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TRANSPACIFIC AIRLINE FUEL EFFICIENCY RANKING, 2016

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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EXECUTIVE SUMMARY

Until recently, there has been very little public information on airline fuel efficiency. Starting in 2013, the International Council on Clean Transportation (ICCT) began assessing the fuel efficiency of U.S. airlines on domestic operations for 2010, with subsequent updates for 2011 through 2014. In 2015, the ICCT compared the fuel efficiency of 20 major airlines operating in the transatlantic market, specifically nonstop passenger flights between North America and Europe. This report extends the previous work on airline efficiency to the transpacific market.

Figure ES-1 illustrates the fuel efficiency of the 20 carriers analyzed. Passenger-based fuel efficiency was estimated after correcting for cargo carried on passenger flights ("belly freight"), which increases the absolute burn of a given flight but improves the fuel efficiency per unit of mass moved. Hainan Airlines and All Nippon Airways (ANA) were the most fuel-efficient airlines on transpacific operations in 2016, both with an average fuel efficiency of 36 passenger-kilometers per liter of fuel (pax-km/L), 16% better than the industry average. Qantas Airways ranked as the least fuel-efficient, falling 41% below the industry average. Qantas burned an average of 64% more fuel per passenger-kilometer than Hainan and ANA in 2016.

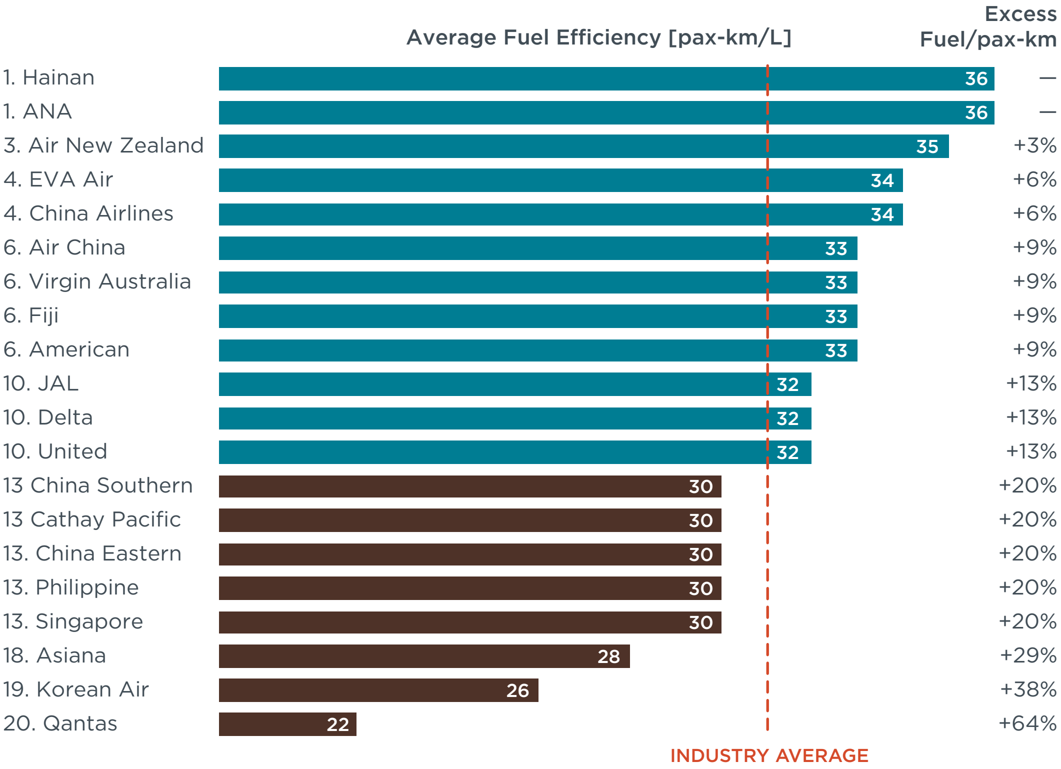

Figure ES-1. Fuel efficiency of 20 airlines on transpacific passenger routes, 2016

Hainan and ANA achieved the same overall fuel efficiency using very different strategies. Hainan's efficiency rating mostly reflected its very advanced fleet, as 81% of its available seat kilometers were aboard Boeing 787 Dreamliner aircraft. ANA, in contrast, operated aircraft with higher fuel burn but carried more payload, especially cargo. ANA carried about three times as much belly freight per passenger as Hainan, equaling 48% of total payload carried. Qantas recorded poor fuel efficiency because it operated the most fuel-intensive aircraft at very low load factors for both passengers and freight.

The report also assesses key drivers of the observed fuel efficiency gap across carriers (Figure ES-2). Factors investigated include aircraft fuel burn, seating density, passenger load factor, and freight share of total payload. Of these, freight share was found to be the most important driver overall, explaining almost half of the variation in airline fuel efficiency across carriers, followed by seating density, which accounted for nearly one quarter of the variation. Aircraft fuel burn and passenger load factors were relatively less important.

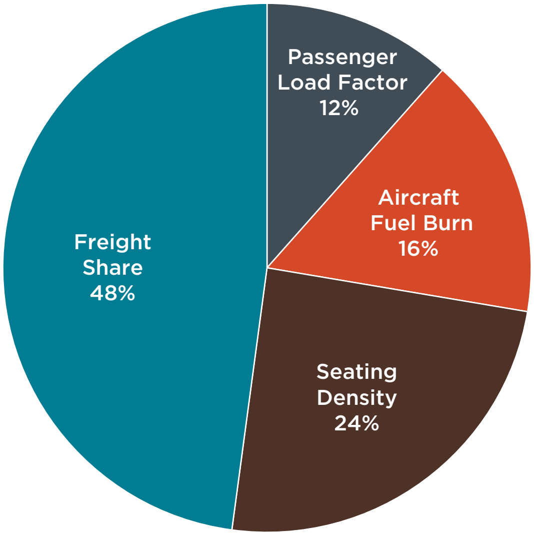

Figure ES-2. Key drivers of airline fuel efficiency

Other conclusions of this work include:

- There was an inverse relationship between aircraft size and fuel efficiency on transpacific operations—as aircraft weight, or maximum takeoff mass (MTOM), increases, fuel efficiency declines. This is predominantly because aircraft with four engines are generally less fuel-efficient than those with two.
- The estimated gap between the most and least fuel-efficient transpacific airlines was wider than was observed on transatlantic routes in 2014. This may be due to the incorporation of actual, as opposed to estimated, belly freight carriage into this report. Freight carriage explained almost half of the variation in the transpacific fuel efficiency in this work, compared with just 9% for transatlantic flights.
- Simplified online carbon calculators, such as the International Civil Aviation Organization's (ICAO's) carbon calculator, produced estimates of average aircraft fuel burn and fuel efficiency comparable to the findings of this report. ICAO's carbon calculator does not quantify carrier- or flight-specific estimates, however, with results varying significantly for carriers that are much more or less efficient than average.

1. INTRODUCTION

Until recently, there has been very little public information on airline fuel efficiency. U.S. carriers report quarterly fuel burn and operations by aircraft type and market, whether domestic or international, to the Bureau of Transportation Statistics (BTS) of the U.S. Department of Transportation (DOT). Fuel burn data is not required from foreign carriers, nor are similar data sets published by governments other than that of the United States. Several online carbon calculators, including from the International Civil Aviation Organization (ICAO) (2017a), ClimateCare (2017), and individual airlines (United Airlines, 2017), can be used to estimate fuel consumed and carbon dioxide (CO_2) emissions over origin-destination pairs for passengers and air freight. These calculators do not provide carrier- or flight-specific comparisons and are designed mostly to support carbon offsetting programs rather than to help consumers choose more fuel-efficient flights or carriers.

Starting in 2013, the International Council on Clean Transportation (ICCT) began assessing the fuel efficiency of U.S. airlines in its benchmark study of domestic operations for 2010 (Zeinali, Rutherford, Kwan & Kharina, 2013), with subsequent updates for 2011 through 2016 (Kwan, Rutherford & Zeinali, 2014; Kwan & Rutherford, 2014; Li, Kwan & Rutherford, 2015; Olmer & Rutherford, 2017). The gap between the most and least efficient airlines on U.S. domestic operations was 25% in 2014. This led the ICCT to compare the fuel efficiency of 20 major airlines operating in the transatlantic market, specifically nonstop passenger flights between North America and Europe. For 2014, there was a 51% gap between the most and least efficient airlines flying over the North Atlantic (Kwan and Rutherford, 2015). Overall, airlines with more fuel-efficient aircraft, less premium seating, and higher passenger and freight load factors operated more fuel-efficient flights.

This report extends the previous work on airline efficiency to the transpacific market. According to an ICAO forecast of future airline traffic, in 2020 “Europe and Asia/Pacific will have the largest share of CO_2 emissions from international aviation with 36.6% and 31%, respectively, followed by North America with 14.8%” (ICAO, 2013). This market differs from the U.S. domestic and transatlantic markets in important ways. Twin-aisle and very large aircraft are prevalent on flights across the Pacific Ocean but are rarely used for domestic operations. While twin-aisle and very large aircraft are also used on transatlantic flights, more premium flight offerings are available for the Asian market, typically resulting in fewer seats on each plane.

In addition, the amount of freight transported between Asia and the United States, both in dedicated freighter aircraft and in the cargo hold of a passenger plane, dwarfs what is carried between the United States and Europe. Accordingly, for the first time, we’ve directly integrated primary, as opposed to estimated, data of freight carriage on passenger flights data into the methodology. This belly freight accounts for approximately 25% of the total payload mass moved on passenger flights.

This report is structured as follows. Section 2 introduces the methodology to estimate airline fuel efficiency. Section 3 presents and discusses the results of the analyses with respect to airline, aircraft, and key routes. Section 4 offers conclusions along with potential future work to refine and extend the methodology presented.

2. METHODOLOGY

In the previous ICCT study (Kwan & Rutherford, 2015), a methodology was derived to estimate airline fuel efficiency on nonstop transatlantic routes. An international flight schedule database and detailed operational data reported to the BTS were used to model airline fuel burn for 20 major airlines. The estimated airline fuel efficiencies were validated using activity and fuel burn data reported by three American carriers. A similar methodology was used in this study.

All airlines operating flights to, from, and in the United States must report operations data to the BTS. The data is made available to the public via the BTS T-100 database. We purchased T-100 International Segment data from Airline Data Inc., which completes quality assurance and control procedures on the BTS data. The T-100 data provides information on air carrier, flight origin and destination, frequency, distance, aircraft type, seats available, passenger load factors, and freight transported. Separately, fuel burn reported through BTS Form 41 financial data was used to validate fuel burn modeling (see appendix). Calendar year 2016 was used in this analysis.

2.1 AIRLINE SELECTION

A list of 22 airlines was derived based on nonstop flights from the mainland United States to East Asia and Oceania. Flights to/from Hawaii and Guam were excluded from this analysis because the short flight distances could skew fuel burn comparisons. Flights to and from Canada were excluded because operations data reported to Transport Canada are not publicly available. Polar routes were included in the analysis and did not greatly impact average flight distance. Because Air France has only a single transpacific route and Air India only flies transpacific in the eastbound direction, these carriers were removed from the analysis.

Table 1 presents the 20 airlines analyzed in this report, along with each airline’s total number of transpacific flights, average flight length, share of available passenger seat kilometers (ASKs), share of available freight tonne kilometers (ATKs), and the prevalent aircraft used by each airline in its transpacific operations. More information on all of the aircraft types used in 2016 for transpacific flights is included in Table 2.

Table 1. Airlines evaluated

Airline	Flights Performed	Average flight length (km)	Share of ASKs	Share of ATKs	Most Prevalent Aircraft
Air China	5,441	10,547	5%	4%	Boeing 777-300ER
Air New Zealand	2,824	10,761	3%	3%	Boeing 777-300ER
ANA	8,300	9,726	5%	7%	Boeing 777-300ER
American	9,516	10,911	7%	8%	Boeing 787-8
Asiana	4,041	9,873	4%	2%	Boeing 777-200ER
Cathay Pacific	8,404	12,265	8%	8%	Boeing 777-300ER
China Airlines	2,596	11,193	3%	3%	Boeing 777-300ER
China Eastern	4,325	11,038	4%	5%	Boeing 777-300ER
China Southern	2,942	12,008	3%	3%	Boeing 777-300ER
Delta	12,237	9,956	9%	9%	Boeing 777-200LR
EVA Air	6,091	11,254	6%	7%	Boeing 777-300ER
Fiji	711	8,998	< 0.5%	< 0.5%	Airbus A330-200
Hainan	3,236	10,252	2%	6%	Boeing 787-8
JAL	6,395	9,901	4%	4%	Boeing 787-8
Korean Air	8,094	10,485	8%	6%	Boeing 777-300ER
Philippine	2,338	11,699	2%	2%	Boeing 777-300ER
Qantas	3,794	12,543	5%	4%	Airbus A380-800
Singapore	2,756	10,178	2%	3%	Boeing 777-300ER
United	20,033	10,741	17%	16%	Boeing 777-200ER
Virgin Australia	1,458	11,912	2%	1%	Boeing 777-300ER
Total	**115,532**	**10,738**	**100%**	**100%**	

ASK = Available seat kilometers, ATK = Available tonne kilometers, Source: Airline Data Inc., 2017

Table 2. Aircraft types serving transpacific operations

Aircraft	MTOM (tonnes)	Typical seating capacity	Cargo capacity (m³)	Number of Engines, Max Thrust	Range (km)
Boeing 767-300ER	187	261	114	2 @ 282 kN	11,070
Boeing 787-8	228	242	137	2 @ 280 kN	13,620
Airbus A330-200	242	247	132	2 @ 316 kN	13,450
Airbus A330-300	242	277	158	2 @ 316 kN	11,750
Boeing 787-9	254	290	173	2 @ 320 kN	14,140
Airbus A340-300	277	277	162	4 @ 151 kN	13,500
Airbus A350-900	280	325	162	2 @ 375 kN	15,000
Boeing 777-200ER	298	313	202	2 @ 417 kN	13,080
Boeing 777-200LR	347	317	151	2 @ 513 kN	15,840
Boeing 777-300ER	352	396	202	2 @ 513 kN	13,650
Boeing 747-400	397	416	160	4 @ 282 kN	11,250
Boeing 747-400ER	413	416	160	4 @ 282 kN	14,000
Boeing 747-8I	448	410	176	4 @ 296 kN	14,816
Airbus A380-800	575	544	184	4 @ 311 kN	15,200

MTOM = maximum takeoff mass
Sources: Airbus, 2017; Boeing, 2006; Boeing, 2008; Boeing, 2010; Boeing, 2011; Boeing, 2017

2.2 FUEL BURN MODELING

Similar to the ICCT's previous transatlantic fuel efficiency ranking (Kwan & Rutherford, 2015), aircraft fuel burn was modeled using Piano 5, an aircraft performance and design software (Lissys Ltd., 2017). Piano 5 requires various inputs to model aircraft fuel burn, and Table 3 contains a list of the key modeling variables and sources.

Table 3. Key modeling variables

Type	Variable	Sources
Airline scheduled flights	Route	BTS T-100 International Segments
	Aircraft used	
	Available seats	
	Departures	
	Passenger load factor	
	Freight carriage	
Airline-specific aircraft parameters	Type and count	Ascend Fleets
	Engine	
	Winglets/Scimitar	
	Maximum takeoff mass	
	Seats	
Aircraft weights	Operating empty weight	Piano 5
	Passenger weight	Industry standard
	Seat and furnishings weight	ICAO default
Aircraft fuel burn	Engine thrust	Piano 5
	Drag	
	Fuel flow	
Other operational variables	Taxi time	BTS T-100 International Segments, FAA Part 121, Piano 5
	Fuel reserves	
	Flight levels	
	Speed	

The Ascend Fleets database from FlightGlobal provides comprehensive carrier fleet and aircraft specific information (FlightAscend Consultancy, 2017). This database was used to assign representative Piano 5 aircraft to each airline by matching aircraft type, use of wingtip device, engine type, seat count, and maximum takeoff mass (MTOM) as closely as possible.

For flight distance, the great circle distance[1] of each flight was reported in the T-100 data and was adjusted upward by 125 km based on ICAO methodologies for flights greater than 5,500 km (ICAO, 2017b).

International flights carry both passengers and freight, so the fuel burn of individual flights must be apportioned between passengers and freight based on mass. The

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[1] Great circle distance is the shortest distance between two points on a sphere. Aircraft may deviate from great circle distance for a variety of reasons, including to maintain communications with air traffic control towers and avoid turbulence or weather.

average payload per flight was estimated using Equation 1 for each airline-aircraft-seat count-distance flight group given the reported number of departures, available seats, passenger load factor, and freight carriage. The industry-wide standard mass for a passenger and luggage of 100 kg is used (ICAO, 2017b). Changes in aircraft weight due to an aircraft type having multiple seating configurations were incorporated into the modeling by adjusting the default number of seats in Piano, assuming 50 kg per seat.

$$payload\ [kg] = \left(\frac{seats}{departures}\right)(load\ factor_{pax})\left(\frac{100\ kg}{pax}\right) + \left(\frac{freight\ [kg]}{departures}\right) \qquad \text{(Eq. 1)}$$

Default Piano 5 values for operational parameters such as engine thrust, drag, fuel flow, available flight levels, and speed were used because of the lack of airline- and aircraft-specific data. Cruise speeds were set to allow 99% maximum specific air range. Taxi times were set at 34 minutes, as estimated by T-100 International Segments data for transpacific flights by the three U.S. carriers (DOT, 2017). This is equal to the average taxi time used in the transatlantic rankings (Kwan & Rutherford, 2015). Fuel reserves were set for a 370 km diversion distance, 10% mission contingency fuel to account for weather, congestion, and other unforeseen events, and 45 minutes at normal cruising fuel consumption, corresponding to a U.S. Federal Aviation Administration (FAA) Operations Specification B043 (FAA, 2014).

2.3 FUEL EFFICIENCY CALCULATION

The fuel efficiency of each flight was calculated using the method developed for the ICCT's previous transatlantic ranking (Kwan & Rutherford, 2015). The average fuel efficiency for each airline (represented by index *a*) was calculated using a bottom-up approach.

After modeling each unique airline-aircraft-seat count-distance-payload flight group, represented by index *i*, the total liters (L) of fuel consumed for the full set of nonstop transpacific flights flown by each of the 20 airlines was calculated according to Equation 2.

$$fuel\ [L]_a = \sum\nolimits_i (fuel\ [L]_{a,i})\,(departures_{a,i}) \qquad \text{(Eq. 2)}$$

Aircraft fuel use is proportional to the total payload mass transported. For passenger flights that also carry cargo ("belly freight"), payload is calculated as the total mass of passengers and freight per flight. Belly freight, while increasing the absolute burn of a given flight, improves the fuel efficiency of an airplane per unit of mass moved because the airframe is loaded closer to its maximum payload capability. The ratio of payload-distance to fuel burned for each airline was used as a starting point for the average fuel efficiency metric. This was then converted to the passenger-based metric, passenger-kilometers per liter of fuel (pax-km/L), using the passenger weight factor, as shown in Equation 3.

$$pax\text{-}km/L_a = \frac{\sum\nolimits_i (payload\ [kg]_{a,i})\,(distance\ [km]_{a,i})}{(fuel\ [L]_a)\,(100\ kg/pax)} \qquad \text{(Eq. 3)}$$

The resulting fuel efficiencies for the 12 aircraft types operated by U.S. airlines was validated using Form 41 fuel burn data, as described in the appendix.

3. RESULTS

The bottom-up methodology allows for comparison of transpacific fuel efficiency at the airline, aircraft, and route level. Sections 3.1 and 3.2 present the overall and airline-specific fuel efficiency results. Section 3.3 drills down to the level of individual routes, and Section 3.4 relates the results to the aircraft types. Section 3.5 explains the high-level airline rates in terms of key drivers of fuel efficiency, including aircraft fuel burn, seating capacity, passenger load factor, and freight carriage.

3.1 AIRLINE COMPARISONS

The average fuel efficiencies in pax-km/L of 20 airlines operating transpacific routes in 2016 are shown in Figure 1. The orange dashed line indicates the industry average fuel efficiency of 31 pax-km/L. Hainan Airlines and All Nippon Airways (ANA) tied as the most fuel-efficient airlines with an average fuel efficiency of 36 pax-km/L, 16% higher than the industry average. Qantas Airways ranked as the least fuel-efficient, at 41% below the average. Qantas burned on average 64% more fuel per passenger-kilometer than Hainan and ANA in 2016. This gap is 13 percentage points higher than that seen on 2014 transatlantic flights (Kwan & Rutherford, 2015).

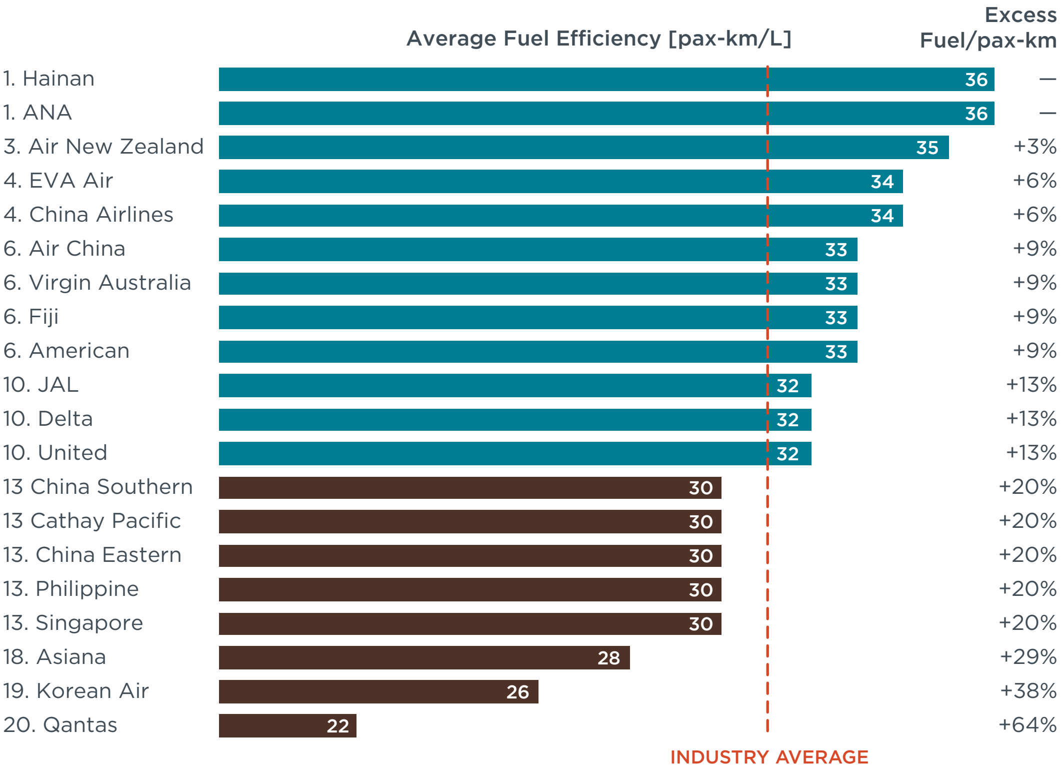

Figure 1. Fuel efficiency of 20 airlines on transpacific passenger routes, 2016

A few other patterns emerge from Figure 1. The fuel efficiency of the two Japanese carriers were both above average, with a moderate, 4 pax-km/L, difference between first-ranked ANA and tenth-ranked JAL. Both airlines flew the Boeing 777-300ER, 787-8, and 787-9, with similar seating densities and load factors. However, ANA's freight share was 11 percentage points higher than that of its Japanese competitor. The three

U.S. carriers—American, Delta, and United—demonstrated similar and slightly above-average fuel efficiencies. American's average fuel efficiency was 1 pax-km/L better than that of Delta, which had the highest passenger load factor, and that of United, with the most ASKs.

Carriers registered to mainland China and Hong Kong exhibited a wide range of fuel efficiencies, from first-place Hainan to 13th-place China Southern and China Eastern Airlines. Finally, the passenger airlines of South Korea were notably less fuel-efficient than their peers, taking two of the bottom three spots in the ranking. Both Asiana and Korean Air flew large, four-engine aircraft for more than half of ASKs in 2016. We return to the relationship between aircraft size and fuel efficiency below.

3.2 AIRLINE-SPECIFIC DISCUSSIONS

The aircraft used, passenger load factor, and freight carriage are key determinants of airline fuel efficiency. This section outlines how the fuel efficiency of each airline could be adjusted by improvements in these parameters.

Hainan Airlines (T-1st: 36 pax-km/L), is a Chinese carrier rated five star by SKYTRAX, a consultancy that reviews and ranks global airlines and airports (SKYTRAX, 2017). The Haikou, Hainan-based airline took the top spot in the transpacific rankings because of its use of very fuel-efficient aircraft. The Boeing 787 Dreamliner flew more than 80% of Hainan's 3,200 transpacific flights, with the Airbus A330 accounting for the rest. Hainan could further increase its fuel efficiency by elevating its passenger load factor or freight carriage. Both are currently at the industry average.

All Nippon Airways (T-1st: 36 pax-km/L) is Japan's largest airline and has a five-star rating. It was named the world's third-best airline in 2017 by SKYTRAX. With hubs at Tokyo's Haneda and Narita airports, the carrier flies Boeing 777-300ER, 787-8, and 787-9 aircraft on its transpacific routes. ANA had the highest freight-to-payload ratio at 48%, compared with the industry average of 25%, but one of the lowest passenger load factors at 76%, compared with the industry average of 82%. The high freight carriage improved ANA's fuel efficiency despite the relatively low number of passengers carried per flight. Increasing the number of passengers or mass of cargo on each flight would further boost fuel efficiency, although fuel efficiency will plateau when payload mass restrictions are met.

Air New Zealand (3rd: 35 pax-km/L) is the four-star flag carrier for the Oceanic nation, ranked the second-safest airline in the world by Germany's Jet Airliner Crash Data Evaluation Centre (JACDEC, 2017). The carrier, with hubs at Auckland, Wellington, and Christchurch, flew the Boeing 777-200ER or -300ER on all flights between the United States and New Zealand. Air New Zealand used the less fuel-efficient Boeing 767-300ER for 90% of flights between Los Angeles and Rarotonga of the Cook Islands. In 2017, the Kiwi carrier retired the Boeing 767 from service (Air New Zealand, 2017) and now uses the Boeing 777-200ER on the once weekly roundtrip flight. While the 777 is more fuel-efficient than the 767, we expect a negligible increase in the carrier's fuel efficiency metric from this switch because only a small number of flights, 96, were flown with the 767.

EVA Air (T-4th: 34 pax-km/L) used Boeing 777-300ER aircraft on all routes between the United States and Taipei, with the exception of 250 flights using a Boeing 747-400. EVA retired its Boeing 747s in August 2017 (Blachly, 2017). While the 777 is more fuel-efficient than the 747, there would be a negligible increase in the airline's fuel efficiency metric related to the aircraft switch because the 747 accounted for only about 4% of flights. EVA would have to increase its passenger load factor or freight carriage, both of which are already above the industry average, to increase efficiency.

China Airlines (T-4th: 34 pax-km/L) deployed the Boeing 777-300ER on all transpacific routes with the exception of two flights of a Boeing 747-400. In 2017, China Airlines started flying the Airbus A350-900 on its Taipei-San Francisco route (Hofmann, 2017). If the same passenger load factors and freight shares for the Boeing 777 are maintained on the A350 between Taipei and San Francisco, then the fuel efficiency of this route would increase from 35 to 42 pax-km/L. If all transpacific operations are flown with the A350 instead of the 777, assuming the same passenger load factors and freight shares, then China Airlines' fuel economy would be 40 pax-km/L.

Air China (T-6th: 33 pax-km/L), the flag carrier of the People's Republic of China, is challenging to assess in terms of improvement potential. Air China mistakenly misreported the aircraft used on flights between the United States and Asia to DOT. Despite weeks of discussions with Airline Data Inc. and DOT, not all 2016 T-100 International Segment data for Air China could be corrected before publication of this report. Therefore, nearly 12% of departures were removed from this analysis because of incorrect reporting of aircraft and other operational variables. There is uncertainty on whether the airline's total fuel efficiency would change from the current calculation with the addition of corrected data, possibly affecting its place in the rankings. Air China has since rectified this error with DOT.

Virgin Australia (T-6th: 33 pax-km/L), the four-star carrier and second-largest airline in Australia, used Boeing 777-300ER aircraft on its flights between Los Angeles and Brisbane and Sydney. There are no current orders for other wide-body aircraft. Therefore, Virgin Australia would have to increase passenger load factor or freight carriage to raise its fuel efficiency metric. Loading an additional 1,000 kg of freight or 10 passengers to each flight would increase Virgin Australia's fuel efficiency to 34 pax-km/L.

Fiji Airways (T-6th: 33 pax-km/L) is the Nadi-based flag carrier of the South Pacific island country. It uses Airbus A330-200 and -300 aircraft on flights between Nadi International Airport and San Francisco and Los Angeles. These flights are the shortest of the transpacific flights. Since Fiji has no current orders for other wide-body aircraft, it would have to increase passenger load factor or freight carriage to improve its fuel efficiency. Loading an additional 1,000 kg of freight or 10 passengers to each flight would increase its fuel efficiency to 34 pax-km/L.

American Airlines (T-6th: 33 pax-km/L), the world's largest carrier by RPKs, flies Boeing 777-200ER, 777-300ER, 787-8, and 787-9 aircraft on transpacific operations. American's average passenger load factor and freight share of total payload were both above the industry average. However, American could improve its fuel efficiency to 40 pax-km/L by replacing the 777 with the 787 on all possible routes, assuming the number of passengers and freight share of total payload remained the same.

Japan Airlines (T-10th: 32 pax-km/L), a four-star flag carrier, flies Boeing 777-300ER, 787-8, and 787-9 aircraft between Japan and the United States. JAL placed orders for Airbus A350 aircraft to eventually replace the Boeing 777s (Holliday, 2014). However, since the airline has not announced the seating configuration for the A350s on international routes, estimating its fuel efficiency on transpacific operations is impractical.

Delta Air Lines (T-10th: 32 pax-km/L), the world's second-largest carrier and JACDEC's safest airline in North America, had above-average fuel efficiency in part because of its passenger load factor of 88%, the highest of any airline on transpacific flights. Delta was hurt by the use of Boeing 747-400 aircraft. Delta announced that it will retire its 747 fleet by the end of 2017 and deploy Airbus A350-900 aircraft (Russell, 2017b). If the same passenger load factor and freight share of total payload reported for the 747 operations are maintained for future A350 operations, then the fuel efficiency for all Delta transpacific operations would rise to 34 pax-km/L.

United Airlines (T-10th: 32 pax-km/L) is a U.S. legacy airline with hubs in Chicago, Denver, Guam, Houston, Los Angeles, Newark, Tokyo Narita, and Washington, DC—all serving transpacific operations. Guam is excluded from the analysis due to its proximity to Asia, which would skew average flight length and potentially favor airlines operating those shorter flights. United, the third-largest carrier in the world, uses a Boeing wide-body fleet of 747-400s, 777-200ERs, 787-8s, and 787-9s for transpacific operations. United announced that it would retire its fleet of 747s by October 2017 and replace those planes with Boeing 777-300ER aircraft (Russell, 2017a). If the 747's passenger load factor and freight share of total payload are maintained for future 777-300ER operations, the fuel efficiency for all United transpacific operations would improve to 34 pax-km/L.

China Southern Airlines (T-13th: 30 pax-km/L), the world's sixth-largest and four-star rated carrier, uses Airbus A380-800 and Boeing 777-300ER and 787-8 aircraft on its transpacific routes. The airline had the second-highest average passenger load factor but also the third-lowest freight share of total payload (12%), compared to the industry average of 26%. If the amount of belly freight were increased to the industry average, the fuel efficiency for all China Southern transpacific operations would rise to 34 pax-km/L. This large jump in fuel efficiency reflects the very low 7-8% freight share of total payload for the Boeing 787. Although the Dreamliners in the China Southern fleet already recorded fuel efficiency of 33 pax-km/L, increasing cargo volume to the industry average would raise the plane's fuel efficiency metric by 18% to 39 pax-km/L.

Cathay Pacific (T-13th: 30 pax-km/L), the five-star flag carrier of Hong Kong and the world's safest airline according to JACDEC, uses Boeing 777-300ER aircraft on all flights between the United States and Hong Kong. Cathay Pacific announced it would use its newly acquired Airbus A350 aircraft between San Francisco and Hong Kong starting in October 2017 (Cathay Pacific Airways, 2017). If the same passenger load factors and freight share of total payload that were reported for 777 operations are maintained for future A350 operations, then fuel efficiency on this route would increase from 32 to 38 pax-km/L. If all Cathay Pacific transpacific operations are flown with the A350, assuming the same passenger load factors and freight share of total payload, then total fuel efficiency would increase to 40 pax-km/L.

China Eastern Airlines (T-13th: 30 pax-km/L), the 10th-largest airline in the world based on RPKs, uses Airbus A330-200 and Boeing 777-300ER aircraft on its flights between the United States and Asia. Flights between the United States and the airline's hub at Shanghai Pudong International Airport had an average passenger load factor of 81%. However, China Eastern's flights between San Francisco and Qingdao had a very low passenger load factor of 35%. Between Los Angeles and Nanjing, the load factor was also low at 58%. If China Eastern could increase the passenger load factor for these two routes, accounting for 9% of its transpacific operations, to match the Shanghai route's 81%, then its total fuel efficiency would equal the industry average of 31 pax-km/L.

Philippine Airlines (T-13th: 30 pax-km/L), the flag carrier for the Southeast Asia nation, will receive six Airbus A350-900s starting in 2018 to replace some of its inefficient A340s (Toh, 2016). This will help Philippine Airlines in future transpacific rankings. The twin-engine A350s are expected to have approximately 300 seats, while the four engine A340s have 254 seats. If the passenger load factor and freight share of total payload are maintained with the A350s, then Philippine's fuel efficiency would improve to 33 pax-km/L, or above average.

Singapore Airlines (T-13th: 30 pax-km/L), the five-star flag carrier and SKYTRAX's second-best airline in the world, uses Airbus A350-900, A380-800, and Boeing 777-300ER aircraft on its flights to Los Angeles and San Francisco. The airline has fifth freedom[2] rights to fly to the United States from Japan, South Korea, and Hong Kong, in addition to Singapore. The A380, configured with either 379 or 441 seats, is the least fuel-efficient aircraft in its fleet, with an average of 304 passengers per flight. If an additional 50 passengers flew on each A380 flight, then the aircraft's fuel efficiency metric would increase from 24 to 27 pax-km/L. The same fleet fuel efficiency metric of 30 pax-km/L could be achieved by loading an additional 1,000 kg of freight or 10 passengers to all flights. Singapore recently inked a deal to purchase 20 Boeing 777-9s for use on long-haul routes and 19 787-10s for medium-haul routes (Nensel, 2017).

Asiana Airlines (18th: 28 pax-km/L), a five-star airline and the second-largest carrier in South Korea, used Airbus A330-300, A380-800, and Boeing 777-200ER aircraft on its flights between Seoul and the United States in 2016. As of 2017, Asiana no longer uses the A330 on its flights to and from Seattle in favor of the 777-200ER. Assuming the same number of passengers and freight, this switch would decrease the fuel efficiency on the route by 3 pax-km/L and would lower Asiana's transpacific fuel efficiency to 27 pax-km/L. The carrier could boost its fuel efficiency by increasing freight carriage. In 2016, Asiana had one of the lowest freight share of total payload. If the amount of belly freight increased to the industry average, Asiana's fuel efficiency would rise to 32 pax-km/L.

Korean Air (19th: 26 pax-km/L), the four-star flag carrier of South Korea, flies a mixture of Airbus A330 and A380 and Boeing 747 and 777 aircraft. The airline announced that it will retire its fleet of Boeing 747-400s by the end of 2017 and replace them with 747-8 aircraft (Schofield, 2016). This will make a negligible improvement to its fuel efficiency because only nine transpacific flights were flown with the 747-400s. Korean Air will have to increase passenger load factor or freight carriage to improve its fuel efficiency. In 2016, the carrier had one of the lowest passenger load factors, more than 7 percentage points below the industry average. If the passenger load factor across all flights increased by 10 percentage points, Korean Air could achieve a fuel efficiency of 29 pax-km/L.

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2 Fifth freedom traffic rights allow an airline to carry passengers between two foreign countries when the origin or final destination of the flight is the airline's domicile country. Singapore uses these rights to operate flights between other Asian countries and the United States.

Qantas (20th: 22 pax-km/L), the four-star flag carrier of Australia, deploys the Airbus A380 and Boeing 747-400ER, two of the most fuel-inefficient aircraft, on its transpacific routes. The airline also has the longest average flight length, at more than 12,000 km, with the longest route being between Houston and Sydney. Qantas had the lowest average passenger load factor of any airline on transpacific flights, filling only 74% of available seats, as well as one of the lowest freight shares at 12% of total payload. Adding 1,000 kg of freight or 10 passengers to each flight would have a negligible effect on the total fuel efficiency of the Flying Kangaroo. Qantas will receive eight Boeing 787-9 aircraft through 2018, which will be used on flights to and from the United States (Taylor, 2017). If the same passenger load factor and freight share are maintained on the new Dreamliners, then the carrier's overall fuel efficiency would increase to 28 pax-km/L.

3.3 ROUTE COMPARISONS

In addition to these high-level results, we selected seven routes with the most airline competition as case studies to evaluate how aircraft, passenger load factor, and freight carriage affect fuel efficiency. Route-level data can also be compared with results from carbon calculators developed by ICAO to test the value of our higher fidelity approach.

Los Angeles-Tokyo. The transpacific route with the most airline competition is between Los Angeles and Tokyo. For this analysis, we combined both Tokyo airports—Haneda and Narita—because airlines split their operations across the two airports and the differences in flight distance would have a negligible effect on fuel efficiency. In 2016, six airlines completed 6,604 flights between the two cities, or nearly 6% of all transpacific flights, as shown in Figure 2. The effect of aircraft type on fuel efficiency is clearly visible in the results. United, which flew nearly all Boeing 787 Dreamliners, was the most fuel-efficient airline on the route, beating the fuel efficiency of its competitors by 16% to 65%. On the other end of the spectrum, Singapore used the Airbus A380 on two-thirds of its flights and had the worst fuel efficiency by a large margin. JAL, Delta, and American all had similar average fuel efficiencies, with JAL flying the Boeing 777-300ER, Delta using Boeing 767-300ERWs and 777-200LRs, and American flying Boeing 777-200ERs, 777-300ERs, and 787-8s. ANA also used the Boeing 777-300ER, but greater freight carriage provided for higher fuel efficiency.

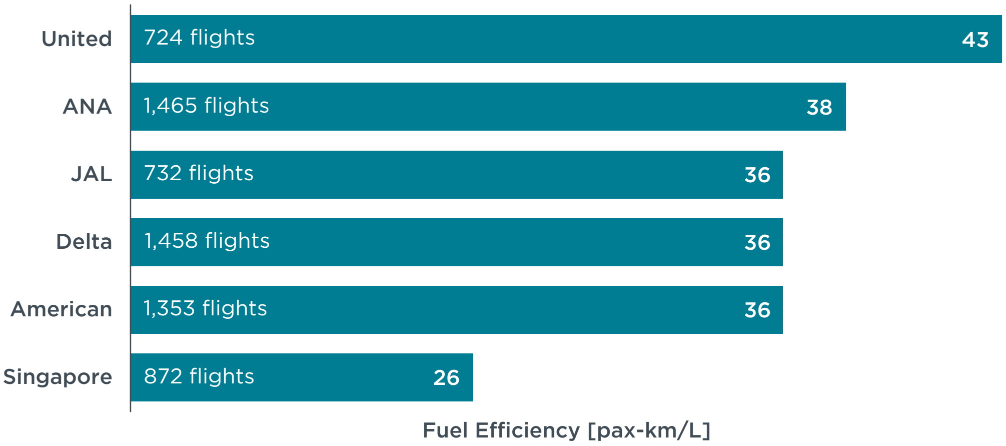

Figure 2. Fuel efficiency for airlines serving Los Angeles-Tokyo routes

Chicago-Tokyo. Results are significantly different for flights connecting Tokyo's two international airports with Chicago. Four of the airlines that flew to Tokyo from Los Angeles also flew from Chicago. Figure 3 depicts the average fuel efficiency for American, ANA, JAL, and United on the route. While United flew the Dreamliner on its Tokyo flights to and from Los Angeles, nearly two-thirds of the flights to and from Chicago were with the inefficient Boeing 747-400. As the airline using Dreamliners on the route, American won the title as most fuel-efficient. ANA and JAL both flew Boeing 777-300ERs. JAL's average passenger load factor was 8 percentage points higher than ANA's, equating to an extra 10 passengers per flight. However, ANA's average freight share of total payload was nearly 14 percentage points higher than for JAL, or the equivalent mass of 75 passengers. This explains ANA's better fuel efficiency.

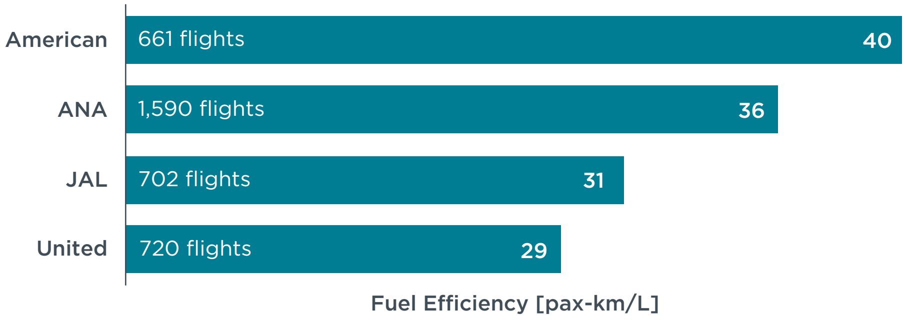

Figure 3. Fuel efficiency for airlines serving Chicago-Tokyo routes

Los Angeles-Sydney. Five airlines served the route between Los Angeles and Sydney, which accounted for 3% of transpacific flights. Delta was the most fuel-efficient, as shown in Figure 4, followed closely by Virgin Australia and United. On this route, Delta flew Boeing 777-200LR aircraft; Virgin Australia, Boeing 777-300ERs; and United, mostly Boeing 787s. Like Virgin Australia, American used Boeing 777-300ER aircraft. However, American's average passenger load factor was 72%, 9 percentage points lower than Virgin Australia's. The average fuel efficiency for Qantas between Los Angeles and Sydney was 3 pax-km/L higher than its fuel efficiency over all routes. More than three-quarters of the Flying Kangaroo's flights were operated with Airbus A380s.

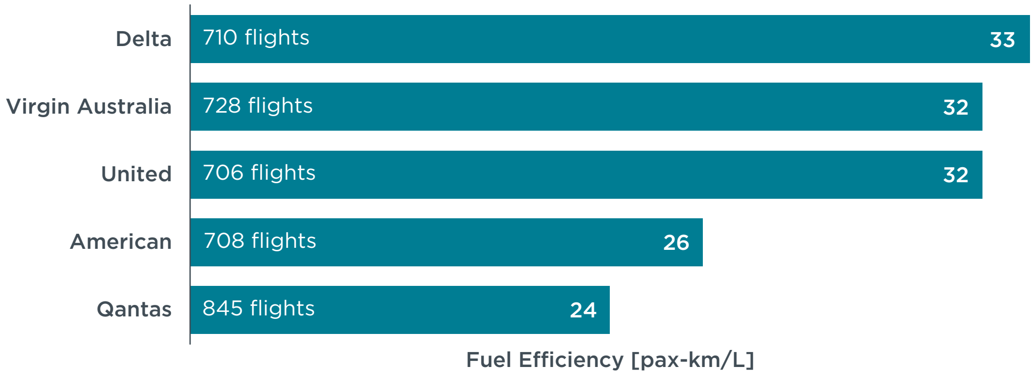

Figure 4. Fuel efficiency for airlines serving Los Angeles-Sydney route

San Francisco-Seoul. Three of the four airlines that served the San Francisco-Seoul route had similar average fuel efficiencies: Asiana, Singapore, and United (Figure 5). However, each airline flew a different aircraft. Asiana and Singapore both flew Boeing 777s, but Asiana used the -200ER variant while Singapore operated the -300ER variant. Asiana's 89% average passenger load factor was 11 percentage points higher than Singapore's, a leading element of why the two airlines had similar fuel efficiencies. United flew three-quarters of its flights with inefficient Boeing 747-400s, but its fuel economy was helped by the 15% of flights flown with Boeing 787s.

The dominant airline out of Seoul, Korean Air, used mostly Boeing 747-8 aircraft, leading to an average of 16% more fuel use per passenger-kilometer than Singapore.

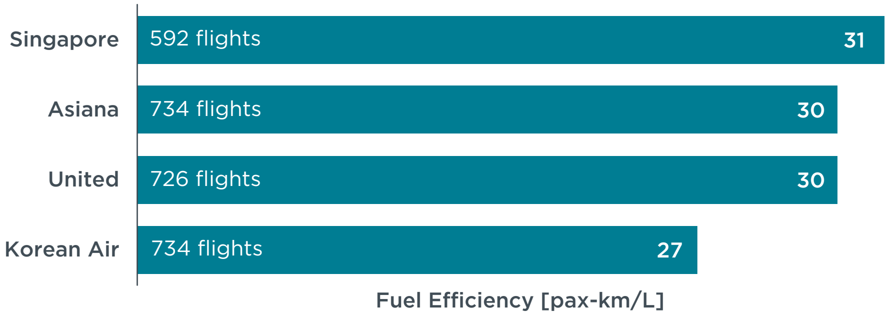

Figure 5. Fuel efficiency for airlines serving San Francisco-Seoul route

San Francisco-Hong Kong. The flag carriers of Hong Kong and Singapore were most fuel-efficient on the route between San Francisco and Hong Kong International Airport, as depicted in Figure 6. Cathay Pacific and Singapore Airlines both flew Boeing 777-300ERs on the route. Singapore's average passenger load factor was 2 percentage points higher than Cathay Pacific's, but its planes had 62 fewer seats. Therefore, Cathay Pacific carried an average of 281 passengers per flight, compared with Singapore's average of 235 passengers. In terms of freight carriage, Singapore transported the equivalent mass of 42 passengers more freight than Cathay, nearly eliminating the difference in passenger payload. The difference in the average payload between the two airlines was 253 kilograms.

United fared worst, using Boeing 747-400 aircraft.

Figure 6. Fuel efficiency for airlines serving San Francisco-Hong Kong route

San Francisco-Beijing, Chicago-Beijing. Two popular routes between Beijing and the United States are from the San Francisco Area (including San Jose, CA) and Chicago. Hainan and United served both of these routes, with Air China flying to Beijing from San Francisco and American from Chicago. Because Hainan was the overall most efficient airline on transpacific flights, one might assume it would also be the most efficient on each route. While Hainan is easily the most fuel-efficient airline on the San Francisco-Beijing route, as shown in Figure 7, it lags behind American on the Chicago-Beijing route, as shown in Figure 8. American and Hainan both flew the Boeing 787-8 Dreamliner on the route, but American's passenger load factor averaged 86% while Hainan's averaged 84%. In addition, the average freight share of total payload for American was 4 percentage points higher than for Hainan.

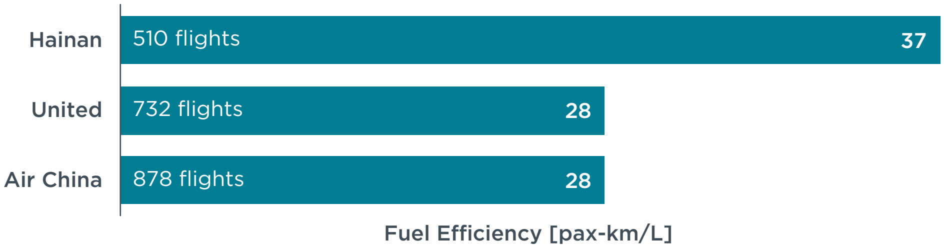

Figure 7. Fuel efficiency for airlines serving San Francisco-Beijing routes

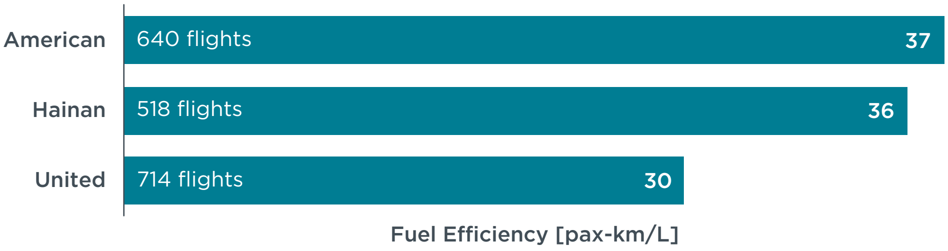

Figure 8. Fuel efficiency for airlines serving Chicago-Beijing route

These route-based analyses can be compared with findings of other resources for benchmarking airline fuel efficiency. For example, as part of its CO_2 calculator, ICAO estimates the average total fuel burn per flight using a formula derived from fuel burn data reported by U.S. airlines to BTS (ICAO, 2017b). The total fuel burn on a route is the weighted average of fuel burn by each aircraft type on the route, based on flight frequency. The roundtrip fuel burn was calculated for these seven city pairs using the ICAO CO_2 calculator as a comparison with our Piano-modeled results. On average, ICAO's fuel burn estimates ranged from -7% to +9% compared with the results presented above, depending on route.

Larger deviations are seen at the airline level. For example, a Boeing 777-300ER flown by an American carrier may have vastly different seating configuration and payload from those of a Boeing 777-300ER flown by an Asian carrier. Furthermore, freight share and seating configuration are major drivers of fuel efficiency. The information provided by the ICAO CO_2 calculator is not useful for selecting individual carriers or routes and may deviate significantly from the fuel burn of best and worst carriers operating on a given route. For example, ICAO estimates total fuel use to be 232 tonnes for a roundtrip flight between Los Angeles and Sydney. According to our methodology, United's average fuel burn for the roundtrip flight was 33% lower than the ICAO average, while Qantas's was 44% higher.

3.4 AIRCRAFT-SPECIFIC DISCUSSIONS

These high-level and route-specific fuel efficiency comparisons are related to the underlying fuel burn of the aircraft used. Figure 9 depicts the difference in aircraft model average fuel efficiency from the transpacific average of 31 pax-km/L. The Boeing 777 family of aircraft was the most widely used on transpacific routes in 2016, accounting for 57% of all flights. Its fuel efficiency averaged approximately 1 pax-km/L better than the industry average. The Boeing Dreamliner and the Airbus A330-300, in contrast, were notably more fuel-efficient at 35 to 39 pax-km/L. The Airbus A350-900, with its fuel efficiency just above average, did not perform as well as might be expected given its technology level because of the small number of transpacific flights flown in 2016—280. We expect the plane's average fuel efficiency to improve as more airlines fly the aircraft at higher passenger load factors and freight share.[3]

As shown in Figure 9, the A340 and A380 were the most inefficient Airbus aircraft, while the 747s were the least efficient for Boeing. A general trend is a decrease in fuel efficiency as MTOM increases. Heavier aircraft require more than two engines for propulsion and, as seen in Figure 9, aircraft with four engines are generally less fuel-efficient than those with two. It is important to note that variations in passenger load factors and freight carriage could affect the magnitude of difference in fuel efficiency.

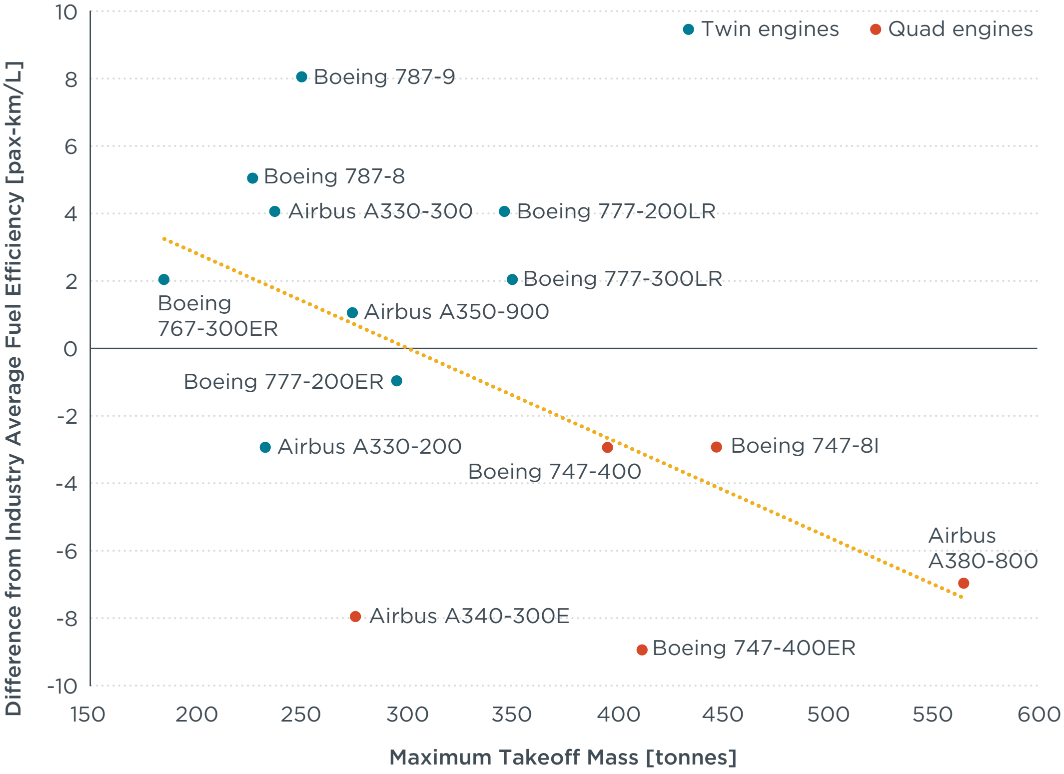

Figure 9. Difference from industry average fuel efficiency of 31 pax-km/L for 14 aircraft types used on transpacific routes, 2016

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[3] For example, Singapore's A350s had passenger load factors around the industry average, but its freight share was 11 percentage points lower than the industry average.

3.5 DRIVERS OF TRANSPACIFIC AIRLINE EFFICIENCY

Table 4 summarizes key airline operational parameters, including passenger load factor, freight share, premium seating share, overall seating density,[4] and relative fuel burn of the aircraft operated[5] for 2016 nonstop transpacific carriers in order of efficiency. As shown in the table, the share of belly freight as a share of total payload varied by a factor greater than four across carriers, from 11% for Asiana to 48% for ANA, compared with an average of 25%. Relatively smaller were differences in passenger load factors, from 74% to 88%, and aircraft fuel burn, from -8% to +11% of ICAO's fuel efficiency standard. Average seating densities ranged from 0.70 seats/m^2 for ANA to 1.15 seats/m^2 for Fiji, ranking second to freight share in terms of variation across carriers.

As the table indicates, airlines can operate at the same overall fuel efficiency despite having very different operational strategies. A case in point is Hainan and ANA. Hainan operated efficiently mostly because of its advanced fleet, flying 81% of ASKs using Boeing 787 Dreamliner aircraft. ANA, in contrast, operated aircraft with a fuel burn only slightly better than average but carried about three times as much belly freight per passenger as Hainan, or 48% of total payload. That high freight carriage also offset ANA's low seating density and second-highest share of premium seating, both of which translate into fewer passengers per flight.

Other notable carriers included Air New Zealand, which ranked third in fuel efficiency despite operating aircraft with average fuel burn because it had above-average passenger load factor, belly freight carriage and seating density. Likewise, JAL, which operated less fuel-intensive aircraft than competitor ANA, carried similar numbers of passengers, but was 4 pax-km/L less fuel-efficient because of lower freight carriage. Delta, in contrast, outperformed its inefficient fleet, which was second-worst at +8%, by combining the highest passenger load factor observed with high seating densities. Rounding out the pack was Qantas, whose poor fuel efficiency was explained by operating the most fuel-intensive aircraft at very low load factors for both passengers and freight.

A multivariate regression model was developed to relate overall airline fuel efficiency to technological and operational parameters, or drivers, including aircraft fuel burn, seating density, passenger load factor, and freight share of total payload. This is the same approach as taken in our transatlantic rankings (Kwan and Rutherford, 2015). Like the transatlantic rankings, the Shapley method was used to quantify the relative importance of each driver to fuel efficiency, with the results shown in Figure 10.

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[4] As measured by seats per square meter of Reference Geometric Factor, or RGF. RGF is a close proxy for the pressurized floor area of an aircraft. It was developed by the International Civil Aviation Organization as a means to assess aircraft fuel efficiency. See ICCT (2013) for further details.

[5] As measured by margin from the International Civil Aviation Organization's fuel efficiency or CO_2 standard, which established an internationally agreed means of assessing and comparing aircraft efficiency. Negative values indicate the use of more fuel-efficient fleets, while positive values indicate more fuel-intensive aircraft. See ICCT (2017) for details.

Table 4. Airline operational parameters

Rank	Airline	Passenger load factor	Freight share of total tonne-km	Premium seating share	Overall seating density (seats/m²)[1]	Aircraft fuel burn[2]
1	**Hainan**	81%	24%	15%	0.97	-8%
1	**ANA**	75%	48%	26%	0.70	+2%
3	**Air New Zealand**	84%	28%	26%	0.99	+5%
4	**EVA Air**	82%	29%	29%	0.92	+4%
4	**China Airlines**	82%	20%	11%	1.00	+4%
6	**Air China**	82%	30%	17%	0.84	+5%
6	**Virgin Australia**	82%	23%	18%	0.95	+4%
6	**Fiji**	81%	17%	8%	1.15	+1%
6	**American**	83%	25%	16%	0.92	-1%
10	**JAL**	78%	36%	23%	0.71	-3%
10	**Delta**	88%	19%	14%	0.97	+8%
10	**United**	83%	23%	18%	0.91	+6%
13	**China Southern**	88%	15%	13%	0.84	—
13	**Cathay Pacific**	86%	22%	19%	0.82	+4%
13	**China Eastern**	79%	22%	18%	0.89	+2%
13	**Philippine**	80%	15%	12%	1.01	+6%
13	**Singapore**	79%	29%	20%	0.73	+2%
18	**Asiana**	85%	11%	13%	0.85	+5%
19	**Korean Air**	74%	23%	20%	0.73	+4%
20	**Qantas**	74%	12%	16%	0.79	+11%
	Industry Average	**82%**	**25%**	**18%**	**0.87**	**+4%**

[1] As measured by seats per square meter or RGF. See footnote 4 for details.
[2] As measured by the average margin of aircraft to ICAO's CO_2 standard. See footnote 5 for details.

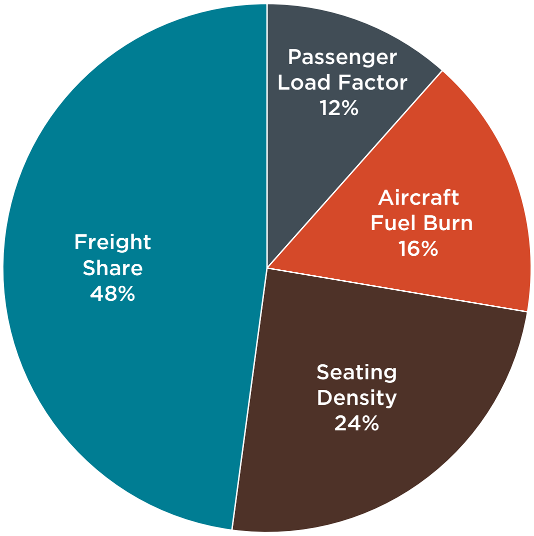

Figure 10. Key drivers of airline fuel efficiency

In order of decreasing importance, the key drivers of transpacific airline fuel efficiency were freight share of total payload, seating density, aircraft type, and passenger load factor. Freight share of payload was the most important of these, explaining almost half of the variance across carriers. Bootstrapping analysis indicates significant overlap in the 95% confidence interval for all four estimated drivers: freight share, 19%~68%; seating density, 11%~55%; aircraft fuel burn, 1%~31%; and passenger load factor, 4%~31%. Nonetheless, it can be concluded that freight share was the most important driver of transpacific fuel efficiency in 2016. This helps explain, for example, why ANA was more fuel-efficient overall than carriers with higher passenger load factors, higher seating density, and more efficient aircraft.

As similarly observed in the transatlantic rankings, seating configuration, or seating density, also influences airline fuel efficiency. The seating densities on transatlantic operations were generally higher than for transpacific operations, with a higher share of premium seats—first and business class—for transpacific flights. Given that premium seats are, on average, three times as carbon-intensive as economy seats (Bofinger & Strand, 2013), this could be one explanation for why average fuel efficiency for transpacific operations at 31 pax-km/L was lower than for transatlantic operations at 32 pax-km/L.

4. CONCLUSIONS AND NEXT STEPS

4.1 CONCLUSIONS

There is a wide gap of 64% between the fuel efficiency of industry leaders Hainan Airlines and All Nippon Airways and bottom-ranked Qantas Airways on transpacific operations. This gap is wider than was observed on transatlantic routes in 2014. One main driver of this was freight carriage, which explained almost half of the variation in transpacific fuel efficiency compared with just 9% for transatlantic flights. Additionally, the freight share of total tonne-km for transpacific operations was higher than for transatlantic flights. The effect of freight on transpacific fuel efficiency is demonstrated by ANA, which tied for first in the ranking despite having the most premium seating, the lowest seating density, and one of the lowest passenger load factors in the industry.

More generally, we see that carriers with very different combinations of aircraft, passenger load factor, freight carriage, and seating configuration operate with similar fuel efficiency. JAL and Delta, for example, exhibited identical overall fuel efficiency despite JAL operating on average a much more efficient fleet. Delta was able to bridge the gap by carrying relatively more passengers, reflecting high load factor and denser seating. Conversely, ANA operated much more efficiently than JAL despite having a less-advanced fleet due in large part to superior freight carriage practices.

A general trend observed is the fuel burn per passenger kilometer increases on transpacific routes as the aircraft size and weight increase. Airlines that predominantly use very large aircraft—Asiana, Korean Air, and Qantas—had the lowest overall fuel efficiency on transpacific flights. This is largely because aircraft with four engines have generally higher fuel burn per passenger than those with two. This, combined with the fact that fuel is typically the single largest operational expense for airlines, helps explain the industry-wide trend of retiring aging Boeing 747 aircraft and the sluggish market for the superjumbo Airbus A380 (Goldstein, 2017).

ICAO has established a long-term, aspirational goal of increasing the fuel efficiency of international flights by 2% annually (ICAO, 2016). The introduction of more fuel-efficient wide-body aircraft, such as the Airbus A350 and the Boeing 787, can contribute to achieving this goal. As the demand for air travel to, from, and within Asia increases, more new aircraft will be purchased. Models like the A350 and 787, as well as models under development like the A330neo and 777X, will eventually come to dominate the global airline wide-body fleet. All things being equal, airlines operating aircraft with lower fuel burn tend to be more efficient, but operational parameters such as payload carried are also important and should be tracked.

4.2 NEXT STEPS

Regarding future work, we will continue to work with DOT and our data provider to ensure that airlines report accurate operational data for use in subsequent domestic, transatlantic, and transpacific rankings. We will also seek data to support the inclusion of routes to and from Canada in future rankings. Future updates to the transpacific rankings will help evaluate changes in fuel efficiency due to changes in an airline's fleet, such as the retirement of Boeing 747-400 aircraft and the further introduction of Airbus A350s and Boeing 787s. Finally, assuming widespread cooperation from ranked airlines, our methodology could be shifted from a modeling approach to one in which primary fuel burn data from all carriers is analyzed to encompass the full range of operational measures that affect airline fuel efficiency.

The pronounced effect of freight on airline fuel efficiency was examined in this study. Many of the Asian carriers in this study also use dedicated freighters to move goods across the Pacific. Future work will quantify and compare the difference in the amount of fuel burned to transport a tonne of freight by way of a dedicated freighter compared with using passenger aircraft freight capacity.

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APPENDIX: MODEL VALIDATION

The methodology described in Section 2 was validated using fuel burn data reported to the BTS by American Airlines, Delta Air Lines, and United Airlines for each aircraft type operating on transpacific flights (DOT, 2017). The average fuel efficiency for each aircraft type was calculated directly from this data and compared with the modeled fuel efficiency. The uncertainty introduced by modeling fuel burn with Piano using standardized assumptions for operating parameters could be assessed. A total of 12 airline-aircraft type combinations were included in the model validation analysis, shown in Figure A-1.

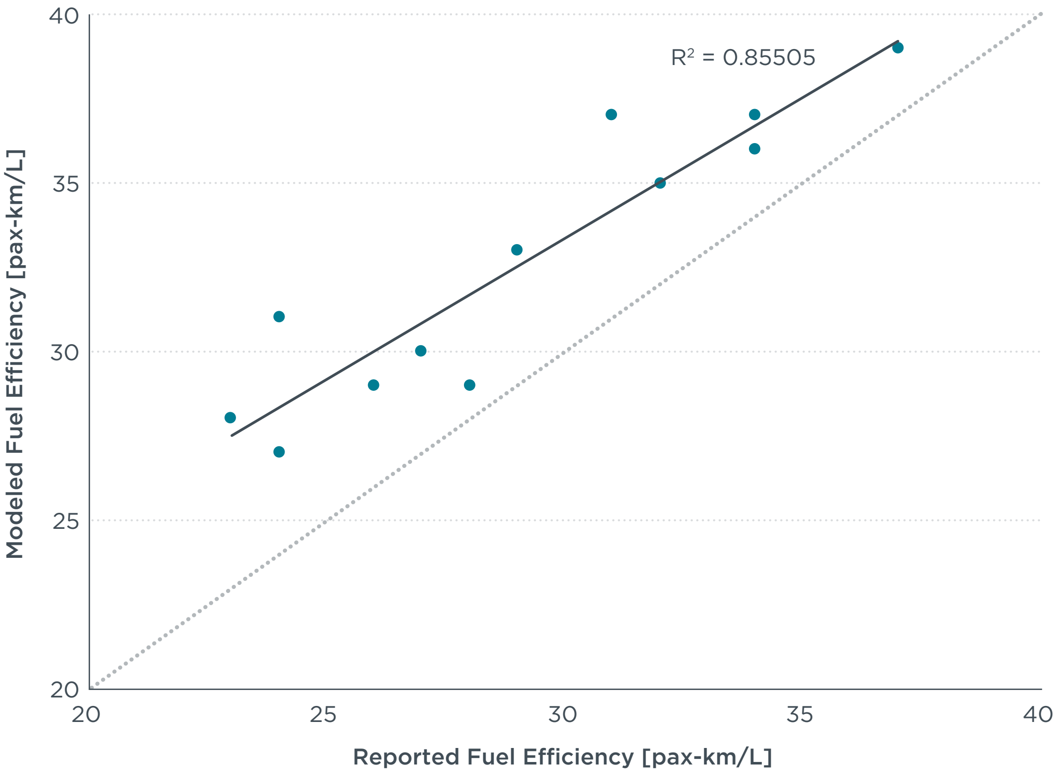

Figure A-1. Airline-reported versus modeled fuel efficiency

This validation results suggest that our modeling approach is robust and appropriate for the purpose of comparing the relative fuel efficiency of transpacific operations. While the model overestimates fuel efficiency compared with reported fuel burn data on the order of 10%, a good linear fit (R^2 of 0.86) was observed. These validation findings are broadly consistent with those reported in the Intergovernmental Panel on Climate Change's report, *Aviation and the Global Atmosphere*.[6] This indicates that changes to the modeling parameters are unlikely to lead to major shifts in the rankings.

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[6] "The assumption of great circle flight paths results is an underestimate of distance flown.... A combination of factors [e.g., deviation from great circle distance, delay, engine deterioration, etc.] results in systematic underestimation of total fleet fuel burned by 15-20% for domestic operations." (Intergovernmental Panel on Climate Change, 1999)

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