

Recent trends in payload fuel energy efficiency: An analysis of U.S. air carriers from 2003 to 2017

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Abstract

A simple payload fuel energy efficiency (PFEE) metric is used here to establish the year-on-year fuel efficiency performance of both scheduled and non-scheduled U.S. air carriers operating in the domestic and international markets over a 15-year period from 2003-2017. The operational data used in this study is sourced from the U.S. Bureau of Transportation Statistics, Schedules T-2 and P-12(a), which allows revenue payload distances to be determined and related to the associated fuel quantities consumed. The resulting time-series show the trends in PFEE at a fleet level, and illustrate how the year-on-year efficiency improvements in the domestic market (2.50% p/a) have outstripped those in the international market (1.38% p/a) between 2003 and 2017.

1 Introduction

Commercial airlines and governments worldwide recognize the vital role which international aviation plays in global economic and social development. To ensure that international aviation continues to develop in a sustainable manner there are many challenges to address, not least the phenomenal growth of air travel which threatens to outpace its fuel-economy improvements and associated CO₂ emissions. In June 2009, IATA's Board of Governors underlined their commitment to addressing carbon emissions - agreed upon collectively by the worldwide aviation industry – by proposing, amongst other things, a 1.5% average annual fuel efficiency improvement between 2010 and 2020¹. The urgency of this situation has not been lost on the aviation industry, which has responded over the past decade with the introduction of many newer, lighter, and more fuel-efficient aircraft types, such as the 737 MAX and 787 series from Boeing and the A320 NEO and A350 series from Airbus.

A simple payload fuel energy efficiency (PFEE) metric, as described by Nangia (2006) and Hileman *et al.* (2008), is used herein to assess the overall average energy efficiency of a representative fleet of commercial aircraft over a 15-year period, spanning 2003-2017. As Peeters *et al.* (2005) astutely observe, "The ambition of

¹ This commitment was adopted by IATA at the 2010 AGM Resolution on Climate Change (CNG2020 n.d.)

generating a time series for the world's commercial air transport fleet is frustrated by the absence of globally comparable transport volume and aviation energy use statistics. Although world aviation traffic statistics are available from several sources, relevant fuel consumption data for commercial aviation are hardly available in an appropriate format.”

To the authors' knowledge, the only freely-available source of commercial aviation data that includes both traffic volumes *and* fuel consumption usage belongs to the U.S. Bureau of Transportation Statistics (BTS Schedule T-100, 2018), and for this reason, the content of this paper is restricted only to U.S. air carriers. Although the U.S. is the largest aviation market in the world, in terms of revenue tonne kilometres, it only accounts for approximately 20% of total worldwide aviation activity² (IATA 2018). Hence the trends in U.S. aviation efficiency reported here may not be fully reflective of other regions, but nonetheless provide an indication of what might be expected.

2 Background

2.1 Payload Fuel Energy Efficiency

Aircraft fuel efficiency performance encompasses a wide range of capabilities such as range, payload, speed, altitude etc. As a result, many different studies have been conducted, ranging from comparisons between different aircraft types (Lee *et al.* 2001, Babikian *et al.* 2002) to the energy efficiency of entire airlines (Miyoshi and Merkert 2010, Cui and Li 2015, Cui and Li 2016). Although aircraft fuel efficiency has been improving over time, it has been noted that the rate of efficiency improvement is currently slowing as aircraft designs approach the technical optimum (Kharina and Rutherford 2015, Peeters *et al.* 2005).

Simpler metrics of aircraft fuel energy efficiency are discussed by Nangia (2006), Hileman *et al.* (2008), and Peeters *et al.* (2005). Even these rely on the availability of certain airline data, such as fuel usage, which is frequently considered company confidential and not released in the public domain. Hileman *et al.* (2008) showed that the productivity of aviation could be estimated as the “product of passenger and cargo payload and the distance travelled while the cost is examined in terms of fuel energy consumed”. This metric, which they termed the Payload Fuel Energy Efficiency (PFEE), provides a simple measure of useful work done (payload moved a given distance) per unit of fuel energy consumed by the aircraft.

The main advantages of using such a simple measure are:

- Only a limited amount of input data is required, improving the chances of success.
- A given fleet of aircraft will generally be represented by a mix of efficient and less efficient aircraft. The PFEE method will hence provide an overall fleet average.
- The PFEE is an absolute measure of how much payload has actually been transported in a given time period³, and how much fuel energy was expended in the process.

² In 2018 the North American passenger market (RPK) and air cargo market (FTK) accounted for 22.6% and 20.6% respectively of the world market.

³ This is preferable to using a relative measure, such as the passenger or cargo load factor, which is not a technical property of the aircraft but more a measure of the operational efficiency of the airline.

It is also noted that the fuel burn can vary significantly as a function of both the payload carried and the mission range for a given trip, and less so with a variety of other operational factors that cannot easily be predicted⁴. However, all these complicating factors are accounted for in the PFEE method, since only the gross fuel consumption in a given time period is required.

In the context of commercial aviation, the unit of payload depends on whether the aircraft is being used to transport passengers, freight/post/express, or a combination of these. This study accounts for both scheduled and non-scheduled flights, and the role of cargo, to assess the overall productivity afforded by aviation. Attention is paid to the following three types of service:

- (i) cargo payload (freight and mail) carried on scheduled or non-scheduled all-cargo dedicated freighter aircraft, e.g., Boeing 777F.
- (ii) cargo payload (freight and mail) carried on scheduled or non-scheduled passenger aircraft (this is sometimes referred to as belly-freight), e.g., Airbus A330-200.
- (iii) passenger payload carried on scheduled or non-scheduled passenger aircraft, e.g., Airbus A380-800.

There are two standard measures frequently used in aviation.

- Air passenger traffic is measured in RPKs, Revenue Passenger-Kilometres. A revenue passenger-kilometre is generated when one revenue-paying passenger is transported one kilometre.
- Air cargo traffic is measured in RTKs, Revenue Tonne-Kilometres. A revenue tonne-kilometre is generated when a metric tonne of revenue load is carried one kilometre.

Hence, for consistency, and to reflect the productivities of both passenger transport and cargo, it is necessary to convert the number of RPKs to RTKs. This conversion requires an average weight for passengers, including their luggage, assumed here to be 200 lbf (90.7 kg) per passenger (BTS Schedule T-100, 2018). The payload fuel energy efficiency (PFEE) can then be formulated as:

$$PFEE = (RTK_{pax} + RTK_{freight} + RTK_{mail}) / (V_{fuel} H_{fuel}). \quad (1)$$

V_{fuel} is the volume in litres of fuel required to deliver the service performed, and H_{fuel} is the average heat of combustion⁵, such that the PFEE shown in Equation 1 has units RTK/MJ.

The lack of recent PFEE data over an extended timeframe is identified as a gap in the literature worthy of attention - by providing time-series trend plots extending for more than a decade for RTKs performed, and the resulting fleet-wide PFEE, the authors are

⁴ These operational factors include the cruising altitude (often decided by ATC controllers, not the aircrew), en-route traffic conditions (which means the cruising altitude can change several times during a single flight), airport restrictions on climb-out to minimise the noise footprint (which means more fuel is consumed because the flaps must be extended for a longer time), and, of course, the fact that in straight and level cruise conditions, the fuel consumption reduces as the plane gets lighter as it gradually burns its own fuel (which is a key assumption used in deriving the Breguet Range equation).

⁵ The most commonly used fuel for commercial aviation is referred to as Jet A-1 in Australia, the UK, Europe, and most other parts of the world, but Jet A in the USA. According to ASTM D1655 (2018), the average heat of combustion, H in equation (1), is 34.6 MJ/L (124,000 BTU/gal).

able to establish whether or not airline fuel efficiency is gradually improving on a fleet-wide basis. Non-scheduled carriers were included in this study since these can contribute up to 5% of total revenue payload distance – it is hence important to include this often overlooked sector to properly account for productive work and its associated cost in fuel consumption. For the reasons explained in Section 1, this work is limited to U.S. air carriers during 2003-2017. However, individual airlines worldwide could easily assess their own performance since they will own many years' worth of all the relevant data required by Equation (1).

2.2 U.S. Bureau of Transportation Statistics

The Bureau of Transportation Statistics is a U.S. Department of Transport database freely available to the general public that provides a wealth of data on commercial aviation, multimodal freight, and transportation economics (BTS Schedule T-100, 2018). The Air Carrier Statistics database, referred to as Form 41 Traffic, contains domestic and international airline market and segment data. Certificated U.S. air carriers report monthly air carrier traffic information using Form T-100. The data is collected by the Office of Airline Information, Bureau of Transportation Statistics.

2.2.1 T-100 Segment (All Carriers)

The T-100 database combines domestic and international T-100 segment data reported by U.S. and foreign air carriers, and contains non-stop segment data by aircraft type and service class for transported passengers, freight and mail, available capacity, scheduled departures, departures performed, aircraft hours, and load factor.

2.2.2 Schedule T-2: U.S. Air Carrier Traffic And Capacity Statistics by Aircraft Type

The Schedule T-2 database (BTS Schedule T-2, 2018) summarizes the T-100 traffic data reported by U.S. air carriers only. The quarterly summary is compiled by aircraft types/configurations, carrier entities (geographical regions in which a carrier operates), and service classes, and includes available seat miles (ASMs), available ton miles (ATMs), revenue passenger miles (RPMs), revenue ton miles (RTMs), and aircraft fuels issued in U.S. gallons⁶. For a given single year of operation, this information generally amounts to thousands of lines of numerical data (5,000-6,500).

2.2.3 Schedule P-12(a) (All Carriers)

Schedule P-12(a) (BTS Schedule P-12(a), 2018) contains monthly reported fuel costs, and U.S. gallons of fuel consumed, by air carrier and category of fuel use, including scheduled and non-scheduled service for domestic and international traffic regions.

⁶ It is noted that fuel data can only be found in Schedule P-12(a), although it should appear in Schedule T-2 in the column "AIRCRAFT_FUELS_921" – most likely this column is suppressed due to company confidentiality issues, and only fleet-wide totals by geographical region are provided in Schedule P-12(a).

2.2.4 Data filtering and manipulation

The Schedule T-2 data used in the current work were filtered by year under the following column headings, carrier region⁷, and service class⁸:

- REV_PAX_MILES_140
- REV_TON_MILES_240 (total RTM – freight, mail and passengers performed in a given time period)
- REV_TON_MILES_FREIGHT_247
- REV_TON_MILES_MAIL_249

The data filtering reduces the number of numerical records. For the work reported here, although different years contained different volumes of data, no single year contained less than 2,600 entries. Each column of data identified above is summed, and then rendered into the corresponding SI unit:

- To convert Revenue Passenger Miles into Revenue Tonne Kilometres, the average weight for passengers, including their luggage, is assumed here to be 200 lb (90.7 kg or 0.0907 tonnes) per passenger (BTS Schedule T-100, 2018). This assumption is already embedded in the Schedule T-2 database when determining REV_TON_MILES_240.
- The weight of both freight and mail is given in short tons. 1 short ton = 907 kg or 0.907 tonnes. Freight and mail are lumped together here under the heading “cargo”.
- 1 statute mile = 1.6093 km; 1 U.S. gallon = 3.7854 Litres

2.2.5 Limitations

It is noted that Carrier Region includes *A* ~ Atlantic, *D* ~ Domestic, *I* ~ International, *L* ~ Latin America, *P* ~ Pacific and *S* ~ System. No information could be found to explain what the categories *I* ~ International and *S* ~ System referred to; both contained sparse data and probably result from incorrect data entries in the T-100 database; both were omitted from this work.

Apart from the limitation concerning the available fuel data described in Section 2.2.2, it is noted that for a given year and geographical region, the list of air carriers shown in Schedule P-12(a) does not always correspond with the list shown in Schedule T-2 – a sample of the degree of overlap is shown in Table 1 for all regions in 2017. Figure 1 (a) and (b) illustrates this discrepancy in more detail by rendering the airlines listed in Schedules T-2 and P-12(a) for both the Latin American and Pacific regions in 2017 as a Venn diagram. This naturally raises some questions about the validity of the fuel quantities quoted in Schedule P-12(a) and whether they are truly representative of the fuel consumed by all the airlines whose data is shown in Schedule T-2. Other than noting this inconsistency as a limitation there is no simple redress available.

⁷ Carrier region is limited to: *A* ~ Atlantic, *D* ~ Domestic, *L* ~ Latin America, and *P* ~ Pacific.

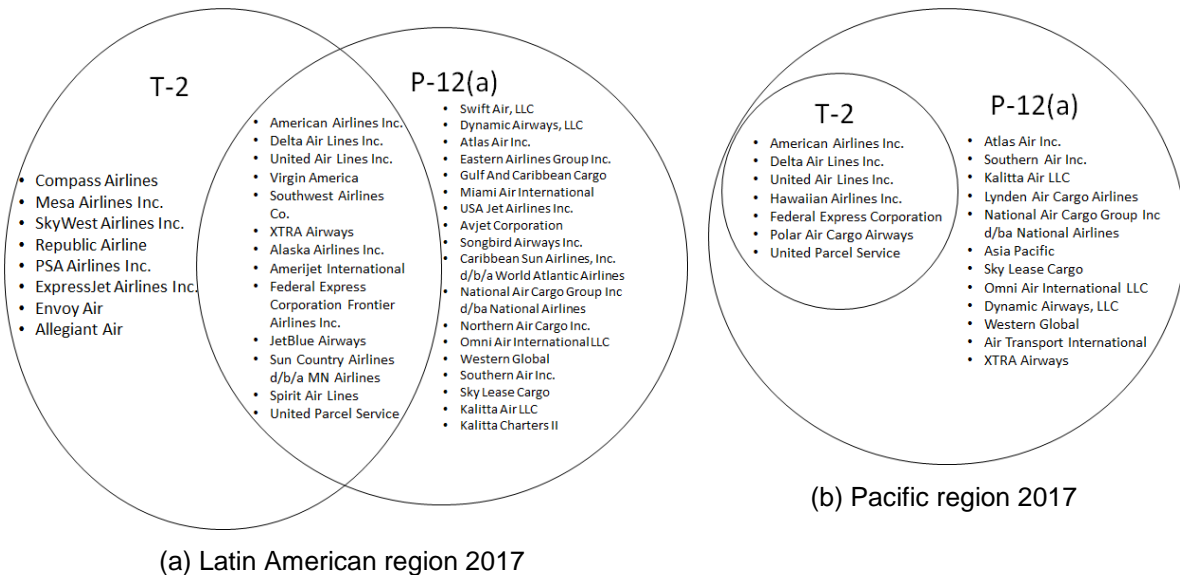
⁸ Service class is limited to:

- F - Schedule Passenger Service (includes Freight/Mail in the Belly),
- G - Scheduled ALL Cargo Service (NO Passengers),
- L - Non-Scheduled Passenger Service (includes Freight / Mail in the Belly), and
- P - Non-Scheduled ALL Cargo Service (NO Passengers)

Table 1. The number of airlines listed in both Schedules T-2 and P-12(a) in 2017.

Region	Schedule T-2	Schedule P-12(a)	Common entries
Atlantic	7 airlines	19 airlines	6 airlines
Pacific	7 airlines	19 airlines	7 airlines
Latin America	22 airlines	32 airlines	14 airlines
Domestic	120 airlines	44 airlines	40 airlines

Figure 1. Airlines listed in Schedules T-2 and P-12(a) for the Latin American and Pacific regions in 2017. (BTS Schedule T-2, 2018; BTS Schedule P-12(a), 2018). Source – authors.



2.3. Methodology

The title problem was investigated using secondary data. This enabled a deductive approach to be used based on proven quantitative methods. All the operational data for this study were obtained from the U.S. DoT Schedules T-2 and P-12(a) (BTS Schedule T-100, 2018). All subsequent data manipulation followed standard analytical procedures, as described in Section 2.4.

2.4. Sample calculation

Hileman *et al.* (2008) presented detailed results for U.S. air carriers in a single year, 2007, which makes a good baseline for comparison purposes. A sample calculation is presented in Table 2 to illustrate the procedure adopted herein.

Table 2. RTK and PFEE for scheduled and non-scheduled U.S. carriers, Domestic region, 2007.

ID	Summed values	(BTS Schedule T-2, 2018)	SI Converted values
[1]	REV_PAX_MILES_140	6.0699×10^{11}	
[2]	RPM converted to RTM	5.5065×10^{10}	$RTK_{pax} = 8.8600 \times 10^{10}$
[3]	REV_TON_MILES_240 (This is the sum of [2], [4], and [5]):	7.5806×10^{10}	$RTK_{total} = 1.1065 \times 10^{11}$
By comparison, Hileman <i>et al.</i> (2008) reported a domestic payload distance 110.5×10^{12} kg-km			
[4]	REV_TON_MILES_FREIGHT_247	1.4577×10^{10}	$RTK_{freight} = 2.1277 \times 10^{10}$
[5]	REV_TON_MILES_MAIL_249	5.3021×10^8	$RTK_{mail} = 7.7393 \times 10^8$
[6]	Fuel volume consumed by U.S. carriers operating domestically in 2007. (BTS Schedule P-12(a), 2018)	1.3651×10^{10} U.S. gallons	5.1675×10^{10} Litres
[7]	Average heat of combustion, <i>H</i> . ASTM D1655 (2018)	124,000 BTU/gal	34.6 MJ/L
[8]	PFEE from Equation (1)		$= ([2]+[4]+[5]) / ([6] \times [7])$ $= (1.1065 \times 10^{11}) / (5.1675 \times 10^{10} \times 34.6)$ $= 61.887 \times 10^{-3} \text{ RTK/MJ}$

3. Results

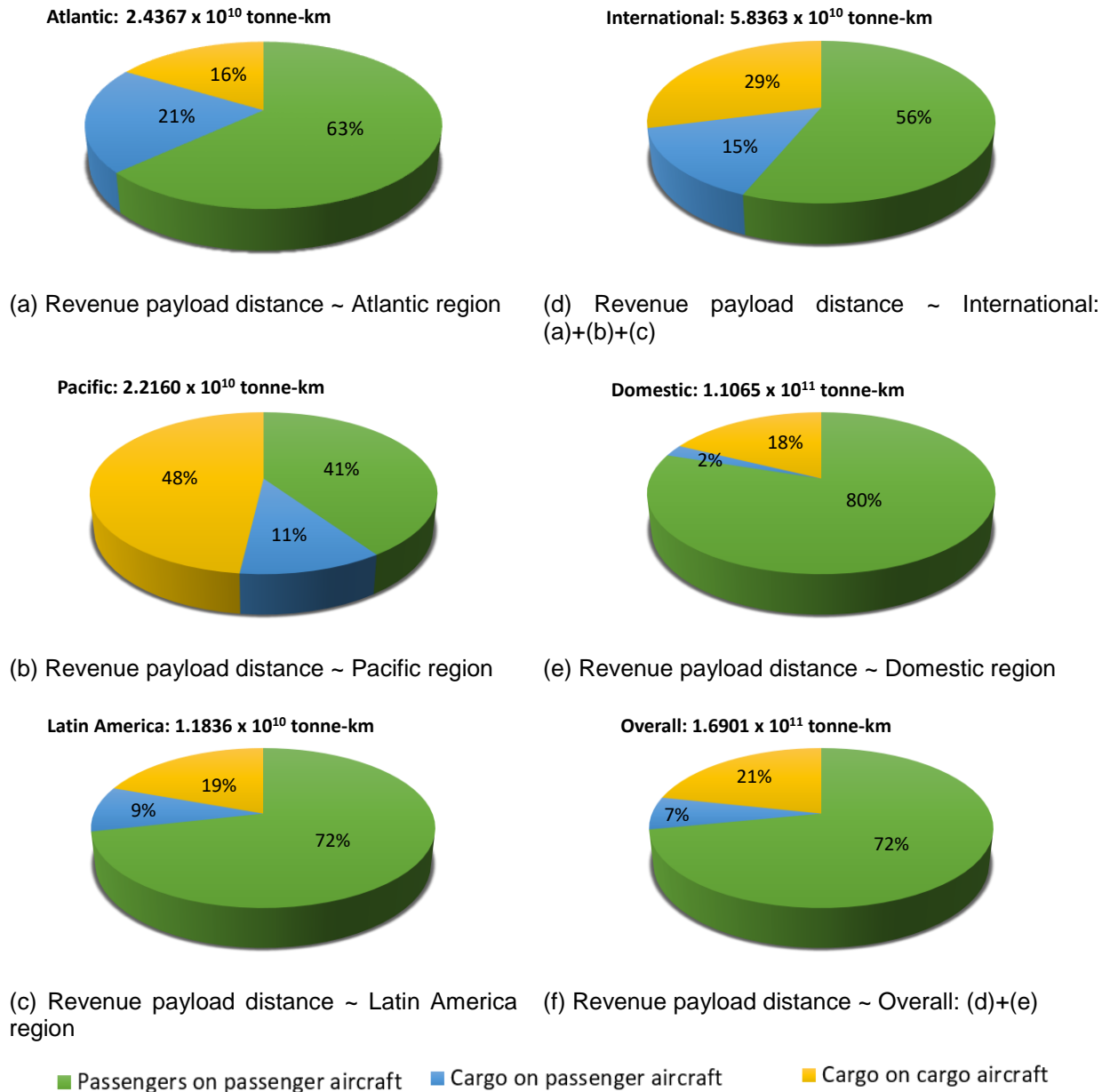
3.1. RTK trends by region: U.S. air carriers 2003 - 2017

Figure 2 shows the RTKs performed in 2007 for scheduled and non-scheduled flights by U.S. air carriers in all three international regions and the domestic market - this information is fundamental to the subsequent determination of PFEE. These results concur fully with those from Hileman *et al.* (2008) validating the current authors' understanding of the Schedule T-2 database. It is interesting to note that the U.S. domestic market RTKs are almost *double* the total U.S. international market RTKs, illustrating just how important the U.S. domestic market is and why it is currently the largest in the world.

The revenue payload distance for all U.S. air carriers operating scheduled and non-scheduled flights is then determined on an annual basis, as illustrated in Figure 3, for each of the fifteen years from 2003-2017. Results, in the form of a time series, are presented in Figures 3(a)-3(d) which summarize international RTKs; Figure 3(e) shows domestic RTKs and Figure 3(f) shows a summation of all activity from both international and domestic markets. Selected years of data are shown in Table 3 for ease of reference.

Overall, the revenue payload distance in all regions exhibits a positive growth trend, albeit punctuated by a distinct reduction localized around the time of the global financial crisis between 2008-2010. According to Figures 3(a)-3(d), all regions exhibit quite different distributions of passengers on passenger aircraft, cargo on passenger aircraft and cargo on all-cargo aircraft. The colour key used in Figure 2 retains the same meaning in Figure 3.

Figure 2. Scheduled and non-scheduled RTKs performed by U.S. air carriers in 2007



With reference to Figure 3(a), the revenue payload distances for Atlantic operations since 2012 have remained relatively constant, indicating a mature market with no significant growth apart from the distinct upturn in 2017. The proportions of passengers on passenger aircraft, cargo on passenger aircraft, and cargo on all-cargo aircraft have likewise remained essentially constant. However, the RTKs associated with all three service categories have grown substantially compared with 2003 levels.

Figure 3(b) graphically conveys the importance of cargo to the productivity being delivered by aviation in the Pacific Region, where strong trade links between the U.S.A. and Asia dominate the cargo sector. From 2003 to 2017, over 50% of the revenue payload distance for Pacific operations has resulted from cargo operations.

Figure 3. RTKs performed by U.S. air carriers from 2003-2017

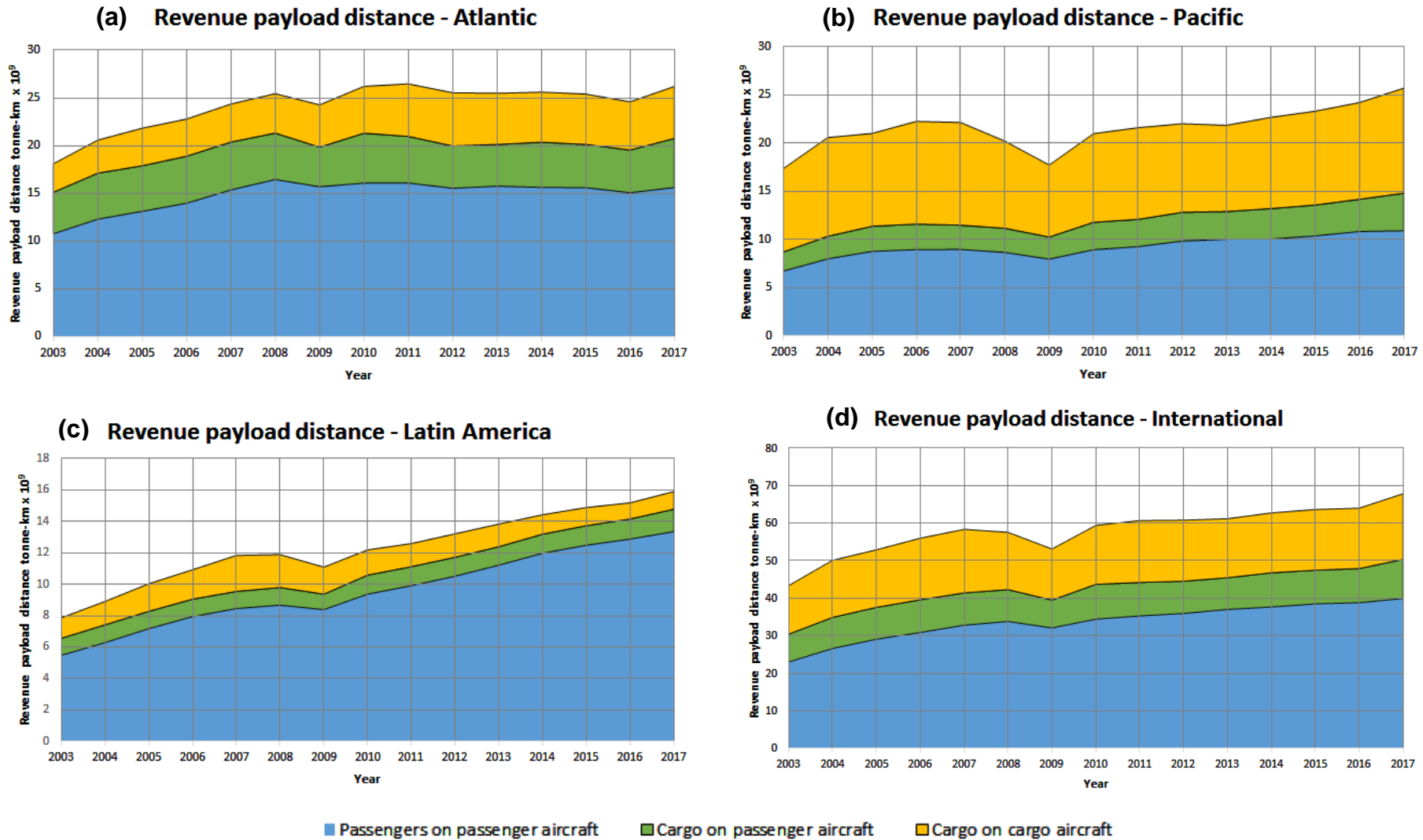


Figure 3...(Cont). RTKs performed by U.S. air carriers from 2003-2017

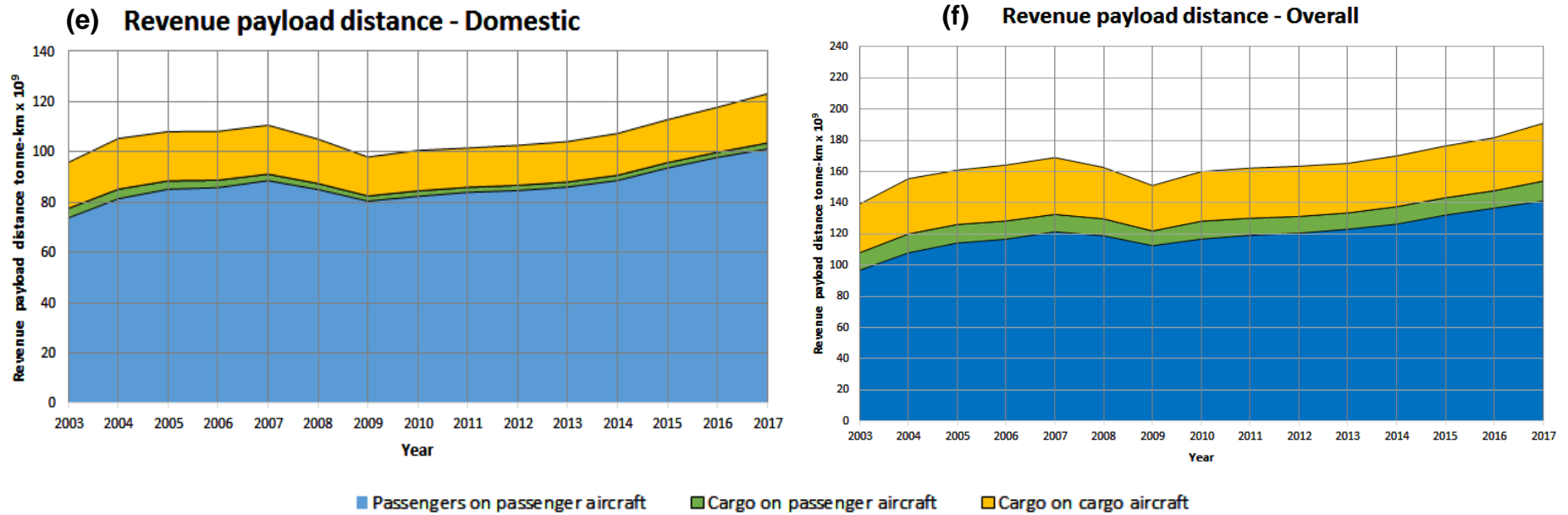


Table 3. Selected RTK values by region performed by U.S. air carriers (2003-2017)

Year	Atlantic RTK x 10 ⁹			Pacific RTK x 10 ⁹			Latin America RTK x 10 ⁹			International RTK x 10 ⁹			Domestic RTK x 10 ⁹		
	Pax on pax a/c	Cargo on pax a/c	Cargo on cargo a/c	Pax on pax a/c	Cargo on pax a/c	Cargo on cargo a/c	Pax on pax a/c	Cargo on pax a/c	Cargo on cargo a/c	Pax on pax a/c	Cargo on pax a/c	Cargo on cargo a/c	Pax on pax a/c	Cargo on pax a/c	Cargo on cargo a/c
2003	10.798	4.339	2.982	6.725	1.992	8.646	5.481	1.084	1.305	23.004	7.415	12.932	73.746	3.814	18.328
2007	15.383	5.005	3.980	8.972	2.516	1.067	8.454	1.092	2.290	32.809	8.612	16.942	88.600	2.572	19.481
2008	16.469	1.647	4.123	8.667	2.505	9.048	8.672	1.120	2.097	33.807	8.484	15.268	85.072	2.380	17.652
2009	15.712	1.571	4.422	7.970	2.290	7.481	8.388	9.860	1.722	32.070	7.424	13.625	80.453	2.032	15.488
2010	16.098	1.610	4.908	8.943	2.850	9.205	9.372	1.214	1.606	34.413	9.278	15.719	82.340	2.178	16.094
2017	15.638	5.130	5.444	10.912	3.896	10.909	13.357	1.428	1.122	39.907	10.453	17.475	101.220	2.341	19.569

In 2017, the total revenue payload distance for the Latin America region was 15.907×10^9 tonne-kilometre, which was approximately one half that observed for either the Atlantic region or the Pacific region. See Figure 3(c). But when the average growth rate of the revenue payload distance in the Latin America region is considered, it is more than double that of the other two regions. This suggests that as far as U.S. air carriers are concerned, the Latin American market is the fastest growing international region, and Figure 3(c) shows it is dominated by passenger travel.

Figure 3(d) sums the results from Figures 3(a)-3(c) to provide a composite picture of the International revenue payload distance. The general trend shows that passengers on passenger aircraft, cargo on passenger aircraft, and cargo on dedicated cargo aircraft are all increasing.

From Figure 3(e) passenger operations are seen to dominate the steady increase of domestic revenue payload distance following the global financial crisis. This can be attributed largely to the introduction of new routes, increased service frequencies and new aircraft. The proportion of cargo carried on passenger aircraft has remained slight from 2003 until 2017, averaging 2.4%, which implies low levels of belly-hold freight persist in domestic cargo operations. However, even though the total cargo revenue payload distance associated with the U.S. Domestic market represents a relatively small percentage of the total domestic productivity (between 17% and 23%), in absolute terms it consistently exceeds the *total* revenue payload distance attributed to cargo from all *international* operations!

3.3. Payload Fuel Energy Efficiency: U.S. air carriers 2003 - 2017

The payload fuel energy efficiency is now determined by region for all scheduled and non-scheduled flights by U.S. air carriers on an annual basis for the fifteen years from 2003-2017, noting the limitations stated in Section 2.2.5.

A summary by year of RTKs, volumes of fuel consumed, and the resulting PFEE at a domestic and international fleet level is presented in Table 4.

Table 4. Domestic, International, and Total U.S. Air Carrier Fleet values of RTK, Fuel volume, and PFEE by year.

Year	Domestic RTK $\times 10^9$	Domestic Litres of fuel used $\times 10^9$	Domestic PFEE* [RTK/MJ] $\times 10^{-3}$	International RTK $\times 10^9$	International Litres of fuel used $\times 10^9$	International PFEE* [RTK/MJ] $\times 10^{-3}$	Total RTK $\times 10^9$	Total Litres of fuel used $\times 10^9$	Total PFEE* [RTK/MJ] $\times 10^{-3}$
2003	95.888	49.382	56.120	43.352	18.723	66.919	139.240	68.106	59.089
2004	105.371	53.211	57.233	50.097	20.058	72.185	155.468	73.269	61.326
2005	108.074	52.782	59.178	52.892	21.175	72.191	160.967	73.957	62.904
2006	108.197	51.715	60.467	55.999	21.781	74.305	164.195	73.497	64.568
2007	110.651	51.675	61.887	58.363	22.565	74.753	169.014	74.240	65.798
2008	105.104	47.901	63.416	57.558	22.463	74.056	162.663	70.365	66.813
2009	97.973	42.820	66.128	53.118	20.581	74.593	151.091	63.401	68.876
2010	100.613	42.507	68.410	59.410	21.608	79.463	160.023	64.115	72.135
2011	101.582	41.667	70.461	60.685	22.924	76.510	162.267	64.591	72.608
2012	102.645	39.411	75.273	60.798	23.338	75.291	163.443	62.750	75.280
2013	104.139	39.023	77.129	61.191	23.654	74.765	165.330	62.677	76.237
2014	107.349	39.493	78.561	62.733	23.608	76.799	170.082	63.101	77.902
2015	112.821	41.270	79.009	63.633	23.923	76.876	176.454	65.193	78.226
2016	117.758	42.954	79.233	64.006	23.384	79.108	181.764	66.339	79.189
2017	123.129	43.760	81.321	67.834	23.868	82.140	190.963	67.629	81.610

* Note: To evaluate the PFEE, the volume of fuel shown in columns 3, 6, and 9 above must be multiplied by the average heat of combustion, 34.6MJ/L, to obtain an energy value.

The fuel volumes have been obtained from the P-12(a) database and converted from U.S. gallons to litres. In addition, these fuel volumes need to be multiplied by the average heat of combustion, 34.6MJ/L, to obtain an energy value in MJ, prior to evaluating the PFEE. By way of comparison, Hileman *et al.* (2008) produce a total overall PFEE of 66 kg-km/MJ for their 2007 data, which is in striking agreement (allowing for rounding) with the total value of 65.798×10^{-3} RTK/MJ obtained here for the same year.

Trends are plotted for the domestic, international, and overall total markets in Figure 4. It is clear from Figure 4 that the PFEE for both scheduled and non-scheduled domestic and international flights by U.S. carriers has shown a steady improvement over the past 15 years. To obtain the average annual percentage improvement in PFEE from 2003 to 2017 there is some merit in using the standard compound annual growth rate formula given by Equation (2).

$$PFEE_{2017} = PFEE_{2003} (1 + x\%)^{15} \quad (2)$$

Although this simple measure assumes uniform compound growth, and hides fluctuations such as the global financial crisis, it nonetheless provides a good indication of the longer term average improvement rate for the industry.

Figure 4. PFEE for U.S. air carriers for domestic and international fleets (2003-2017)

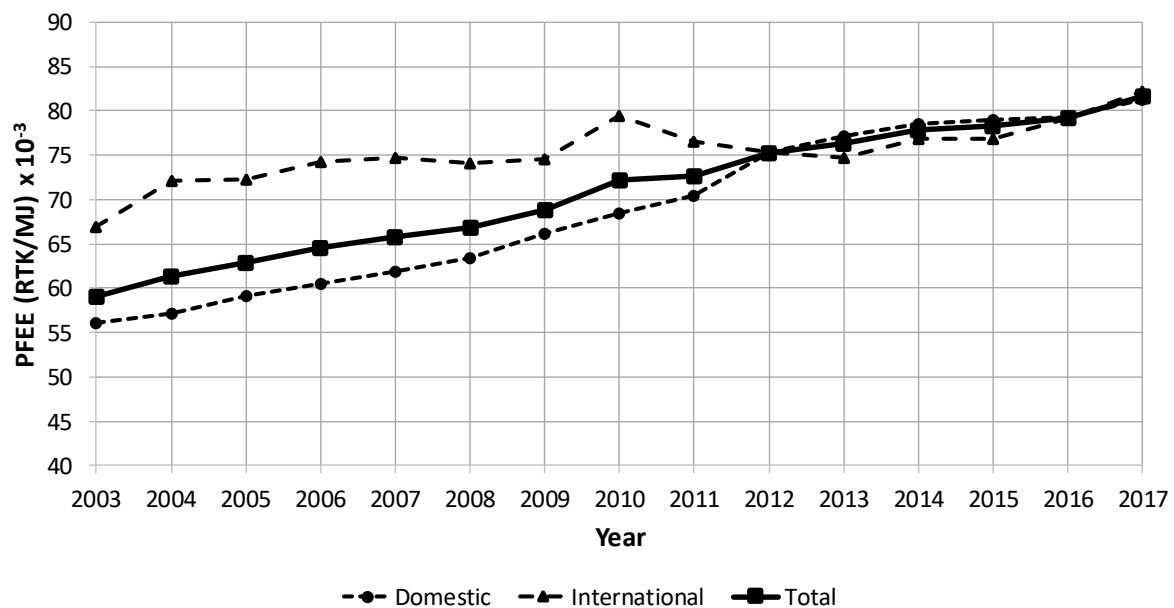


Table 5 presents the solution for x in Equation (2) for domestic, international, and total U.S. air carrier fleets over the 15-year time period considered here. Although the overall total annual PFEE improvement is 2.18%, perhaps of more significance is the fact that U.S. international aviation PFEE has improved by only 1.38% per annum between 2003 and 2017, just below IATA's 1.5% target (CNG2020 n.d.), while domestic U.S. aviation has improved by 2.50% per annum. This suggests

- (i) there is an increased uptake of more efficient aircraft and/or other efficiency-improving changes in the domestic U.S. aviation market (e.g., increased passenger load factors year-on-year), and
- (ii) international operations are already relatively efficient and any efficiency gains made in this market have less of an overall impact.

These year-on-year PFEE figures certainly imply that for the time being, the fuel efficiency of U.S. air carriers is keeping pace with the increased growth in air travel.

Table 5. Domestic, International, and Total U.S. Air Carrier Fleet PFEE compound annual growth rates

Year	Domestic PFEE [RTK/MJ] x 10 ⁻³	International PFEE [RTK/MJ] x 10 ⁻³	Total PFEE [RTK/MJ] x 10 ⁻³	Source
2003	56.120	66.919	59.089	Table 4
2017	81.321	82.140	81.610	Table 4
Solution for the compound annual growth rate, x from Eqn (2)				
x	0.0250	0.0138	0.0218	Eqn (2)

It is also interesting to note that although Domestic RTK always exceeds International RTK, as evidenced by Figures 3(e) and 3(d), the PFEE trends shown in Figure 4 suggest domestic operations are much less fuel efficient. This has been noted previously by Bardell & Yue (2018), who showed that a large quantity of domestic flights in the U.S.A. occur over short distances, and hence incur a fuel penalty, although it could also be attributed to the limitations noted in Section 2.2.5 concerning Schedule P-12(a).

4. Discussion of results

4.1. Domestic air cargo

There is significant demand for air cargo within the U.S.A. since it offers an optimal solution for time sensitive and/or specialist consignments. The upward trend shown in Figure 3(e) is primarily attributed to e-commerce and the rise of online shopping (Zaroban 2018). Express carriers and integrators, such as FedEx and UPS, have acquired significant portions of the total U.S. market (FedEx 2017, UPS 2017) and cargo on dedicated all-cargo aircraft has consistently provided between 15% and 19% of the total domestic revenue payload distance during the period 2003 to 2017. It is of interest to note that there is relatively little belly-hold (cargo on passenger aircraft) freight transported by air in the U.S.A., although its strong destination mix and the high service frequency help explain why it remains an important part of the cargo mode (Morell 2011).

4.2. New commercial aircraft

According to historic trends, civil aircraft fuel efficiency has improved significantly in the past 40 years (IATA 2010). Kharina and Rutherford (2015) estimated that the average fuel burn of new aircraft has reduced by approximately 45% from 1968 to 2014. Such gains can largely be attributed to improvements in:

- jet engine technology, e.g., the geared turbofan (Pratt & Whitney 2018, IATA 2010),
- airframe technology, e.g., the widespread adoption of carbon fibre composites for primary structure, resulting in a lighter flight vehicle (Boeing 2018),

- more optimal aircraft size (e.g., efficient large twin engine designs like the Boeing 787-8/-9/-10, 777-8 and the Airbus A350-1000XWB), and
- operational improvements, e.g., flexitracks (Airservices Australia 2013)

which have all had a positive impact on fuel efficiency. Many of these breakthroughs have occurred in the past 5-10 years, and are reflected in the associated PFEE improvement trends. As one of the wealthiest nations on earth, U.S. airlines tend to operate a relatively young fleet of passenger aircraft both domestically and internationally, and thus they reap the benefits of all the aforementioned efficiency gains as they become available. However, since different aviation regions worldwide are unlikely to match the same uptake of new aircraft as seen in the U.S.A., it would be misleading to extrapolate the current promising results to a global level. Indeed, as worldwide airlines update their individual fleets, it is common for many older aircraft to be on-sold to lower-income aviation markets in developing countries, or re-purposed as passenger-to-freighter conversions. Hence, whilst technological improvements are just managing to keep U.S. air carriers abreast of IATA's ambitious target (CNG2020 n.d.), at a global level the dominance of types older than 10 years will continue to be a drag on global aircraft fuel efficiency (IATA 2018).

5. Conclusions

A simple payload fuel energy efficiency (PFEE) metric, based on the work of Hileman *et al* (2008), has been used to establish the fuel efficiency trends of scheduled and non-scheduled U.S. air carriers over the fifteen years from 2003 to 2017. Whilst the overall fuel efficiency is shown to have improved annually by just over 2%, there are differences in the rates of improvement in the international market (improved by 1.38% p/a) and the domestic market (improved by 2.50% p/a) between 2003 and 2017.

This work has also distinguished between the various types of payload that aircraft typically carry, accounting for passengers on passenger aircraft, cargo on passenger aircraft, and cargo on all-cargo aircraft. The resulting charts, showing how revenue payload distance varies with time, vividly illustrate the contribution of air cargo to the productivity of the aviation industry and also highlight the different proportions of payload composition between international and domestic regions.

The lack of publicly available data from anywhere except the U.S.A. (BTS Schedule T-2, 2018, and BTS Schedule P-12(a)) necessarily limits this work to U.S. air carriers. However, the methods developed herein can be used by individual airlines to assess their own performance and formulate strategies for improvement.

Further research needs to focus on establishing the fleet-wide PFEE trends in other significant world markets such as Europe and China – this would add to the current results and give a more accurate picture of worldwide aviation fuel efficiency trends. However, the lack of publicly available databases that share relevant information from these regions is regrettable.

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