The Historical Fuel Efficiency Characteristics of Regional Aircraft from Technological, Operational, and Cost Perspectives

Raffi Babikian, Stephen P. Lukachko and Ian A. Waitz*
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
77 Massachusetts Ave., Cambridge, MA 02139

ABSTRACT

To develop approaches that effectively reduce aircraft emissions, it is necessary to understand the mechanisms that have enabled historical improvements in aircraft efficiency. This paper focuses on the impact of regional aircraft on the U.S. aviation system and examines the technological, operational and cost characteristics of turboprop and regional jet aircraft. Regional aircraft are 40% to 60% less fuel efficient than their larger narrow- and wide-body counterparts, while regional jets are 10% to 60% less fuel efficient than turboprops. Fuel efficiency differences can be explained largely by differences in aircraft operations, not technology. Direct operating costs per revenue passenger kilometer are 2.5 to 6 times higher for regional aircraft because they operate at lower load factors and perform fewer miles over which to spread fixed costs. Further, despite incurring higher fuel costs, regional jets are shown to have operating costs similar to turboprops when flown over comparable stage lengths.

Keywords: Regional aircraft, environment, regional jet, turboprop

1. INTRODUCTION

The rapid growth of worldwide air travel has prompted concern about the influence of aviation activities on the environment. Demand for air travel has grown at an average rate of 9.0% per year since 1960 and at approximately 4.5% per year over the last decade (IPCC, 1999; FAA, 2000a). Barring any serious economic downturn or significant policy changes, various

* Contact author: 617-253-0218 (phone), 617-258-6093 (fax), iaw@mit.edu (email)

organizations have estimated future worldwide growth will average 5% annually through at least 2015 (IPCC, 1999; Boeing, 2000; Airbus, 2000). As with all modes of transportation, improvements in the energy efficiency of the aviation system have failed to keep pace with industry growth, resulting in a net increase in fuel use and emissions with potential climate impacts (Lee *et al*., 2001). Carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_X), sulfur oxides (SO_X), and particulates (soot), are examples of aircraft emissions which may alter atmospheric processes. A scientific assessment published by the Intergovernmental Panel on Climate Change (IPCC) attributes 3.5% of the total radiative forcing resulting from human activities to aviation and suggests that the impact of aircraft emissions at altitude is potentially twice as severe with respect to climate change when compared to ground level emissions (IPCC, 1999).[1] The forcing contribution of aircraft emissions is expected to increase in future decades as aviation fuel consumption continues to grow. Governments, airlines and manufacturers are currently debating the need for future limits on aircraft emissions and the effectiveness of various emission-reduction strategies.

At the same time, regional aircraft are playing an increasingly important role in the evolution of U.S. airline operations.[2] Traffic flown by regional airlines grew almost 20% in 1999 in the U.S. and is expected to grow 7.4% annually during the next decade, compared to 4% to 6% for the major U.S. airlines (FAA, 2000a). This growth has been spurred by the widespread adoption of the regional jet (RJ), which has allowed airlines to expand hub-and-spoke operations, replace larger jets in low-density markets, replace or add to turboprop (TP) equipment in longer short-haul markets, and create new hub-bypass routes (Trigerio, 1999; FAA, 2000b; Dresner *et al*., 2002). Regional jets made up ~25% of the regional aircraft fleet in 2000, up from only 4.2% in 1996 and their share is expected to increase to nearly 50% by 2011 (FAA, 2001). The success of the RJ has been largely attributed to their popularity with travelers, who prefer them because they are more comfortable, quieter and faster than TP's (FAA, 2000b).

Although regional aircraft currently perform just under 4% of domestic revenue

[1] Radiative forcing expresses the change to the energy balance of the earth-atmosphere system in watts per square meter (Wm^{-2}). A positive forcing implies a net warming of the earth, and a negative value implies cooling.

[2] For the purpose of this study, regional aircraft are referred to as those with more than 19 but fewer than 100 seats. Large aircraft, on the other hand, refer to aircraft with more than 100 seats.

passenger kilometers (FAA, 2000a), they account for almost 7% of jet fuel use and for 40% to 50% of total departures (ATA, 2000; RAA, 2001). In addition, the increased use of RJ's is changing the dynamics of airport and airway congestion. Regional jets are designed to fly at altitudes flown by larger commercial aircraft, increasing high-altitude traffic and burdening airspace capacity. Regional jets also require longer runways than TP's, which may strain already congested airports.

Future regulations or agreements aimed at reducing the environmental impact of aviation will need to consider the rising importance of regional aircraft to the U.S. aviation system. To assist in such an evaluation, this paper quantifies and explains the historical energy efficiency of regional aircraft through an investigation of their technological and operational characteristics. It further relates trends in energy efficiency to aircraft operating costs. Differences between turboprops and regional jets are highlighted to provide insight into the potential impact of the growth of regional aircraft use on the energy efficiency of the U.S. aviation system. The characteristics of regional aircraft are also compared to those of larger narrow- and wide-body aircraft, providing alternative perspectives from which to analyze technological evolution, airline operations, and costs.

2. DATA AND METHODS

Trends in regional aircraft energy use were related to technological, operational, and cost characteristics using an integrated database of aircraft performance parameters, financial measures, and traffic statistics. The aerodynamic, structural, and propulsion efficiencies of thirty-three of the most important regional aircraft introduced in the last forty years were compiled from published sources and through correspondence with industry representatives (ICAO, 1995; Gunston, 1998; Eurocontrol, 2000; JIG, 2001). The same technological metrics for large aircraft types were taken from Lee (2000). Detailed traffic and financial statistics were obtained from the U.S. Department of Transportation (DOT) Form 41 Schedule T2 and P5.2, respectively (DOT, 2001). Traffic data includes, among other statistics, available seat kilometers (ASK), revenue passenger kilometers (RPK), aircraft kilometers, and fuels issued. Due to DOT reporting rules, the statistics presented herein are not compiled from all U.S. airlines operating regional aircraft, but rather from airlines operating both regional aircraft and those with more than 60 seats.

Currently, about 60% of all RPK's are performed by regional airlines reporting on Form 41 (FAA, 2001). Cost data from Schedule P5.2 was divided into direct operating costs (DOC) and investment related costs (I). Flying operations costs including fuel, crew, and direct maintenance costs make up the direct operating cost (DOC), while investment costs (I) consist of depreciation and amortization accounts.[3] When appropriate, they are taken together as the DOC+I. All costs were discounted to 1996 dollars using GDP deflators provided by the Bureau of Economic Analysis of the U.S. Department of Commerce (DOC, 2001).

3. THE ENERGY INTENSITY OF REGIONAL AIRCRAFT

Energy efficiency, related to energy consumed, is a useful metric for evaluating aircraft environmental performance. The energy efficiencies of aircraft are measured by the specific energy usage (E_U) and specific energy intensity (E_I), expressed in units of energy consumed per ASK (Joules/ASK) and energy consumed per revenue passenger kilometer (Joules/RPK), respectively. E_U indicates how much energy is required to perform a unit of potential work—moving a single seat one kilometer—and is closely related to environmental performance of the aircraft system itself. E_I, in comparison, is a measure of how much energy is required to perform a unit of actual work—moving a passenger one kilometer. E_I and E_U are related by the load factor (α), the ratio of boarded passengers to available seats, as shown in Equation (1). Load factors close to one signal that an aircraft and its fuel are being effectively utilized.

$$E_I = \frac{E_U}{\alpha} \tag{1}$$

Energy usage varies greatly for different types of aircraft according to the level of technological advancement, size, mission, propulsion system type and various operational efficiencies. Figure 1 shows the historical E_U characteristics of regional aircraft. The average E_U of TP's and RJ's are plotted versus year of introduction along with the overall fleet efficiencies. The vertical bars in the figure represent the range of values obtained for each aircraft type over the period 1968-1999 on a per annum basis. The energy usage of regional aircraft consistently improved over this period. Using as benchmarks the Lockheed L-188 and the DHC-8-300,

[3] Crew costs in this case only consist of pilot, copilot and other flight personnel salaries, as cabin crew costs are not reported on Form 41.

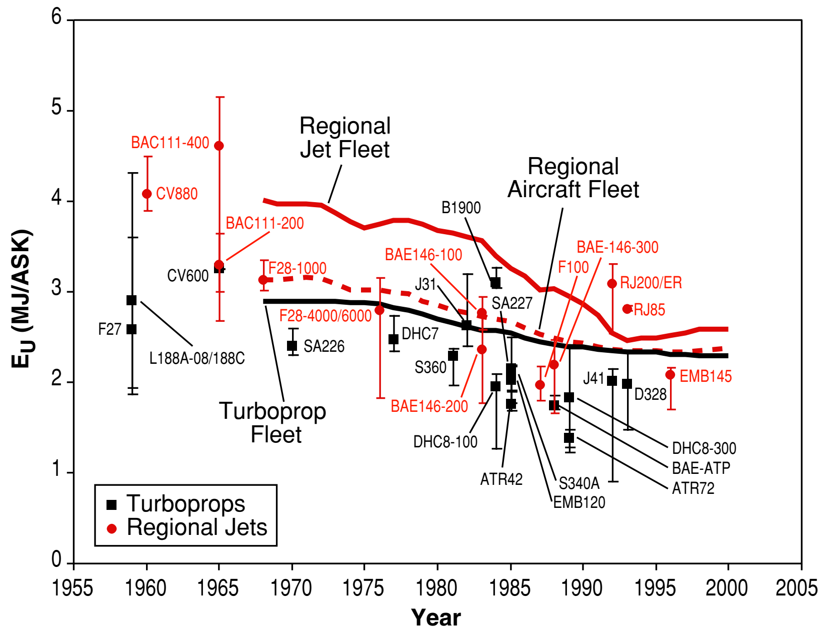

Figure 1: The E_U of regional aircraft and fleet averages.

introduced in 1959 and 1989 respectively, the E_U of turboprops has decreased by ~40%, improving at an annual rate of around 1.5%. Regional jets improved ~50% over a similar time period, averaging almost 2% annual improvement when the highly successful CV-880 and ERJ-145 are used as benchmarks. Regional jets have been approximately 10% to 60% less efficient than TP's, although they have improved their E_U at a faster rate and have recently approached the efficiencies of modern turboprops.

Figure 1 also shows that the regional aircraft fleet average is heavily weighted towards the E_U of the TP fleet, reflecting the fact that TP's have traditionally made up a majority of the aircraft operated. As regional jets such as the CRJ-200 and the ERJ-145 replace TP's and become an increasingly important part of regional airline operations, the fleet E_U curve will approach the average usage of RJ's. This suggests that the average fleet E_U may increase in the future. In fact, the beginning of such a trend is already apparent; between 1975 and 1992, the E_U of the regional fleet decreased by approximately 22%, but increased by approximately 0.5% following the introduction of the new generation of RJ's in 1992.

Figure 2 shows the E_U of regional aircraft compared to thirty-one larger aircraft studied in Lee *et al*. (2001). These aircraft, introduced between 1959 and 1995, reflect the evolution of

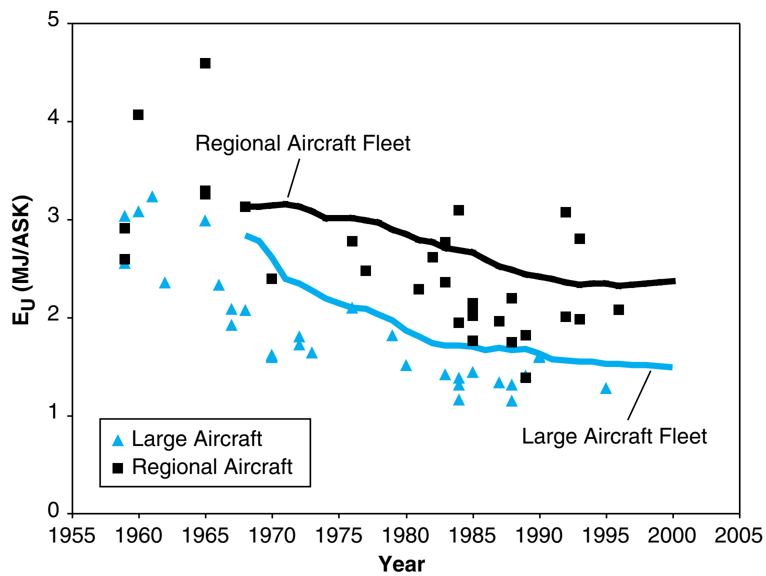

Figure 2: The E_U of regional aircraft compared to large aircraft.

aircraft technology since the beginning of the jet era and were selected to represent the U.S. fleet. Historically, regional aircraft E_U has been 10% to 100% higher than that of their larger counterparts.

4. TECHNOLOGICAL AND OPERATIONAL INFLUENCES ON ENERGY USAGE

The technological and operational characteristics of regional jets, turboprops, and large aircraft were analyzed to explain historical reductions in E_U. Aircraft technology characteristics were described by three aircraft performance metrics, which relate directly to the energy usage of aircraft in cruise flight according to the specific air range (SAR) equation. Engine efficiencies were quantified in terms of thrust specific fuel consumption (TSFC), the thrust produced by the engine divided by the rate of fuel flow. Aerodynamic efficiencies were assessed in terms of maximum lift over drag ratio (L/D_{MAX}). Finally, structural efficiency was evaluated using operating empty weight (OEW) divided by maximum take-off weight (MTOW), a measure of the structural weight necessary to carry the structure itself, fuel and payload.

4.1 <u>Engine Efficiencies</u>

Cruise values of thrust specific fuel consumption (TSFC) have improved approximately 25% since 1960 for both RJ and TP engines, as shown in Figure 3. Increases in TSFC have been

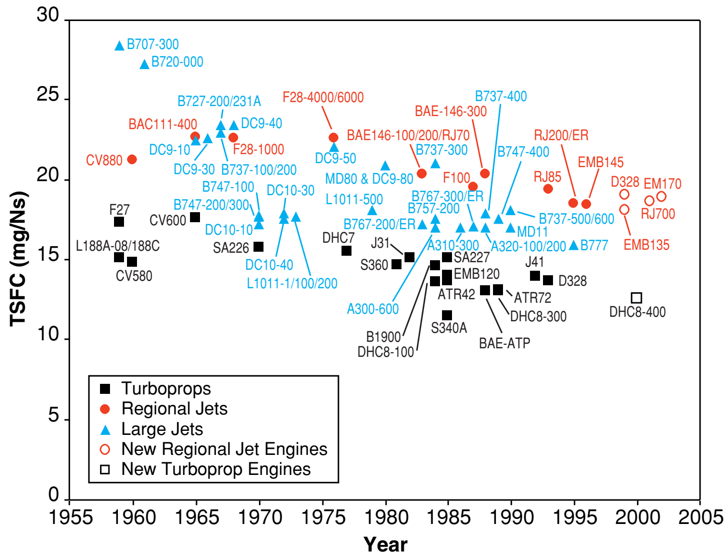

Figure 3: Improvements in TSFC for different aircraft types at cruise.

the result of improvements in propulsive and thermal efficiencies (η_P and η_T), whose product is the overall propulsion system efficiency (η_O). Propulsive efficiencies have significantly improved with the development of the high-bypass ratio engine. Initially developed for long-haul, wide-body aircraft, high-bypass ratio engines contributed to the noticeable drop in TSFC values in the early 1970's, evident in Figure 3. However, high-bypass ratio engines were not installed on smaller aircraft until more than a decade later. For example, the DC-9-80 and the 737-300, both introduced in the first half of the 1980s, were equipped with low-bypass engines. Only in the latter half of the decade were turbofans developed for RJ's and the smallest of what are called large aircraft in this study.

One result of this delay in technology adoption is that the $TSFC_{CR}$ values for RJ engines have been 10% to 25% higher than those of large aircraft since the early 1970s. Even when the influence of large differences in bypass ratio is accounted for, small jet engines exhibit higher TSFC's than larger engines. For engines with bypass ratios between 4.5 and 6.5, those with thrust ratings smaller than 100kN are 5% to 10% less efficient than engines with thrust ratings above 100kN. This trend is partly caused by the lower pressure ratios, and as a result, lower thermal efficiencies of small engines. They generally have fewer compressor stages or they utilize space saving but less efficient centrifugal compressors.

Figure 3 shows that TP engines are 10% to 30% more efficient than jet engines at cruise. Turboprops typically derive 85% of their thrust from a propeller, while jet exhaust provides the remaining thrust. Their high TSFC is the result of the propellers' ability to accelerate large amounts of air at low speeds. This is particularly advantageous during take-off and climb stages of flight when aircraft move relatively slowly. The efficiency of a propeller decreases with increasing airspeed and altitude however, limiting the operation of turboprops to Mach numbers below 0.7 and altitudes below 25,000 feet.

4.2 Structural Efficiencies

A 1% reduction in the gross weight of an empty aircraft will reduce fuel consumption between 0.25% and 0.75% (Greene, 1995; Lee *et al.*, 2001). Advanced materials such as improved aluminum alloys and composites have been successfully used for control surfaces, flaps, and slats on civil aircraft. However, despite the development and use of advanced materials, Figure 4 shows that the structural efficiencies of aircraft have decreased between 10% and 25% for all aircraft types since 1959. The lack of improvement is partly due to the fact that most aircraft today are still about 97% metallic, with composites used only on relatively few components such as the tail. Furthermore, structural weight reductions have been largely offset by structural weight increases to enable improvements in aerodynamics and the integration of in-flight entertainment systems, and to accommodate increased engine weights (IPCC, 1999).

Figure 4 shows that RJ's are less structurally efficient than large aircraft, and that TP's in turn are less efficient than RJ's. There may be several reasons for this trend, but an important effect is that of engine weight. Engine weights do not scale linearly with thrust, and engines with smaller thrust ratings typically have lower thrust-to-engine weight ratios (T/W_E). Typically, engines producing less than 100kN of thrust have T/W_E ratios 25% lower than engines producing more than 200kN of thrust. Turboprops have comparatively low T/W_E ratios because of the extra weight required for the mechanisms that alter propeller pitch and a reduction gearbox that connects the turbine to the propeller (Ojha, 1995). As a result, aircraft powered by small turbofans and turboprops are relatively heavier for the payload they carry compared to large aircraft.

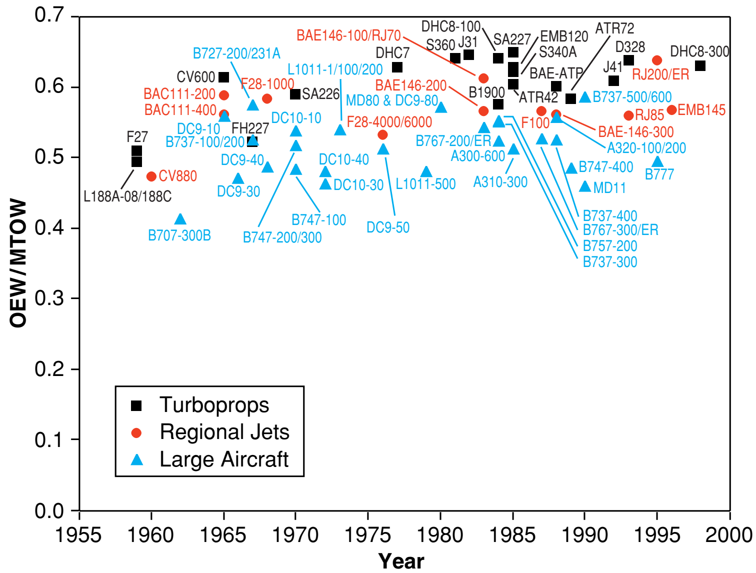

Figure 4: Historical trends in structural efficiency.

4.3 Aerodynamic Efficiencies

Historical trends in aerodynamic efficiency, or maximum lift-over-drag (L/D_{MAX}) ratio, are shown in Figure 5. Aerodynamic efficiencies of large aircraft have improved approximately 15% since 1959, averaging 0.4% per year (Lee *et al.*, 2001). These gains, mostly realized after 1980, have been driven by better wing design and improved propulsion/airframe integration made possible by improved computational and experimental techniques (IPCC, 1999). Less of a trend is evident for either RJ's or TP's, partly because L/D_{MAX} for several older aircraft models are unavailable. Nevertheless, Figure 5 shows that the aerodynamic efficiencies of regional aircraft are similar to those of large aircraft.

4.4 Influence of Technology on Energy Usage

The technological parameters examined above can be used to estimate the cruise values of E_U ($E_{U,CR}$), making it possible to compare the energy usage of aircraft based on technology characteristics alone. In this section, calculated $E_{U,CR}$ values are compared across aircraft types, and then compared to total E_U values plotted on Figure 2.

$E_{U,CR}$ can be calculated using the specific air range equation (SAR). The SAR is the basic model for describing the physics of aircraft in steady cruise flight, and it quantifies the distance

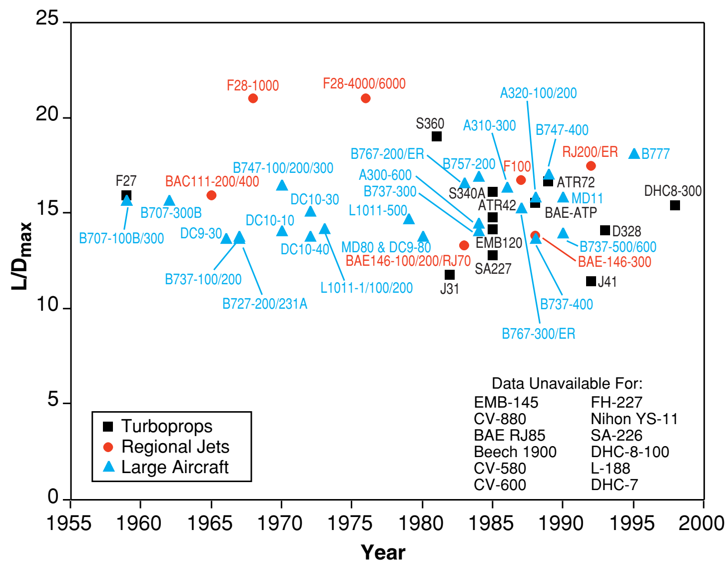

Figure 5: Historical trends in L/D_{MAX} ratios.

flown per unit of energy consumed. The SAR equations are shown below as Equations (2) and (3) for jets and turboprops respectively.

jet:

$$SAR_{JET} = \frac{Velocity}{TSFC \cdot h_F} \cdot \frac{L}{D} \cdot \frac{1}{W} \tag{2}$$

turboprop:

$$SAR_{TURBOPROP} = \frac{\eta_{PR}}{PSFC \cdot h_F} \cdot \frac{L}{D} \cdot \frac{1}{W} \tag{3}$$

where: $W = W_{FUEL} + W_{PAYLOAD} + W_{STRUCTURE} + W_{RESERVE}$

h_F = Heating value of jet fuel

η_{PR} = Propeller efficiency

Additional manipulation of the SAR equations yields formulas for estimating the $E_{U,CR}$ for jet and turboprop aircraft (Equations 4 and 5):

jet:

$$\frac{J}{ASK} = \frac{1}{SAR_{JET} \cdot Capacity} = \frac{TSFC \cdot W}{Velocity \cdot \frac{L}{D} \cdot Capacity} \tag{4}$$

turboprop: $$\frac{J}{ASK} = \frac{1}{SAR_{TURBOPROP} \cdot Capacity} = \frac{PSFC \cdot W}{\eta_{PR} \cdot \frac{L}{D} \cdot Capacity} \qquad (5)$$

In all calculations, turbofan and turbojet powered aircraft, including RJ's, are assumed to cruise at 35,000 ft. at Mach 0.85, while TP's are assumed to cruise at 20,000 ft. and at velocities specified in JIG (2001). For turboprops, η_{PR} is set to 0.85, a reasonable figure for modern propellers (Anderson, 1989; Ojha, 1995). It is also assumed that velocity and TSFC remain constant for jets, PSFC and η_{PR} remain constant for turboprops, and L/D remains constant for both. Values of W_{FUEL} and $W_{PAYLOAD}$ were taken from data available in Form 41. $W_{RESERVE}$ is taken as half the per block hour fuel consumption of a given aircraft to account for fuel reserve regulations. Also, for the twelve regional aircraft for which L/D information was not available, values from similarly sized aircraft with the same engine type were substituted.

Figure 6 shows that $E_{U,CR}$ values for regional aircraft and large aircraft fall approximately within the same band of variability in any given time period. Neither RJ's, TP's, nor large aircraft have a distinct technological advantage that results in lower fuel consumption under optimal cruise conditions. Turboprops were shown to have better TSFCs than RJ's, but the benefits of this advantage are offset by lower TP structural efficiencies. Comparisons of calculated $E_{U,CR}$ and total E_U values further reveal that large aircraft achieve total efficiencies much closer to their

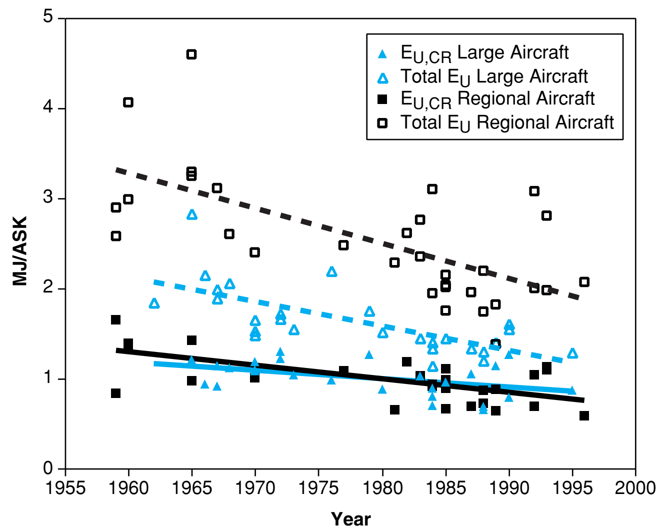

Figure 6: Differences between E_U and $E_{U,CR}$ for regional and large aircraft.

cruise values than regional aircraft. Differences in E_U and $E_{U,CR}$ must therefore be caused by fuel consumption incurred during non-cruise portions of aircraft operations. Figure 6 shows that total E_U is on average 2.6 times higher than the calculated $E_{U,CR}$ for regional aircraft, but only 1.6 times higher for large aircraft. A closer inspection of regional aircraft $E_{U,CR}$ indicates that while total TP E_U values are on average 2.5 times greater than $E_{U,CR}$, total RJ E_U values are approximately 3.2 greater than $E_{U,CR}$ values.

4.5 Influence of Operations on Energy Usage

Aircraft operations—airports served, stage lengths flown, and flight altitudes—have a particularly significant impact on the E_U of regional aircraft. They fly shorter stage lengths than large aircraft, and as a result, spend more time at airports taxing, idling, and maneuvering into gates, and in general spend a greater fraction of their block time in non-optimum, non-cruise stages of flight. The impact of operational differences, and especially distance flown, on E_U is evident in Figure 7, which shows the variation of E_U with stage length for turboprop and jet-powered aircraft (both RJ's and large jets) introduced during and after 1980. Aircraft flying stage lengths below 1000 km have E_U values between 1.5 to 3 times higher than aircraft flying stage lengths above 1000 km. Also, TP's show a distinct pattern from that of jets, and are, on average, more efficient at similar stage lengths. Insight into the causes of these trends can be gained by examining the efficiencies associated with ground and airborne activity characteristics of RJ's, TP's and large jets.

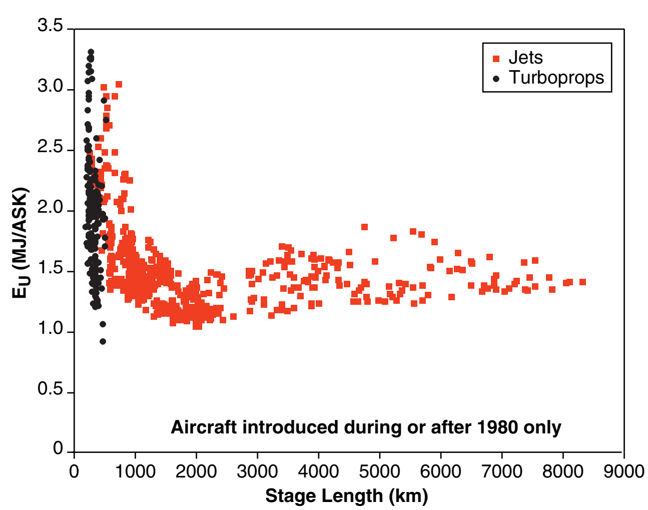

Figure 7: Variation of E_U with stage length.

4.6 Ground Efficiencies

All aircraft consume fuel on the ground at the airport while taxing, maneuvering to and from gates, and idling due to delays. A useful efficiency metric for evaluating the amounts of time aircraft spend on the ground compared to in the air is the ratio of airborne hours to block hours (η_g). Aircraft that fly short stage lengths have lower η_g because of the need to taxi and maneuver more often for every unit of time spent in the air. They therefore incur a fuel consumption penalty relative to longer flying aircraft. This is evident in Figure 8, which shows a steadily decreasing η_g with decreasing stage length for all aircraft types. The η_g of regional aircraft varies between 0.65 and 0.90, compared to between 0.75 and 0.90 for large aircraft. The high variability in ground efficiency for regional aircraft in general may be reflective of the fact that they serve airports of various sizes. Regional aircraft flying into large airports are likely to have to taxi further to get to the runway and face greater congestion-related delays than aircraft serving smaller community airports.

Because regional aircraft take-off and land so often, they are an important part of major airport operations. Continued rapid growth of the regional airline industry has the potential to worsen congestion and delays at already stressed airports. Regional jet service additions to date have focused on congested major urban airports as opposed to secondary urban airports (Dobbie, 1999). Four of the top ten airports in terms of regional aircraft operations are also among the top

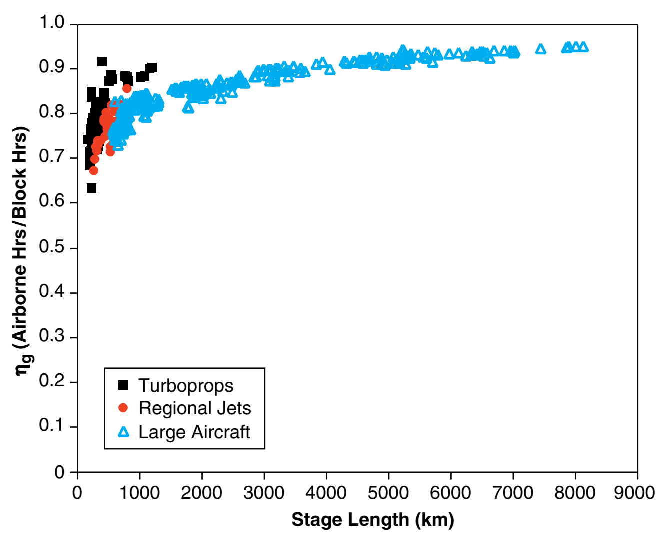

Figure 8: Variation of η_g with stage length.

ten airports with the greatest minutes of delay per operation (FAA, 2000b; RAA, 2001). Further compounding congestion problems, regional jets require longer runways than turboprops. One estimate by a TP manufacturer suggests that a 50-seat RJ requires 40% more runway length than a similarly sized TP for a 550 km mission at full load (ATR, 2002). The fact that regional jets require runway lengths similar to large aircraft may prove a bottleneck at some airports as regional jet routes are introduced, in part replacing or augmenting turboprop operations. Future efforts to reduce taxi times and improve the timely routing of aircraft to runways to improve ground efficiencies will need to consider the increasing importance of regional aircraft, and in particular, of RJ's in airport operations.

4.7 Airborne Efficiencies

Regional aircraft spend a significant part of their airborne hours climbing to or descending from cruise altitudes. During these stages of flight, the energy usage of an aircraft is different than during cruise, and is especially high during the energy-intensive climb stage. The larger the fraction of airborne time an aircraft spends climbing, the longer it spends at high rates of fuel consumption. This characteristic of short stage length flight contributes to the higher E_U of regional aircraft. The ratio of minimum flight hours to airborne hours, or airborne efficiency (η_a) serves to quantify the fraction of flight time aircraft spend at cruise speeds. Minimum hours refers to the shortest amount of time required to fly a given stage length along a great circle (minimum distance) route, and assumes that this distance is flown at cruise speed with no additional time required for take-off, climb, descent or landing. It is worth noting that the airborne efficiency metric also captures the influence of other in-flight inefficiencies, such as indirect routings, flight plan changes due to airway congestion, and time spent performing holding patterns above congested airports. Each of these inefficiencies, in addition to take-off and climb effects, increases the average energy usage above that incurred during cruise.

Figure 9 shows the variation of airborne efficiency with stage length. Even for stage lengths shorter than those typically flown by RJ's, TP's exhibit efficiencies that are approximately 20% higher than regional jets. While RJ's follow the trend associated with large aircraft, decreasing logarithmically below 1000 km, TP's follow a more efficient pattern. This can be explained by the fact that TP's typically cruise at altitudes several thousand feet below jets

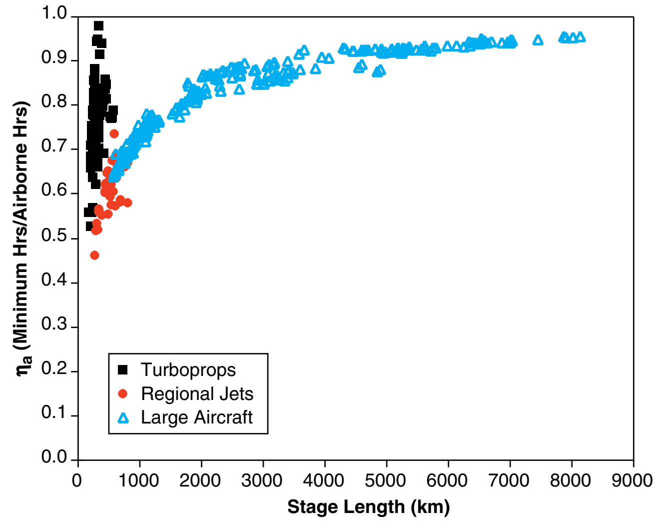

Figure 9: Variation of η_a with stage length.

and therefore spend less time climbing to cruise altitudes. They also spend less time at the high rates of energy usage associated with climbing flight. The airborne efficiencies of TP aircraft may also be higher because they serve smaller airports where they are less likely to encounter congestion-related airborne delays. The typical operational altitude of RJ's has other implications. Because regional jets fly at the same altitude as large aircraft, overall high altitude airspace congestion is likely to worsen as regional jets increase in popularity.

4.8 Total Impact of Operations on Energy Usage

The ground and airborne efficiencies together capture the important operational characteristics of commercial aircraft and effectively explain the differences between E_U and $E_{U,CR}$ shown in Figure 6. Figure 10 shows the variation of the $E_U/E_{U,CR}$ with the product of the ground and airborne efficiencies. As operational efficiencies decrease, total energy usage becomes a greater multiple of the cruise, or optimum, energy usage. For values of $\eta_g*\eta_a$ below 50%, the total energy usage can be expected to be more than three times cruise values of energy usage. For long-range aircraft capable of achieving combined efficiencies of more than 90%, the total energy usage is expected to be only 10% to 20% higher than cruise values of energy usage.

Ground and airborne efficiencies also help explain the shape of the E_U vs. stage length trend shown for turboprop and jet-powered aircraft in Figure 7. E_U increases rapidly for all

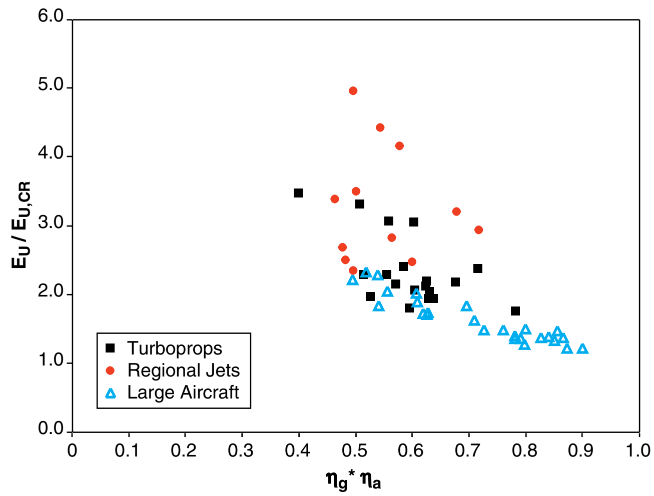

Figure 10: Variation of $E_U/E_{U,CR}$ with ground and airborne efficiencies.

aircraft flying stage lengths smaller than 1000 km due to the lower η_g and η_a achieved at these distances. Turboprops have lower E_U compared to RJ's at similar or shorter stage lengths because they achieve higher airborne efficiencies. At stage lengths greater than 1000 km, the influence of ground and airborne efficiencies on E_U is diminished, and the E_U begins to rise steadily above 2000 km. This rise is caused by the need for long-range aircraft to carry a greater fuel load, which translates into higher average fuel consumption at cruise. As a result, aircraft operating at stage lengths between 1000 km and 3000 km have the lowest energy usage among aircraft considered in this study.

4.9 Influence of Load Factor

Figure 11 shows historical load factor trends for large aircraft, regional jets and turboprops reporting on Form 41. Load factors improved almost 50% for large aircraft between 1960 and 1999. Even if aircraft technologies during this period afforded no improvement to the E_U of the large aircraft fleet, the E_I would nevertheless have improved by a third. Although the TP fleet has historically had lower E_U than the RJ fleet, the RJ fleet has been used more efficiently. Over the period covered, RJ's have consistently had load factors 10% to 30% higher than for turboprops. The effect this has had on E_I is illustrated in Figure 12. In 1970, while the E_U of the RJ fleet was 40% higher than for the TP fleet, the E_I was only 9% higher. Similarly in 1999, the RJ fleet E_U was 13% higher than for the TP fleet, but the E_I was only 3% higher.

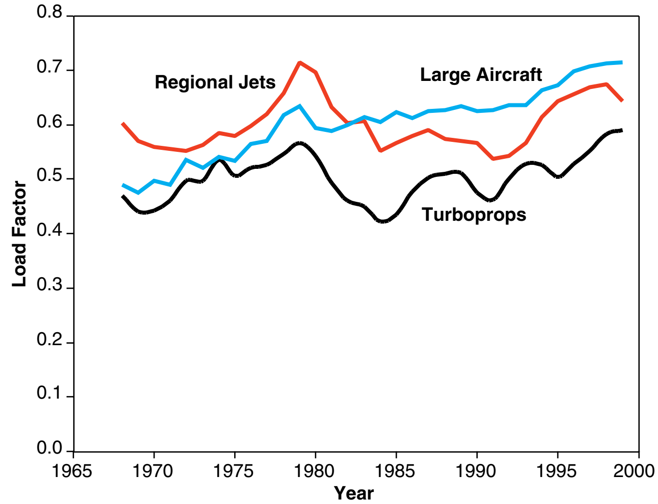

Figure 11: Historical changes in load factor.

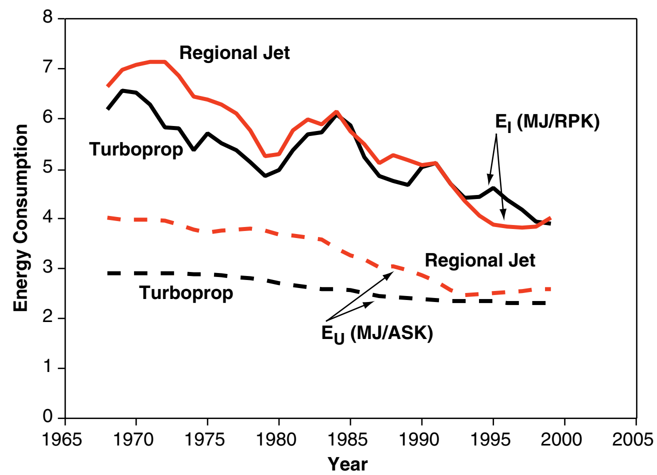

Figure 12: Effect of load factor on fleet energy intensity.

5. COST CHARACTERISTICS OF REGIONAL AIRCRAFT

The development and implementation of new technologies and the adoption of efficient operational practices have generally been the means by which airlines and aircraft manufacturers have pursued cost savings, often decreasing the energy usage of the fleet at the same time. Although RJ's are characterized by higher energy usage, and consequently, higher fuel costs, they are nevertheless cost competitive with turboprops. This occurs for two reasons: RJ's have historically operated at higher load factors, and variable costs, such as fuel, are less important components of the unit costs of aircraft flying short stage lengths. As a result, there is less cost-saving incentive for regional airlines to operate more energy efficient aircraft than for airlines operating larger aircraft. A historical relationship between regional aircraft operating and capital costs is identified in this section, providing an outline of the acquisition costs airlines have been willing to assume in return for operating cost savings.

5.1 Regional Aircraft Operating Costs

As compared to larger narrow- and wide-body aircraft, fuel costs make up a smaller percent of the total operating and ownership costs of regional aircraft. Figure 13 provides a breakdown of DOC+I in 1999 for the large jets considered in Lee (2000) and the regional jets

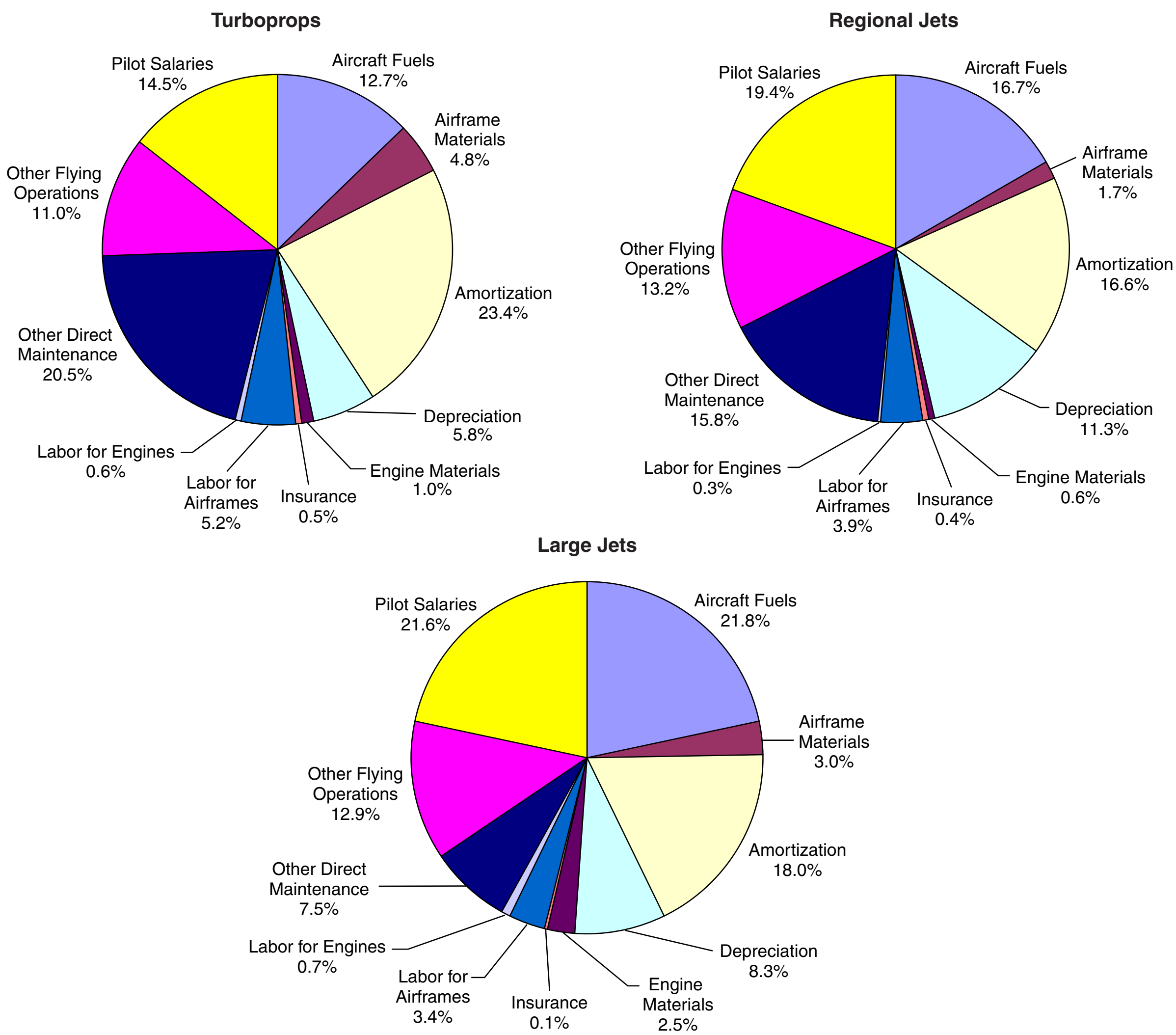

Figure 13: DOC+I breakdown for different aircraft types in 1999.

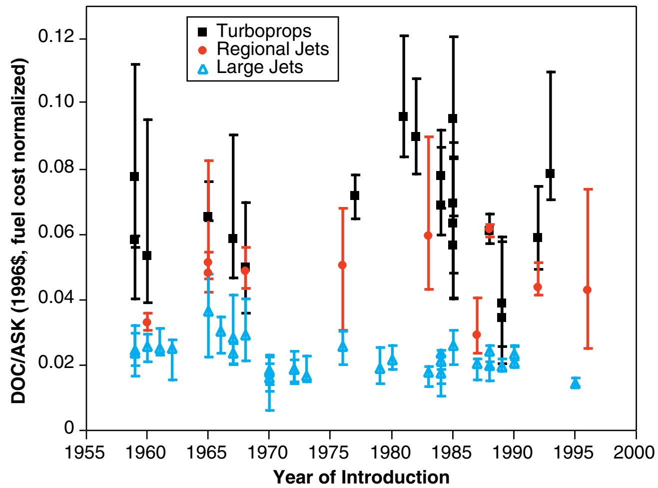

Figure 14: Unit direct operating costs of large jets, regional jets and turboprops.

and turboprops examined in this study. For the large aircraft, fuel costs made up almost 22% of the DOC+I costs, while they only made up 17% and 13% of the total costs of RJ's and TP's, respectively. In general, fuel costs as a fraction of total costs steadily decrease as stage lengths decrease. Lower fuel costs are largely offset by increased maintenance costs, which make up a higher portion of DOC+I for regional aircraft.

5.2 <u>Regional Aircraft Unit Costs</u>

Unit cost, when measured as DOC/ASK, is the cost of a unit of potential passenger service and is a useful means through which to elucidate the relationship between the technological and operational characteristics of an aircraft and the costs of its operation. When expressed as DOC/ASK, demand-side considerations such as achievable load factors, which are important for judgments on the competitiveness of different aircraft types, are not taken into account. Figure 14 plots the average DOC/ASK cost for regional and large aircraft types. The vertical bars represent the range of values found in the data. The historical trend for large aircraft shows a 25% to 35% improvement between 1959 and 1995, the result of improvements in avionics and reductions in maintenance and fuel costs. In contrast, regional aircraft show no distinct upward or downward historical trend, and they exhibit considerable variability both within the same aircraft type and from one aircraft type to another. In addition, regional aircraft are two to five times more expensive to operate than large aircraft, and turboprops have unit costs sometimes twice as high as regional jets. When load factors are considered (which are 10% to 20% lower than for large aircraft), regional aircraft are 2.5 to 6 times more expensive to operate than large aircraft on a DOC/RPK basis. The high unit costs of regional aircraft are reflected in the yields of regional airlines (the price charged per RPK), which in 1999 were approximately 2.5 times those charged by the major airlines (FAA, 2000a). Further discussion of demand-side considerations for regional jet operations is provided by Dresner (2002).

To explain the unit cost characteristics of regional aircraft, multivariable regression analyses were performed to identify the key parameters that determine the DOC/ASK of regional aircraft. Only data from 1990 to 1999 were used because of an irregularity in the Form 41 traffic database that prevented stage lengths from being calculated for records dated prior to 1990. In general, this limits the scope of the analysis to aircraft introduced after 1975. The analysis was performed separately for both regional jets and turboprops. Several potential explanatory variables were considered based on insight gained from previous work (Lee, 2000) and additional knowledge of the particular characteristics of regional aircraft. It was found that stage length (SL) and E_U could account for most of the variability in unit costs, according to the relationships shown in Equations (6) and (7).

turboprop: $$\frac{DOC}{ASK} = 11.106 \cdot \frac{1}{SL} + 2.529 \times 10^{-2} \cdot \frac{MJ}{ASK} - 0.0208 \qquad (6)$$

$R^2 = 0.689$, N = 78, t/t_{CRIT} for coefficients: 3.93, 3.29, 3.06 respectively

regional jet: $$\frac{DOC}{ASK} = 15.917 \cdot \frac{1}{SL} + 9.742 \times 10^{-3} \cdot \frac{MJ}{ASK} - 0.0111 \qquad (7)$$

$R^2 = 0.786$, N = 33, t/t_{CRIT} for coefficients: 3.956, 2.064, 0.897 respectively

The relationships in Equations (6) and (7) can be interpreted physically. The 1/SL term represents the contribution of fixed costs to total unit costs. Fixed costs do not vary with stage length flown, although they may be expected to increase with aircraft size. Longer-flying aircraft have a greater number of miles over which to spread fixed costs, and their contribution to DOC/ASK decreases with increasing stage length. Fixed costs are therefore less important for longer-flying large aircraft, but they contribute significantly to DOC/ASK at short stage lengths.

For example, many maintenance costs are fixed and are accrued on a per cycle basis. Neither TP's nor RJ's exhibit distinct maintenance cost trends with increasing stage length, suggesting that fixed maintenance and other similarly fixed costs play an important role in determining unit costs of aircraft flying short distances. The MJ/ASK term of Equations (6) and (7) captures the influence of variable costs such as fuel and pilot wages, which vary in some relation to stage length, but remain constant on a per mile basis. In general, aircraft with lower MJ/ASK values have lower variable costs not only because of lower fuel costs but also because of the lower cost of operation made possible by the use of advanced technologies and designs.

5.3 Unit Costs of Regional Jets and Turboprops Compared

Equations (6) and (7) are also useful for comparing the unit cost characteristics of TP's and RJ's at common stage lengths and at typical values of energy usage. Figure 15 shows the estimated unit costs of TP's and RJ's at high, low, and median values of energy usage plotted versus stage length. High, low, and median values were determined by the average values of E_U for the various aircraft studied. Operational data are also superimposed on the curves. From a cost perspective, fuel-efficient RJ's are competitive with all but the most efficient TP's, particularly when the higher load factors achieved by RJ's are considered. At stage lengths flown by both aircraft types, TP's with low E_U (about 1.5 MJ/ASK) are capable of achieving unit costs that are approximately 15% lower than RJ's with low E_U (about 2.0 MJ/ASK). However, this is

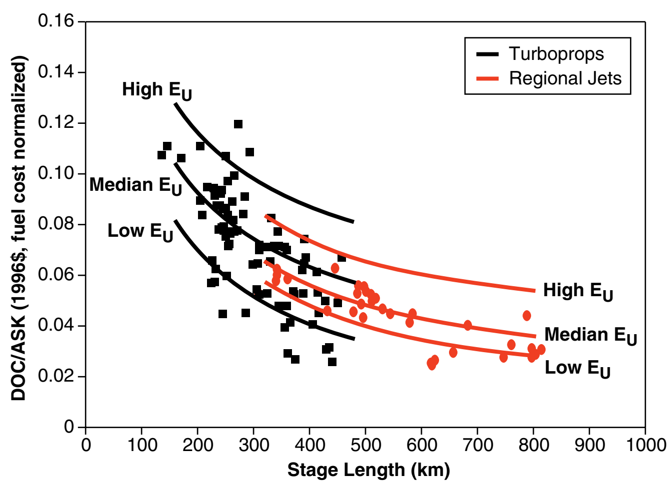

Figure 15: Variation of DOC/ASK according to stage length and E_U.

not the case as fuel efficiencies worsen. At median values of energy usage (about 2.3 MJ/ASK for TP's, 2.8 MJ/ASK for RJ's), regional jets have unit costs that are 9% to 15% lower than turboprops.

The impact of both stage length and level of technology on unit costs is made apparent in Figure 15. For a TP with low energy usage, a 77% increase in unit costs can be expected when flying a 250 km route compared to a 450 km route. Similarly, for a low energy usage RJ, a 45% increase in unit costs is anticipated when flying a 400 km stage length instead of a 650 km stage length. The dependence of regional aircraft unit costs on stage length explains the cost characteristics of regional aircraft identified in Figure 14. Specifically, regional aircraft have higher unit costs than large aircraft because they fly much shorter stage lengths. The variability in unit costs among regional aircraft is caused by the significant impact of small differences in stage length flown. Finally, RJ's have lower unit costs than TP's because they have historically served longer routes.

Variations in E_U within regional aircraft types also have an important influence on unit costs. Figure 15 shows that unit costs are twice as high for a TP with high E_U flying a 300 km route compared to a TP with low E_U. Similarly, a RJ with a high E_U flying a 600 km stage length has unit costs 1.8 times higher than a RJ with low E_U. In general, for any given stage length, the unit cost savings achieved by low E_U TP's compared to high E_U TP's is between 0.044 and 0.056 1996$/ASK. This corresponds to a 40% to 60% savings depending on stage length flown. For RJ's, unit costs reductions at a given stage length are smaller, and are between 0.024 and 0.026 1996$/ASK, which corresponds to savings between 30% and 46% depending on stage length flown. Note that these are not all fuel cost savings, but include savings due to maintenance and other non-fuel related cost reductions. Recognizing that the unit fuel costs for a given E_U can be calculated by multiplying the E_U (in MJ/ASK) by the fuel price (1996$/MJ, fuel cost normalized to the 1996 price), the unit cost savings in going from high to low E_U can be calculated. This calculation yields a 0.009 1996$/ASK fuel cost saving in going from high E_U to low E_U for TP's, and a 0.013 1996$/ASK fuel cost saving for RJ's. Fuel cost savings make up 16% to 21% of the unit cost savings of TP's, but make up 49% to 51% of the unit cost savings of regional jets. These results suggest that reductions in fuel costs have played a more important role in reducing

DOC/ASK for RJ's than for turboprops. This is not surprising, given that fuel costs are a smaller portion of total DOC for TP's compared to RJ's, and that the E_U of RJ's has improved a greater amount over the time period covered than the E_U of turboprops.

5.4 Aircraft Capital and Operating Cost Relationship

Large aircraft capital costs, normalized on a per seat basis, are correlated with DOC/RPK (Lee *et al*., 2001). This suggests that airlines operating large aircraft are willing to pay higher capital costs in return for lower operating costs realized over the life of the aircraft. Regional aircraft exhibit a similar trend, although only when the influence of stage length is factored out. Figure 16 shows the variation in new aircraft cost when unit costs have been adjusted to a 400 km stage length (using Equations (6) and (7)). Aircraft costs were taken from Thomas and Richards (1995). There is a pattern showing that unit costs are lower for more expensive aircraft. Specifically, a 0.031 1996$/ASK decrease in unit costs from 0.077 1996$/ASK to 0.046 1996$/ASK is worth between $80K and $90K per seat in acquisition costs.

It was shown earlier that, in general, aircraft technologies have improved over time resulting in more fuel-efficient aircraft. However, the ability of new aircraft to impact total aviation emissions will depend on how fast it takes to integrate them into the airline fleet. The rate of fleet replacement depends on many factors, including safety requirements, growth in

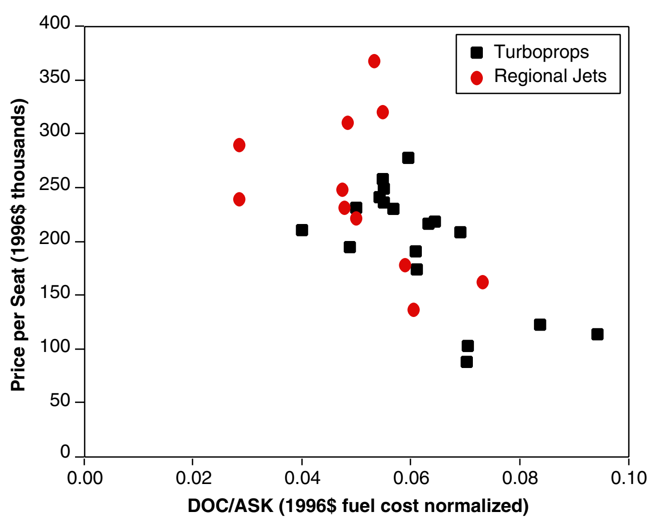

Figure 16: Variation of regional aircraft cost with unit costs adjusted to 400 km stage length using Equations (6) and (7).

demand, prices of labor and fuel, industry profitability, and the availability of financing (Balashov and Smith, 1992). Even though advances in technologies offer the potential to reduce the impact of aviation on the environment and lower operating costs, these benefits must be considered in terms of the economic and customer requirements of airlines and aircraft manufacturers (IPCC, 1999; ADL, 2000).

6. SUMMARY AND CONCLUSIONS

In the U.S., efforts to mitigate the impact of aviation on the environment will have to take into consideration the increasing importance of regional aircraft operations. Although they only perform approximately 4% of domestic revenue passenger miles (FAA, 2000a), they account for 7% of jet fuel use and for 40% to 50% of total departures (ATA, 2000; RAA, 2001). In addition, regional traffic, stimulated by the widespread acceptance of the RJ, is expected to grow faster than the rest of industry. In an effort to gain insight into the potential impact of the simultaneous growth and transformation of regional air travel on the energy efficiency of the U.S. aviation system, this paper has characterized the historical reductions in the energy use of regional aircraft by quantitatively describing and comparing their technological, operational, and cost characteristics. These characteristics were also compared with those of larger narrow- and wide-body aircraft.

Regional aircraft have values of energy usage on the order of 1.5 to 2 times greater than larger aircraft. The difference in E_U is not caused by significant differences in technological sophistication, but rather by operational differences. Regional aircraft fly shorter stage lengths and therefore spend a disproportionate amount of time on the ground taxing and maneuvering compared to large aircraft. In addition, regional aircraft spend a larger fraction of airborne time climbing to altitude at inherently higher rates of fuel burn. In this respect, TP's are at an advantage compared to RJ's because they are designed to cruise efficiently several thousand feet below jet aircraft and can therefore reach cruising altitude and speed in less time than RJ's.

The cost drivers for technology development and implementation for regional aircraft were also investigated. Fuel costs currently make up 26% of the DOC of large aircraft compared to 20% for regional jets and 13% for turboprops. Technologically advanced RJ's can compete in terms of direct operating cost with all but the most efficient TP's, despite being less fuel-efficient. This occurs because fuel costs have less of an impact on the operating costs of regional aircraft compared to large aircraft. In addition, RJ's have historically operated at load factors approximately 10% to 30% higher than turboprops. As a result, the E_I of the RJ fleet has been comparable to or better than the E_I of the TP fleet.

REFERENCES

ATA, Air Transport Association, 2000. *2000 Annual Report*. Air Transport Association of America, Washington, D.C.

Airbus, Airbus Industrie, 2000. *Airbus Global Market Forecast 2000-2019.* Airbus, Blagnac, France.

Anderson, J. D., 1989. *Introduction to Flight*. Third Edition. McGraw-Hill, New York, New York.

ADL, Arthur D. Little, Ltd. 2000. *Study into the potential impact of changes in technology on the development of air transport in the UK*. Final Report to Department of Environment, Transport and Regions (DETR). ADL, Cambridge, U.K.

ATR, Avions de Transport Regional, 2002. ATR—Versatility to Suit Regional Operation. ATR, Balgnac, France.

Back Aviation Solutions, 2001. *Back Fleet Database v.4.0*. Back Associates, New Haven, Connecticut.

Balashov, B., Smith, A., 1992. ICAO analyses trends in the fuel consumption by world's airlines. ICAO Journal 47(6), 18-21.

Boeing, The Boeing Company, 2000. *Boeing Market Outlook 2000*. Boeing, Seattle, Washington.

Dobbie, L., 1999. Airlines see direct link between improved environmental performance, sustainable growth. ICAO Journal 54(7), 15-17, 29.

Dresner, R.W., 2002. Regional Jet Services: Supply and Demand, Journal of Air Transport Management, In press.

Eurocontrol, 2000. *Base of Aircraft Data R.3.3*. Eurocontrol Experimental Centre, Bretigny, France.

FAA, Federal Aviation Administration, 2001. *FAA Aerospace Forecast Fiscal Years 2001-2012*. FAA, Washington, D.C.

FAA, Federal Aviation Administration, 2000a. *FAA Aerospace Forecast Fiscal Years 2000-*

2011. FAA, Washington, D.C.

FAA, Federal Aviation Administration, 2000b. *2000 Aviation Capacity Enhancement Plan*. FAA, Washington, D.C.

Greene, D. L., 1995. Commercial air transport energy use and emissions: is technology enough? Presented at the Conference on Sustainable Transportation–Energy Strategies. Pacific Grove, California.

Gunston, B., ed, 1998. *Jane's Aero-Engines*. Jane's Information Group, Alexandria, Virginia.

IPCC, Intergovernmental Panel on Climate Change, 1999. *Aviation and the Global Atmosphere*. Cambridge University Press, Cambridge.

ICAO, International Civil Aviation Organization, 1995. *ICAO Engine Exhaust Emissions Data Bank*. First Edition. ICAO, Montreal.

JIG, Jane's Information Group, 2001. *Jane's All the World's Aircraft*. Samson Low, Martin & Co., New York, New York.

Lee, J.J., Lukachko, S.P., Waitz, I.A., Schafer, A., 2001. Historical and future trends in aircraft performance, cost and emissions. Annual Review of Energy and the Environment 26, 167-200.

Lee, J.J., 2000. *Historical and future trends in aircraft performance, cost and emissions*. MS Thesis. Massachusetts Institute of Technology, Cambridge.

Ojha, S. K., 1995. *Flight Performance of Aircraft*. \AIAA. Washington, D.C.

RAA, Regional Aircraft Association, 2001, www.raa.org.

Thomas, A., Richards, J., 1995. *The Airliner Price Guide of Commercial, Regional & Commuter Aircraft*. Fall Edition. Airliner Price Guide, Oklahoma City, OK.

Trigerio, W., 1999. *The impact of regional jets on congestion in the NAS*. The MITRE Corporation. McLean, Virginia.

DOC, U.S. Department of Commerce, Bureau of Economic Analysis, 2001. *National Income and Product Accounts Tables*. DOC, Washington, D.C.

DOT, U.S. Department of Transportation, Bureau of Transportation Statistics,, 2001. *Form 41 Schedule P5.2 and T2, 1968-1999*. DOT, Washington, D.C.