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TRANSATLANTIC AIRLINE FUEL EFFICIENCY RANKING, 2014

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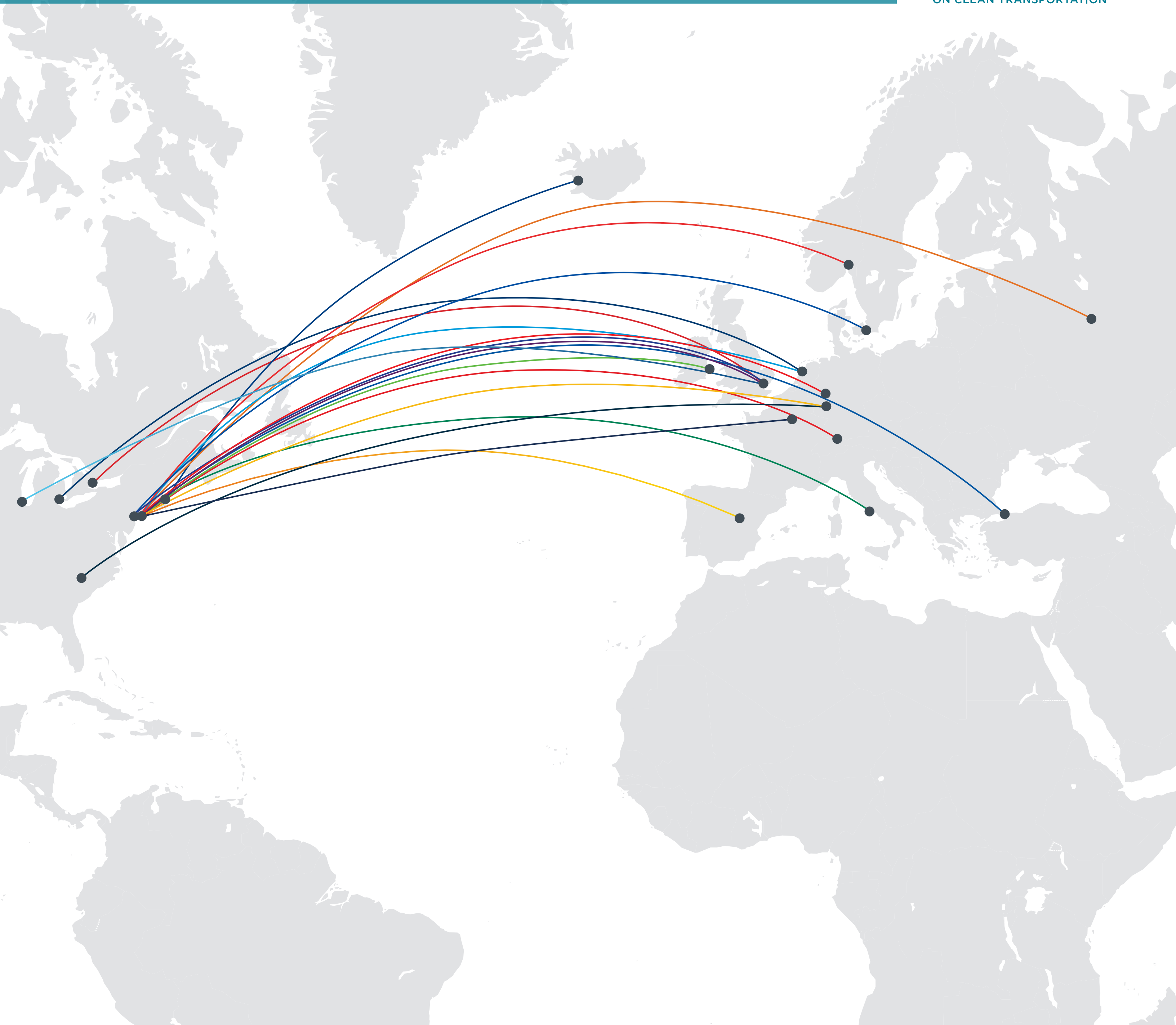

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EXECUTIVE SUMMARY

Surprisingly little public information is available about the fuel efficiency, and therefore carbon intensity, of international flights. This report summarizes the first public, transparent assessment of the fuel efficiency of the top 20 airlines operating nonstop transatlantic passenger flights linking Europe to the U.S. and Canada. This study combines the highest quality publicly available and commercial operations data with sophisticated aircraft fuel burn modeling to benchmark the fuel efficiency of carriers on a passenger kilometer basis. The study explains the fuel efficiencies of individual carriers and highlights the most important drivers of efficiency in the aggregate.

Figure ES-1 illustrates the fuel efficiency of the 20 carriers analyzed. Norwegian Air Shuttle, the world's seventh largest low-cost airline, was the most fuel-efficient airline on transatlantic routes, on average providing 40 passenger kilometers per liter (pax-km/L) of fuel on its predominately Boeing 787-8 fleet. Airberlin, Germany's second largest airline, came in second with a fuel efficiency of 35 pax-km/L, though burning 14% more fuel per passenger kilometer than Norwegian, followed by Aer LIngus, the national flag carrier airline of Ireland, with a fuel efficiency of 34 pax-km/L. KLM Royal Dutch Airlines, Air Canada, Aeroflot Russian Airlines, Turkish Airlines, and Air France were tied for fourth place with an average fuel efficiency of 33 pax-km/L. Delta Air Lines, which had the largest transatlantic market share of any carrier, and Icelandair, which operates an old fleet of Boeing 757 aircraft from its hub in Reykjavik, both provided the industry average fuel efficiency of 32 pax-km/L (indicated by the dotted blue vertical line).

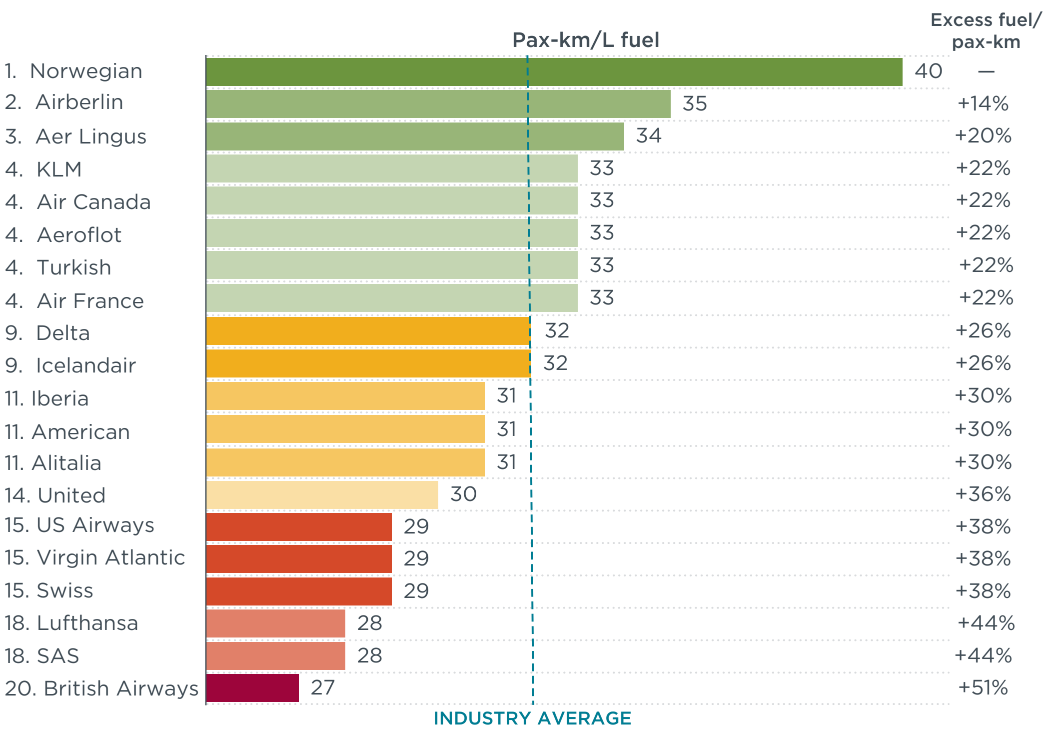


Figure ES-1. Fuel efficiency of the top 20 airlines on transatlantic routes, 2014

Many legacy carriers displayed below average fuel efficiency on transatlantic operations, including the U.S. carriers American Airlines, United Airlines, and US Airways, along with Spain's Iberia Airlines and Italy's Alitalia. Virgin Atlantic, a British airline and subsidiary of the Virgin Group, and Swiss International Air Lines, the flag carrier airline of Switzerland, tied with US Airways for

15th place with fuel efficiency of 29 pax-km/L. The least efficient airlines were Lufthansa German Airlines, SAS Scandinavian Airlines and British Airways, who were collectively responsible for 20% of the transatlantic available seat kilometers (ASKs) but burned at least 44% more fuel per passenger kilometer than Norwegian.

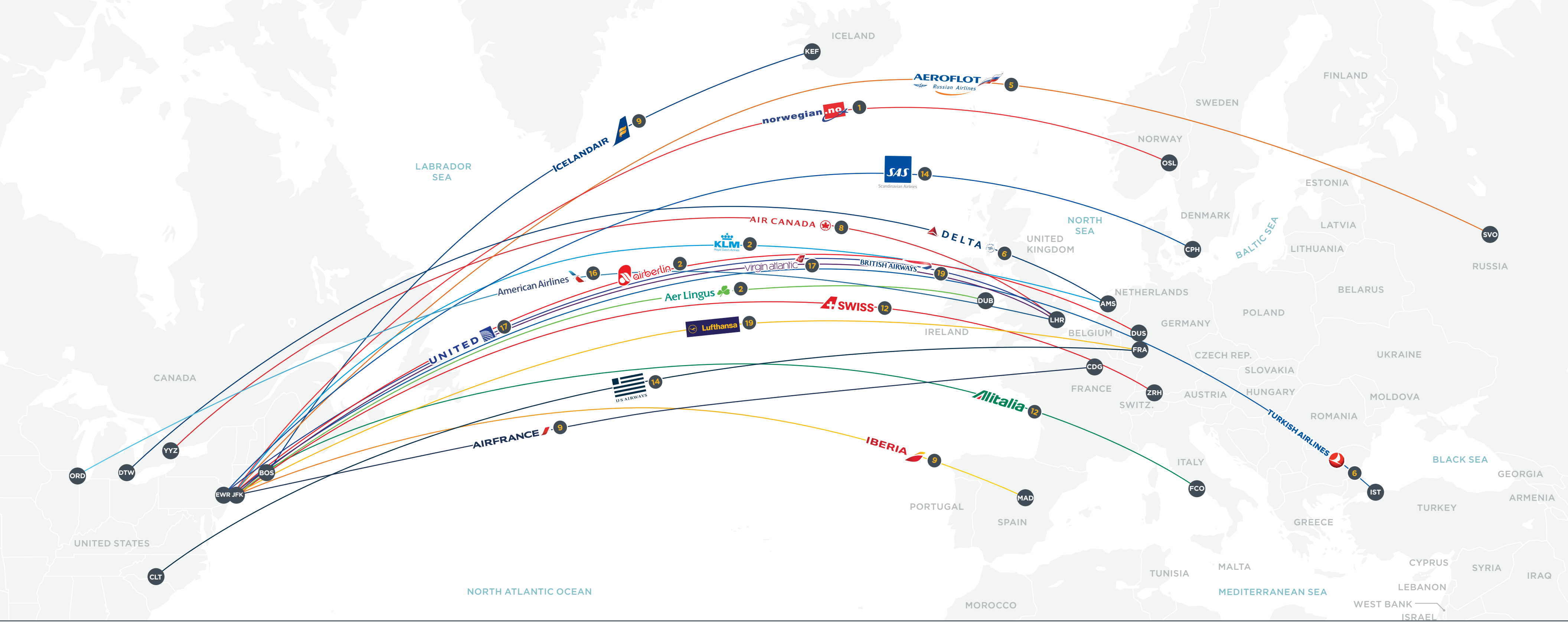
Figure ES-2 compares the fuel efficiency of these carriers on specific routes rather than on an overall airline basis. It presents fuel efficiency (pax-km/L), along with the absolute carbon dioxide (CO_2) emissions in kilograms, for a nonstop round-trip itinerary on the most prevalent transatlantic route flown for each airline.

Figure ES-2 shows that Norwegian, the most efficient airline overall, is also the most efficient airline on its most prominent route between New York's John F. Kennedy International Airport (JFK) and Oslo Airport (OSL), the busiest airport in Norway. The average fuel efficiency on this route was 42 pax-km/L, about 4% more efficient than its overall efficiency (40 pax-km/L), and equivalent to about 720 kg CO_2 per passenger round trip. Airberlin, KLM, and Aer Lingus also retained their top four rankings in this analysis, each averaging 36 pax-km/L on their most frequent transatlantic routes. Lufthansa and British Airways were the least efficient on their top routes, Frankfurt (FRA) to JFK and London Heathrow (LHR) to JFK, respectively. The gap between the most efficient airline on a route basis was about 57%, or almost 6% larger than overall. On average, a nonstop transatlantic flight averaged about one tonne of CO_2 emissions per passenger round trip, or equivalent to emissions from a 35-km daily commute in a Toyota Prius over a work year.

The report investigates key drivers of the observed fuel efficiency gap across carriers. Factors investigated include the average fuel burn of the aircraft operated along with operational parameters like aircraft seating configuration, passenger load factor, and belly freight carriage. Seating configuration and the average fuel burn of aircraft operated were found to be the two most important drivers overall, collectively explaining about 80% of the variation in airline fuel efficiency. Passenger load factor and freight carriage were found to be relatively less important. The impact of premium seating on emissions is substantial: first class and business seats accounted for only 14% of ASKs flown on transatlantic routes but were responsible for approximately one third of overall emissions.

Other conclusions of this work are as follows:

1. The significant gap (up to 51%) between industry leaders such as Norwegian Air Shuttle and legacy carriers such as Lufthansa, SAS, and British Airways reveals a large disparity in airline fuel efficiency on transatlantic operations. Surprisingly, the transatlantic efficiency gap is roughly double that seen for the U.S. domestic market, which was only 25% in 2014.
2. The very high fuel efficiency of Norwegian Air Shuttle demonstrates the central role of technology in reducing CO_2 emissions from the aviation sector. Airlines that invest in new, advanced aircraft are more fuel-efficient than airlines that use older, less efficient aircraft. This finding draws attention to the importance of reducing aircraft fuel burn, in particular the role of new, more advanced aircraft types in improving overall airline efficiency.
3. The 50%+ gap in fuel efficiency suggests there is a large and underestimated potential for in-sector CO_2 emission reductions. This highlights the role for additional policies to limit aviation emissions, notably the CO_2 standard being developed by the International Civil Aviation Organization (ICAO) and a global market-based measure (MBM) to price aviation carbon.
4. Finally, accurate and transparent data are the cornerstone for assessing the fuel efficiency of airlines. Improved data reporting would help travelers concerned about their carbon footprint make more informed purchasing decisions and help policymakers craft policies to reduce the environmental impact of flying.



Rank	Airline	Airport pair	pax-km/L	kg CO_2 per round-trip itinerary
1	norwegian.no	JFK ⇄ OSL	42	720
2	airberlin	DUS ⇄ JFK	36	840
2	KLM	AMS ⇄ JFK	36	830
2	Aer Lingus	DUB ⇄ JFK	36	720
5	AEROFLOT Russian Airlines	JFK ⇄ SVO	35	1100
6	TURKISH AIRLINES	IST ⇄ JFK	34	1200
6	DELTA	AMS ⇄ DTW	34	1000
8	AIR CANADA	LHR ⇄ YYZ	33	870
9	ICELANDAIR	BOS ⇄ KEF	32	620
9	IBERIA	JFK ⇄ MAD	32	920

Rank	Airline	Airport pair	pax-km/L	kg CO_2 per round-trip itinerary
9	AIRFRANCE	CDG ⇄ JFK	32	930
12	Alitalia	FCO ⇄ JFK	31	1100
12	SWISS	JFK ⇄ ZRH	31	1000
14	US AIRWAYS	CLT ⇄ FRA	30	1200
14	SAS	CPH ⇄ EWR	30	1000
16	American Airlines	LHR ⇄ ORD	29	1100
17	virgin atlantic	JFK ⇄ LHR	28	1000
17	UNITED	LHR ⇄ EWR	28	1000
19	Lufthansa	FRA ⇄ JFK	27	1200
19	BRITISH AIRWAYS	LHR ⇄ JFK	27	1100

Figure ES-2. Fuel efficiency on prominent transatlantic routes, 2014

1. INTRODUCTION

Commercial aviation underpins the modern global economy, transporting more than three billion passengers and 47 million metric tons of freight annually while generating in excess of $600 billion of gross domestic product (GDP) per year (Air Transport Action Group, 2015; Perovic, 2013). At the same time, aircraft emitted about 700 million metric tons of carbon dioxide (CO_2) globally in 2013, with a tripling of emissions expected by 2050 under business-as-usual scenarios (Lee et al., 2013). If aviation were a country, it would rank 21st in terms of GDP (Air Transport Action Group, 2015), but seventh in terms of CO_2 emissions, behind Germany and well ahead of Korea (Kwan & Rutherford, 2014).

Policymakers and industry continue to discuss ways to constrain the growth of aviation emissions. In 2010, the 37th Session of the International Civil Aviation Organization (ICAO) Assembly established two aspirational goals for the international aviation sector: improving fleet-wide fuel efficiency by 2% annually and stabilizing net CO_2 emissions from the aviation sector at 2020 levels (ICAO, 2010). ICAO, the de facto regulator of airlines worldwide, is currently working to finalize a CO_2 (efficiency) standard for new aircraft in early 2016. In addition, ICAO is developing a framework for market-based measures (MBMs) to address CO_2 emissions from international aviation, with hopes of reaching agreement in 2016 and implementing by 2020 (ICAO, 2013a). Meanwhile, the airline industry, including aircraft manufacturers and airlines, are making advancements in technology and operations to improve aircraft fuel efficiency and reduce the sector's carbon footprint.

Until recently, there has been very little public information on airline fuel efficiency. The International Council on Clean Transportation (ICCT) assessed the fuel efficiency of U.S. airlines in its benchmark study for domestic operations in 2010 (Zeinali, Rutherford, Kwan, & Kharina, 2013), followed by updates for 2011-2012 (Kwan & Rutherford, 2014), 2013 (Kwan & Rutherford, 2014), and 2014 (Li, Kwan, & Rutherford, 2015). The latest study found that the average fuel efficiency of U.S. domestic flights improved by 1.7% from 2013 to 2014, with most of the gain attributable to increasing load factors and seating densities, rather than reductions in aircraft fuel burn. Overall, the gap between the most and least efficient airlines on U.S. domestic operations was 25% in 2014.

This report extends the previous work on airline fuel efficiency to the transatlantic market, specifically nonstop passenger flights between U.S./Canada and Europe. This market is significant in terms of passengers carried, revenue generated, and pollution emitted. According to ICAO's traffic forecast in 2020, "Europe and Asia/Pacific will have the largest share of CO_2 emissions from international aviation with 36.6 per cent and 31 per cent, respectively, followed by North America with 14.8 per cent" (ICAO, 2013b). This study compares the fuel efficiency of 20 major airlines representing the U.S., Canada, and 12 European countries in 2014. The results hold implications for how carriers might be affected by policies to mitigate aviation's environmental impact, notably a global aviation MBM to establish a cost for aviation CO_2 emissions.

The structure of this report is as follows. Section 2, along with supplemental detail provided in Appendices A and B, introduces the methodology developed to estimate the fuel efficiency of airlines on nonstop transatlantic flights. Section 3 presents the results of the analysis and introduces the key drivers of variations in fuel efficiency across carriers. Section 4 offers conclusions and policy implications from the work, along with potential future work to refine and extend the methodology developed.

2. METHODOLOGY

Previous studies (Zou, Elke, Hansen, & Nafle, 2014; Zeinali, Rutherford, Kwan, & Kharina, 2013; others) on U.S. domestic airline fuel efficiency compared carriers using a statistical "frontier" approach accounting for the fact that they provide both mobility, in revenue passenger miles, and access, in number of flights.[1] This approach, while key to an apples-to-apples fuel efficiency comparison for airlines serving the U.S. domestic market, was not applied for this study for two reasons. First, because only U.S. carriers report primary fuel burn data to the U.S. Department of Transportation (U.S. DOT), the frontier method could not be applied with confidence for the majority of carriers serving the transatlantic market. Second, because the operations of carriers flying over the North Atlantic are more or less comparable in terms of aircraft gauge and stage length, variations in fuel use per landing and takeoff cycle among airlines are relatively minor. For this reason, a simplified "ratio" metric of the average passenger kilometers moved to the liters of fuel burned (pax-km/L) on a typical nonstop transatlantic flight was used to compare transatlantic fuel efficiency.

To evaluate the fuel efficiency of 20 major airlines on nonstop transatlantic flights, an international flight schedule database and detailed operational data reported to U.S. DOT were used to model airline fuel burn using Piano 5, an aircraft performance and emissions model widely used for policy and environmental analysis worldwide. The following sections provide an overview of the methodology applied; further detail can be found in Appendix A. The estimated airline efficiencies were validated using U.S. carriers' reported fuel and traffic data available from U.S. DOT's Bureau of Transportation Statistics (BTS) (U.S. Department of Transportation, 2015) as described in Appendix B.

2.1 AIRLINE SELECTION

The OAG schedules data provide information on carrier, origin, destination, frequency, distance, time, aircraft type, seat count, and other flight-specific characteristics (OAG, 2014).[2] Data was collected for 2014 transatlantic routes — those flying nonstop to and from the U.S./Canada and Europe — and filtered for passenger flights and operating carriers to avoid double-counting due to code sharing. Only nonstop and one-stop flights,[3] which made up more than 99% of total flights, were included in this study in order to manage the analysis burden. Using this dataset, the top 20 carriers (each having about 1% or higher share of total ASKs) making up 91% of the total ASKs on transatlantic flights were identified.[4]

Table 1 presents the 20 airlines analyzed in this report along with each airline's share of transatlantic ASKs, most prevalent route, and the number of flights on that route in 2014.

1 The U.S. domestic airline rankings also account for two other factors influencing airline fuel efficiency: (1) major airlines having regional affiliates or partners who operate their flights, and (2) circuitous routing or deviation from direct flight paths due to one or more layovers that require extra travel distance. However, in the case of international operations, flight itinerary information such as that from BTS DB1B Coupon (U.S. Department of Transportation, 2015) was not available to determine mainline-affiliate relationships and calculate an airline's degree of circuitous routing. For this reason, this study only covers only nonstop flights between U.S./Canada and Europe.

2 OAG provides *scheduled* flight data, not actual operations flown in a given year. OAG flights were found to be comparable to actual flights performed by several U.S. carriers (from BTS) and two European carriers, with some differences resulting from flight cancellations, reporting differences, etc.

3 For one-stop flights, domestic U.S. or intra-EU flights were used to determine the top 20 carriers but not to estimate airline fuel efficiency in order to avoid overlap with U.S. domestic fuel efficiency studies.

4 Air Transat, a Canadian charter "holiday travel" airline (Air Transat, 2015), was among the top 20 transatlantic carriers by ASKs but excluded from the analysis.

Table 1. Airlines evaluated

Airline	Share of transatlantic ASKs	Top transatlantic route	Flights per year on top route
Aer Lingus	1%	Dublin ⇄ New York	1,396
Aeroflot	1%	Moscow ⇄ New York	1,455
Airberlin	1%	Düsseldorf ⇄ New York	850
Air Canada	5%	Toronto ⇄ London	2,866
Air France	5%	Paris ⇄ New York	3,394
Alitalia	1%	Rome ⇄ New York	1,764
American	9%	Chicago ⇄ London	2,531
British Airways	10%	London ⇄ New York	6,121
Delta	14%	Detroit ⇄ Amsterdam	2,576
Iberia	1%	Madrid ⇄ New York	1,454
Icelandair	1%	Reykjavik ⇄ Boston	1,214
KLM	3%	Amsterdam ⇄ New York	1,302
Lufthansa	9%	Frankfurt ⇄ New York	1,404
Norwegian	1%	Oslo ⇄ New York	416
SAS	1%	Copenhagen ⇄ Newark	1,036
Swiss	2%	Zürich ⇄ New York	1,456
Turkish	3%	Istanbul ⇄ New York	1,880
United	10%	Newark ⇄ London	3,525
US Airways	7%	Charlotte ⇄ Frankfurt	1,042
Virgin Atlantic	4%	London ⇄ New York	2,830

2.2 FUEL BURN MODELING

Previous ICCT studies on airline fuel efficiency (Zeinali, Rutherford, Kwan, & Kharina, 2013; Li, Kwan, & Rutherford, 2015; others) used primary fuel consumption data reported by U.S. carriers to the U.S. DOT to compare the relative efficiency of carriers on U.S. domestic operations. Because non-U.S. carriers do not report their fuel consumption to the U.S. DOT, this analysis of international flights required that aircraft fuel burn be modeled using Piano 5, an aircraft performance and design software (Lissys Ltd, 2015).

Piano 5 requires various flight inputs in order to model aircraft fuel burn, most importantly, payload and stage length (flight distance) but also operational variables such as speed, flight level (altitude), and fuel reserves, among others. International flights carry both passenger and freight payload, so the fuel burn of individual flights must be apportioned between passengers and freight on a mass basis.

Because OAG schedules data does not provide data on passengers enplaned, the BTS T-100 International Segment database, which provides nonstop flight segment information for all carriers originating or ending in the U.S.,[5] was used to estimate each airline's

5 The BTS dataset includes only flights that originate or end in the U.S., so flights between Europe and Canada were assumed to have the same load factor as flights between the Europe and the U.S.

passenger load factor, or the percentage of seats filled on an average flight.[6] Data was filtered for transatlantic flights from January 2014 to December 2014 and average airline passenger load factors were calculated as the ratio of total revenue passenger miles to total available seat miles. Estimated load factors by airline for transatlantic flights are summarized in Table 2.[7]

Table 2. Load factors on 2014 transatlantic flights

Airline	Average passenger load factor	Average belly freight load factor	Freight share of total tonne-km
Aer Lingus	84%	22%	12%
Aeroflot	80%	29%	21%
Airberlin	81%	22%	16%
Air Canada[1]	82%	37%	21%
Air France	83%	42%	20%
Alitalia	80%	29%	18%
American	83%	35%	21%
British Airways	83%	43%	24%
Delta	84%	30%	16%
Iberia	80%	34%	21%
Icelandair	83%	18%	6%
KLM	88%	37%	21%
Lufthansa	84%	42%	19%
Norwegian	86%	35%	15%
SAS	82%	32%	13%
Swiss	86%	31%	17%
Turkish	84%	43%	22%
United	80%	34%	21%
US Airways	74%	23%	16%
Virgin Atlantic	79%	45%	22%

[1] Air Canada does not report its Atlantic flights to the U.S. DOT, so its passenger load factor was retrieved from http://aircanada.mediaroom.com/index.php?s=43&item=843.

Source: BTS T-100 via Data Base Products, Inc. (2015); Air Canada (2015)

Passenger payload was estimated according to Equation 1 below:

$$Payload_{pax}[kg] = 100kg * SeatCount * LoadFactor_{pax} \quad \text{(Eq. 1)}$$

where 100 kg (or 220 pounds) is the industry-wide standard weight for a passenger and his/her luggage, SeatCount is the aircraft's number of seats specified in the OAG flight data, and $LoadFactor_{pax}$ is the average passenger load factor for an airline identified in Table 2. Changes in aircraft weight due to a larger or smaller number of seats than the

6 Flights with more than 100 seats (with the exception of the Airbus A318 32-seater by British Airways) were filtered to capture passenger flights. See U.S. Department of Transportation (2015); Data Base Products, Inc. (2015).

7 Calculated load factors also compared well against those provided by airline Corporate Social Responsibility (CSR) reports, environmental reports, or news releases on the web.

Piano aircraft equivalent were incorporated into the modeling by adjusting the Piano aircraft operating empty weight (OEW) by 50 kg per seat (ICAO, 2014).

In addition to passengers, international passenger aircraft carry a significant amount of "belly" freight, although public data regarding the actual masses moved are scarce. OAG does not provide freight carriage information but reports the tonnes of freight capacity for most flights. Average belly freight load factors by aircraft type were estimated using BTS Form 41 data for U.S. carriers and in one case with data provided directly by an airline whose cargo operations differed significantly from the U.S. average. The freight carriage on a given flight was estimated as the product of aircraft freight capacity and estimated freight load factor (see Appendix A).

For flight distance, the average great circle distance (GCD) of each flight group was calculated using OAG schedules data, adjusted by 4% upward from GCD to account for air traffic management inefficiencies over the North Atlantic (see Appendix A). The fuel burn of flights was modeled for every unique seating configuration flown for a given airline and aircraft within 500-mile (805 km) bins using Piano. For example, "Norwegian Air Shuttle — Boeing 787-8 — 291 — 3500" designates a flight on Norwegian Air Shuttle's Boeing 787-8 aircraft with 291 seats, flying its average distance between 3,500 and 4,000 miles.

The Ascend Fleets online database, which provides comprehensive carrier fleet and aircraft-specific information (Ascend Flightglobal Consultancy, 2015), was used to assign representative Piano 5 aircraft to the 20 airlines by matching aircraft type, winglet or no winglet, engine type, seat count, and maximum takeoff weight (MTOW)[8] as closely as possible. In total, 46 representative aircraft were identified.

Detailed information on operational parameters such as engine thrust, drag, fuel flow, available flight levels (altitude), and speed were not available for individual airlines, so Piano default values were used instead. Cruise speeds were set to allow 99% maximum specific air range. Taxi times were set at 34 minutes, as estimated by BTS T-100 data for Atlantic flights with either origin or destination in the U.S. for 19 airlines. 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 an Operations Specification B043.[9]

A summary of the key modeling variables and sources for this analysis is provided in Table 3.

8 MTOW is a regulatory maximum weight of a loaded aircraft at takeoff.

9 OpSpec B043 is a typical release type chosen by flight dispatchers for U.S. carrier international operations. Other fuel requirements exist under this specification including an en route reserve fuel for 10% of Class II navigation; however, due to lack of resources to calculate this, a 10% of total mission contingency fuel assumption was made to capture this and other types of reserve fuel. For more information, see Federal Aviation Administration (2014).

Table 3. Key modeling variables

Type	Variable	Sources
Airline scheduled flights	Route	Official Airline Guide
	Aircraft used	
	Available seats	
	Flights per year	
	Freight capacity	
Load factors	Passenger	BTS T-100 International[1]; Air Canada website
	Freight	BTS Form 41[1]; Airline-specific data
Airline-specific aircraft parameters	Type and count	Ascend Fleets; Piano 5
	Engine	
	Winglets	
	MTOW	
	Seats	
	Age	
Aircraft weights	Operating empty weight	Piano 5
	Passenger weight	Industry standard
	Seat and furnishings weight	ICAO
Aircraft fuel burn	Engine thrust	Piano 5
	Drag	
	Fuel flow	
Other operational variables	Taxi time	BTS T-100 International[1]
	Fuel reserves	FAA Part 121; Piano 5
	Flight levels	Piano 5
	Speed	Piano 5

[1] U.S. DOT BTS data was obtained via Data Base Products, Inc. (2015)

2.3 FUEL EFFICIENCY CALCULATION

While previous ICCT airline fuel efficiency studies applied a metric that benchmarked the efficiency of each airline against the "transport service" it provides — measured as a combination of revenue passenger miles, a measure of mobility, and the number of departures, a measure of access — this study applied a simple "ratio" metric of passenger kilometers per liter of fuel consumed.

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" flight group (represented by index *i*), the total fuel consumption and total tonne-km moved for the full set of nonstop transatlantic flights flown by each of the 20 airlines was calculated according to Equations 2 and 3:

$$fuel_a[L] = \sum_i fuel_{a,i} * frequency_{a,i} \quad \text{(Eq. 2)}$$

$$tonnekm_a = \sum_i tonnekm_{a,i} * frequency_{a,i} \quad \text{(Eq. 3)}$$

The ratio of tonne-km flown to fuel burned for each airline was used as a starting point for the average fuel efficiency metric. This was then converted to a passenger-based metric, pax-km/L fuel, using a passenger weight factor of 100 kg as shown in Equation 4.

$$paxkm/L_a = \frac{tonnekm_a * 10^3\ kg/tonne}{fuel_a * 100kg/pax} \qquad \text{(Eq. 4)}$$

The 20 airlines were then ranked from highest to lowest on this fuel efficiency metric.

2.4 OTHER VARIABLES INFLUENCING AIRLINE EFFICIENCY

Numerous factors influence airline fuel efficiency, including aircraft-level parameters such as fuel burn, operational practices, and environmental factors (Zeinali, Rutherford, Kwan, & Kharina, 2013). Because most international carriers do not report primary fuel consumption data, this study focuses only on aircraft parameters and operational practices for which information is available. Operational factors for which airline specific data are unavailable, for example, cruise speed or engine maintenance practices, cannot be assessed via this methodology. Likewise, environmental factors such as congestion and weather that influence airline fuel efficiency are beyond the scope of this work.

AIRCRAFT FUEL BURN

The fuel burn of a given aircraft is dependent upon the mission flown (payload and range) and also the way in which the aircraft is operated (flight levels, speed, fuel reserves, etc.). To estimate the relationship between aircraft fuel burn and airline efficiency, a proxy metric for aircraft fuel burn is needed. As part of the effort to establish a CO_2 standard for new aircraft, ICAO's Committee on Aviation Environmental Protection (CAEP) developed a metric value (MV) to measure cruise fuel burn performance (ICAO, 2012). The MV is a function of an aircraft's specific air range (SAR), or cruise fuel consumption rate, measured at three equally weighted gross weights and corrected for the aircraft size. The latter value is represented by an aircraft's reference geometric factor (RGF), a proxy for aircraft pressurized floor area (Dickson, 2013). ICAO's MV is defined according to Equation 5 and is in units of [kg fuel/km x $m^{0.48}$]:

$$MV = \frac{(1/SAR)_{ave}}{RGF^{0.24}} \qquad \text{(Eq. 5)}$$

In this study, a reference line was developed that represents the average cruise metric value for a specified MTOW based on 2014 new aircraft deliveries. This line was used as a tool to compare each aircraft's relative fuel burn, with more efficient aircraft having MVs below the reference line (i.e. negative percent "margin to reference line") and aircraft with higher relative fuel burn having MVs above the reference line (i.e. positive percent "margin to reference line"). Airline average margins to the reference line were calculated by averaging the MV margin for each aircraft type in an airline's fleet, weighted by the corresponding airline's aircraft ASKs. The results are presented in Table 4 (see Section 3.3.1).

More information on the calculation of aircraft metric value and margin to reference line can be found in Appendix A and Kharina & Rutherford (2015).

AIRCRAFT SEATING CONFIGURATION

One important operational parameter influencing airline fuel efficiency is aircraft seating configuration, which is related to the number of passengers that can be moved on a single flight. All other things being equal, airlines operating aircraft with fewer seats than average tend to be less fuel-efficient because the aircraft and fuel weight used to move those passengers is divided over a smaller number of passengers.

Two separate metrics were developed to characterize the influence of seating configuration on airline efficiency. The first is simply the share of first and business class seats as a proportion of the total number of seats on the plane. The second metric is aircraft seating density, measured as the number of seats on an aircraft divided by the aircraft RGF, which was estimated for each aircraft type according to Equation 6:

$$eRGF\ [m^2] = fuselage\ width * cabin\ length \qquad \text{(Eq. 6)}$$

Both metrics are presented for the top 20 airlines in Table 5 (see Section 3.3.2).

3. RESULTS

3.1 THE LEAST EFFICIENT AIRLINES USE UP TO 51% MORE FUEL THAN BEST-IN-CLASS

The average fuel efficiencies, in passenger kilometers per liter of fuel, of the 20 major airlines flying transatlantic routes in 2014 are shown in Figure 1. The dotted blue vertical line, corresponding to Delta Air Lines and Icelandair, indicates the industry average fuel efficiency in 2014.

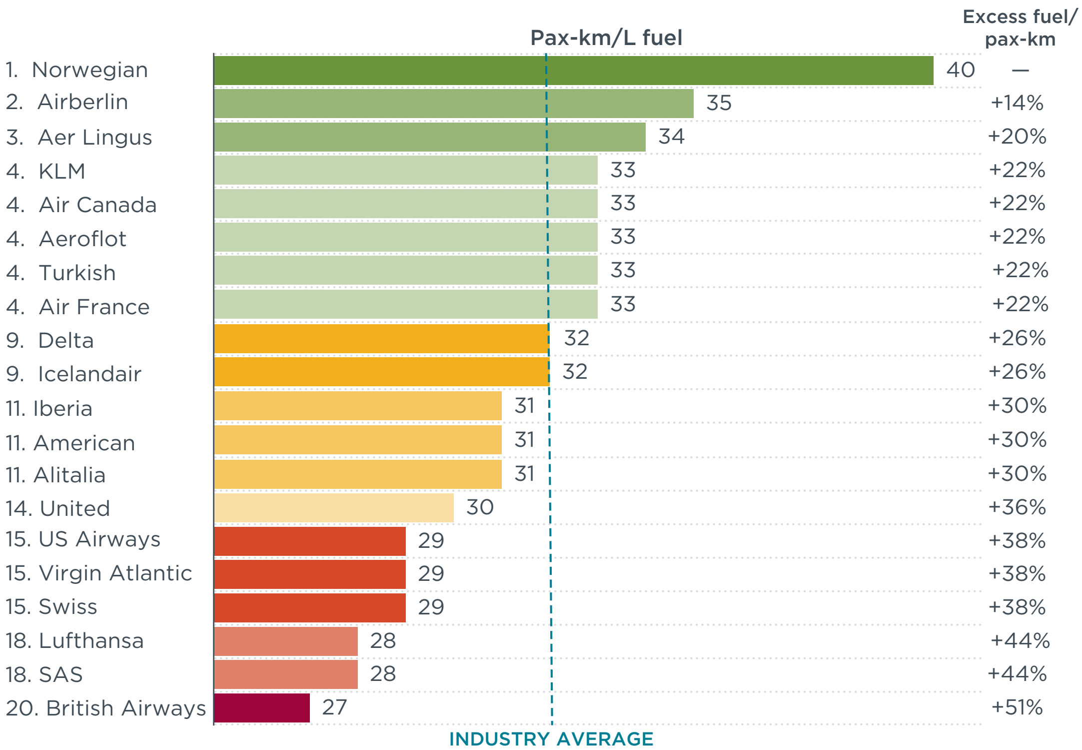


Figure 1. Fuel efficiency of the top 20 airlines on transatlantic routes, 2014

As Figure 1 indicates, estimated transatlantic airline fuel efficiencies varied from 40 pax-km/L down to only 27 pax-km/L. Norwegian Air Shuttle was the most fuel-efficient airline, on average providing 40 passenger kilometers per liter of fuel on transatlantic flights in 2014. Airberlin, Germany's second largest airline, was the second most fuel-efficient carrier at 35 pax-km/L fuel, though burning a full 14% more fuel per passenger kilometer than Norwegian. In third place was Aer Lingus, the national flag carrier airline of Ireland, with a fuel efficiency of 34 pax-km/L. These three carriers together had a relatively small share of the transatlantic market, accounting for only 4% of total ASKs.

KLM Royal Dutch Airlines, Air Canada, Aeroflot Russian Airlines, Turkish Airlines, and Air France were tied for fourth place with an average fuel efficiency of 33 pax-km/L. Delta Air Lines, which had the largest share of ASKs (14%) on transatlantic flights, along with Icelandair, which operates a relatively old fleet of Boeing 757 aircraft from its hub in Reykjavik, provided the industry average fuel efficiency of 32 pax-km/L. Both carriers burned an estimated 26% more fuel per passenger kilometer than the most efficient carrier, Norwegian.

Many legacy carriers were ranked below average in transatlantic fuel efficiency, including three U.S. carriers — American Airlines, United Airlines, and US Airways — along with Iberia Airlines, the largest airline in Spain, and Alitalia, the national airline of Italy. Virgin Atlantic Airways and Swiss International Air Lines, the flag carrier airline of Switzerland, tied with US Airways for 15th place with a fuel efficiency of 29 pax-km/L. The least efficient carriers analyzed were Lufthansa German Airlines, SAS Scandinavian Airlines, and British Airways, which were responsible for 20% of the total ASKs on transatlantic routes and burned at least 44% more fuel per passenger kilometer than Norwegian. The heavy use of older, less efficient large twin-aisle aircraft, namely the Airbus A340 and especially the Boeing 747-400, with extensive premium seating was common across these carriers. The 51% gap between the most efficient airline, Norwegian, and the least efficient airline, British Airways, reveals a large disparity in how airlines operate across the Atlantic. The specific drivers of airline fuel efficiency are discussed in the next section.

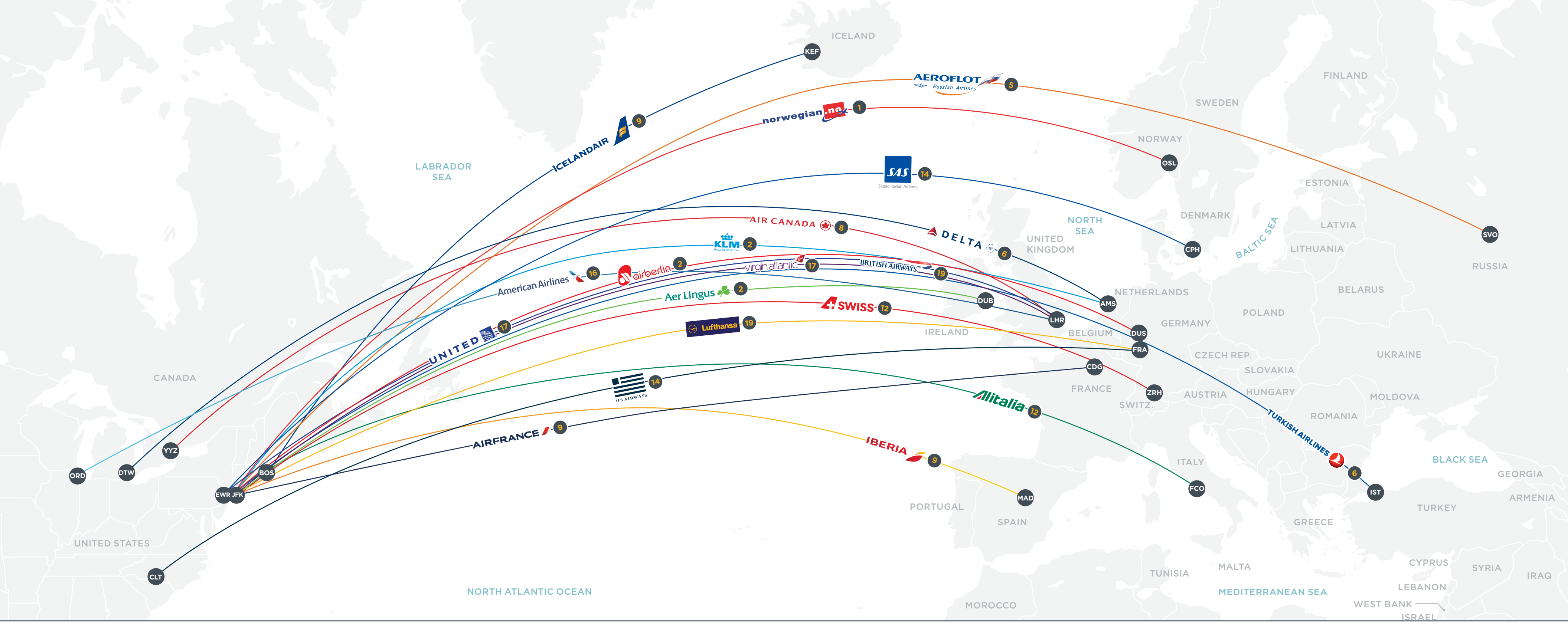
Figure 2 compares the fuel efficiency of these carriers on specific routes rather than on an overall airline basis. It presents pax-km/L fuel efficiency along with absolute CO_2 emissions in kilograms for a nonstop round-trip itinerary on the most prevalent transatlantic route flown for each airline.

As shown in Figure 2, Norwegian Air Shuttle, the most efficient airline on transatlantic routes overall, is also the most efficient airline on its most prominent route between John F. Kennedy International Airport (JFK) and Oslo Airport, Gardermoen (OSL), the busiest airport in Norway. The average fuel efficiency on this route was 42 pax-km/L fuel, about 4% more efficient than Norwegian overall, which was 40 pax-km/L. An estimated 720 kg CO_2 was emitted per passenger round-trip between JFK and OSL. Airberlin, KLM, and Aer Lingus also retained their top four rankings in this analysis, each averaging 36 pax-km/L on their most frequent routes across the Atlantic.

SAS's estimated fuel efficiency on its most prominent route, Copenhagen Airport (CPH) to Newark (EWR), was 30 pax-km/L, 8% better than its overall fuel efficiency due to a higher average load factor on this route (86%). In contrast, United Airlines' top route between Heathrow Airport (LHR) and Newark Liberty International Airport (EWR) was disproportionately inefficient due to an average 75% load factor operated on relatively old 767-300 aircraft. Lufthansa and British Airways were the least efficient on their top routes, between Frankfurt Airport (FRA) and JFK, and between London Heathrow (LHR) and JFK, respectively. Both had a fuel efficiency of 27 pax-km/L on these routes, and averaging well over one tonne of CO_2 per passenger round-trip.

The gap between the most efficient airline on its most prominent route, Norwegian, and British Airways was about 57%, or 6% larger than at the overall airline level. This larger gap is not surprising because of the greater variation in aircraft choice, load factors, seat densities, and other factors at the route level.[10] On average, the 20 ranked airlines had a fuel efficiency of 32 pax-km/L on their top routes, identical to their overall fuel efficiency on all nonstop transatlantic flights. For comparison, the emissions on a typical nonstop

10 Previous work on airline fuel efficiency on the top 10 U.S. domestic routes (Zeinali, Rutherford, Kwan, & Kharina, 2013) revealed that an airline which has high fuel efficiency overall does not necessarily have high fuel efficiency on all its routes, especially when circuitous routing and layovers are taken into account.



Rank	Airline	Airport pair	pax-km/L	kg CO_2 per round-trip itinerary
1	norwegian.no	JFK ⇄ OSL	42	720
2	airberlin	DUS ⇄ JFK	36	840
2	KLM	AMS ⇄ JFK	36	830
2	Aer Lingus	DUB ⇄ JFK	36	720
5	AEROFLOT Russian Airlines	JFK ⇄ SVO	35	1100
6	TURKISH AIRLINES	IST ⇄ JFK	34	1200
6	DELTA	AMS ⇄ DTW	34	1000
8	AIR CANADA	LHR ⇄ YYZ	33	870
9	ICELANDAIR	BOS ⇄ KEF	32	620
9	IBERIA	JFK ⇄ MAD	32	920

Rank	Airline	Airport pair	pax-km/L	kg CO_2 per round-trip itinerary
9	AIRFRANCE	CDG ⇄ JFK	32	930
12	Alitalia	FCO ⇄ JFK	31	1100
12	SWISS	JFK ⇄ ZRH	31	1000
14	US AIRWAYS	CLT ⇄ FRA	30	1200
14	SAS	CPH ⇄ EWR	30	1000
16	American Airlines	LHR ⇄ ORD	29	1100
17	virgin atlantic	JFK ⇄ LHR	28	1000
17	UNITED	LHR ⇄ EWR	28	1000
19	Lufthansa	FRA ⇄ JFK	27	1200
19	BRITISH AIRWAYS	LHR ⇄ JFK	27	1100

Figure 2. Fuel efficiency on prominent transatlantic routes, 2014

round-trip flight averaged about one tonne of CO_2 per passenger round trip, or equivalent to emissions from a 35-km daily commute in a Toyota Prius over a work year.[11]

3.2 SPECIFIC DRIVERS OF FUEL EFFICIENCY VARY BY CARRIER

Additional qualitative details for the carriers ranked in this survey are provided here.

Norwegian Air Shuttle, the "first low-cost carrier to fly non-stop between the U.S. and Scandinavia" (Norwegian Air Shuttle, 2015b) and the world's seventh largest low-cost airline (Norwegian Air Shuttle, 2015a), was by a large margin the most fuel-efficient carrier on transatlantic operations with 40 pax-km/L overall. Norwegian first launched long-haul routes in 2013 (Norwegian Air Shuttle, 2015c) and is seeking to expand low-cost, long-haul services connecting Europe with the U.S. and Asia (Teodorczuk, 2015). Norwegian's outstanding performance is attributable to its young fleet, which averaged 2 years old; the use of fuel-efficient Boeing 787-8 aircraft for the large majority of its flights; a high (86%) passenger load factor; and a below average prevalence of business and first class seats (11%). Since 2005, Norwegian's fleet size has increased six-fold, in particular with the addition of 81 Boeing 737-800 aircraft to its domestic fleet (Kenney, 2015) — similar to that of Alaska Airlines, the most fuel-efficient U.S. domestic carrier in 2014 (Li, Kwan, & Rutherford, 2015).

Airberlin, the second largest airline in Germany after Lufthansa (Airberlin group, 2015), ranked second in this survey with an average fuel efficiency of 35 pax-km/L, and operated exclusively A330-200 aircraft with an average age of 11 years for its transatlantic fleet, equal to the industry average on transatlantic flights. Similar to Norwegian, airberlin operated flights with relatively little premium seating and with the third highest average seating density among the 20 airlines in this survey. Despite burning approximately 14% more fuel per passenger kilometer than Norwegian, airberlin was significantly more efficient than its German rival Lufthansa, which consumed 25% more fuel per passenger kilometer on transatlantic flights than airberlin. Nonetheless, airberlin remains a small player in this market, providing only 1.3% of available seat kilometers, or less than a sixth of that of Lufthansa.

Aer Lingus, the national flag carrier airline of Ireland and third ranked airline in this survey, is similar to airberlin in several respects including the use of the A330 aircraft (83% of ASKs), the low provision of premium class seating, and a relatively small market share. Aer Lingus operated very efficiently on its top route from Dublin to New York JFK at 36 pax-km/L due to the use of the stretch A330-300 with very high load factors (89%). In contrast, the UK-based airlines Virgin Atlantic and British Airways burned approximately 30% more fuel per passenger kilometer on a comparable flight between London and New York, as explained below. Aer Lingus also experienced major long-haul expansion in 2014, opening new routes between Dublin and San Francisco flown with A330 aircraft as well as Dublin-Toronto and Shannon-New York/Boston supported by its wet lease[12] of 757 aircraft (ASL Aviation Group, 2015).

KLM Royal Dutch Airlines, the flag carrier airline of the Netherlands and the oldest airline in the world still operating under its original name (KLM Royal Dutch Airlines,

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11 Assumes a 45 miles per gallon (mpg) Toyota Prius fuel economy and a 234-work day year.

12 An arrangement (usually short-term) for leasing aircraft from a leasing company or airline, which is often used to provide temporary increase of capacity — for example, to help launch new routes or supplement a busy season — without the purchase of aircraft.

2015), was the top ranked full service legacy carrier and provided on average 33 passenger kilometers per liter of fuel, burning 22% more fuel than top-ranked Norwegian. It tied for fourth place with four other airlines. Based in the Netherlands, KLM accounted for 3% of total ASKs on transatlantic routes. KLM achieved its efficiency due in part to achieving the highest average passenger load factor seen (88%) on a diverse set of aircraft, including 747-400s (27% of ASKs), A330s (43%), 777s (18%), and Douglas MD-11 aircraft (13%). KLM had a slightly older fleet at 13 years of age than the average fleet age for all the ranked airlines.

Air Canada, the largest full service airline in Canada, tied for fourth with KLM, providing 33 passenger kilometers per liter of fuel on transatlantic flights overall as well as on its top route between London and Toronto (YYZ). It holds a strong niche in transatlantic operations, providing about 40% of the ASKs between Canada and Europe and 5% of total transatlantic ASKs. Of its total transatlantic ASKs, 38% were flown on 777-300 aircraft, with an 82% passenger load factor (Air Canada, 2015), slightly below the average load factor for the ranked airlines. However, its use of relatively efficient aircraft including the A330-300 enabled Air Canada to be one of the more efficient airlines.

Aeroflot Russian Airlines, the largest airline of the Russian Federation, also tied in fourth place with an average fuel efficiency of 33 pax-km/L. It performed even more efficiently on its top route between New York JFK and Moscow (SVO), providing 35 passenger kilometers per liter fuel. Its average stage length was 8186 km, the second longest average flight among the 20 airlines. Aeroflot flew predominately A330-300 aircraft on transatlantic routes, with an average fleet age of 4 years old. 17% of Aeroflot's ASKs were flown on 777-300 aircraft. Since 2013, it has received 10 of the 16 Boeing 777 orders that would enable it to increase its long-haul capabilities and is also expecting to take delivery of 22 Boeing 787 Dreamliners and 22 Airbus A350 jets in the future (Aeroflot, 2015).

Turkish Airlines, which began its transatlantic operations to North America in 1988 (Turkish Airlines, 2015a), also tied for fourth in this survey, providing 33 passenger kilometers per liter of fuel and burning 22% more fuel than top-ranked Norwegian. The national flag carrier airline of Turkey and the fourth largest carrier by number of destinations (Turkish Airlines, 2015b), Turkish flew about 3% of the total transatlantic ASKs using its fleet of 777-300 and A330-200/300 aircraft with an average age of 4 years, similar to Aeroflot and third youngest overall. Turkish flew the longest flights, averaging 8,786 km, and with an 84% passenger load factor. On its top route between Istanbul (IST) and New York JFK, Turkish operated at a higher fuel efficiency of 34 pax-km/L and 87% load factor. Turkish began partnering with Sabre this year to implement the AirCentre Flight Plan Manager solution to support flight route decision-making including addressing fuel efficiency and CO_2 emissions (MarketWatch, 2015a).

Air France, the flag carrier of France and a subsidiary of Air France-KLM Group since 2004, tied for fourth along with its merger partner KLM, Air Canada, Aeroflot, and Turkish. It provided 33 passenger kilometers per liter fuel and was the only carrier flying a plurality of its ASKs (29%) on the A380, the largest aircraft commercially available. Overall, Air France flew the second largest aircraft averaging 342 seats per flight, and had the second highest load factor, 87%, among the 20 airlines in the survey behind only KLM. Air France was somewhat less efficient, 32 pax-km/L, on its top route between Charles de Gaulle Airport (CDG) and JFK. It flew predominately 777-200 aircraft on this route with a high 88% load factor.

Delta Air Lines, the oldest airline still operating in the U.S. and the largest transatlantic carrier on an ASK basis (14% of total), was the most efficient American carrier flying across the Atlantic. Delta was ranked ninth in fuel efficiency, providing the industry average fuel efficiency of 32 passenger kilometers per liter of fuel and achieving an above average load factor of 84%. Delta achieved an above average fuel efficiency of 34 pax-km/L on its top translantic route between Amsterdam (AMS) and Detroit (DTW). In 2014 Delta flew a diverse fleet on transatlantic routes including 767-300 winglet aircraft (36% of its ASKs), A330-200/300 (33%), 747-400 (25%), 777-200 (5%), and 757-200 (2%), which had an overall fleet age of 14 years. Delta's fleet is among the oldest for transatlantic as well as domestic operations; however, Delta plans to replace its older four-engined 747s with new A330-300 aircraft and A350 aircraft in 2017. The A330 will have a "double-digit fuel efficiency improvement over the 747" and with 22% fewer seats enable better matching of capacity to demand (Levine-Weinberg, 2015).

Icelandair, the main airline in Iceland and serving as a hub between the U.S. and Europe (Icelandair, 2015), was tied with Delta for ninth in fuel efficiency. On an ASK basis, it was also the smallest carrier ranked. Icelandair was notable in this study for several reasons. In 2014 Icelandair operated an all single-aisle Boeing 757 fleet, in contrast to its rivals, which operate predominately larger, twin-aisle aircraft. This strategy is enabled by its strategic hub location in Reykjavik in the northern Atlantic, as demonstrated by its low average stage length (4,607 km). Second, Icelandair operated with a very low share of premium seating, only 5% of total, and had the highest seating density of operations by a wide margin. This allowed Icelandair to provide average fuel efficiency despite having the oldest fleet in the survey (18 years).

Iberia, the flag carrier and largest airline in Spain, was tied for 11th along with American and Alitalia, with a fuel efficiency of 31 pax-km/L. It burned 30% more fuel per passenger kilometer on average than Norwegian. 74% of its ASKs were flown on A330-300 aircraft and the rest on less efficient four-engine A340 aircraft. Iberia had the youngest transatlantic fleet, averaging about 2 years, equaling Norwegian. It also had the lowest share of premium seating (3% of its total seats available). Iberia averaged about 80% on passenger load factor overall, but achieved a slightly higher 82% load factor and 32 pax-km/L fuel efficiency on its busiest route between New York JFK and Madrid (MAD).

American Airlines, now merged with US Airways, tied for 11th place with a fuel efficiency of 31 pax-km/L, burning roughly 4% more fuel per passenger kilometer than its U.S. rival, Delta. American accounted for 9% of total transatlantic ASKs in 2014. Although American was the least efficient carrier on U.S. domestic operations from 2012 to 2014 (Li, Kwan, & Rutherford, 2015), it was the second most efficient among the U.S. carriers on transatlantic operations and just below the industry average among all 20 airlines. Though a majority (53%) of its ASKs were flown on less efficient 767-300 aircraft, American intends to retire some of these aircraft as well as take deliveries of new, more efficient 777 aircraft (Harty, 2015).

Alitalia, Italy's largest airline, was tied for 11th with Iberia and American, providing 31 passenger kilometers per liter of fuel and burning about 30% more fuel than top-ranked Norwegian. Alitalia averaged 83% on passenger load factor and flew 66% of its ASKs on A330-200 aircraft and 34% on 777-200 aircraft. Its average transatlantic fleet age was seven years. On its top route, between Rome (FCO) and New York (JFK), Alitalia also achieved a 31 pax-km/L fuel efficiency, flying predominately A330-200 aircraft. Alitalia has been partnering with GE Aviation since 2011 to identify potential fuel savings based on automated reporting and analysis of their daily fuel usage (GE Aviation, 2013).

United Airlines was ranked 14th with a fuel efficiency of 30 pax-km/L and burned 36% more fuel than Norwegian. It tied for second in market share with British Airways, both flying 10% of total transatlantic ASKs. United had a below-average load factor of 80% and even lower, 75%, on its top route between London and Newark (EWR). It flew 31% of its ASKs on 777-200 aircraft, and had the second oldest fleet of 17 years, one year younger than Icelandair's. United Airlines, which offers the most international nonstop flights from New York/Newark and Washington D.C., will be increasing its daily transatlantic services to various European cities including Athens, Barcelona, and Lisbon next year (MarketWatch, 2015b).

US Airways, which began merging with American Airlines in late 2013 but continued to operate separately in 2014, accounted for 7% of total transatlantic ASKs, tying for 15th along with two other airlines with a 29 pax-km/L fuel efficiency. US Airways was the least efficient U.S. carrier, burning about 12% more fuel per passenger kilometer than Delta and 8% more than its merger partner, American. It had by far the lowest passenger load factor (74%) among the 20 airlines. However, it performed slightly better at 30 pax-km/L on its top route between Frankfurt (FRA) and its primary hub in Charlotte, North Carolina (CLT). In 2014, US Airways added nonstop flights to Barcelona, Lisbon, Brussels, and Portugal from CLT as the number of international travelers from that hub has been increasing sharply (Portillo, 2013).

Virgin Atlantic, a member of the Virgin group and the seventh largest airline in the UK, was tied for 15th with a fuel efficiency of 29 pax-km/L, burning 38% more fuel than Norwegian. Virgin Atlantic operated the most fuel burn intensive fleet overall (see Table 4 in Section 3.3.1), flying 62% of its ASKs on 747-400 aircraft, and had the second lowest average passenger load factor 79%. Virgin Atlantic struggled financially between 2010 and 2013, ultimately selling a 49% share to Delta (Clark, 2015) and closing off subsidiary routes to Africa, Asia, and Australia. Another member of the Virgin Group, Virgin America, likewise struggles on fuel efficiency in the U.S., ranking 12th of 13 major airlines in 2014 (Li, Kwan, & Rutherford, 2015). Virgin, however, aims to increase efficiency and improve fuel conservation through the Honeywell Flight Management System, which will be implemented on its long-haul A330 and A340 fleet (Wagenen, 2015).

Swiss International Air Lines, the national airline of Switzerland and part of the Lufthansa Group, tied for 15th with US Airways and Virgin Atlantic, providing 29 passenger kilometers per liter of fuel and burning 38% more fuel than Norwegian. Swiss was just 5% more efficient than its sister company, Lufthansa German Airlines. It had the second highest share of premium seating (23%) after British Airways and also the lowest average seating density. Swiss flew 76% of its ASKs on A330-300 aircraft with an above-average 86% passenger load factor, but flew 24% of its ASKs on less efficient four-engine A340-300 aircraft. Like Alitalia, Swiss has partnered with GE Aviation's Flight Efficiency Services this year to help identify and prioritize fuel savings opportunities through evaluation and analysis of flight and operational data (GE Aviation, 2015).

Lufthansa German Airlines ranked among the three least fuel-efficient airlines on 2014 transatlantic operations, with an average efficiency of 28 pax-km/L, or 44% more fuel consumed than Norwegian and 25% more than its German rival, airberlin. Lufthansa is the largest airline in Germany and largest airline in Europe when combined with its subsidiaries. Lufthansa flew 23% of its available seat kilometers on 747-400 aircraft, had an overall fleet age of 9 years, and used extensive premium seating on translatlantic flights, leading to the third lowest average seating density. In addition to the 747, Lufthansa operated the super jumbo A380-800 aircraft on its busiest route from Frankfurt to New York JFK, providing 27 pax-km/L on a relatively low 78% passenger load factor. In 2009, Lufthansa launched its "Fuel Efficiency" program aiming to reduce jet fuel consumption (Lufthansa Group, 2012). The Lufthansa Group, which includes the network carriers Lufthansa Passenger Airlines, Swiss and Austrian Airlines, reported an overall fuel consumption of 3.84 L fuel per 100 passenger kilometers (or about 26 pax-km/L) for both domestic and international passenger flights in 2014, a 1.6% improvement from 2013 (Lufthansa Group, 2015).

SAS Scandinavian Airlines, the flag carrier of Sweden, Norway and Denmark and the largest airline in Scandinavia, tied with Lufthansa for 18th with a fuel efficiency of 28 pax-km/L on 2014 transatlantic routes. SAS flew almost half its ASKs on the A340-300, making it the only transatlantic carrier using that four-engine jet extensively. SAS operated somewhat more efficiently (30 pax-km/L) on its top route linking Copenhagen to Newark using the A330-300, the twin-engine and more fuel-efficient brother of the A340. It maintained an 86% load factor on that route compared to an 82% load factor on average. SAS was also the only ranked airline that flew transatlantic flights on 737 aircraft, which flew up to 44 business class passengers along the "oil route" between Houston and Stavanger (Scandinavian Airlines, 2015).

British Airways, which along with United had the second largest transatlantic market share after Delta, was the least fuel-efficient carrier in 2014, on average consuming 51% more fuel than Norwegian on a passenger kilometer basis. British Airways, while operating a diverse fleet of Boeing and Airbus aircraft, was fuel-inefficient due to heavy use of the four-engine 747-400 aircraft (48% of its ASKs), its 15-year-old fleet, and industry leading use of premium seating (24% of seats, almost double the industry average). Despite their fuel intensiveness, BA remains committed to the 747-400 due to its lower capital costs and ability to manage capacity constraints at London Heathrow airport (Lundgren & Johnsson, 2015). British Airway's focus on business class is not limited to the 747, however, as indicated by its one-class, 32-business seat A318 flights from London City Airport and Shannon Airport (Ireland) to New York JFK, with 1550 flights total in 2014 (OAG, 2014).

3.3 AIRCRAFT FUEL BURN AND OPERATIONAL PRACTICES ARE THE KEY DRIVERS OF AIRLINE EFFICIENCY

This section summarizes key drivers of fuel efficiency for the 20 airlines outlined above, notably aircraft fuel burn, passenger load factor, freight carriage, and seating configuration.

3.3.1 AIRCRAFT FUEL BURN VARIES SUBSTANTIALLY AMONG CARRIERS

The fuel burn of aircraft operated is an important factor influencing an airline's overall fuel efficiency. For U.S. domestic operations, Zeinali et al. (2013) estimated that about one third of the variation in fuel efficiency could be explained by differences in technology alone. Airlines that flew aircraft with lower fuel burn due to efficient technologies — winglets, high-bypass-ratio engines, and lighter airframes — tended to be more fuel-efficient overall.

One important proxy for aircraft fuel burn is the efficiency metric value designed by ICAO as a part of its development of a fuel efficiency standard for new aircraft (International Council on Clean Transportation, 2013), as indicated by the margin to a reference line (see Section 2.3 and Appendix A). Table 4 shows each airline's average fleet age, average margin to the MV reference line, most prevalent aircraft type, and that aircraft type's share of the airline's total transatlantic ASKs flown. A positive margin to the MV reference line indicates that an airline's average aircraft burn more fuel than the 2014 new deliveries average, while a lower (negative) value indicates the use of more efficient aircraft on transatlantic flights.

Table 4. Airline transatlantic fleet characteristics in 2014

Rank	Airline	Average fleet age, in years[1]	Margin to MV reference line[1]	Prevalent aircraft type	Prevalent aircraft share of airline's ASKs
1	**Norwegian**	2	-11%	Boeing 787-8	84%
2	**Airberlin**	11	-2%	Airbus A330-200	100%
3	**Aer Lingus**	9	-2%	Airbus A330-200/300	83%
4	**KLM**	13	+5%	Boeing 747-400	27%
4	**Air Canada**	12	+1%	Boeing 777-300ER	38%
4	**Aeroflot**	4	-2%	Airbus A330-300	46%
4	**Turkish**	4	-2%	Boeing 777-300ER	57%
4	**Air France**	10	0%	Airbus A380-800	29%
9	**Delta**	14	+2%	Boeing 767-300 (winglets)	36%
9	**Icelandair**	18	+6%	Boeing 757-200 (winglets)	90%
11	**Iberia**	2	-1%	Airbus A330-300	74%
11	**American**	15	+3%	Boeing 767-300	53%
11	**Alitalia**	7	-1%	Airbus A330-200	66%
14	**United**	17	+5%	Boeing 777-200	31%
15	**US Airways**	12	0%	Airbus A330-300	40%
15	**Virgin Atlantic**	12	+11%	Boeing 747-400	62%
15	**Swiss**	6	-1%	Airbus A330-300	76%
18	**Lufthansa**	9	+4%	Boeing 747-400	23%
18	**SAS**	12	+1%	Airbus A340-300	50%
20	**British Airways**	15	+5%	Boeing 747-400	48%

[1] ASK-weighted average value by airline for transatlantic routes.

The top-ranked carrier, Norwegian, flew 84% of its transatlantic flight ASKs on the efficient Boeing 787-8 aircraft; correspondingly, Norwegian's average aircraft in 2014 had about 11% lower fuel burn based on the reference line and had the most efficient fleet among the 20 airlines. The three next most efficient airlines, airberlin, Aer Lingus, and KLM, flew predominately Airbus A330 aircraft, which on ICAO's MV are approximately 10% more fuel-intensive during cruise operations than the 787-8. In contrast, three of the five bottom-performing airlines — Virgin, Lufthansa, and British Airways — flew predominately Boeing 747-400 aircraft on transatlantic routes, which are estimated to burn approximately 30% more fuel than the 787-8 on ICAO's MV. British Airways, which had the worst fuel efficiency on transatlantic routes, flew about 48% of its flights on Boeing 747-400 aircraft and 4% (about 1550 flights) on Airbus A318 aircraft in a very fuel intensive 32-business seat aircraft. British also had one of the oldest fleets among the 20 airlines, averaging 15 years, in contrast to Norwegian and Iberia, whose fleets averaged only 2 years old.

3.3.2 OPERATIONAL PRACTICES DIFFER ACROSS CARRIERS

Key operational parameters were also investigated to help explain the observed differences in fuel efficiency across airlines.

LOAD FACTORS

Passenger load factors on transatlantic routes for the 20 airlines varied from 74% (US Airways) to 88% (KLM), averaging 83%. Although the ability of an airline to fill its seats impacts fuel efficiency, the relatively narrow range in airline load factors (standard deviation of only 3%) means that load factor itself is not a major determinant of overall airline fuel efficiency. However, it can be noted that the airline with the highest passenger load factor of 88%, KLM, ranked fourth in fuel efficiency, while the airline with the lowest passenger load factor, US Airways, ranked 15th.

As noted above, airline specific belly carriage data is not publicly available. Instead, for this analysis belly freight load factors by aircraft type were estimated (see Appendix A) and combined with OAG freight capacity data to model freight carriage. Analyzed via this approximation, the belly freight loaded onto an airplane did not strongly influence the airlines' overall fuel efficiency. However, airlines that moved more freight on passenger flights than average would have higher fuel efficiencies, and the lack of data means the exact impact of airline freight practices on airline efficiency cannot be precisely analyzed.

SEATING CONFIGURATION

Among the operational variables assessed, seating configuration, that is, the ratio of premium to total seating and the number of seats per square meter of fuselage floor area, appears to have the strongest impact on fuel efficiency. On the former metric, Iberia (ranked 11th) and Icelandair (9th) had the fewest business and first class seats, while British Airways (20th), Swiss (15th), and Lufthansa (18th) had the highest share of premium seats.

An analysis of overall seating density supports the contention that seating configuration influences airline fuel efficiency. Along with Icelandair, which flew all single-aisle aircraft with the highest average aircraft seating density (1.35 seats/m^2), Norwegian, airberlin, and Aer Lingus also had high seating densities on transatlantic flights (1.18, 1.17, and 1.14 seats/m^2, respectively). In contrast, the least-efficient airlines typically had seating densities less than 1.00 seat/m^2 due to their larger proportion of first and business class seats, which take up more floor area than economy or standard seats. At 0.79 seat/m^2, British Airways had the lowest average seating density on transatlantic flights, due to both the large number of premium seats on its 747-400s and its 32-business seat A318 flights. The environmental consequences of premium seating are significant: first and business class seats accounted for only 14% of available seat kilometers flown on nonstop transatlantic routes but were responsible for approximately one third of overall emissions from passengers, assuming that business and first class seats are on average three times as carbon intensive as economy seats.[13]

Table 5 summarizes airline operational parameters for 2014 nonstop transatlantic flights by efficiency ranking.

Table 5. Airline operational parameters

Rank	Airline	Passenger load factor	Freight share of total tonne-km	Premium seating share	Overall seating density (seats/ m^2 eRGF)	Average flight length (GCD km)
1	Norwegian	86%	15%	11%	1.18	7,263
2	Airberlin	81%	16%	6%	1.17	7,084
3	Aer Lingus	84%	12%	8%	1.14	5,388
4	KLM	88%	21%	11%	1.02	6,787
4	Air Canada	82%	21%	11%	1.01	6,119
4	Aeroflot	80%	21%	15%	1.02	8,186
4	Turkish	84%	22%	9%	0.96	8,786
4	Air France	87%	20%	15%	0.91	6,677
9	Delta	84%	16%	14%	1.05	6,625
9	Icelandair	83%	6%	5%	1.35	4,607
11	Iberia	80%	21%	3%	0.97	6,529
11	American	80%	21%	16%	1.00	6,738
11	Alitalia	83%	18%	9%	0.99	7,247
14	United	80%	21%	15%	1.01	6,477
15	US Airways	74%	16%	8%	1.08	6,282
15	Virgin Atlantic	79%	22%	10%	0.97	6,649
15	Swiss	86%	17%	23%	0.82	7,124
18	Lufthansa	84%	19%	21%	0.85	7,263
18	SAS	82%	13%	15%	0.89	6,770
20	British Airways	83%	24%	24%	0.79	6,519

3.3.3 DIFFERENCES IN SEATING CONFIGURATION AND AIRCRAFT FUEL BURN EXPLAIN MOST OF THE FUEL EFFICIENCY GAP

A multivariate regression model was developed to relate overall airline fuel efficiency to technological and operational parameters, or "predictors", including aircraft fuel burn (as measured by the MV margin to a reference line, or RL), passenger load factor, aircraft seat density, and freight carriage as a percent of the total tonne-km carried (Equation 7):

$$paxkm/L = a_1 * (margin\ to\ RL) + a_2\ (seat\ density) + a_3 * (load\ factor) + a_4 * (freight\ carriage) + a_0 \qquad \text{(Eq. 7)}$$

13 See Bofinger and Strand (2013) for an in-depth discussion of the emission implications of business and first class air travel.

The results of the regression are presented in Table 6.

Table 6. Regression model of airline fuel efficiency

Parameter	Variable	Units	Coefficient	Standard error	t-statistic	p-value
Airline fuel efficiency	*paxkm/L*	pax-km/L	–	–	–	–
Aircraft fuel burn	*margin to RL*	–	a_1: -33.737	4.894	-6.89	0.000
Seating configuration	*seat density*	seat/m² eRGF	a_2: 21.691	2.236	9.70	0.000
Passenger load factor	*load factor*	–	a_3: 33.897	6.896	4.92	0.000
Freight share of total tonne-km	*freight carriage*	–	a_4: 37.730	6.761	5.58	0.000
	constant	pax-km/L	a_0: -24.745	7.191	-3.44	0.004

Number of observations = 20, R^2 = 0.926

Currently, there is no standard approach to measure the relative importance of predictors in a multiple regression, or in other words, the contribution of different variables to the explained variance in fuel efficiency (Azen and Budescu, 2003). Two methods which partition the explained variance among multiple predictors while accounting for multicollinearity[14] are relative weights analysis and Shapley value analysis (or dominance analysis) (Tonidandel, & LeBreton, 2011). Relative weights analysis uses a variable transformation to create a new set of variables that are statistically independent from one another for which a "relative weight" for each predictor can then be computed. The Shapley method starts with the full regression model (see Table 6) and "successively removes regressor variables one by one and according to a particular ordering of the variables" to estimate each variable's marginal contribution (Huettner & Sunder, 2012).

Results from the relative weights and Shapley values (or dominance analysis) approaches were nearly identical. The Shapley method results are shown in Figure 3 below.

The model estimates that approximately 46% of the variation in transatlantic fuel efficiency in 2014 was explained by differences in seating configuration, compared to 35% for the underlying fuel burn of the aircraft operated. (This latter value is identical to that seen for U.S. domestic airlines in 2010).[15] Other operational factors captured in the modeling — passenger load factor and freight carriage — explain only about 20% of the variation among carriers.[16]

The reliability of these point estimates was assessed by developing 90% confidence

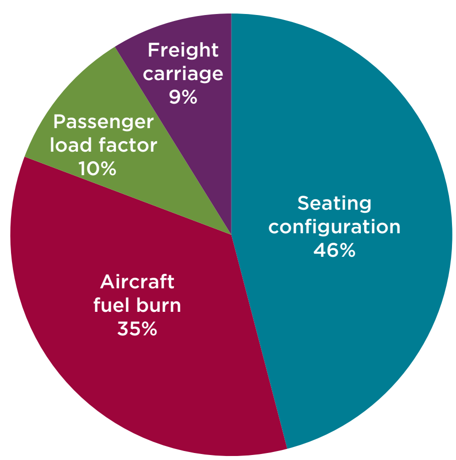

Figure 3. Key drivers of airline fuel efficiency

14 Another approach, the squared product-moment correlation method, uses the square of the correlation between the dependent variable, airline fuel efficiency (pax-km/L), and each of the predictor variables (margin to RL, seat density, load factor, freight carriage) to estimate the degree to which various parameters drive airline fuel efficiency when the individual predictors are true independent variables (i.e. uncorrelated). In this case, the predictors are correlated, so this method could not be used with confidence.

15 See Zeinali et al. (2013) for more information.

16 Note that about 93% (i.e. R^2) of the variation in fuel efficiency can be explained by the multivariate regression model. The rest, 7%, is explained by other factors not included in the discussion.

intervals through a random sampling method known as "bootstrapping." The results are shown in Figure 4.

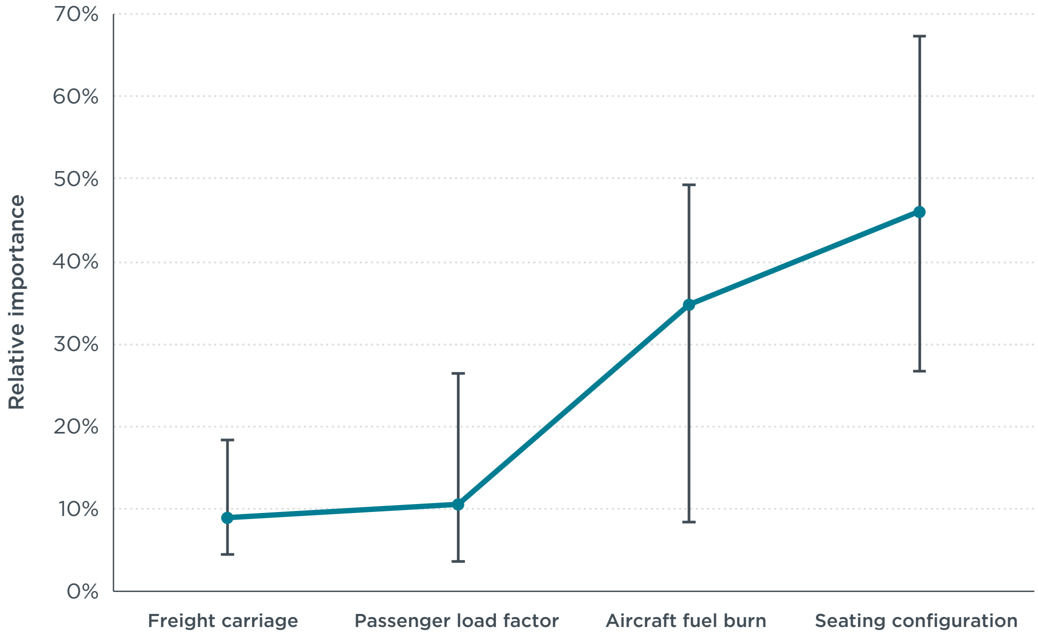

Figure 4. 90% Confidence intervals for key variables influencing airline fuel efficiency

Figure 4 confirms the impression that the key drivers of transatlantic fuel efficiency in 2014 were, in order of decreasing importance, seating configuration, aircraft fuel burn, passenger load factor, and freight carriage. At the same time, significant overlap is seen in the confidence intervals for seating configuration (27% to 67% of variance explained) and aircraft fuel burn (8% to 49%), and also between passenger load factor and freight carriage. Given this overlap, and also the underlying uncertainties associated with this methodology, it can be concluded that seating configuration and aircraft fuel burn were the two most important drivers of transatlantic fuel efficiency in 2014, with passenger load factor and freight carriage being relatively less important.

4. CONCLUSIONS, POLICY IMPLICATIONS, AND NEXT STEPS

The conclusions, policy implications, and next steps from this work are as follows.

CONCLUSIONS

Clearly, some airlines are making more efforts than others to improve their fuel efficiency on transatlantic routes. The 51% gap between the efficiency of industry leaders such as Norwegian Air Shuttle and laggards like British Airways highlights that there are significant differences in the environmental performance of carriers flying over the North Atlantic. Overall, airlines with more fuel-efficient aircraft, less premium seating, and higher passenger and freight load factors provide less carbon-intensive travel options for passengers. Interestingly, the efficiency gap on nonstop transatlantic operations was roughly double that seen for the U.S. domestic market, which was only 25% in 2014 (Li, Kwan & Rutherford, 2015). While some of this may be attributable to differences in methodologies,[17] this result suggests that differences in the fuel efficiency of airlines on international routes may be larger than initially anticipated.

As noted in Section 3.3.1, one of the largest drivers of this efficiency gap was the underlying fuel burn of aircraft operated. Airlines that have invested in new, advanced aircraft such as Boeing 787-8s are more fuel-efficient than airlines that use primarily older, less efficient aircraft like Boeing 747-400s or the Airbus A340. Some airlines at the bottom of the ranking, for example British Airways, SAS, and Lufthansa, may be underinvesting in fuel efficiency, increasing emissions, and spending more on fuel than necessary. This finding draws attention to the importance of lowering aircraft fuel burn, and in particular the role of new, more advanced aircraft types in improving overall airline efficiency.

Moreover, this study highlights the fact that operational factors also have a strong impact on airline fuel efficiency. Some differences in observed airline efficiency can be traced to variations in passenger load factors and belly freight carriage, but seating configuration is the dominant driver. As summarized in Table 5, a higher proportion of first and business class seating is clearly associated with lower fuel efficiency on a passenger kilometer basis. Premium seating accounted for only 14% of available seat kilometers on transatlantic flights in 2014 but was responsible for approximately one third of emissions, assuming that business and first class seats are on average three times as carbon intensive as economy seats. For two airlines, Swiss and British Airways, premium seating accounted for nearly half of overall CO_2 emissions from passenger movement.

These two factors — aircraft fuel burn and seating configuration — appear to be linked to prominent business models for transatlantic service. Poor overall airline fuel efficiency is highly correlated with the use of older, large twin-aisle aircraft such as the Boeing 747-400 with extensive first and business class seating. In contrast, the most fuel-efficient carriers tend to operate newer, smaller twin-aisle aircraft with more economy seating. The combination of older, less efficient aircraft with extensive premium seating makes

17 Due to data limitations, this study applied a simple pax-km/L metric on nonstop transatlantic flights as estimated by advanced fuel burn modeling. ICCT's U.S. domestic fuel efficiency rankings, which use airline primary fuel burn data, also take into account the fuel efficiency implications of regional operations, layovers, and circuitous routing. The U.S. rankings therefore provide a more comprehensive evaluation of the range of fuel efficiencies demonstrated by airlines.

the economic performance of the least efficient carriers vulnerable to fuel price volatility and any future policies to price aviation carbon.

POLICY IMPLICATIONS

This work holds implications for policies under development to reduce carbon emissions from the aviation sector. These can roughly be broken up into policies to reduce the fuel burn of new aircraft and policies meant to reduce or offset emissions from the in-service aircraft operated by airlines.

The major policy under development to reduce the average fuel burn of new aircraft is ICAO's CO_2 standard. The very high fuel efficiency of Norwegian Air Shuttle demonstrates the key role of technology in reducing CO_2 emissions from the airlines. A robust CO_2 standard should help accelerate technology development and adoption by manufacturers and airlines. In particular, a CO_2 standard covering all new aircraft, not just new designs, will avoid perverse incentives against the introduction of new types and help ensure that technologies developed for advanced aircraft types like the 787-8 are deployed more widely across manufacturers' full product lines.[18]

Other policies are also under development to reduce or offset emissions from in-service aircraft. A global market-based measure (MBM) to establish a carbon price on aviation could help limit aircraft emissions and address the airline efficiency gap identified in this study. Starting in 2012, CO_2 emissions from domestic and intra-European flights were integrated into the European Union's Emissions Trading System (ETS), with ICAO currently developing a proposal for a global MBM for international emissions. The 51% efficiency gap identified in this report points to a large potential for in-sector reductions under such a system. Furthermore, it suggests that any MBM based upon emissions trading with other sectors or offsetting should ensure that any credits or offsets used to replace in-sector reductions are of the highest integrity, leading to real reductions in emissions (International Coalition for Sustainable Aviation, 2015).

The final policy conclusion relates to data transparency. Accurate and transparent data are crucial for assessing the fuel efficiency of airlines and enabling low carbon decision-making. Currently, there is no easy way for environmentally conscious consumers to choose less carbon-intensive flights. Even this study, while based upon best available public data and sophisticated modeling tools, cannot capture the fuel efficiency impacts of operational practices like speed and routing at the airline, route, or flight level. Better data — at a minimum, primary-reported fuel consumption data for all carriers similar to that already reported to the U.S. DOT by U.S. carriers — would help travelers and policymakers alike make more informed choices. Better information about the fuel burn of individual aircraft types could be provided through the creation of a robust database of aircraft certified under ICAO's CO_2 standard, while information about in-service emissions collected under monitoring, reporting, and verification requirements for the EU ETS or a future ICAO's MBM (International Coalition for Sustainable Aviation, 2015) could help fill this gap.

18 ICAO is currently discussing applicability options for the CO_2 standard. Under one proposal being considered, all existing aircraft designs certified before the standard takes effect would be grandfathered into the standard, with only completely new designs regulated. This raises the danger that manufacturers may delay the introduction of new types in order to avoid regulation, and would also delay the effectiveness of any standard (Kharina, 2015). A CO_2 standard applied to all new aircraft delivered after a certain date is likely to minimize these risks.

NEXT STEPS

This research has highlighted several possible areas of future work. First, given the surprising finding that there is a larger gap in fuel efficiency on transatlantic routes than on U.S. domestic routes, expanding the methodology to cover additional routes, for example, transpacific routes, could help to assess the generalizability of this finding to other markets. Eventually, a global assessment of airline fuel efficiency may be appropriate, although data limitations for flights that occur entirely outside the U.S. would need to be considered. Second, a future update for transatlantic carriers could help evaluate relative changes in airline fuel efficiency over time and investigate the impact of new aircraft types, for example the Boeing 787-9, on airline efficiency. Finally, assuming widespread cooperation from ranked airlines, the methodology introduced here could be shifted from a modeling approach to one analyzing primary fuel burn data to encompass the full range of operational measures that impact airline fuel efficiency.

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APPENDIX A: DETAILED METHODOLOGY

This appendix provides further detail on three methodological questions highlighted in the main text — the estimation of freight carried, actual flight distance, and aircraft fuel burn.

FREIGHT PAYLOAD

Freight payload was calculated in a manner similar to the passenger payload calculation (Equation A1):

$$Payload_{freight}\,[\text{kg}] = FreightCapacity[tonne] * 10^3 kg/tonne * LoadFactor_{freight} \quad \text{(Eq. A1)}$$

The belly freight load factor was estimated using BTS traffic data for U.S. carriers' (American, Delta, United, and US Airways) transatlantic flights according to Equation A2.[19] Note that the denominator represents an estimate of the total available freight tonne-km (or capacity).

$$LoadFactor_{freight,\ U.S.\ aircraft} = \frac{FTK + MTK}{ATK - ASK * PaxWeight * tonne/10^3 kg} \quad \text{(Eq. A2)}$$

where FTK= freight tonne-km
MTK = mail tonne-km
ATK = available tonne-km
ASK = available seat-km
$PaxWeight$ = 90.7 kg (200 lb)[20]

These derived load factors, averaged by aircraft type across the four U.S. airlines, are shown in Table A1.

Table A1. Transatlantic belly freight load factors for U.S. carriers by aircraft type, 2014

Aircraft	Freight share of revenue tonne-km	Estimated belly freight load factor
Airbus A330-200	22%	22%
Airbus A330-300	19%	31%
Boeing 747-400	17%	47%
Boeing 757-200	2%	6%
Boeing 767-400/ER	23%	32%
Boeing 767-200/ER/EM	17%	22%
Boeing 767-300/300ER	24%	28%
Boeing 777-200ER/200LR/233LR	28%	43%
Boeing 777-300/300ER/333ER	44%	50%

Source: U.S. DOT BTS Form 41 via Data Base Products, Inc. (2015)

19 International Civil Aviation Organization (2009) includes average belly freight load factors for international passenger flights of 30% for North America and 45.5% for Europe in 2007. To improve the accuracy of this study's methodology, individual freight load factors were estimated by aircraft type, summarized in Table A2. Overall, the type average belly freight load factor was estimated to be 35% for transatlantic flight in 2014, very close to the simple ICAO average of 38%.

20 BTS uses a standard weight of 200 lb per passenger and baggage to compute the revenue ton-miles from aircraft miles flown and the number of pounds of revenue traffic (passengers, freight, mail) carried. See U.S. Department of Transportation (2007).

As shown in Table A1, the smaller single-aisle aircraft (Boeing 757-200) have relatively little freight — only 2% of the total tonnage carried and 6% of the total capacity. Because no U.S. airlines operated smaller single-aisle aircraft across the Atlantic, this 6% belly freight load factor was used for all single-aisle aircraft in the modeling, with one exception.[21]

For aircraft types used by the 16 non-U.S. carriers[22] not listed in Table A1, a linear regression was used to estimate the remaining aircrafts' ("missing ac") belly freight load factors. Using the aircraft in Table A1 as data points and the assumption that aircraft cargo capacity by volume (HoldVolume) is proportional to the amount of freight carried (i.e. more space available leads to proportionately more space occupied), the following regression equation was determined (Equation A3):

$$LoadFactor_{freight,\ missing\ ac} = 0.003 * HoldVolume[m^3] - 0.0657 \qquad \text{(Eq. A3)}$$

Table A2 lists the final belly freight load factors used in the analysis by aircraft type.

Table A2. Transatlantic belly freight load factors by aircraft type, 2014

OAG aircraft type	Estimated belly freight load factor
Airbus A318	6%
Airbus A319	6%
Airbus A330-200	22%
Airbus A330-300	31%
Airbus A340-200	34%
Airbus A340-300	37%
Airbus A340-500	39%
Airbus A340-600	55%
Airbus A380-800 Passenger	44%
Boeing (Douglas) MD-11 Passenger	51%
Boeing 737-700 (winglets) Passenger	6%
Boeing 747 (Passenger)	47%
Boeing 747-400 (Passenger)	47%
Boeing 747-8i Passenger	41%
Boeing 757-200 (winglets) Passenger	6% (18%, Icelandair)
Boeing 757-200 Passenger	6%
Boeing 757-300 (winglets) Passenger	6% (18%, Icelandair)
Boeing 767-200 Passenger	22%
Boeing 767-300 (winglets) Passenger	28%
Boeing 767-300 Passenger	28%

continued on next page

21 One exception was for Icelandair, which flew all of its transatlantic flights on Boeing 757-200 and 757-300 single-aisle aircraft from a small island hub. Because Icelandair had an all-single-aisle fleet, its calculated fuel efficiency is very sensitive to assumptions about belly freight carriage. Cargo data provided by Icelandair revealed that the amount of belly freight moved on an average flight was about 18% of the freight capacity on a tonne-km basis, or about three times the U.S. carrier-estimated load factor. Thus, an 18% load factor was applied for all Icelandair flights.

22 One U.S. carrier, United, operated Boeing 787-8s on a limited number of transatlantic flights and thus reported belly freight carriage data to U.S. DOT. Upon investigation, the freight data for these flights were judged to be outliers, possibly due to the limited number of operations that year. That data was not used to derive a type-specific belly freight load factor for the 787-8, which was instead determined via regression along with other missing types.

OAG aircraft type	Estimated belly freight load factor
Boeing 767-400 Passenger	32%
Boeing 777-200/200ER Passenger	43%
Boeing 777-200LR	43%
Boeing 777-300ER Passenger	50%
Boeing 787-8	34%
Boeing 787-9	39%
ATK-weighted average	***35%***

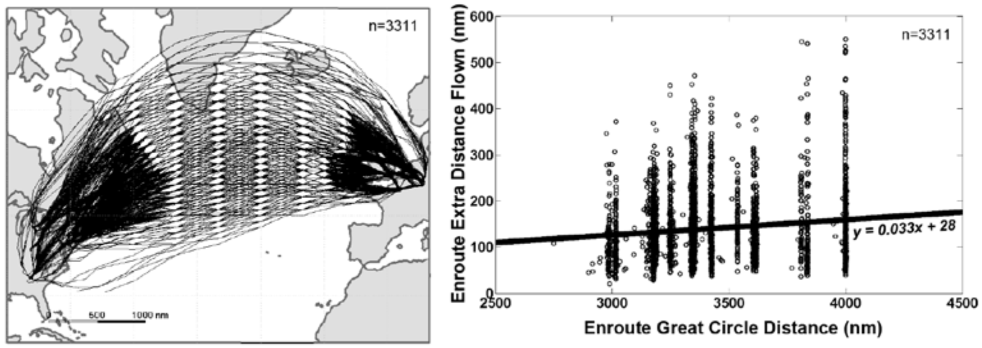
These load factors were multiplied by the overall freight capacity for each flight within the OAG database to estimate freight carriage. Within the OAG dataset, many flights had missing values for freight capacity. For those flights, a linear regression model relating mass freight capacity (tonnes) to cargo hold volume was used to estimate missing values (Equation A4):

$$FreightTons\ [tonne] = 0.0901 * HoldVolume[m^3] + 3.9101 \qquad \text{(Eq. A4)}$$

In addition, to ensure that a certain aircraft's freight capacity was appropriate for the Piano aircraft it was matched to (and thus avoid modeling flights over capacity), the freight capacity of the Piano aircraft was also calculated and compared to that reported in OAG. Ultimately, the smaller of the two freight capacity values was used in the fuel burn modeling to determine actual freight carriage.

FLIGHT DISTANCE

OAG routes were used to calculate great circle distance flight paths, which are known to be an underestimation of actual aircraft routing. According to the Intergovernmental Panel on Climate Change (IPCC), actual flight routing distance can vary significantly from great circle paths due to flight routing, procedural separation rules, and weather. A study of international and domestic flights from German airports revealed an average 10% increase in great circle distance for medium- and long-haul flights longer than 700 km (IPCC, 1999). A study by Reynolds (2008) provides information on actual distance flown for flights from western Europe to eastern U.S. using ground tracks data. According to Reynolds, the Atlantic Ocean airspace is out of radar surveillance and Very High Frequency (VHF) radio communication coverage; thus aircraft follow procedural separation rules, resulting in a more "rigid track structure" (as shown by the "diamond" pattern in the tracks in Figure A1), and therefore less efficiency than what is possible with more advanced communication and surveillance. The Reynolds study, however, did not account for the impact of winds on flight routing. Though an important factor affecting actual flight distance, no correction factor was made for wind when modeling aircraft fuel burn.



Source: Reynolds (2008) (used with permission)

Figure A1. Flight paths in the North Atlantic (left) and en route extra distance flown vs. en route great circle distance (right)

The regression equation for North Atlantic flight inefficiency estimated by Reynolds [*Extra Distance Flown (nm) = 0.033*Great Circle Distance + 28*] was used to adjust the great circle distances for modeling in Piano (Equation A5):

$$FlightDistance[nm] = GCD[nm] + 0.033 * GCD[nm] + 28 \qquad \text{(Eq. A5)}$$

Similarly, a study conducted by the Civil Air Navigation Services Organisation (CANSO) and Boeing (2012) shows that horizontal en route extension, actual distance flown minus an "ideal benchmark unimpeded distance," was around 4% and 2.5% for flights longer than 1000 nm within Europe and the U.S., respectively. The ideal benchmark distance is unlikely to refer to the great circle distance here, so it would be more comparable to the 4% value estimated using the Reynolds regression equation.

AIRCRAFT FUEL BURN

The International Civil Aviation Organization's (ICAO) metric value (MV) takes into account aircraft cruise performance and can be used as a proxy for aircraft fuel burn performance. The MV is a function of an aircraft's Specific Air Range, or ratio of true air speed to gross fuel consumption (in meters per kilogram), measured at three equally weighted gross weights and the aircraft size, which is represented by an aircraft's Reference Geometric Factor (RGF) — a close proxy for the pressurized floor area of the aircraft. More specifically, ICAO's metric value is defined below and is in units of [kg fuel/km x $m^{0.48}$]:

$$MV = \frac{(1/SAR)_{ave}}{RGF^{0.24}} \qquad \text{(Eq. A6)}$$

The following steps were taken to calculate metric values for newly-delivered aircraft in 2014.

Step 1: For each aircraft type, aircraft RGF was estimated according to the equation:

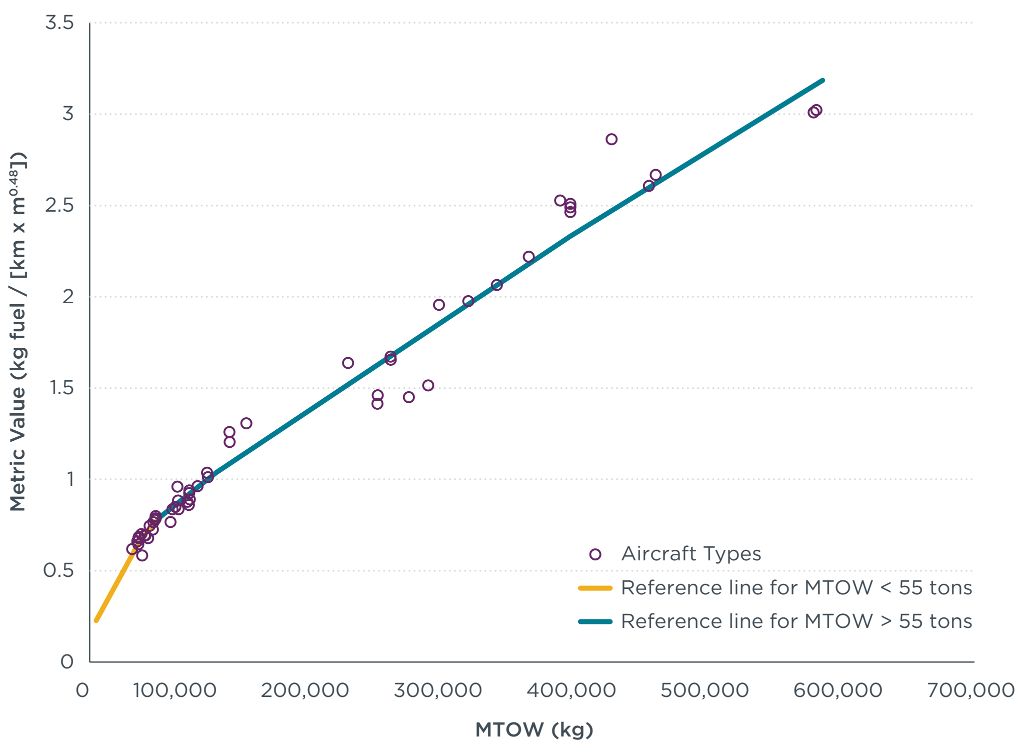
$$eRGF\ [m^2] = fuselage\ width \times cabin\ length \qquad \text{(Eq. A7)}$$

Step 2: The maximum cruise SAR value of each aircraft type was modeled at cruise speeds enabling 99% maximum SAR using Piano 5 for ICAO's high, medium, and low gross weight points.[23] A simple average of the inverses of these three SAR values (1/SAR) was calculated.

23 In practice, the same aircraft type is delivered and operated at different MTOWs for various reasons, so the highest MTOW variant available was analyzed for each type, consistent with ICAO's CO_2 certification requirement.

Step 3: Each aircraft MV was calculated by using estimated RGF values (Step 1) and average 1/SAR values (Step 2) as inputs to Equation A6.

Step 4: A reference line was created to normalize the results for different size aircraft. Because the productivity (payload and range) of aircraft vary in rough proportion to their MTOWs, the relative fuel burn of aircraft can only be compared via differences to a reference line. For this study, a reference line for 2014 in-production aircraft, shown in Figure A2, was determined from a second order log-log regression of cruise metric values of all aircraft types with an entry into service (EIS) after 1999 on the aircraft MTOW. The reference line is a combination of two separate lines: one drawn to best fit airplane types with MTOWs under 55 tonnes and the other drawn to best fit airplane types with MTOWs over 55 tonnes.



Source: Kharina & Rutherford (2015)

Figure A2. Reference line for normalizing aircraft metric values

Step 5: The margin (in terms of percent difference) to the reference line identified in Step 4 was calculated for each aircraft type.

Step 6: Each airlines' fleet average margin to the reference line was determined as a proxy for the average fuel burn of its fleet on comparable operations. First, the aircraft types operated on transatlantic flights and their corresponding available seat kilometers (ASK) were identified. Then an ASK-weighted average margin to the reference line was calculated for all aircraft types operated by an airline.

APPENDIX B: MODEL VALIDATION

The methodology outlined in Section 2 and Appendix A was validated using primary-reported fuel burn data reported by U.S. airlines for each aircraft type operated across the Atlantic. BTS Form 41 data provides data on fuel and traffic for the U.S. carriers on Atlantic operations. The average fuel efficiency for each aircraft type operated by the four U.S. carriers was calculated directly from this data and compared against the estimated fuel efficiency using the modeling assumptions described above. In doing so, the uncertainty introduced by modeling fuel burn with Piano using standardized assumptions for operational parameters such as routing, freight carriage, fuel loading, speed, and so forth could be assessed. A total of 19 airline-aircraft type reported fuel efficiencies were compared against modeled values (Figure A3).

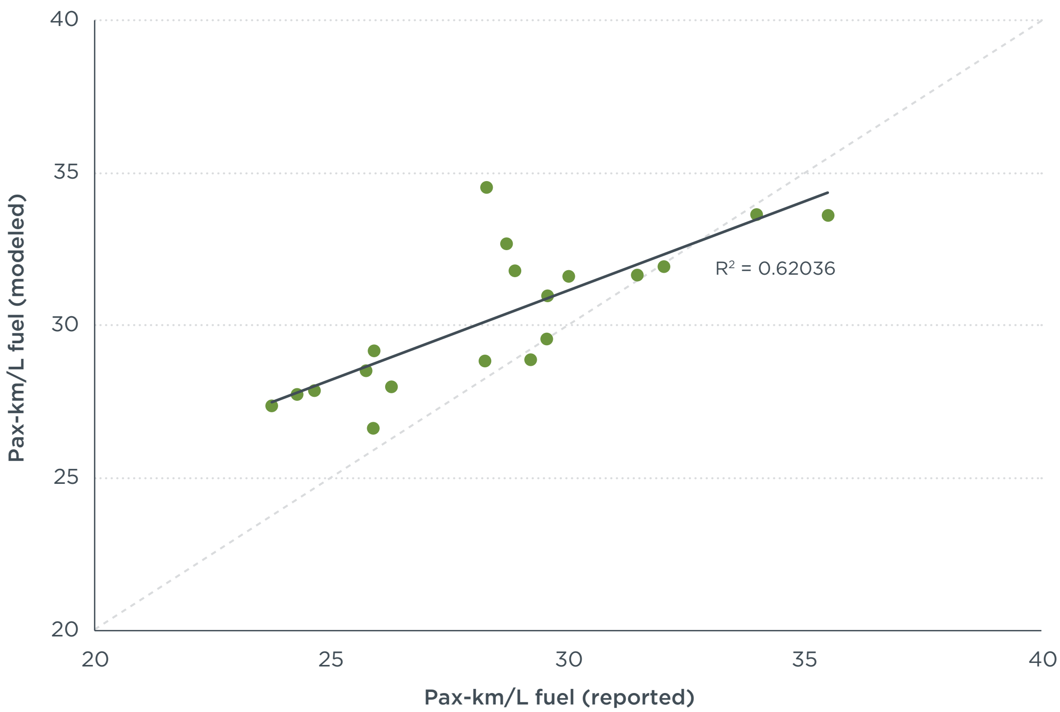


Figure A3. Airline-reported vs. modeled fuel efficiency

The validation exercise suggests that the modeling approach developed is robust and fit for the purpose of comparing the relative fuel efficiency of transatlantic operations. Even without airline-specific values for parameters such as flight routing, freight carriage, and fuel loaded, the modeling approach predicted actual airline fuel efficiency for U.S. carriers well. A good linear fit (R^2 of approximately 0.6) was seen, indicating that changes to the modeling parameters are unlikely to lead to major shifts in the rankings.[24] As Figure A2 indicates, on average there was a modest deviation of approximately 7% from estimated fuel efficiency compared to actual fuel efficiency data, with the fuel efficiency of most aircraft types being somewhat overestimated

24 An even higher correlation (R^2 approximately 0.8) would be obtained by excluding United's limited 787-8 operations from this exercise, which as noted above were determined to be outliers for the determination of freight load factors.

compared to actual data. These validation findings are broadly consistent with those reported in the report *Aviation and the Global Atmosphere*[25] (IPCC, 1999).

25 "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." (IPCC, 1999)

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