THE HISTORICAL FUEL EFFICIENCY CHARACTERISTICS OF REGIONAL AIRCRAFT FROM TECHNOLOGICAL, OPERATIONAL, AND COST PERSPECTIVES

by

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ABSTRACT

The air transport industry has grown at an average annual rate of 9% worldwide since 1960 and is expected to experience 5% annual growth worldwide for the foreseeable future. Recently, this rapid growth has fueled concern about the contribution of aviation activities to global climate change. Governments, airlines and manufacturers are currently debating the feasibility and effectiveness of various strategies aimed at mitigating the environmental impact of aircraft emissions. Policy responses including the implementation of taxes, emissions trading schemes, environmental charges and voluntary agreements between airlines and governments are all being considered.

In order to design effective approaches towards emissions reduction, there is a need to understand the mechanisms that have enabled historical improvements in aircraft efficiency. This thesis focuses on the impact regional aircraft have had on the efficiency of the U.S. aviation system, and examines how the technological, operational and cost characteristics of turboprop and regional jet aircraft have influenced the fuel efficiency of the regional aircraft fleet. These characteristics have been compared to larger narrow and wide body aircraft, providing two different perspectives on technology evolution, airline operations and the impact of costs on both.

Regional aircraft are playing an increasingly important role in the evolution of U.S. airline operations. In particular, the widespread adoption of the regional jet is transforming the aviation landscape by expanding hub operations, replacing larger jets in low-density markets, replacing turboprops in short-haul markets, and opening up new hub-bypass routes. The impact of this transformation on congestion and aircraft emission issues is not yet obvious, but there is potential to exacerbate existing problems. Regional aircraft consume more fuel per unit of passenger travel than larger aircraft and they take up considerable space at already congested airports. Although they currently perform just under 4% of domestic revenue passenger miles in the U.S., they account for almost 7% of jet fuel use by U.S. airlines, and for 40% to 50% of departures at U.S. airports. In addition, regional traffic is expected to grow 7% to 8% annually in the U.S. during the next decade compared to 4%-6% for the major U.S. commercial airlines.

Comparisons show that regional aircraft are 40%-60% less fuel efficient than their larger counterparts, while regional jets are 10%-60% less fuel efficient than turboprops. It is revealed that fuel efficiency differences can largely be explained by distinctions in aircraft operations. Aircraft flying short stage lengths spend approximately 15% more time on the ground for each hour spent in the air than longer flying aircraft, therefore consuming more fuel while taxing and maneuvering at airports. They also spend between 20% and 60% of their airborne time climbing to altitude, at

associated high levels of fuel consumption, compared to approximately 10% for large aircraft. In this respect, turboprops are shown to be more efficient than regional jets because they are designed to fly at lower altitudes. As a result of these operational differences between aircraft types, large aircraft realize total energy efficiencies much closer to their optimum rate of efficiency achieved during cruise flight than regional aircraft. The total rate of fuel consumption of regional aircraft was found to be 2.7 times higher than rate of fuel consumption achieved during cruise flight. For large aircraft, the total rate of fuel consumption was only 1.6 times higher than at cruise. A similar comparison of regional aircraft revealed that the total fuel consumption of regional jets was on average more than 3.5 times as high as that achieved at cruise, while for turboprops this figure was closer to 2.3 times as high. It is also shown that regional airlines have been able to operate regional jets at higher load factors than turboprops, such that the energy consumed per unit of passenger travel for regional jets and turboprops has been comparable, even though turboprops have higher fuel efficiencies.

The economic characteristics of regional aircraft were also examined. Direct operating costs per RPM are shown to be 2½-6 times higher for regional aircraft because they perform fewer miles over which to spread fixed costs incurred every time an aircraft performs a flight, regardless of distance flown. The higher operating costs of regional aircraft are consistent with the yields of regional airlines, which in 1999 were on average 2½ times higher than those of large airlines.

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Finally, this thesis is dedicated to my mother, who, despite my best efforts, wanted to make something out of me. Her love and dedication can never be repaid.

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NOMENCLATURE

ACRONYMS:

ASK	Available Seat Kilometer
ASM	Available Seat Mile
BADA	Base of Aircraft Data
CAEP	Committee on Aviation Environmental Protection
CFRP	Carbon Fibre Reinforced Plastic
CICA	Convention of International Civil Aviation
DOT	U.S. Department of Transportation
EPA	Environmental Protection Agency
F41	U.S. Department of Transportation Form 41
FAA	Federal Aviation Administration
GDP	Gross Domestic Product
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
LTO	Landing and Take-Off
MTOW	Maximum Take-Off Weight
OEW	Operating Empty Weight
PM	Particulate Matter
PSFC	Power Specific Fuel Consumption
RPK	Revenue Passenger Kilometer
RPM	Revenue Passenger Mile
SAR	Specific Air Range
TSFC	Thrust Specific Fuel Consumption
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile Organic Compound
YOI	Year of Introduction

ROMAN:

DOC	Direct Operating Cost
C_D	Drag Coefficient
C_{Do}	Parasitic Drag Coefficient
E_I	Energy Intensity (gal/RPM)
E_U	Energy Usage (gal/ASM)
$E_{U,CR}$	Cruise Values of Energy Usage
g	Gravity Constant
Gal	Gallons of Fuel
I	Investment Cost
K	Induced Drag Coefficient
L/D	Lift over Drag Ratio
T/W_E	Thrust-to-Engine Weight Ratio
W	Weight

GREEK:

α	Load Factor
η_g	Ground-Time Efficiency
η_a	Airborne Efficiency
η_{PR}	Propeller Efficiency

1 INTRODUCTION

1.1 BACKGROUND

The rapid growth of worldwide air travel has prompted concern about the influence of aviation activities on the environment. While local air quality and noise issues have always provided a motivation to mitigate the environmental impact of aircraft operations, attention has recently focused on the release of gases and particulates from gas turbine engines into the upper atmosphere. Commercial aircraft emit greenhouse gases such as carbon dioxide (CO_2), water vapor (H_20), nitrogen oxides (NO_X), sulfur oxides (SO_X) and soot, and have the potential to change natural concentrations of atmospheric gases. A recent scientific assessment published by the International Panel on Climate Change (IPCC) attributes 3.5% of the total radiative forcing[1] of all human activities to aviation, and further states that the radiative forcing of aviation's fuel use is two to four times higher than for CO_2 alone. In contrast, the forcing of all human activities is 1.5 times higher than CO_2 alone, suggesting that the impact of aircraft emissions at altitude is potentially more severe with respect to climate change than those occurring at ground level.

Demand for air travel, meanwhile, has grown at an average annual rate of 4.5% in the last decade and at approximately 9% annually since 1960 [1][2]. Barring any serious economic downturn or significant policy changes, various organizations have estimated future worldwide growth to average 5% annually at least through 2015 [1][3][4]. The U.S. air transport industry, which accounts for approximately 24%-26% of the total world market [2][4], is similarly expected to maintain a high rate of expansion: domestic and international revenue passenger miles (RPMs) in the US are forecast to grow at annual rates of 4% and 6% respectively throughout the next decade [2].

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[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.

Growing awareness of the influence of aviation activities on climate change and rapid industry growth has put increasing scrutiny on the amount of energy consumed by aviation, which is directly proportional to emissions of greenhouse gases. Aviation is consuming an ever-greater share of the fuel supplied to the transportation sector. In 1970, aviation gasoline and jet fuel comprised approximately 11% of the fuel consumption of the U.S. transportation sector. This figure had risen to 14% by 1980, and was estimated to be at 19% by 1999 [5]. As with all modes of transportation, improvements in the energy efficiency, or energy usage (E_U) have failed to keep pace with the industry's growth, resulting in a net increase in fuel use and greenhouse gas emissions. E_U is measured in gallons of fuel used per available seat mile (ASM) traveled, and is a metric of the energy consumed to perform a potential unit of output.

Governments, airlines and manufacturers are currently debating the possibility of future limits on aircraft emissions and the effectiveness of various emission-reduction strategies. The International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) is studying the possible modification of ICAO emission standards to encompass climb and cruise phases of flight in addition to landing and take-off (LTO) cycles, a change that will have a direct bearing on CO_2 emissions [6]. Other policy options, including the implementation of taxes, emissions trading schemes, environmental charges and voluntary agreements are all being considered. Aircraft manufacturers and airlines are also responding to environmental concerns. According to Airbus, the A380 will be the first Airbus program to actively consider the environment as part of its design criteria [7]. Furthermore, one major airline alliance has recently delivered a joint environmental agreement in which all alliance partners have committed to a common environmental policy [8].

Within this context of industry growth and environmental concern, regional aircraft are playing an increasingly important role in the evolution of US airline operations. In particular, the widespread adoption of the regional jet is transforming the aviation landscape by expanding hub operations, replacing larger jets in low-density markets, and permitting new hub-bypass operations. In addition, regional traffic grew 19.7% in 1999 in the U.S. and is expected to grow 7.4% annually during the next decade, compared to 4%-6% for the major U.S. airlines [2]. The impact of this simultaneous growth and transformation on aircraft emission issues is not yet obvious, but there is potential to exacerbate existing problems. Although regional aircraft currently perform just under 4% of domestic revenue passenger miles [2], they account for almost 7% of jet fuel use and for 40%-50% of total departures [9][10]. Their share of aviation's energy consumption is disproportionately higher than the traffic they carry, and they take-up considerable space at capacity-constrained airports. There is a need to understand the efficiency characteristics of regional aircraft, how they compare to larger jets, and how they influence the aviation system a whole. Future regulations or agreements aimed at minimizing or reducing the impact of the regional industry and that of the entire air transportation system on the environment will have to be formulated bearing in mind the sources of historical gains in aircraft and operations efficiency.

1.2 THESIS OVERVIEW

The goal of this thesis is to identify the mechanisms that have enabled historical reductions in the energy intensity of regional aircraft by quantitatively describing the technological, operational and cost characteristics of regional aircraft. It also seeks to compare these characteristics to those of larger narrow and wide body aircraft, providing alternative perspectives from which to analyze technology evolution, airline operations and the impact of costs on both. In addition, this thesis attempts to provide insight into the potential impact of the rapid growth of regional jet use on the energy efficiency of the US aviation system.

The thesis is organized into six chapters. Chapter 2 gives an overview of the data used throughout this study, highlighting where its suitability and its limitations. Chapter 3 reviews the various impacts of aviation activities on the environment, and discusses the growth being experienced by the industry. In particular, emphasis is placed on the how regional aviation is changing and the contribution of the regional jet. Improvements in the energy intensities of regional and large aircraft are then presented, establishing a framework from which to understand the impact of technology, operations and cost on fuel efficiency. Chapter 4 examines historical trends in regional aircraft technology, and compares them to that of larger aircraft. In addition, the influence of aircraft operations on fuel efficiency is quantified. Chapter 5 identifies the cost characteristics of regional aircraft and compares them to larger aircraft. The impact of these characteristics on fuel efficiency is discussed. Finally, Chapter 6 summarizes the important findings of this thesis and the potential implications of its conclusions on the environmental performance of aviation.

2 AIRCRAFT AND DATA

2.1 INTRODUCTION

This chapter reviews the sources and organization of the data used to analyze the performance, fuel efficiency and financial characteristics of regional aircraft. The aircraft selected for study are identified, and the methodology used to select them is explained. Limitations inherent to the data are also discussed.

2.2 THE INTEGRATED AIRCRAFT TECHNOLOGY AND OPERATIONS DATABASE

2.2.1 DATABASE COMPONENTS

Aircraft characteristics and airline traffic and financial statistics were integrated into a single relational database in Microsoft® Access to facilitate analysis requiring information from different sources. Figure 2-1 shows the major components of the database, and illustrates how they are connected.

Airline traffic and financial statistics were obtained from the U.S. Department of Transportation's (DOT) Form 41 (F41) records [11]. Airlines operating aircraft with sixty or more seats are required to file a F41 report each quarter. Traffic statistics are reported on F41 Schedule T2 on a per year, per quarter, per airline, per aircraft type basis and are therefore aggregate figures for a given aircraft type operated by a single airline. The subset of traffic statistics included in the integrated database is shown in Appendix A. Financial statistics are taken from F41 Schedule P5.2, which only contains information on aircraft operating expenses. Unlike F41 Schedule T2, information on schedule P5.2 is categorized on a per year, per quarter, per airline, per aircraft type, per account basis, where each account is a specific cost category. As a result, there are several Schedule P5.2 records for each Schedule T2 record submitted by an airline. The accounts recorded in schedule P5.2 are listed in

Appendix A. Different schedules contain other relevant airline financial figures, including balance sheets and profit and loss statements, but these are not included in the integrated database.

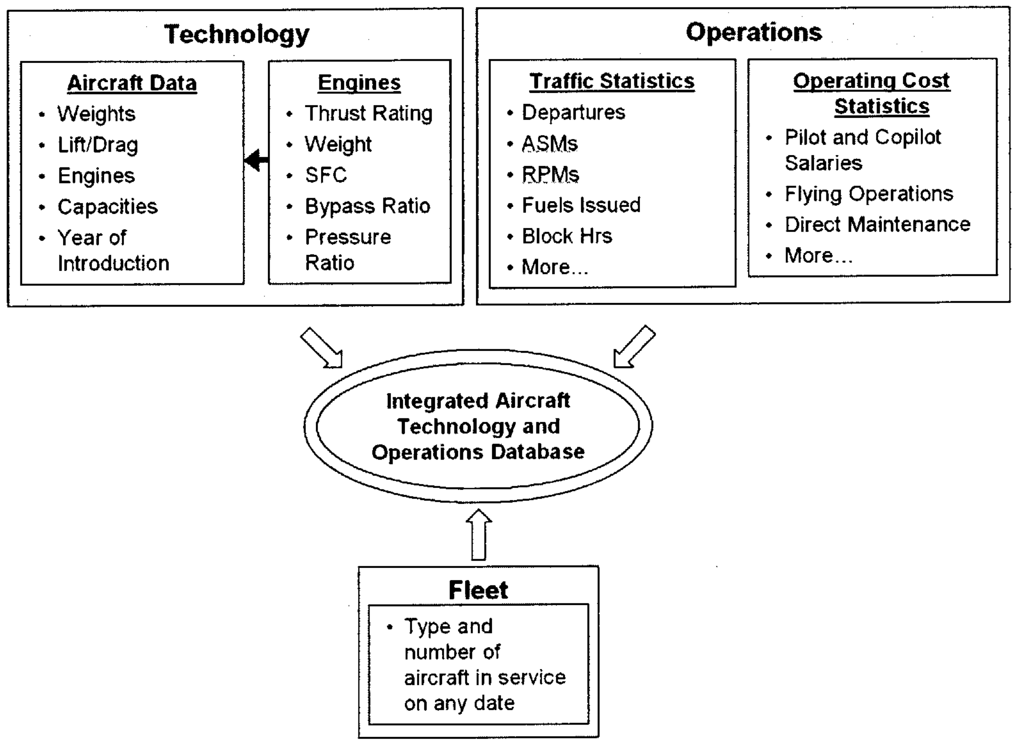


Figure 2-1 Integrated database components

A database of aircraft and engine technical characteristics initially compiled in [12] for thirty-one of the most important narrow and wide body aircraft flown since 1960 was further enhanced for this thesis with the addition of thirty-three regional aircraft and regional aircraft engines. Included in the technical characteristics for aircraft are various weights, seating capacity and lift-over-drag ratio (L/D). With the exception of L/D ratios, aircraft specifications were obtained from [13] and [14]. Some L/D values were obtained directly from manufacturers, but most were taken from a database maintained by Eurocontrol, the European Organization for the Safety of Air Navigation [15]. This database, known as "The Base of Aircraft Data" (BADA), is used by Eurocontrol for trajectory simulation and prediction. It contains performance and operating procedures for 186 different aircraft types.

Basic aircraft engine performance and technical parameters detailed in [16][17][14] are also maintained in the database. This includes weight information, take-off and cruise values of specific fuel consumption, year of certification, and thrust rating. When possible, engine characteristics were obtained directly from manufacturers.

Finally, the above databases were supplemented by a database of the historical fleets of all the world's airlines [18]. This database was purchased from a commercial organization. It served to complement incomplete traffic data.

2.2.2 DATABASE LIMITATIONS

The data available in F41 is extensive, but it also has limitations with respect to regional aircraft performance analysis. For example, aircraft type distinctions are made according to categories outlined in DOT Form 41 Schedule F2. The categorization follows an inconsistent pattern, sometimes defining several aircraft derivatives as a single aircraft type, or sometimes assigning a new type to each derivative. For example, airlines are required to report the Beech 1900C and Beech 1900D models under the same code, although the derivatives are seven years apart and may exhibit different performance characteristics. On the other hand, the Canadair RJ-100 and RJ-200, introduced only 3 years apart and nearly identical in performance each have their own code. There are many other similar cases. As a consequence, calculations of performance parameters made using F41 data may be averaged over several derivatives of an aircraft type.

Another limitation of F41 data is that it contains limited information on smaller aircraft types. Many regional airlines are not required to report on F41 because they do not operate aircraft with more than sixty seats. For example, Comair, the largest regional jet operator in the world, does not report on F41 despite being the third largest regional airline in the U.S. [10]. Instead, these airlines report on U.S. DOT Form 298-C, which has much less detailed reporting requirements. The information contained on Form 298-C is inadequate for the various analyses performed in this thesis.

As a result of the reporting requirements, F41 does not have continuous nor complete statistics on regional aircraft. For example, the total revenue passenger miles (RPMs) performed by a selected aircraft type in a given year is not accurately reflected in F41 traffic data because not all the airlines operating that aircraft type are required to report. Data that is available on F41 has been used to provide averages of point-in-time unit traffic and financial statistics. For example, fuel efficiency calculations are performed on a gallons of fuel per available seat mile basis (gal/ASM). Such averages are assumed to be representative of the characteristics of all the aircraft of that type in service, including those not reported on F41.

In cases where annual fleet-wide averages were required, unit traffic or financial statistics for each aircraft were used in combination with a weighting factor based on the number of aircraft in service. The general formula used for calculating averages is shown in Equation 2-1.The number of aircraft in service in a given year, differentiated by aircraft type, was obtained from the fleet database.

$$A_Y = \sum_{i}^{N} W_{Y,i} \cdot A_{Y,i} \tag{2-1}$$

Where: A_Y = Fleet averaged statistic in year Y

N = Total number of aircraft types

$W_{Y,i}$ = Weighting factor for aircraft i in year Y = $W_{Y,i} = \dfrac{n_{Y,i}}{\sum_{j}^{N} n_{Y,j}}$

$n_{Y,i}$ = Number of i-type aircraft in year Y (from fleet database)

$A_{Y,i}$ = Averaged statistic for aircraft i in year Y (from F41 data)

2.3 AIRCRAFT SELECTION

The technological, operational and cost characteristics of two major groupings of aircraft were studied in this thesis. Regional aircraft are the focus of the thesis, and they are defined here as aircraft that typically serve 100-600 mile stage lengths with more than 19 but fewer than 100 seats. Regional aircraft can be broken down further according to propulsion system type. Turboprop aircraft, or more simply turboprops, are airplanes powered by gas turbine engines that derive most of their thrust from a propeller. Regional jets, as the name implies, are powered by jet engines. It should be noted that the term regional jet has recently become almost exclusively associated with the new generation of 30-70 seat jets such as the Bombardier CRJ-200 and Embraer EMB-145. However, a more general interpretation of the term is used herein to refer to any jet-powered aircraft with fewer than 100 seats and serving short-haul markets.

Regional aircraft studied in this thesis were selected according to information available in F41 statistics as well as a subjective review of what might be considered important regional aircraft. A list was generated from F41 traffic statistics summing up the total RPMs performed by individual aircraft types since 1968, sorted in descending order. The top thirty aircraft that met the "regional" criteria outlined above were selected for analysis. It was recognized that more recently introduced aircraft would be at a relative disadvantage using this approach. The list was therefore scanned for records below the top thirty for aircraft that met the criteria but had been introduced within the last ten years.

Three aircraft, the AVRO RJ85, the DHC-8-300 and the Dornier 328 were thus added to the group of regional aircraft studied.

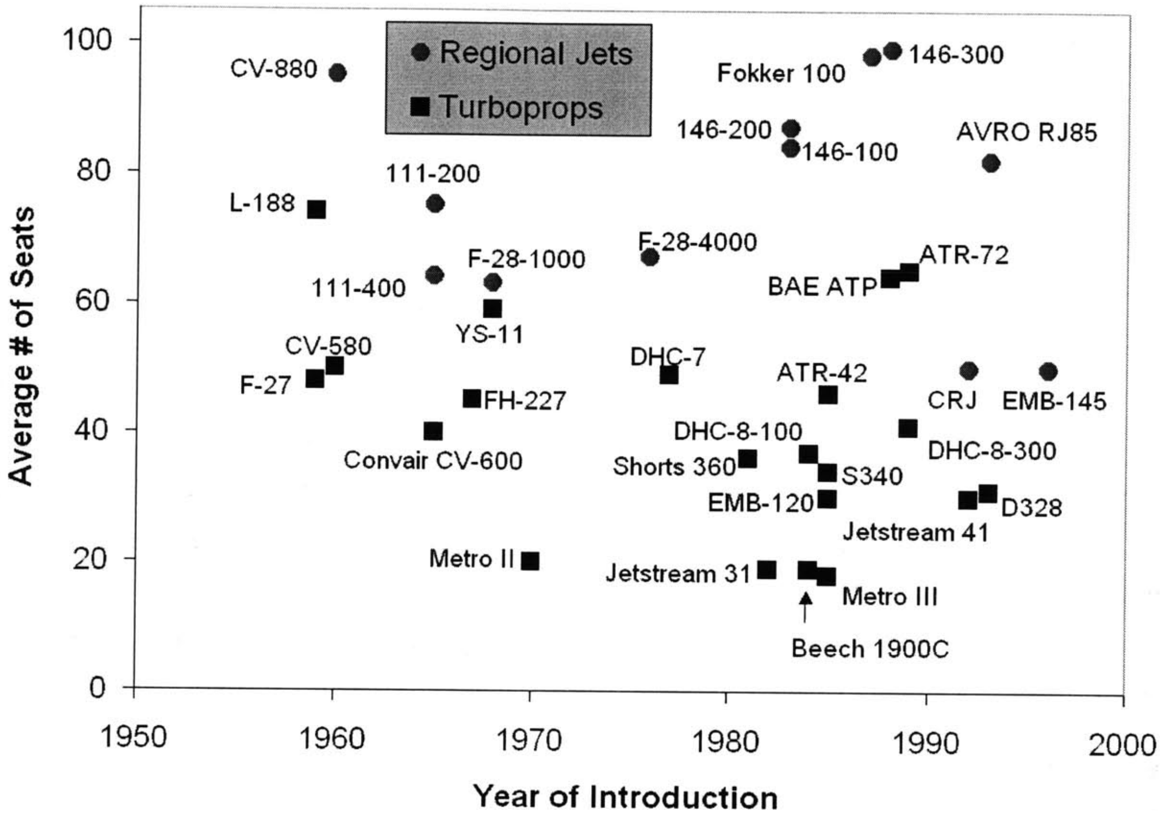


Figure 2-2 Capacities of selected regional jets.

The thirty-three regional aircraft selected for study are plotted in Figure 2-2 according to their capacities and year of introduction. A full list of the regional aircraft selected is provided in Appendix B, along with the matching engine combinations. Matching engine combinations were found in [13]. Note that, in general, regional jets have been traditionally larger than turboprop aircraft. The average capacity of the regional jets selected is 76 seats, while that of the turboprops is 40.

Aircraft referred to as *large* aircraft in this thesis consist of a group of thirty-one of the most widely used narrow and wide body jet powered aircraft. The aircraft included in this group are listed in Appendix B. These aircraft were studied in [12], and their technological, operational and cost characteristics are used for comparison purposes throughout this thesis. They range in size from 100 to 400+ seats.

3 THE ENVIRONMENTAL IMPACT AND ENERGY USAGE OF REGIONAL AIRCRAFT

3.1 INTRODUCTION

This chapter describes how aircraft and aviation activities effect the environment and details the rapid growth of regional aviation in the US. Furthermore, the implications of the transformation of the regional airline industry from one dominated by small turboprop aircraft to one using increasingly sophisticated regional jets are identified. Finally, historical changes in the energy intensity of regional aircraft are quantified, establishing a framework from which to examine the influence of technology, operations and cost on fuel efficiency.

3.2 AVIATION AND THE ENVIRONMENT

Aviation activities influence the environment in a variety of ways. These can be classified into local and global effects, the former encompassing local air quality concerns and noise, and the latter the release of gases and particulates into the upper atmosphere.

The local impact of aviation is generally limited to the vicinity of airports, and has historically attracted the greatest public and government attention. The issues that have been raised include air quality, noise from take-offs and landings, contamination of water supplies, and land-use, among others [19]. Local air quality and noise are the most serious of these concerns. Aircraft emit five major pollutant species, including volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter (PM) and sulfur dioxides. The emissions of VOCs and CO are highest when engines operate at low power, such as during taxi and idling. NO_X emissions, on the other hand, increase with power level and are highest during take-off and climb-out [20]. The

Environmental Protection Agency (EPA) reports that aircraft are responsible for about one percent of the total US ground-level emissions from mobile sources, and it estimates that the aircraft component of total emissions in the regions of 10 major US airports will increase from an average 0.37% to 1.33% for VOC, 1.06% to 3.63% for NO_X, and 0.16% to 0.58% for SO_2 between 1990 and 2010 [20]. Noise emanating from aircraft impacts airport surroundings and operations in many ways. It can depress property values, prevent airport expansion, and limit the time and frequency of aircraft operations.

Attention has recently focused on the potential of aircraft emissions to contribute to climate change. Aircraft engines emit several gases into the upper troposphere and lower stratosphere, including carbon dioxide (CO_2), water vapor, NO_X, SO_X, water vapor, and various hydrocarbons. Most subsonic commercial aircraft travel in the troposphere, while supersonic aircraft typically cruise in the lower stratosphere. In general, aircraft emissions can alter the climate by changing the amount of energy either reaching or leaving the surface of the earth. Many aircraft emissions are greenhouse gases in themselves, capable of trapping energy in the atmosphere, while others alter atmospheric concentrations of aerosols and other greenhouse gases. In any case, the impact of these emissions is widespread, sometimes contradictory, and not always well understood, but their combined effect is believed to be a net warming of the earth.

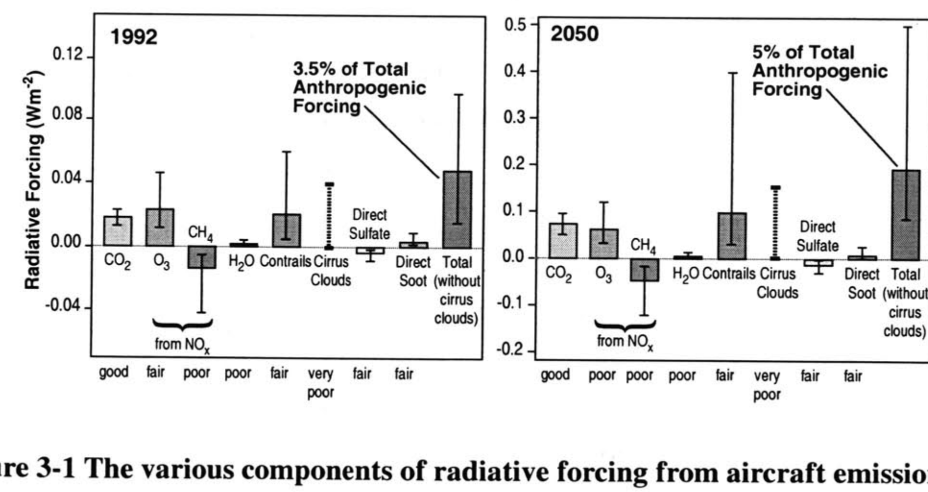


Figure 3-1 The various components of radiative forcing from aircraft emissions [1]

A useful measure for evaluating the influence of emissions on the atmosphere is the concept of radiative forcing, which 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, while negative values imply cooling. The estimated radiative forcing for various aircraft related emissions is shown in Figure 3-1 for 1992 and 2050. Note that the level of scientific understanding of each component is described at the bottom of the figure. The best estimate for the total radiative forcing of aviation activities in 1992 was 0.05 Wm^{-2}, or 3.5% of the total radiative forcing from all anthropogenic activities. This is expected to increase to between 0.13 Wm^{-2} and 0.56 Wm^{-2} by 2050 [1]. Furthermore, aviation-related radiative forcing is two to four times higher than for CO_2 alone. In contrast, the forcing of all human activities is 1.5 times higher than CO_2 alone, suggesting that the impact of aviation emissions at altitude are more severe than those emitted at the surface of the earth.

Carbon dioxide is a greenhouse gas and is an unavoidable by-product of combustion produced in direct proportion to the amount of fuel burned. Its effect on climate change depends on its atmospheric concentration. In the upper atmosphere, CO_2 has the effect of absorbing infrared radiation emitted by the earth and the lower atmosphere, resulting in a net warming of the troposphere and cooling of the stratosphere. Aircraft accounted for approximately 2% the total anthropogenic emissions of CO_2 in 1992 [1]. Water vapor emitted by aircraft engines into the atmosphere is small relative to the natural amounts already present, but contributes to global warming by changing the radiative effects of clouds, altering atmospheric chemistry and contributing to contrail formation. Contrails are visible line clouds that form behind aircraft as the result of condensation and tend to warm the surface of the earth much like a thin high cloud. Contrail coverage is forecast to increase from 0.1%-0.5% by 2050 [1]. Furthermore, cirrus clouds, which on average tend to warm the earth, have been observed to develop after the formation of persistent contrails [1]. At cruise altitudes, aircraft NO_X emissions perturb the complex chemical reactions of the atmosphere, generally contributing to the formation of ozone, a greenhouse gas. On the other hand, NO_X emissions are known to decrease atmospheric concentrations of methane (CH_4), another greenhouse gas, partially offsetting the warming effect of the increased ozone [1]. Finally, aircraft engines also emit various particles that can similarly contribute to climate change. These particles evolve in the engine and in the atmosphere to form various particles mainly composed of soot and sulfuric acid (H_2SO_4) from the sulfur found in aviation fuels. These particles play a role in determining the radiative properties of contrails [1].

The local and global impact of aviation on the environment has elicited various regulatory responses from governments and industry stakeholders. At the international level, ICAO has established as standards in Annex 16 to the Convention of International Civil Aviation (CICA) limits on fuel venting and the emissions of smoke, hydrocarbons (HC), CO, and NO_X from various sized engines based on a landing and take-off cycle extending no higher than 3000 ft. Regulations pertaining to noise have also been implemented throughout the world under the coordination of the ICAO CAEP.

In the U.S., the EPA is responsible for setting aircraft emission standards while the Federal Aviation Administration (FAA) is charged with ensuring compliance. Current regulations, codified in [22], are similar to the standards established by ICOA. The Airport Noise and Capacity Act of 1990 mandated, with few exceptions, that all aircraft above 75,000 lbs operating in the United States comply with Stage 3 noise limits by January 1st, 2000. As result of these efforts, the FAA estimates that the number of people significantly affected by aircraft noise was 600,000 in 2000, compared with seven million in 1975 [8].

Aircraft emissions during climb and cruise have lacked any regulatory control. In light of the Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCC) of 1997 mandating industrialized countries to reduce their collective emissions of greenhouse gases by approximately 5% by 2008-2012 compared to 1990, governments and industry stakeholders are seeking ways to control aviation's fuel consumption. In particular, CAEP is carrying out an assessment to consider the suitability of modifying ICAO standards to address emission of greenhouse gases [6]. Various regulatory measures are being considered to promote the development and adoption of new, fuel-efficient technology as well as the implementation of efficient operational procedures. Options considered include imposing taxes on emissions and emission trading schemes.

3.3 THE GROWTH OF REGIONAL AIR TRAVEL

At the same time that the global impact of aviation is becoming a concern, regional aircraft are becoming a more important part of the US aviation system. Stimulated by the deregulation of the industry initiated in 1978, the overall growth in air traffic, and more recently by the widespread adoption of a new generation of 30 to 70 seat regional jets, traffic carried by regional aircraft is expected to grow at a faster rate than the traffic of the major US airlines.

World traffic is expected to grow approximately 4%-6% annually at least over the next 20 years, and has grown at approximately 9% per year since 1960 [1]. Future demand will continue be driven by worldwide economic expansion, but will also be stimulated by lower fares, more services, and growing international trade [1].

In the US, passenger traffic on domestic airlines has grown nearly fivefold since 1970, as shown in Figure 3-2. The success of the industry has been spurred by the increased competition introduced by the Airline Deregulation Act of 1978, which phased out the role of the Civil Aeronautics Board in determining routes and fares. Deregulation permitted airlines to provide service wherever and whenever they felt demand would allow without the need for regulatory approval. As a result, competition among airlines intensified, productivity throughout the industry increased and most markets benefited from lower fares and better service [23].

After deregulation, the airlines shifted dramatically from offering mostly point-to-point services to operating hub-and-spoke systems. Under the hub-and-spoke model, airlines maintain a "hub" airport where groups of flights, referred to as "banks," all arrive within a specified interval of time, allowing travelers to connect to other flights leaving shortly thereafter. Benefits include offering travelers from small, "spoke" cities access to hundreds of destinations through the hub, while allowing the airlines to benefit from economies of traffic density achieved through connecting passengers.

The widespread adoption of the hub-and-spoke concept was a boon for regional aviation in the US and increased the role of regional aircraft. As major airlines sought to maximize the traffic passing through their hubs, they increased the number of spoke destinations served and boosted frequencies of service. In many cases, unprofitable, low-density short and medium-haul routes were passed-on from the major airlines to regional airlines flying much smaller turboprop aircraft [23]. During this period,

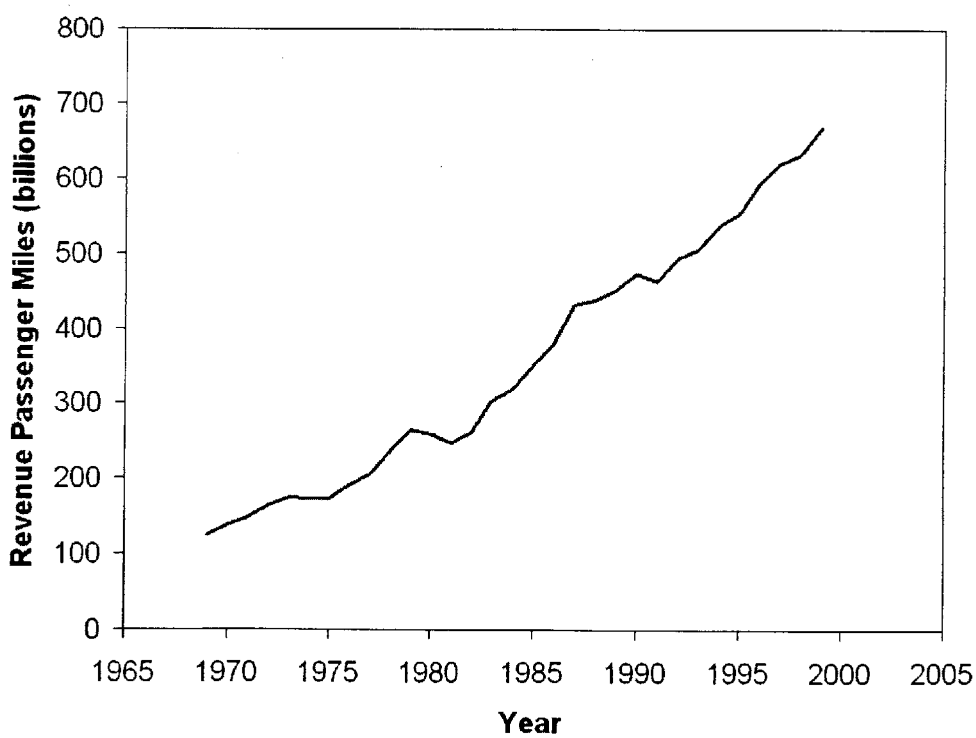


Figure 3-2 The growth of passenger travel in the US

most regional airlines either partnered with major carriers through code-share agreements or were acquired by them. A code-share agreement is an arrangement whereby airlines can carry one another's passengers on specific flights and routes. In 1999, 97% of regional airline passengers flew airlines with code-share agreements with the larger carriers [10].

The increased integration with major airlines resulted in tremendous growth for the regional airline industry. Table 3-1 compares the growth of the regional carriers with that of the major airlines. In 1999 alone, regional airline traffic grew by 19.7% compared with 4.6% for the larger carriers, and growth is expected to average 7.4% and 4.2% respectively through 2011 [2].

		Regional Airlines	Ten Major Airlines
Revenue Passenger Miles (Billions)	1978	1.28	143.9
	1999	20.8	593.1
	Average Annual Growth	14.2%	6.9%
Aircraft in Service	1978	1,047	1206
	1999	2,187	3609
	Average Annual Growth	3.6%	5.4%

Table 3-1 The growth of regional airlines compared to the majors

Like deregulation, a new generation of regional jets is causing yet another transformation in the industry. Seating between 35 and 70 passengers, they are smaller than previously available jet-powered aircraft and were first introduced into the aviation landscape by the 50-seat Bombardier CRJ-100/200 in 1992. They have gained significant popularity amongst passengers and airlines alike because of their speed, comfort and perceived safety relative to turboprops [23][24][25].

The airlines are using regional jets to expand hub operations, replace turboprops, and offer new point-to-point flights. Their most common applications are shown diagrammatically in Figure 3-3. In most cases, regional jets are being used to feed airline hubs by complementing or replacing turboprops on existing routes. The range of the new jets is also permitting the development of feeder routes to low-density markets that are beyond the range of turboprops, as well as the replacement of larger jets on unprofitable routes. Finally, in what is being called "hub-bypass" operations, regional jets are being flown directly from one spoke of the network to another, saving time for travelers and decreasing congestions at the hub [24]. Despite the potential for hub-bypass operations and other new point-to-point flights, 91% of current regional jet operations are focused on the hub [25]. However, there is reason to believe that point-to-point markets will offer future avenues of growth for regional airlines. If low cost carriers such as Southwest can be profitable serving several point-to-point routes in larger, 130-seat, aircraft such as the Boeing 737, many other routes may exist that can be served by smaller 30-70 seat jets.

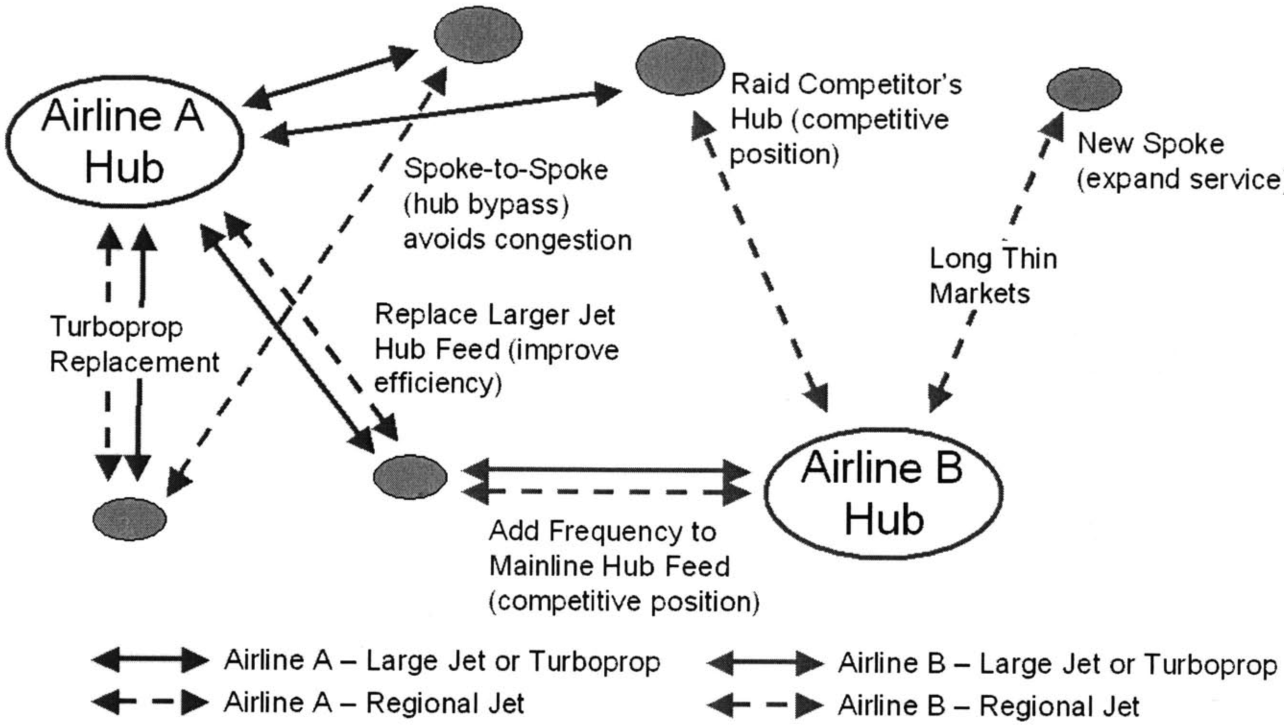


Figure 3-3 Common uses of the regional jet [24]

The popularity and utility of regional jets is gradually changing the US regional airline fleet. In 1996, jets made up only 2.7% of the fleet, but today that figure has risen to 15.3%. Furthermore, the FAA estimates that 1,200 regional jets will be delivered to US airlines by 2011 and will soon make up at least 50% of the fleet [2]. Figure 3-4 shows one industry estimate of the rise in prominence of regional jets in the U.S. passenger fleet [26]. As the role of regional jets expand, turboprops are losing their fleet share. Figure 3-5 shows the increase and decrease of weekly departures and city pairs served by regional jets and turboprops respectively.

The growth in regional traffic and the differences between regional jets and turboprops will help shape the future energy consumption of the US aviation system, and as a result, will play an important role in determining the future impact of aviation activities on the environment. As the fastest growing segment of the industry, regional aircraft will increasingly contribute to aviation emissions, and have the potential to decrease the efficiency of the aviation system by causing increased congestion and airports and in the airways. Governments and other industry stakeholders will have to consider the unique characteristics of regional aircraft and the operations of regional airlines before implementing any regulatory measures aimed at reducing the impact of aviation on the environment. The next section outlines the historical energy intensity characteristics of selected regional aircraft and of the regional airline fleet and serves as a basis for analyzing the contribution of technology, operations and cost to the evolution of efficiency.

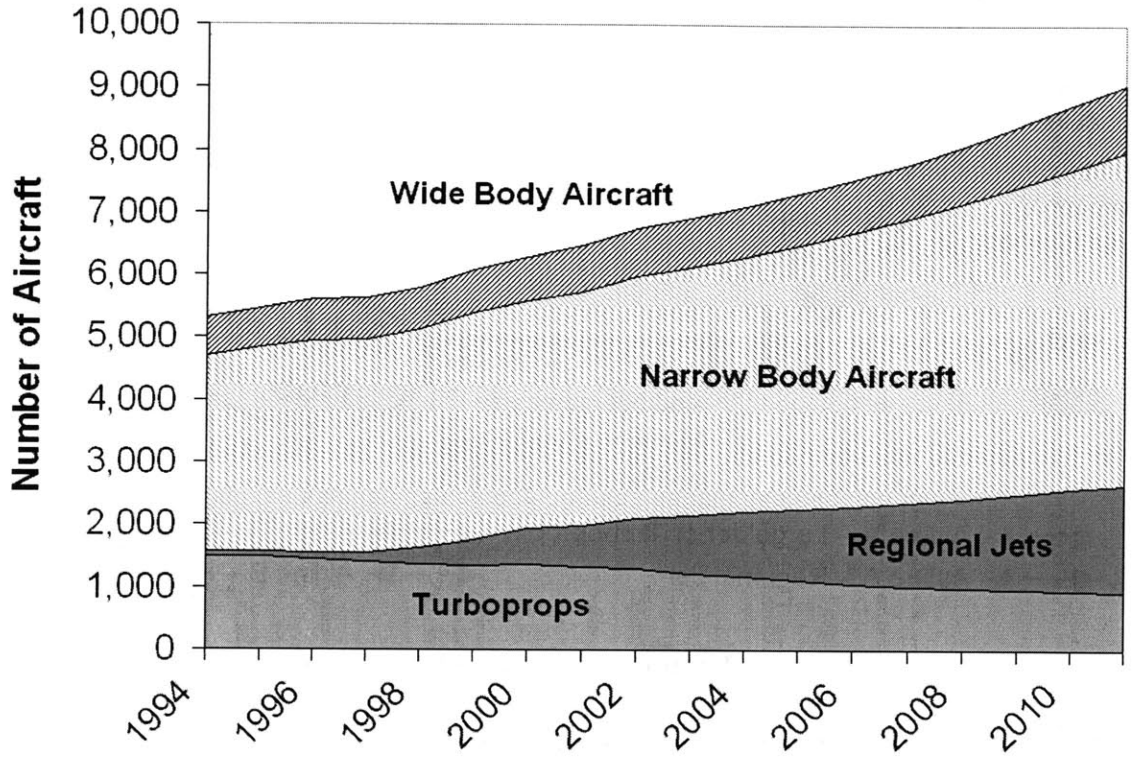


Figure 3-4 Future U.S. passenger fleet forecast [26]

3.4 THE ENERGY USAGE OF REGIONAL AIRCRAFT

The impact of aviation activities on the environment is correlated with the amount of aircraft emissions produced during various phases of flight. Most of these emissions, in turn, are proportional to the energy consumed by an aircraft. Therefore, the specific energy usage (E_U) and specific intensity (E_I) of aircraft, measured in gallons of fuel used per available seat mile (gal/ASM) and gallons of fuel used per revenue passenger mile (gal/RPM) respectively, serve as useful metrics for evaluating the performance of aviation systems with respect to environmental impact. The E_U indicates how much energy is required to perform a unit of potential output – moving a single seat one mile, and is therefore closely related to environmental performance of an aircraft system. The E_I, in comparison, is a measure of how much energy is required to perform a unit of actual output – moving a passenger a single mile, and therefore incorporates an additional efficiency related to how efficiently the aircraft

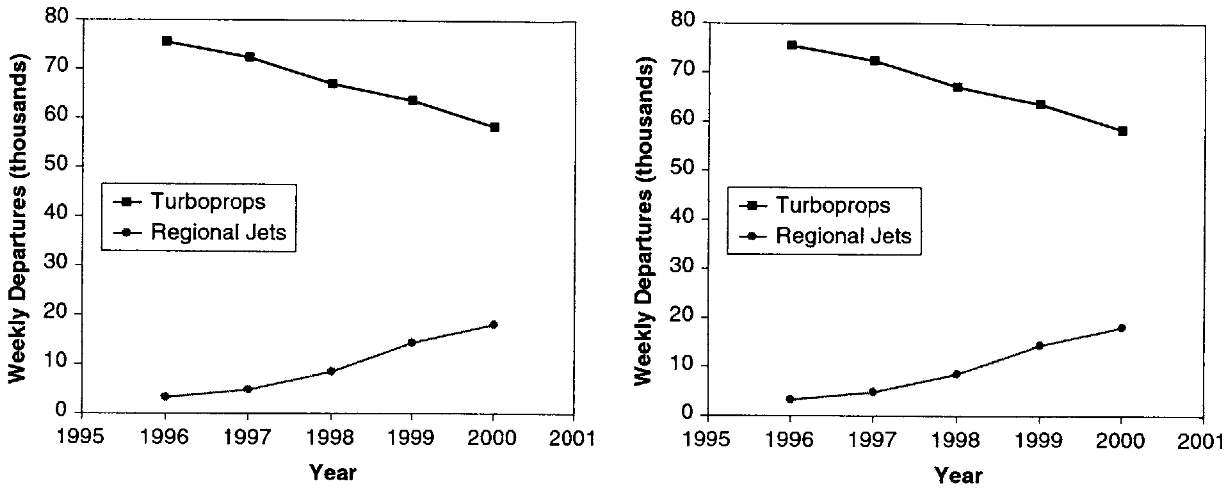


Figure 3-5 The increasing and decreasing popularity of the regional jet and turboprop

is being used. This additional efficiency is the load factor, and its impact on the fuel efficiency the aviation system is discussed in Section 4.4.

Energy usage varies greatly for different types of aircraft according to level of technological advancement, size, mission, propulsion system type and various operational efficiencies. Figure 3-6 shows the historical E_U characteristics of regional aircraft. The average E_U of turboprop and regional jet aircraft are plotted in their year of introduction along with the overall fleet efficiencies.

It can be seen that the energy usage of newly introduced aircraft consistently improved over the time-period considered. Using as benchmarks the Lockheed L-188 and the DHC-8-300, introduced in 1959 and 1989 respectively, the E_U of turboprops has decreased by 37%, improving at an annual rate of 1.2%. Regional jets improved 49% over a similar time period, averaging an almost 2% annual improvement rate when the highly successful CV-880 and ERJ-145 are used as benchmarks. Over the time period covered, regional jets have been approximately 10%-60% less efficient than turboprop aircraft, although they have improved their E_U at a faster rate and have recently approached the efficiencies of modern turboprops.

It should be noted that, as shown on Figure 3-6, there is considerable variation in E_U between aircraft even of the same era. The CRJ-200 and the ERJ-145, for example, are same generation, similarly sized aircraft with similar performance characteristics. The data reveals, however, that the CRJ's efficiency is closer to that of a Fokker F-28 jet, introduced into service in 1968 than the ERJ-145. The trends in such variations will be explained in the following chapters when the influence of technological and operational characteristics on E_U is explored.

The fleet efficiency curves of Figure 3-6 also show that the fleet curve is heavily weighted towards the efficiency of the turboprop fleet, reflecting the fact that turboprops have traditionally made up a majority of the aircraft operated. As jets such as the CRJ-200 and the ERJ-145 replace turboprops and become an increasingly important part of regional airline operations, the fleet E_U curve will approach the average efficiency of the jets. This suggests that the fleet efficiency may actually worsen in the future. In fact, the beginning of such a trend is already becoming apparent. Between 1975 and 1992, the fuel efficiency of the regional fleet improved in approximately a linear fashion by 22%, decreasing its E_U by approximately 4.67×10^{-4} gal/ASM per year. However, in the years following the introduction of the new generation regional jets the efficiency has worsened slightly, and the E_U has risen from .02850 gal/ASM in 1992 to .02863 gal/ASM in 1999, a +0.46% change.

Figure 3-7 shows the E_U of regional aircraft compared to that of a select group of larger aircraft studied in [12]. As can be seen, regional aircraft have historically been between 10% and 50% less efficient than their larger counterparts. This is further reflected in the average E_U of the two fleets.

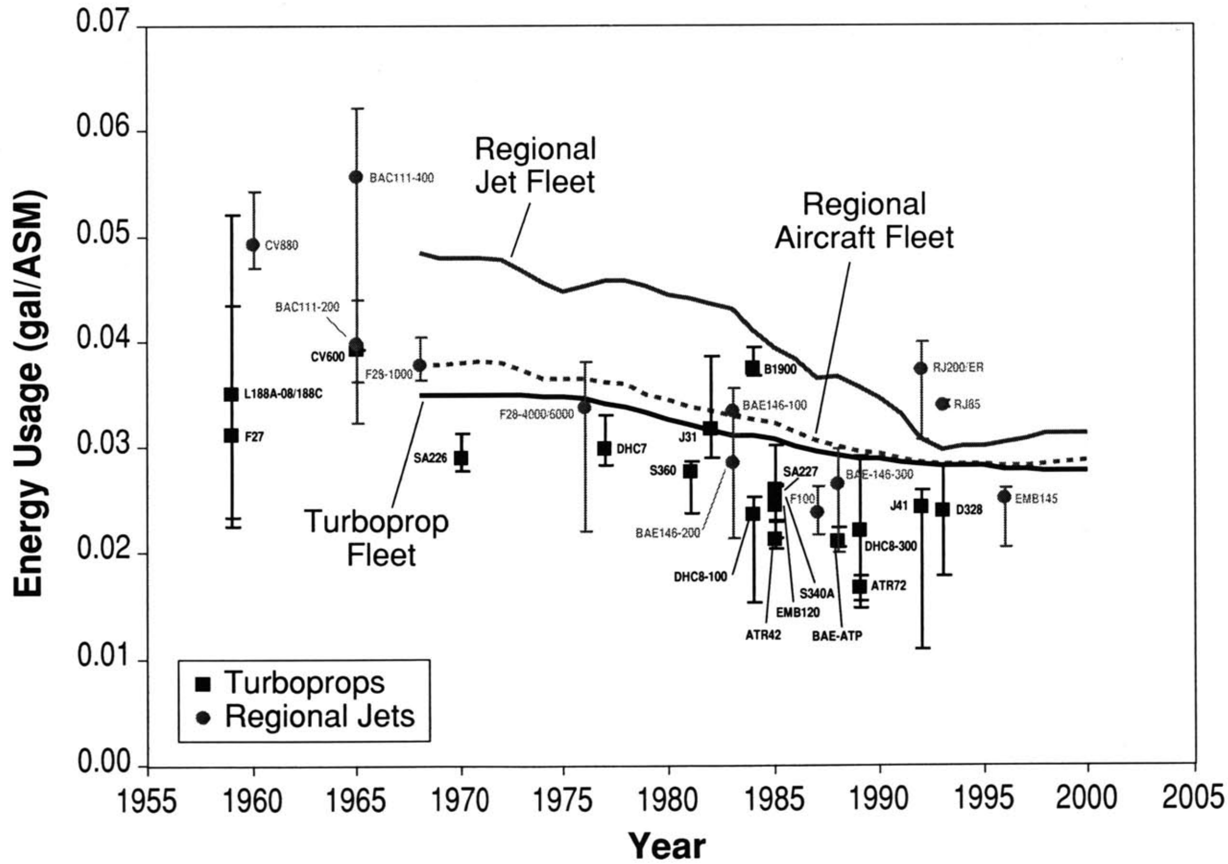


Figure 3-6 The E_U of regional aircraft and fleet averages

The causes of these differences will be examined in the following chapter.

As has been shown, there exist considerable differences between the energy usage of different types of regional aircraft, as well as between regional and larger narrow and wide body aircraft. The energy usage metric measures many aspects of aircraft performance and operations. First, there is the inherent level of technology of an aircraft. Higher efficiency propulsion systems, improved aerodynamics, and better materials invariably translate into more efficient use of fuel. Smaller sizes, an inevitable trait of regional aircraft may limit technological efficiencies. The operational characteristics of aircraft also have an important impact on energy usage. Regional aircraft take-off and land more often, therefore spending more time taxing and maneuvering at airports and climbing and descending from cruise altitude. The influence of technology and operations on the E_U of regional aircraft will be examined in the following chapter.

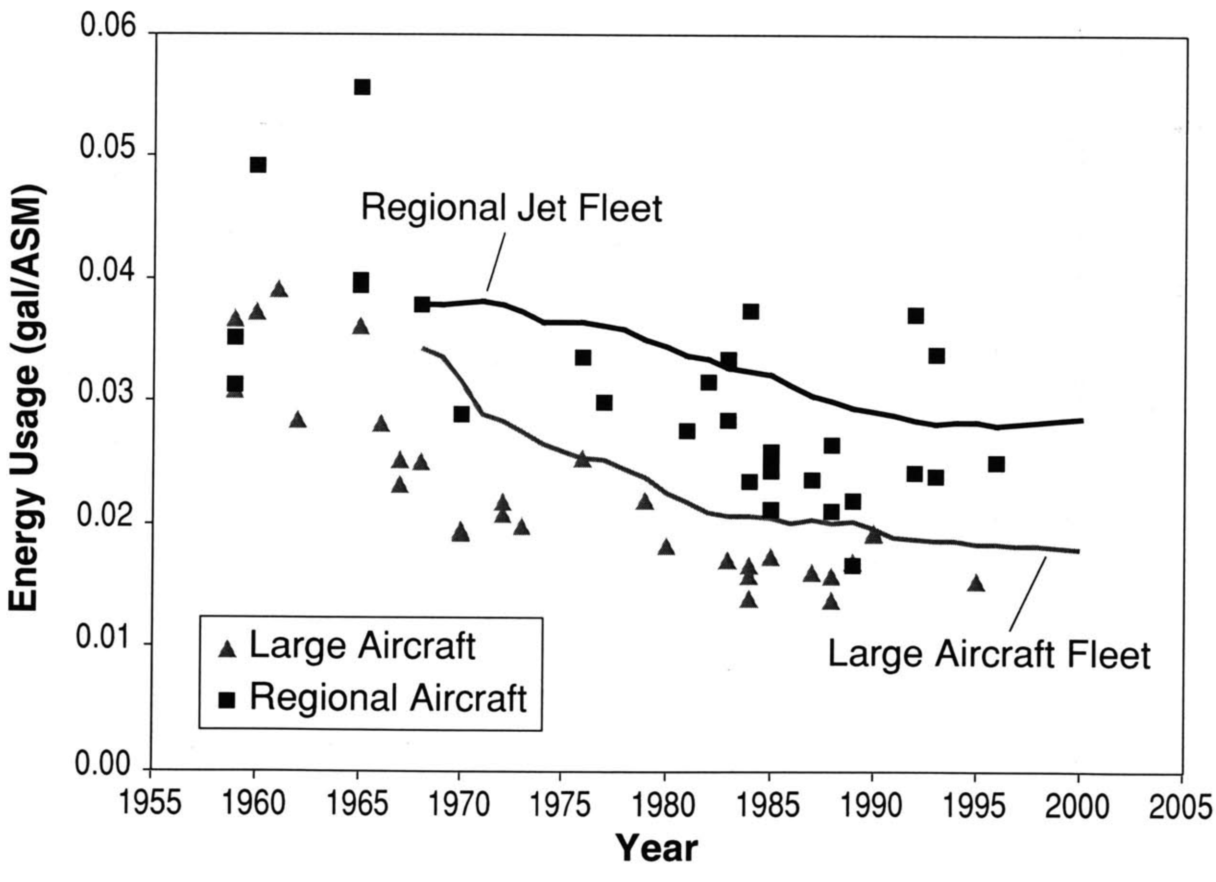


Figure 3-7 The E_U of regional aircraft compared to large aircraft

3.5 CHAPTER SUMMARY

The aviation system impacts the environment in various ways. It contributes to local air quality problems around airports, and is an important source of community noise. Recently, concern has focused on the potential of aircraft emissions released into the atmosphere to contribute to global climate change. In addition, the demand for air travel is growing faster than any for any other mode of transportation, exacerbating existing environmental concerns. Various regulatory options are being considered by governments and industry stakeholders to address these concerns. In the US, efforts to mitigate the impact of aviation activities will need to consider the increasingly important role of regional airlines in the aviation system. The energy usage of regional aircraft is higher than for their larger counterparts, and the regional fleet is moving away from turboprop aircraft towards the adoption of less energy efficient jets. In the following chapters, the technological, operational and cost characteristics of regional aircraft will be examined for how they influence or contribute to energy usage, with the intent of identifying the causes of differences in the energy usage achieved by turboprop, regional jet and large aircraft.

4 TECHNOLOGICAL AND OPERATIONAL INFLUENCES ON ENERGY USAGE

4.1 INTRODUCTION

In this chapter, differences in engine, structural and aerodynamic technologies between turboprop aircraft, regional jets and large aircraft are identified. Cruise values of E_U are then computed and compared to quantify the effect of these technological differences on fuel efficiency and aircraft emissions. The influence of aircraft operations on energy usage is then discussed using ground and airborne efficiency metrics.

The results of the chapter show that despite differences in technology-related efficiencies, the E_U of turboprops, regional jets and large aircraft are similar during cruise flight. It is shown that the discrepancies in energy usage between aircraft types identified in Chapter 3 can be explained by differences in aircraft operations. Aircraft flying short stage lengths spend more time on the ground for each hour spent in the air and therefore consume fuel inefficiently while taxing and maneuvering at airports. They also spend more of their airborne time climbing to altitude, at associated high levels of fuel consumption. In this respect, turboprops are more efficient than regional jets because they cruise efficiently at much lower altitudes than jet powered aircraft. It is shown that, when taken together, ground and airborne efficiencies can explain the difference between cruise, or optimum, E_U and actual E_U.

4.2 THE IMPACT OF TECHNOLOGY ON ENERGY USAGE

To assess the impact of technological innovation on the E_U characteristics of regional aircraft, engine, aerodynamic and structural efficiencies were first identified, then used to estimate cruise values of E_U. Engine efficiencies were quantified in terms of thrust specific fuel consumption (TSFC), which relates the rate of fuel burn in an engine to the amount of thrust produced. Aerodynamic efficiencies

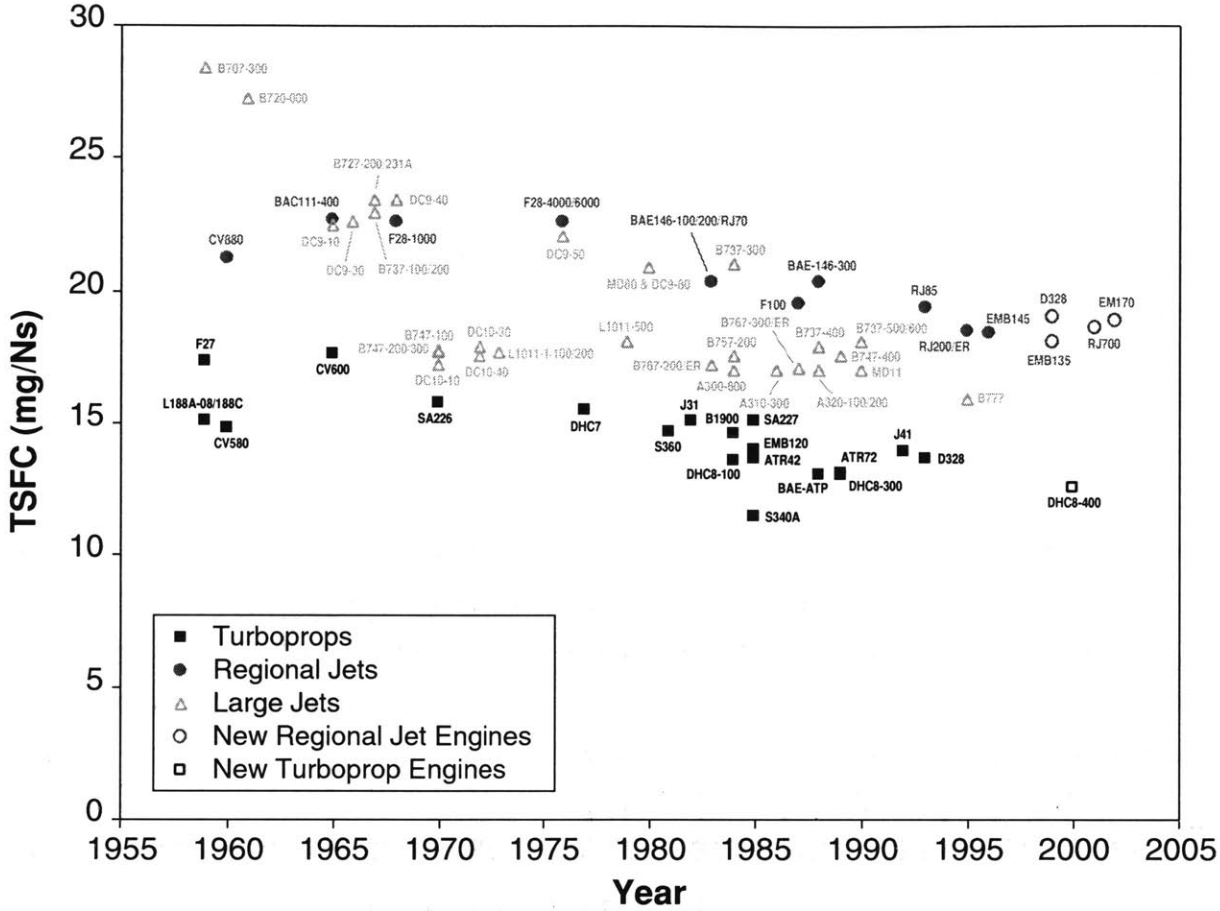


Figure 4-1 Improvement in thrust specific fuel consumption for different aircraft types at cruise

were assessed in terms of maximum lift over drag ratio (L/D_{MAX}). Finally, structural efficiency was evaluated as operating empty weight (OEW) divided by maximum take-off weight (MTOW). It provides a measure of the amount of structural weight required to carry a unit of structure, fuel and payload. These efficiencies quantify the most important characteristics of aircraft and relate directly to the E_U of aircraft in steady-state cruise flight.

4.2.1 Engine Efficiencies

Improved engine efficiencies have significantly contributed to reductions in energy usage of turboprop, regional jet and large aircraft. Cruise values of thrust specific fuel consumption (TSFC) have improved approximately 23% since 1960 for both regional jet engines and turboprops, as shown in Figure 4-1.

The cruise values of TSFC ($TSFC_{CR}$) plotted here were obtained directly by correspondence with engines manufacturers and from sources in the literature [17][16]. When $TSFC_{CR}$ values were not found, they were approximated using a take-off TSFC ($TSFC_{T/O}$) versus $TSFC_{CR}$ model described in Appendix C. For turboprops, specific fuel consumption is specified in units of fuel flow per unit of power produced (PSFC). This was converted to fuel flow per unit of thrust using Equation 4-1. For all turboprops, cruising velocity was taken as 300 mph, and the propeller efficiency (η_{PR}) was set to 0.85. A η_{PR} of 0.85 is reasonable for most modern propellers [27][28].

$$TSFC = \frac{PSFC \times Velocity}{\eta_{PR}} \qquad (4\text{-}1)$$

Where η_{PR} is the propeller efficiency

Increases in TSFC have largely been the result of technology advances detailed in [1],[29] and [16]. In particular, advances in material technologies have increased operating temperatures, while the improved understanding of aerodynamic flows in turbomachinery has led to the development of more efficient compressors and turbines.

The development of high bypass ratio jet engines, also called turbofans, have significantly improved TSFC by increasing propulsive efficiencies. Initially developed for long haul, wide body aircraft, they contributed to a noticeable drop in TSFC values in the early 1970s evident in Figure 4-1. However, high bypass ratio engines were not developed for 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 regional jets and the smallest of what are called large aircraft in this study. As a result of this difference in technology adoption, the $TSFC_{CR}$ of regional jet engines have been 10%-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 TSFCs than larger engines. Figure 4-2 shows the $TSFC_{CR}$ vs. Thrust Rating for engines with bypass ratios between 4.5 and 6.5. It can be seen that engines smaller than 100kN are 5%-10% less efficient than engines with thrust ratings above 100kN. This can be explained by the fact that the smaller engines typically have lower pressure ratios, also plotted on Figure 4-2. Pressure ratio is directly related to engine thermal efficiency (η_{TH}), which in turn influences TSFC. Pressure ratios are lower for smaller engines because they generally have fewer compressor stages or they utilize less efficient centrifugal compressors. It is possible that the small blades required for high-pressure compressor stages may be too difficult or expensive to manufacture at required levels of tolerance. Further, additional compressor stages may not be worth increments in weight or maintenance costs. As will be seen in Chapter 5, costs other than fuel become increasingly important for regional aircraft.

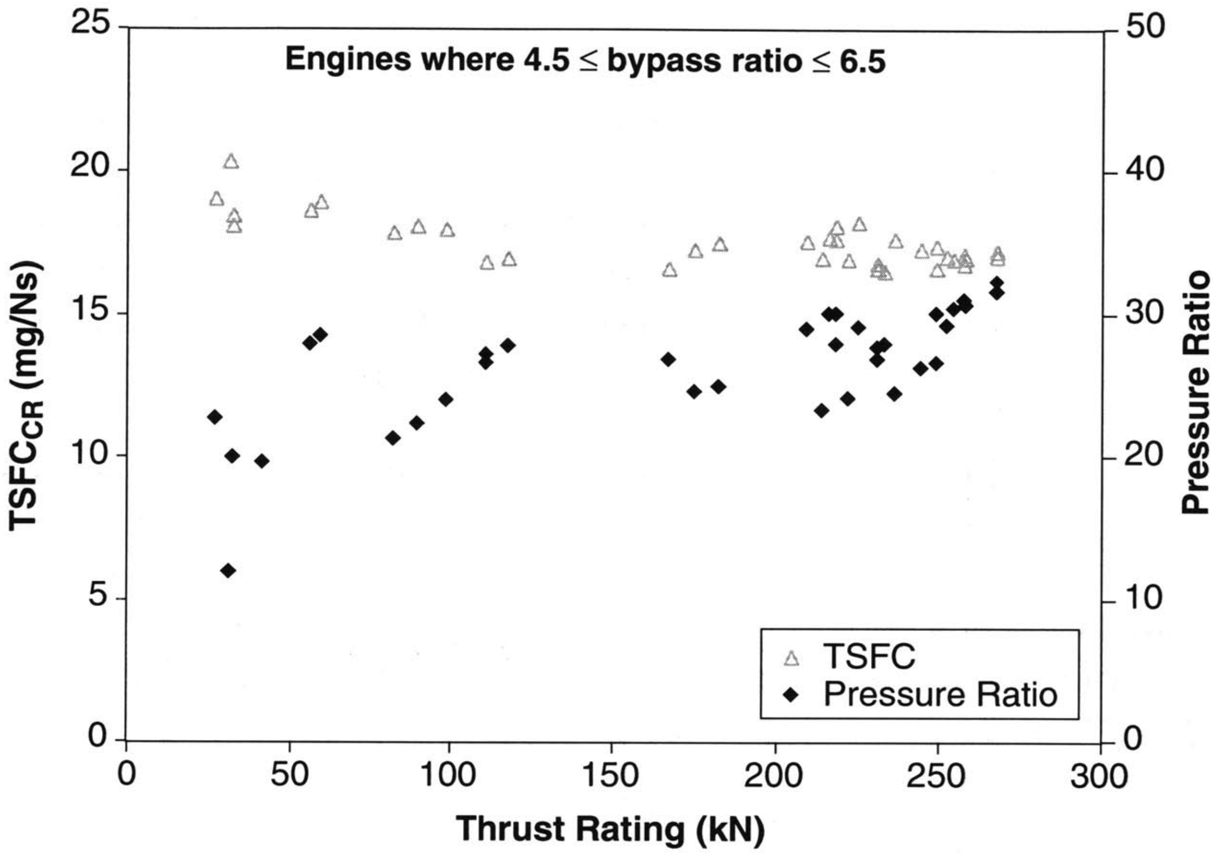


Figure 4-2 Variation of engine efficiency with thrust rating

Figure 4-1 shows that turboprop engines are 10%-30% more efficient than jet engines at cruise condition. Turboprops typically derive 85% of their thrust from a propeller, while the rest is provided by jet exhaust. Their high TSFC is the result of the propellers' ability to accelerate large amounts of air at low airspeeds. 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 between 0.4 and 0.7 and altitudes below 25,000 feet. Hence, turboprop aircraft generally fly slower and lower than aircraft with turbofan engines as a trade-off for lower fuel consumption.

4.2.2 STRUCTURAL TECHNOLOGY

Structural technologies are primarily those that permit reductions in aircraft weight through the use of new materials and designs. A one percent reduction in the gross weight of an empty aircraft will reduce fuel consumption approximately between 0.25% and 0.75% [12][29]. Advanced materials such as improved aluminum alloys and composites have already been successfully used for control surfaces, flaps, and slats on civil aircraft such as the Boeing 777 and various Airbus models. The A310-300 was the first aircraft to feature a vertical stabilizer made entirely out of carbon fibre [7]. Regional aircraft have also benefited from the use of advanced materials. The outer wing box of the ATR 72, for example, is constructed mostly out of carbon fibre reinforced plastic (CFRP), resulting in a 130kg weight saving [30]. Furthermore, the ATR 72 has highest percentage of structure made of composite material among commercial aircraft [31].

Despite the development and use of advanced materials, Figure 4-3 shows that the structural

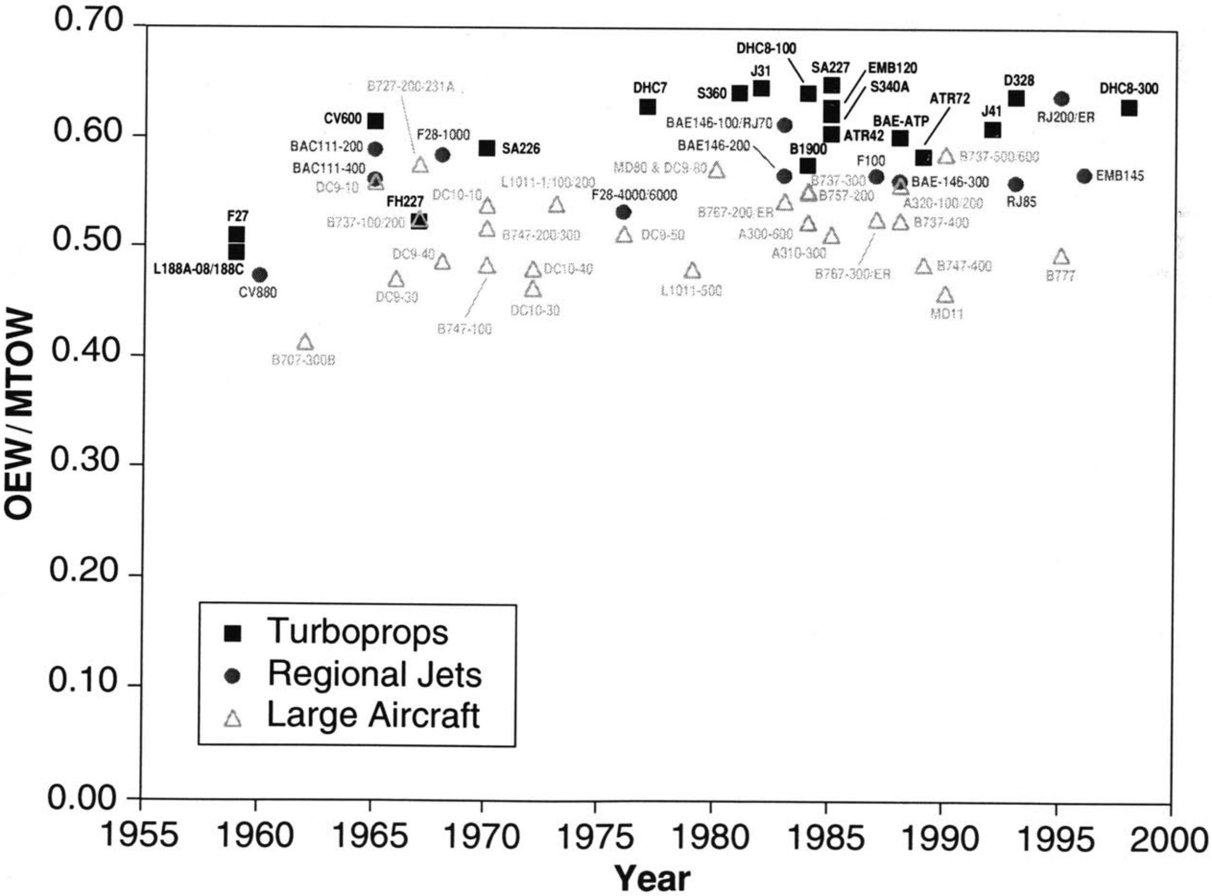


Figure 4-3 Historical trends in structural efficiency

efficiencies of aircraft may have actually decreased between 10% and 25% for all aircraft types since 1959. The lack of improvement may be due to the fact that most aircraft today are still about 97% metallic, with composites used only on relatively few components such as fins and tailplanes [29]. Furthermore, structural weight reductions have been largely offset by improvements in aerodynamics, integration of in-flight entertainment systems and increases in engines weights [1].

Figure 4-3 shows that regional jets are less structurally efficient than large aircraft, and that turboprops in turn are less efficient than regional jets, suggesting that aircraft size influences structural efficiency. Indeed, Figure 4-4 shows that structural efficiency decreases approximately 25% from larger aircraft to smaller turboprops. 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

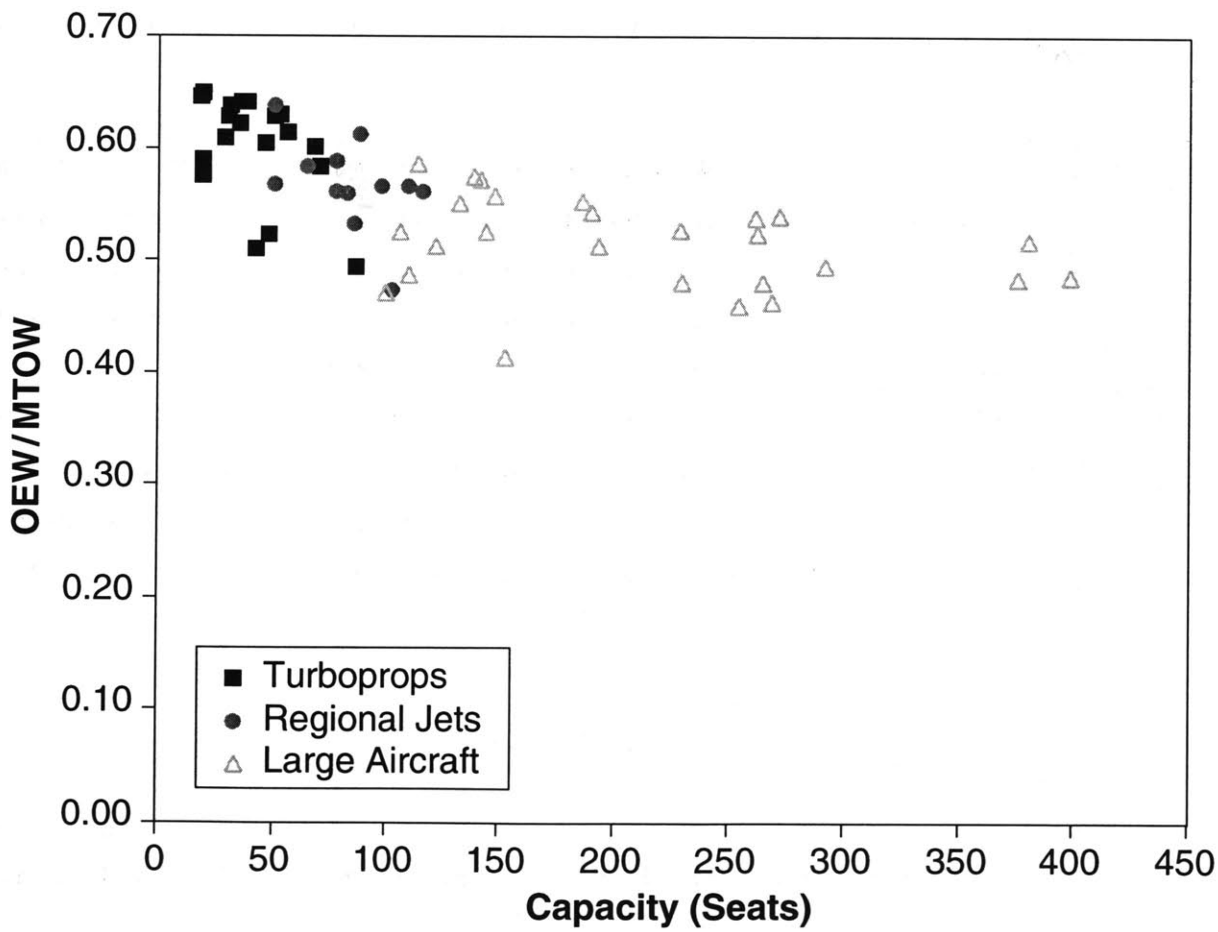


Figure 4-4 Variation of structural efficiency with size

have lower thrust-to-engine weight ratios (T/W_E). As a result, smaller aircraft must pay an engine weight penalty compared to larger aircraft. Figure 4-5 shows how T/W_E ratios vary with engine thrust rating and engine type. Only engines introduced during or after 1985 have been shown. It can be seen that 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 [27]. As a result, aircraft powered by small turbofans and turboprops are relatively heavier for the payload they carry compared to large aircraft.

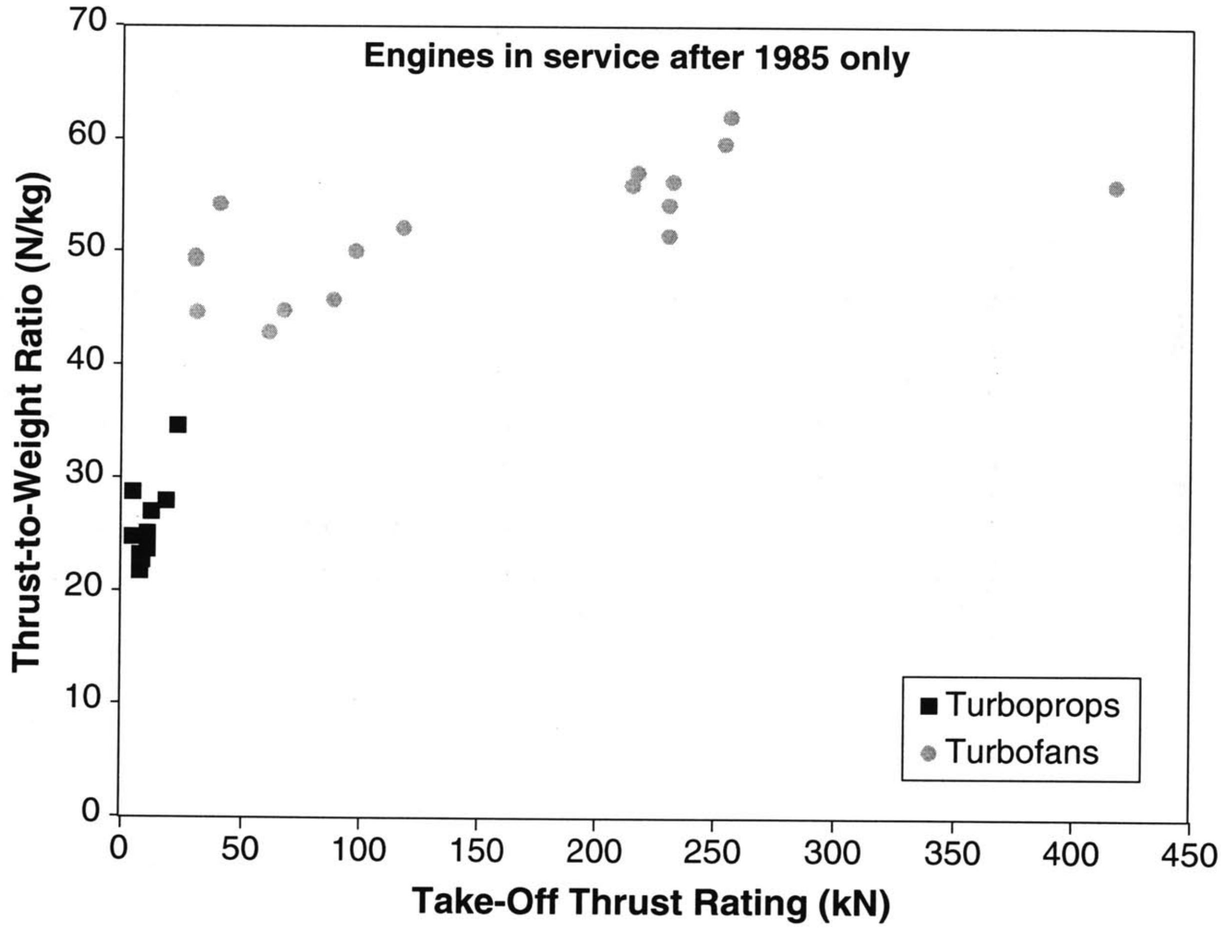


Figure 4-5 Variation of Thrust-to-Weight Ratio with Thrust Rating

4.2.3 AERODYNAMICS

Historical trends in aerodynamic efficiencies, or maximum lift-over-drag (L/D_{MAX}) ratios, are shown in Figure 4-6. Values for large aircraft have been taken from [12]. For regional aircraft, the data was obtained from manufacturers when possible. However, for eighteen out of thirty aircraft for which specifications from manufacturers were not available, L/D_{MAX} values were derived using estimated aircraft parasitic and induced drag coefficients (C_{Do} and K respectively) found in BADA [15]. Assuming the total drag (C_D) on a subsonic aircraft can be expressed as Equation 4-2, the L/D_{MAX} can be found using Equation 4-3 [27][28].

$$C_D = C_{Do} + K \cdot C_L^{\ 2} \tag{4-2}$$

$$\left(\frac{L}{D}\right)_{MAX} = \frac{1}{2 \cdot \sqrt{C_{Do} \cdot K}} \tag{4-3}$$

Where $C_L^{\ 2}$ is the coefficient of lift

Because performance coefficients included in BADA are derived from many sources and are often estimates taken from the available literature, user manuals and other publicly available information, there is considerable error associated with the L/D_{MAX} values of regional aircraft shown in Figure 4-6. In some cases, the L/D_{MAX} seems suspiciously high. The accuracy of BADA is discussed in Appendix D.

Figure 4-6 shows that the aerodynamic efficiencies of large aircraft have improved approximately 15% since 1959, averaging 0.4% per [12]. 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 [1]. Less of a trend is evident for either regional jets or turboprops, partly because L/D_{MAX} for several older aircraft models are unavailable. Nevertheless, Figure 4-6 shows that the aerodynamic efficiencies of regional aircraft are within the same range of values as for large aircraft.

4.2.4 Influence of Technology on Energy Usage

The technological parameters examined in sections 4.2.1, 4.2.2, and 4.2.3 provide an idea of the relative advantages and disadvantages of smaller and larger aircraft and of turboprop and jet propulsion systems. However, they do not provide an obvious indication about how differences or historical improvements in efficiencies impact E_U. Therefore, cruise values of E_U ($E_{U,CR}$) were estimated for regional and large aircraft using the technology parameters discussed above and the

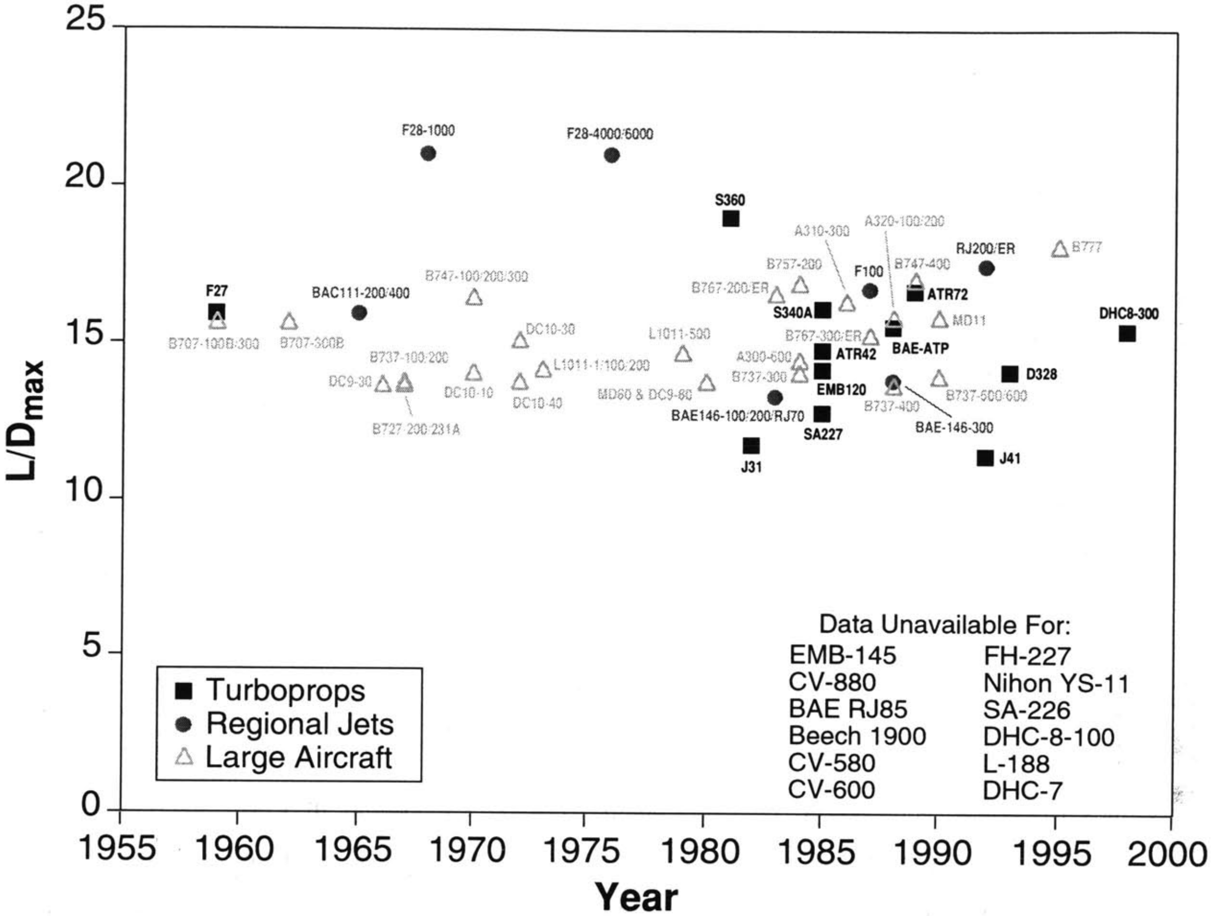


Figure 4-6 Historical trends in lift-over-drag ratios

specific air range (SAR) equation. The SAR is the basic model for describing the physics of aircraft in steady cruise flight, and it quantifies the distance flown per unit of fuel burn. Its derivation can be found in [27] and [28]. The SAR equations are shown below as equations 4-2 and 4-3 for turboprops and jets respectively.

Jet: $$SAR_{JET} = \frac{Velocity}{TSFC} \cdot \frac{L}{D} \cdot \frac{1}{W} \qquad (4\text{-}2)$$

Turboprop: $$SAR_{TURBOPROP} = \frac{\eta_{PR}}{PSFC} \cdot \frac{L}{D} \cdot \frac{1}{W} \qquad (4\text{-}3)$$

Where $W = W_{FUEL} + W_{PAYLOAD} + W_{STRUCTURE} + W_{RESERVE}$

$W_{RESERVE}$ is an amount of reserve fuel loaded onto the aircraft, but not used under normal circumstances. All turbofan and turbojet powered aircraft, including regional jets, are assumed to cruise at 35,000 ft at Mach 0.85, and turboprops are assumed to cruise at 20,000ft. While there is some variation in actual operation, these figures are reasonable estimates of typical jet and turboprop operational parameters specified by manufacturers in [13]. 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.

Additional manipulation of the SAR equations yields a formula for estimating the $E_{U,CR}$ for jet and turboprop aircraft:

Jet:
$$\frac{gal}{ASM} = \frac{\rho_f}{SAR_{JET} \cdot Capacity} = \frac{\rho_f \cdot TSFC \cdot W}{Velocity \cdot \frac{L}{D} \cdot Capacity} \qquad (4\text{-}4)$$

Turboprop:
$$\frac{gal}{ASM} = \frac{\rho_f}{SAR_{TURBOPROP} \cdot Capacity} = \frac{\rho_f \cdot PSFC \cdot W}{\eta_{PR} \cdot \frac{L}{D} \cdot Capacity} \qquad (4\text{-}5)$$

Where ρ_f is the density of fuel in units of gal/lbs

Values of W_{FUEL} and $W_{PAYLOAD}$ were taken from data available in Form 41. Federal Aviation Regulations require that aircraft have enough extra fuel on-board to fly an additional 30 minutes during the day and an additional 45 minutes at night upon reaching the vicinity of the final destination. Therefore, $W_{RESERVE}$ is taken as half the per block hour fuel consumption of a given aircraft. Also, for aircraft for which L/D information was not available, values from similarly sized aircraft were substituted.

Average $E_{U,CR}$ values calculated for different aircraft types are shown in Figure 4-7. It can be seen that average cruise values of energy usage calculated for regional jets, turboprops and large aircraft fall approximately within the same band of variability in any given time period. It seems that neither regional jets, turboprops nor large aircraft have a distinct technological or size advantage that results in lower fuel consumption under optimal cruise conditions. Turboprops were shown to have better TSFCs than regional jets, but the benefits of this advantage were negated by the fact that turboprops had lower structural efficiencies than regional jets. This reflects the trade-offs inherent in aircraft design.

Comparison of calculated $E_{U,CR}$ results and total E_U values identified in Chapter 3 reveals that large aircraft achieve total efficiencies much closer to their cruise values than regional aircraft. As will be discussed in Section 4.3, differences in E_U and $E_{U,CR}$ are caused by fuel consumption incurred during non-cruise portions of aircraft operations. Figure 4-8 shows that total E_U is on average 2.6 times higher than calculated $E_{U,CR}$ for regional aircraft, but only 1.6 times higher for large aircraft. A closer inspection of regional aircraft $E_{U,CR}$ values shows that while the total E_U of turboprops are on average 2.5 times greater than $E_{U,CR}$, the total E_U values of regional jets are approximately 3.15 greater than $E_{U,CR}$ values. The E_U and $E_{U,CR}$ comparisons suggest that most of the differences in total E_U observed in Chapter 3 between regional aircraft and large aircraft, and also between turboprops and regional jets are not the result of technological differences, but rather due to differences in the way aircraft are used.

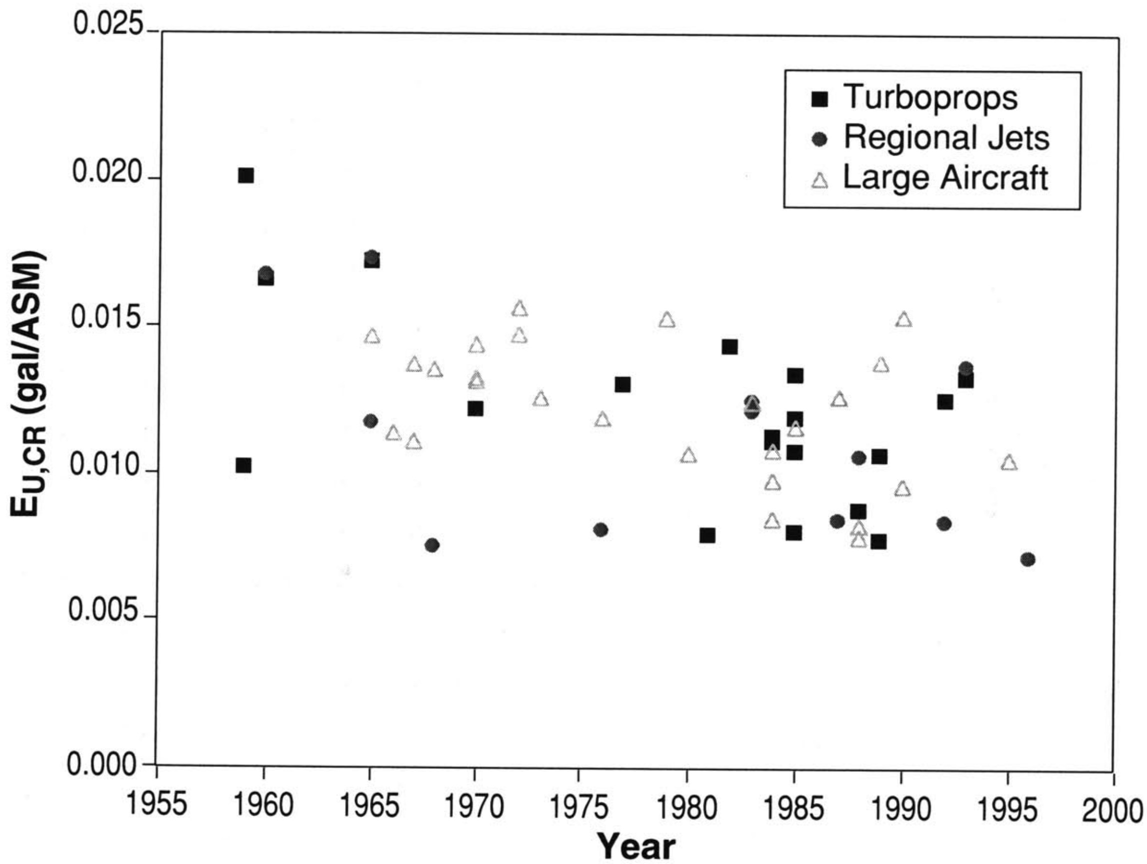


Figure 4-7 Calculated $E_{U,CR}$ for regional and large aircraft

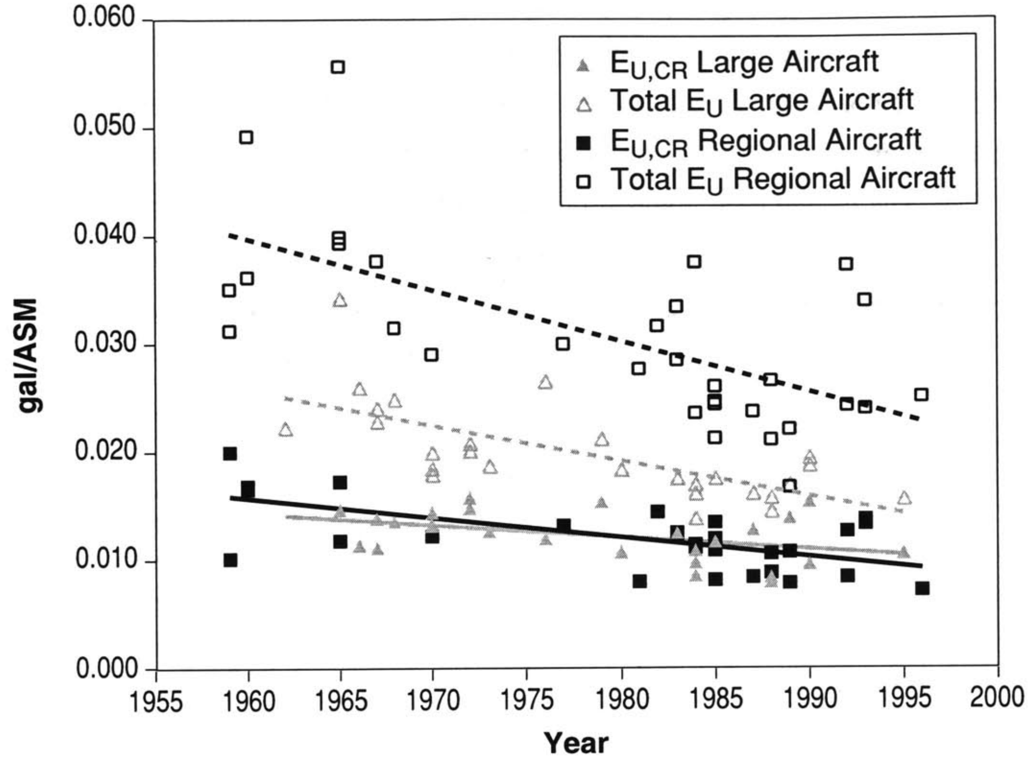


Figure 4-8 Difference between E_U and $E_{U,CR}$ for regional and large aircraft

4.3 IMPACT OF OPERATIONS ON ENERGY USAGE

Differences in aircraft operations - the airports they serve, the stage lengths they fly, and the altitudes they fly at - have already been shown to have important implications for the energy usage of aircraft. These differences have been shown to be have a particularly significant impact on the E_U of regional aircraft, which fly shorter stage lengths than large aircraft, and as a result, spend more time at airports taxing, idling and maneuvering into gates, and expend a greater fraction of their flight time in non-optimum, off-cruise stages of flight. The impact of operational differences, and especially distance flown, on E_U is evident in Figure 4-9, which shows the variation of E_U with range for turboprops and jet-powered aircraft (both regional jets and large jets) introduced during and after 1980. It is evident that aircraft flying stage lengths below 600 miles have E_U values between one-and-a-half to three times higher than aircraft flying stage lengths above 600 miles. Also, turboprops show a distinct pattern from that of jets, and are, on average more efficient. Insight into the cause of these trends can be gained by examining the efficiencies associated with ground and airborne activity characteristics of regional jets, turboprops and large jets

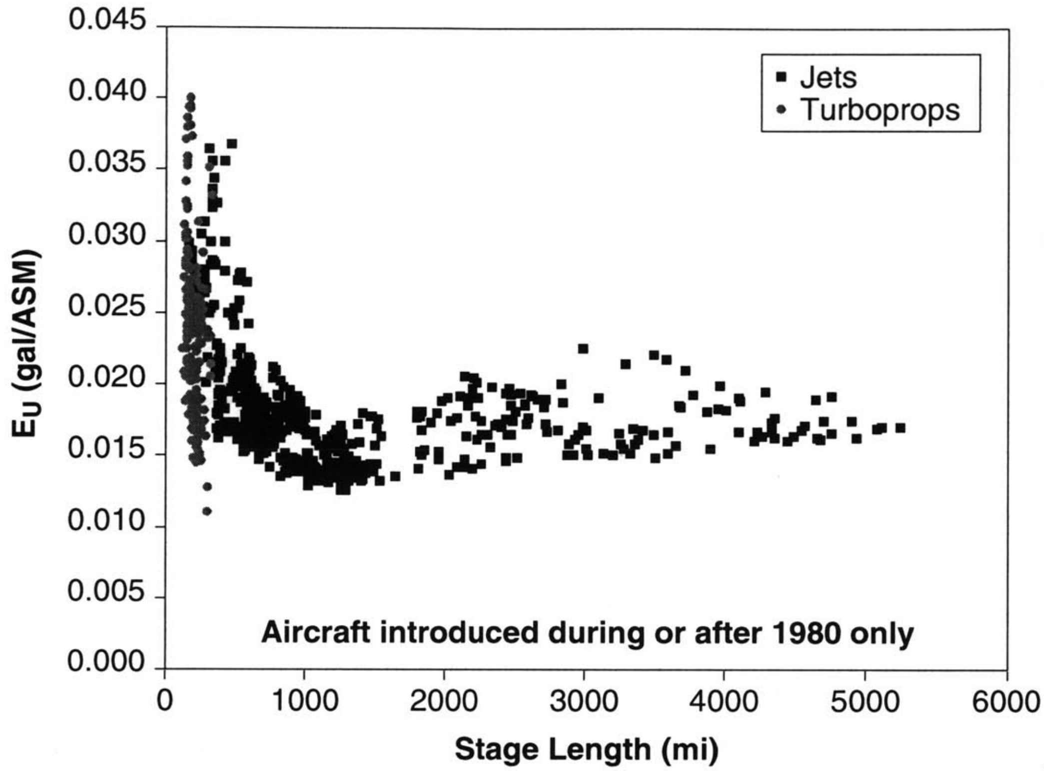


Figure 4-9 Variation of E_U with stage length

4.3.1 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). The η_g of regional aircraft varies between 0.65 and 0.90, compared to between 0.75 and 0.90 for large aircraft. Naturally, aircraft that fly short stage lengths should be expected to have a lower η_g because of the need to taxi and maneuver more often for every unit of time spent in the air. This is evident in Figure 4-10, which shows a steadily decreasing η_g with decreasing stage length for all aircraft types. The high variability in 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 likely have to taxi further to get to the runway and face greater congestion-related delays than aircraft serving smaller community airports. The implication of the trend displayed in Figure 4-10 is that regional aircraft incur a fuel consumption penalty relative to longer flying aircraft because they spend greater amounts of time involved in ground operations relative to air operations.

Rank	Airport	Daily Regional Departures	% Regional	Rank	Airport	Daily Regional Departures	% Regional
1	Cincinnati (CVG)	337	60.9	6	Chicago (ORD)	281	25.7
2	Dallas/Ft. Worth (DFW)	327	31	7	Pittsburgh (PIT)	257	47.2
3	Washington, DC (IAD)	323	59	8	Seattle (SEA)	246	47
4	Boston (BOS)	292	47	9	Atlanta (ATL)	241	21.2
5	Los Angeles (LAX)	286	32.1	10	Cleveland (CLE)	216	57.6

Table 4-1 Top ten airports with regional aircraft operations [10]

Because regional aircraft take-off and land so often, they are an important part of major airport operations. Table 4-1 shows the top ten U.S. airports serving regional aircraft. Continued rapid growth of the regional airline industry, as suggested in Chapter 3, has the potential to worsen congestion and delays at already over-strained airports. In fact, regional jet service additions to date have focused on already congested major urban airports as opposed to secondary urban airports [8]. Four of the airports listed above fall within the top ten airports with the greatest minutes of delay per operation, while nine fall within the top twenty-five [21]. Further compounding congestion problems, regional jets require longer runways than turboprops. One study by a turboprop manufacturer revealed that while 50-seat turboprops could operate out of 80% of the airports reported in the OAG, 50-seat regional jets could only operate out of only 55% [35]. The fact that regional jets require runway lengths similar to large aircraft may prove a bottleneck at some airports as RJ flights replace turboprops, further worsening congestion and delays. It is evident that 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 regional jets in airport operations. Limiting regional jet operations at large airports would unlikely be an acceptable solution to airlines, as it would undermine hub operations. Regional aircraft manufacturers, for their part, may be able to help relieve the problem through the use of high lift devices that would permit regional jets to use shorter runways.

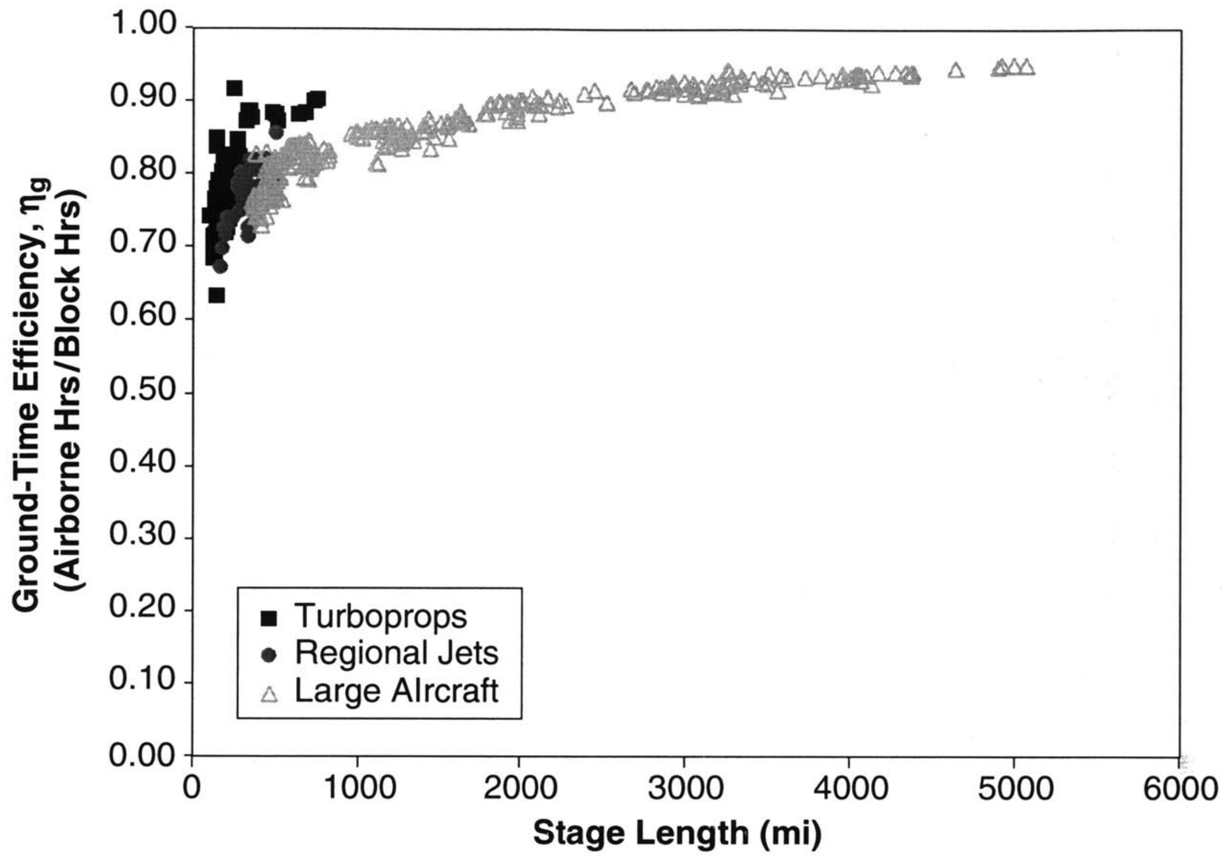


Figure 4-10 Variation of η_g with stage length

4.3.2 AIRBORNE EFFICIENCIES

Regional aircraft fly short stage lengths and therefore 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. Simply, an aircraft must use more energy to gain altitude than to cruise at constant altitude. 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.

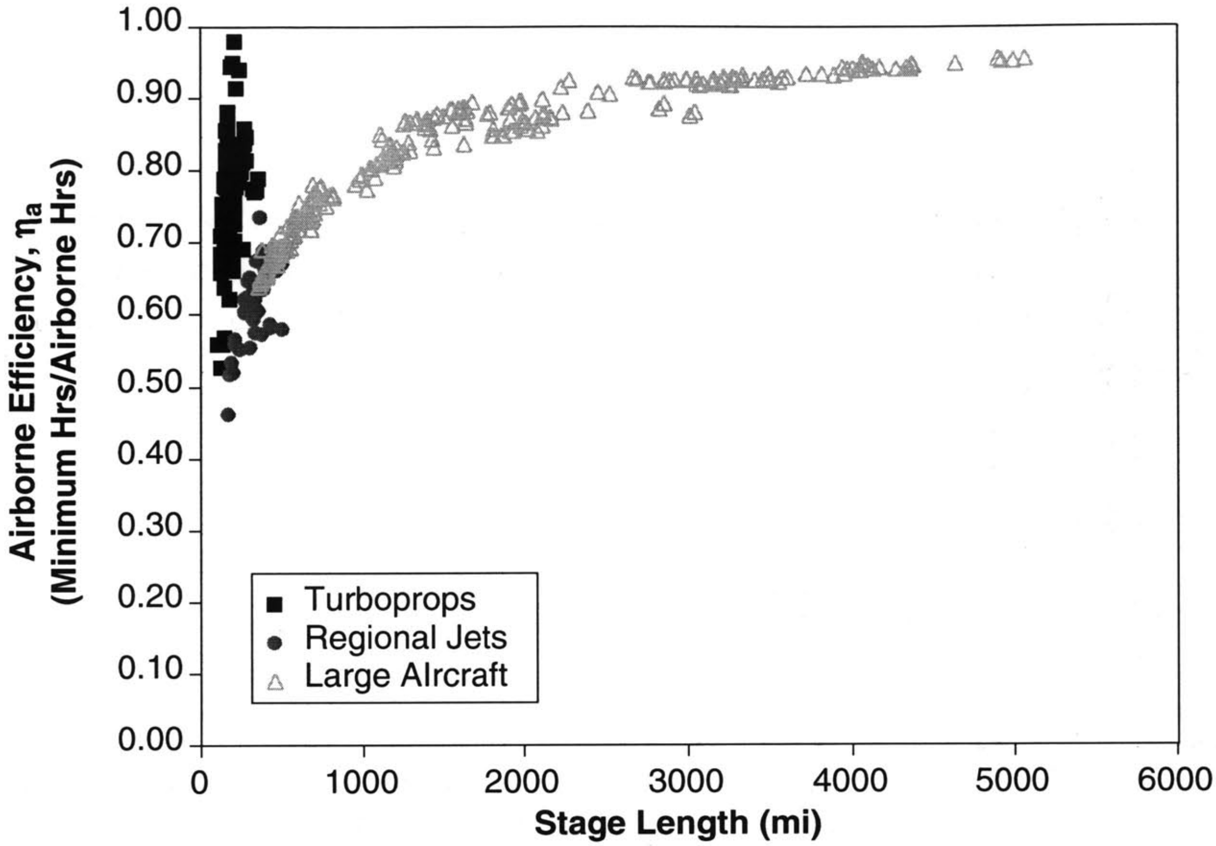


Figure 4-11 Variation of η_a with stage length

The ratio of minimum flight hours to airborne hours, or airborne efficiency (η_a) serves to quantify the fraction of time aircraft spend at cruise speeds. Minimum hours are the shortest amount of time required to fly a given stage length along a great circle (minimum distance) route. It assumes that this distance is flown at cruise speed with no additional time required for take-off, climb, descent or landing. To simplify the analysis, all jet-powered aircraft are assumed to fly at Mach 0.85 at 35,000 ft, while turboprops are assumed to fly at cruise speeds specified for each aircraft type in [13]. 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 wasted performing holding patterns above congested airports. Each of these inefficiencies, in addition to take-off and climb effects, contributes to increasing the energy usage above that incurred during cruise.

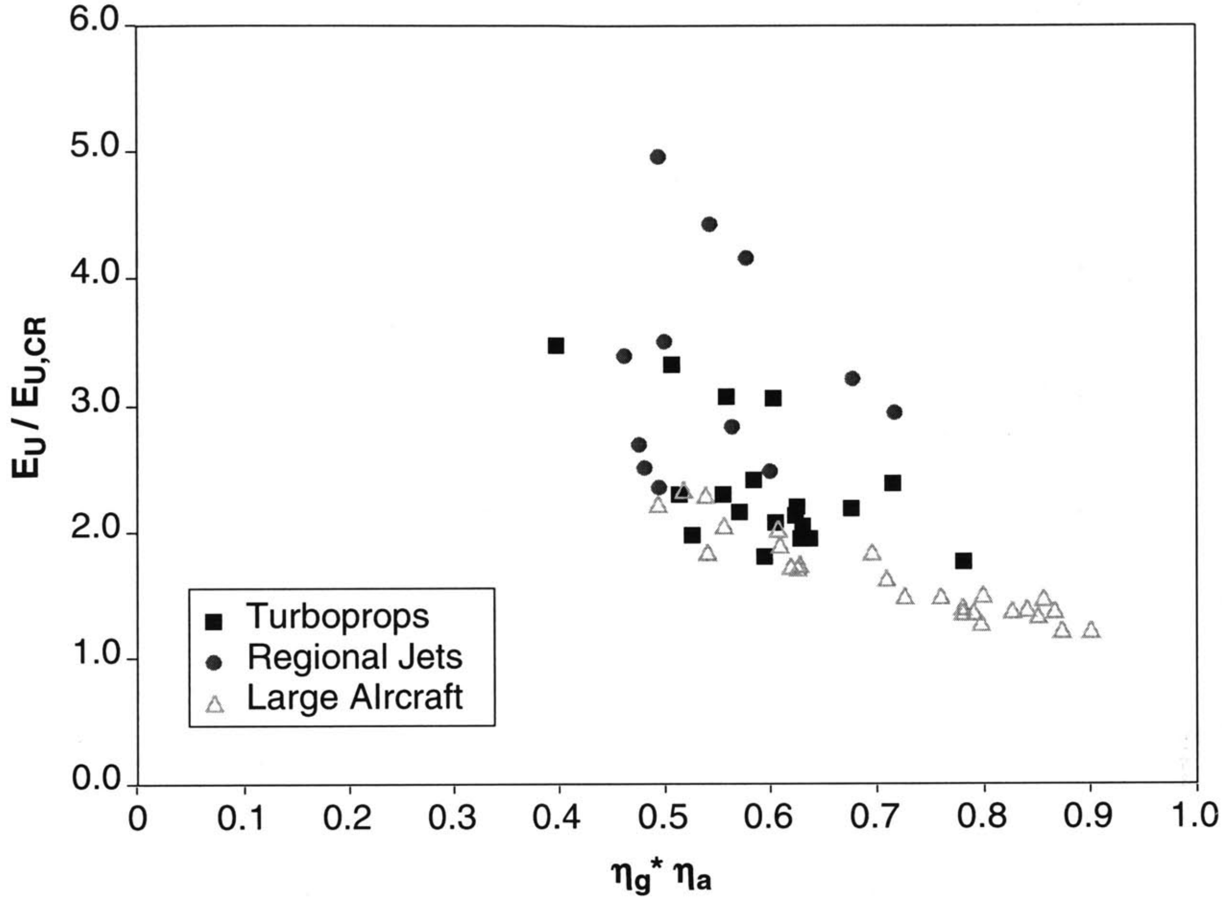


Figure 4-12 Variation of $E_U/E_{U,CR}$ with ground and airborne efficiencies

Figure 4-11 shows the variation of airborne efficiency with stage length. It can be seen that regional jets follow the trend associated with large aircraft, decreasing logarithmically below 1000 miles. Turboprops, on the other hand, follow a distinctly different pattern. Even for stage lengths shorter than those typically flown by regional jets, turboprops exhibit efficiencies that are on average approximately 20% higher than regional jets. This can be explained by the fact that turboprops typically cruise at altitudes several thousand feet below jets. In general, turboprop aircraft cruise efficiently at approximately 20,000 ft, while jets cruise at 35,000 ft. Because of the difference in operational altitude, turboprops spend less time climbing and as result, achieve higher airborne efficiencies and spend less time at the high rates of energy usage associated with climbing flight. This helps explain why in Figure 4-9 turboprops on average have lower E_U than jet-powered aircraft at similar or shorter stage lengths.

The typical operational altitude of regional jets has further implications for efficiency and energy use. 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 and replace turboprops flying at lower altitudes [24].

4.3.3 TOTAL IMPACT OF OPERATIONS ON ENERGY USAGE

The ground and airborne efficiencies together capture enough of the important operational characteristics of commercial aircraft to effectively explain the differences between E_U and $E_{U,CR}$ found in Section 4.2.4. Figure 4-12 shows the variation of the $E_U/E_{U,CR}$ with the product of the ground and airborne efficiencies. In general, 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%-20% higher than cruise values of energy usage.

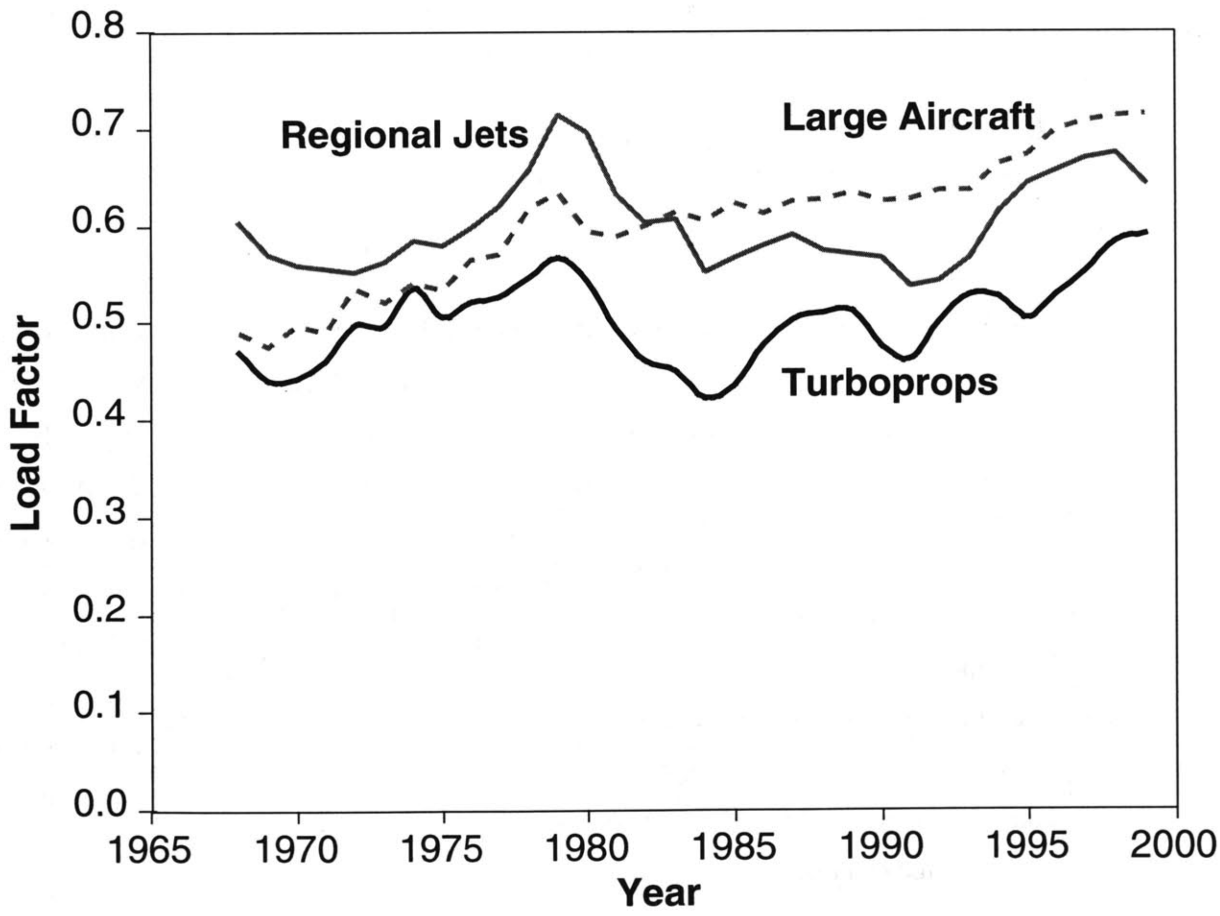


Figure 4-13 Historical changes in load factor

4.4 THE INFLUENCE OF LOAD FACTOR

E_U expresses the amount of energy required to perform a unit of potential output. E_I, on the other hand, measures of how much energy is required to perform a unit of actual output. The E_I and E_U are related by the load factor (α), the ratio of boarded passenger to available seats, as shown in Equation 4-6.

$$E_I = \frac{E_U}{\alpha} \tag{4-6}$$

Load factors close to one signal that an aircraft and its fuel are being effectively utilized. Figure 4-13 shows historical load factor trends for large aircraft, regional jets and turboprops. 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 have nevertheless improved by a third. The load factors of regional aircraft have been characterized by considerable variation throughout the period covered, but regional jets have consistently had load factors 10%-30% higher than for turboprops. The effect this has had on the E_I is illustrated in Figure 4-14. In 1970, while the E_U of the regional jet fleet was 40% higher than for the turboprop fleet, the E_I was only 9% higher. Similarly in 1999, the regional jet fleet E_U was 13% higher than for the turboprop fleet E_U, but the E_I was only 3% higher. Although the turboprop fleet has historically had lower E_U than the regional jet fleet, the regional jet fleet has been used more efficiently.

Noting the influence of load factor is recognition that effective use of aircraft resources is an important part of achieving higher efficiencies. With load factors at historical highs, it is unlikely that operators of large aircraft will be able to achieve further gains due to practical constraints. However operators of regional aircraft, especially of turboprops, still have the potential to increase load factors and improve E_I.

4.5 CHAPTER SUMMARY

In this chapter, differences in the technological and operational characteristics of regional and large aircraft and between regional jets and turboprops were identified and their impact on E_U quantified. It was shown that regional aircraft engine efficiencies have improved approximately 25% since 1960, and that turboprop engines are 10%-30% more efficient than jet engines. However, turboprop engines were shown to be heavier than jets, resulting in lower structural efficiencies for turboprop aircraft. Regional jets, turboprops and large aircraft were all found to have similar aerodynamic efficiencies.

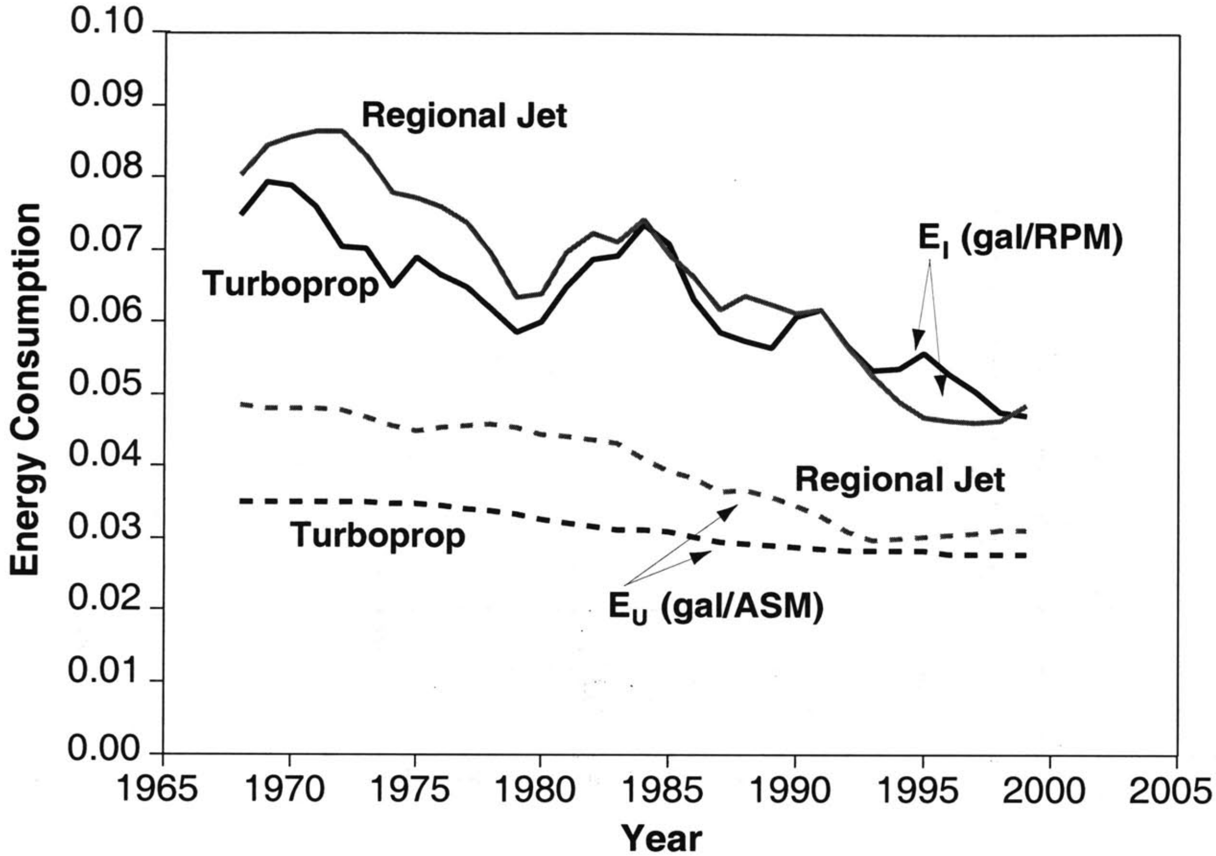


Figure 4-14 Effect of load factor on fleet energy intensity

The technological parameters were used to estimate cruise values of E_U for each regional and large aircraft. It was found that all three aircraft types have $E_{U,CR}$ values within the same range of variability in any given time period, suggesting that differences in E_U between regional and large aircraft and between regional jet and turboprop aircraft are not the result of large technological differences, but rather differences in aircraft operations. Large aircraft realize total energy efficiencies much closer to their optimum rate of energy usage achieved during cruising flight than regional aircraft. The total energy usage of regional aircraft, which includes energy consumed during ground operations and non-cruise portions of flight, was found to be on average 2.7 times higher than energy consumed during cruising flight, but only 1.6 times higher for larger aircraft. A similar comparison of regional aircraft revealed that the total energy usage of regional jets was on average more than 3.5 times as high as energy use during cruise, while for turboprops this figure was closer to 2.3 times as high. Differences in E_U and $E_{U,CR}$ were shown to be functions of how much time aircraft spend on the ground and the fraction of time in the air they spend at off-cruise flight conditions. Regional aircraft spend more time on the ground than larger aircraft because they take-off and land more often. In the air, regional aircraft spend a greater percentage of their flight time climbing and descending to and from cruise altitudes at non-optimum rates of fuel consumption. Regional jets are particularly inefficient in this respect because they must typically operate at higher altitudes than turboprop aircraft.

Finally, it was shown that regional jets have typically operated at load factors 10%-30% higher than turboprops, suggesting that regional airlines have been able to use regional jets more efficiently. As a result, while the E_U of the regional jet fleet was 40% higher than for the turboprop fleet in 1970, the E_I was only 9% higher. In 1999, the E_U of the regional jet fleet was 13% higher than for the turboprop fleet, but the E_I was only 3% higher. This shows that to take advantage of the superior environmental performance of turboprops, they must be more efficiently utilized.

5 COST CHARACTERISTICS OF REGIONAL AIRCRAFT

5.1 INTRODUCTION

In this chapter, the operating and capital cost characteristics of regional aircraft are identified and compared to larger aircraft. Specifically, differences in the breakdown of operating costs are quantified, and trends in the operating costs per mile of regional aircraft are explained. The purpose of the chapter is to identify whether regional aircraft share the same cost-related drivers of technological advancement that have contributed to energy efficiency gains of large aircraft.

Aircraft operating and investment costs typically account for approximately half of the total operating expenses incurred by airlines [12][36]. As a result, there is a strong incentive to reduce the direct operating costs of aircraft to maximize profits. The development and implementation of new technologies and the adoption of efficient operational practices have generally been the means that airlines and aircraft manufacturers have pursued to achieve such reductions. For example, advances in avionics during the early 1980's gradually allowed for the elimination of the third crew member required on most medium and long-haul aircraft, contributing to an approximate 14% reduction in the total crew costs of wide body aircraft between 1975 and 1995.

In the absence of regulations limiting aircraft emissions at altitude, improvements in aircraft fuel efficiency resulting from advances in technology and changes in operations have been driven more so by market forces aiming to reduce fuel costs rather than concerns about the environmental impact of aviation [32]. In this regard, the economic characteristics of aircraft will continue to play an important role in determining how aircraft technologies will evolve over time.

It is therefore important to understand the relationship between fuel efficiency, operating cost and price. In previous work [12], a statistically relevant relationship between unit operating costs (costs per ASM) and fuel efficiency of narrow and wide body aircraft was identified. In addition, aircraft prices were found to be correlated to direct operating costs, such that more expensive aircraft were cheaper to operate. This relationship quantifies how much airlines have been willing, under past economic and regulatory conditions, to pay for incremental reductions in operating costs.

Regional aircraft have different characteristics. Fuel costs are a lower percentage of operating costs than for large aircraft and unit costs are found to not only vary with fuel efficiency, but also with stage length. Stage length is relevant because the contribution of fixed, per flight costs to DOC/ASM varies inversely with distance flown. Fixed costs therefore become an important component of unit costs for aircraft flying short distances. When the influence of stage length is accounted for, it becomes apparent that the unit costs of turboprops have decreased 40%-60%, while those of regional jets have decreased 30%-46% due to reduction in fuel, maintenance and other costs. Fuel cost savings make up approximately half of the total reduction in unit costs for regional jets and approximately a fifth of the reduction in unit costs of turboprops. Fuel costs are a greater portion of total unit cost reductions for regional jets for two reasons. First, fuel costs are a greater percent of the DOC of regional jets compared to turboprops, such that improvements in E_U have had a greater impact on unit costs of regional jets. Second, the improvement in the E_U of regional jets has been greater than that of turboprops, as shown in Chapter 3. Finally, as for large aircraft, a relationship between regional aircraft price and unit cost was found, but only after the influence of stage length was accounted for, showing that regional airlines are also willing to trade higher capital costs for lower operating costs.

5.2 SOURCES AND MANIPULATION OF DATA

Throughout the chapter, aircraft operating cost data from the Department of Transportation's Form 41 schedule P5.2 is used [11]. Aircraft prices are taken from the Airliner Price Guide series [14]. Aircraft direct operating (DOC) and investment costs (I) reported by the airlines are split into categories as outlined in Table 5-1. The DOC+I categories are organized according to the groupings used in [12]. The sum of flying operations and direct maintenance costs make up the direct operating cost (DOC), while investment costs (I) consist of depreciation and amortization accounts. When appropriate, they are taken together as the DOC+I. DOC+I has four principle components; crew, fuel, maintenance and investment costs. 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. Maintenance covers the costs of labor and materials directly attributable to the maintenance and repair of aircraft and other flight equipment. Investment costs, meanwhile, include the charges incurred for depreciation and amortization on operating and capital leases. It should be noted that although Form 41 accounts attempt to impose uniformity among reported data, airlines often employ various accounting methods. As a result, there are differences in reporting procedures among the airlines, introducing considerable variability in the data.

In the analyses that follow, costs are presented in 1996 dollars to account for inflation using Gross Domestic Product (GDP) deflators provided by the U.S. Department of Commerce's Bureau of Economic Analysis (BEA) (Appendix E). This allows for comparison of costs across different time periods. In addition, fuel costs have been normalized when appropriate to account for the significant fluctuations in price that have occurred over the last forty years. Fuel costs in a given year are normalized to the price of fuel in 1996. This procedure, along with the annual fuel prices used, is detailed in Appendix F.

Category	Accounts and Descriptions			
Flying Operations	51230	Pilots and Copilots Salaries	51470	Rentals (operating lease)
	51240	Other Flight Personnel	51530	Other Supplies
	51281	Trainees and Instructors	51551	Insurance Purchased - General
	51360	Personnel Expenses	51570	Employee Benefits and
	51410	Professional and Technical	51580	Pensions
		Fees and Expenses	51680	Injuries, Loss, and Damage
	51437	Aircraft Interchange Charges	51690	Taxes - Payroll
	51451	Aircraft Fuels	51710	Taxes - Other Than Payroll
	51452	Aircraft Oils		Other Expenses
Direct Maintenance	52251	Labor - Airframes	52462	Materials - Aircraft Engines
	52252	Labor - Aircraft Engines	52721	Airworthiness Allowance
	52431	Airframe Repairs - Outside		Provision - Airframes
	52432	Aircraft Engine Repairs -	52723	Airframe Overhauls Deferred
	52437	Outside		(credit)
	52461	Aircraft Interchange Charges	52726	Airworthiness Allowance
		Materials – Airframes		Provision - Engines
			52728	Aircraft Engine Overhauls
				Deferred (credit)
Depreciation	70751	Airframes	70755	Other Flight Equipment
	70752	Aircraft Engines	70758	Hangar and Maintenance
	70753	Airframe Parts	70759	Equipment
	70754	Aircraft Engine Parts		General Ground Property
Amortization	70741	Developmental and	70761	Capital Leases - Flight
		Preoperating Costs	70762	Equipment
	70742	Other Intangibles		Capital Leases – Other
Other	70981	Expense Of Interchange Aircraft - Flying Operations	70982	Expense Of Interchange Aircraft – Maintenance

Table 5-1: Categorization of Form 41 cost accounts.

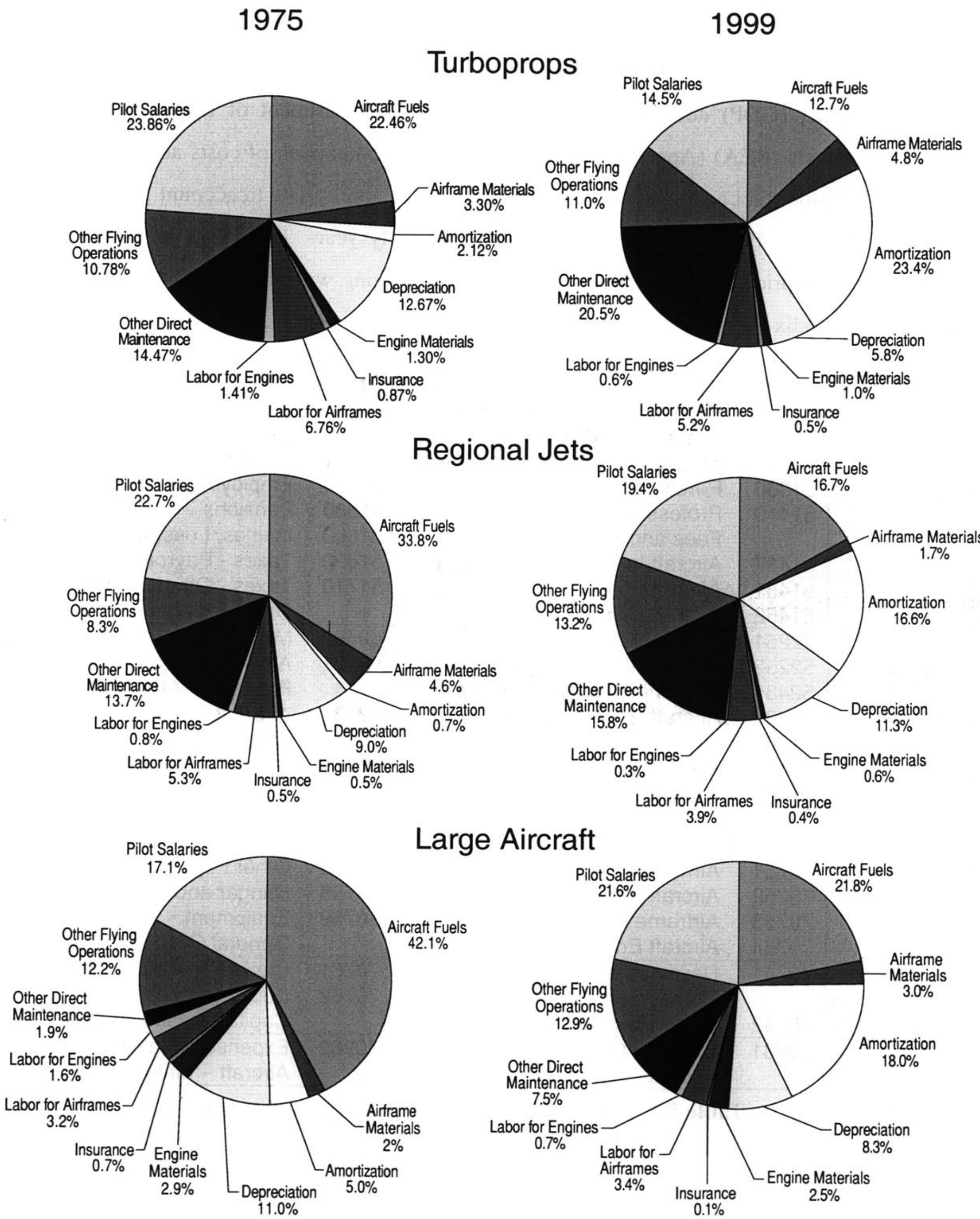


Figure 5-1 DOC+I breakdown of regional aircraft

5.3 REGIONAL AIRCRAFT OPERATING COST BREAKDOWN

Regional aircraft have different economic characteristics compared to larger narrow and wide body aircraft, including lower fuel costs as a percent of operating and ownership costs. Figure 5-1 provides a breakdown of DOC+I in 1975 and 1999 for the large jets considered in [12] and the regional jets and turboprops examined in this thesis. Fuel costs have not been normalized. It can be seen that fuel costs are a significantly smaller percentage of DOC+I for regional jets, and smaller still for turboprops. Lower fuel costs are largely offset by increased maintenance costs, which make up a significantly higher portion of DOC+I for regional aircraft.

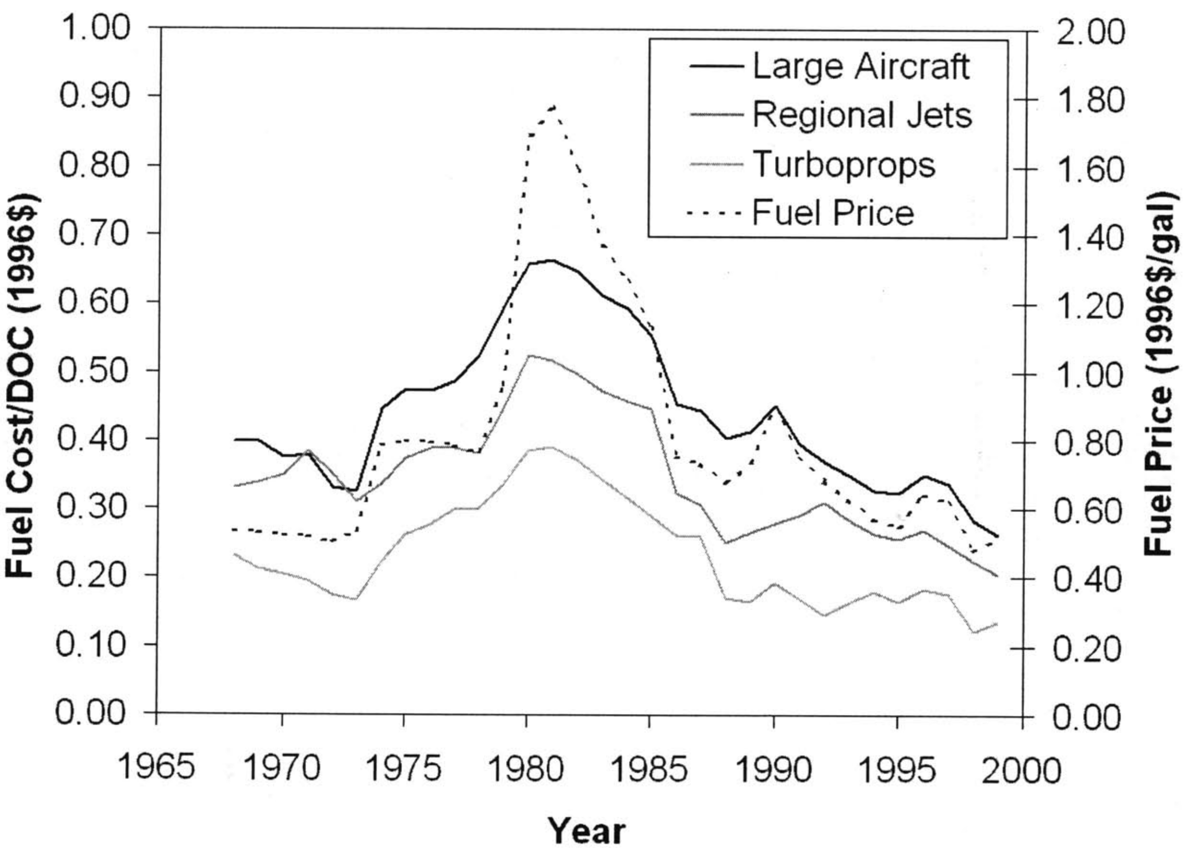


Figure 5-2 Historical values of fuel cost as % of DOC

Figure 5-2 shows the historical fluctuations of fuel as a percentage of DOC for large aircraft, regional jets and turboprops. It can be seen that during the fuel crisis of the late 1970's, the fuel component of DOC for large aircraft was more than 65%. By contrast, that of the regional jet slightly exceeded 50%, while remaining below 40% for turboprops. Since the spike in fuel price caused by the Gulf

War in 1990, fuel as a component of DOC has decreased gradually to 26% in 1999 for large aircraft, 20% for regional jets, and 13% for turboprops. While fuel costs are an important component of operating costs for all types of aircraft, other costs such as maintenance become increasingly important for regional aircraft, potentially limiting the ability of fuel efficiency improvements to contribute to reductions in operating costs. The next section explores the influence of these additional costs on the direct operating costs of regional aircraft on a per mile basis.

5.4 REGIONAL AIRCRAFT UNIT COSTS

The concept of a unit cost is useful for evaluating the economic performance of aircraft. Measured in units of DOC/ASM, it represents the cost of a unit of output of potential passenger service. Figure 5-3 plots the average DOC/ASM cost for regional and large aircraft types. The historical trend in large aircraft DOC/ASM shows a 25%-35% improvement between 1959 and 1995, the result of improvements in avionics and reductions in maintenance and fuel costs. In contrast, regional aircraft

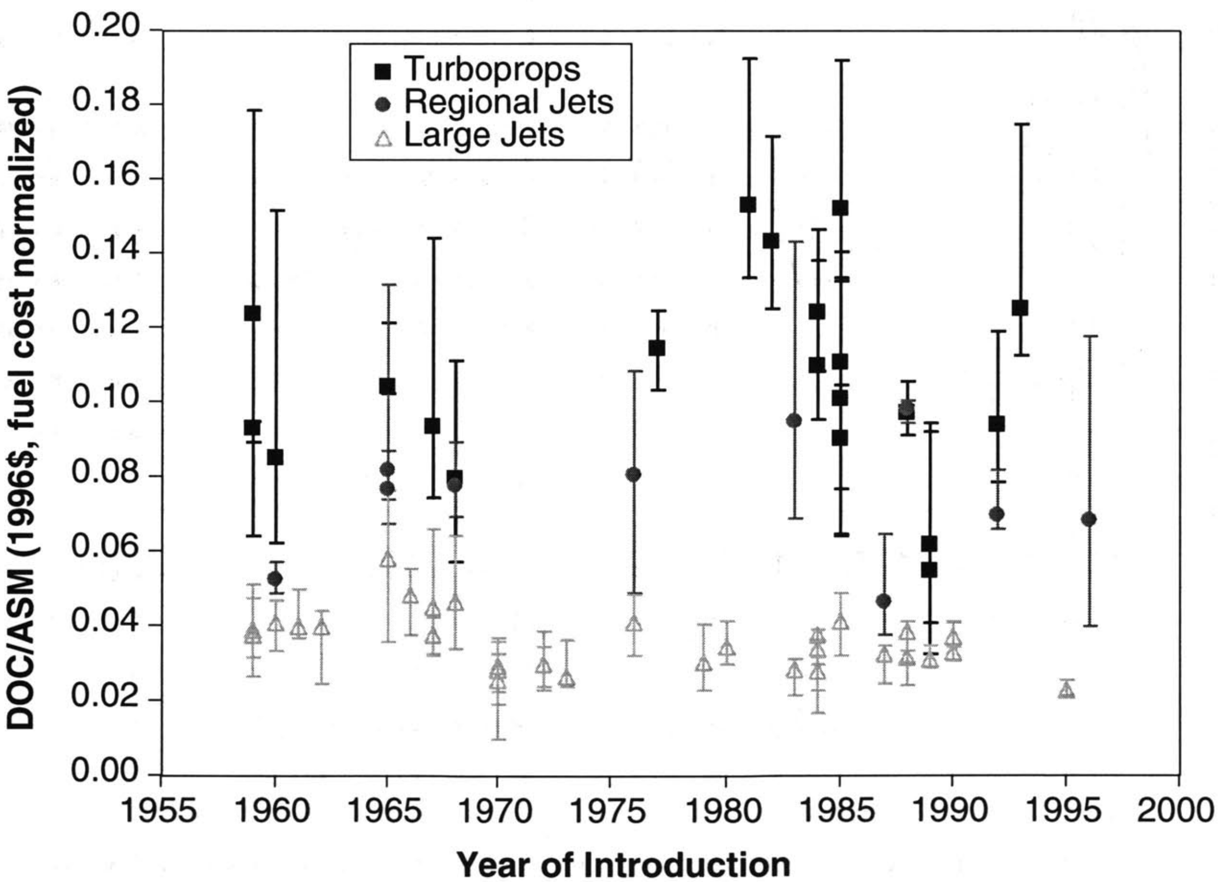


Figure 5-3 Unit direct operating costs of large jets, regional jets and turboprops

show no distinct upward or downward historical trend, and they exhibit considerable variability both within the same aircraft type and from one aircraft 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 the fact that regional aircraft typically operate at load factors 10%-20% lower than large aircraft is considered, regional aircraft are 2½-6 times more expensive to operate than large aircraft on a 1996$/ASM basis. The high unit costs of regional aircraft are reflected in the yields of regional airlines (the price charged per RPM), which in 1999 were approximately 2½ times as high as those charged by the major airlines [2].

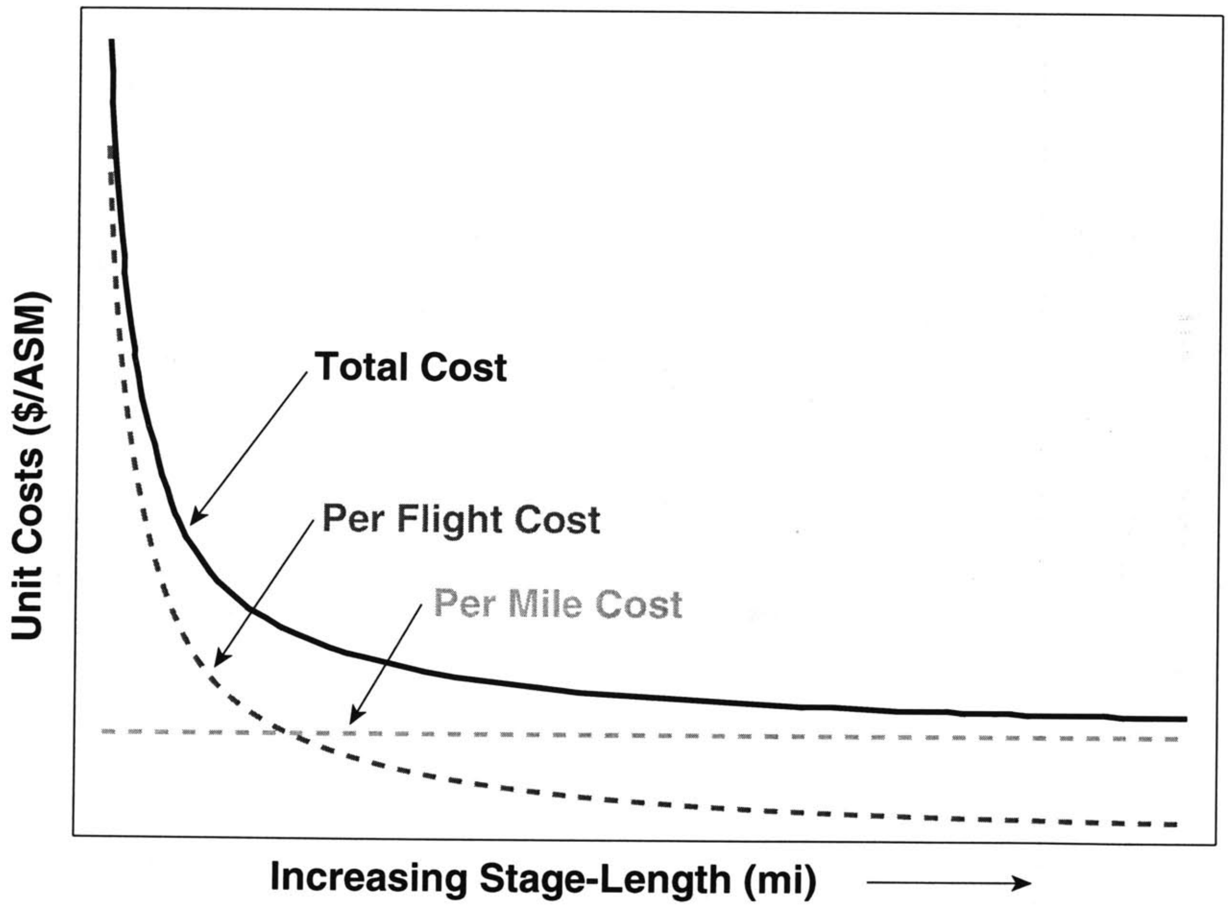


Figure 5-4 Contribution of fixed and variable costs to DOC/ASM

To explain these characteristics, a multivariable regression analysis was performed to identify the key parameters that determine the DOC/ASM of regional aircraft. Several potential explanatory variables were considered based on insight gained from previous work [12] and with additional knowledge of the particular characteristics of regional aircraft. Stage length, capacity, energy usage and aircraft year of introduction (YOI) were chosen as initial regressors.

Stage length was chosen as an explanatory variable because of its importance in determining the contribution of fixed costs to total unit costs. Costs are referred to as *fixed* if they are incurred every time an aircraft completes a take-off and landing cycle. They do not vary with stage length flown. Longer-flying aircraft have a greater number of miles over which to spread these costs, and their contribution to DOC/ASM decreases with increasing stage length. They are therefore less important for longer-flying large aircraft, but they contribute significantly to DOC/ASM at short stage lengths. Other costs, such as fuel and pilot's wages, vary in some relation to stage length, and therefore increase with increasing stage length, but remain constant on a per mile basis. Such costs are referred to as *variable*, or *per mile*, costs. Figure 5-4 illustrates how the contribution of both per cycle and per mile cost change with increasing units of distance.

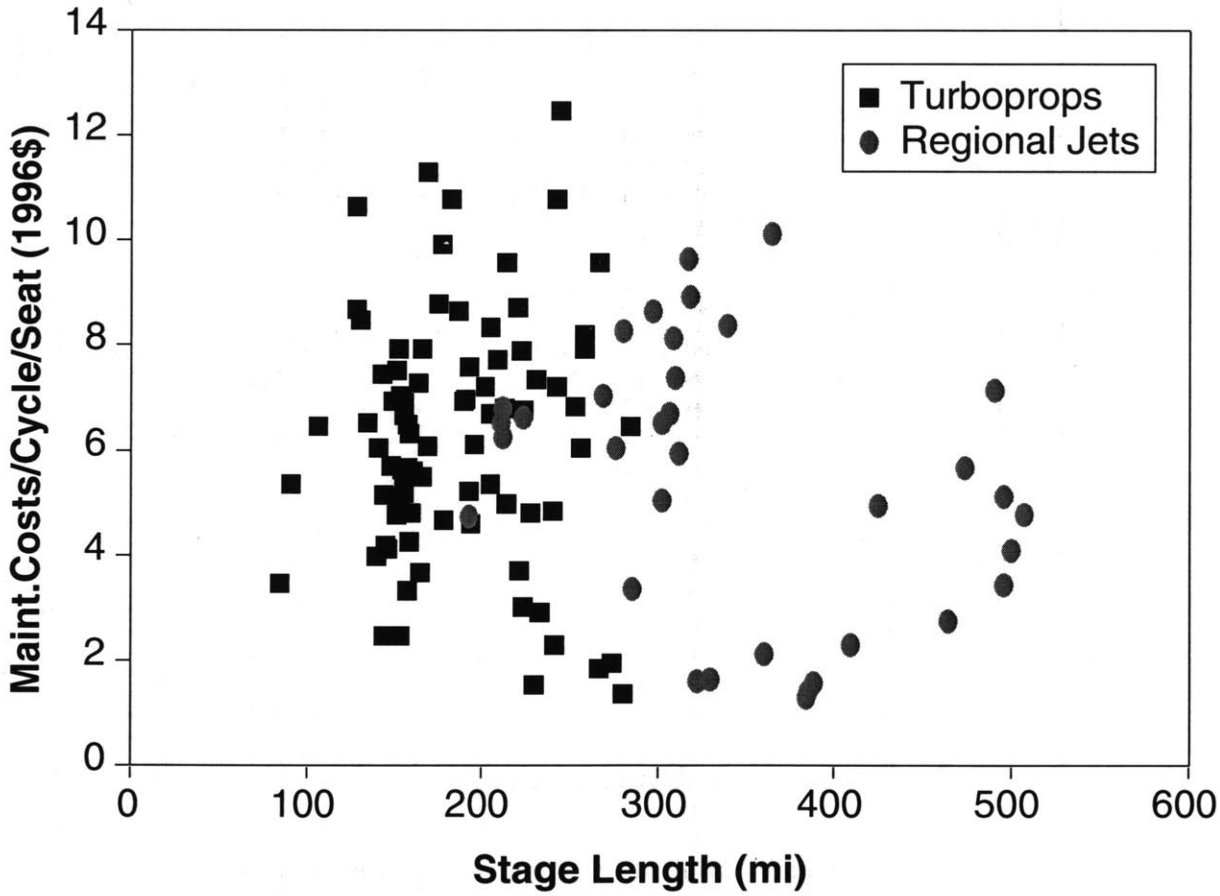


Figure 5-5 Variation of maintenance costs with stage length

Figure 5-5 and Figure 5-6 show how maintenance and flying operations costs on a per cycle, per seat basis vary with stage length. With the exception of flying operations costs for regional jets, neither cost categories exhibit very distinct trends with increasing stage length, suggesting that fixed costs are

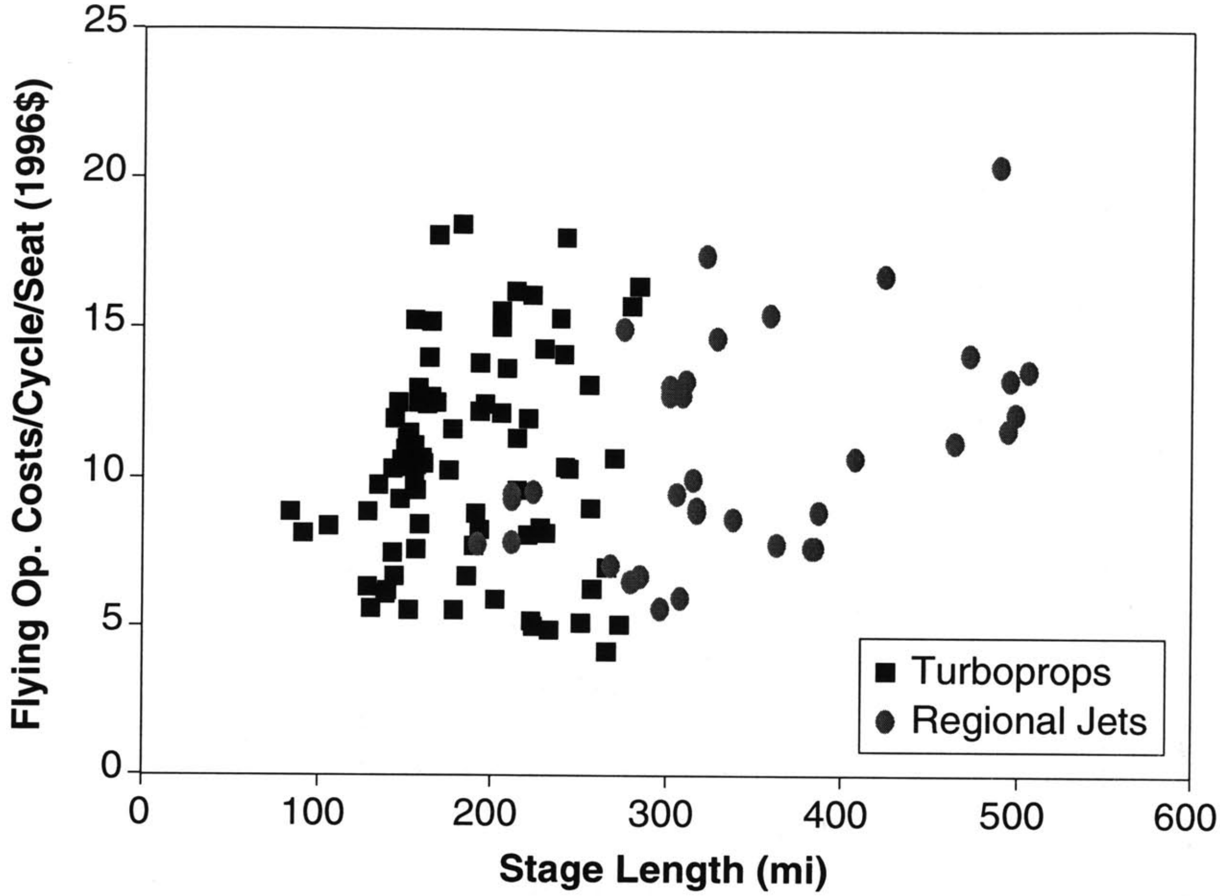


Figure 5-6 Variation of flying operations costs with stage length

important in both categories for regional aircraft. It is therefore not surprising that the contributions of both categories to DOC/ASM increase rapidly as stage length decreases, as shown in Figure 5-7 Including the stage length, or more accurately, the stage length to some negative power, in the regression was expected to capture the significant contribution of fixed costs to the unit costs of regional aircraft.

Aircraft capacity was chosen as another explanatory variable. Like stage length, increments in capacity increase the ASMs with which unit costs are absorbed. Figure 5-8 shows how unit costs vary with capacity.

Finally, energy usage and YOI were also included in the regression. Decreases in energy usage, as described in Chapter 3, should decrease unit costs by lowering fuel costs. The YOI was included to account for historical improvements in technologies that may have contributed to decreasing unit costs not accounted for by energy usage.

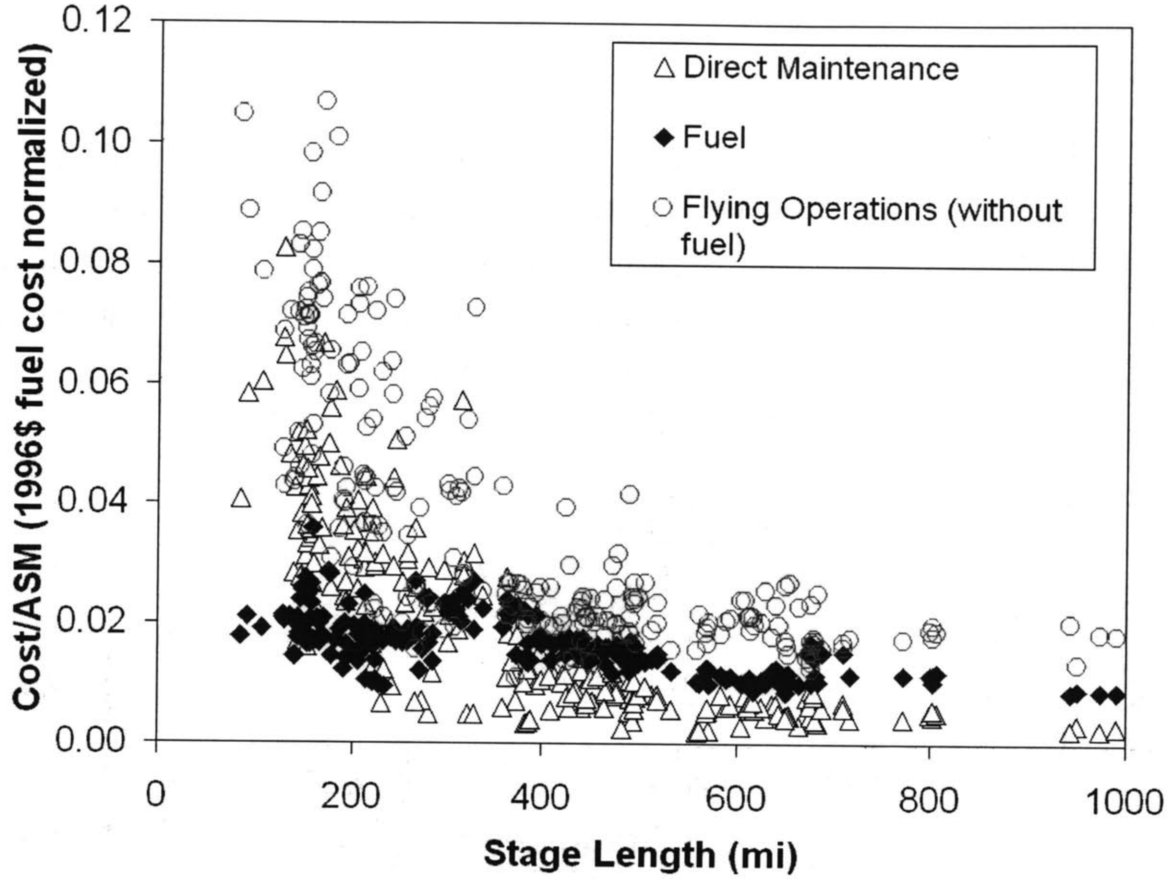


Figure 5-7 Influence of stage length on different components of DOC/ASM

A least squares regression was performed with the explanatory variables transformed as in Equation 5-1. Both capacity (CAP) and stage length (SL) were initially raised to a power of minus one to reflect their expected inverse relationship to unit costs. Cost data from Form 41 was aggregated on a per aircraft, per year basis to help filter irregular data points and to normalize variability caused by different airline reporting practices as well as seasonal variations. Only data from 1990 to 1999 was used because of an irregularity in the F41 traffic database that prevented stage lengths from being calculated for records dated prior to 1990. As a result, data for the CV-580, CV-600, FH-227, YS-11, Metro II, BAC-111-200/400, and BAE146-100, and CV-880 are not included in the analysis. 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.

The preliminary regression results revealed important collinearity between regressors. For turboprops and regional jets, YOI and 1/CAP were found to be significantly correlated to gal/ASM. These

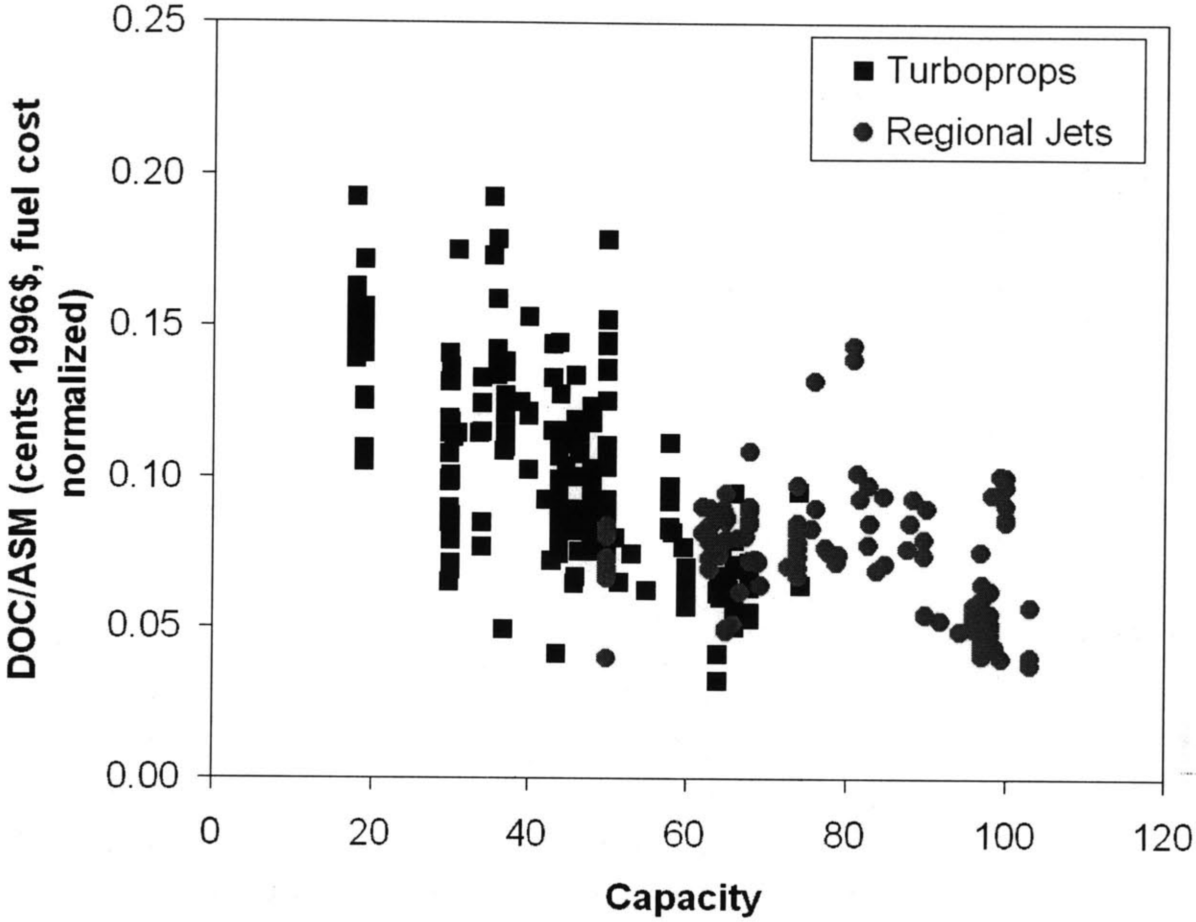


Figure 5-8 Variation in unit costs with capacity

relationships are not unexpected given that gal/ASM has improved for both regional jets and turboprops over time, and that larger aircraft generally have lower energy usage. In the case of regional jets, YOI and 1/CAP were also correlated. Indeed, a review of the regional jets considered in this thesis reveals that, with the exception of the 50-seat CRJ-200 and EMB-145, capacities of newly introduced aircraft have increased over the time period considered.

$$\frac{DOC}{ASM} = A \cdot \frac{1}{SL} + B \cdot \frac{1}{CAP} + C \cdot YOI + D \cdot \frac{gal}{ASM} + E \tag{5-1}$$

The regression analysis was repeated with knowledge of the correlations among variables. It was decided to remove 1/CAP and YOI for both turboprops and regional jets because of the ability of the gal/ASM variable to capture the effects of both. Further, gal/ASM has particular meaning in the context of this thesis because of its relationship to aircraft technologies and emissions. Because of the correlations, the gal/ASM should be interpreted as a general "level of technology" variable that, as was shown in Chapter 4 depends on both technological and operational parameters. Maintenance or other costs that decrease because of the use of newer technologies will also be captured by this variable. The models obtained from the regression are shown in Equations 5-2 and 5-3 for turboprops and regional jets respectively. Note that transforming the 1/SL term to $1/(SL)^{0.5}$ resulted in a better fit for turboprops. A more complete summary of the regression analysis can be found in Appendix G.

Turboprops:

$$\frac{DOC}{ASM} = 1.7920 \cdot \frac{1}{\sqrt{SL}} + 3.2780 \cdot \frac{gal}{ASM} - 0.1022 \tag{5-2}$$

$R^2 = 0.697$, N = 78, t/t_{CRIT} for coefficients: 3.93, 3.29, 3.06 respectively

Regional Jets:

$$\frac{DOC}{ASM} = 15.9158 \cdot \frac{1}{SL} + 1.2950 \cdot \frac{gal}{ASM} - 0.0178 \tag{5-3}$$

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

The regression results show that 70% of the variation in DOC/ASM for turboprops, and 79% of the variation in DOC/ASM of regional jets can be explained by distance flown and E_U. The models themselves can be interpreted physically. The 1/SL term represents the contribution of fixed costs to the total unit costs. As expected, this contribution will decrease as stage length increases. The gal/ASM term, on the other hand represents the contribution of variable costs to total unit costs.

The relationships identified in Equations 5-2 and 5-3 are consistent with the relationship between unit costs and energy intensity for large aircraft identified in [37] and shown here as Equation 5-4. Conversion to \$/RPM and RPM/gal units yields Equation 5-5. Additional manipulation of this equation reveals that DOC/RPM is approximately a linear function of gal/RPM for large aircraft, as shown in Equation 5-6. It is similar in form to the DOC/ASM model developed for regional aircraft, without the 1/SL term. This is not surprising given that fixed costs contribute a negligible amount to the unit costs of large aircraft.

$$\ln\left(\frac{DOC(¢)}{RPK}\right) = -0.958 \cdot \ln\left(\frac{ASK}{kg} \cdot \alpha\right) + 3.83 \tag{5-4}$$

Where:
RPK = Cents/Revenue passenger kilometers
ASK = Available seat kilometers
kg = kilograms of fuel

$$\alpha = \text{RPK/ASK}$$

$$\ln\left(\frac{DOC(\$)}{RPM}\right) = -0.958 \cdot \ln\left(\frac{RPM}{gal}\right) + 0.372 \tag{5-5}$$

$$\frac{DOC}{RPM} = \exp(0.372) \cdot \left(\frac{RPM}{gal}\right)^{-0.958} \approx K \cdot \frac{gal}{RPM} \tag{5-6}$$

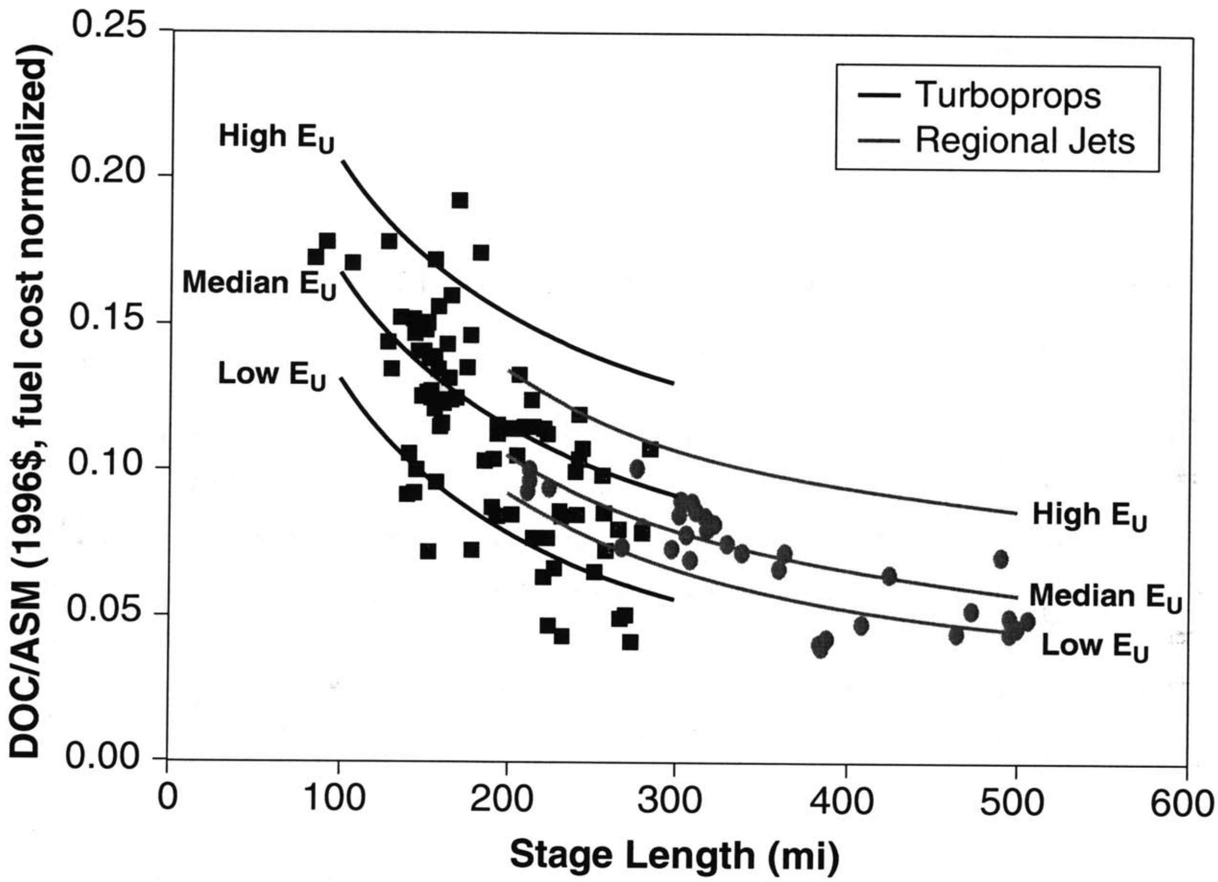


Figure 5-9 Variation of DOC/ASM according to stage length and E_U

Equations 5-2 and 5-3 are particularly useful for comparing the unit cost characteristics of turboprops and regional jets at common stage lengths and at typical values of energy usage. Figure 5-9 shows the estimated unit costs of turboprops and regional jets at high, low, and median values of energy usage plotted vs. stage length. High, low and median values were taken from the average values of E_U for different aircraft types discussed in Chapter 3, and they are listed in Table 5-2. Actual operational data is also superimposed on the curves.

	Turboprops		Regional Jets	
E_U Level	E_U (gal/ASM)	Aircraft	E_U gal/ASM	Aircraft
High	.0394	CV-600	.0556	BAC-111-400
Median	.0276	Shorts 360	.0337	Fokker F-28-400
Low	.0166	ATR-72	.0237	Fokker 100

Table 5-2 High, median and low values of E_U used in Figure 5-9

Figure 5-9 highlights differences in the unit costs of turboprops and regional jets. It can be seen that between 200 and 300-mile stage lengths, turboprops with low E_U are capable of achieving unit costs that are approximately 15% lower than regional jets with low E_U. However, this is not the case as fuel efficiencies worsen. At median values of energy usage, regional jets actually have unit costs that are 9%-15% lower than turboprops. This suggests that, from a cost perspective, fuel-efficient regional jets are competitive with all but the most efficient turboprops.

The impact of both stage length and level of technology on unit costs is also made apparent in Figure 5-9. In terms of the influence of stage length, a turboprop with low energy usage will experience a 77% increase in unit costs by flying a 150-mile route compared to a 300-mile route. Similarly, a low energy usage regional jet will incur a 45% increase in unit costs by flying a 250-mile stage length instead of a 400-mile stage length. The dependence of regional aircraft unit costs on stage length explains the cost characteristics of regional aircraft identified in Figure 5-3. Specifically, regional aircraft have higher unit costs than large aircraft because they fly much shorter stage lengths. The variability in unit costs is caused by the significant impact even small differences in stage length flown can have on unit costs. Finally, regional jets have lower unit costs than turboprops because they have historically served longer routes.

The level of technology of an aircraft, represented by the energy usage, has a significant impact on unit costs. Figure 5-9 shows that a turboprop with high E_U flying a 200-mile route will have unit costs twice as high as an aircraft with low E_U. Similarly, a regional jet with a high E_U flying a 400-mile stage length will have unit costs 1.8 times higher than a regional jet with low E_U.

In general, it can be seen that, for any given stage length, the DOC/ASM savings achieved by a low E_U compared to a high E_U turboprop is between 0.070-0.090 $/ASM. This corresponds to a 40%-60% savings depending on stage length flown. For regional jets, unit costs reductions at a given stage length are smaller, and are between 0.039-.041 1996$/ASM, which corresponds to savings between 30%-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 gal/ASM) by the fuel price

(1996$/ASM, fuel cost normalized), the unit cost savings in going from high to low E_U can be calculated. This calculation yields a 0.0146 1996$/ASM fuel cost saving in going from high E_U to low E_U for turboprops, and a 0.0204 1996$/ASM fuel cost saving for regional jets. Fuel cost savings make up 16%-21% of the unit cost savings of turboprops, but make up 49%-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/ASM for regional jets than for turboprops. This is not surprising, given that fuel costs are a smaller portion of total DOC for turboprops compared to regional jets, and that the E_U of regional jets has improved a greater amount over the time period covered than the E_U of regional jets.

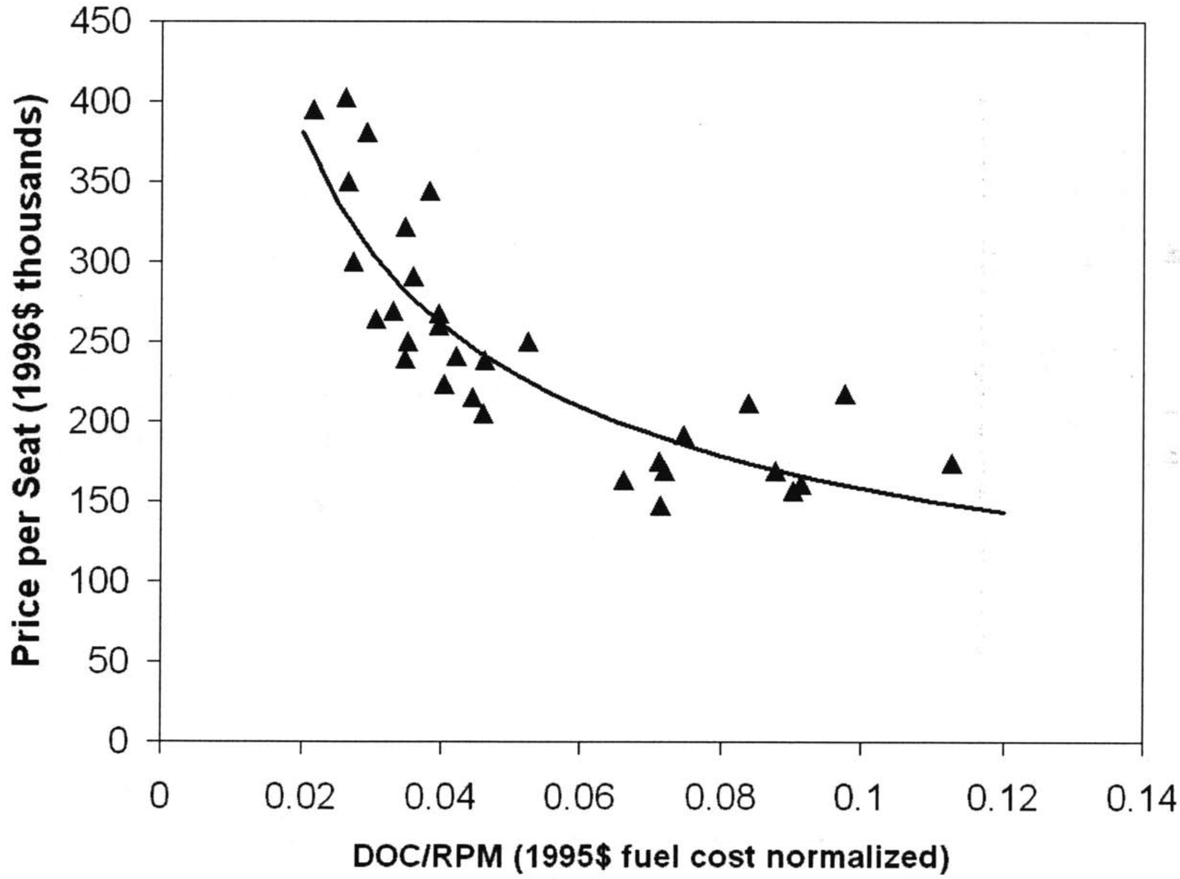


Figure 5-10 Aircraft Price and operating cost trade-off for large aircraft

5.5 AIRCRAFT PRICE AND OPERATING COST RELATIONSHIP

Large aircraft prices, normalized on a per seat basis, have been found to be correlated to DOC/RPM, as shown in Figure 5-10 [12]. This suggests that airlines 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 5-11 shows how regional aircraft prices vary with average unit costs on a DOC/ASM basis calculated from operational data. It is difficult to assess whether or by how much increases in aircraft price have impacted unit costs. To reduce variability introduced by differences in stage length flown, the unit cost models for turboprops and regional jets developed in Section 5.4 were used to estimate unit costs for all aircraft when flying 250-mile stage lengths.

Figure 5-12 shows the variation in aircraft price when unit costs have been adjusted for a 250-mile stage length. A clearer pattern emerges, showing that unit costs are lower for more expensive aircraft. Specifically, a 0.05 $/ASM decrease in unit costs from 0.125 $/ASM-0.075 $/ASM is worth between $80-$90 thousand per seat in purchase price (all figures in 1996 dollars, fuel costs normalized).

It was shown in Chapter 4 that, in general, aircraft technologies have improved over time resulting in more fuel-efficient aircraft. However, the ability of new aircraft to impact aviation's total emissions will depend on how fast it takes to integrate them into the airline fleet. Technology take-up is the process of fleet replacement through which old aircraft are either sold or retired and new aircraft are purchased or leased. The rate of technology take-up depends on many on many factors, including safety requirements, growth in demand, prices of labor and fuel, industry profitability, and the availability of financing [38]. 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 [1][32]. The relationships between aircraft price and unit operating costs shown in Figure 5-11 and Figure 5-12 quantify what major and regional airlines have been willing to pay in increased capital costs for reductions in operating costs in the last forty to fifty years. Possible approaches to promoting faster technology take-up may include finding ways to lower the price of increments in unit costs savings, thereby making it more affordable for airlines to maintain younger and more efficient aircraft fleets.

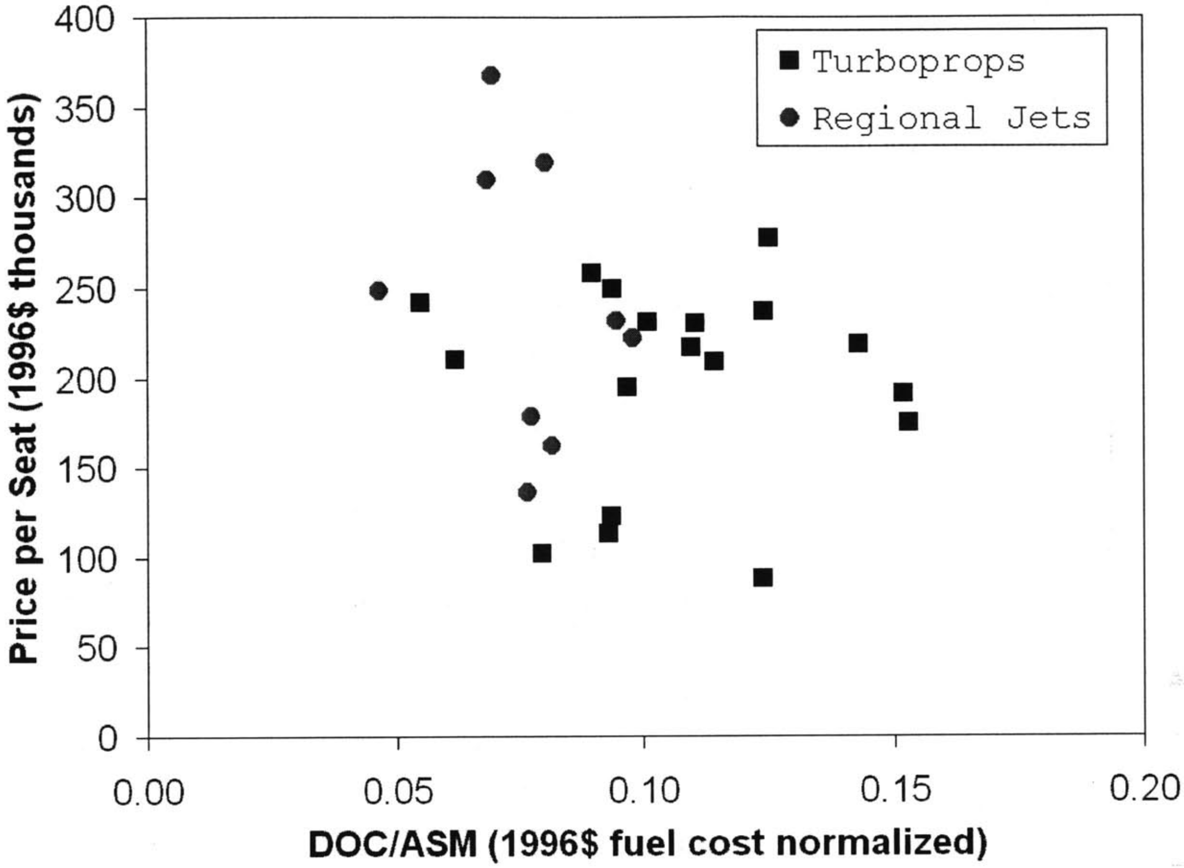


Figure 5-11 Variation of aircraft price with unadjusted unit cost

5.6 CHAPTER SUMMARY

The potential for economic gains has always provided an incentive to reduce the operating costs of aircraft. It was shown in [12] that for large aircraft, such reductions have been achieved using technologies that have simultaneously improved fuel efficiency and reduced the impact of aviation on the environment. Further, along with the lower operating costs came more expensive aircraft, suggesting that airlines are willing to exchange capital costs for reductions in operating costs.

Regional aircraft, however, have different cost characteristics than large aircraft. First, fuel costs are a smaller component of operating costs, reducing the impact of fuel efficiency improvements on cost reductions. Second, the unit costs of regional aircraft have a significant fixed cost component. The importance of these fixed costs varies with stage length to a negative power, such that variations in distance flown can have as big an impact on unit costs as the level of technology of an aircraft.

When the significant influence of stage length is accounted for, it can be shown that advances in technologies have permitted fuel, maintenance, and flying operations cost savings of 40%-60% for turboprops and 30%-46% for regional jets. Fuel cost savings make up approximately half of the total reduction in unit costs for regional jets and approximately a fifth of reduction in unit costs of turboprops, suggesting that fuel efficiency improvements have a bigger impact on the operating costs of regional jets than turboprops. This is consistent with the fact that fuel has historically been a larger portion of the DOC of regional jets than for turboprops, and that the E_U of regional jets has improved more than the E_U of turboprops over the time period considered (49% vs. 37%). Finally, it was shown that more expensive regional aircraft have unit operating costs lower than less expensive aircraft when the effect of stage length is normalized. Specifically, a 0.05 (1996$/ASM) reduction in unit costs is worth approximately $80-$90 thousand per aircraft seat.

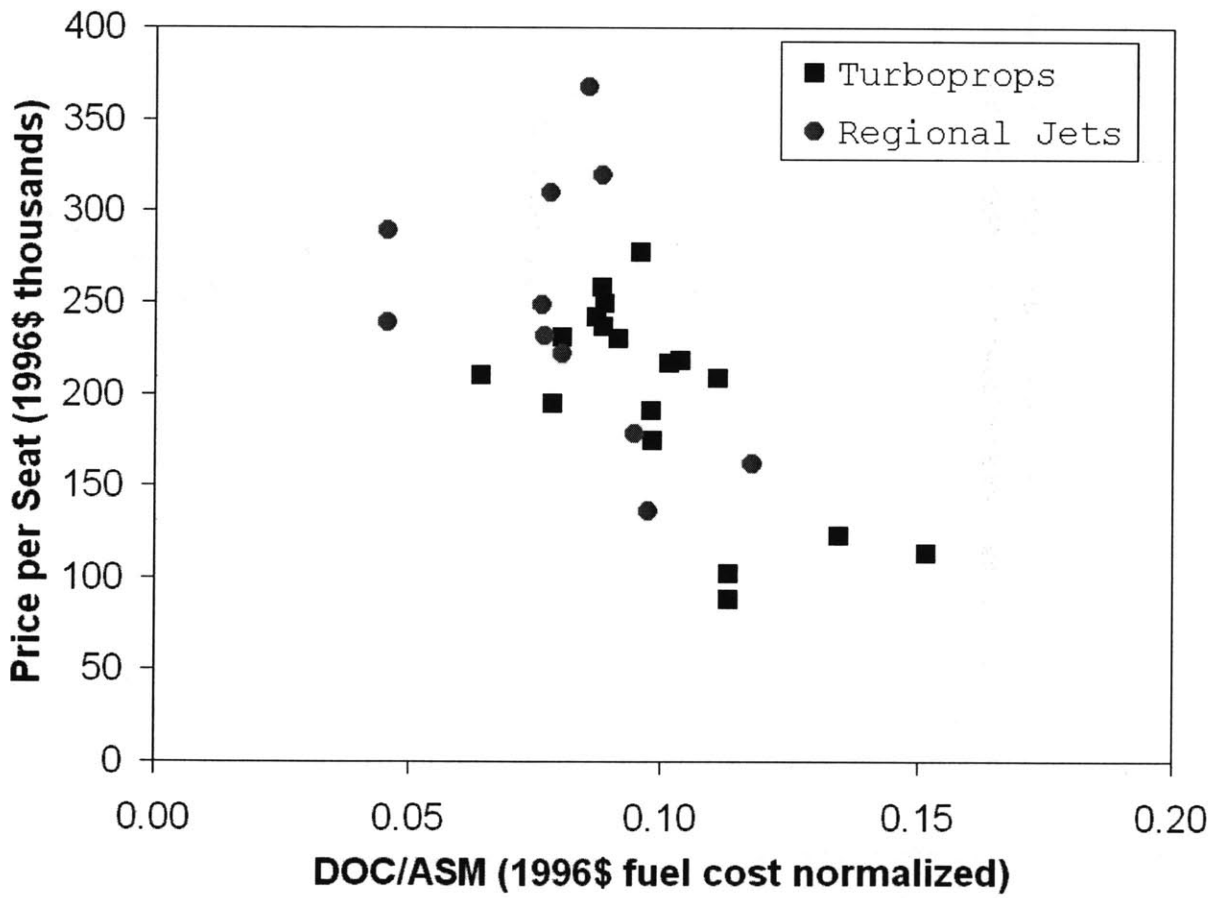


Figure 5-12 Variation of regional aircraft price with adjusted unit cost

6 SUMMARY AND CONCLUSIONS

The demand for air travel has increased approximately 9% since 1960, and forecasts from various organizations predict that it will grow at approximately 5% per year at least though 2015 [1][2]. This rapid growth has prompted increasing concern about the impact of aircraft operations on the environment. Aircraft are a source of community noise, and their emissions contribute significantly to air pollution in the vicinity of airports. More recently, attention has focused on the contribution of aviation activities to climate change and the amount of energy consumed by aviation, which is directly proportional to emissions of greenhouse gases. Industry, government and environmental groups are currently debating the effectiveness and feasibility of various policy options aimed at reducing aircraft emissions, including emissions trading and limits on cruise levels of fuel consumption.

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 [2], they account for 7% of jet fuel use and for 40%-50% of total departures [9][10]. In addition, regional traffic, stimulated by the widespread acceptance of the regional jet, is expected to grow faster than the rest of industry.

In this context, this thesis has identified the mechanisms that have enabled historical reductions in the energy intensity of regional aircraft by quantitatively describing the technological, operational and cost characteristics of turboprop and regional jet aircraft. These characteristics were compared to those of larger narrow and wide body aircraft, providing two different perspectives of technology evolution, airline operations and the impact of costs on both. In addition, this thesis provided insight into the potential impact of the rapid growth of regional jet use on the energy efficiency of the US aviation system.

It is shown that advances in regional aircraft technologies have resulted in a 37% reduction in energy usage for turboprops and a 49% reduction for regional jets since 1960, compared to the 60% improvement experienced by large aircraft. However, regional aircraft have fuel efficiencies are 1.5

to 2 times worse than larger aircraft. This difference was found not to be the result of large differences in the technological sophistication of the various aircraft types, but rather as a result of 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. The fuel consumed during these operations has an important influence on total fuel efficiency. In addition, increases in regional aircraft operations, which already make up a significant number of the take-offs and landings performed at U.S. airports, may lead to increased delays at already congested airports, potentially reducing the ground efficiencies of other aircraft as well. The rising popularity of the regional jet will likely only compound the problem, since these aircraft require longer runways than the turboprops they are replacing.

Regional aircraft also spend a larger fraction of their airborne time climbing to altitude at inherently higher rates of fuel burn. Turboprops are at an advantage compared to regional jets because they are designed to cruise efficiently several thousand feet below jet aircraft and can therefore reach cruising altitude and speed faster than regional jets. Regional jets again have the potential to complicate congestion problems because they fly at the same altitude as large aircraft, increasing traffic in high altitude airspace.

Differences in ground and airborne efficiencies generally explain why regional aircraft are less efficient than large aircraft. They also explain why regional jets are approximately 10% less efficient than turboprops. In particular, turboprops achieve higher airborne efficiencies at shorter stage lengths than regional jets.

Even though turboprops were shown to have higher fuel efficiencies than regional jets, it was found that airlines were able to operate regional jets at higher load factors than turboprops. As a result, while the E_U of the regional jet fleet was 40% higher than for the turboprop fleet in 1970, the E_I was only 9% higher. In 1999, the E_U of the regional jet fleet was 13% higher than for the turboprop fleet, but the E_I was only 3% higher. This shows that to take advantage of the superior environmental performance of turboprops, they must be more efficiently utilized.

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. Thus, improvements in fuel efficiency have less of an impact on the unit costs. Advances in technologies have permitted fuel, maintenance, and flying operations cost savings of 40%-60% for turboprops and 30%-46% for regional jets. Fuel cost savings make up approximately half of the total reduction in unit costs for regional jets and approximately a fifth of reduction in unit costs of turboprops.

The unit costs of regional aircraft were shown to vary not only with the level of technological sophistication of the aircraft, but also with the stage length flown. Aircraft that fly short stage lengths have fewer miles over which to spread fixed costs that are incurred every time an aircraft performs a flight, regardless of how far it flies. As a result, these fixed costs contribute significantly to the unit costs of regional aircraft, which are two to five times more expensive to operate on a unit basis than large aircraft. When the fact that regional aircraft typically operate at load factors 10%-20% lower than large aircraft is considered, regional aircraft are 2½ to 6 times more expensive to operate than large aircraft on a 1996$/RPM basis. This is reflected in the yields of regional airlines, which were on average 2½ times higher than those of large aircraft [2]

A multivariable regression analysis revealed that the unit costs of regional aircraft were largely a function of the inverse of the stage length flown and energy usage. Using this model, the effect of stage length was normalized, revealing that, like large aircraft, the unit costs of regional aircraft have improved with time. The unit costs of turboprops have decreased 40%-60%, and those of regional jet aircraft have decreased 30%-46% since 1960. For turboprop aircraft, most of the reductions in unit costs have been the result of reductions in maintenance and other non-fuel costs, while reductions in fuel costs have made up the bulk of the savings for regional jets.

The conclusions drawn in this thesis about the technological, operational and cost characteristics of regional aircraft help explain why regional jets are gaining widespread acceptance with airlines. They also point out challenges with respect to energy efficiency and airport and airway congestion that the industry will have to address if regional jets replace turboprops to the extent forecast. The success of regional jets is often attributed to passenger preference, because of their speed, comfort and perceived safety relative to turboprops. But the success of the regional jet can also be traced to its economic characteristics and the ability of airlines to use them efficiently. Specifically, it was shown that technologically advanced regional jets could compete in terms of direct operating cost with all but the most efficient turboprops, 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, regional jets have historically operated at load factors approximately 10%-30% higher than turboprops. As a result, the E_I of the regional jet fleet has actually been comparable to or better than the E_I of the turboprop fleet.

The growth in the number of regional jets in service does, however, present some challenges. As was explained in Chapter 3, regional jets are primarily being used to service the hub airports of major airlines. A significant increase in their numbers has the potential to increase congestion at already congested airports. Furthermore, regional jets require longer runways than the turboprops they are replacing, potentially causing additional bottlenecks at airports where regional jet flights replace turboprop flights.

Turboprops ultimately have the potential to be more fuel-efficient than regional jets. However, for this potential to be realized, it is apparent that several issues must be addressed. First, turboprops operators must strive to achieve load factors similar to those achieved on regional jets. Second, manufacturers must find ways to change public perceptions of turboprops. Specifically, passenger comfort issues must be addressed through the use of technologies that reduce engine vibrations and cabin noise. Also, manufacturers may consider offering additional customer amenities, to allow airlines to offer full cabin service, as is available on regional jets. To address the speed disadvantage of turboprops compared to regional jets, manufacturers might invest in technologies that will permit operations at higher mach numbers. Speed gains will likely have to be balanced with increased fuel consumption. It is apparent that at the range of stage lengths flown by regional aircraft, factors other than fuel costs and fuel efficiency become increasingly important in aircraft purchasing decisions.

APPENDIX A: FORM 41 SCHEDULE T2 AND P5.2

FORM 41 SCHEDULE T2 ACCOUNTS MAINTAINED IN DATABASE

Account	Description
Z140	Revenue Passenger Miles
Z240	Revenue Ton Miles
Z280	Available Ton Miles
Z320	Available Seat Miles
Z410	Revenue Aircraft Miles Flown
Z510	Revenue Aircraft Departures Flown
Z610	Revenue Aircraft Hours (Airborne)
Z620	Non-Revenue Aircraft Hours (Airborne)
Z630	Revenue Aircraft Hours (Ramp to Ramp)
Z650	Total Aircraft Hours (Airborne)
Z810	Aircraft Days Assigned to Service – Carriers Equipment
Z820	Aircraft Days Assigned to Service – Carriers Routes
Z921	Aircraft Fuels Issued (Gallons)

FORM 41 SCHEDULE P5.2 ACCOUNTS MAINTAINED IN DATABASE

Account	Description
51230	Pilots and Copilots Salaries
51240	Other Flight Personnel
51281	Trainees and Instructors
51360	Personnel Expenses
51410	Professional and Technical Fees and Expenses
51437	Aircraft Interchange Charges
51451	Aircraft Fuels
51452	Aircraft Oils
51470	Rentals (operating lease)
51530	Other Supplies
51551	Insurance Purchased - General
51570	Employee Benefits and Pensions
51580	"""Injuries, Loss, and Damage """
51680	Taxes - Payroll
51690	Taxes - Other Than Payroll
51710	Other Expenses
52251	Labor - Airframes
52252	Labor - Aircraft Engines
52431	Airframe Repairs - Outside
52432	Aircraft Engine Repairs - Outside
52437	Aircraft Interchange Charges
52461	Materials - Airframes

52462	Materials - Aircraft Engines
52721	Airworthiness Allowance Provision - Airframes
52723	Airframe Overhauls Deferred (credit)
52726	Airworthiness Allowance Provision - Engines
52728	Aircraft Engine Overhauls Deferred (credit)
70751	Airframes
70752	Aircraft Engines
70753	Airframe Parts
70754	Aircraft Engine Parts
70755	Other Flight Equipment
70758	Hangar and Maintenance Equipment
70759	General Ground Property
70741	Developmental and Pre-operating Costs
70742	Other Intangibles
70761	Capital Leases - Flight Equipment
70762	Capital Leases - Other
52796	Applied Maintenance Burden - Flight Equipment
70739	Net Obsolescence and Deterioration - Expendable Parts
70981	Expense Of Interchange Aircraft - Flying Operations

APPENDIX B: SELECTED AIRCRAFT-ENGINE DESCRIPTIONS

TURBOPROPS

Aircraft Name	F41 Code	Engine	YOI	Capacity
Beech B-1900	405	PT6A-65B	1984	19
British Aero. BAE-ATP	408	PW 127D	1988	64
Convair CV-580	430	501-D22G	1960	50
Convair CV-600	435	Mk 542-4	1965	40
ATR-42 Aerospatial	441	PW 120	1985	46
ATR-72 Aerospatial	442	PW 124B	1989	65
Dornier 328	449	PW 119B	1993	31
Fokker/Fairchild F-27	450	Mk 536-2	1959	48
Fairchild Hiller FH-227	454	Mk 532-7	1967	45
SAAB-Fairchild 340A	456	CT7-5A	1985	34
Embraer EMB-120 Brasilia	461	PW118	1985	30
Nihon YS-11	465	Mk 542-4	1968	59
Swearingen Metro II SA-226	466	TP 331-3UW-303G	1970	20
Swearingen Metro III SA-227	467	TP 331-11U-612G	1985	18
British Aero. BAE Jetstream 31	469	TPE 331-10UG	1982	19
BAE Jetstream 41	471	TPE 331-14GR	1992	30
De Havilland DHC 8-100	483	PW 120A	1984	37
De Havilland DHC 8-300	484	PW 123	1998	41
Shorts 360	489	PT6A-65R	1981	36
Lockheed L-188A-08/188C	550	501-D13A	1959	74

REGIONAL JETS

Aircraft Name	F41 Code	Engine	YOI	Capacity
Fokker F28-1000	601	Mk 555-15P	1968	63
Fokker F-28-4000/6000	602	Mk 555-15P	1976	67
Fokker 100	603	Tay MK620-15	1987	98
Fokker 100	603	Tay MK650-15	1987	75
British Aero. BAC-111-400	610	Mk 511	1965	64
Canadair RJ-200/RJ-200ER	629	CF34-3B1	1995	50
Embraer EMB-145	675	AE 3007A	1996	50
Convair CV-880	825	CJ-805-3	1960	95
Avro Int'l Aerospace Avroliner RJ85	835	LF 507-1F	1993	82
British Aero. BAE-146-100/RJ70	866	ALF-502R-5	1983	88
British Aero. BAE-146-200	867	ALF-502R-5	1983	84
British Aero. BAE-146-300	868	ALF-502R-5	1988	99

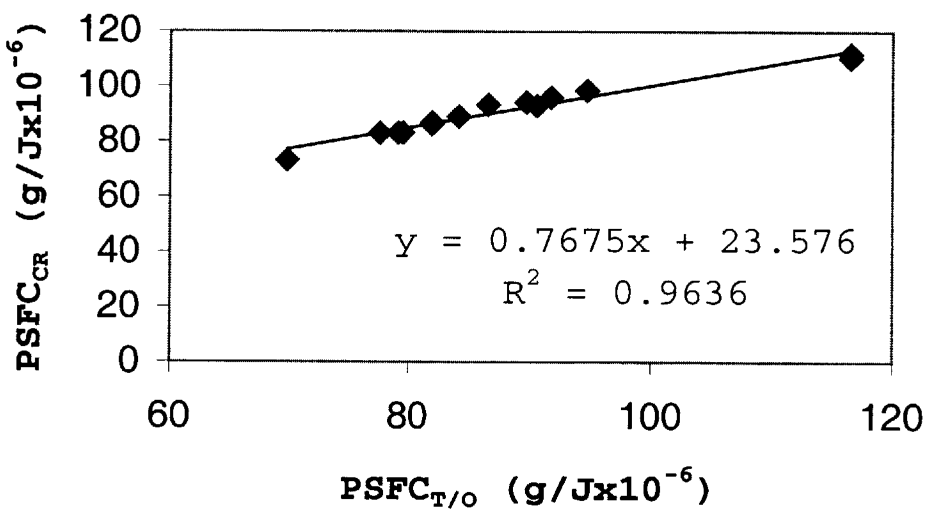
LARGE AIRCRAFT (FROM [12])

Name	F41 Code	Class	YOI	PAX High
Boeing B-737-500/600	616	NB	1990	113
Boeing B-737-400	617	NB	1988	144
Boeing B-737-300	619	NB	1984	132
Boeing B-737-100/200	620	NB	1967	105
Boeing B-757-200	622	NB	1984	186
Boeing B-767-200/ER	625	WB	1983	190
Boeing B-767-300/ER	626	WB	1987	228
Boeing B-777	627	WB	1995	291
Douglas DC-9-10	630	NB	1965	76
Douglas DC-9-30	640	NB	1966	99
Douglas DC-9-40	645	NB	1968	109
Douglas DC-9-50	650	NB	1976	121
MD-80 & DC-9-80 All	655	NB	1980	141
Airbus Industrie A-300-600/R/CF/RCF	691	WB	1984	262
Airbus Industrie A310-300	693	WB	1985	193
Airbus Industrie A320-100/200	694	NB	1988	148
Boeing B-727-200/231A	715	NB	1967	138
Douglas DC-10-10	730	WB	1970	261
Douglas DC-10-30	732	WB	1972	268
Douglas DC-10-40	733	WB	1972	264
Douglas MD-11	740	WB	1990	254
Lockheed L-1011-1/100/200	760	WB	1973	271
Lockheed L-1011-500Tristar	765	WB	1979	229
Boeing B-707-100B	802	NB	1959	132
Boeing B-707 300	806	NB	1959	149
Boeing B-707-300B	808	NB	1962	152
Boeing B-720-000	812	NB	1961	118
Boeing B-720-000B	814	NB	1960	110

APPENDIX C: SFC ESTIMATION PROCEDURE

In cases where cruise values of SFC were unavailable, they were estimated using take-off SFC data found in [16] and cruise vs. take-off SFC curve-fits. The curve-fits were calculated for turboprop and regional jet engines using data that was available. The curve fits are shown below, as well as the engines for which SFC was estimated.

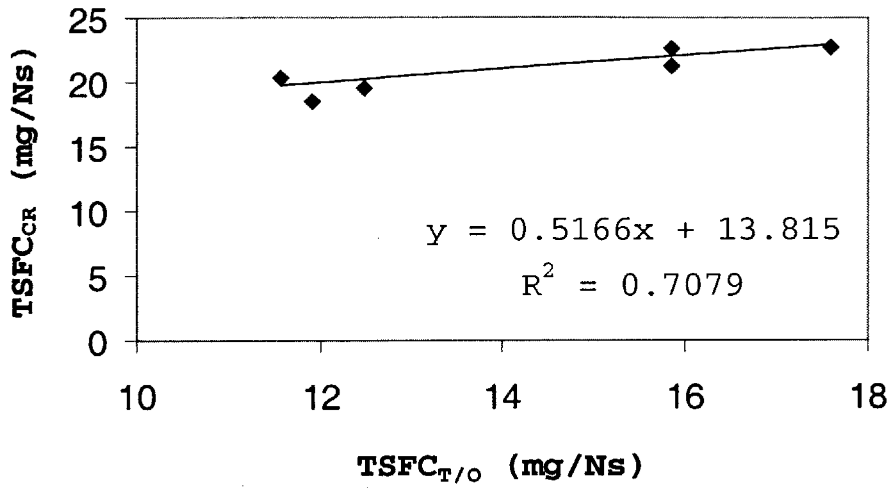
TURBOPROPS ENGINES



The above curve fit was used to estimate the $PSFC_{CR}$ of the following engines:

Engine	Aircraft
TP 331-3UW-303G	SA-226
TPE 331-10UG	BAE Jetstream 31
PW 119B	Dornier 328
TP 331-11U-612G	SA-227
TPE 331-14GR	BAE Jetstream 41

The regression for the turboprop engines has a standard error of 2.0999. Hence, the estimates for PSFC have an estimated error of ±6.2997 μg/J with 3σ confidence, ranging between 7%-8% of the estimated value.



The above curve was used to estimate the $TSFC_{CR}$ for the following engines:

Engine	Aircraft
CF34-3B1	RJ-200/RJ-200ER
LF 507-1F	Avro RJ85

The regression for the regional jet engines has a standard error of 0.8661. Hence the estimates for the $TSFC_{CR}$ have an estimated error of ±2.5982 mg/Ns with 3σ confidence, ranging between 13% and 14% of the estimated value.

APPENDIX D: BADA L/D ERROR ESTIMATE

L/D_{MAX} values for 18 of the 33 regional aircraft examined in this thesis were calculated using drag component coefficients found in BADA [15]. Because data contained in BADA is based on information derived from a variety of sources such as flight manuals and published literature, there is considerable variability associated with the data. To quantify this variability, L/D_{MAX} values were calculated for a group of thirteen large aircraft for which L/D_{MAX} data was published in [12]. The data published for large aircraft in [12] was verified by industry sources and is estimated to be correct to within ±5%. L/D_{MAX} values derived from BADA are compared below to the L/D_{MAX} values found in [12].

Aircraft	L/D_{MAX} from BADA	L/D_{MAX} from [12]	Difference
Boeing B-757-200	16.3082	16.9647	3.9%
Douglas DC-9-30	14.3444	13.6941	-4.7%
Airbus Industrie A-300-600/R/CF/RCF	15.7563	14.4706	-8.9%
Airbus Industrie A320-100/200	14.8178	15.8824	6.7%
Boeing B-727-200/231A	15.2145	13.7059	-11.0%
Douglas MD-11	17.6777	15.8824	-11.3%
Boeing B-747-400	15.8910	17.0588	6.8%
B-737-300	15.0756	14.1017	-6.9%
MD-80	15.8745	13.8118	-14.9%
B-767-300/300ER	19.0901	15.2941	-24.8%
A310-300	16.9750	16.3529	-3.8%
DC-10-10	20.8493	14.1176	-47.7%
L-1011-500Tristar	17.6777	14.7059	-20.2%

It can be seen that with the exception of four aircraft, L/D_{MAX} values calculated from BADA are within 11.3% of the L/D_{MAX} values identified in [12]. Errors associated with the four other aircraft are considerable, and may be due to several factors related to the methods used by the developers of BADA. So while it is certain that there are several aircraft for which BADA will yield very inaccurate L/D estimates, it is assumed for the purpose of this thesis that for most aircraft, the BADA estimate for L/D_{MAX} is within approximately ±12%. While this is a significant error, BADA was the only source found that could provide data for the wide-range of regional aircraft studied in this thesis.

APPENDIX E: GDP DEFLATORS

Year	Deflator
1968	26.3
1969	27.59
1970	29.06
1971	30.52
1972	31.82
1973	33.6
1974	36.62
1975	40.03
1976	42.3
1977	45.02
1978	48.23
1979	52.25
1980	57.04
1981	62.37
1982	66.25
1983	68.88

Year	Deflator
1984	71.44
1985	73.69
1986	75.31
1987	77.58
1988	80.21
1989	83.27
1990	86.51
1991	89.66
1992	91.84
1993	94.05
1994	96.01
1995	98.1
1996	100
1997	101.95
1998	103.22
1999	104.77

$$1996\,U.S.\$ = \left(\frac{GDP\ Deflator, 1996}{GDP\ Deflator, Year\ i} \right) Year\ i\ U.S.\$ \qquad \text{(E.1)}$$

Source: U.S Department of Commerce, Bureau of Economic Analysis, *National Income and Product Account Tables*, www.bea.doc.gov

APPENDIX F: FUEL PRICES AND PRICE NORMALIZATION PROCEDURE

Year	Jet Fuel Price (1996$/gallon)	Crude Oil Price (1996$/barrel)
1968	0.53	12.54
1969	0.53	12.54
1970	0.52	12.23
1971	0.52	12.33
1972	0.50	11.82
1973	0.53	12.74
1974	0.78	20.59
1975	0.80	20.90
1976	0.80	21.00
1977	0.78	20.69
1978	0.76	20.08
1979	0.96	25.99
1980	1.69	40.47
1981	1.77	54.23
1982	1.59	45.77
1983	1.37	40.27
1984	1.26	38.02
1985	1.13	34.05
1986	0.75	17.23
1987	0.73	20.59
1988	0.67	16.21
1989	0.73	19.47
1990	0.90	23.55
1991	0.75	18.65
1992	0.68	17.53
1993	0.63	15.29
1994	0.57	13.76
1995	0.55	14.88
1996	0.64	18.45
1997	0.62	16.82
1998	0.48	10.40
1999	0.51	10.70

$$Fuel\ Cost\ Normalized = \left(\frac{Fuel\ Price, 1996}{Fuel\ Price, Year\ i}\right) Fuel\ Cost, Year\ i \qquad \text{(F.1)}$$

All Costs in 1996$

Notes: The above prices and Equation F.1 are used to normalize fuel prices where appropriate. For the period 1968 to 1979, jet fuel prices are obtained based on crude oil prices. Equation F.2 shows the relationship between jet fuel prices and crude oil prices between 1980 and 1999. The regression equation is then used to convert crude oil prices to jet fuel prices for the period 1968 to 1979.

$$\textit{Fuel Price, Year } i \text{ (1996\$)} = 0.0299 \times \textit{Crude Oil Price (1996\$), Year } i + 0.1579 \tag{F.2}$$
$$R^2 = 0.9866$$

Source: Air Transport Association [33] and Energy Information Administration [5].

APPENDIX G: UNIT COST REGRESSION SUMMARIES

TURBOPROPS

Summary of Fit

R^2	0.696583
R^2 Adj	0.688492
Root Mean Square Error	0.01824
Mean of Response	0.11322
Observations	78

Parameter Estimates

Term	Estimate	Std. Error	t-ratio	Prob>|t|
Intercept	-0.102247	0.016797	-6.09	<0.0001
gal/ASM	3.2279891	0.501302	6.54	<0.0001
1/SQR(SL)	1.7919594	0.228736	7.83	<0.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F-Ratio	Prob>F
gal/ASM	1	1	0.01389075	42.7580	<0.0001
1/SQR(SL)	1	1	0.01993868	61.3745	<0.0001

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.05593751	0.027969	86.0923
Error	75	0.02436519	0.000325	Prob>F
C Total	77	0.08030270		<0.0001

REGIONAL JETS

Summary of Fit

R^2	0.786057
R^2 Adj	0.771794
Root Mean Square Error	0.00924
Mean of Response	0.070996
Observations	33

REGIONAL JETS CONT.

Parameter Estimates

Term	Estimate	Std. Error	t-ratio	Prob>|t|
Intercept	-0.017827	0.009726	-1.83	<0.0768
gal/ASM	15.915757	1.973163	8.07	<0.0001
1/SL	1.2950083	0.307326	4.21	<0.0002

Effect Test

Source	Nparm	DF	Sum of Squares	F-Ratio	Prob>F
gal/ASM	1	1	0.00555520	65.0622	<0.0001
1/SL	1	1	0.00151606	17.7561	<0.0002

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.00941128	0.004706	55.1122
Error	30	0.00256148	0.000085	Prob>F
C Total	77	0.01197276		<0.0001

REFERENCES

[1] Intergovernmental Panel on Climate Change, *Aviation and the Global Atmosphere*, Cambridge University Press, 1999

[2] Federal Aviation Administration, *FAA Aerospace Forecast Fiscal Years 2000-2011*, 2000

[3] Boeing, *Boeing Market Outlook 2000*, 2000

[4] Airbus Industrie, *Airbus Global Market Forecast 2000-2019*, 2000

[5] Energy Information Administration, *Annual Energy Review*, US Department of Energy, 2000

[6] ICAO Secretariat, *ICAO Facing Complex and Evolving Challenges in the Environmental Field*, ICAO Journal, September 1999

[7] Vincedon, M., von Wrede, R., *Aircraft Builder Continually Seeking New Ways to Limit Impact on the Environment*, ICAO Journal, September 1999

[8] Dobbie, L., *Airlines See Direct Link Between Improved Environmental Performance, Sustainable Growth*, ICAO Journal, September 1999

[9] Air Transport Association, *2000 Annual Report*, 2000

[10] www.raa.org

[11] U.S. Department of Transportation, Bureau of Transportation Statistics, *Form 41 Schedule P5.2 and T2*, U.S. Department of Transportation, 1968 - 1999

[12] Lee,J.J., *Historical and Future Trends in Aircraft Performance, Cost and Emissions*, MS Thesis, Massachusetts Institute of Technology, 2000

[13] Jane's, *Jane's All the World's Aircraft*, Samson Low, Martin & Co., Editions 1960 through 2000

[14] Thomas, A., Richards, J., *The Airliner Price Guide of Commercial-Regional & Commuter Aircraft*, Fall 1995 Edition

[15] Eurocontrol, *Base of Aircraft Data*, Revision 3.3, December 2000

[16] Gunston, B., ed, *Jane's Aero-Engines*, Jane's, September 1998

[17] International Civil Aviation Organization, *ICAO Engine Exhaust Emissions Data Bank*, First Edition, 1995

[18] Back Aviation Solutions, *Back Fleet Database*, Back Associates, Version 4.0, April 2001

[19] General Accounting Office, *Aviation and the Environment: Airport Operations and Future Growth Present Environmental Challenges*, August 2000

[20] Environmental Protection Agency, *Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft*, April 1999

[21] Federal Aviation Administration, *2000 Aviation Capacity Enhancement Plan*, December 2000

[22] 62 FR 89 Environmental Protection Agency, *Control of Air Pollution From Aircraft and Aircraft Engines, Emission Standards and Test Procedures; Final and Proposed Rule*, May 1997

[23] Poole, R., Butler, V., *Airline Deregulation: The Unfinished Revolution*, RPPI, December 1998

[24] Trigerio, W., *The Impact of Regional Jets on Congestion in the NAS,* The MITRE Corporation, February 1999

[25] Diamond, M., *Regional Jet Trends and U.S. Airports*, SH&E International Air Transport Consultancy, 2000 ACI-NA Economic Specialty Conference, April 2000

[26] Hudson, M., Rolls-Royce-Allison Inc., Personal Correspondence, 2001

[27] Ojha, S. K., *Flight Performance of Aircraft*, AIAA, 1995

[28] Anderson, J. D., *Introduction to Flight, Third Edition, McGraw Hill*, 1989

[29] Greene, D. L., *Commercial Air Transport Energy Use and Emissions: Is Technology Enough?*, Conference on Sustainable Transportation – Energy Strategies, 1995

[30] Medda, B., *ATR-72 – The First Civil Aircraft with a Carbon Fibre Reinforced Plastic Wing*, Aerospatiale Aircraft Division, 1989

[31] Long, G., *Future Directions in Aeronautical Composites*, 21st ICAS Congress 13-18 September 1998, Melbourne, Australia

[32] Arthur D. Little Limited, *Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK*, Final Report to Department of Environment, Tansport and Regions (DETR), November 2000

[33] Air Transport Association, *Fuel Cost and Consumption*, 2000

[34] Szodruch, J., Oelkers, W., Schumacher, J., *The Environmental Challenge as Chance For the Next Century Aircraft Design*, 21st ICAS Congress 13-18 September 1998, Melbourne, Australia

[35] Association de Transport Regionale, *ATR Presentation – The -500 Series*, March 2000

[36] Simpson, R., Belobaba, P., *Notes for Air Transportation Economics, Chapter 5: Air Transportation Operating Costs*, Massachusetts Institute of Technology, August 1996

[37] Lee, J.J., Lukachko, S.P., Waitz, I.A., Schafer, A., *Historical and Future Trends in Aircraft Performance, Cost and Emissions*, Upcoming in the Annual Review of Energy and the Environment, June 2001

[38] Balashov, B., Smith, A., *ICAO Analyses Trends in the Fuel Consumption by World's Airlines*, ICAO Journal, August 1992

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