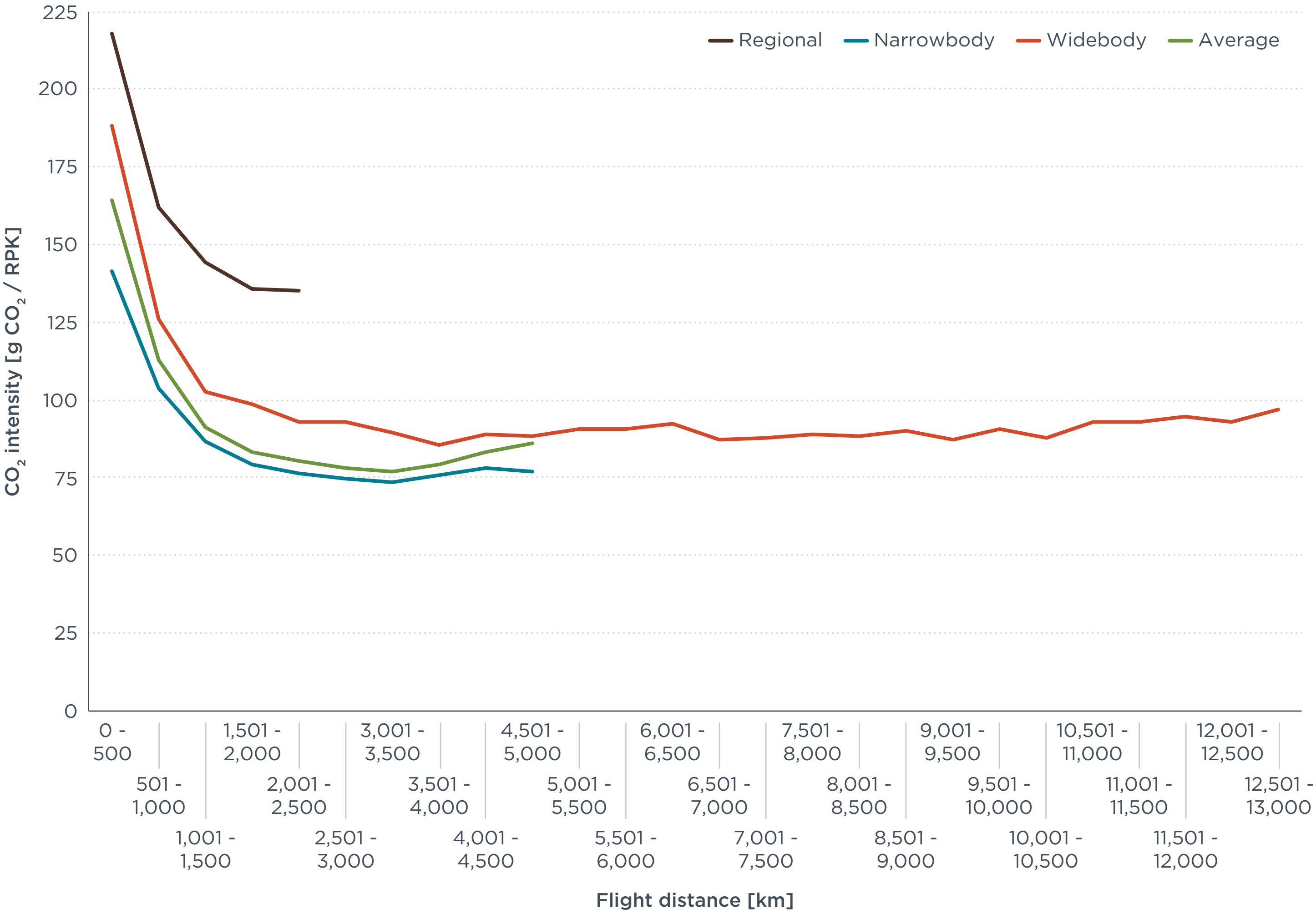

Figure 10. Passenger CO_2 intensity in 2019, by stage length and aircraft class

For short-haul flights, the average carbon intensity is roughly 110 g CO_2 per RPK, or about 35% higher than the medium-haul average. For regional flights of 500 km or less, the carbon intensity is roughly double, 160 g CO_2 per RPK. This is because the extra fuel used for takeoff becomes relatively large compared with the more fuel-efficient cruise segment, and also because of the use of less fuel-efficient regional jets on the shortest flights.

Domestic flights are typically shorter in distance than international flights, and operate using regional and narrowbody aircraft. Therefore, we expect domestic operations to have higher CO_2 intensity. In 2019, the average CO_2 intensity for domestic flights was 97 g CO_2 per RPK, 12% higher than for international flights.

3.5 PASSENGER CO_2 EMISSIONS AND INTENSITY BY SEATING CLASS

Based on the number of seats and the estimated passenger load factors of each seating class on each flight, the average emissions per passenger in each seating class were estimated. Figure 11 depicts the results of this analysis, with the addition of CO_2 emissions from cargo transport.

Of the total in 2019, 179 Mt of CO_2 emissions, or nearly 20% of emissions from commercial aviation, are attributed to passengers in premium seating classes (i.e., first class and business class). This is larger than the emissions associated with the transport of cargo. Of all premium class seats, 88% are on narrowbody and widebody aircraft. Widebodies, which typically have the largest proportion of premium seats per flight, also had the largest proportion of emissions from premium seating at 35%. First or business class passengers emitted 13% of emissions from narrowbodies.

In the United States, larger regional jets typically contain first-class seats. In 2019, CO_2 emissions of premium class passengers on regional aircraft accounted for approximately 1% of total passenger transport emissions and 16% of all regional aircraft emissions.

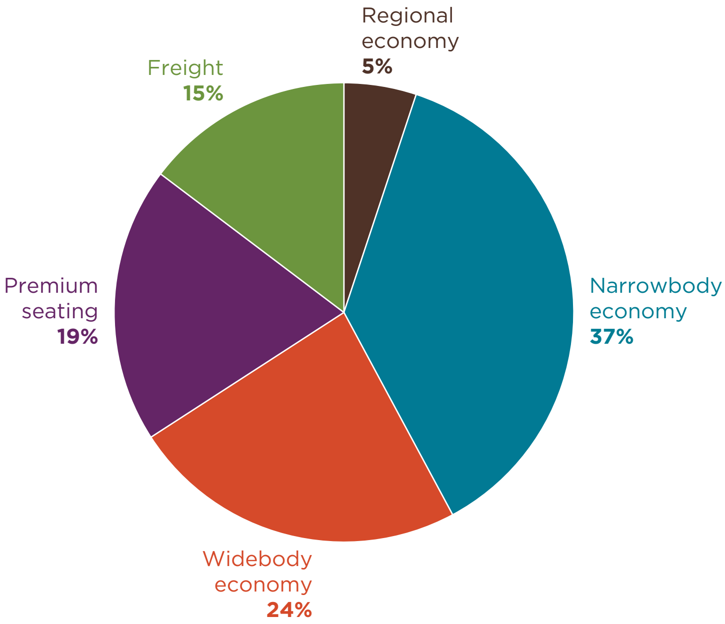

Figure 11. CO_2 emissions by operations and aircraft seating class, 2019

Premium class seats, and the amenities that go with them (e.g., dedicated lavatories, galleys, bars, and showers), take up a larger footprint compared with economy seats. With fewer passengers on each flight and larger footprints, the emissions credited to premium passengers per kilometer are greater than for economy passengers, as shown in Figure 12. In this analysis, premium passengers on a regional aircraft are apportioned 2.6 times more CO_2 per kilometer than a passenger in economy. The multiplier is even higher for narrowbody and widebody aircraft, at 3.7 and 4.3, respectively. The analysis conducted by the World Bank (Bofinger & Strand, 2013) suggested an even higher CO_2 emissions multiplier for premium class seating. This could be due to differences in aircraft layouts at the time of the World Bank analysis—that is, more seats have been added to aircraft recently, as airlines show a preference for business class seating over first class—as well as the difference in assumed passenger load factors in each seating class, as average passenger load factors have been increasing. The report mentions that seating class passenger load factors need further investigation, and that they did not include upgrades in their analysis. Higher passenger load factors in a seating class lower the emissions per passenger in that section.

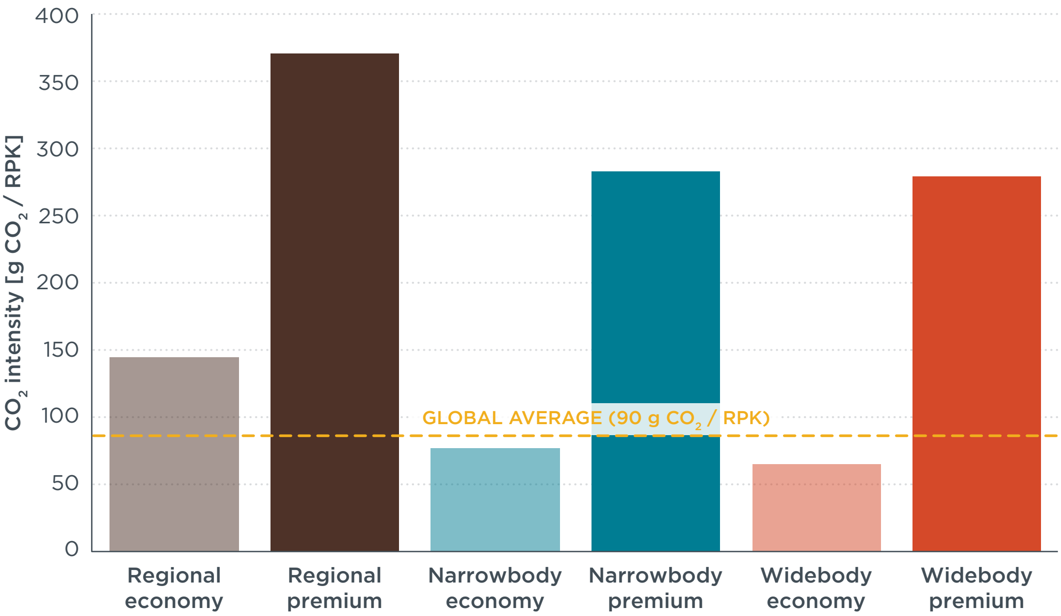

Figure 12. Passenger CO_2 intensity in 2019, by seating class

As previously discussed, at the aircraft class level, the average carbon intensity of narrowbody aircraft was slightly lower, by about 3 g CO_2/RPK, than that of widebody aircraft in 2019. After accounting for premium seating, however, the carbon intensity of economy class on widebody aircraft fell to 65 g CO_2 per RPK, or 12 g CO_2 per RPK less than narrowbody economy and 27% lower than the widebody average. This finding highlights the value of better emissions disclosure by airlines to provide consumers with the option to choose less-emitting flights, including avoidance of first and business class seating.

For example, let us take the same narrowbody aircraft flown by two different air carriers, one with 175 economy seats and the other with 10 fewer total seats to accommodate a premium seating class. They fly the same route with the same passenger load factor (85%) and no cargo. The aircraft with the premium seating, because of the 6% fewer seats and passengers, would emit 1.5% less CO_2 per flight, but 4.5% more CO_2 per passenger. This comparison would be exacerbated if the narrowbody aircraft was a widebody. As stated earlier, the increasing emissions observed over the six-year analysis period is due primarily to the increasing number of passengers. To carry 10,000 total passengers, the narrowbody with premium seating would have to fly 5% more flights than the aircraft with only economy class seating, emitting 3.5% more CO_2.

4 CONCLUSION AND POLICY IMPLICATIONS

This analysis shows that passenger aircraft continue to dominate overall fuel use and emissions, and were responsible for 85% of commercial aviation CO_2 in 2019. While global passenger operations are becoming more fuel-efficient—carbon intensity fell to 90 g CO_2 per RPK in 2019, or 12% lower than 2013—this is not happening fast enough to offset traffic growth. Commercial traffic has increased nearly four times faster than fuel efficiency improvement, and passenger aircraft CO_2 emissions increased 33% between 2013 and 2019.

Regarding the distribution of aviation CO_2, the top 10 countries—the United States, China, United Kingdom, Japan, Germany, United Arab Emirates, India, France, Spain, and Australia—accounted for almost 60% of passenger CO_2 in 2019. The three largest markets (the United States, European Union 28 as a bloc, and China) were responsible for a similar (55%) share. The U.S. market, while still the largest, is growing more slowly over time than the rest of the world. The United States also holds the distinction of being the most carbon intensive major market, emitting 12% more CO_2 per RPK than the global average. Nine of the top 10 airports in the world, in terms of CO_2 emissions from domestic operations, are in the United States.

Narrowbody aircraft accounted for almost two-thirds of flights and more than half of RPKs and CO_2 in 2019. This is an increase of 3 percentage points for RPKs and CO_2 and 5 percentage points for departures since 2013. Regional jets' share of all of these has shrunk since 2013, although they remain about twice as carbon intensive per RPK as narrowbody and widebody aircraft. The greater use of turboprops, which are about 15% less carbon intensive than regional jets, could improve the fuel efficiency of regional flights.

From 2013 to 2019, there was a general trend in upgauging, or increasing the number of seats, for all aircraft classes. Larger, more fuel-efficient "stretch" versions of aircraft (Airbus A321, Boeing 787-9, Boeing 777-300 / -300ER, Airbus A330-300) saw large increases in traffic, while "shrink" aircraft use was stagnant. Older, less fuel-efficient aircraft types like the McDonnell Douglas MD-80, Boeing 767-300 / -300ER and Boeing 747-400 also saw large reductions in use. Upgauging not only means more seats on an aircraft or on a route, by switching from a small aircraft to a larger aircraft, but could also mean an increase in the number of premium seats offered.

In 2019, nearly 20% of emissions from commercial aviation were attributable to premium passengers, more than all freight transport (belly plus dedicated) at 15% of emissions. Premium seating can be considered up to 4.3 times more CO_2 intensive than economy seating. This, along with research spotlighting how frequent fliers are the majority of airline passengers, supports the understanding that a large share of aviation emissions is linked to the travel of a relatively small number of wealthy individuals (Rutherford, 2019; Ivanova & Wood, 2020).

Three main implications can be drawn from this work. First, the United States is both a particularly large and particularly carbon intensive aviation market. Yet, there are still no binding GHG policies in place to curb emissions from the large U.S. domestic fleet. If it aims to meet its goal of carbon neutral growth from 2020 for its carriers (United States Government, 2015), the United States will need to adopt a meaningful aircraft (Rutherford & Kharina, 2016) or airline (Graver & Rutherford, 2019; Rutherford, 2020) fuel efficiency standard. The standard must be stringent enough to require additional investments in fuel-efficient technologies and operations. More generally, national and regional measures are needed to curb GHGs from domestic aviation, which is responsible for nearly 40% of global passenger CO_2 emissions and falls outside the jurisdiction of ICAO.

Second, this work highlighted the value of emissions disclosure by airlines to consumers. Historically, both airlines and environmental activists have acted as if every airline, aircraft, and route is equally carbon intensive, focusing efforts instead on biofuels and demand reduction, respectively, as the primary way of reducing emissions. In reality, we find significant differences in the carbon intensity of flights at all levels of the analysis: market, aircraft class, aircraft type, and seating class. These differences grow as the analysis becomes more granular. For example, we find that traveling in a premium seat on a regional jet emitted, on average, six times more CO_2 per RPK than an economy class seat on a widebody aircraft. Differences of 30% to 50% in the carbon intensity of aircraft within the same class are also seen. Better emissions disclosure, for example requiring airlines to disclose the carbon intensity of each itinerary to consumers at the time of purchase, would help consumers steer their business to lower emitting carriers.

Third, an expanding body of literature finds that frequent fliers contribute disproportionately to aviation emissions. Traveler survey data collected by IPSOS (Heimlich & Jackson, 2017) found that more than half of all trips in the United States in 2016 were taken by 7% of the adult population, and this group made on average of 19 round trips per year. This statistic is consistent with other countries. According to a UK Department for Transport survey, 10% of fliers in England took more than half of international flights in 2018, while the top 1% took one-fifth of all flights abroad that year (Kommenda, 2019). Ivanova and Wood (2020) found near-zero GHG emissions from air travel from the poorest 90% of EU households, while more than 40% of total GHG emissions for the top 1% of EU households by income were attributable to air travel.

If the goal of public policy is to reduce emissions while avoiding unfair socioeconomic impacts and regressive taxation, this data implies that aviation may be a particularly appropriate means of intervention. Current carbon pricing systems for aviation—the EU Emissions Trading System and ICAO's CORSIA agreement—are largely agnostic to seating class because they are based on total fuel burn irrespective of configuration. It is for airlines to apportion those costs to passengers. Other, less direct incentives either do not recognize the different carbon intensity of seating class, like the proposed frequent flier levy, or impose a price increase below the emissions multiplier identified here (e.g., the UK air passenger levy). This implies that carbon pricing for aviation could be improved, and be made more equitable, by properly reflecting the emissions increase due to premium travel. Graduating those fees based upon seating class so that premium travelers pay more could help generate revenue for climate mitigation in a progressive way.

We see a variety of areas for future refinement of this study, and better disaggregation of freight carriage is one. As passenger airlines temporarily convert their passenger aircraft to dedicated freighters due to the COVID-19 pandemic, emissions associated with freight have presumably increased, as well. While we had geographic allocation of emissions from dedicated freighters for many operators, we were missing data from two of the largest carriers. Data from the U.S. DOT can help us fill in some of the gaps, especially for flights departing from or arriving at a U.S. airport. But the lack of information on flights between non-U.S. airports prevents us from fully partitioning emissions to specific countries. Additional data sources may allow this.

Another area of further research is the effect that COVID-19 will have on future commercial aviation operations and emissions. We know that reduced demand will mean CO_2 emissions and fuel efficiency will be lower, with planes flying with fewer passengers, in 2020 compared with past years, and this may continue for a few years. Airlines are using this time period to "right size" their operations by retiring fuel-inefficient aircraft that are costly to operate and dropping service to markets that have not been profitable. In some cases, though, airlines are also deferring delivery of new, fuel-efficient aircraft due to financial constraints and are thus continuing to fly less fuel-efficient aircraft. Will the climate promises made by the airlines in early 2019 regarding carbon-neutral operations through offsetting and operational changes still hold in 2021, when a better sense of the full economic impact of the pandemic is realized?

The original aim was to update this work annually to provide policymakers with the data needed to develop strategies that reduce carbon emissions from commercial aviation while still accommodating future passenger and freight demand. However, as it might take some time for demand to return to 2019 levels, we will instead renew this report once comparing CO_2 emissions from commercial passenger operations to historical trends can provide relevant insights.

REFERENCES

Air Transport Action Group. (2020). *Fact sheet #3 – Tracking aviation efficiency*. Retrieved from https://aviationbenefits.org/media/166901/fact-sheet_3_tracking-aviation-efficiency.pdf

Bofinger, H., & Strand, J. (2013). Calculating the carbon footprint from different classes of air travel. Policy Research Working Paper 6471. World Bank. Retrieved from http://documents.worldbank.org/curated/en/141851468168853188/Calculating-the-carbon-footprint-from-different-classes-of-air-travel

British Broadcasting System (2019, March 14). Boeing grounds entire 737 Max crash aircraft fleet. Retrieved from https://www.bbc.com/news/business-47562727

Carrington, D. (2020, February 27). Heathrow third runway ruled illegal over climate change. The Guardian. Retrieved from https://www.theguardian.com/environment/2020/feb/27/heathrow-third-runway-ruled-illegal-over-climate-change

Doganis, R. (2019). *Flying Off Course: Airline Economics and Marketing*. (5th Edition) Routledge: New York

Economist Magazine (2020, July 4). Airlines blame covid-19 for rowing back climate commitments. Retrieved from https://www.economist.com/business/2020/07/04/airlines-blame-covid-19-for-rowing-back-climate-commitments

Graver, B. (2020). COVID-19's big impact on ICAO's CORSIA baseline [Blog post]. Retrieved from the International Council on Clean Transportation website: https://theicct.org/blog/staff/covid-19-impact-icao-corsia-baseline

Graver, B., Zhang, K., & Rutherford, D. (2019). *CO_2 emissions from commercial aviation, 2018*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf

Graver, B.; Rutherford, D. (2019). *U.S. Passenger Jets under ICAO's CO_2 Standard, 2018-2038*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/sites/default/files/publications/Aircraft_CO2_Standard_US_20181002.pdf

Graver, B.; Rutherford, D. (2018a). *Transatlantic airline fuel efficiency ranking, 2017*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/sites/default/publications/Transatlantic_Fuel_Efficiency_Ranking_20180912_v2.pdf

Graver, B.; Rutherford, D. (2018b). *Transpacific airline fuel efficiency ranking, 2016*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/sites/default/publications/Transpacific-airline-fuel-efficiency-ranking-2016_ICCT-white-paper_16012018_vF.pdf

Graver, B. (2018). Does it matter to your carbon footprint whether you're flying across the Atlantic or the Pacific? [Blog post]. Retrieved from the International Council on Clean Transportation website: https://theicct.org/blog/staff/carbon-footprint-flying-across-atlantic-or-pacific

Heimlich, J.; Jackson, C. (2018). *Air travelers in America: Findings of a survey conducted by Ipsos*. Retrieved from https://www.airlines.org/wp-content/uploads/2018/02/A4A-AirTravelSurvey-20Feb2018-FINAL.pdf

International Air Transport Association (2020). Industry statistics fact sheet. Retrieved from https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance-june-2020-data-tables/

International Civil Aviation Organization. (2017). *ICAO carbon emissions calculator methodology, version 10*. Retrieved from https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v10-2017.pdf

International Civil Aviation Organization. (2019a). *Glossary of terms – ICAO Data Plus*. Retrieved from https://data.icao.int/newDataPlus/content/docs/glossary.pdf

International Civil Aviation Organization, (2019b). *Presentation of 2018 Air Transport statistical results*. Retrieved from https://www.icao.int/annual-report-2018/Documents/Annual.Report.2018_Air%20Transport%20Statistics.pdf

International Civil Aviation Organization. (2020a). *2019 Environmental Report*. Retrieved from https://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1_WEB%20(1)pdf

International Civil Aviation Organization. (2020b). *ICAO Data+*. Retrieved from https://data.icao.int/newDataPlus/Tools

Ivanova D., & Wood, R. (2020). The unequal distribution of household carbon footprints in Europe and its link to sustainability. *Global Sustainability* 3, e18, 1–12. https://doi.org/10.1017/sus.2020.12

Kharina, A., Rutherford, D., & Zeinali, M. (2016). *Cost assessment of near- and mid-term technologies to improve new aircraft fuel efficiency*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/cost-assessment-near-and-mid-term-technologies-improve-new-aircraft-fuel-efficiency

Kommenda, N. (2019, September 25). 1% of English residents take one-fifth of overseas flights, survey shows. *The Guardian*. Retrieved from https://www.theguardian.com/environment/2019/sep/25/1-of-english-residents-take-one-fifth-of-overseas-flights-survey-shows

Olmer, N., & Rutherford, D. (2017). International Civil Aviation Organization's Carbon Offset and Reduction Scheme for International Aviation (CORSIA). Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/ICAO-carbon-offset-and-reduction-scheme-international-aviation

Piano 5 for Windows [Aircraft modeling software]. Woodhouse Eaves, UK: Lissys Limited.

Rutherford, D. (2020). Standards to promote airline fuel efficiency. Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/airline-standard-2020

Rutherford, D. (2019). Should you be ashamed of flying? Probably not.* [Blog post]. Retrieved from the International Council on Clean Transportation website: https://theicct.org/blog/staff/should-you-be-ashamed-flying-probably-not

Rutherford, D., & Kharina, A. (2016). *International Civil Aviation Organization CO_2 standard for new aircraft*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/international-civil-aviation-organization-co2-standard-new-aircraft

United States Transportation Safety Administration. (2020). TSA checkpoint travel numbers for 2020 and 2019. Retrieved from https://www.tsa.gov/coronavirus/passenger-throughput

United States Department of Transportation. (2020). *Air carrier statistics (Form 41 Traffic) – All carriers* [Database]. Retrieved from https://www.transtats.bts.gov/Tables.asp?DB_ID=111

United States Government (2015). United States Aviation Greenhouse Gas Emissions Reduction Plan, submitted to the International Civil Aviation Organization, June 2015. Retrieved from https://www.icao.int/environmental-protection/Lists/ActionPlan/Attachments/30/UnitedStates_Action_Plan-2015.pdf

APPENDIX: ICAO STATISTICAL REGIONS

Source: ICAO, 2019a

Africa

Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cabo Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion Island, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Togo, Tunisia, Uganda, United Republic of Tanzania, Western Sahara, Zambia, Zimbabwe

Asia/Pacific

Afghanistan, American Samoa, Australia, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, Coco Islands, Cook Islands, Democratic People's Republic of Korea, Fiji, French Polynesia, Guam, India, Indonesia, Japan, Johnston Island, Kazakhstan, Kingman's Reef, Kiribati, Kyrgyzstan, Lao People's Democratic Republic, Malaysia, Maldives, Marshall Islands, Micronesia (Federated States of), Midway, Mongolia, Myanmar, Nauru, Nepal. New Caledonia, New Zealand, Niue Islands, Norfolk Island, Pakistan, Palau, Palmyra, Papua New Guinea, Philippines, Republic of Korea, Saipan (Mariana Islands), Samoa, Singapore, Solomon Islands, Sri Lanka, Tajikistan, Thailand, Timor-Leste, Tonga, Turkmenistan, Tuvalu, Uzbekistan, Vanuatu, Viet Nam, Wake Island, Wallis and Futuna Islands

Europe

Albania, Andorra, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Faroe Islands, Finland, France, Georgia, Germany, Gibraltar, Greece, Greenland, Holy See (The), Hungary, Iceland, Ireland, Isle of Man, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine

Latin America and Caribbean

Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, British Virgin Islands, Caribbean Netherlands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Easter Island, Ecuador, El Salvador, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, St. Helena and Ascension, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela (Bolivarian Republic of), Virgin Islands

Middle East

Bahrain, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, State of Palestine, Syrian Arab Republic, United Arab Emirates, Yemen

North America

Bermuda, Canada, United States, St. Pierre and Miquelon

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

BEIJING | BERLIN | SAN FRANCISCO | SÃO PAULO | WASHINGTON