PAYLOAD FUEL ENERGY EFFICIENCY AS A METRIC FOR AVIATION ENVIRONMENTAL PERFORMANCE

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Keywords: *Energy, Fuel Efficiency, Aviation, Environment, Metric*

Abstract

Aviation provides productivity in the form of transporting passengers and cargo long distances in a shorter period of time than is available via land or sea. Given the recent rise in fuel prices and environmental concerns, a consistent metric is needed for the assessment of commercial aviation fuel efficiency, or equivalently the productivity delivered per unit of fuel consumption or environmental cost. This work presents an assessment of payload fuel energy efficiency (PFEE) as a means to quantify how efficiently the energy consumed by aviation is being used on a fleet-wide basis.

1 Introduction

The ability of aviation to transport people and cargo over long distances in a short period of time has been the culmination of many decades of development to meet the conflicting motivations of speed and energy efficiency. In the decades following the Second World War, the aviation industry worked to minimize the amount of time it took for people and goods to travel between any two places on the planet. This motivation led to the jet age of transportation and it culminated in the development of the Concorde, a supersonic, but fuel inefficient aircraft design. During this period of time speed was more important than fuel efficiency. The energy crisis of the 1970s changed the priority from speed to maximizing the efficiency with which fuel is used. The recent rise in the price of oil and the demands on improved energy utilization due to global climate change and other environmental concerns have combined to reinforce the need to improve the efficiency of travel in terms of reducing both fuel use and environmental impact.

1.1 Fuel Efficiency Metrics

Despite the inherent differences between aviation and other transportation modes, it is of value to examine the efficiency metrics used by various transportation modes (see Appendix A). These metrics give productivity per unit of fuel consumed (i.e., a fuel efficiency) or the amount of fuel required to deliver a unit of productivity (i.e., an energy intensity). Since transportation modes are used primarily to move either passengers or cargo, it is logical that the efficiency indicators used differ for passenger and cargo modes. In general, the efficiency of passenger modes is measured in terms of the fuel or energy consumed and the distance traveled by the vehicle or passengers (to account for differences in vehicle use and occupancy rates for different passenger modes). The efficiency of cargo modes is generally measured in terms of the fuel or energy consumed and the load transported (measured in cargo weight). Aviation is unique in that the same vehicle is used for passenger operation, cargo[1] operation, or hybrid operation where an individual aircraft

[1] In the context of this paper, cargo refers to revenue freight and mail. The luggage carried by passengers is not considered to be cargo; instead it is book-kept weight-wise with passengers.

will carry both passengers and revenue payload.[2]

1.2 Aviation Fuel Efficiency Metrics

Aircraft and fleet-wide fuel efficiency have been examined in the research literature using similar metrics to those presented in Appendix A. Often, the metrics consider aircraft level fuel efficiency with fuel use given in terms of engine, aerodynamic, and structural performance.

Lee et al. [1] and Babikian et al. [2] examined energy intensity in terms of energy consumed per seat kilometer for various aircraft types. They compared estimates for as-operated aircraft energy intensity to fleet-wide trends in energy intensity. The authors examined historical technological improvements to project the energy intensity for future aircraft types. Jamin et al. [3] extended the use of energy intensity as a metric to assess various scenarios of aviation development. Peeters et al. [4] further used energy intensity to examine more recent jet aircraft as well as piston-powered aircraft from the 1930s to 1960s. For the most part, these studies do not consider cargo payload. The implications of not including cargo payload are examined at length in this paper.

Green [5,6] and Nangia [7] used the Breguet range equation to define a fuel efficiency metric, payload fuel efficiency (PFE), in terms of range, payload weight, and mission fuel weight. Green used PFE as a figure or merit to examine optimal aircraft design range for minimal fuel use. This metric was not evaluated at a fleet-wide level.

In a departure from examining efficiency as productivity per cost in terms of fuel consumption, McMasters and Cummings [8] defined a productivity index as aircraft speed times payload divided by aircraft gross weight. This metric has a cost function that combines structural weight, payload weight, and fuel weight. Because both an aspect of productivity (payload) and an aspect of cost (fuel weight) are in the denominator, this productivity index is not an efficiency metric.

The approach presented in this work differs from those listed above in that it considers the productivity of aviation as a product of passenger and cargo payload and the distance travelled while the cost is examined in terms of fuel energy consumed.

2 Payload Fuel Energy Efficiency (PFEE)

Based on the arguments presented below, the metric of payload fuel energy efficiency given by *total payload carried * great-circle distance / fuel energy consumed* was chosen to examine fleet-wide aviation fuel efficiency.[3] This metric provides a means to track the amount of productivity (payload moved a given distance) per unit of energy consumed by the aircraft.

Much of the analysis within this work is based upon data that was extracted from the U.S. Department of Transportation Bureau of Transportation Statistics Form 41 Schedule T-2 database (hereafter referred to as Form 41 data) [9]. All of the analysis using the Form 41 data is from 2007 unless otherwise noted.

2.1 Total Payload Carried

As discussed in the introduction, most efficiency metrics have some measure of the payload (passengers and cargo) that is being carried. By not considering payload, a small aircraft would be shown to be more efficient than a large aircraft (see Figure 1). It is intuitive that a smaller aircraft will need less fuel to fly a given distance than a large one, but a metric of fuel economy in distance travelled per fuel use would indicate that the most fuel efficient way to carry passengers from for example Los Angeles to New York is not with a narrow- or wide-body aircraft but with a regional jet that makes several stops along the way. Furthermore, by not considering payload, an aircraft that is operating without payload will appear to be more efficient than a fully loaded

[2] "Revenue" payload refers to the actual payload on an aircraft. This can be compared to the "available" payload which is the total payload that the aircraft could carry. The ratio of these values is known as the "load factor".

[3] For the remainder of the paper, distance implies great-circle distance.

aircraft. Consequently, a metric for the assessment of commercial aviation efficiency that includes payload is needed.

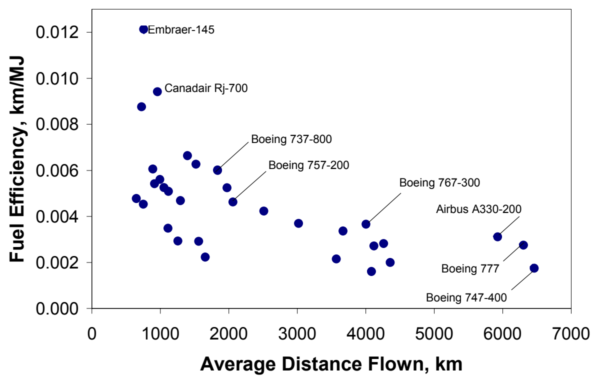

Figure 1: Fuel economy in revenue miles per gallon (data from [9] for 2005).

Payload can be broken into three categories as follows:

1. Cargo payload (freight plus mail) carried on freighter aircraft (either by passenger or cargo carriers).
2. Cargo payload (freight plus mail) carried on passenger aircraft. This is sometimes referred to as belly-freight.
3. Passenger payload carried on passenger aircraft.

The revenue payload distance for each of these payload categories are given in Figure 2. In 1991, the split of revenue payload distance flown by U.S. carriers, as a percentage of the total, was 15.0 / 10.9 / 74.1 among cargo on freighter aircraft / cargo on passenger aircraft / passengers. In 2007, this ratio had changed to 25.9 / 6.2 / 68.0, respectively. Cargo now represents roughly 1/3 (32.0%) of revenue payload flown by U.S. carriers and roughly 1/5 (19.3%) of this cargo is being carried in passenger aircraft in the form of belly-freight. The data within Figures 2 points to the importance of cargo to the productivity being delivered by aviation.

In Figure 3, the Form 41 data has been broken out into domestic operations and into international operations, such as over the Pacific, over the Atlantic, and to Latin America. Even though little belly-freight is carried domestically (2% of the domestic revenue

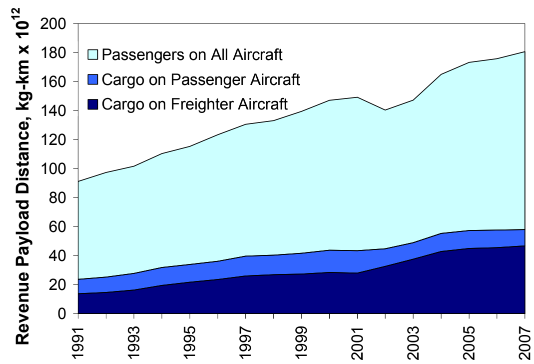

Figure 2: Historical revenue payload distance by U.S. carriers on various types of operations and aircraft types (data from [9]).

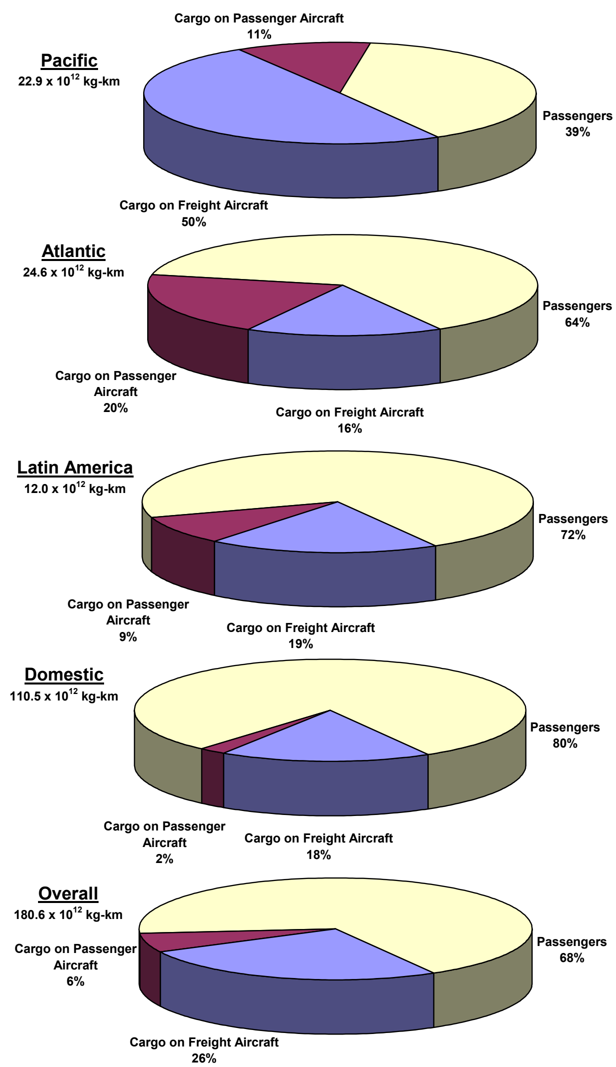

Figure 3: Regional distribution of payload distance flown by U.S. carriers for the year 2007 (data from [9]).

payload distance), cargo constitutes 20% of the total revenue payload distance for domestic operations. Cargo accounts for a larger portion of the international revenue payload distance. Depending on the destination, belly-freight constitutes between 9% and 20% of the revenue payload distance, while cargo on freighter aircraft account for between 16% and 50% of the revenue payload distance. For operations over the Pacific, cargo accounts for 61% of the payload distance flown.

Based on an analysis of the data shown in Figure 3, roughly half (49.1%) of the revenue payload distance flown in 2007 by U.S. Carriers was in the form of passengers being carried domestically and over a tenth (10.7%) of the revenue payload distance flown was by domestic cargo operations on freighter aircraft. As noted, considerable amounts of cargo are being carried on freighter aircraft over the Pacific (6.3% of the total revenue payload distance flown). These data reinforce the importance of cargo to the productivity delivered by aviation.

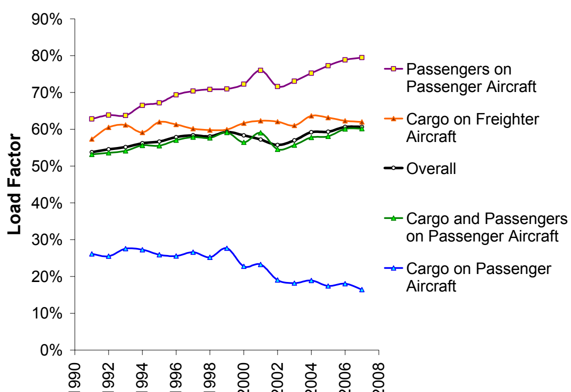

Figure 4: Historical load factors for U.S. carriers on various types of operations and aircraft types (data from [9]).

Cargo payload also has an influence on aviation load factors. Historical load factors for aviation that considers passenger, belly-freight, and cargo payload are presented in Figure 4. The passenger load factor was 79% in 2007; however, when belly-freight is taken into account, the load factor for passenger operations drops to 60%. This is because the load factor for belly-freight was only 16%. The load factor for cargo operations (cargo on freighter aircraft) was 62%. The overall load factor for aviation (cargo, passengers, and belly-freight) was 61% in 2007. With the exception of belly-freight, load factors have been increasing since 1991.

2.2 Great-circle Distance

The productivity delivered by any mode of transportation can be defined as the product of the payload (passengers and cargo) and the distance between the origin and destination of the payload. Thus, for productivity purposes, the distance of interest is the shortest distance from A to B, which is known as the great-circle distance.[4] Any diversions from the great-circle distance are not adding to productivity, and can be considered within the cost function of a change in fuel use. Such diversions may lead to decreased fuel use by taking advantages of prevailing winds or they may lead to increased fuel use from inefficient routing as dictated by for example weather or air space restrictions. There may be benefits from analysis of the ultimate origin and destination; however, such information is often not available.

2.3 Fuel Energy Consumed

The present high cost of jet fuel and environmental considerations related to aviation fuel combustion dictate that aviation efficiency needs to be given in terms of productivity per unit of fuel consumed. Within the past year fuel costs have overtaken labor as the leading component of airline operating costs on a per available seat mile basis [10]. Simultaneously, concerns about energy efficiency and the environmental impact of aviation have increased dramatically. This has promoted interest in finding alternatives to petroleum-derived fuels across all transportation modes. A metric of PFE which relies on fuel weight (or volume) is inappropriate for use with alternative fuels. This is because the energy content per unit volume or weight of an alternative fuel varies depending on the fuel's chemical composition and this impacts the energy use for a given flight distance (see [11] for additional insight). To be equitable with alternative jet fuels, the quantity

[4] The Form 41 database provides great-circle distances.

of fuel consumed needs to be given in terms of energy. For this reason, fuel energy is used in the definition of PFEE.

2.4 Time

Aviation has enabled the rapid movement of cargo and passengers around the globe. However, the variation in speed among jet aircraft is relatively small; all jet aircraft, including regional jets, travel at speeds that are within 15% of the maximum (see Figure 5). Propeller aircraft travel slower, but they constitute less than 1% of the total revenue payload distance in 2005 [9]. For reference, as shown in Figure 5, jet aircraft travel at speeds of roughly 800 to 950 km/h, while cars and trucks typically travel at 100 km/h, and the fastest passenger trains travel at 300 km/h.[5]

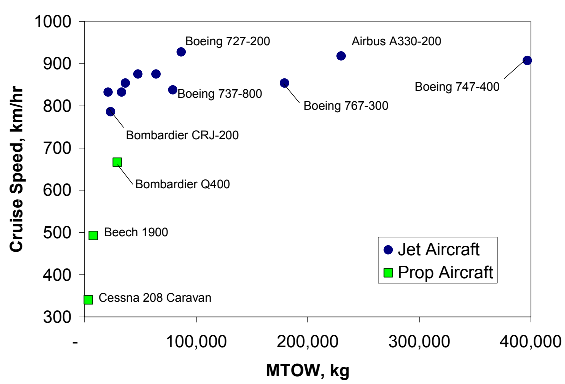

Figure 5: Typical cruise speeds for select aircraft, as reported by the manufacturers.

The amount of time a payload requires to travel from its origin to its destination is determined by the time that is needed for ground movements at the airport, takeoff operations, high altitude cruise, and approach operations. The Form 41 database contains this information in the form of ramp-to-ramp (i.e., block) time between when "an aircraft first moves under its own power for purposes of flight, until it comes to rest at the next point of landing." This measure of time combines the aircraft cruise speed with the operational requirements of flight. The aircraft distance flown has been divided by the ramp-to-ramp time in Figure 6 to provide an effective cruise speed that accounts for all of operations within the flight envelope. Based on these data, there is a 5% difference in effective cruise speed from the high of 575 km/hr in 1995 to the low of 550 km/hr in 2003. The average of the effective speeds shown in Figure 6 is 563 km/hr, roughly 2/3 of the jet aircraft cruise speeds shown in Figure 5. This effective speed is still considerably higher than is achieved with any other transportation mode. It should be noted that other modes of transport would also have effective speeds that are lower than the typical highway or rail speeds that were listed at the beginning of this subsection.

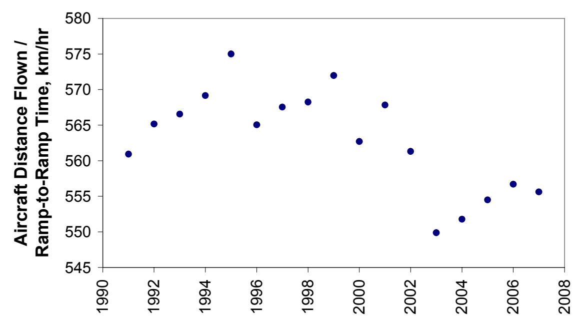

Figure 6: Effective cruise speeds for U.S. carriers (data from [9]).

Although it is important when comparing the relative productivity of aviation versus other transportation modes, time is not included in the fuel efficiency metric presented here. This is because it has varied by less than one percent between 1991 and 2007 and as will be shown in Section 3, this is relatively small compared to the payload fuel energy efficiency gains of aviation over this time period.

3 PFEE Evaluation

Within this section, the PFEE metric is used to evaluate historical trends in aviation energy efficiency and to show the importance of the productivity delivered by cargo payload.

3.1 Formulation

Payload fuel energy efficiency, PFEE, can be estimated on a fleet-wide basis from:

[5] The French TGV set a European record for rail travel on conventional tracks with a speed of 574.8 km/h on April 3, 2007. A Japanese magnetic levitation train holds the absolute train speed record at 581 km/hr, which was set in 2003. These speeds are not typical of daily operation. [12]

$$PFEE = (RevPaxMiles * X + RTM\_freight + RTM\_mail) / (V_f * H_v) \quad (1)$$

where

PFEE = payload fuel energy efficiency, kg-km/MJ
RevPaxMiles = revenue passenger miles
RTM_freight = freight revenue ton miles
RTM_mail = mail revenue ton miles
V_f = volume of fuel consumed
H_v = fuel volumetric energy content, 34.6 MJ/L (124,000 BTU/gal)
X = weight allotment per passenger, 90.7 kg (200 lbs/passenger)

All of the components in the formula for PFEE, except for fuel volumetric energy content and passenger weight allotment, can be found within the Form 41 database. The passenger weight allotment is comprised of the weight that is allotted for each passenger and his/her luggage as discussed in Appendix B. The fuel volumetric energy content is based on the specification [13] that defines jet fuel.[6]

3.2 Fleet-wide PFEE

Fleet-wide payload fuel energy efficiency was calculated from the Form 41 data using Equation 1. The fleet-wide data has been broken into two categories: cargo operations that have zero passengers and all other operations that have passengers. Figure 7 shows PFEE for the two categories and for their combination. With the exception of inconsistent behavior of cargo PFEE in 1991 and 2001, the data follows relatively consistent trends. The cargo PFEE was largely unchanged from 1992 to 2000, but then has improved in the years following 2001 to the current value of 97 kg-km/MJ. U.S. cargo and passenger carriers have improved the efficiency of their overall operations by 51% between 1991 and 2007. In 2007, the average revenue payload fuel energy efficiency for U.S. carriers was 66 kg-km/MJ.

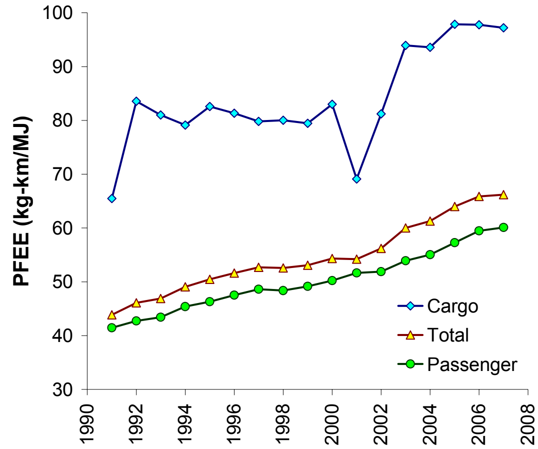

Figure 7: Historical fleet-wide PFEE for U.S. operations, divided into those carrying passengers and those that only carry cargo (data from [9]).

Figure 8 provides a comparison of the PFEE data from Figure 7 to the fleet-wide energy intensity time history presented by Lee et al., [1]; the latter has been converted to PFEE using a weight of 200 lbs per passenger. The difference between the "Passenger PFEE" data of Figure 7 and the Lee et al. data is that the latter does not account for the productivity being delivered by belly-freight. According to the analysis of the Form 41 data, the PFEE for passenger operations for 2007 was 60 kg-km/MJ; however, if the belly-freight is ignored, then this value drops to 55 kg-km/J. This is an 8% difference.

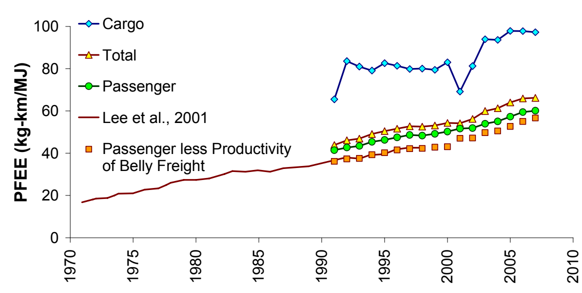

Figure 8: Comparison of data from [1] with the historical fleet-wide PFEE data from Figure 7.

Care must be exercised when examining aviation fuel efficiency data to ensure cargo is properly considered. A case in point is provided by the Transportation Energy Data Book (TEDB) [15], which presents energy intensities

[6] The volumetric heat of combustion of 124,000 BTU/gal was obtained by multiplying the minimum specified heat of combustion (18,400 BTU/lb) with the mean of the specified density range (6.47 lb/gal to 7.01 lb/gal). The average heat of combustion for jet fuel is likely higher than this value. As an example, an analysis of the energy content of the jet fuel used by the U.S. Air Force, JP-8, shows an average heat of combustion of 34.8 MJ/L (analysis of [14] contained in [9]).

Carrier	Aircraft Type	Distance (km)	Fuel Use[8] (MJ)	Payload (kg)	Fuel Economy[9] (km/MJ)	PFEE[10] (kg-km/MJ)
Passenger Carrier 1	Single Aisle	2693	611725	14457	0.0044	64
Passenger Carrier 2	Single Aisle	2236	493020	14296	0.0045	65
Passenger Carrier 3	Single Aisle	3618	753202	13497	0.0048	65
Passenger Carrier 4	Single Aisle	1962	405100	14054	0.0048	68
Passenger Carrier 5	Single Aisle	2034	427463	14213	0.0048	68
Passenger Carrier 6	Single Aisle	2325	467486	13106	0.0050	65
Passenger Carrier 7	Single Aisle	1927	456248	14351	0.0042	61
Cargo Carrier 1	Single Aisle Freighter	1170	265644	18266	0.0044	80
Passenger Carrier 2	Double Aisle	5184	1439985	21400	0.0036	77
Passenger Carrier 4	Double Aisle	4803	1344243	19674	0.0036	70
Passenger Carrier 6	Double Aisle	4046	1110901	21514	0.0036	78
Cargo Carrier 1	Double Aisle Freighter	2762	775221	36123	0.0036	129
Passenger Carrier 5	Jumbo Jet	6453	3508786	36764	0.0018	68
Passenger Carrier 6	Jumbo Jet	8246	4380346	32284	0.0019	61
Cargo Carrier 1	Jumbo Jet Freighter	4822	2095141	63426	0.0023	146
Cargo Carrier 2	Jumbo Jet Freighter	4037	2568607	64677	0.0016	102

Table 1: Comparison of three aircraft types that are currently used by both cargo and passenger carriers. Distance, fuel use and payload are average values per departure (data from [9]).

(energy per productivity) for a range of transportation modes. The TEDB aviation energy intensity data includes all of the fuel used by aviation, but it accounts for neither the productivity of cargo operations nor for the productivity of belly-freight on passenger operations. Because of this omission, the TEDB aviation energy intensity is equivalent to a PFEE of 47 kg-km/MJ,[7] which is 29% below the PFEE of 66 kg-km/MJ that includes both passengers and cargo as payload. The PFEE differences outlined in this subsection further reinforce the need for including cargo within the productivity portion of an aviation fuel efficiency metric.

3.3 PFEE for Cargo and Passenger Operations

Due to the structural weight differences that arise from aircraft use, cargo operations typically have higher payload fuel energy efficiency than passenger operations. This difference is due to the requirements of carrying passengers within aircraft (as opposed to freight or mail). Although they have the same outer dimensions, there are considerable differences between aircraft that are configured for passenger and cargo operations. These variations result in the OEW being heavier for passenger configurations than for freighter configurations.

Table 1 provides information on average distance, average fuel use, average payload, fuel economy (distance per fuel use, which does not account for the productivity of payload), and PFEE for three aircraft types that are used for passenger and cargo operations. As shown by the data contained within Table 1, cargo operations typically have comparable fuel efficiency to passenger operations. However, the increased payload that is being carried during cargo operations leads to cargo operations having higher payload fuel energy efficiencies than passenger operations.

[7] Table 2.14 of the TEDB [15] lists aviation as having an energy intensity of 3,228 BTU per passenger mile. This is equivalent to 42.9 kg-km/MJ with a passenger weight of 90.7 kg. The TEDB data uses a gross jet fuel energy content of 135,000 BTU/gal; a correction to a net energy content of 124,000 BTU/gal yields 46.6 kg-km/MJ.

[8] Based on fuel energy content of 34.6 MJ/L.

[9] Fuel economy = distance / fuel use

[10] Payload fuel energy efficiency = distance * payload / fuel use = fuel economy * payload

3.4 PFEE for Passenger Aircraft and Automobiles

Because of the continuous improvements in technology and operational procedures, on an average basis travel via passenger aircraft is more efficient than travel via passenger vehicles within the U.S. According to TEDB data [15], in 2006 automobiles had an average PFEE of 42 kg-km/MJ.[11] To reach 60 kg-km/MJ, the PFEE for passenger aircraft in 2007, the average automobile would need a fuel economy of 31.5 miles per gallon (mpg).[12] This is in excess of the 2007 U.S. Corporate Average Fuel Economy (CAFE) standard for passenger vehicles of 27.5 mpg. It should be noted that in 2002, new European automobiles achieved fuel economy of 37.2 mpg which are in excess of the PFEE for passenger aircraft and that EU automobile fuel economy has been increasing with time.[13] It should be noted that these comparisons have ignored the time advantages of travel by aircraft relative to automobiles.

4 PFEE as Environmental Performance Metric

PFEE could be used to create environmental performance metrics that quantify the mass of pollutants per unit of productivity. One such metric is carbon dioxide (CO_2) emission intensity with units of g CO_2/kg-km. This metric could be created by dividing the CO_2 emissions index by the product of PFEE and the fuel energy content per unit mass. As an example, for every kilogram of fuel that is consumed within an aircraft, approximately 3.16 kilograms of CO_2 are emitted from the jet engine; equivalently, about 73 g of CO_2 are emitted per megajoule of fuel energy that is consumed by the jet engines. Combustion represents part of the life-cycle emissions of the fuel. During the process of extracting crude oil, refining it to jet fuel, and transporting the various product streams, roughly 14 g of carbon dioxide are emitted. Therefore, approximately 87 g of carbon dioxide are emitted over the fuel life-cycle per megajoule of fuel energy consumed by the aircraft.[14] By dividing this life-cycle emissions index by the fleet-wide PFEE value, one can ascertain that aviation in 2007 emitted an average of 1.3 g CO_2 per kg-km. This formulation has also been used to assess the relative life-cycle CO_2 emissions from alternative jet fuels [11, 19].

Other cost functions could potentially be used besides carbon dioxide emissions to yield other environmental performance metrics. These could include emissions of for example nitrogen oxides (NO_X), sulfur oxides (SO_X), or particulate matter (PM).

PFEE could be used to examine inefficiencies in operations of the current fleet. This could be done via analysis of the fuel use term within PFEE. If an ideal, minimum fuel use were determined, then the difference between the theoretical minimum use and the actual use could be examined to determine inefficiencies. This could partially be performed through comparison of actual distances flown versus great-circle distances and in a comparison of a minimum time required for surface movements and the actual time accounting for delays.

[11] Table 2.14 of the TEDB lists cars as having an energy intensity of 3,512 BTU per passenger mile. This is equivalent to 39.4 kg-km/MJ with a passenger weight of 90.7 kg. The TEDB data uses a gross jet fuel energy content of 125,000 BTU/gal; a correction to a net energy content of 116,400 BTU/gal (32.4 MJ/L, [16]) yields 42.4 kg-km/MJ.

[12] The PFEE value of 60 kg-km/MJ is equivalent to 31.5 vehicle miles/gallon with 320 lb of payload per vehicle and a gasoline energy content of 32.4 MJ/L. The payload is estimated from an average occupancy of 1.6 passengers per vehicle [17] and a passenger weight of 200 lbs with the assumption that fuel consumption is independent of passenger occupancy.

[13] The European Union (EU) has established a CO_2 standard instead of a fuel economy (mpg) standard like the CAFE program in the United States. The EU New European Drive Cycle (NEDC) is the basis for the EU standard. It has a lower average speed and different acceleration, deceleration, distance as compared to the CAFE cycle. All of these factors affect fuel economy; values reported here have been corrected to CAFE-based fuel economy. The EU CO_2 standard has a 2008 target of 140 gCO2/km (44.2 mpg) and European Automobile Manufacturer's Association (ACEA) data show 2002 new vehicle average CO_2 emissions were 165 gCO_2/km (37.2 mpg). [18]

[14] The life-cycle CO_2 was based on diesel fuel refining as a surrogate for jet fuel refining. Ongoing analysis indicates that this simplifying assumption may result in an over prediction of roughly 5%.

5 Summary

Payload Fuel Energy Efficiency (PFEE) provides a measure of the productivity delivered by aviation, measured as the product of payload and great circle distance, per unit cost of fuel energy consumed. This metric formulation was chosen to account for the productivity of cargo being carried in freighter aircraft and belly-freight in passenger aircraft. This is important as cargo represents roughly 1/3 (32%) of revenue payload distance carried by U.S. airlines and roughly 1/5 (19%) of this is being carried in passenger aircraft in the form of belly-freight. Fuel energy was chosen as the cost function for the efficiency metric because it allows for the comparison of alternative fuels to the kerosene based fuels being used today.

On a fleet-wide basis aviation had a PFEE of 66 kg-km/MJ in 2007. Because of the improvements in aircraft technology and operations, the 2007 value of PFEE is a 51% improvement over 1991. Cargo operations have a fleet-wide average PFEE of 97 kg-km/MJ while passenger operations, which include the productivity of both passengers and belly-freight as payload, have a fleet-wide average PFEE of 60 kg-km/MJ in 2007. The average passenger aircraft PFEE is 43% higher than the average PFEE of U.S. automobiles, but is 15% below model year 2002 European automobiles.

PFEE could be combined with emissions indices to derive the mass of pollutant per unit of productivity with units of g emissions per kg-km. The fuel use term within PFEE could also be examined to quantify the improvement in fuel use that could accompany changes in flight routing and reduction in delays.

6 Acknowledgments

The authors would like to thank Mr. David Senzig for his assistance in examining the differences in freighter and passenger aircraft design, Dr. Elena de la Rosa Blanco for her assistance in refining the document, and Dr. Mohan Gupta of the FAA for managing this MIT/Volpe effort. The concepts behind this work have benefitted from input and review from many individuals including, but not limited to, Mr. Sandy Webb, Dr. Lourdes Maurice, Mr. Curtis Holsclaw, Prof. Jeremiah Creedon and Prof. Ian Waitz.

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Copyright Statement

Appendix A: Transportation Efficiency Metrics

Table 2 presents a summary of the efficiency metrics used to track and measure performance goals in other transportation modes. The information presented makes reference to metrics used for policy, regulatory, and analytical (research) purposes.

Appendix B: Passenger and Luggage Weight Allowance

The passenger and luggage weight allowance of 200 lbs/passenger is based on a survey of sources. The Form 41 database [9] uses 200 lb per passenger (including luggage). The International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) suggest a weight of 90 kilograms (198.4 lb) per passenger (including luggage) [20]. AC120-27E (Par 201) recommends allotting a weight of 220 lb per passenger for aircraft operation (average adult weight of 190 lbs with a checked luggage allowance of 30 lbs, an additional 5 pounds per passenger is recommended during winter months to account for extra clothing) [21].

The worldwide air traffic data for 2001 (as reported using the ICAO Air Transport Reporting Form A [22]) was used to estimate the weight allotment per passenger for the six ICAO statistical regions of airline registration (North America, Europe, Asia and Pacific, Latin America and the Caribbean, Africa, and the Middle East) [23]. The total tonne-km and freight tonne-km data were used to estimate the passenger tonne-km for each of the six regions (see Table 3). These values were divided by the corresponding passenger km values to calculate the average weight per passenger for each of the respective regions (see Table 4). The estimated values for passenger weight varied between 202 lb and 212 lb per passenger, with a worldwide weighted average of approximately 206.7 lb per passenger.

Source:	Efficiency indicator						
	Passenger modes			Cargo Modes			
	Air	Highway	Rail	Air	Highway	Rail	Marine
FAA Flight Plan	vehicle mile / fuel	N/A	N/A	vehicle mile / fuel	N/A	N/A	N/A
Environmental Protection Agency and National Highway Traffic Safety Administration	N/A	vehicle mile / gallon	N/A	N/A	N/A	N/A	N/A
Bureau of Transportation Statistics	BTU / passenger mile	vehicle mile / gallon -or- BTU / passenger mile	BTU / passenger mile	BTU / ton mile	BTU / ton mile	BTU / ton mile	BTU / ton mile
DOE Energy Information Administration (EIA) Annual Energy Outlook 2007	seat miles / gallon	vehicle mile / gallon	N/A	N/A	miles / gallon	ton miles / BTU	ton miles / BTU
DOE Indicators of Energy Intensity in the United States	BTU / passenger mile	BTU / passenger mile	BTU / passenger mile	BTU / ton mile	BTU / ton mile	BTU / ton mile	BTU / ton mile
DOE Energy Efficiency Report	energy / vehicle mile -or- energy / passenger mile	energy / vehicle mile -or- energy / passenger mile	energy / vehicle mile -or- energy / passenger mile	energy / ton mile	energy / ton mile	energy / ton mile	energy / ton mile
United Nations Division of Sustainable Development	energy / passenger km	energy / passenger km	energy / passenger km	energy / ton km	energy / ton km	energy / ton km	energy / ton km
Intergovernmental Panel on Climate Change	energy / passenger km	energy / vehicle km -or- energy / passenger km	energy / passenger km	energy / ton km	energy / ton km	energy / ton km	energy / ton km

Table 2: Efficiency metrics that are commonly used for various modes of transportation.

	Africa	Asia & Pacific	Europe	Middle East	Latin America & Caribbean	North America
Total tonne km (millions)	8230	105770	108320	13580	16430	133040
Freight tonne km (millions)	2050	37730	32590	4580	4130	29600
Passenger km (millions)	67260	736040	787410	96840	134040	1108780

Table 3: Regional distribution of air traffic (data from [23]).

	Africa	Asia & Pacific	Europe	Middle East	Latin America & Caribbean	North America
Passenger tonne km (total - freight)	6180	68040	75730	9000	12300	103440
Passenger weight (kg/passenger)	91.9	92.4	96.2	92.9	91.8	93.3
Passenger weight (lb/passenger)	202.6	203.8	212.0	204.9	202.3	205.7

Table 4: Estimated regional passenger weight allotment (data from [23]).