Historical and Future Trends in Aircraft Performance, Cost, and Emissions

by

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B.S., Mechanical Engineering

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Submitted to the Department of Aeronautics and Astronautics and
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Abstract

Air travel is continuing to experience the fastest growth among all modes of transport. Increasing total fuel consumption and the potential impacts of aircraft engine emissions on the global atmosphere have motivated the industry, scientific community, and international governments to seek various emissions reduction options. Despite the efforts to understand and mitigate the impacts of aviation emissions, it still remains uncertain whether proposed emissions reduction options are technologically and financially feasible.

This thesis is the first of its kind to analyze the relationship between aircraft performance and cost, and assess aviation emissions reduction potential based on analytical and statistical models founded on a database of historical data. Technological and operational influences on aircraft fuel efficiency were first quantified utilizing the Breguet range equation. An aviation system efficiency parameter was defined, which accounts for fuel efficiency and load factor. This parameter was then correlated with direct operating cost through multivariable statistical analysis. Finally, the influence of direct operating cost on aircraft price was statistically determined.

By comparing extrapolations of historical trends in aircraft technology and operations with future projections in the open literature, the fuel burn reduction potential for future aircraft systems was estimated. The economic characteristics of future aircraft systems were then determined by utilizing the technology-cost relationship developed in the thesis. Although overall system efficiency is expected to improve at a rate of 1.7% per year, it is not sufficient to counter the projected annual 4 to 6% growth in demand for air transport. Therefore, the impacts of aviation emissions on the global atmosphere are expected to continue to grow. Various policy options for aviation emissions reduction and their potential effectiveness are also discussed.

Thesis Supervisor: Ian A. Waitz
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Nomenclature

Roman

FC	Fuel consumption
FE	Fuel efficiency
g	Gravity constant
SL	Stage length
V	Velocity
W	Weight

Greek

α	Load factor
$\delta_{\text{correction}}$	Correction factor for deviation in the calculation of the Breguet range equation
$\eta_{\text{aviation system}}$	Aviation system efficiency
η_{energy}	Aircraft energy efficiency in available seat miles per gallon of fuel burn
$\eta_{\text{load factor}}$	Load factor expressed as efficiency of utilizing aircraft seats
σ^2	Variance

Subscripts

f	Fuel
i	Individual passenger
p	Payload
r	Reserve, fuel
s	Structure, aircraft

Glossary

ADL	Arthur D. Little
AERO	The Dutch Aviation Emissions and Evaluation of Reduction Options
Airborne Hours	Time duration for which aircraft stays in the air
ASE	Aviation system efficiency
ASM	Available seat miles
ATM	Air traffic management, or available ton miles
Block Hours	Time duration for which aircraft leaves away from the gate when blocks are removed from the wheels
Block Speed	Average speed of aircraft for a trip based on block hours (Stage Length/Block Hours)
CAEP	Committee on Aviation Environmental Protection
CO	Carbon monoxide
CO_2	Carbon dioxide
DLR	The Deutsches Zentrum für Luft- and Raumfahrt
DOC	Direct operating cost
DOC+I	Direct operating cost plus investment
DTI	Department of Trade and Industry
ECoA	Environmental Compatibility Assessment
EDF	Environmental Defense Fund
ETSU	The Energy Technology Support Unit
FESG	Forecasting and Economic Support Group
gal	Gallons of jet fuel
GDP	Gross domestic product
GHG	Greenhouse gas
GNP	Gross national product
H_2O	Water vapor
HC	Hydrocarbons
HSCT	High-speed civil transport
ICAO	International Civil Aviation Organization

IPCC	Intergovernmental Panel on Climate Change
L/D	Lift-to-drag ratio
LEBU	Large-eddy break up devices
LFC	Laminar flow control
Load Factor	Percentage of seats filled by passengers (RPM/ASM)
LTO	Landing and takeoff
Minimum Hours	Minimum time duration for a trip
MPH	Miles per hour
MTOW	Maximum takeoff weight
NRC	National Research Council
NO_x	Nitrogen oxides
OEW	Operating empty weight
OEW/MTOW	Operating empty weight-to-maximum takeoff weight ratio
Payload	Weight of passengers and cargo carried on board
RPM	Revenue passenger miles
SFC	Specific fuel consumption
SO_x	Sulfur oxides
Stage Length	Aircraft distance flown for a trip between airports
TAM	Total aircraft miles
UHB	Unducted ultra-high-bypass ratio engines
UNFCCC	UN Framework Convention on Climate Change
USDOT	U.S. Department of Transportation
UV-B	Ultraviolet-B
VLA	Very large aircraft
WWF	World Wildlife Fund

Chapter 1

Introduction

1.1 Background

Air travel is continuing to experience the fastest growth among all modes of transport, averaging 5 to 6% per year. Increasing total aviation emissions from aircraft engines and their potential impacts on the global atmosphere have drawn the attention of the aviation industry, the scientific community, and international governments. Aircraft engines emit a wide range of greenhouse gases (GHGs) including carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), sulfur oxides (SO_x), and particulates. The radiative forcing from these aircraft emissions discharged directly at altitude is estimated to be 2 to 4 times higher than that due to aircraft carbon dioxide emissions alone, whereas the overall radiative forcing from the sum of all anthropogenic activities is estimated to be a factor of 1.5 times that of carbon dioxide emissions at the ground level (IPCC, 1999).

If the strong growth in air travel continues, world air traffic volume may increase five-fold to as much as twenty-fold by 2050 compared to the 1990 level and account for roughly two-thirds of global passenger-miles traveled (IPCC, 1999; Schafer and Victor, 1997). Global modeling estimates directed by the Intergovernmental Panel on Climate Change (IPCC) show that aircraft were responsible for about 3.5% of the total accumulated anthropogenic radiative forcing of the atmosphere in 1992, and their radiative forcing may increase to 5.0% of the total anthropogenic forcing with a 1σ uncertainty range of 2.7% to 12.2% by 2050 (IPCC, 1999).

Given the strong growth in air travel and increasing concerns associated with the effects of aviation emissions on the global atmosphere, the aviation industry is likely to face a significant environmental challenge in the near future (Aylesworth, 1996). Current estimates show that global air traffic volume is growing so fast that total aviation fuel consumption and subsequent aviation emissions' impacts on climate change will continue to grow despite future improvements in engine and airframe technologies and aircraft operations (IPCC, 1999; Greene, 1995). This implies that current technological and operational improvements alone may not fully offset the increasing aviation emissions while the aviation sector sees an impetus to find alternatives to mitigate the potential effects of aviation emissions on the global atmosphere.

In response to this, a global dialog has arisen to address the growing environmental concerns of aviation. The United Nations (UN) gave the International Civil Aviation Organization (ICAO) the authority to monitor aviation industry's emissions reduction efforts and seek further options to mitigate the impacts of aviation emissions on local air quality and the global atmosphere through its Committee on Aviation Environmental Protection (CAEP). In a broader perspective of climate change, the Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCC), which was adopted in December 1997, was the first international initiative to include two provisions that were particularly relevant to aviation emissions.

Despite these various efforts to understand and mitigate aviation's emissions impacts, it still remains uncertain which emissions abatement options are feasible ones under the various constraints of the aviation sector. Most importantly, it is not clear whether proposed emissions abatement options are financially feasible for the aviation sector. Air transport requires higher capital and operating costs than other modes of transport do while its typical profit margin is only 5% (NRC, 1992). Thus, economic feasibility may be one of the most important limiting factors in aviation emissions abatement efforts.

In this regard, insights into future aviation emissions mitigation require the simultaneous understanding of the relationship between technological improvements and their associated economic characteristics as accepted by the aviation sector in the past. However, very little system-level understanding of feasible aviation emissions abatement technologies and costs exists at present. Hence, this thesis is the first of its kind to analyze the relationship between aircraft performance and cost, and assess aviation emissions reduction potential based on analytical and statistical models founded on a database of historical data.

1.2 Goals and Objectives

The primary goal of this thesis is to quantitatively understand technological and operational influences on aircraft performance as measured by environmental metrics relevant to aviation's impacts on climate change and relate the performance metrics to aircraft cost in order to determine the technological and economic feasibility of aviation emissions reduction potential in the future.

In order to accomplish the primary goal, two analysis objectives are identified as follows:

(A) To understand historical trends in aircraft performance and cost and establish a quantitative relationship between them.
(B) To project the technological and economic characteristics of future aircraft systems and assess total emissions reduction potential for the aviation sector.

1.3 Methodology

The analysis approach of this thesis consists of two phases. In the first phase, a comprehensive technology-cost relationship is determined by analyzing historical data for aircraft engine, aerodynamic, and structural technologies as well as aircraft direct operating cost (DOC) and prices. The flying range of aircraft systems, as determined by technologies and operational conditions, is analytically understood by utilizing the Breguet range equation and contrasted to that observed in actual aircraft operations data. By further employing the Breguet range equation, aircraft fuel consumption measured in fuel burn per revenue passenger-mile (RPM) is modeled based on technology and operability parameters. A multivariable statistical analysis is then employed to establish a quantitative relationship between aviation system efficiency (ASE), which is defined to capture improvements in aircraft technology and operations, and DOC. Lastly, the relationship between DOC and aircraft prices is also statistically analyzed.

In the second phase, projections are made for the technological and economic characteristics of future aircraft systems. As for technological and operational improvements, extrapolations of historical trends and resulting fuel efficiency improvement are compared with the projections made by National Aeronautics and Space Administration (NASA) and other major studies in the open literature. The technology-cost relationship obtained in the first phase is then utilized to determine the potential DOC and price impacts of future aircraft systems. Once fuel efficiency improvement potential and resulting costs for future aircraft systems are projected, the feasibility of total aviation emissions reduction is examined. In addition, various policy measures to further mitigate aviation emissions growth are discussed.

1.4 Organization of the Thesis

Chapter 2 reviews the current status of aviation's impacts on the global atmosphere. Various aircraft emissions and their global warming potential are discussed in light of strong air traffic growth. Policy responses to address increasing concerns associated with aviation emissions are also discussed.

Chapter 3 examines historical trends in aircraft performance and cost. It first describes the data used and then discusses historical trends and drivers in aircraft fuel consumption, DOC, and prices.

Chapter 4 contains a parametric modeling of technology-operability-fuel consumption relationships. The impacts of technology and operability on aircraft fuel consumption are analytically quantified based on the Breguet range equation.

Chapter 5 describes the parametric modeling of a technology-cost relationship. By means of statistical analyses, the relationship between aircraft technology, DOC, and prices are quantified.

Chapter 6 examines future trends in aircraft performance, cost, and emissions. Aircraft fuel consumption reduction potential based on technological and operational improvements is discussed. The DOC and prices of future aircraft systems are also projected and discussed. Lastly, an outlook for future aviation emissions trends is discussed in light of expected improvements in aircraft fuel efficiency, air traffic growth, and various constraints in aviation systems.

Chapter 7 is a discussion of various policy options to further address growing aviation emissions. As an example of a market-based policy option, the impacts of a fuel tax on airline costs are examined based on an application of the technology-cost relationship developed in this thesis.

Chapter 8 summarizes the important findings of this thesis and draws conclusions relative to historical and future trends in aircraft performance, cost, and emissions.

All figures and tables are shown at the end of each chapter while all appendices are shown at the end of the thesis.

Chapter 2

Aviation Growth and Impacts on the Global Atmosphere

2.1 Introduction

This chapter reviews the current issues concerning growing aviation emissions and their impacts on the global atmosphere. Recent industry trends in air traffic growth and the technological and economic uniqueness of air transport systems are discussed as they are relevant to the climate-related environmental performance of aviation. Policy responses to address increasing concerns associated with aviation emissions are also discussed.

2.2 Aviation and the Environment Today

Aviation has now become a major mode of transportation and an integral part of the infrastructure of modern society. Currently, aircraft account for more than 10% of world's passenger miles traveled (Schafer and Victor, 1997b). Aviation directly impacts the global economy in the form of commercial passenger travel, freighter transport, and business travelers, involving the suppliers and operators of aircraft, component manufacturers, fuel suppliers, airports, and air navigation service providers. In 1994, the aviation sector accounted for 24 million jobs globally and financially provided $1,140 billion in annual gross output (IATA, 1997).

Because of its growing influence on the global economy and the wide range of industries involved, the activities of the air transport industry have been directly circumscribed by public interest. Energy use and environmental impact, as represented by air pollution and noise, are two important drivers for today's aviation sector. Currently, aviation fuel consumption corresponds to 2 to 3% of the total fossil fuels used worldwide, and more than 80% of this is used by civil aviation. In comparison, the entire transportation sector burns 20 to 25% of the total fossil fuels consumed. Thus the aviation sector alone uses 13% of the fossil fuels consumed in transportation, being the second largest transportation sector after road transportation (IPCC, 1996b).

In the future, total aviation fuel consumption is expected to continue to grow due to the rapid growth in air traffic volume. The subsequent increase in aircraft engine emissions has drawn particular attention among the aviation industry, the scientific community, and international governments in light global climate change. Through various forums among global participants, the effort to address these issues concerning growing aviation emissions has recently culminated in the IPCC Special Report on Aviation and the Atmosphere. In review of this document, the U.S. General Accounting Office (GAO) describes the current status of aviation and global climate as, "Aviation's effects on the global atmosphere are potentially significant and expected to grow" (GAO, 2000).

Aircraft engines emit a wide range of greenhouse gases including carbon dioxide, water vapor, nitrogen oxides, hydrocarbons, carbon monoxide, sulfur oxides, and particulates. The environmental issues concerning these aircraft emissions originally arose from protecting local air quality in the vicinity of airports and have grown to global environmental issues, two of which may bear the direct consequences of aviation. One is climate change, which may alter weather patterns, and, for supersonic aircraft, stratospheric ozone depletion and resultant increase in ultraviolet-B (UV-B) at the earth's surface (IPCC, 1999).

The resultant radiative forcing from these aircraft emissions discharged directly at altitude is estimated to be 2 to 4 times higher than that due to aircraft carbon dioxide emissions alone, whereas the overall radiative forcing from the sum of all anthropogenic activities is estimated to be a factor of 1.5 times that of carbon dioxide emissions at the ground level. IPCC global modeling estimates show that aircraft were responsible for about 3.5% of the total accumulated anthropogenic radiative forcing of the atmosphere in 1992 as shown in Figure 2.1 (IPCC, 1999).

A number of direct and indirect species of aircraft emissions have been identified to affect climate. Carbon dioxide and water directly influence climate by radiative forcing while their indirect influences on climate include the production of ozone in the troposphere, alteration of the methane lifetime, formation of contrails, and modified cirrus cloudiness. As for the species that have indirect influences on climate, nitrogen oxides, particulates, and water vapor impact climate by modifying the chemical balance in the atmosphere (IPCC, 1999).

The atmospheric sources and sinks of CO_2 occur principally at the earth's surface through exchange between the biosphere and the oceans. CO_2 molecules in the atmosphere absorb the infrared radiation from the earth's surface and lower atmosphere. An increase in CO_2 atmospheric concentration causes a warming of the troposphere and a cooling of the stratosphere. Thus, the atmospheric concentration of CO_2 is one of the most important factors in climate change (IPCC, 1999).

Water influences climate through its continual cycling between water vapor, clouds, precipitation, and ground water. Both water vapor and clouds have large effects on the radiative balance of climate and directly influence tropospheric chemistry. Water is also important in polar ozone loss though the formation of polar stratospheric clouds. This can directly affect the radiative balance of climate and have a chemical perturbation on stratospheric ozone. Furthermore, it takes longer for water emissions to disappear in the stratosphere than in the troposphere, so these aircraft water emissions increase the ambient concentration and directly impact the radiative balance and climate. Thus, new concerns have arisen regarding increasing contrails and enhanced cirrus formation. Figures 2.2a and 2.2b show a contrail coverage in 1992 and its estimate in 2050 (IPCC, 1999).

Nitrogen oxides are present throughout the atmosphere. Their influence is important in the chemistry of both the troposphere and the stratosphere as well as in ozone production and destruction processes. In the upper troposphere and lowermost stratosphere, NO_x emissions from subsonic aircraft tend to increase ozone concentrations. The ozone then acts as a greenhouse gas. On the other hand, NO_x emissions from supersonic aircraft at the higher altitudes tend to deplete ozone. NO_x emissions are also known to contribute to the reduction in the atmospheric lifetime of methane, which is another greenhouse gas (IPCC, 1999).

Particles related to aviation are principally sulfate aerosols and soot particles, which impact the chemical balance of the atmosphere. During operation, aircraft engines emit a mixture of particles and gases (*e.g.* SO_2) evolving into a variety of particles mainly composed of soot from incomplete combustion and sulfuric acid (H_2SO_4) from the sulfur in the aviation fuel. These particles then contribute to the seeding of contrails and cirrus clouds, potentially altering the total cloud cover in the upper troposphere. The sulfate aerosol layer in the stratosphere affects stratospheric NO_x and hence ozone (IPCC, 1999).

Overall, aircraft emissions are unique because they are directly discharged at the high altitudes and may affect the atmosphere in a different way than ground level emissions do. The radiative forcing from aircraft engine emissions is estimated to be 2 to 4 times higher than that due to aircraft carbon dioxide emissions alone, whereas the overall radiative forcing due to the sum of all anthropogenic activities is estimated to be a factor of 1.5 times that of carbon dioxide emissions at the ground level (IPCC, 1999).

2.3 Aviation Growth and Future Emissions

Driving the increasing concerns associated with aviation emissions is the strong growth in air travel. Air traffic growth has averaged about 5% per year during the period 1980 to 1995, and it is continuing to experience the fastest growth among all modes of transport (IPCC, 1999). Figure 2.3 shows historical trends and forecasts in modal market shares of passenger traffic volume for aircraft, railways, buses and automobiles in North America. If the strong growth in air travel continues, world air traffic volume may increase up to five- to twenty-fold by 2050 compared to the 1990 level and account for roughly two-thirds of global passenger-miles traveled (IPCC, 1999; Schafer, 1998). The evolution of this passenger transport is driven by two factors. One is the travel money budget, which indicates that humans dedicate a fixed share of their income to travel. The other factor is the travel time budget, which describes that humans spend an average of 1.1 hours on travel per day in a wide variety of economic, social, and geographic settings. Thus, human mobility rises as income level rises while the constant travel time budget pushes people towards faster transport modes as their demand for mobility increases (Schafer *et al.*, 1998; Schafer and Victor, 1997b). As a result, continuing growth in world population and gross domestic product (GDP) are expected to lead to a high growth in air travel demand in the future.

Most of today's market forecasts also show that air travel is expected to continue to grow rapidly at annual growth rates of 5 to 6%, as closely related with world economic growth as shown in Figure 2.4 (Schafer and Victor, 1997a; IPCC, 1999; FAA, 1999; Jeanniot, 1999; ICAO, 1997; Boeing, 1999; Airbus, 1999). ICAO and Federal Aviation Administration (FAA) economic growth forecasts are measured in GDP growth while Schafer and Victor and IPCC use the IS92a reference scenario where gloss national product (GNP) is used as a measure of economic growth.

Various emissions inventory studies have been conducted in parallel to air traffic growth scenarios. Figure 2.5 shows CO_2 emissions forecasts with future improvements in aircraft technologies. In absence of further technological improvements beyond 1997 level, global aviation CO_2 emissions per year is expected to triple by 2050. However, even with 25% fuel burn reduction technologies introduced in 2007 and 50% fuel burn reduction technologies introduced in 2025, total aviation CO_2 emissions level continues to grow. Even if zero CO_2 emission aircraft were introduced in 2027, total accumulated CO_2 emissions in the atmosphere would not drop below the 1990 level until 2040. Airport infrastructure and airspace congestion is also expected to cause extra fuel consumption leading to increased aircraft emissions around airports. Note, however, that these scenarios are subject to a great deal of uncertainty as to what are available technologies and what will happen to the economy. For example, if a second generation of high-speed civil transport (HSCT) aircraft could be operational in significant numbers, emissions in the stratosphere may become increasingly important. Additional factors that may change future emissions scenarios are the development of airport infrastructure, aircraft operating practices, and air traffic management (ATM) (IPCC, 1999).

Figure 2.6 shows estimated radiative forcing due to various aircraft emissions in the future. According to these IPCC global modeling estimates, the radiative forcing due to sum of all aircraft emissions may increase to 5.0% of the total accumulated anthropogenic radiative forcing of the atmosphere with 1σ uncertainty range of 2.7% to 12.2% by 2050 (IPCC, 1999). Note the high uncertainties associated with the radiative forcing effect of aviation emissions, as they are mainly attributable to limited scientific understanding and uncertainty in industry growth and technological improvements.

These uncertainties associated with the exact effects of aircraft emissions and tradeoffs between them (*e.g.* CO_2 against NO_x) currently make it difficult to focus abatement efforts. For example, the reduction of NO_x, particles, CO, and HC is complicated by the fact that engine fuel efficiency improvements from higher cycle temperature and pressure ratio tend to worsen these emissions for a given type of combustor technology. Combustor design changes to offset this effect may result in increased weight and complexity in engine design. Further, higher efficiency engines (lower CO_2) increase the potential for contrail formulation (IPCC, 1999).

2.4 Policy Responses

The rapid increase in air travel demand, fuel consumption, and associated emissions has given rise to a global dialog to address the potential impact of aviation on climate change. In the 1944 Chicago Convention, the International Civil Aviation Organization was created as the UN specialized agency with authority to develop Standards and Recommended Practices regarding all aspects of aviation, including certification standards for emissions and noise. Since 1977, ICAO has promulgated international emissions and noise standards for aircraft and aircraft emissions through its Committee on Aviation Environmental Protection. ICAO has also developed broader policy guidance on fuel taxation and charging principles (IPCC, 1999).

In protecting local air quality in the vicinity of airports, the U.S. first introduced legislation to set domestic regulation standards. ICAO subsequently developed International Standard and Recommended Practices for the control of fuel venting and of emissions of carbon monoxide, hydrocarbons, nitrogen oxides and smoke from aircraft engines over a prescribed landing/take-off (LTO) cycle below 3,000 feet. While there is no regulation or standard for aircraft emissions during cruise, these LTO standards also contribute to limiting aircraft emissions during cruise (IPCC, 1999).

In a broader perspective of climate change, the UN Framework Convention on Climate Change seeks to stabilize atmospheric greenhouse gases from all sources and sectors, but it does not specifically refer to aviation. The Kyoto Protocol to the Convention, adopted in December 1997, is the first international initiative to include two provisions that are particularly relevant to aviation. First, the Kyoto Protocol requires industrialized countries to reduce their total national emissions by an average of 5% for the average of the period 2008 to 2012 compared to 1990 the level. Second, the Kyoto Protocol's Article 2 contains the provision that industrialized countries pursue policies and measures for limitation or reduction of greenhouse gases from aviation bunker fuels. In relation to other aircraft engine emissions, IPCC has underlined the continuing uncertainties associated with the impacts of nitrogen oxides, water vapor, and sulfur while asking for further research (IPCC, 1999).

2.5 Chapter Summary

In light of the rapid growth in air travel and increasing concerns associated with the impacts of aviation on the global atmosphere, the desire to reduce aviation emissions is likely to intensify in the near future. While technological and operational options for emissions reduction may exist, it is still unclear which ones are feasible and meet the various constraints of the aviation sector. Economic feasibility may be one of the most important limiting factors in aviation emissions abatement activities. The rest of this thesis is, therefore, devoted to developing a system-level, analytic approach to understanding the underlying relationship between aircraft performance and cost and assessing feasible aviation emissions reduction potential in the future.

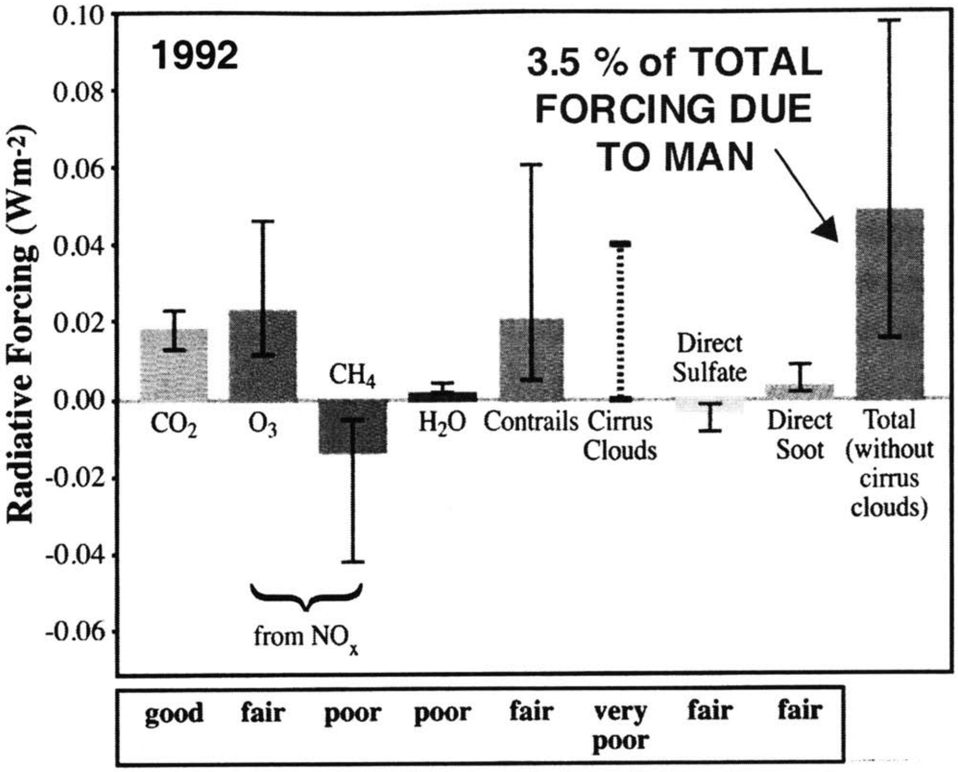

Figure 2.1: Radiative Forcing Due to Aircraft Emissions in 1992 (Source: IPCC, 1999)

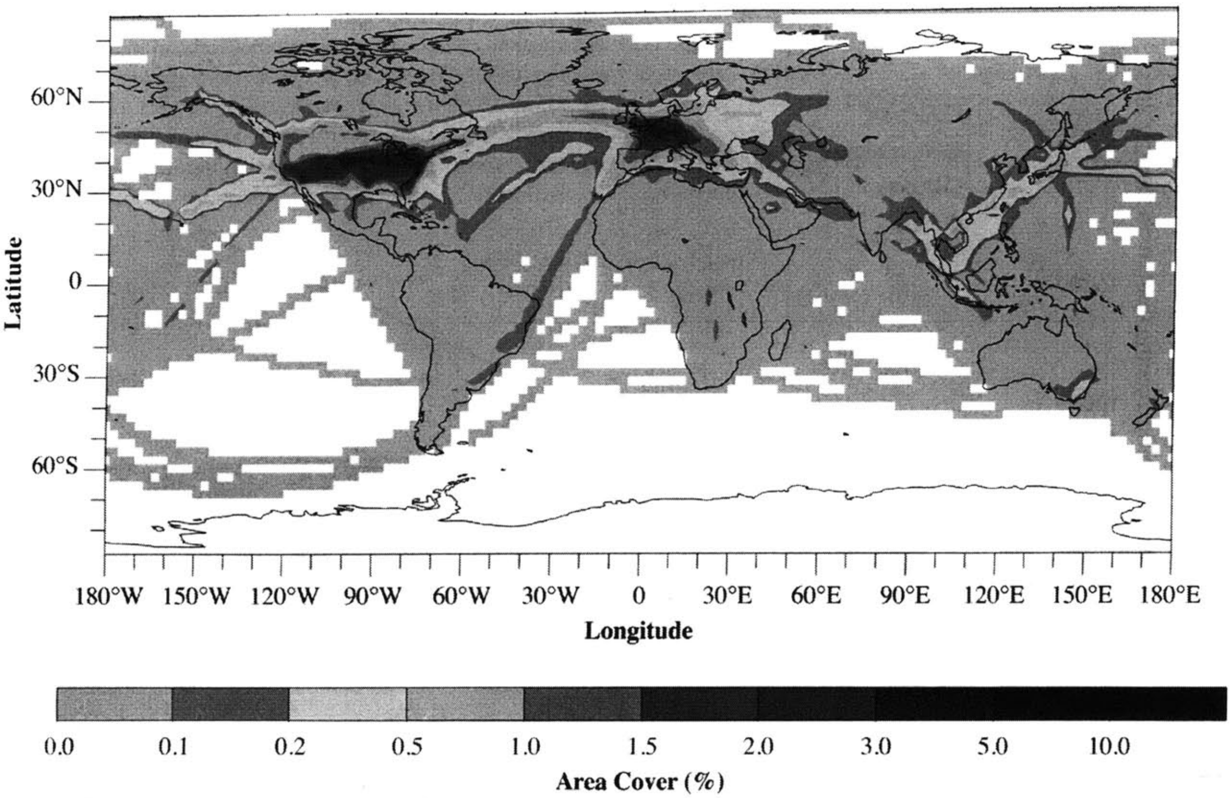

Figure 2.2a: Global Contrail Coverage in 1992 (Source: IPCC, 1999)

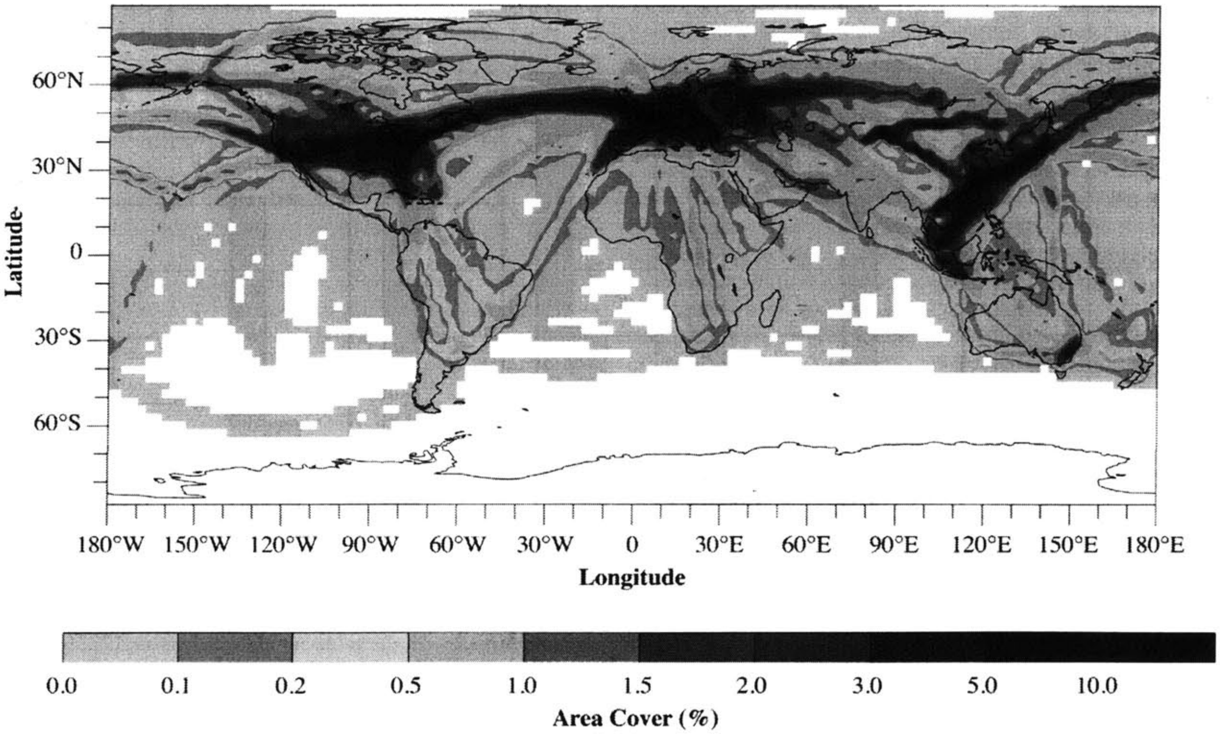

Figure 2.2b: Global Contrail Coverage in 2050 (Source: IPCC, 1999)

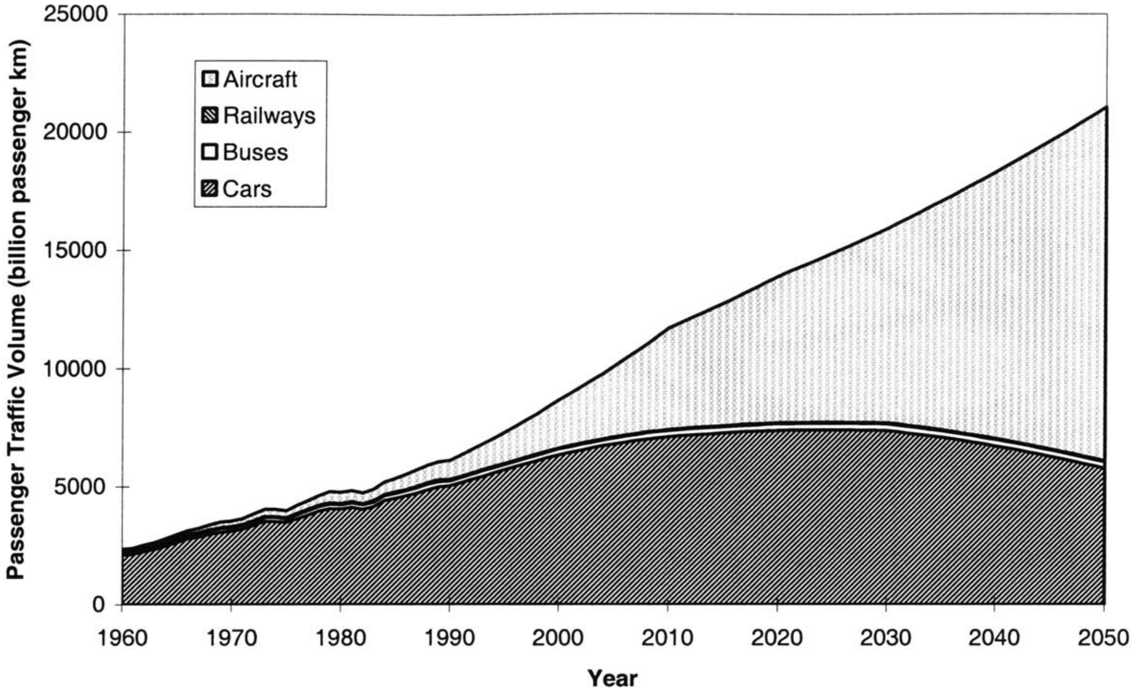

Figure 2.3: Modal Traffic Demand Forecast (Source: Schafer, 1998b; North America only)

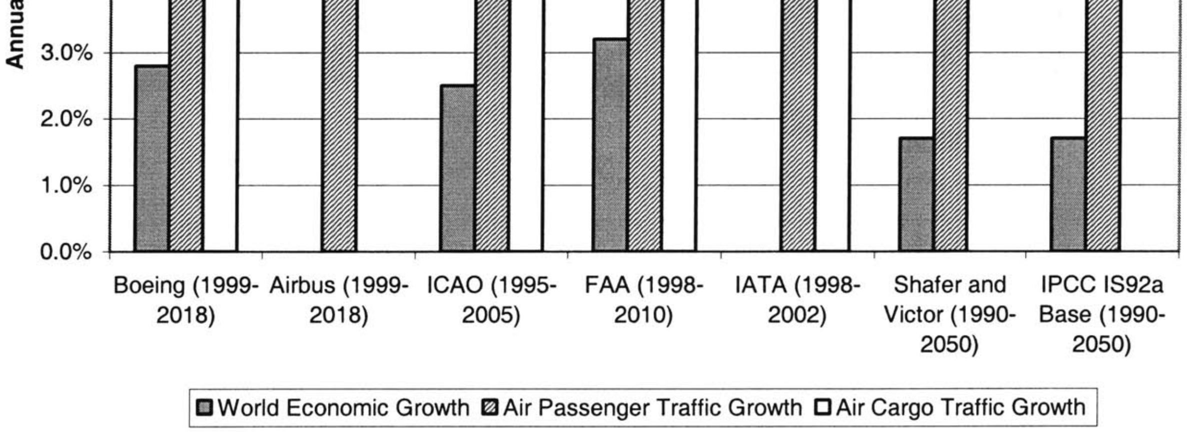

Figure 2.4: Various Air Traffic Growth Forecasts

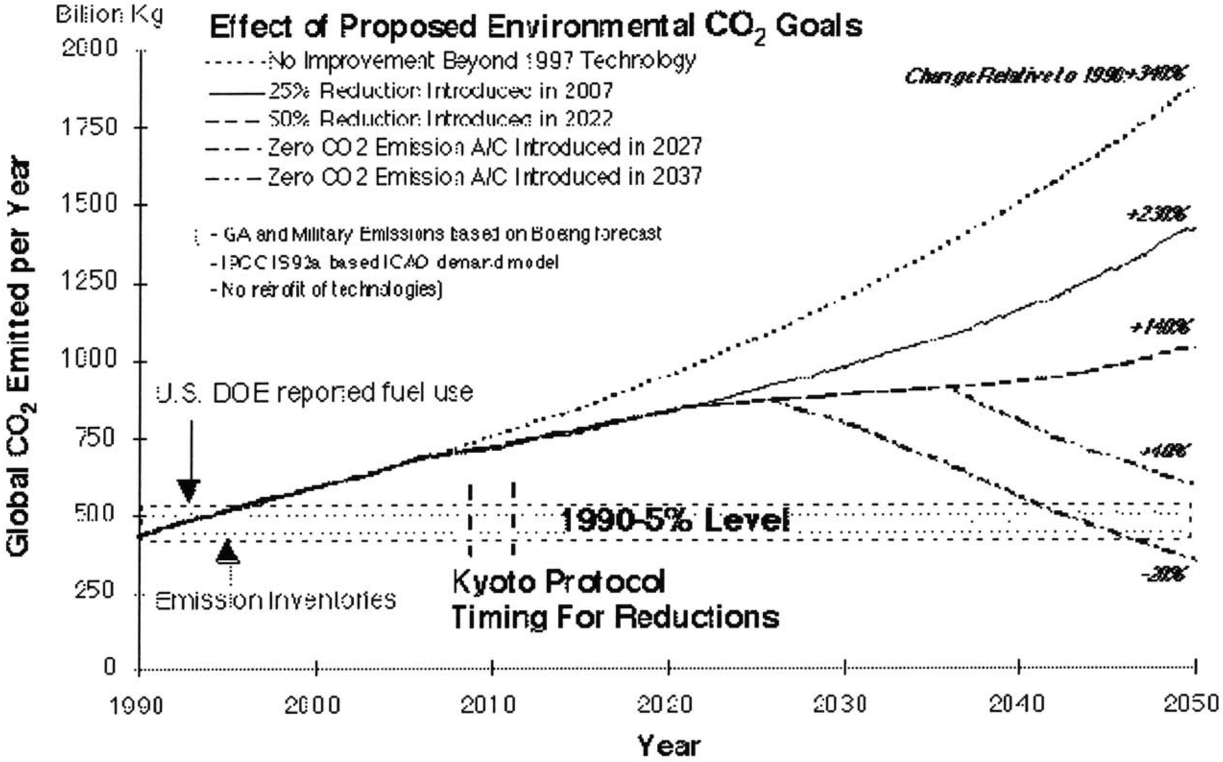

Figure 2.5: NASA Global CO_2 Emissions Reduction Scenarios (Source: Rohde, 1999)

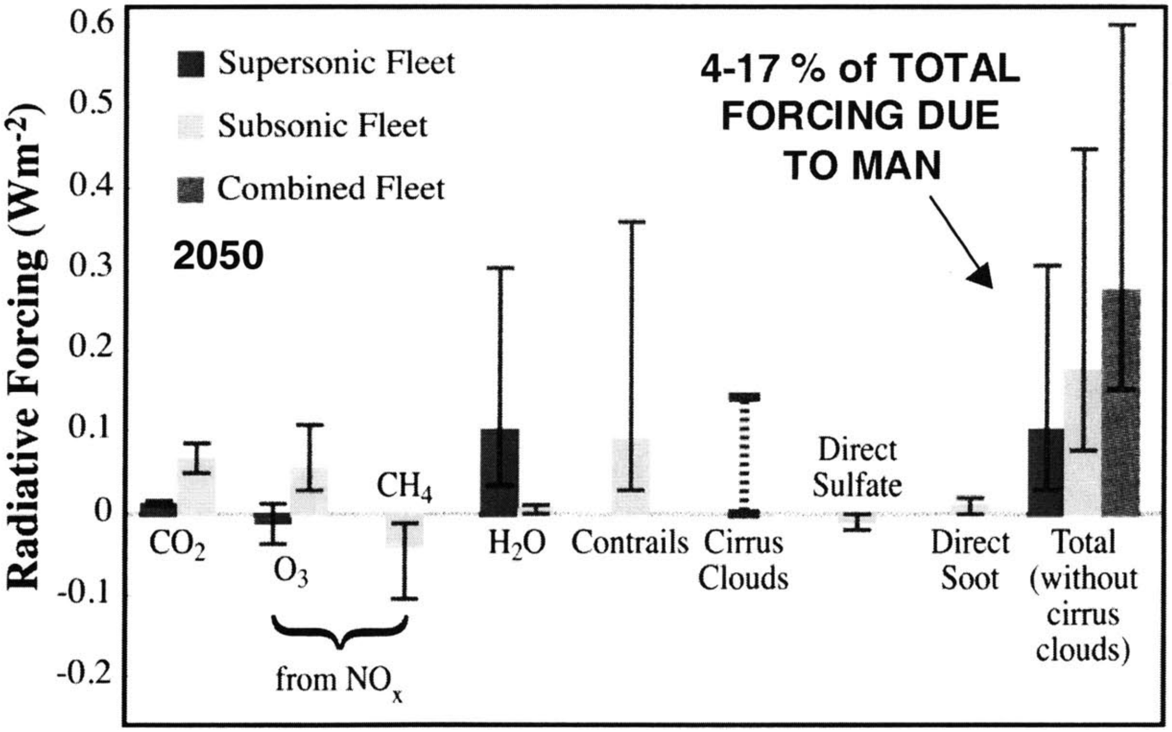

Figure 2.6: Radiative Forcing Due to Aircraft Emissions in 2050 (Source: IPCC, 1999)

Chapter 3

Historical Trends in Aircraft Performance and Cost

3.1 Introduction

In this chapter, overall historical trends in aircraft performance and cost are examined, and their driving factors are qualitatively discussed. By examining the relationship between fuel efficiency and costs of aircraft systems, the key parameters in aircraft performance and cost are identified, and a parametric modeling framework is formulated for further study.

3.2 Databases

Aircraft technology, operations, and financial data have been assembled and analyzed to fulfill the study objectives of this thesis. The technology database consists of specific fuel consumption (SFC), lift-to-drag ratio (L/D), and aircraft operating empty weight (OEW) and maximum take-off weight (MTOW). Take-off and cruise SFC data are available from Jane's Aero-Engines (Gunston, 1996), ICAO Engine Exhaust Emissions Data Bank (ICAO, 1995), and Mattingly's Elements for Gas Turbine Propulsion (Mattingly, 1996). Appendix 1 shows a detailed procedure by which cruise SFC is calculated based on ICAO data and then calibrated against those provided in Jane's Aero-Engines. Appendix 2 shows engine/planform configurations for the aircraft types studied in this thesis. Since many aircraft have the same planform but different engine types on the wing, an average SFC value of all available engines is used for each planform. The aerodynamic database is obtained from NASA studies (Bushnell, 1998) and calculated, when unavailable, using NASA Aircraft Synthesis (ACSYNT), a systems model for aircraft design with various analysis modules including propulsion, aerodynamics, weights, mission performance, and economics (Hasan, 1997). An internal investigation based on communications with an airframe manufacturer has also provided L/D values for some aircraft. SFC and L/D data have been informally checked with industry representatives for accuracy.

Lastly, the aircraft weight information (OEW and MTOW) is available from Jane's All the World's Aircraft (Jane's, 1999) and the Airliner Price Guide (Thomas and Richards, 1995a, 1995b, and 1995c). Overall, the estimated errors in the specification of SFC, L/D, and weights are 7%, 8%, and less than 5%, respectively, with 2σ confidence. Note that the relatively large uncertainty associated with cruise SFC values arises from the calibration between take-off SFC and cruise SFC.

Detailed traffic and financial data for all aircraft operated on domestic and international routes by all U.S. carriers since 1968 are available from U.S. Department of Transportation (USDOT) Form 41 (USDOT, 1968-Present). Schedule T-2 reports various traffic statistics including revenue passenger miles, available seat miles (ASM), total aircraft miles (TAM), revenue ton miles (RTM), available ton miles (ATM), airborne hours, block hours, aircraft days, fuels issued, and departures performed. Based on this information, further operating statistics, such as load factor and fleet size, are calculated. Schedule P-5.2 reports detailed direct operating cost plus investment (DOC+I) data including pilot salaries, fuel cost, direct maintenance cost, insurance, depreciation, and amortization. Appendix 3 shows actual DOC+I data fields for Form 41 Schedule P-5.2.

Complete annual transaction prices of aircraft are available from the Airliner Price Guide (Thomas and Richards, 1995a, 1995b, and 1995c). The reported prices are average market values paid in then-year dollars for new airplanes at the time of purchase. For example, a B-737-300 cost $23 million in 1984 and $23.5 million in 1985 in then-year dollars. Thus the Airliner Price Guide serves as a history book for all aircraft prices in the past. While three editions of the Airliner Price Guide are available every year, the prices in the fall 1995 edition for the last trimester, which contains prices for B-777, have been used for the analysis purposes of this thesis. On a few occasions, the three editions of the Airliner Price Guide report slightly inconsistent prices, in which case an average price based on all three editions has been used to account for mistakes in reporting.

All economic values from these cost data are deflated and shown in 1995 U.S. dollars in this thesis. The GDP deflators used to discount cost data and discounting procedures are shown in Appendix 4.

3.3 Fleet Selection and Categorization

Thirty-one commercial passenger aircraft types have been selected as shown in Table 3.1 and examined for the study objectives of this thesis. A significant fraction of the total number of the 31 types of aircraft is owned and operated by 10 major U.S. passenger airlines. USDOT defines major airlines to be the ones with annual operating revenues exceeding $1 billion. Currently, 10 major U.S. passenger airlines are Alaska Airlines (AS), America West Airlines (HP), American Airlines (AA), Continental Airlines (CO), Delta Airlines (DL), Northwest Airlines (NW), Southwest Airlines (WN), Trans World Airlines (TW), United Airlines (UA), and US Airways (US). In addition, Pan American World Airways (PA) is added just for the period 1968 to 1989 because it was a large operator of long-range aircraft in that period. Figure 3.1 shows that the 31 aircraft types operated by these major airlines cover over 85% of all domestic and international revenue passenger miles performed by all aircraft types operated by all U.S. airlines during the period 1991 to 1998. While they account for a smaller fraction of total U.S. passenger miles for other time periods, the 31 aircraft types flown by these ten major U.S. airlines are still believed to capture most of U.S. fleet characteristics such as fleet average fuel consumption as discussed in Section 3.4.1.6. Furthermore, these 31 aircraft types, introduced during the period 1959 to 1995, reflect technology evolution since the beginning of the commercial jet aircraft era. Thus, examining the technological and economic characteristics of these aircraft types provides fundamental insight into the underlying relationship between aircraft performance and cost. In addition, the 31 aircraft types represent all classes of large-commercial passenger aircraft ranging from single-aisle, short-range aircraft to double-aisle, long-range aircraft.

Table 3.1 shows various configuration and operating facts for the 31 aircraft types. Most distinctively, average stage length of 1,000 miles divides between short- and long-range aircraft. In addition, most short-range aircraft have less than 150 seats whereas most long-range aircraft have 150 seats or above. Engine/planform configuration also provides a useful guideline for aircraft categorization. In general, 2-engine/narrow body jets are short-range aircraft while 3- or 4-engine/wide body jets are long-range aircraft. One notable exception of this trend is B-777 for which only 2 engines provide enough thrust in place of the more conventional 4 engines.

3.4 Historical Trends in Aircraft Performance and Cost

3.4.1 Aircraft Performance

3.4.1.1. Fuel consumption

Figures 3.2 and 3.3 show the fuel consumption improvement of short- and long-range aircraft types with respect to year of introduction based on the operating data during 1991 to 1998. Overall, aircraft fuel economy as measured in gallons of fuel burn per RPM has improved by about 70%, or 3.3% per year on average, during the period 1959 to 1995. More specifically, short-range aircraft fuel consumption has decreased from 0.06 gal/RPM for aircraft introduced in 1965 to 0.02 gal/RPM for aircraft introduced in 1988. Similarly, long-range aircraft fuel consumption has decreased from 0.07 gal/RPM for aircraft introduced in 1960 to 0.02 gal/RPM for aircraft introduced in 1995. For modern aircraft types, long-range aircraft appear slightly more fuel-efficient than short-range aircraft by approximately 5% as they can carry more passengers over a longer distance while fuel spent on non-cruise flight segments such as take-off and landing is a much smaller fraction of the total fuel use. Note that the variations in the fuel consumption of each aircraft type are due to different operating conditions, such as load factor, flight speed, altitude, and routing, by different operators.

3.4.1.2. Engines

The reductions in fuel consumption mainly originate from significant improvements in aircraft engine and aerodynamic technologies in the past. To be more specific, SFC, as a measure of engine efficiency, has decreased by approximately 40% during 1959 to 1995 as shown in Figure 3.4 (NRC, 1992). Note that most of reduction occurred in 1960's while the rest of the improvement gradually took place after 1970. These engine efficiency improvements are mainly attributable to current high bypass ratio engines achieving greater propulsion efficiency by sending 5 to 6 times as much air around the engine core. However, as the bypass ratio increased, the engine diameter also became larger, causing increase in engine weight and aerodynamic drag. Thus, development of lightweight metal alloys, advanced aerodynamic designs for engines and fans, and advanced gearing systems all enabled the fuel economy advantages of higher bypass ratio engines (Greene, 1992). Other engine efficiency improvements include increased engine inlet temperature, high temperature materials, increased compressor pressure ratio, and improved fan and nacelle performance. In addition, the reduction of noise and emissions and improved reliability have led to the significant improvement of modern jet engine performance (Greene, 1995).

3.4.1.3. Aerodynamics

Figure 3.5 shows historical trends in aerodynamic efficiency during 1959 to 1995. The L/D ratio has increased by about 15% in the past while most of this improvement was realized after 1980. Note that aerodynamic improvements before the 1980's have contributed to countering the increased aerodynamic drag of high bypass ratio engines with bigger diameters. Even though aerodynamic efficiency has achieved a moderate progress compared to the engine performance improvement, better wing designs using computational fluid dynamics (CFD) and improved wind tunnel testing techniques, and propulsion/airframe integration have led to the overall improvement in L/D and will continue to do so in the future (NRC, 1992; IPCC, 1999).

3.4.1.4. Structures

Historical trends in aircraft structural weight improvement are less evident (NRC, 1992). Figure 3.6 shows structural efficiency seen from the ratio of operating empty weight to maximum take-off weight during 1959 to 1995. Note that OEW/MTOW is a measure of how light an airplane can be to lift the same amount of payload, fuel, and structural weight. This lack of change in structural efficiency is due to the fact that aircraft today are still made mainly out of aluminum, about 75% metallic by weight, with composites used for a very limited number of components, such as fins and tailplanes (NRC, 1992; Greene 1992). In addition, improvements in aircraft weight through some use of light-weight materials in the past have been largely offset by improved operational performance, which includes greater range, better altitude capability, better low-speed performance, lower noise, wide-body comfort, better cargo handling, improved systems response and redundancy, and longer structural life (NRC, 1992). Note also that as the engine bypass ratio increases, the bigger engine diameter causes extra weight, offsetting improvements in aircraft structural weight due to use of light-weight materials.

According to the IPCC Special Report, about 30% fuel efficiency improvement has resulted from airframe technologies including improved aerodynamics and weight reduction (IPCC, 1999). However, small improvement associated with aircraft structural efficiency as observed in the historical trends makes the IPCC estimates questionable.

3.4.1.5. Operational factors

In addition to these technological factors, increasing size, higher load factors, and operational changes contribute to the improved aircraft fuel economy (NRC, 1992). For example, the same aircraft type can have quite different fuel consumption characteristics under different operating conditions as previously observed in variations in the fuel consumption of each aircraft type in Figures 3.2 and 3.3. To further illustrate this point, Figure 3.7 shows that fuel burn per RPM for B-747-400 has significantly improved just by increasing load factor. Furthermore, fuel economy, as measured in fuel burn per ASM, for B-747-400 has also improved with respect to increase in number of seats as shown in Figure 3.8. Thus, both technology and operability impact aircraft fuel economy, and quantifying the coupled impact of technology and operability improvements on overall aircraft fuel consumption characteristics is a key to understanding the environmental performance improvement potential of future aircraft systems.

3.4.1.6. Fleet fuel consumption

Driven by these technological and operational improvements, the average fuel consumption of the entire U.S. fleet has also decreased significantly by more than 60% averaging about 3.3% per year during the period 1971 to 1998 as shown in Figure 3.9. Note that the average fuel consumption of the fleet composed of the 31 aircraft types is approximately the same as that of the entire U.S. fleet. It is also noteworthy that average load factor for the entire U.S. fleet has improved by more than 40% during the period 1971 to 1998, and it is closely related to the large reduction in fleet average fuel consumption.

Another important observation is that it has typically taken 15 to 20 years in the past for the total U.S. fleet to achieve the same fuel efficiency as that of newly introduced aircraft. In general, separate from aircraft performance improvements alone, the rate of improvement in the average fuel efficiency of the total fleet is determined by the gradual process of absorption of new, more fuel-efficient aircraft into the existing fleet. This process, called technology uptake, depends on various factors, such as the growth in traffic demand, prices and performance of competing aircraft, prices of labor and fuel, environmental regulations, industry profitability, and the availability of aircraft financing (Balashov, 1992). In assessing future aviation fuel consumption and emissions, it is important to consider this time delay between technology introduction and its full absorption by the world fleet.

3.4.2 Aircraft Cost

3.4.2.1. Direct operating cost and investment

DOC and price are the two major elements of aircraft cost. While price is a one-time cost for aircraft acquisition, DOC is a recurring cost over the lifetime of an airplane. However, in practice, both elements appear together as part of aircraft operating cost, DOC+I, as the value of an airplane is depreciated and amortized over a large fraction of its lifetime.

DOC+I roughly accounts for half of an airline's entire operating budget while the other half of the operating budget is indirect operating cost elements such as ticket commissions, ground operations, various fees, and administrative costs. DOC+I mainly consists of four major categories, crew cost, fuel cost, maintenance cost, and investment or ownership cost as each of these categories comprises roughly 20 to 30% of DOC+I. Crew cost includes pilot and flight attendant salaries. Note, however, flight attendant salaries are not classified as part of DOC+I in the USDOT Form 41 standard. Thus, the subsequent analyses of this thesis will consider only pilot salaries as crew cost. Maintenance cost includes labor and materials for airframes and engines. Included in ownership cost are insurance, depreciation, and amortization for both operating leases (rentals) and capital leases. Overall, these four major categories account for about 85% of DOC+I. Other flying operations and maintenance costs include taxes, aircraft interchange charges, and outside repairs and account for the rest of DOC+I. A typical composition of DOC+I is shown in Figure 3.10.

Figure 3.11 shows historical trends in DOC+I for 10 major U.S. airlines for the period 1968 to 1998. Total DOC+I approximately tripled from \$8.6 billion in 1968 to \$27.7 billion in 1998, indicating the significant growth of the industry over the past 30 years. The rapid increase in DOC+I in the late 1980's was largely stimulated by the deregulation and the introduction of new families of advanced commercial jet aircraft. B-767-200/200ER, A300-600, B-757-200, A310-300, B-767-300/300ER, B-747-400, and MD-11 all entered the market during this period. The large fluctuations in the DOC+I trends were mainly due to variations in annual fuel prices, and it is noteworthy that fuel cost was as much as 60% of total DOC+I during the second oil crisis in 1980.

3.4.2.2. Direct operating cost

A useful insight into the technology-cost relationship can be obtained by examining the DOC categories alone without fuel cost for the selected 31 aircraft types. Note that the reason for the exclusion of fuel cost here is to avoid the impact of fuel efficiency improvement on DOC trends, which has been already observed in the previous section.

Figures 3.12 and 3.13 show the direct operating cost improvement of short- and long-range aircraft types with respect to year of introduction based on the operating data during 1991 to 1998. Overall, DOC without fuel cost per RPM for both short- and long-range aircraft types decreased significantly by about 65% during 1959 to 1995 as newer models were introduced. More specifically, the DOC/RPM without fuel cost of short-range aircraft decreased from 8 cents for aircraft introduced in 1965 to 3 cents for aircraft introduced in 1990. Similarly, the DOC/RPM without fuel cost of long-range aircraft decreased from 6 cents for aircraft introduced in 1959 to 2 cents for aircraft introduced in 1995. It is noteworthy that the reduction in DOC without fuel cost occurred with respect to the technological improvements of newer aircraft models as it is mainly attributable to improved avionics and lower maintenance cost. Note also that the DOC/RPM of long-range aircraft is about 20 to 30% lower than that of short-range aircraft because the marginal cost of flying operations and maintenance per passenger-mile decreases with respect to increasing size and range of an airplane.

3.4.2.3. Price

Since the ownership cost categories in DOC+I are subjective, and reporting practices vary significantly from airline to airline, a better measure for the investment portion of DOC+I is the price that airlines actually paid to purchase an airplane. Figures 3.14 and 3.15 show historical trends in short- and long-range aircraft prices. Short-range aircraft price per seat has risen approximately 70% from $140 thousand in 1965 to $240 thousand in 1995 while long-range aircraft price per seat has increased roughly 130% from $170 thousand in 1960 to $390 thousand in 1995. It is interesting to note that the price of a B-747 peaked in late 1970's and gradually reduced to current levels. Considering the price peak coincided with the deregulation after which several classes of long-range aircraft including MD-11, A310-300, and L-1011 were introduced, added competition might have driven down the price of B-747 in 1980's. When the prices of short- and long-range aircraft are compared, long-range aircraft are slightly more expensive even on a per-seat basis, indicating the higher capital investment required for aircraft acquisition.

Another interesting observation is that the same aircraft model becomes cheaper after introduction. This trend may be explained by learning effects and obsolete technologies. Learning is a prevalent phenomenon in the aircraft manufacturing industry where it becomes cheaper to produce one more unit as the cumulative output increases (Argote and Epple, 1990; Marx *et al.*, 1998b). As result, aircraft price goes down as more and more aircraft are produced at lower cost after initial introduction. Another possible factor for the declining price trend with age is that obsolete technologies become cheaper by virtue of market competition and replacement by new technologies.

By observing these historical trends in aircraft price, a qualitative relationship between technological improvement and price can also be obtained. That is, aircraft price goes up as newer technologies are introduced. This trend is even clearer from Figures 3.16 and 3.17 where the annual prices of each short- and long-range aircraft are averaged and plotted with year of introduction of each aircraft type. Overall, aircraft price decreases with age of the aircraft model, but a larger investment is required as new models are introduced.

In general, airlines are willing to pay higher prices for new aircraft if they can lower operating costs by adopting more-fuel efficient, advanced technology. An airline's purchase decision is based on this tradeoff between one-time capital investment and lifetime operating expenses (Morrison, 1984). Historically, DOC and investment cost together for long-range aircraft have stayed approximately the same as a result of large reductions in operating costs offset by increasing aircraft prices (NRC, 1992).

3.5 Chapter Summary

Both technological and operational improvements lead to higher aircraft fuel efficiency in a coupled manner. Furthermore, the examination of historical trends in aircraft performance and cost shows that higher aircraft price is an indicator for advanced technology that directly reduces aircraft fuel consumption as well as direct operating cost. The next two chapters are dedicated to quantifying the impacts of technological and operational changes on aircraft system efficiency, as measured in fuel consumption characteristics, and resulting DOC and price. This analysis framework is graphically shown in Figure 3.18.

Table 3.1: Configurations and Typical Operations for 31 Aircraft Types (Short-range aircraft; arranged on the order of increasing stage length)

Form 41 Code	Aircraft Type	Year of Introduction	No. of Powerplants	Body Type	Average Seats	Average Stage Length	Classification
6301	DC-9-10	1965	2	Narrow	76	372	Short-range
6401	DC-9-30	1966	2	Narrow	99	440	Short-range
6501	DC-9-50	1976	2	Narrow	122	452	Short-range
6201	B-737-100/200	1967	2	Narrow	106	457	Short-range
6451	DC-9-40	1968	2	Narrow	109	491	Short-range
6161	B-737-500/600	1990	2	Narrow	113	536	Short-range
6191	B-737-300	1984	2	Narrow	132	601	Short-range
6171	B-737-400	1988	2	Narrow	144	630	Short-range
7151	B-727-200/231A	1967	3	Narrow	138	706	Short-range
6551	MD-80/DC-9-80 All	1980	2	Narrow	141	736	Short-range
6941	A320-100/200	1988	2	Narrow	148	1054	Short-range

Table 3.1 (continued): Configurations and Typical Operations for 31 Aircraft Types (Long-range aircraft; arranged on the order of increasing stage length)

Form 41 Code	Aircraft Type	Year of Introduction	No. of Powerplants	Body Type	Average Seats	Average Stage Length	Classification
6221	B-757-200	1984	2	Narrow	186	1137	Long-range
6911	A300-600/R/CF/RCF	1984	2	Wide	262	1228	Long-range
7601	L-1011-1/100/200	1973	3	Wide	271	1409	Long-range
7301	DC-10-10	1970	3	Wide	262	1491	Long-range
7331	DC-10-40	1972	3	Wide	265	1854	Long-range
6251	B-767-200/200ER	1983	2	Wide	190	2087	Long-range
6261	B-767-300/300ER	1987	2	Wide	228	2187	Long-range
8021	B-707-100B	1959	4	Narrow	132	N/A	Long-range
8061	B-707-300	1959	4	Narrow	149	N/A	Long-range
6931	A310-300	1986	2	Wide	193	2605	Long-range
8081	B-707-300B	1962	4	Narrow	152	N/A	Long-range
8121	B-720-000	1961	4	Narrow	118	N/A	Long-range
8141	B-720-000B	1960	4	Narrow	110	N/A	Long-range
6271	B-777	1995	2	Wide	291	2725	Long-range
7651	L-1011-500Tristar	1979	3	Wide	230	2954	Long-range
7321	DC-10-30	1972	3	Wide	268	3000	Long-range
8161	B-747-100	1970	4	Wide	375	3068	Long-range
8171	B-747-200/300	1970	4	Wide	380	3794	Long-range
7401	MD-11	1990	3	Wide	254	3895	Long-range
8191	B-747-400	1989	4	Wide	398	4603	Long-range

Source: The Airliner Price Guide, FAA (Hoffer *et al.*, 1998), and USDOT Form 41

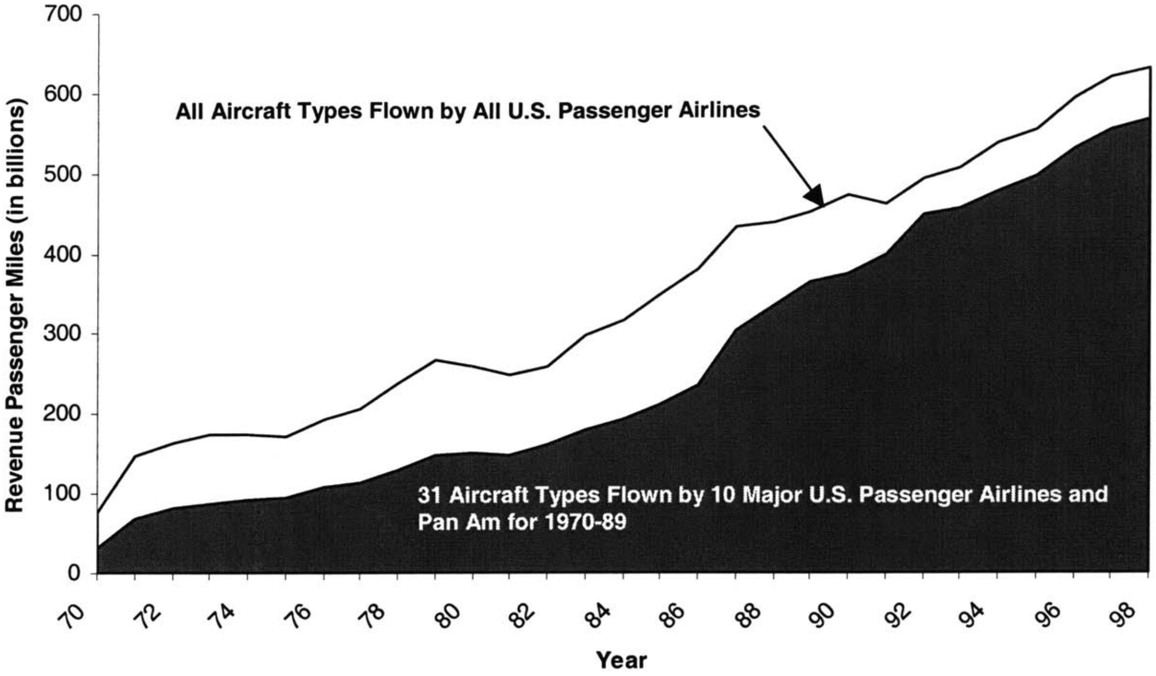

Figure 3.1: Comparison of RPMs Performed by 31 Aircraft Types Operated by 10 Major U.S. Passenger Airlines and RPMs Performed by All Aircraft Types Operated by All U.S. Passenger Airlines (Pan Am added for 1970-89)

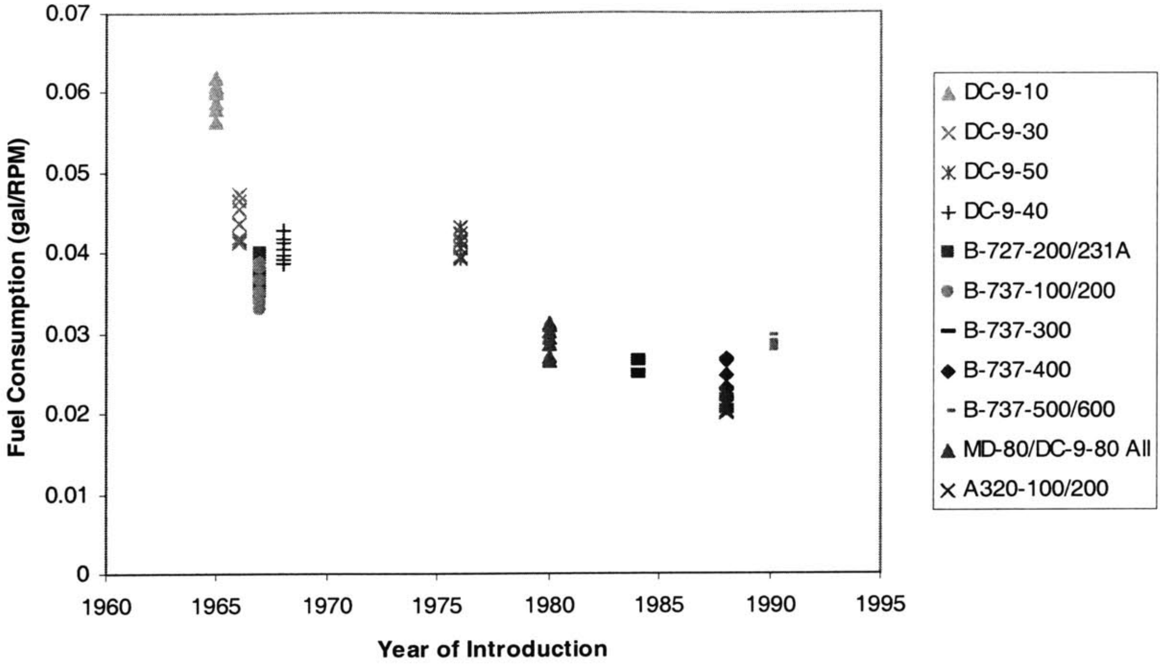

Figure 3.2: Historical Trends in Fuel Burn for Short-range Aircraft (based on 1991-98 operating data)

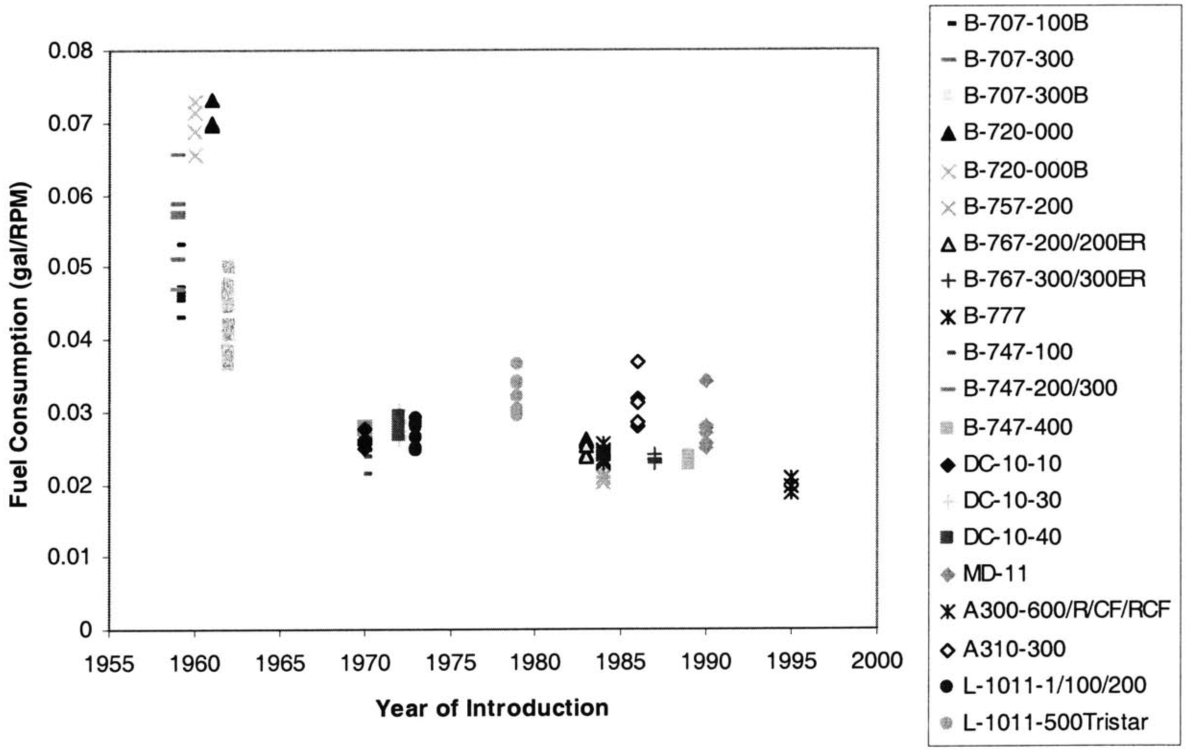

Figure 3.3: Historical Trends in Fuel Burn for Long-range Aircraft (based on 1991-98 operating data except for B-707 and B-720)

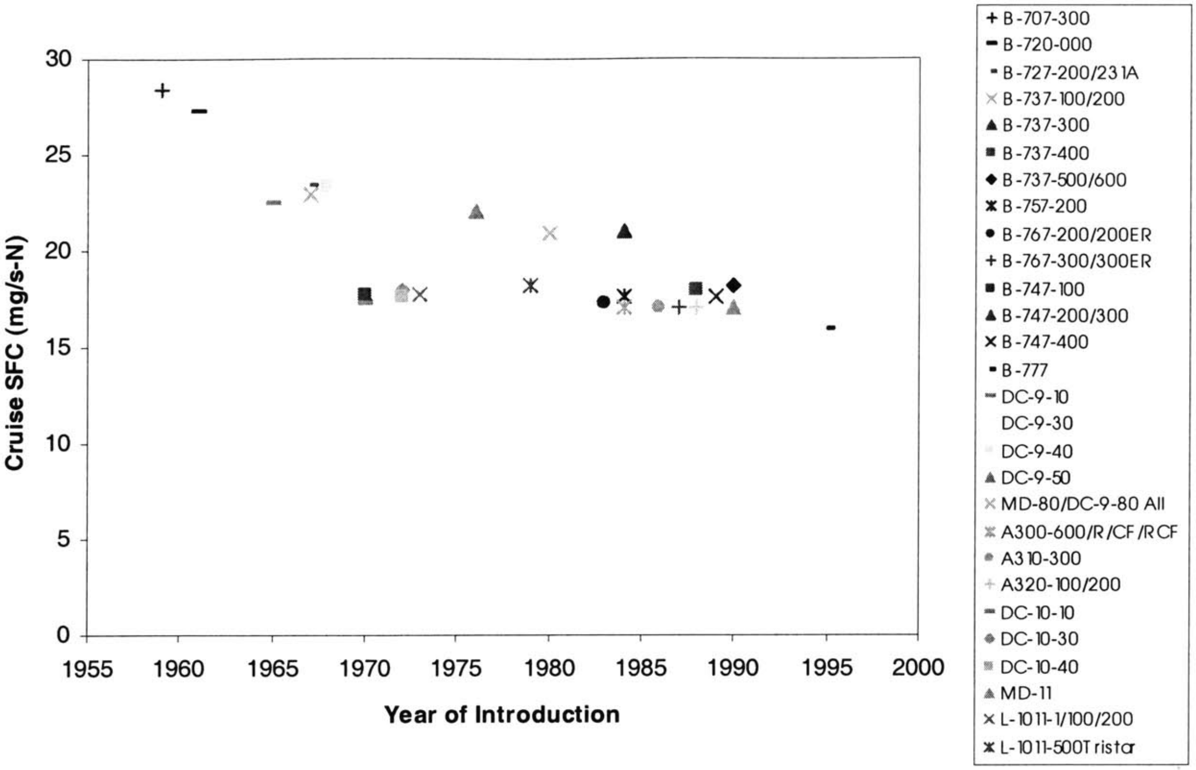

Figure 3.4: Historical Trends in Engine Efficiency

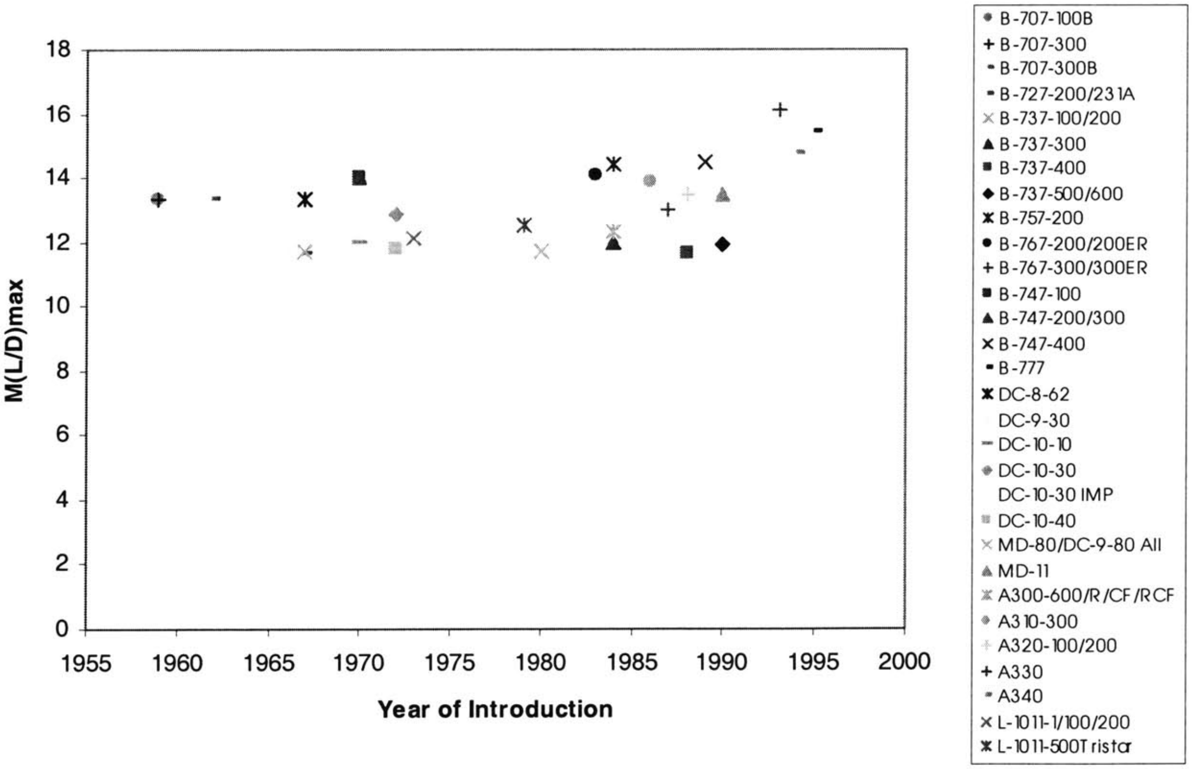

Figure 3.5: Historical Trends in Aerodynamic Efficiency

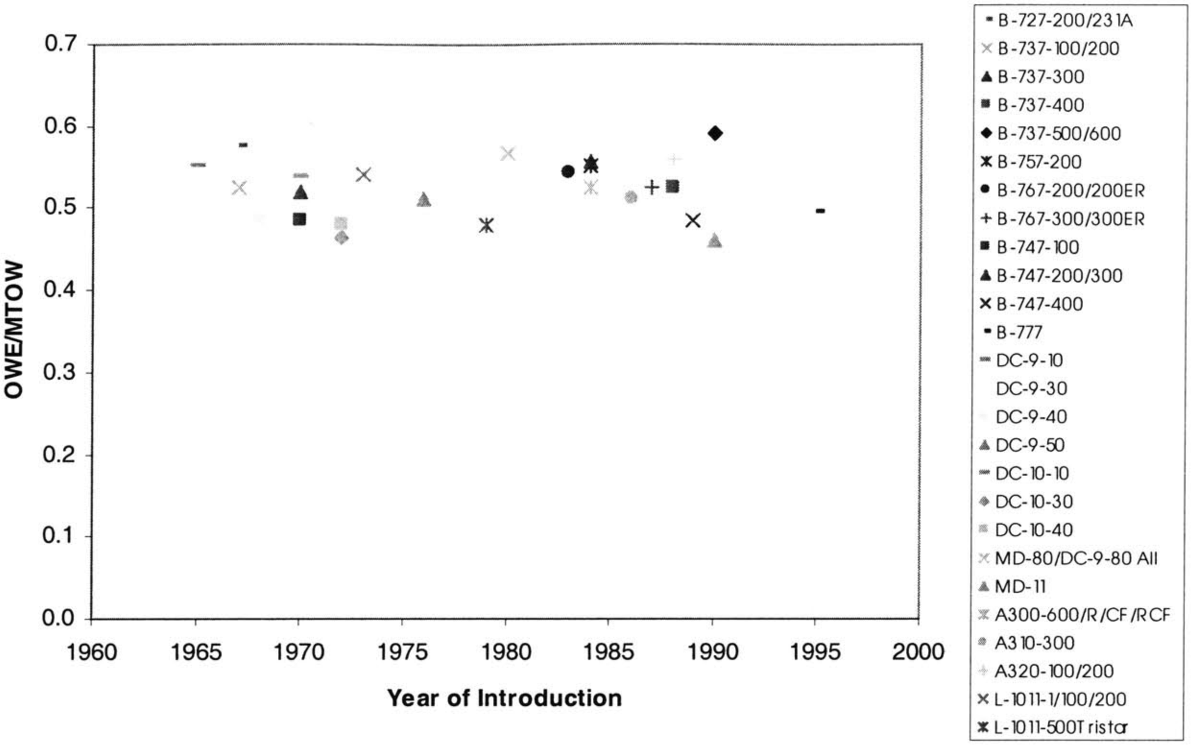

Figure 3.6: Historical Trends in Structural Efficiency

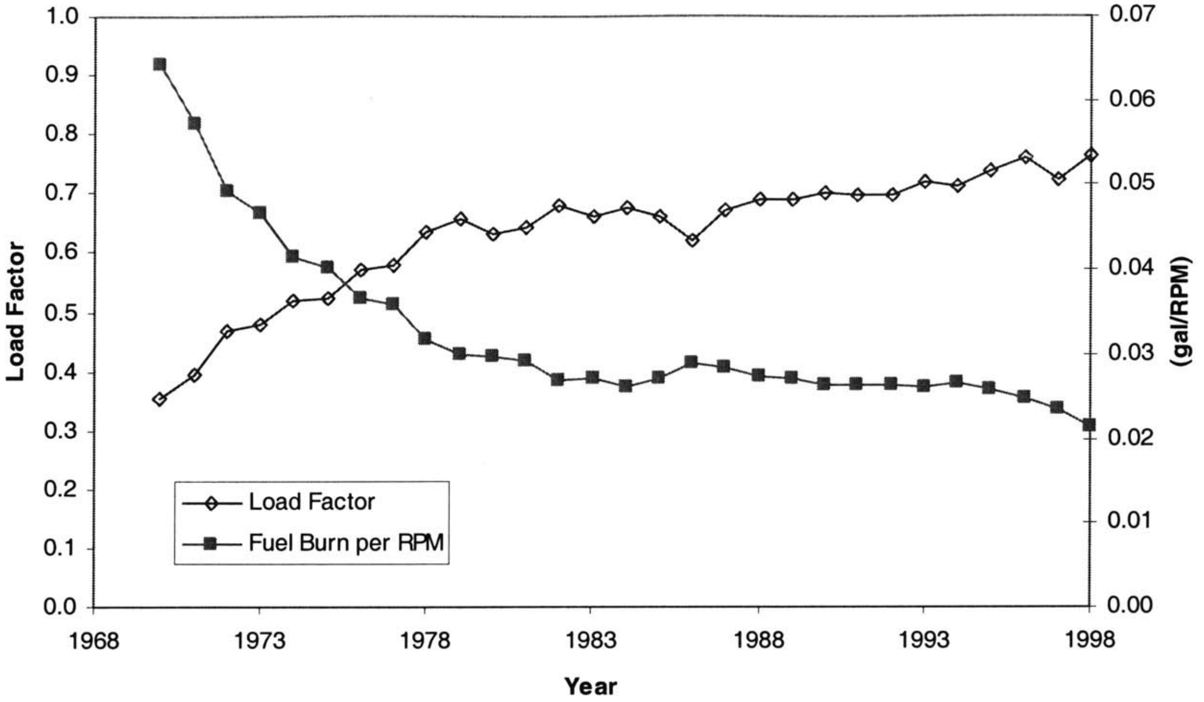

Figure 3.7: Historical Trends in Fuel Burn and Load Factor for B-747-400

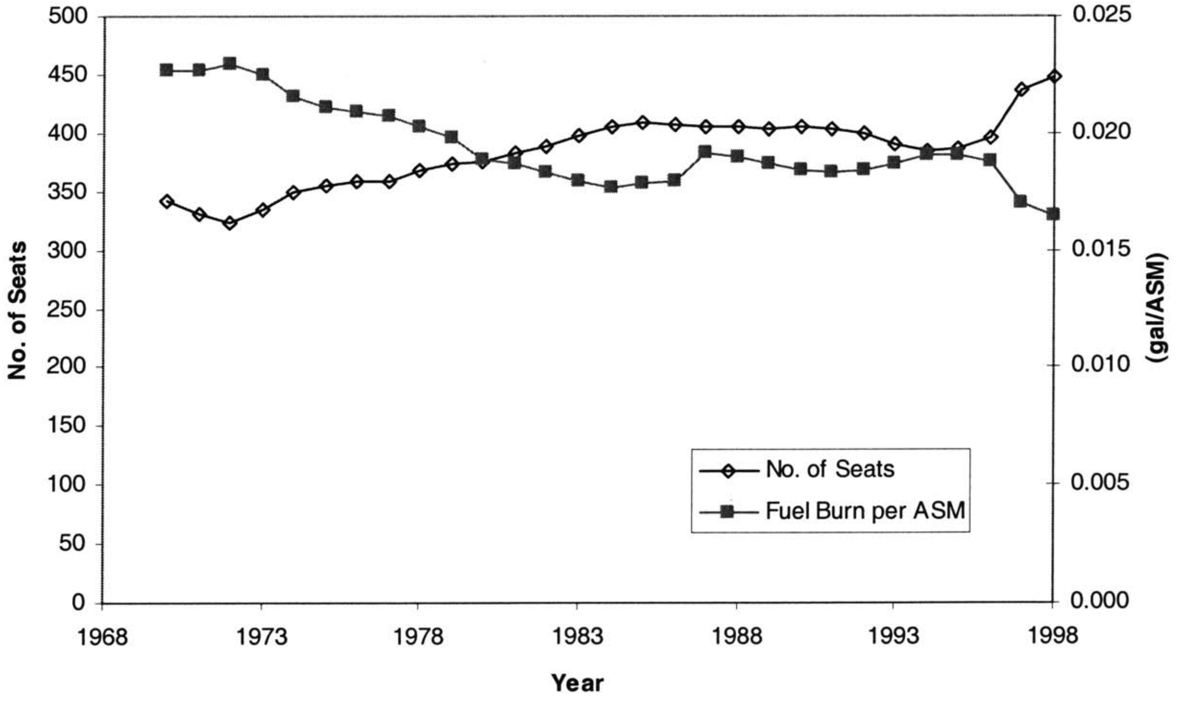

Figure 3.8: Historical Trends in Fuel Burn and Seats for B-747-400

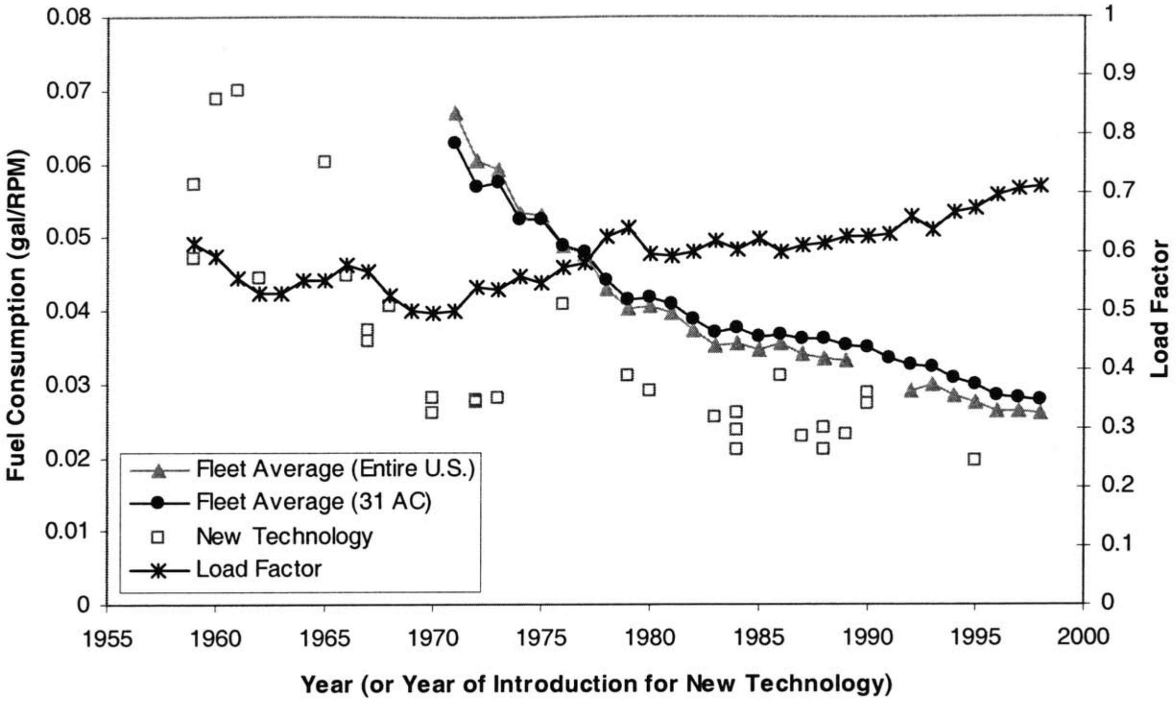

Figure 3.9: Historical Trends in U.S. Fleet Fuel Consumption and Technology Uptake (no data available for entire U.S. fleet during 1990 and 1991)

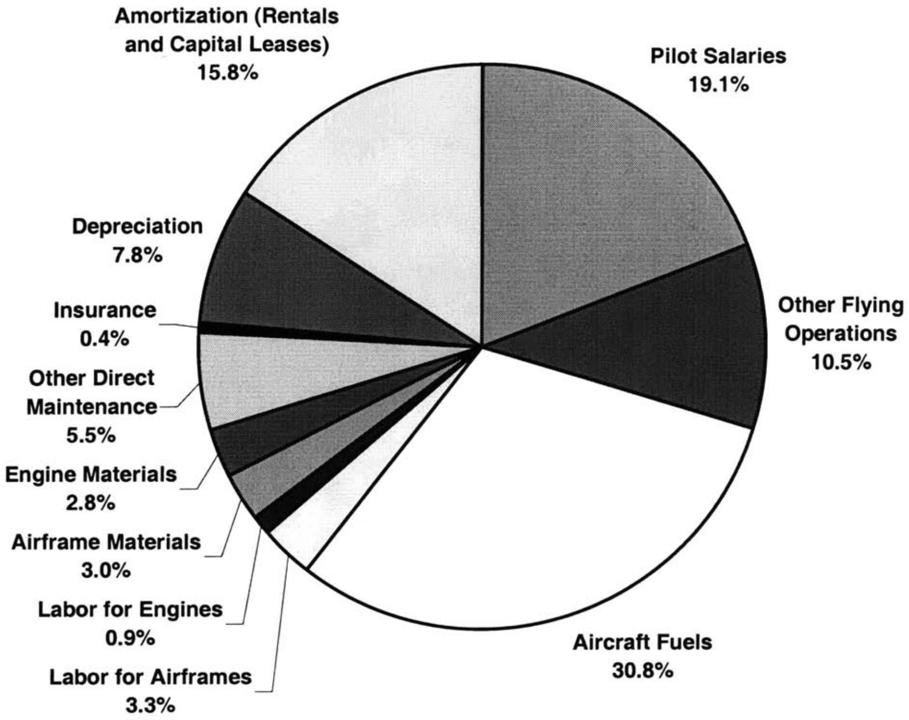

Figure 3.10: Typical DOC+I Composition (10 major U.S. airlines during 1992-98; flight attendant salaries not included as part of Form 41 standard)

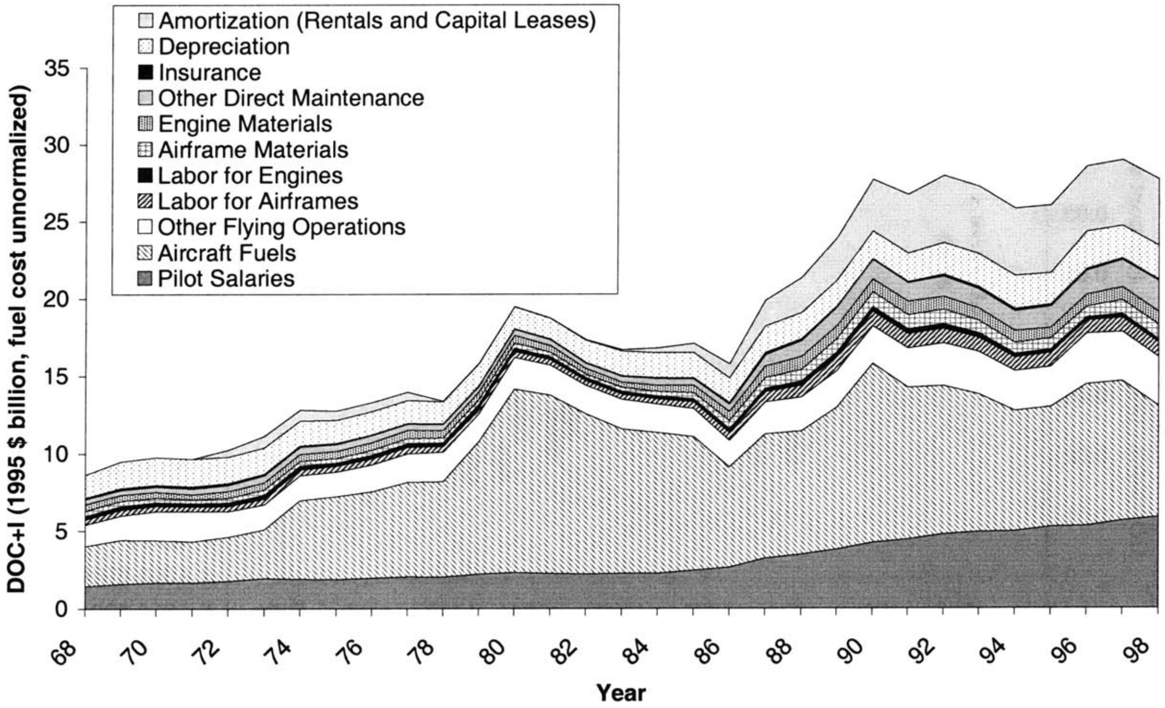

Figure 3.11: Historical Trends in DOC+I (all aircraft flown by 10 major U.S. airlines for period 1968-98)

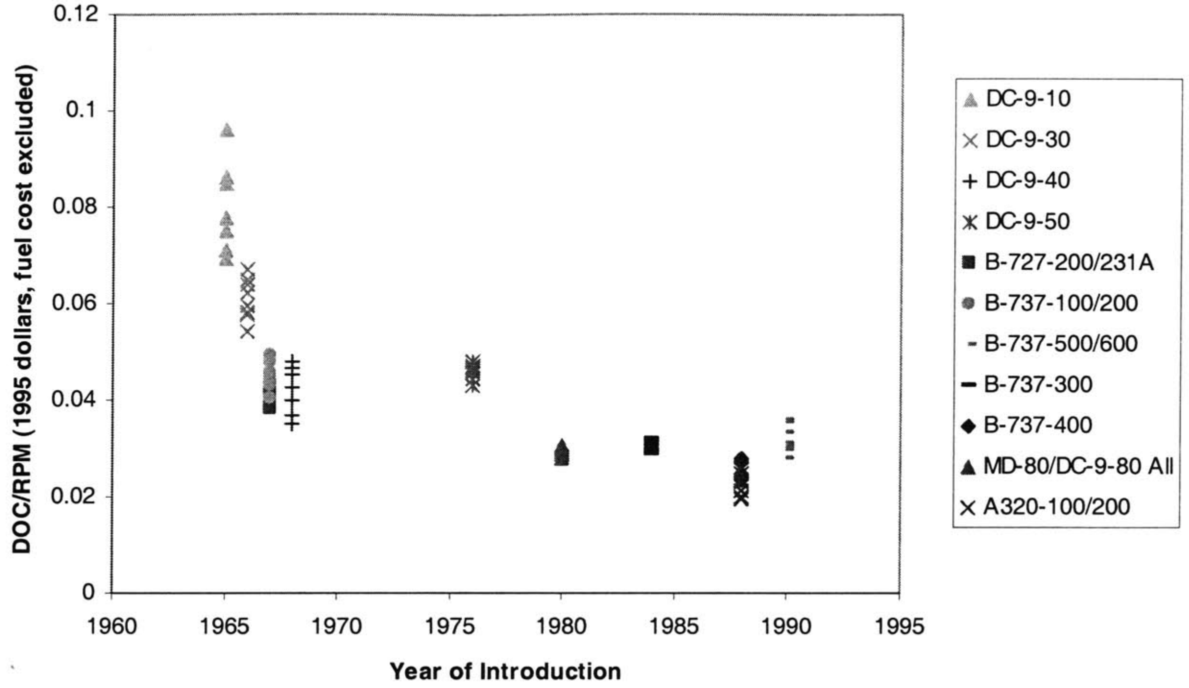

Figure 3.12: Historical Trends in DOC without Fuel Cost for Short-range Aircraft (based on 1991-98 operating data)

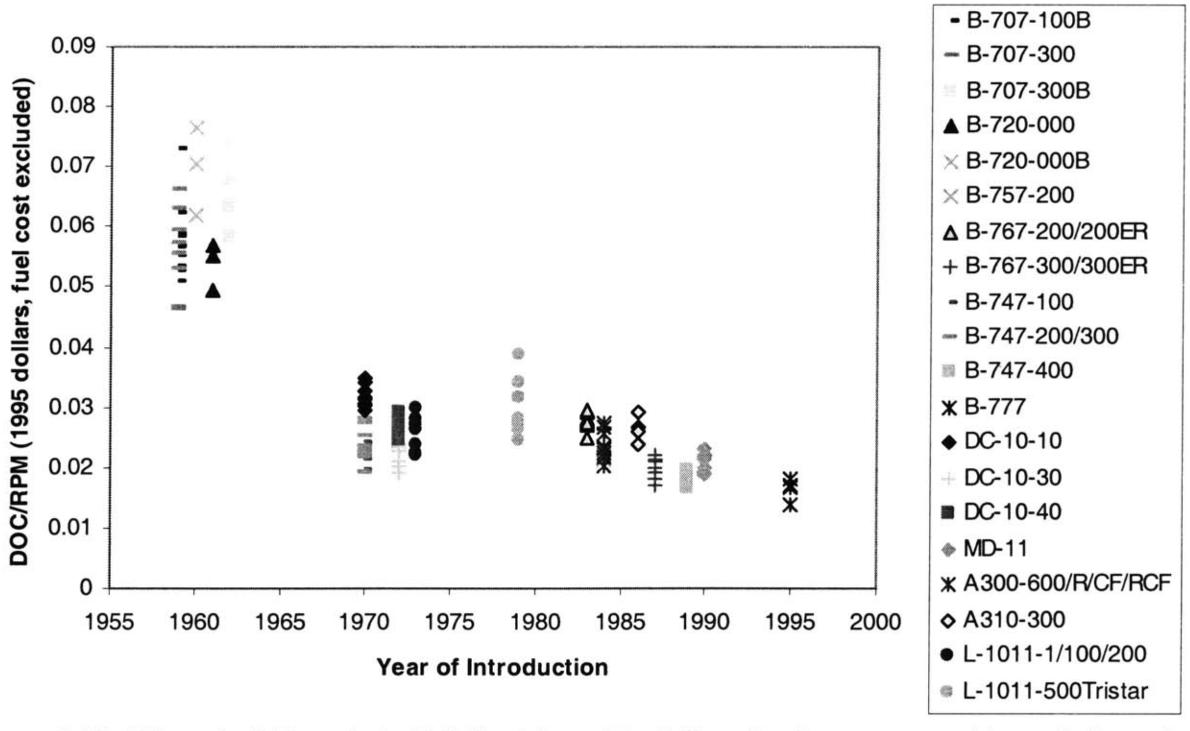

Figure 3.13: Historical Trends in DOC without Fuel Cost for Long-range Aircraft (based on 1991-98 operating data except for B-707 and B-720)

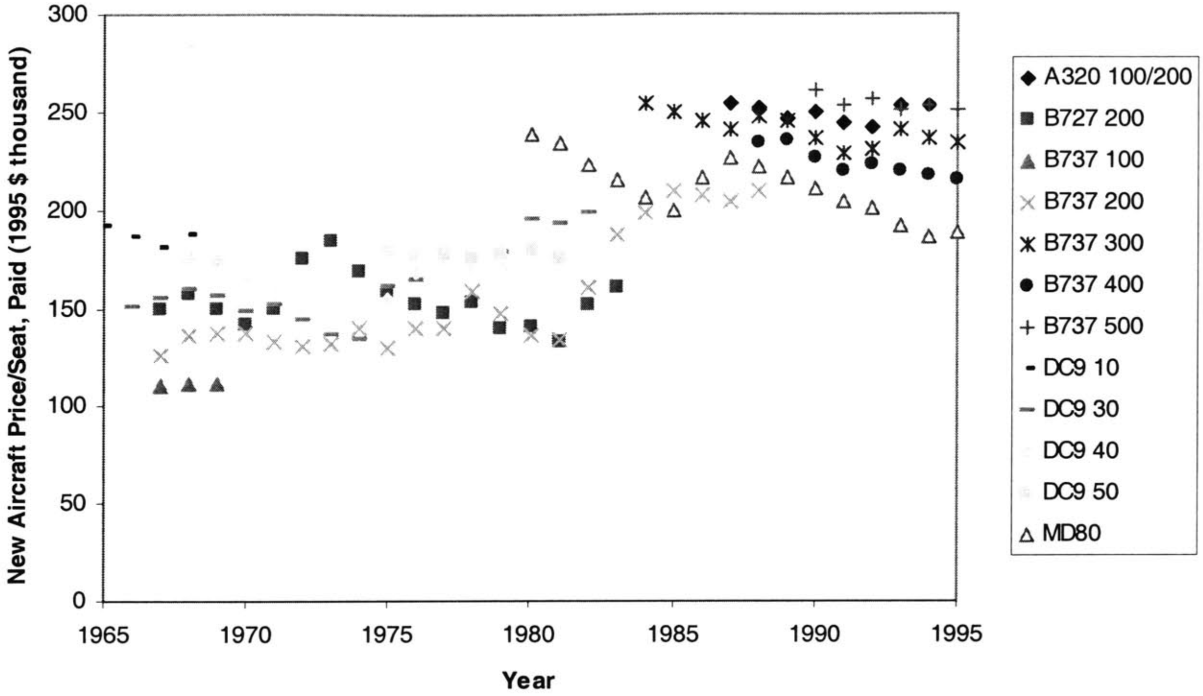

Figure 3.14: Historical Trends in Short-range Aircraft Prices

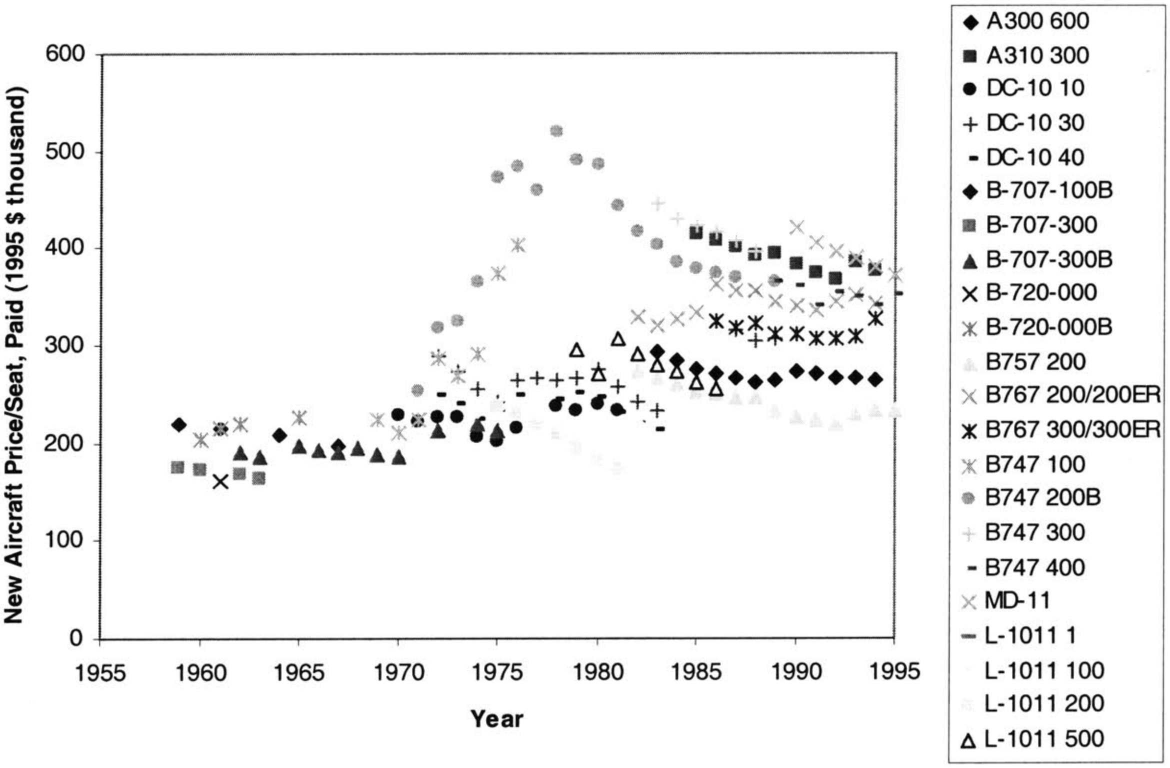

Figure 3.15: Historical Trends in Long-range Aircraft Prices

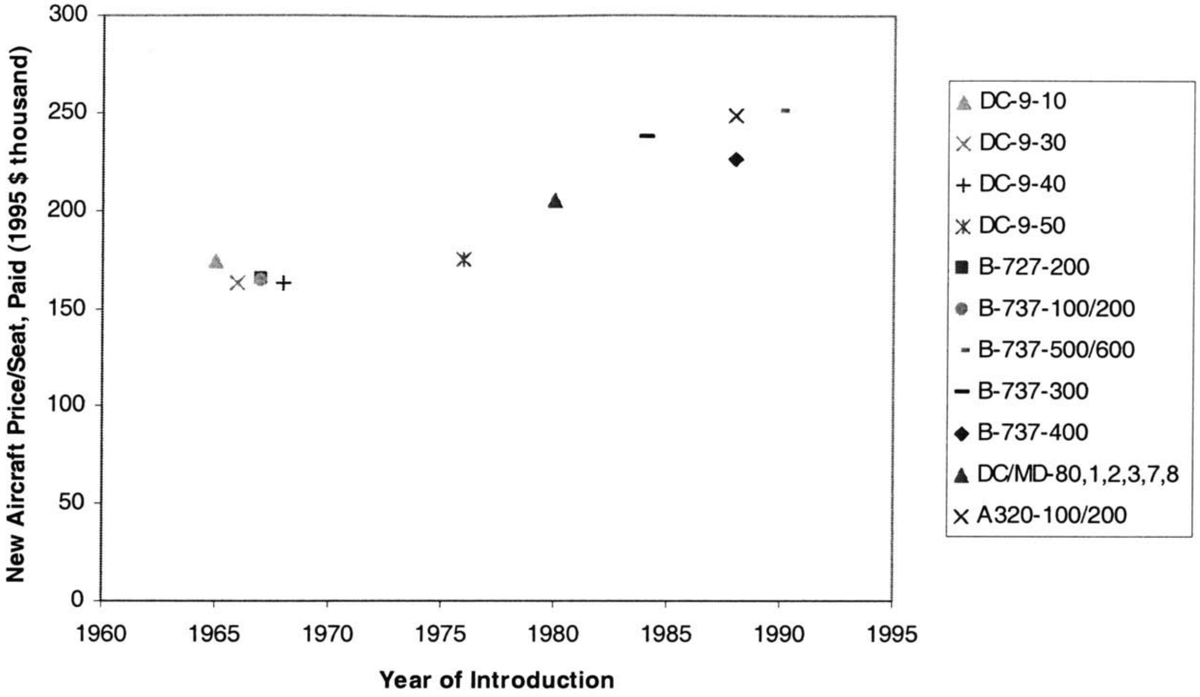

Figure 3.16: Price versus Year of Introduction for Short-range Aircraft

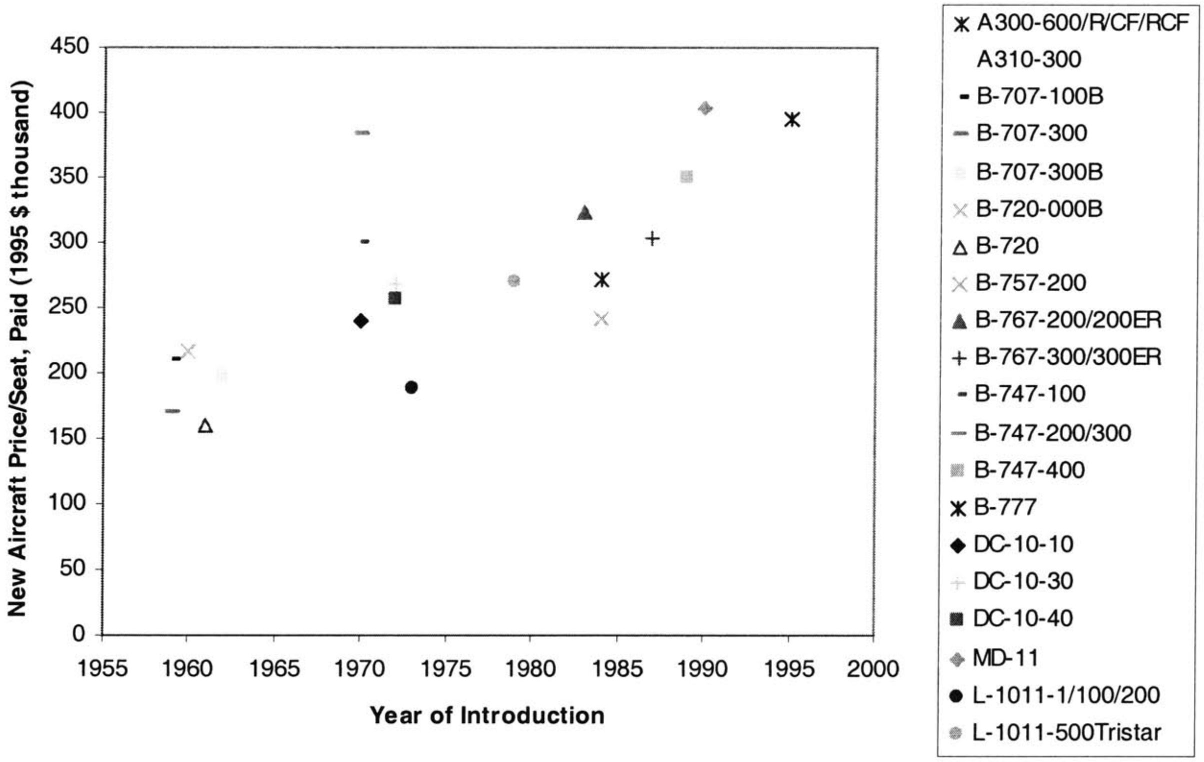

Figure 3.17: Price versus Year of Introduction for Long-range Aircraft

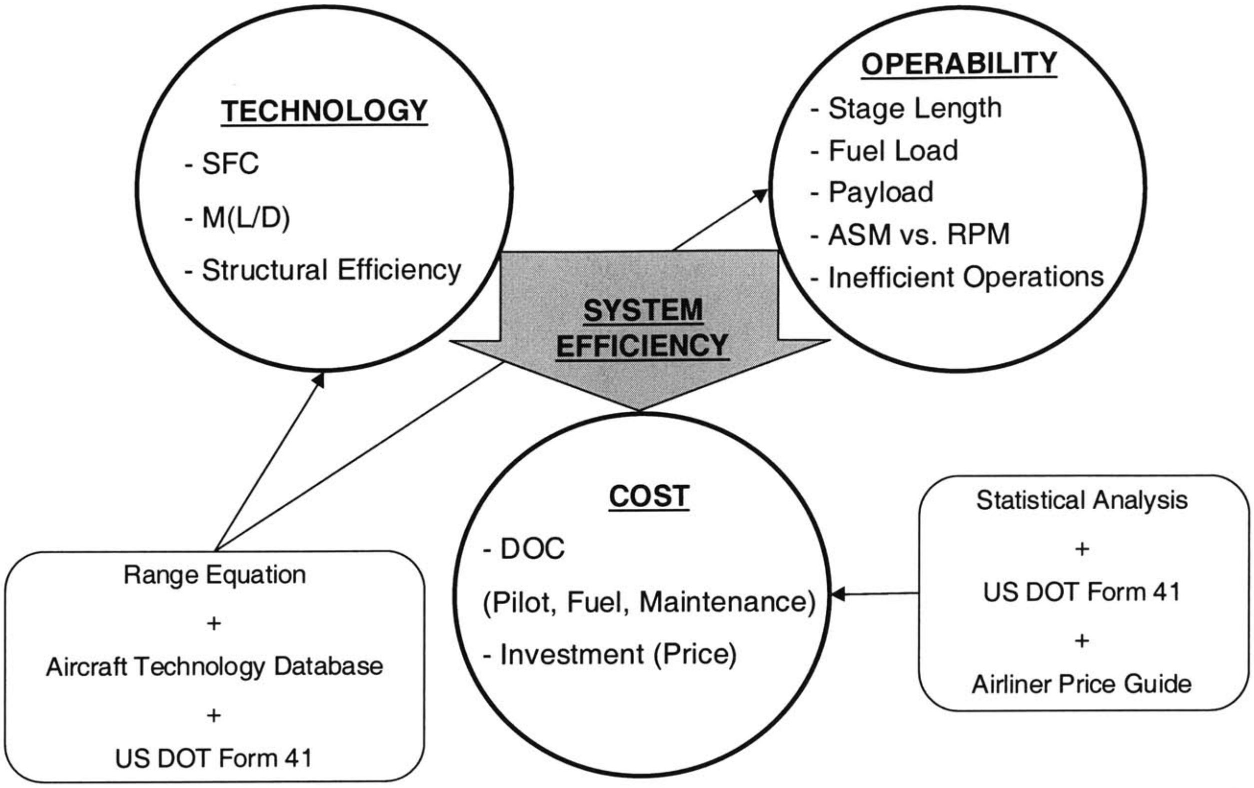

Figure 3.18: Parametric Modeling Framework for Aircraft Performance and Cost

Chapter 4

Parametric Modeling of Technology-Operability-Fuel Economy Relationships

4.1 Introduction

In this chapter, the impact of technology and operability on aircraft fuel economy is analytically understood based on the Breguet range equation. Fuel consumption, as measured in gallons of fuel burn per RPM to reflect advancement in technology and operability, is a direct measure for CO_2 emissions, the most important greenhouse gas. It is also an indirect indicator for other aircraft emissions, such as NO_x and H_2O. Thus, fuel consumption is the key parameter in determining total aviation fuel use and assessing aviation's impacts on global climate. In addition, fuel consumption strongly influences aircraft operating costs and prices as observed previously in the historical trends. Therefore, a technology-cost relationship for aircraft systems will be developed based on this fuel economy-cost analysis in the next chapter.

4.2 The Breguet Range Equation

4.2.1 Theory

The basic model for describing the physics of aircraft in steady cruise flight is the Breguet range equation as shown in (4.1) and (4.2), where engine, aerodynamic, and structural technologies are represented by three parameters, specific fuel consumption, lift-to-drag ratio, and structural weight, respectively. Given these technological characteristics and the amount of payload and fuel on board, the Breguet range equation determines the maximum flight distance. The key assumptions are that SFC, L/D, and flight speed, V are constant, and therefore take-off, climb, and descend portions of flights are not well modeled (McCormick, 1979; Houghton, 1982).

$$Range = \frac{V(L/D)}{g \cdot SFC} ln\left(\frac{W_{initial}}{W_{final}}\right) \tag{4.1}$$

where $W_{initial} = W_{fuel} + W_{payload} + W_{structure} + W_{reserve}$ and $W_{final} = W_{payload} + W_{structure} + W_{reserve}$

By substituting these various weights, the Breguet range equation can be rewritten as follows:

$$Range = \frac{V(L/D)}{g \cdot SFC} ln\left(1 + \frac{W_{fuel}}{W_{payload} + W_{structure} + W_{reserve}}\right) \tag{4.2}$$

where SFC, L/D, and $W_{structure}$ are technology parameters while W_{fuel}, $W_{payload}$, and $W_{reserve}$ are operability parameters.

4.2.2 Range Calculation and Correction

Using data available from the technology databases and traffic statistics in Form 41, range is calculated and compared with actual stage length flown. Note that the explicit values of fuel reserve are not reported. According to Federal Aviation Regulation (FAR), fuel reserve is the extra fuel required to fly additional 30 minutes during the day and 45 minutes at night upon arriving at the vicinity of the final destination. Detailed fuel reserve requirements are shown in Appendix 5. Therefore, fuel reserve is a function of payload and range, and for the analysis purposes of this thesis, 50% of fuel burn per block hour is assumed for fuel reserve amount and used for calculating range.

Since the Breguet range equation addresses neither take-off/landing nor taxing and calculates range based on constant cruise conditions only, its calculated range is expected to be greater than actual distance flown as shown in Figure 4.1, where actual stage length reported in Form 41 is the great circle route distance between airports. Note that only 23 aircraft types are shown, because of the limited aerodynamic data for L/D ratios.

Calculated stage length is larger than actual stage length flown by about 10% for long-range aircraft, and the deviation gradually increases to as large as 120% for short-range aircraft as shown in Figure 4.2. While several factors may be responsible for this trend, the most significant reason is non-cruise, non-ideal flight segments in real aircraft operations. That is, all fuel consumed on the ground and during idle, taxing, take-off, and landing does not contribute to actual stage length. In addition, any deviation from great circle routes, especially during climbing and descending, adds inaccuracy in the range calculation. Flight delays both on the ground and in the air also cause extra fuel burn that does not contribute to actual stage length. Note also that the fuel load entered in the range calculation is directly from Form 41's "Fuels Issued" category. Thus, not all fuels issued may have been consumed, in which case range is overestimated due to left-over fuels.

A proper adjustment for fuel burned during non-cruise segments on the ground can be made by the ratio of airborne hours to block hours. If aircraft could immediately take off without spending any time on the ground upon starting engines, airborne hours would be equal to block hours. In reality, however, the airborne-hours-to-block-hours ratio ranges from 0.75 for short-range aircraft to 0.9 for long-range aircraft, indicating that the fraction of extra fuel burned on the ground during various non-flying operations on total fuel consumption is inversely proportional to stage length as shown in Figure 4.3.

A useful measure to account for the non-cruise portion and flight delays in the air is the ratio of minimum flight hours to airborne hours. Minimum flight hours represents the shortest time required to fly a certain stage length. By assuming that all aircraft fly at Mach 0.85 and at altitude of 35,000 feet in an ideal condition, the maximum flight speed is calculated to be 527.2 miles per hour (MPH) on a block-hour basis. Dividing stage length reported in Form 41 by this flight speed then gives minimum flight hours. Hence, the minimum-flight-hours-to-airborne-hours ratio shown in Figure 4.3 reveals any extra flight time due to non-ideal flight conditions. A detailed calculation procedure for minimum flight hours is shown in Appendix 6.

Multiplying both ratios above gives total flight time efficiency, the ratio of minimum flight hours to block hours, as also shown in Figure 4.3. Note the large inefficiency associated with short-range aircraft where more than 40% of block time is spent on non-cruise, non-ideal flight segments. This fact is quite realistic since for short-haul flights, 40% or more of the total fuel consumption can occur during the initial rapid climbing phase (ETSU, 1992). On the other hand, long-range aircraft seem to operate almost at the best practice as total flight time efficiency is nearly 0.9.

By multiplying total flight time efficiency to the previously calculated range values, most deviation in the range calculation can be corrected as shown in Figure 4.4. After this correction, deviations are only around 10% on average throughout all aircraft types, indicating that most errors associated with the systematic difference between short- and long-range aircraft have been corrected.

Another contributing factor for the deviation of calculated range is fuel reserve and any other non-reported weights such as food on board. Fuel reserve was assumed to be 50% of block fuel consumption, which translates to the amount of fuel burned for approximately 30 minutes. Thus, the actual fuel reserve amount could be greater than the assumed value considering the range of the required extra flight time, 30 to 45 minutes. If more precise fuel reserve amount and non-reported weight elements could be entered in the range calculation, a large fraction of the remaining 10% deviation is expected to be reduced.

Lastly, the variability associated with the values of SFC, L/D, and structural weight mostly causes the rest of the scattered deviation in the range calculation. Further, the technology parameters do not remain constant during the whole flight mission, and therefore take-off, climb, and descend portions of flights are not well modeled through the Breguet range equation. With these uncertainties in mind, however, the best estimates for the technology and operability parameters have been entered in the range calculation analysis, and it is notable that such a simple model as the Breguet range equation describes the physical behavior of complex aircraft systems within a relatively small range of errors.

Since the validity of the Breguet range equation is confirmed, it can be further utilized to model aircraft fuel economy as shown in equation (4.3). The aircraft fuel consumption parameter denotes the amount of fuel consumed to move a certain amount of payload over a certain distance. The fuel consumption parameter is a useful measure, which can be directly translated as a CO_2 emissions index. Note that the correction factor, $\delta_{correction}$ based on the curve fit to the deviation of the calculated stage length in Figure 4.5 is included as a multiplicative term in the fuel consumption equation in order to correct for non-cruise, non-ideal flight segments in actual flight operations. Note that $\delta_{correction}$ then accounts for the sum of the correction made by the ratio of minimum flight hours to block hours and the remaining 10% deviation in the range calculation. An average correction factor calculated for the fleet is 0.72. The aircraft fuel efficiency parameter is just the inverse of the fuel consumption parameter, as its physical meaning is the work created in terms of ASM or RPM per unit energy input. Either measure, fuel consumption or fuel efficiency, shows the energy use performance of an airplane reflecting the level of advancement in technology and operability. The fuel consumption parameter will be further utilized in this thesis in order to understand the influence of technology and operability on aircraft fuel economy.

$$\begin{aligned}
&\boldsymbol{Fuel\ Consumption\left[\frac{gal}{RPM}\right]}\\
&\equiv \frac{W_{fuel}}{Passengers \cdot Stage\ Length \cdot \delta_{correction}}\\
&= \frac{W_{fuel}}{(W_{payload} / W_{individual})} \cdot \frac{g \cdot SFC}{V(L/D)} \cdot \frac{1}{ln\left(1 + \frac{W_{fuel}}{W_{payload} + W_{structure} + W_{reserve}}\right) \cdot \left(\frac{100}{100 + 42707 \cdot Stage\ Length^{-0.933}}\right)}
\end{aligned} \qquad (4.3)$$

where $\delta_{correction}$ and $W_{individual}$ denote the correction factor for the deviation of the Breguet range equation calculation and the weight of an individual passenger with cargo, respectively. Payload divided by the weight of individual passengers with cargo, $W_{payload}/W_{individual}$ then gives the number of passengers. USDOT Form 41 assumes 200 pounds for $W_{individual}$. Lastly, Stage Length denotes calculated range using the Breguet range equation.

Fuel consumption per available seat-mile can be obtained by multiplying load factor by the fuel consumption parameter as follows:

$$\frac{gal}{ASM} = \alpha \frac{gal}{RPM} \tag{4.4}$$

where α denotes load factor. More directly, it can also be obtained by using reported number of seats as follows:

$$\begin{aligned} &\frac{gal}{ASM} \\ &\equiv \frac{W_{fuel}}{Seats \cdot Stage\ Length \cdot \delta_{correction}} \\ &= \frac{W_{fuel}}{Seats} \cdot \frac{g \cdot SFC}{V(L/D)} \cdot \\ &\frac{1}{ln\left(1 + \frac{W_{fuel}}{W_{payload} + W_{structure} + W_{reserve}}\right) \cdot \left(\frac{100}{100 + 42707 \cdot Stage\ Length^{-0.933}}\right)} \end{aligned} \tag{4.5}$$

4.3 Taylor Series Expansion

4.3.1 Theory

A Taylor series expansion is used to convert the nonlinear behavior of the Breguet range equation into a linear form and estimate how much the functional value changes with respect to an incremental change in each of independent parameters based on a series of partial derivative terms called influence coefficients. While it is straightforward to quantify the influence of each of independent parameters on the functional value, the Taylor series works only for a narrow range around the base value because of the linearization assumption.

4.3.2 1st Order Taylor Series Expansion of the Breguet Range Equation

The Breguet range equation was expanded into a Taylor series with only first-order terms as shown in equation (4.6). Note that by observing the influence coefficients, the impact of technology and operability on range can easily be quantified.

$$SL = SL_o + \Delta SFC \left.\frac{\partial SL}{\partial SFC}\right|_o + \Delta(L/D) \left.\frac{\partial SL}{\partial(L/D)}\right|_o + \Delta W_f \left.\frac{\partial SL}{\partial W_f}\right|_o + \Delta W_p \left.\frac{\partial SL}{\partial W_p}\right|_o + \Delta W_s \left.\frac{\partial SL}{\partial W_s}\right|_o + \Delta W_r \left.\frac{\partial SL}{\partial W_r}\right|_o \qquad (4.6)$$

where SL stands for stage length as calculated by the Breguet range equation while W_f, W_p, W_s, and W_r are short forms for W_{fuel}, $W_{payload}$, $W_{structure}$, and $W_{reserve}$. The influence coefficients are as follows:

$$\frac{\partial SL}{\partial SFC} = -\frac{V(L/D)}{g \cdot SFC^2} ln\left(\frac{W_{initial}}{W_{final}}\right) \qquad (4.7)$$

$$\frac{\partial SL}{\partial(L/D)} = \frac{V}{g \cdot SFC} ln\left(\frac{W_{initial}}{W_{final}}\right) \qquad (4.8)$$

$$\frac{\partial SL}{\partial W_f} = \frac{V(L/D)}{g \cdot SFC} \cdot \frac{1}{W_{initial}} \qquad (4.9)$$

$$\frac{\partial SL}{\partial W_p} = \frac{\partial SL}{\partial W_s} = \frac{\partial SL}{\partial W_r} = \frac{V(L/D)}{g \cdot SFC} \cdot \frac{-W_f}{W_{initial} \cdot W_{final}} \qquad (4.10)$$

Figure 4.6 shows that the stage length calculated by the first-order terms of the Taylor series is in good agreement with the stage length calculated by the Breguet range equation where three base values of stage length (913, 2,227, and 4,267 miles) are used to predict the entire flying range of the 23 aircraft types. Note that the Taylor series predictions deviate farther from the original functional values as one gets away from the base values. The deviation can be reduced if higher-order terms in the Taylor series are included.

The influence coefficients make it possible to determine percent improvements in range due to 1% improvement in each of the technology and operability parameters as shown in Figure 4.7. Note that SFC and L/D have exactly the same influence, as 1% improvement in each of them results in 1% increase in range. It is also noteworthy that all aircraft types have almost the same range improvement potential with respect to technological improvements. This is largely because most modern aircraft have the same geometry for engine, fuselage, and wing configurations and are made out of the same material, aluminum.

4.3.3 1^{st} Order Taylor Series Expansion of Fuel Consumption Equation

In order to quantify technological and operational influences on aircraft fuel economy, the fuel consumption equation is expanded into a Taylor series with first-order terms as shown in equation (4.11). Note that the total flight time efficiency is not included as part of the Taylor series expansion while it simply has a one-to-one linear influence coefficient for fuel consumption. In addition, the weight is of an individual passenger with cargo is assumed to be a constant, 200 pounds.

$$FC = FC_o + \Delta SFC \left.\frac{\partial FC}{\partial SFC}\right|_o + \Delta(L/D) \left.\frac{\partial FC}{\partial (L/D)}\right|_o + \Delta W_f \left.\frac{\partial FC}{\partial W_f}\right|_o + \Delta W_p \left.\frac{\partial FC}{\partial W_p}\right|_o + \Delta W_s \left.\frac{\partial FC}{\partial W_s}\right|_o + \Delta W_r \left.\frac{\partial FC}{\partial W_r}\right|_o \qquad (4.11)$$

where FC stands for fuel consumption. The influence coefficients are shown below where W_i is a short notation for $W_{individual}$.

$$\frac{\partial FC}{\partial SFC} = \frac{g}{V(L/D)} \cdot \frac{W_f}{(W_p / W_i)} \cdot \frac{1}{ln\left(\frac{W_{initial}}{W_{final}}\right)} \qquad (4.12)$$

$$\frac{\partial FC}{\partial (L/D)} = -\frac{g \cdot SFC}{V(L/D)^2} \cdot \frac{W_f}{(W_p / W_i)} \cdot \frac{1}{ln\left(\frac{W_{initial}}{W_{final}}\right)} \qquad (4.13)$$

$$\frac{\partial FC}{\partial W_f}=\frac{g\cdot SFC}{V(L/D)}\cdot\frac{W_f}{(W_p/W_i)}\left(\frac{1}{W_f\cdot ln\left(\frac{W_{initial}}{W_{final}}\right)}-\frac{1}{W_{initial}\left(ln\left(\frac{W_{initial}}{W_{final}}\right)\right)^2}\right) \tag{4.14}$$

$$\frac{\partial FC}{\partial W_p}=\frac{g\cdot SFC}{V(L/D)}\cdot\frac{W_f}{(W_p/W_i)}\left(\frac{-1}{W_p\cdot ln\left(\frac{W_{initial}}{W_{final}}\right)}+\frac{W_f}{W_{initial}\cdot W_{final}\left(ln\left(\frac{W_{initial}}{W_{final}}\right)\right)^2}\right) \tag{4.15}$$

$$\frac{\partial FC}{\partial W_s}=\frac{\partial FC}{\partial W_r}=\frac{g\cdot SFC}{V(L/D)}\cdot\frac{W_f}{(W_p/W_i)}\cdot\frac{W_f}{W_{initial}\cdot W_{final}\left(ln\left(\frac{W_{initial}}{W_{final}}\right)\right)^2} \tag{4.16}$$

Figure 4.8 shows percent reductions in fuel consumption per RPM due to 1% improvement in each of the technology and operability parameters. Overall, a 2.7% reduction in fuel burn per RPM can be achieved by simultaneous improvements in engine, aerodynamic, and structural efficiencies by 1% each. Note that all aircraft types also have almost the same fuel economy improvement potential with respect to technological improvements. This indicates that, regardless of short- or long-range aircraft, the emissions reduction potential due to technology advancement is approximately the same for all types of existing aircraft. A large difference in the ability to reduce aviation emissions may then lie in the cost limitation of aircraft development and operations, which will be further addressed in later chapters.

Note that SFC and L/D still have the same influence on fuel burn reduction of 1% with respect to 1% improvement in each of them. Structural weight does not have as strong an influence as engine or aerodynamic efficiency does, as fuel burn reduction due to 1% reduction in structural weight varies between 0.7 and 0.75. This compares with the previous literature estimate that the elasticity of fuel use per aircraft with respect to airframe weight ranges from

0.25 to 0.50, depending on aircraft size and range. That is, a 30% reduction in aircraft weight could reduce cruise fuel consumption by 7 to 15% (Greene, 1992). Note also that structural weight and fuel reserve have exactly the same influence on fuel burn reduction as seen in equation (4.16). Thus, if less fuel can be carried as a reserve, aircraft fuel consumption can also be reduced as a result of overall aircraft weight reduction. Lastly, 1% increase in payload, which is equivalent to 1% increase in load factor, would result in about a 0.8% decrease in fuel burn per RPM as indicated in the sensitivity of fuel consumption on payload. This confirms that increasing load factor is an important aspect of improving fuel consumption for airlines. Changes in fuel on board can improve fuel consumption but with penalties in range.

4.4 Chapter Summary

In this chapter, technological and operational influences on aircraft fuel economy have been quantified. the Breguet range equation, which describes the physics of aircraft cruising flight, has been employed to model aircraft fuel consumption based on engine, aerodynamic, and structural efficiency parameters as well as payload and fuel on board. Through a Taylor series expansion of the fuel consumption equation, a fuel burn reduction potential due to technological and operational improvements has been quantified. Note that analysis results in this chapter explain the historical trends in aircraft performance in the previous chapter where the 40% improvement in SFC and the 15% improvement in L/D analytically comprise 55% reduction for the overall 70% reduction in aircraft fuel burn observed in the historical trends, assuming that the linearity of the Taylor series expansion holds over these ranges. Increase in load factor (15% improvement during the period 1959 to 1995) then accounts for about 12% reduction in fuel burn while other operational improvements including increased seats are to account for the remaining 3% reduction in fuel burn in the past. It is now possible to project the fuel economy improvement potential for future aircraft systems given their technological and operational characteristics and attribute economic values to them once the complete analysis of technology-cost relationship is carried out in the next chapter.

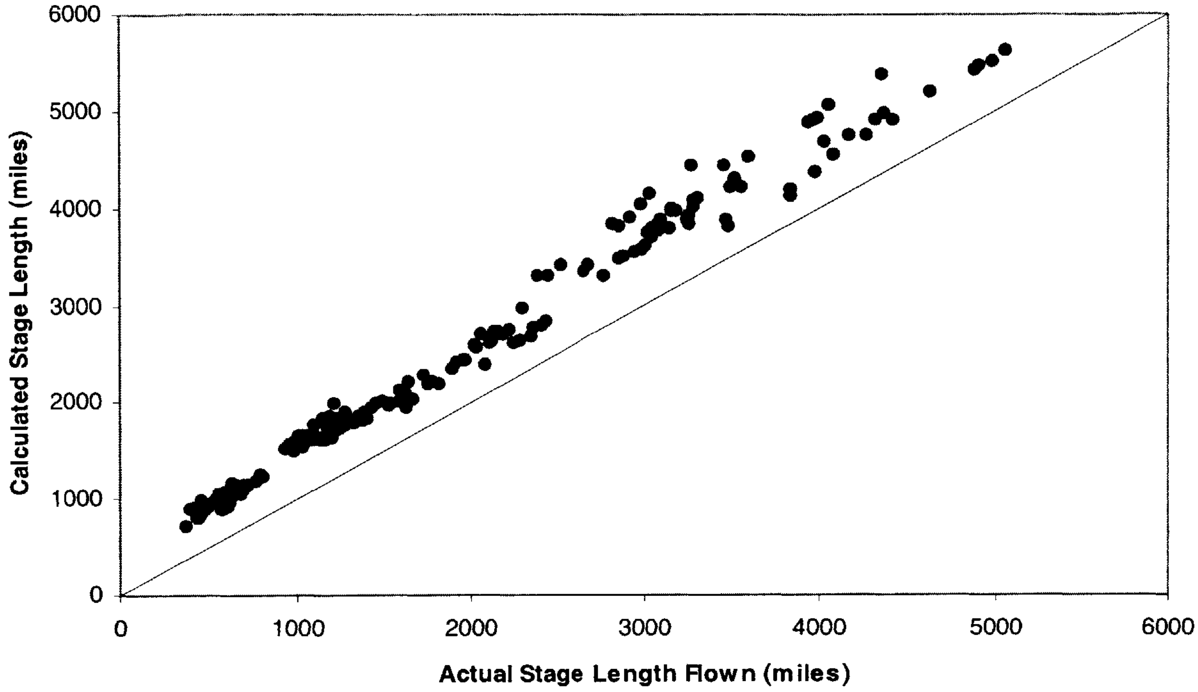

Figure 4.1: Calculated Range versus Actual Stage Length Flown (based on operating data for 1991-98)

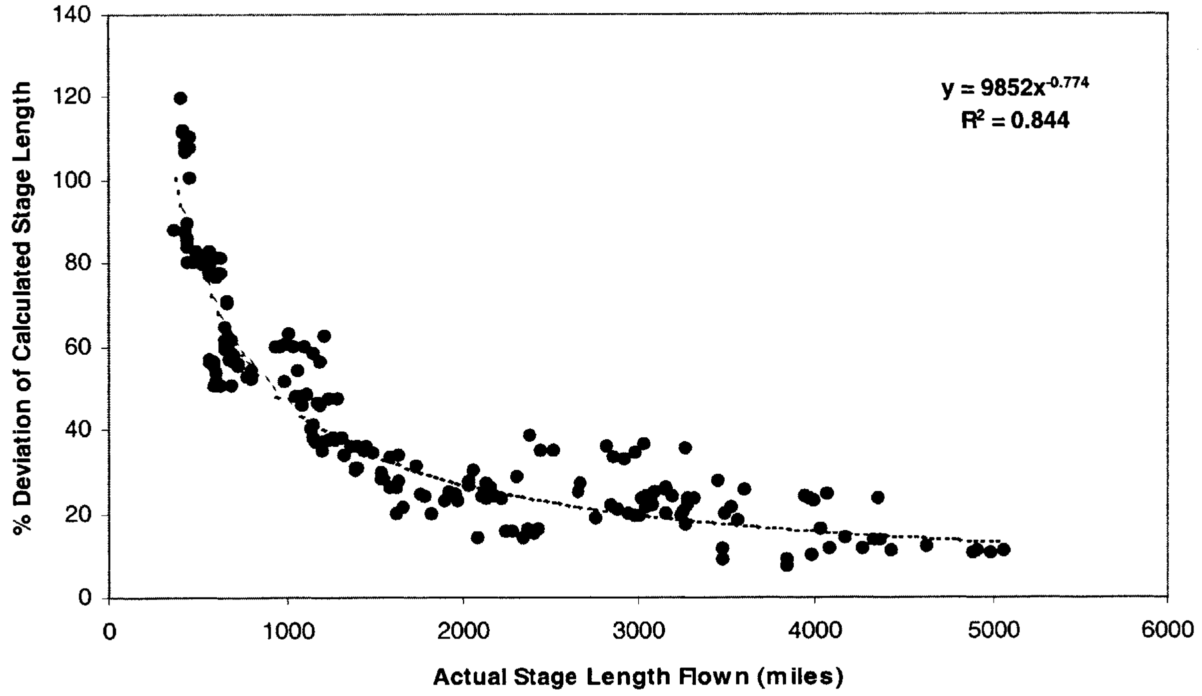

Figure 4.2: Deviation of Calculated Stage Length versus Actual Stage Length Flown

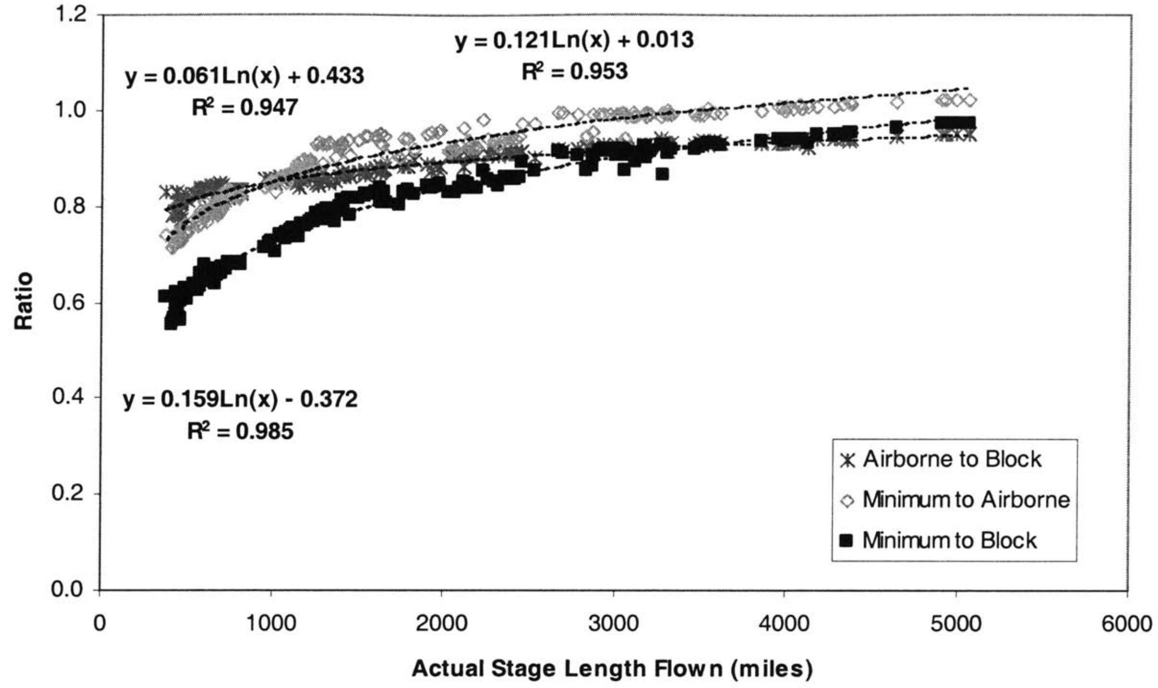

Figure 4.3: Various Ratios of Aircraft Operating Hours (based on operating data for 1991-98)

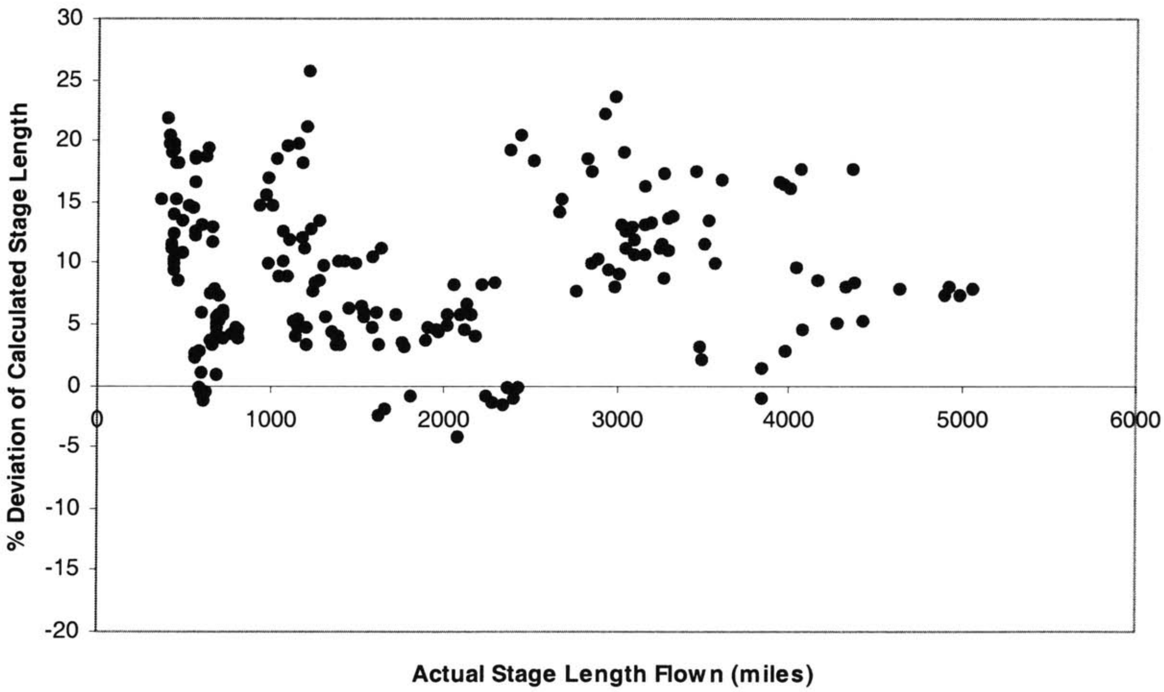

Figure 4.4: Range Calculation Corrected by Ratio of Minimum Flight Hours to Block Hours

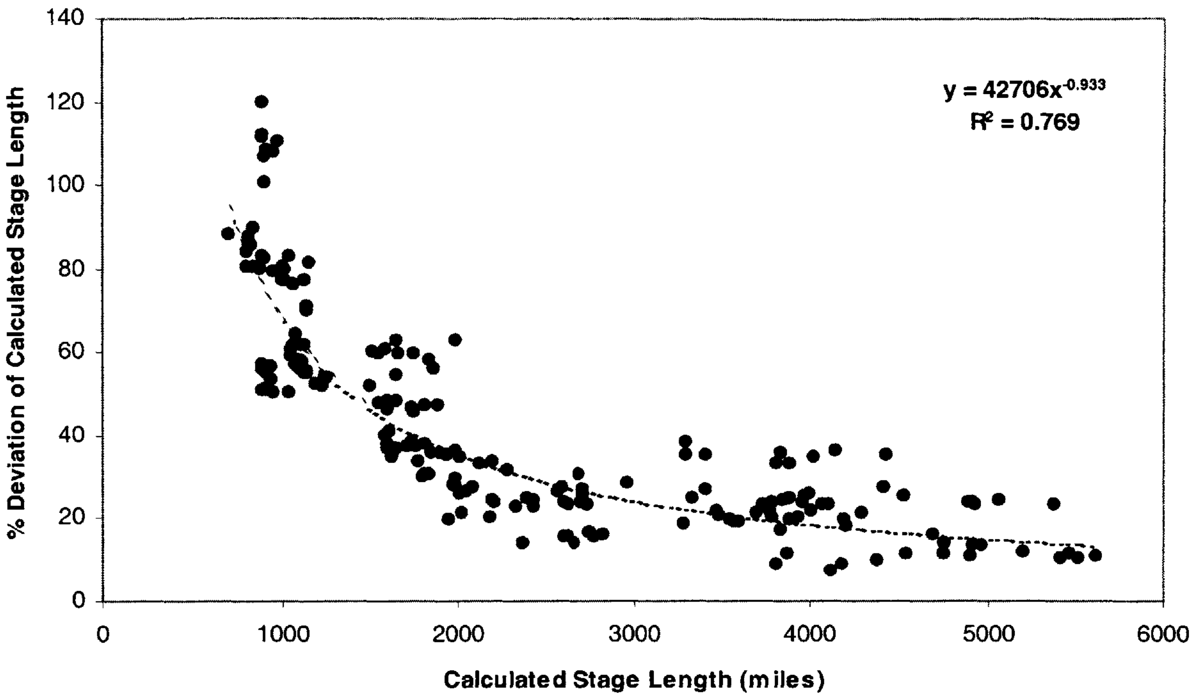

Figure 4.5: Deviation of Calculated Stage Length versus Calculated Stage Length

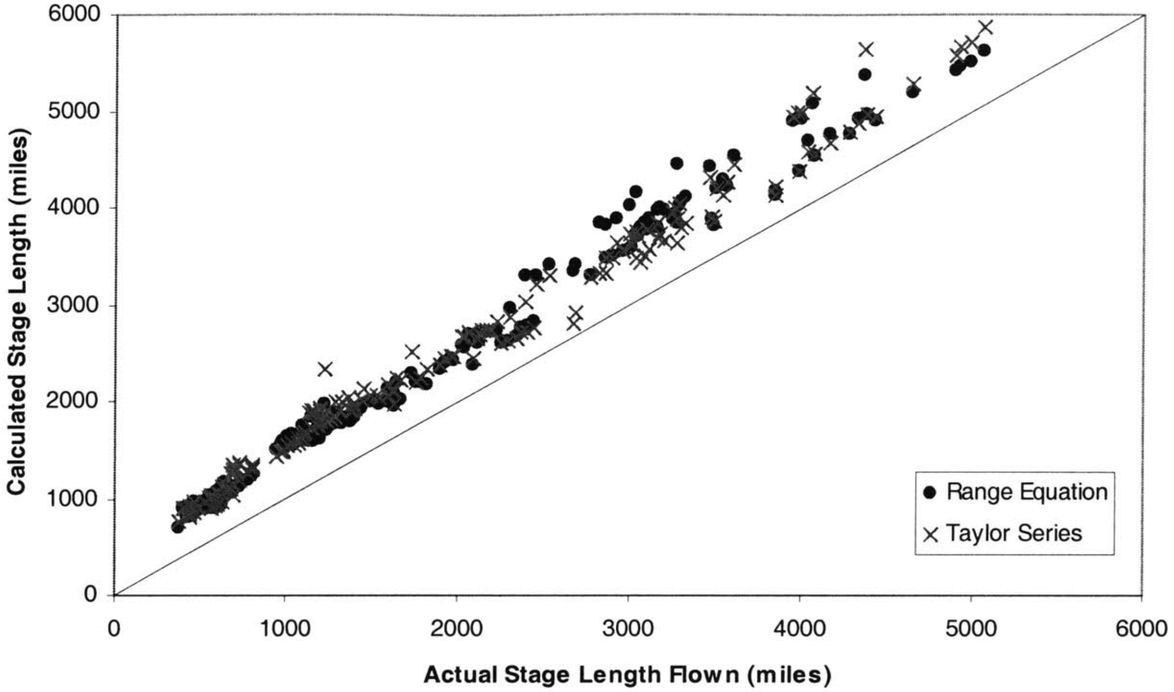

Figure 4.6: Stage Length Calculated by Taylor Series versus Original Function of Breguet Range Equation (three base values at 913, 2,227, and 4,267 miles)

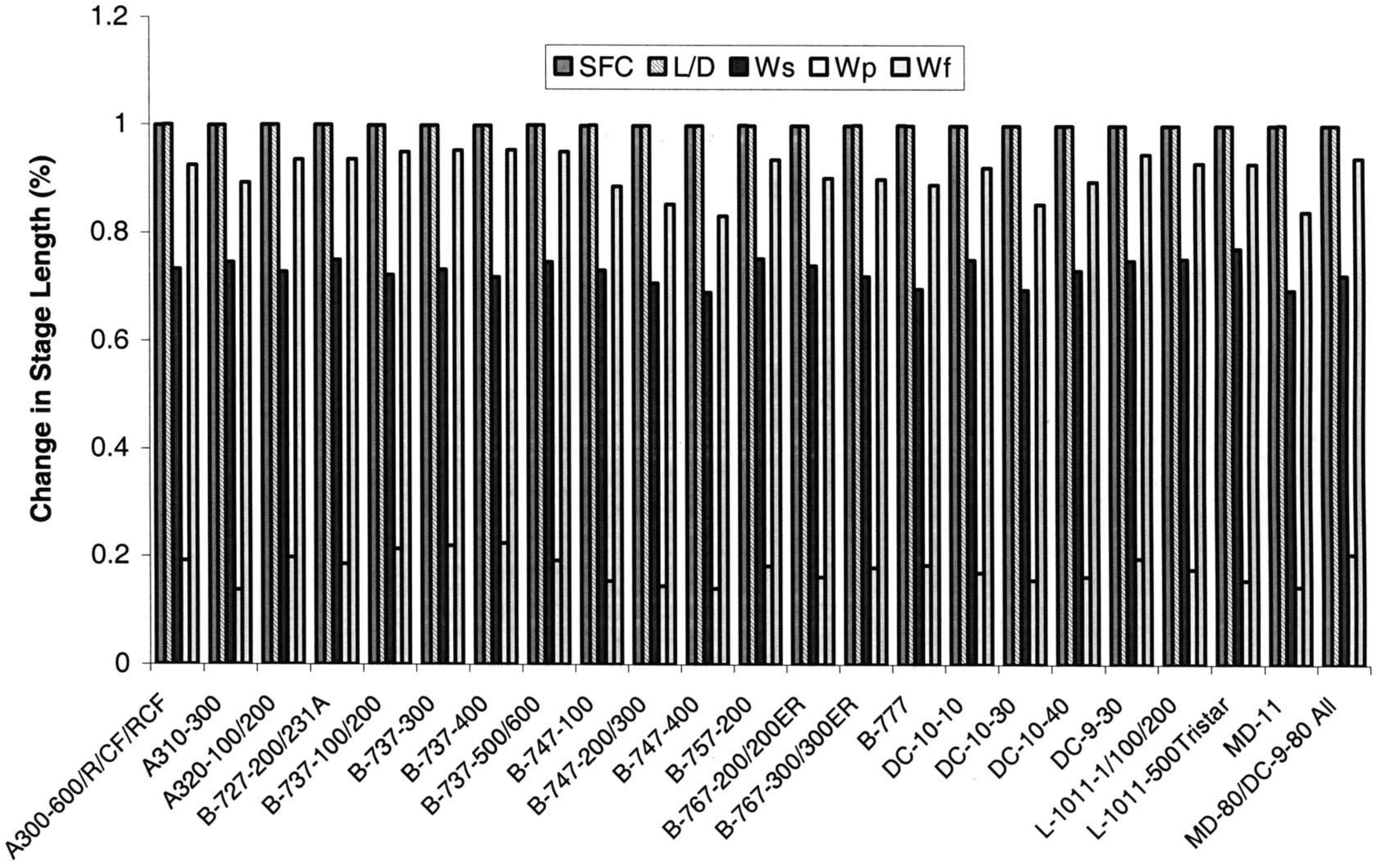

Figure 4.7: Percent Improvement in Range Due to 1% Improvement in Performance and Operability ($W_{payload}$ reduced; W_{fuel} increased; $W_{reserve}$ held constant and not shown)

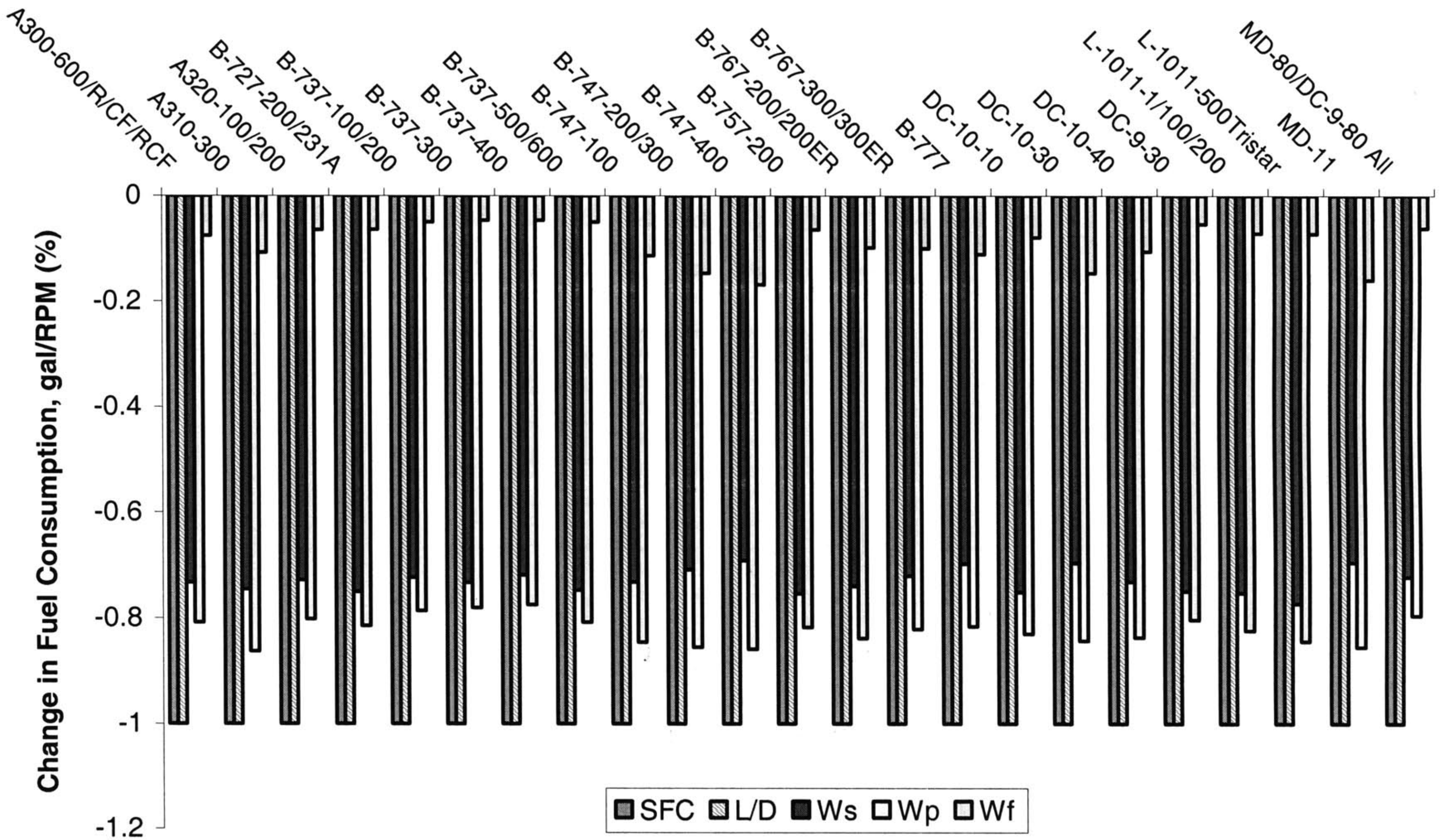

Figure 4.8: Percent Reduction in Fuel Consumption Due to 1% Improvement in Performance and Operability ($W_{payload}$ increased; W_{fuel} reduced; $W_{reserve}$ held constant and not shown)

Chapter 5

Parametric Modeling of Technology-Cost Relationship

5.1 Introduction

This chapter quantitatively examines the relationship between aircraft performance and cost. The impacts of fuel efficiency, as a surrogate for technology advancement, and load factor on direct operating cost are analyzed through multivariable statistical analysis. The correlation between direct operating cost and price is also statistically understood.

All economic values used in the analyses of this chapter are first deflated to 1995 U.S. dollars. In order to account for the impacts of fuel price fluctuations on fuel cost, the entire fuel cost category is divided by annual jet fuel price deflated to 1995 dollars and then multiplied by 1995 jet fuel price. This way, an external economic influence on fuel cost is normalized while a more direct impact of aircraft performance improvement on direct operating cost can be examined. Annual aircraft fuel prices used to normalize fuel cost data are shown in Appendix 7.

5.2 Aircraft System Performance and Cost

5.2.1 Parameter Development

The primary goal of this thesis is to quantitatively understand technological and operational impacts on aircraft performance as measured by environmental metrics relevant to aviation's impacts on climate change and relate the performance metrics to aircraft cost in order to assess the technological and economic feasibility of aviation emissions reduction potential in the future. Therefore, a great deal of effort was made in searching and defining an appropriate parameter that would capture improvements in aircraft technologies and operations and relate well to aircraft direct operating costs and prices. Furthermore, as an overarching requirement, the parameter must signify the environmental impacts of aviation, *e.g.*, the amount of CO_2 emissions produced per passenger-mile.

A number of candidate parameters were initially examined. For example, all technology parameters (SFC, L/D, and structural weight) and operability parameters (payload and fuel weight) in the Breguet range equation could be individually used. Stage length, operating hours, and even aircraft speed were possible candidates as measures of total aircraft usage. Aircraft size in terms of number of seats and number of passengers were also considered. The objective was then to derive the most appropriate environmental metrics to capture technological and operational changes and relate to aircraft cost while reducing the number of variables in a consolidated form to the extent possible.

First, the technology and operability parameters of the Breguet range equation were represented by the fuel consumption parameter, gallons of fuel burn per RPM, since the relationship between them had been analytically understood. This greatly reduced the number of initial variables. Second, aircraft usage and size characteristics were represented by revenue passenger miles (number of passengers multiplied by stage length) and available seat miles (number of seats multiplied by stage length). Operating hours was also accounted for by RPM and ASM because it would be simply proportional to stage length at approximately constant flight speed throughout aircraft types. As a result, aircraft fuel consumption, RPM, and ASM were identified as the key parameters that captured the impacts of aircraft technologies and operations while the aircraft fuel consumption parameter itself was an environmental metric that could be directly translated into a CO_2 emissions index. The next sections examine how these parameters relate to aircraft cost and further develop a simplified parameter based on them.

5.2.1.1. Fuel consumption and direct operating cost and price

Since aircraft fuel economy is directly impacted by technology advancement, examining the relationship between fuel consumption and DOC provides a valuable insight into understanding the influence of aircraft system performance improvement on aircraft cost. Note that some DOC categories, such as aircraft fuel cost and maintenance labor and material costs, have a stronger

These three parameters are captured in an aviation system efficiency parameter, $\eta_{aviation\ system}$, which is defined as a product of two other efficiency measures by inverting the fuel consumption parameter and separating out the ratio of RPM to ASM as follows:

$$\eta_{aviation\ system} \equiv \eta_{energy\ use} \cdot \eta_{load\ factor} = \frac{ASM}{gal} \cdot \frac{RPM}{ASM} \qquad (5.1)$$

ASM/gal signifies the efficiency of aircraft energy use in terms of work created per unit energy input. This fuel efficiency measure can be expressed as a function of all the technology and operability parameters based on the Breguet range equation. Thus, the impacts of changes in technology or operability on aircraft cost can be directly quantified through this parameter. Furthermore, ASM/gal observed in actual aircraft operations data reflects inefficiencies in aircraft operations, such as ground holding, delays, and any other non-cruise, non-ideal flight segments, as examined by the ratio of minimum flight hours to block hours in the previous chapter.

RPM/ASM is the load factor, an operational measure to show how efficiently aircraft seats are filled, and aircraft miles are utilized for revenue generating purposes. Thus, load factor is a efficiency measure to account for total aircraft utilization. It is particularly important in mitigating aviation's environmental impacts because increasing load factor directly leads to improved fuel consumption on a passenger-mile basis. Load factor is also an important parameter for airliners' profitability.

In sum, the aviation system efficiency parameter captures both technological and operational performance of an aircraft. The relationship between this parameter and aircraft operating cost provides useful insight into the technology-cost relationship for aircraft. While it measures the efficiency of moving passengers, its can also be translated into a CO_2 emissions index. Therefore, the aviation system efficiency parameter is the most suitable environmental performance metric to relate aircraft performance, cost, and emissions.

relevance with technology advancement and remain relatively consistent across different air carriers while some other minor DOC categories, such as taxes and training expenses, have a weaker relevance with technology advancement and vary largely across different operators. This parametric study includes all categories of DOC in USDOT Form 41 as shown in Table 5.1.

Figure 5.1 is a scatter plot for direct operating cost versus fuel consumption. For about 67% reduction in fuel burn from about 0.06 gal/RPM to 0.02 gal/RPM, DOC/RPM decreases by about 70% from $0.10 to $0.03. This directly shows that more fuel-efficient aircraft are cheaper to operate largely because of the strong causality between fuel efficiency improvement and savings in fuel cost. Figure 5.2 shows the same scatter plot without fuel cost normalized. Note that the data points are more spread out because of the fluctuations in fuel cost impacted by fuel price changes, and the correlation between direct operating cost and fuel consumption is weaker.

5.2.1.2. Aircraft usage and size and direct operating cost

DOC is not only impacted by aircraft fuel efficiency but also by aircraft utilization. In particular, pilot salaries and maintenance cost vary significantly with total usage and size of the aircraft. Overall, DOC increases with increasing aircraft miles (either RPM or ASM) and operating hours (either block hours or airborne hours) as shown in Figures 5.3 and 5.4. Note that the level of DOC per trip is mainly determined by the number of pilots and engine/planform configurations. That is, 3-pilot 4-engine/wide body aircraft incur higher DOC than 2-pilot 2-engine/narrow body aircraft on each trip because of the greater usage involved in longer aircraft miles and hours and larger aircraft size. Since most aircraft fly at the same speed around Mach 0.85, aircraft miles and operating hours are proportional to each other, suggesting that either RPM or ASM alone can represent the usage and size characteristics of aircraft.

5.2.2 Aviation System Efficiency and Direct Operating Cost

As a result of the parameter development processes, aircraft fuel consumption and operational usage seen from revenue passenger miles and available seat miles have been identified as the key parameters that reflect the level of technology and operability advancement and impact DOC.

Figure 5.5 is a scatter plot for DOC/RPM versus ASE. Notably, all the data points collapse onto one single curve. Note that DOC/RPM is the parameter that reflects the cost incurred to move people over a certain distance. Thus it is directly relevant to airlines' profitability. By performing a natural log transformation on both DOC and ASE and carrying out least-squares regression, the log-linear regression model in (5.2) is obtained. Table 5.2 shows the coefficients and relevant statistics.

$$ln(\frac{DOC}{RPM}) = k_1 \cdot ln(\frac{ASM}{gal} \cdot \frac{RPM}{ASM}) + k_2 \qquad (5.2)$$

where $k_1 = -0.958$; $k_2 = 4.92$; $n = 466$; standard error = 0.204; $R^2 = 0.788$

In order to confirm the validity of the DOC model, cross validation was performed on a separate set of initially held-out 25 data points as shown in Figure 5.6. The DOC model predictions are reasonably in good agreement with the actual values of direct operating cost in the held-out data set.

This result is significant in that the complex technological, operational, and economic behaviors of aircraft performance and cost within the entire aviation system have been described by a single parameter, aviation system efficiency, which has physical meaning and statistical significance.

5.2.3 Direct Operating Cost and Price

Aircraft price is strongly correlated with technology advancement as observed from the historical trends shown in Figures 3.16 and 3.17. Thus, examining the relationship between price and DOC, where DOC serves as a surrogate measure for advancement in aircraft technology, operability, and economic performance, provides a useful insight into understanding the impacts of aircraft system performance on price. Note that aviation system efficiency is captured within DOC so that the impacts of changes in aircraft technology and operability can be traced up to changes in DOC and price. Aircraft price is also influenced by many other exogenous factors, such as fuel prices, tax rates, and leasing rates as well as airlines' negotiations with manufacturers and optional specifications while these external factors are not considered in this thesis. Hence, the technology-cost relationship developed here focuses on quantifying the impacts of aircraft system performance on price.

The scatter plot for aircraft price/seat versus DOC/RPM in Figure 5.7 shows that aircraft price is inversely proportional to DOC. That is, the aircraft that incurs lower direct operating cost is more expensive in the market. For example, DC-9-30 costs around 9 cents/RPM to operate, and its purchase price is around \$160 thousand/seat. On the other hand, B-777's DOC is only 2.2 cents/RPM while its purchase price is around \$400 thousand/seat. This higher aircraft price is mainly attributable to improvements in technology and operability lowering aircraft fuel consumption and maintenance burden. In other words, improvements in aircraft system performance directly leads to increased aircraft price. Note that the parameter, price/seat is the normalized measure of aircraft acquisition cost, which provides a comparison of value among different types of aircraft with respect to changes in aircraft system performance and DOC level.

The relatively large variations in aircraft prices show that DOC is not the only factor that impacts aircraft price. However, the overall trend is significant, and a statistical analysis is carried out for further quantification of the relationship. The log-linear equation in (5.3) is the result of the least-squares regression of price on DOC. Table 5.3 shows the coefficients and relevant statistics.

$$ln(\frac{Price}{Seat}) = k_3 \cdot ln(\frac{DOC}{RPM}) + k_4 \qquad (5.3)$$

where $k_3 = -0.545$; $k_4 = 6.32$; $n = 31$; standard error = 0.146; $R^2 = 0.754$

In this section, a statistically significant relationship between aircraft system performance and price has been obtained. It has been shown that improvements in aircraft system performance (as captured in DOC) lead to increases in aircraft price. Further statistical analysis techniques, such as principal components analysis, can be employed to determine additional factors influencing aircraft price. It is noteworthy that this relationship between DOC and price may imply a future emissions reduction potential for the aviation sector. That is, future improvements in aircraft system performance will lead to a certain reduction in DOC and increase in aircraft price. If the relative changes in DOC and price with respect to technological improvements occur at the level of the historical trends as accepted by the industry, airlines will continue to adopt newer and more efficient technologies at a higher price because they can balance off through savings in DOC. However, it is unclear whether future technologies can be delivered at the same price level that would correspond to the level of savings in DOC in the historical trends. If the price is too high for expected savings in DOC, airlines may not choose to pay more, in which case further environmental performance improvement for the aviation sector may be limited.

5.3 Technology-Cost Relationship and Application

An analytical model based on the Breguet range equation and two statistical models for DOC and price have been developed. The significance of this technology-cost relationship is that all the individual elements of aircraft performance and cost have been connected. That is, the impacts of changes in technology or operability can be traced all the way to changes in DOC and price. In addition, technological and operational changes required to meet a certain level of desired change in DOC and price can be specified.

In order to demonstrate this use of the technology-cost relationship and examine how a technology improvement impacts aircraft cost, the changes in DOC and price of a B-777 with respect to changes in engine, aerodynamic, and structural efficiencies are computed and shown in Table 5.4. As a simulation of technological improvements, SFC is decreased by 5% while the L/D ratio is increased by 5% with an overall weight penalty of 5%. Fuel efficiency is then calculated from the inverse of the fuel consumption equation in (4.5) and corrected by a factor of 0.80. Note that this correction factor is based on the curve fit to the deviation of the Breguet range equation calculation as previously shown in Figure 4.5. By multiplying a typical average load factor of 73% for B-777 to the model-predicted, corrected fuel efficiency, aviation system efficiency is obtained and then used for projecting DOC and price through the cost regression models. As a result of the proposed technological improvements, ASM/gal is expected to increase by 6.8% with 6.1% decrease in DOC/RPM and 3.7% increase in price/seat.

5.4 Uncertainty Analysis

5.4.1 Error Propagation

In this section, the uncertainties associated with the technology and operability parameters used in the Breguet range equation are estimated, and their errors propagated through the technology-cost relationship are analyzed.

Given a function $y = f(x_i)$, the error due to x_i propagated through the function can be evaluated as follows:

$$\sigma_y^2 = \sum_i \left(\frac{\partial f}{\partial x_i} \right)^2 \sigma_{x_i}^2 \tag{5.4}$$

where σ^2 is the variance of a variable.

Errors are propagated over three steps in the technology-cost relationship. First, the error propagated through the fuel efficiency equation is as follows:

$$\begin{aligned} \sigma^2_{\frac{ASM}{gal}\cdot\frac{RPM}{ASM}} &= \sigma^2_{\frac{RPM}{gal}} \\ &= \left(\frac{\partial FE}{\partial SFC} \right)^2 \sigma_{SFC}^2 + \left(\frac{\partial FE}{\partial (L/D)} \right)^2 \sigma_{(L/D)}^2 + \left(\frac{\partial FE}{\partial W_f} \right)^2 \sigma_{W_f}^2 + \\ &\left(\frac{\partial FE}{\partial W_p} \right)^2 \sigma_{W_p}^2 + \left(\frac{\partial FE}{\partial W_s} \right)^2 \sigma_{W_s}^2 + \left(\frac{\partial FE}{\partial W_s} \right)^2 \sigma_{W_s}^2 + \left(\frac{\partial FE}{\partial W_r} \right)^2 \sigma_{W_r}^2 \end{aligned} \tag{5.5}$$

where FE stands for fuel efficiency, and it is the inverse of the fuel consumption equation (4.3) as follows:

$$FE = \frac{(W_{payload} / W_{individual})}{W_{fuel}} \cdot \frac{V(L/D)}{g \cdot SFC} ln\left(1 + \frac{W_{fuel}}{W_{payload} + W_{structure} + W_{reserve}}\right) \quad (5.6)$$

The influence coefficients are as shown below.

$$\frac{\partial FE}{\partial SFC} = -\frac{(W_p / W_i)}{W_f} \cdot \frac{V(L/D)}{g \cdot SFC^2} ln\left(\frac{W_{initial}}{W_{final}}\right) \quad (5.7)$$

$$\frac{\partial FE}{\partial (L/D)} = \frac{(W_p / W_i)}{W_f} \cdot \frac{V}{g \cdot SFC} ln\left(\frac{W_{initial}}{W_{final}}\right) \quad (5.8)$$

$$\frac{\partial FE}{\partial W_f} = \frac{(W_p / W_i)}{W_f} \cdot \frac{V(L/D)}{g \cdot SFC}\left(-\frac{ln\left(\frac{W_{initial}}{W_{final}}\right)}{W_f} + \frac{1}{W_{initial}}\right) \quad (5.9)$$

$$\frac{\partial FE}{\partial W_p} = \frac{(W_p / W_i)}{W_f} \cdot \frac{V(L/D)}{g \cdot SFC}\left(\frac{ln\left(\frac{W_{initial}}{W_{final}}\right)}{W_p} - \frac{W_f}{W_{initial} \cdot W_{final}}\right) \quad (5.10)$$

$$\frac{\partial FE}{\partial W_s} = \frac{\partial FE}{\partial W_r} = \frac{(W_p / W_i)}{W_f} \cdot \frac{V(L/D)}{g \cdot SFC} \cdot \frac{-W_f}{W_{initial} \cdot W_{final}} \quad (5.11)$$

The error propagated through the DOC model is then the following:

$$\sigma^2_{\frac{DOC}{RPM}} = \left(\frac{\partial\left(\frac{DOC}{RPM}\right)}{\partial\left(\frac{ASM}{gal} \cdot \frac{RPM}{ASM}\right)}\right)^2 \sigma^2_{\frac{ASM}{gal} \cdot \frac{RPM}{ASM}} \quad (5.12)$$

The DOC model equation can be rewritten explicitly in terms of DOC/RPM as below.

$$\frac{DOC}{RPM} = e^{\left(k_1 \cdot ln\left(\frac{ASM}{gal} \cdot \frac{RPM}{ASM}\right) + k_2\right)} \tag{5.13}$$

where k_1 and k_2 are the regression coefficients found previously. The influence coefficient is then as follows:

$$\frac{\partial\left(\frac{DOC}{RPM}\right)}{\partial\left(\frac{ASM}{gal} \cdot \frac{RPM}{ASM}\right)} = \frac{k_1}{\left(\frac{ASM}{gal} \cdot \frac{RPM}{ASM}\right)} e^{\left(k_1 \cdot ln\left(\frac{ASM}{gal} \cdot \frac{RPM}{ASM}\right) + k_2\right)} \tag{5.14}$$

Lastly, the error propagated through the price model is as follows:

$$\sigma^2_{\frac{Price}{Seat}} = \left(\frac{\partial\left(\frac{Price}{Seat}\right)}{\partial\left(\frac{DOC}{RPM}\right)}\right)^2 \sigma^2_{\frac{DOC}{RPM}} \tag{5.15}$$

The price model equation can be rewritten explicitly in terms of price/seat as below.

$$\frac{Price}{Seat} = e^{\left(k_3 \cdot ln\left(\frac{DOC}{RPM}\right) + k_4\right)} \tag{5.16}$$

where k_3 and k_4 are the regression coefficients found previously. The influence coefficient is then as follows:

$$\frac{\partial\left(\frac{Price}{Seat}\right)}{\partial\left(\frac{DOC}{RPM}\right)}=\frac{k_3}{\left(\frac{DOC}{RPM}\right)}e^{\left(k_3 \cdot ln\left(\frac{DOC}{RPM}\right)+k_4\right)} \tag{5.17}$$

The estimated errors for SFC is ±7% based on the curve fit between ICAO data and Jane's data with 2σ confidence as shown in Figure A1.2. Based on the internal investigation with industry representatives, the L/D values are correct within ±1, which corresponds to about ±8% error. The estimated errors for W_f, W_p, and W_s are assumed to be all ±5% while they are likely to be less than that given the relatively precise reporting requirements of USDOT Form 41. Lastly, the error for fuel reserve, W_r is expected to be ±30% since an assumed value, 50% of fuel burn per block hour was used. Note that these error values were estimated with 2σ confidence.

The estimated errors are propagated through the three analytical and statistical models above, and the results are summarized in Table 5.5. The error due to uncertainties in the technology and operability parameters propagated through the fuel efficiency equation is ±22.3% with 2σ confidence based on the mean value of all the propagated errors for the 23 aircraft types used for the Breguet range equation. Note that SFC and L/D have the largest impacts on the propagated error. This suggests that reducing the uncertainty associated with the SFC and L/D databases will have the largest impact on reducing overall error in the technology-cost relationship. Since the 2σ of calculated RPM/gal is ±12.5, or roughly ±30% based on the curve fit to the actual RPM/gal shown in Figure 5.8, the propagated error of the technology and operability parameters account for more than two thirds of the total variance in the calculated fuel efficiency values. This indicates that some errors associated with the technology and operability parameters of the Breguet range equation might have been slightly underestimated. In particular, the SFC and L/D error estimates could be higher by 2 to 3%. In addition, some factors in actual aircraft operations might have not been fully accounted for by the technology and operability parameters of the Breguet range equation.

Two-σ confidence intervals for the cost projections made by the DOC and price models are ±0.400 for ln(DOC/RPM) and ±0.286 for ln(price/seat). This is approximately equivalent to

±40% error (–0.706 to +1.06 cents) for DOC/RPM and ±30% error (–\$98,300 to +\$131,000) for price/seat for B-777 type aircraft. Since the errors through the DOC and price models are ±21.6% and ±11.9%, respectively, with 2σ confidence, not all the errors in the technology-cost relationship are accounted for by the uncertainties in the technology and operability parameters. More than half of the error in the price model is attributable to the uncertainty associated with DOC/RPM, not explained by the technology and operability parameters, and other factors not included in the model. Overall, the uncertainties associated with the technology and operability parameters result in a 10 to 20% error in the technology-cost relationship while it can be reduced by continuing to improve existing databases and removing sources of uncertainties.

5.4.2 Sources of Uncertainty

The relatively large errors associated with technology-cost projections are mainly attributable to the variability in the original data sources, USDOT Form 41, the Airliner Price Guide, and technology databases as well as exogenous factors not considered in this thesis. When the 10 U.S. passenger air carriers report their cost and traffic data for Form 41, specific details may differ from airline to airline. Especially, cost data may be subject to each airline's accounting practice, and subsequent additions or omissions may be possible. In fact, it was found that data were not reported for some periods, and the best effort was made to filter out such occasions in data analysis.

Direct operating cost data as well as price data are also subject to fluctuations in economy, such as oil shocks and deregulation. Fuel prices, aircraft leasing rates, salary rates, and various other external factors impact the reported direct operating cost and price data. Aircraft prices also vary according to each airline's purchasing terms. Thus, the cost data used in this thesis represent an aggregated measure of value to purchase and operate an aircraft with a fair degree of variability.

A great deal of variability also exists in Form 41 traffic data. Airlines operate aircraft under different conditions so that performance may turn out quite different even for the same type of aircraft. For example, fuel efficiency can be easily reduced by 10 to 20% for a short-haul aircraft with more frequent take-offs because additional fuel is spent on non-cruise flight segments, such as idling, taxing, climbing, and landing (Greene, 1992).

Lastly, a large amount of uncertainty exists with the values of technology parameters as examined in the previous section. In reality, SFC and L/D are not constant during a flight, and structural weights also vary even for the same type of aircraft depending on configuration modifications. Many aircraft have the same planform but different engine types on the wing, in which case an average SFC value of all the available engines is used. Therefore, when all these technology parameters are put together for each aircraft type, an appropriate aggregation is necessary, and the best available data and estimates for them are used in this thesis.

5.5 Chapter Summary

In this chapter, the impacts of aircraft system performance, mostly technology advancement, on aircraft direct operating cost and price have been quantified. An aviation system efficiency parameter has been defined based on aircraft fuel efficiency and load factor and correlated with direct operating cost by means of statistical analysis. This aviation system efficiency parameter also serves as an appropriate environmental performance metric to understand the impacts of aircraft performance on aviation emissions. The relationship between direct operating cost and price has been understood statistically. In general, improvements in aircraft system performance lead to reductions in direct operating cost but increases in aircraft price. Notably these complex technological and economic behaviors of aviation systems have been described by only a few simplified parameters. The technology-cost relationship obtained here will be further utilized to quantify the technological and economic characteristics of future aircraft systems in the following chapter.

Table 5.1: DOC Categories Used in Parametric Study

	DOC categories strongly related to technology	DOC categories weakly related to technology
Flying Operations	Pilots and Copilots Salaries Aircraft Fuels Aircraft Oils	Other Flight Personnel Expenses Trainees and Instructors Expenses Personnel Expenses Professional and Technical Fees and Expenses Aircraft Interchange Charges Other Supplies Employee Benefits and Pensions Injuries, Loss, and Damage Taxes Other Expenses
Direct Maintenance	Labor for Airframes Labor for Engines Materials for Airframes Materials for Engines Outside Airframe Repairs Outside Aircraft Engine Repairs	Aircraft Interchange Charges Airworthiness Allowance Provision for Airframes Airframe Overhauls Deferred (credit) Airworthiness Allowance Provision for Engines Aircraft Engine Overhauls Deferred (credit)

Table 5.2: Summary Statistics for DOC Regression

Regression Statistics	
Multiple R	0.888
R Square	0.788
Adjusted R Square	0.787
Standard Error	0.204
Observations	466

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	72.0	72.0	1722	2.7E-158
Residual	464	19.4	0.0418		
Total	465	91.3			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	4.92	0.0778	63.2	3.5E-230	4.77	5.07
$\ln(\eta_{\text{aviation system}})$	-0.958	0.0231	-41.5	2.7E-158	-1.00	-0.913

Table 5.3: Summary Statistics for Price Regression

Regression Statistics	
Multiple R	0.868
R Square	0.754
Adjusted R Square	0.745
Standard Error	0.146
Observations	31

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.89	1.89	88.8	2.49E-10
Residual	29	0.617	0.0213		
Total	30	2.51			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	6.32	0.0942	67.1	2.28E-33	6.13	6.512
ln(DOC/RPM)	-0.545	0.0579	-9.43	2.49E-10	-0.664	-0.427

Table 5.4: Impacts of Technological Changes on Fuel Efficiency, DOC, and Price of B-777

		Base Technology	New Technology	% Change
Technology	SFC (mg/s-N)	15.9	15.1	-5.0
	M(L/D)	15.4	16.2	5.0
	Ws (tons)	116	121	5.0
Operability	Fuel Load (tons)	40	40	-
	Payload (tons)	30.7	30.7	-
	Fuel Reserve, assumed (tons)	3.2	3.2	-
Fuel Efficiency	ASM/gal	89.1	95.2	6.8
Correction Factor		0.80	0.80	-
Fuel Efficiency Corrected	ASM/gal	71.3	76.2	6.8
Load Factor	RPM/ASM	0.73	0.73	-
Direct Operating Cost	DOC/RPM (cents)	3.11	2.92	-6.1
Price	Price/Seat ($ thousand)	299	310	3.7

Table 5.5: Summary Results for Propagated Error of Technology-Cost Relationship (typical values of coefficients products for B-777; percent error for all selected aircraft types with standard error shown in parentheses)

	$\left(\frac{\partial FE}{\partial SFC}\right)^2 \sigma^2_{SFC}$	$\left(\frac{\partial FE}{\partial (L/D)}\right)^2 \sigma^2_{(L/D)}$	$\left(\frac{\partial FE}{\partial W_f}\right)^2 \sigma^2_{W_f}$	$\left(\frac{\partial FE}{\partial W_p}\right)^2 \sigma^2_{W_p}$	$\left(\frac{\partial FE}{\partial W_s}\right)^2 \sigma^2_{W_s}$	$\left(\frac{\partial FE}{\partial W_r}\right)^2 \sigma^2_{W_r}$	$\left(\frac{\partial\left(\frac{DOC}{RPM}\right)}{\partial\left(\frac{ASM}{gal}\cdot\frac{RPM}{ASM}\right)}\right)^2 \sigma^2_{\frac{ASM}{gal}\cdot\frac{RPM}{ASM}}$	$\left(\frac{\partial\left(\frac{Price}{Seat}\right)}{\partial\left(\frac{DOC}{RPM}\right)}\right)^2 \sigma^2_{\frac{DOC}{RPM}}$	% Error (2σ)
$\sigma^2_{\frac{ASM}{gal}\cdot\frac{RPM}{ASM}}$	13.1	17.2	0.0801	4.48	3.18	0.0887			±22.3 (0.160)
$\sigma^2_{\frac{DOC}{RPM}}$							0.123		±21.6 (0.238)
$\sigma^2_{\frac{Price}{Seat}}$								463	±11.9 (0.298)

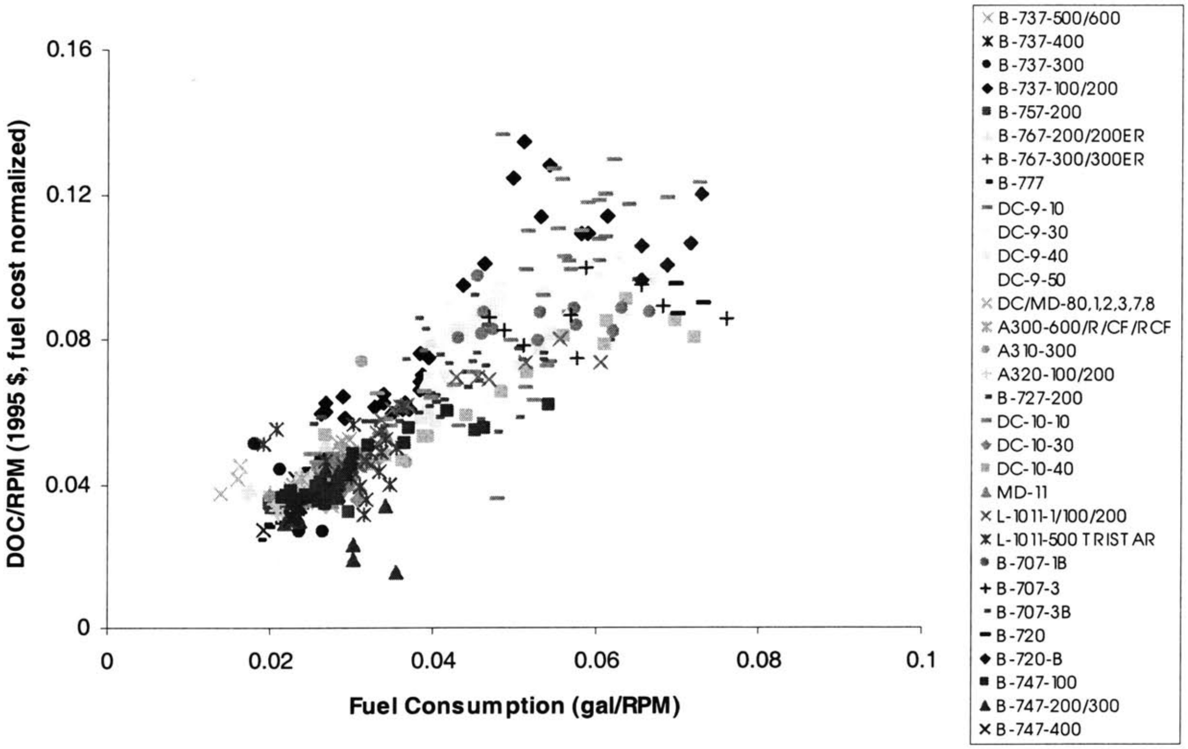

Figure 5.1: Direct Operating Cost versus Fuel Consumption (fuel cost normalized; 31 aircraft types during 1968-98)

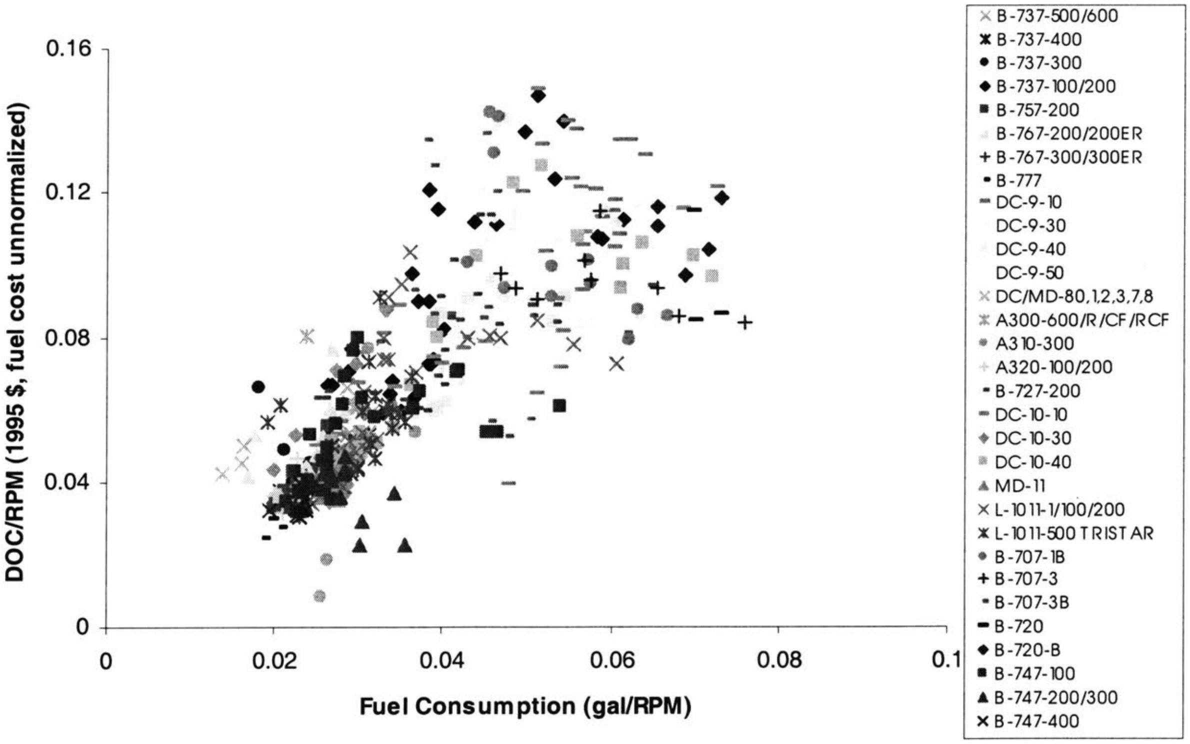

Figure 5.2: Direct Operating Cost versus Fuel Consumption (fuel cost unnormalized; 31 aircraft types during 1968-98)

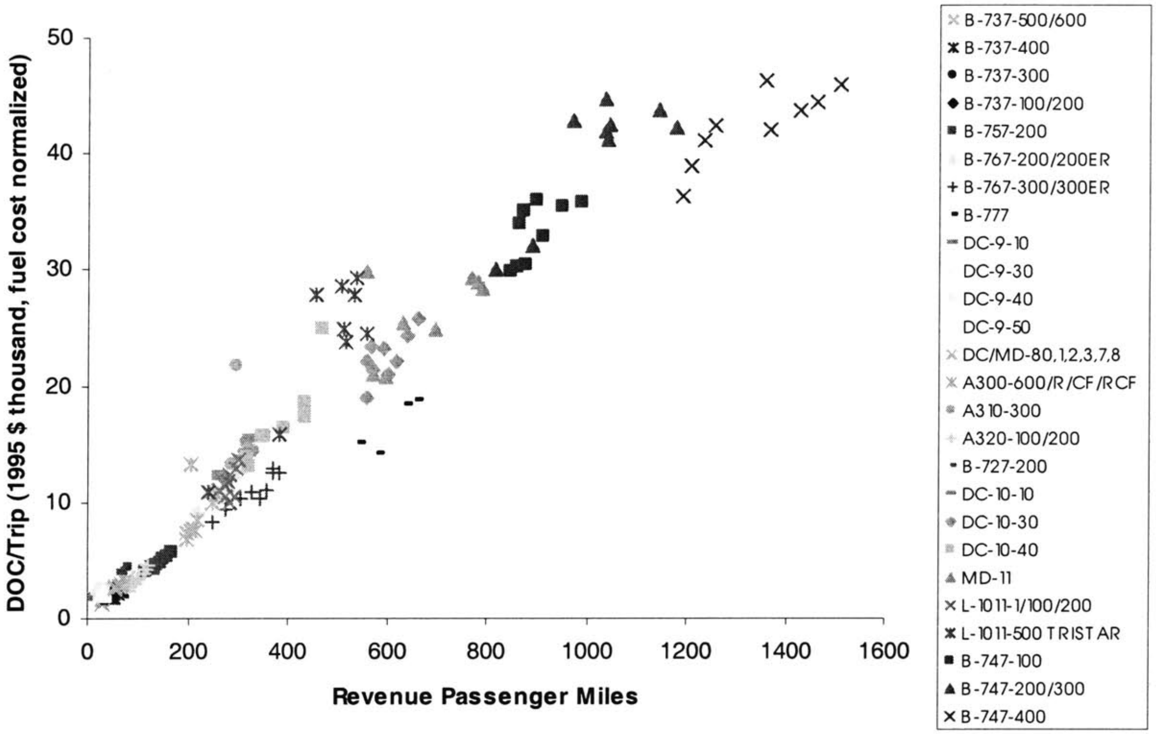

Figure 5.3: Direct Operating Cost versus Revenue Passenger Miles (based on operating data for 1990-98)

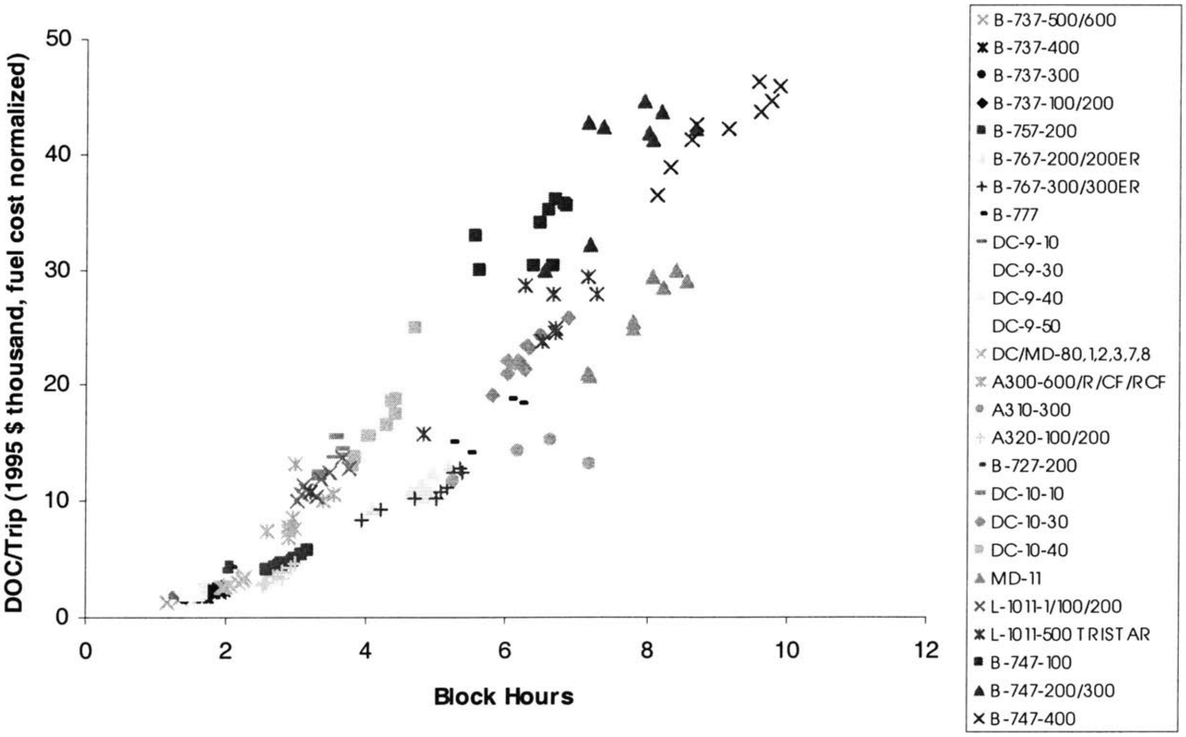

Figure 5.4: Direct Operating Cost versus Block Hours (based on operating data for 1990-98)

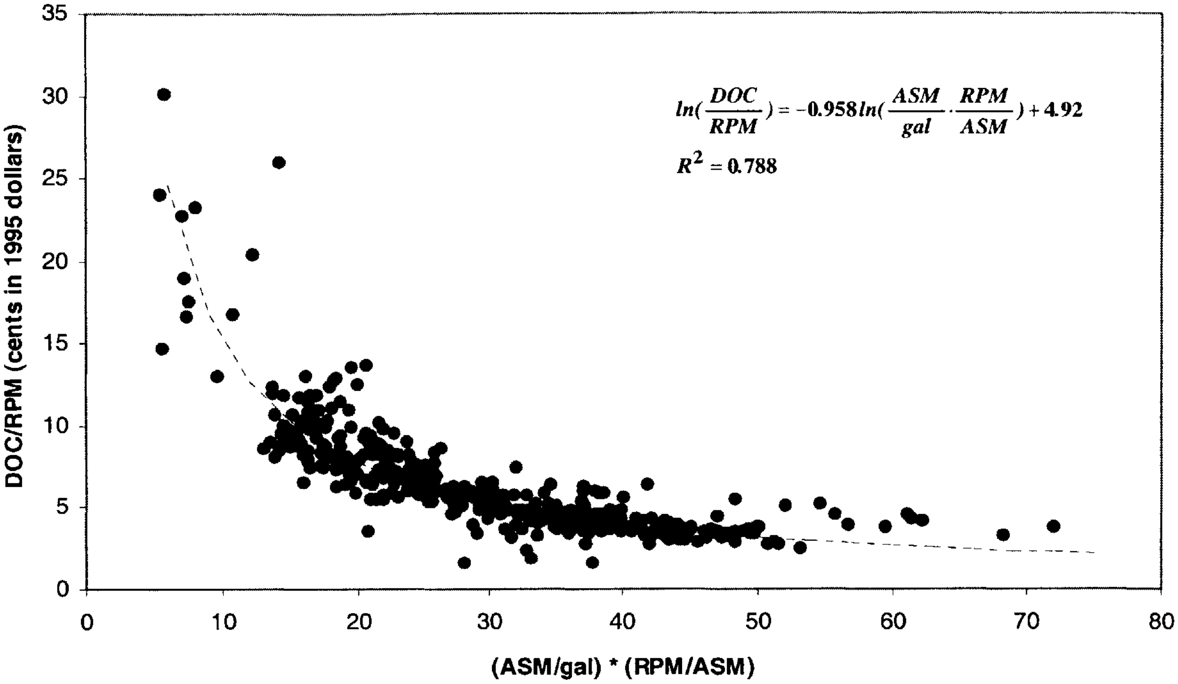

Figure 5.5: Direct Operating Cost versus Aviation System Efficiency (31 aircraft types operated during 1968-98)

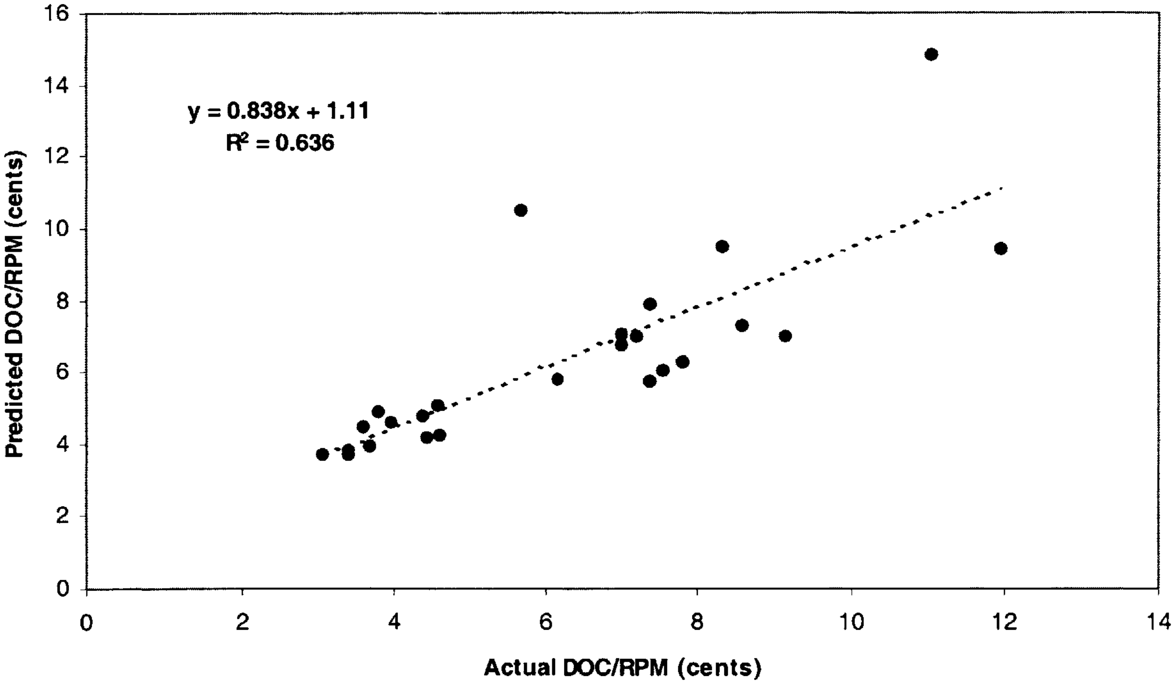

Figure 5.6: Crossvalidation of DOC Model (validation data set for 31 aircraft types randomly held out from the period 1968-98)

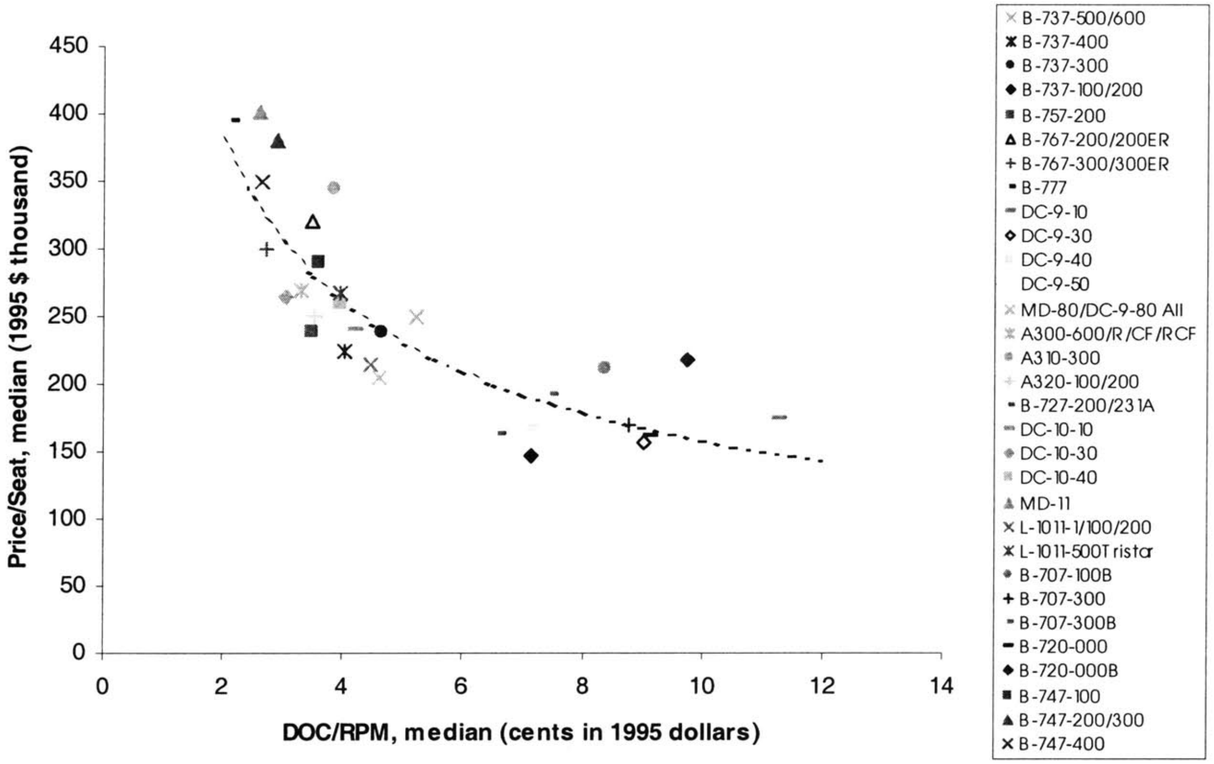

Figure 5.7: Aircraft Price versus Direct Operating Cost (31 aircraft types, median values during 1968-98)

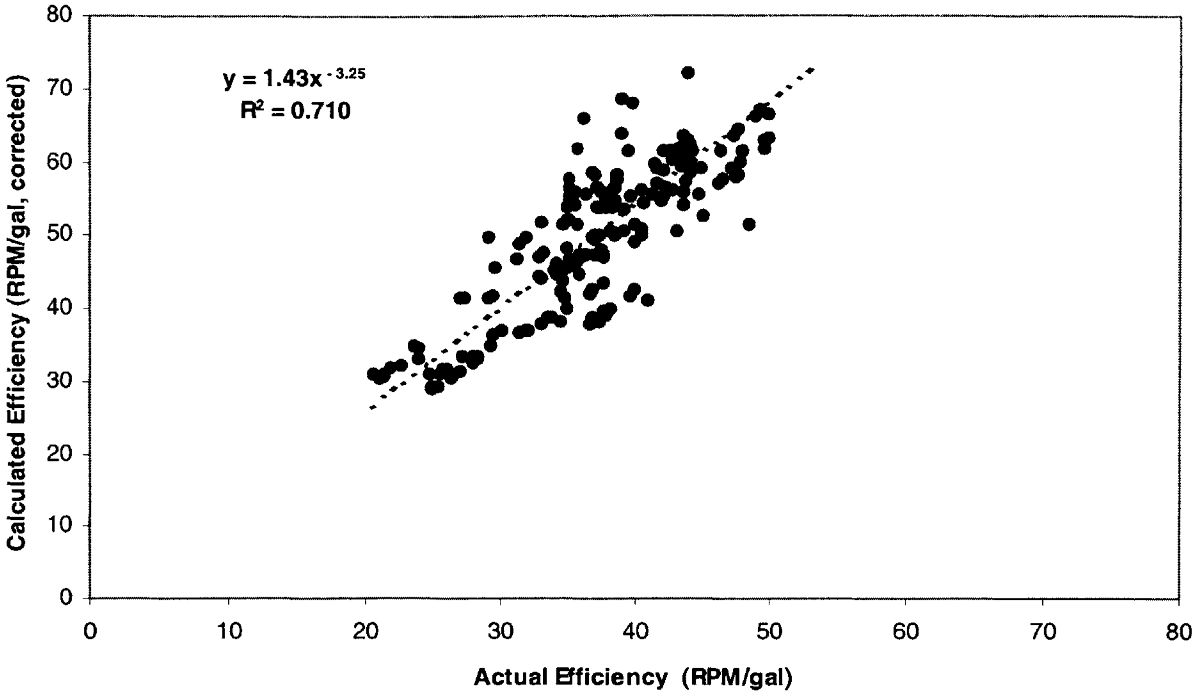

Figure 5.8: Calculated Fuel Efficiency versus Actual Fuel Efficiency (calculated fuel efficiency corrected by correction factor, $\delta_{correction}$ in equation (4.3))

Chapter 6

Future Trends in Aircraft Performance, Cost, and Emissions

6.1 Introduction

This chapter employs the aircraft technology-cost relationship developed in previous chapters and makes projections for the technological and economic characteristics of future aircraft systems and their emissions reduction potential. Technology projections available from extrapolations of historical trends constitute the basis of the technology and cost projections in this chapter, and they are compared with other major studies in the open literature as well as NASA systems studies.

6.2 Comparison of Study Methods

The studies carried out in the past use different methods to determine future trends in aircraft performance. They range from sophisticated systems models to interview techniques with experts. Thus, it is worthwhile to examine the methods of previous studies and compare them with the one developed in this thesis.

NASA uses a systems model to project improvements in engine, aerodynamic, structural, and avionics technologies (NASA, 1999 and 1998b). The impacts of such improvements on aircraft fuel consumption and DOC+I are then analyzed through aircraft design and cost models. Note, however, that the cost projections of NASA are not used in this thesis because it is still unclear which categories of DOC+I the NASA cost model projects and what economic factors it uses.

IPCC is a panel of international governments where various U.S. and European studies using atmospheric models, economic models, technology models, and aviation emissions inventory models are summarized and compared (IPCC, 1999).

National Research Council (NRC) is a group of expert scientists and engineers (NRC, 1992). It reviews every discipline of aircraft design and analyzes the benefits and feasibility of 21st century aeronautical technologies based on internal studies with NASA and reviews of expert panels.

Greene presents the analysis results based on extensive collection of aircraft technology and operating data (Greene, 1992 and 1995). The method of analysis, however, is mostly statistical correlation between individual technologies and fuel efficiency improvement, as opposed to the analytical utilization of the Breguet range equation in this thesis. In addition, the scope of data used in Greene's study is much narrower than the entire USDOT Form 41 data used in this thesis.

The Energy Technology Support Unit (ETSU) performs various energy-related studies for the Department of Trade and Industry (DTI), the European Commission, the International Energy Agency (IEA), and similar organizations (ETSU, 1994). It presents the technical, economic, and environmental data assembled and used as input to the latest appraisal of aircraft technology and design.

The NASA Environmental Compatibility Assessment (ECoA) is part of several NASA studies (NASA, 1998b). It presents various zero emission aircraft technologies. The 2050 best kerosene aircraft used in this thesis is based on this NASA ECoA study.

The European Abatement of Nuisances Caused by Air Transport (ANCAT)/European Commission (EC) Working Group combines European efforts to produce an aircraft NO_x inventory (CAEP, 1995). It has developed extensive global 3-dimensional inventories of aircraft NO_x emissions for the past and future.

The Dutch Aviation Emissions and Evaluation of Reduction Options (AERO) Project is carried out by the Dutch Civil Aviation Department to assess economic and environmental impacts of potential aviation emissions reduction options (AERO, 1997).

Arthur D. Little (ADL) is commissioned by the UK Department of the Environment, Transport, and Regions (DETR) to study the potential impacts of aircraft technology changes on the development of Air Transport in the UK (ADL, 2000). It uses an extensive interview method to compile a database for future aircraft technologies and assess their impacts. The data used in this thesis is based on its draft final report to DETR.

In addition to these studies, the emissions forecasts from the Deutsches Zentrum für Luft- and Raumfahrt (DLR), World Wildlife Fund (WWF), Environmental Defense Fund (EDF), DTI, ICAO Forecasting and Support Group (FESG), and Schafer and Victor are presented based on the contents of the IPCC Special Report (IPCC, 1999).

In comparison to the previous study methods in the open literature, a bottom-up approach has been taken in this thesis where the impacts of each of technology and operability parameters on aircraft fuel efficiency and cost are quantified. Thus, this thesis presents results and makes projections based on an analytical and statistical method rather than qualitative assessment of the future. In addition, the vast scope of aircraft technology, operations, and cost data used in this thesis provides high reliability and representativeness as compared to previous studies.

6.3 Future Trends in Aircraft Performance

6.3.1 Technology

6.3.1.1. Engines

As observed in the historical trends, SFC has improved approximately 40% over the last 35 years, averaging about 1.5% improvement per year as previously shown in Figure 3.4. However, most of this improvement was realized before 1970 while the remaining improvement gradually took place over the last 25 years. At this recent rate of improvement (roughly 0.2% per year), SFC is expected to be lowered only by 10% by 2050 as shown in Figure 6.1 while extrapolation of the entire historical trends in SFC suggests as much as 50% improvement over today's level.

Figure 6.1 also shows various future projections for engine efficiency improvement in the open literature. The GE-90 engines for B-777 are used as a benchmark for future engines. In the short term, incremental improvements to raise core thermal efficiency through continued increases in compressor pressure ratio, higher temperature hot sections, improved component efficiencies, and increased bypass ratio up to a maximum of 10 are expected to lead to 10 to 15% reductions in SFC (ADL, 2000; ETSU, 1992). In the medium term by about 2015, increasing bypass ratio above 10 has a potential for a total of 15 to 20% reductions in SFC (ADL, 2000). In the long term by about 2030, unducted ultra-high-bypass (UHB) ratio engines (bypass ratios of 15 to 20), integrated to the aircraft body, and improved low-weight materials could lead to 20 to 30% gains in SFC compared to today's engines (Greene, 1992; ADL, 2000). However, it seems optimistic to expect these improvements in 30 years, considering SFC improvement has been slowing down in recent years as engine technology is pushing its limits with cost constraints.

Propfan systems, which use eight or more highly swept blades in unducted systems, may enable another 10 to 20% reductions in SFC. If propfan technologies could be implemented on top of the engine efficiency improvements discussed above, a total of about 50% reduction in SFC would be possible by 2050. However, propfans raise concerns regarding noise, vibration, and safety. They also cost twice as much as present-generation high bypass ratio engines (Greene, 1992; Greene, 1995; Barret, 1991). Thus, it is uncertain whether propfan technologies will be implemented in future aircraft systems.

A more practical improvement in SFC, therefore, seems to be 20 to 30% by 2050 with unducted UHB ratio engines and light-weight materials, and this is consistent with the average range of the two types of extrapolations of the historical trends above. For the discussion purpose of thesis, a 20% reduction in SFC by 2050 will be used.

6.3.1.2. Aerodynamics

The L/D ratio has improved by about 15% during the period 1959 to 1995, averaging 0.4% increase per year. If this improvement trend continues, the L/D ratio is expected to increase by about 20% by 2050 compared to today's level.

The projections in the open literature discuss various potential technologies to reduce drag and improve aerodynamic efficiency. Riblets, tiny grooves made in the direction of airflow to lower turbulence and reduce drag over the fuselage, have been shown to reduce skin-friction drag by 4 to 8% (Greene, 1992; NRC, 1992). The large-eddy break up (LEBU) devices have been shown, in wind tunnel experiments, to reduce skin-friction drag by 10% (Greene, 1992). In the long term by around 2030, a promising aerodynamic technology to reduce drag effectively is laminar flow control (LFC). Since the flow on most aircraft surfaces is turbulent, laminar flow control is an effective source of skin-friction drag reduction.

By incorporating these technologies, McDonnell Douglas Aircraft Company projected as much as a 35% increase in L/D compared to 1990's airplanes through aspect ratio increase (15%), LFC on upper wing and tail surfaces (10 to 12%), airfoil development (2 to 3%), turbulence control on fuselage and lower wing (2 to 3%), and induced drag (3 to 4%) (NRC, 1992). In addition to upper wing and tail surfaces, laminar flow nacelles are also possible. If full-chord laminar flow can be maintained this way, fuel savings of up to 25% are feasible (NRC, 1992; 1992; ETSU, 1992; Barret, 1991). However, the upper bound on L/D improvement and fuel savings may not be achievable in practice because of the difficulties associated with maintaining surface smoothness in actual operations and keeping suction grooves entirely free of debris (Greene, 1995). Thus, NRC expects that a more feasible estimate for aerodynamic efficiency improvement is about 10% during the period 1995 to 2020 based on historical trends (NRC, 1992). This is consistent with extrapolations of L/D improvements in the past in this thesis. Therefore, a practically feasible L/D improvement is estimated to be 20% by 2050 as suggested by the historical trends and expert studies in the open literature.

6.3.1.3. Structures

Weight reduction is an important area of improvement for future aircraft. Weight added to aircraft structure requires additional wing area for greater lift, additional engine thrust, and additional fuel to provide the same range. Thus, an initial 1 pound increase in structural weight ends up in increase in gross aircraft weight from 2 to 10 pounds, and vice versa (Greene, 1995). Despite this importance, however, the lack of improvement in structural efficiency in the past as shown in Figure 3.6 suggests that the future fuel burn improvement potential through weight reduction is not evident. According to the structural data provided by Airbus Industrie, A3XX, the next generation very large aircraft (VLA), also has the same structural efficiency as airplanes in the past (Canto, Jr., 2000). On the other hand, if a different type of lighter-weight, high-strength material, such as composites, substitutes current metallic aircraft structures, a large reduction in fuel burn is expected in the future.

Current projections in the open literature propose a gradual 10 to 15% weight reduction by about 2010 and fuel consumption savings of 5 to 15% compared to 1990's airplanes through use of light-weight materials (NRC, 1992; ETSU, 1992). However, this is not supported by the historical trends. Current research is heavily focused on the use of composite materials to substitute light-weight, high-strength materials in aircraft structures. Today's specialized military aircraft, jet fighters, and vertical take-off and landing aircraft are now 40 to 60% composite materials, and new generation commercial aircraft are also expected to be composed of 80% composites, with equal or greater strength. As a result, a 30% weight reduction compared to today's airplanes is expected through use of composite materials (Greene, 1992; Brown, 1998). NRC also projects about a 15% reduction in aircraft weight by 2015 compared to 1990's airplanes, if composite wing and fuselage can be implemented, and additional 2 to 3% weight savings through systems (largely avionics) improvement (NRC, 1992). While it is still unclear when these composite structures will become practical for commercial airplanes, about 10 to 15% weight reductions through use of composite materials seem to be possible by 2050, if active research and development efforts are made in the future. For the discussion purpose of this thesis, a 10% aircraft weight reduction by 2050 will be used.

The technology influence coefficients for fuel consumption determined in this thesis make it possible to translate the technological improvements into an overall reduction in fuel consumption measured in fuel burn per RPM. Since 1% improvement in each of SFC, L/D, and W_s leads to 1%, 1%, and about 0.7% reductions in fuel burn per RPM, respectively, as shown in Figure 4.8, the aforementioned improvements in engine and aerodynamic efficiencies and structural weight (20%, 20%, and 10%, respectively) are expected to lead to about a 47% reduction in fuel burn by 2050, assuming that the linearity of the Taylor series expansion holds over these ranges. Note that this is purely a mechanical performance improvement, and a more feasible estimate for fuel burn reduction for future aircraft requires consideration of air traffic management and operational influences on fuel consumption within the entire aviation system as discussed next.

6.3.2 Operability

The efficiency in ATM and aircraft operations can be assessed through two key parameters, the minimum-flight-hours-to-block-hours ratio as defined in this thesis and load factor. Increased minimum-flight-hours-to-block-hours ratio reduces the fuel consumed during non-cruise, non-ideal flight segments, and increased load factor improves fuel burn per RPM. Note that higher load factor also reduces DOC/RPM. Therefore, combining the improvement potentials for these key parameters of ATM and operations with the mechanical efficiency improvement of aircraft allows for system-level assessment of total fuel efficiency gains and resulting cost changes for future aircraft systems.

6.3.2.1. Air traffic management

According to NASA, avionics technologies to improve air traffic management include relaxed static stability, all flying control surfaces, fly-by-light/power-by-wire, high performance navigation, and intelligent flight systems (NASA, 1997). Improved air traffic control with use of these digital communications technologies and satellite systems reduces non-optimum use of airspace and ground infrastructure by mitigating congestion between high-density routes (IPCC, 1999). Thus, the potential benefits of improvements in ATM need to be considered by examining expected improvements in total flight time efficiency based on its historical trends shown in Figure 6.2.

First, without major improvements in aircraft ground, take-off, and landing operations, the ground time efficiency, the ratio of airborne hours to block hours, is not likely to improve in the future based on the historical trend that it has remained relatively constant around 0.85 in the past. The flight time efficiency, the ratio of minimum flight hours to airborne hours, is also expected to remain around 0.85 if ATM improvement stays at the current level. Therefore, total flight time efficiency is expected to remain at the current level of 0.72 in the future unless major airport capacity increase or significant avionics technology improvement occurs in the near term. The reason for these little net changes in total flight time efficiency is that rapidly growing aircraft fleet size has congested airport alleys and runways, offsetting improvements in ATM. Thus, even significant airport and ATM improvements may merely hold airport delays constant in the future (Greene, 1992).

6.3.2.2. Load factor

Figure 6.3 shows historical and future projections for load factor. It is noteworthy that load factor rather decreased up until 1970, and then increased by 20 percentage points during 1971 to 1998, averaging about 0.74 percentage points increase per year. The large decrease in load factor during the 1960's and 1970's seem to indicate the difficulty associated with airlines' scheduling and fleet planning while they had to fly designated routes regardless of profitability. In 1970's, use of hub-and-spoke systems and deregulation enabled airlines to serve far more markets than they could with the same size fleet (ATA, 1998a). As a result, average load factor has improved continuously and reached today's level of over 0.7. According to Barret (1991), it is possible to boost load factor to 0.9 through advanced booking and use of an optimal size of aircraft. However, early-morning and late-night flights with many empty seats and airport infrastructure and airspace congestion, which lowers the efficiency of hub-and-spoke systems, will significantly limit the upper bound of such an improvement in average load factor. Airbus projects that load factor will continue its recent historical trend and increase only by 3.3 percentage points to about 0.74 by 2018 (Airbus, 1999). At this improvement rate of about 0.17

percentage points per year, the worldwide average load factor is expected to reach around 0.8 by year 2050 as shown in Figure 6.3.

6.3.3 Fuel Consumption

6.3.3.1. Projections based on historical trends

Given total flight time efficiency remaining at the current level, ATM improvement is expected to have little impact on aircraft fuel burn reduction, and the previously mentioned potential fuel burn reduction of about 47% by 2050 based on the improvements in SFC, L/D, and structural weight also remains unchanged. On the other hand, the 12% improvement in load factor from the current level of 0.72 to 0.8 by 2050 is expected to lead to about a 10% reduction in fuel burn per RPM based on the analysis results of the Taylor series expansion of the fuel consumption equation in Chapter 4. Thus, potential aircraft fuel burn reduction by 2050 is around 57%, or 1.7% per year on average, based on the sum of the reductions due to technological and operational improvements. Note that the impact of increased seats on fuel economy improvement is not accounted for in this thesis while it is expected to have a similar effect as increased load factor.

6.3.3.2. Other projections

NASA makes projections for potential fuel burn reductions for future aircraft types including a 600-seat VLA, based on specific improvements in engine, aerodynamic, and structural technologies (NASA, 1999 and 1998b). The NASA systems studies results are summarized with projections from other major studies in Table 6.1 and graphically shown with historical trends in Figure 6.4 (NRC, 1992; Greene, 1992; ETSU, 1994; CAEP, 1995; AERO, 1997; NASA, 1998b; IPCC, 1999; ADL, 2000). Note that B-737-400 is used as a 1990 baseline aircraft while B-777 is used as a 1995 and 2000 baseline aircraft. Note also that all reduction values are measured on a per-seat-mile or per-passenger-mile basis. Thus, if the load factor for passengers and cargo is assumed to be consistent for all studies, these projections provide a meaningful comparison. gal/ASM is used here as a measure of improvements in aircraft technology.

NASA projections have an improvement rate of about 1.5% per year, and a 2050 aircraft is expected to burn about 53% less fuel per ASM than today's aircraft. IPCC projects a 20% improvement in fuel burn by 2015 and a 40 to 50% improvement by 2050 relative to aircraft produced today, implying a 1.0 to 1.5% annual reduction in fuel burn (IPCC, 1999). These projections are consistent with the 47% reduction by 2050 as estimated based on extrapolations of the historical trends in aircraft technologies.

Various other studies make optimistic projections that 30 to 40% fuel burn reductions are possible over a 20-year time period between the 1990's and 2010 and about 50 to 60% reductions by 2025 compared to 1990's aircraft (NRC, 1992; ANCAT, 1995; ECoA, 1998). These reductions are equivalent to about 1.4 to 3.2% improvements per year. Note that these figures are to be slightly larger if the contributions of operational improvements are included.

IPCC estimates about 8 to 18% additional improvements in fuel burn through ATM and other operational improvements, such as increasing load factors, eliminating non-essential weight, optimizing aircraft speed, limiting the use of auxiliary power, *e.g.*, for heating and ventilation, and reducing taxiing. IPCC further estimates that the large majority, 6 to 12%, of this reduction comes from ATM improvements, which will eliminate excess fuel burn and consequently excess emissions due to holding, inefficient routings, and sub-optimal flight profiles. These measures are expected to be fully implemented in the next 20 years, provided that the necessary institutional and regulatory arrangements have been put in place in time (IPCC, 1999). Note, however, that this is not consistent with the projections based on the historical trends as very little contribution from ATM is expected as seen in the constant ratio of minimum flight hours to block hours. Rather, increasing load factor has much larger a potential for fuel burn reduction in the future.

In sum, while aircraft fuel burn per RPM has decreased significantly by 3.3% per year in the past through both technological and operational changes, its improvement is expected to take place at a much slower rate in the future. As a result, aircraft fuel burn is expected to improve at a rate of 1.7% per year, which leads to about 57% reduction by 2050.

Figure 6.5 summarizes the analysis results of this thesis as to major contributors to fuel burn reduction in the past and the future. Overall, engine technology improvements accounted for more than half of the fuel burn reduction in the past while aerodynamic technology and operational improvements accounted for the remaining half. In the future, however, improvements in aerodynamic efficiency as well as engine efficiency are equally expected to account for about 70% of the total fuel burn reduction while operational measures, primarily increase in load factor, and gradual aircraft structural weight reduction make up the remaining fuel burn reduction. Little gains are expected through changes in ATM. Overall, aircraft fuel consumption per revenue passenger-mile is expected to decrease by about 87% compared to the beginning of the jet aircraft era.

6.4 Future Trends in Aircraft Cost

Only a few studies exist as to the economic characteristics of aircraft systems with respect to technological improvements. NASA ACSYNT is an integrated aircraft design model developed under the auspices of the Aviation System Analysis Capability (ASAC) of the NASA Advanced Subsonic Technology Program (AST) (Hasan, 1997). The economics module of ACSYNT provides detailed manufacturing and operating costs and even prices of aircraft where a set of parameters related to propulsion, aerodynamics, weight, mission, and economics are specified based on baseline aircraft models. However, ACSYNT cannot model on its own aircraft cost changes impacted by technology changes unless the user predetermines and inputs such data into the model. Boeing Defense and Space Group and Georgia Institute of Technology have also developed integrated cost and engineering models using a Design-for-Economics approach (Marx *et al.*, 1998a). The models analyze the entire stream of aircraft life-cycle cost with respect to new aircraft designs to improve performance. Thus, these models are more optimization tools to allow for aircraft design changes on a least-cost basis.

The technology-cost relationship developed in this thesis is employed in this section to project the DOC and price of future aircraft systems. The underlying major assumptions are such that the fuel price of 1995 level, $0.54 per gallon, will remain approximately the same, and the proportion of all DOC categories will also remain relatively constant. Note that the projections of load factor are incorporated into the aviation system efficiency parameter as operational improvements when projecting DOC. Thus, future DOC values reflect improvements in both technology and operability within the entire aviation system. Price projections are made based on the projected DOC assuming that the relationship between DOC and price will continue to hold in the future even with a moderate level of fluctuations in economy. All cost figures are in 1995 dollars.

For quantification of relative changes in DOC and price, baseline model projections are generated first. Due to the error associated with fuel consumption, DOC, and price models, a slight discontinuation is observed between historical trends and model projections. Overall, the significance of the cost projections in this section are not so much in the absolute values of the DOC and price of future aircraft systems as in the sensitivity of their values with respect to technological and operational improvements.

6.4.1 Direct Operating Cost and Price

The projected economic characteristics of future aircraft systems are summarized in Table 6.2 and graphically shown in Figures 6.6 and 6.7. As observed in the historical trends, the DOC of the 31 aircraft types has decreased by more than 70% during the period 1959 to 1995. This trend is expected to continue in the future at a slower rate so that in 2050, DOC/RPM is estimated to be lowered by 50% compared to today's level as a result of improvements in aircraft technologies and operational measures. As for price, short- and long-range aircraft prices per seat have risen approximately 70% during 1965 to 1990 and 130% during 1959 to 1995, respectively, as previously shown in Figures 3.16 and 3.17. If this trend continues in the future, aircraft price is expected to increase by more than 200% for both short- and long-range aircraft in 2050. However, analysis results suggest that aircraft price per seat is expected to increase by only about 50% in 2050 compared to today's level. This is largely because technological improvements, which are major drivers for changes in aircraft DOC and price, are expected to be slower for the next 50 years as discussed previously.

6.4.2 Impact of External Factors on Aircraft Cost

Various external factors can also change aircraft cost in the future. Fuel price is the most direct form of such exogenous factors that impact aircraft cost. Figure 6.8 shows two different ASE-DOC curves at two different fuel prices. The lower curve represents for the average fuel price of \$0.57 per gallon during 1996 to 1998 while the upper curve represents for the average fuel price of \$1.65 per gallon during 1980 to 1982. Note that fuel cost is unnormalized for both cases.

It is clear that the large increase in fuel price, \$1.08 per gallon, or 189%, directly raises aircraft direct operating cost by about 60 to 70%. An interesting observation is that the increased fuel price penalizes less efficient aircraft more severely as the percent increase in DOC with respect to the same amount of increase in fuel price grows larger for the aircraft with lower aviation system efficiency.

This increase in DOC is expected to drive airlines' responses in two ways. In the short term, the net increase in DOC is likely to be borne by passengers through increased ticket fares. Depending on air travelers' willingness to pay, which is largely influenced by individual income level, travel time constraint, and costs of other competitive modes of transport, total air travel demand is adjusted. In general, increased airfares are believed to suppress air travel demand. In the long term, however, airlines are expected to lower their increased operating costs by replacing the old fleet with more fuel-efficient aircraft. That is, airlines offset the increase in DOC, of which fuel cost is much larger a fraction, by moving to the right on the upper ASE-DOC curve by adopting newer, more fuel-efficient technologies and increasing load factor. As a result, the historical trends shown in Figure 6.8 suggest that the 189% increase in fuel price is expected to drive as much as 45% improvement in aviation system efficiency, which is the difference between the two curves at the same DOC level, in the long term.

In sum, the future improvements in aircraft technology and operability are expected to reduce DOC by about 50% as a result of reductions in fuel burn and increased load factor while driving up aircraft price by about 50%. Note that these projections of future aircraft cost as well as performance in the previous section are based on analysis of historical trends assuming that the historical relationship between aircraft performance and cost will continue to hold in the future. While history is a strong indicator for the future, the uncertainty associated with what will happen over the next 50 years is not negligible. For example, more active research and development efforts into engine technologies may lead to a higher rate of SFC reduction than 20%. Similarly, if operating barriers associated with laminar flow control are overcome, a greater increase in L/D than the projected 20% may be feasible. Any abrupt changes in economy, such as an oil shock, an introduction of totally new aircraft with non-conventional geometry, development of alternative fuels, and government policy changes, may impact the technology-cost relationship developed in this thesis and result in different technological and economic outcomes.

6.5 Future Trends in Aviation Fuel Use and Emissions

Based on the projected future fuel burn reductions and air traffic growth, total aviation fuel consumption and the subsequent amount of CO_2 emissions can be estimated. For this purpose, it is important to understand the feet evolution and average fuel efficiency of the total world fleet as discussed next.

6.5.1 Fleet Evolution

The future world fleet is expected to be mainly composed of four to five classes of aircraft. Boeing projects that the world fleet will be 28,400 passenger and cargo jets composed of 17% regional jets, 54% single-aisle airplanes, 23% intermediate-size airplanes, and 6% 747-size or larger airplanes in 2018 (Boeing, 1999). Airbus also makes a similar projection that the world jetliner fleet including passenger and freighter jets will grow by more than 11,000 aircraft during 1999 to 2018, and the fleet composition in 2018 will be 11% 70- to 100-seat aircraft, 48% 125- to 175-seat aircraft, 18% 210- to 250-seat aircraft, 17% 300- to 400-seat aircraft, and 6% VLA with more than 400 seats. Airbus also projects that aircraft capacity will increase, as the average number of seats per aircraft will grow by 38 seats to reach 218 seats per aircraft by the end of 2018 (Airbus, 1999).

6.5.2 Technology Uptake

The rate of improvement in the average fuel efficiency of the total fleet is determined by the gradual process of absorption of new, more fuel-efficient aircraft into the existing fleet as discussed in Chapter 3. In assessing future aviation fuel consumption and emissions, therefore, it is important to consider this time delay, which has been historically 15 to 20 years, between technology introduction and penetration. In this section, a 15-year technology uptake is assumed such that that the average efficiency of the world fleet in 2025 will be the same as 2010 new technology level, and 2050 world fleet efficiency will be the same as 2035 new technology level.

6.5.3 Aviation Fuel Consumption and Emissions

6.5.3.1. Emissions forecasts

By combining the fleet average fuel efficiency projections with IPCC demand growth scenarios, the total aviation fuel consumption and CO_2 emissions are estimated for 2025 and 2050 as shown in Table 6.3 and Figure 6.9. For comparison, various other emissions growth scenarios are also shown in Figure 6.9. Note that per gallon of fuel burn, 9.60 kg of CO_2 emissions is assumed. World traffic growth is the CAEP/4-FESG Fa scenario based on IPCC IS92a. Fa scenario is the reference scenario developed by ICAO FESG for mid-range economic growth and technology with both improved fuel efficiency and NO_x reduction (IPCC, 1999). It is further assumed that a 2010 aircraft is expected to consume 11% less fuel than B-777, based on the improvement rate of 57% fuel burn reduction by 2050 including operational measures. Similarly, a 2035 aircraft is expected to consume 40% less fuel than B-777. In other words, 11% fuel burn reduction technology is assumed to be introduced in 2010, and 40% fuel burn reduction technology is assumed to be introduced in 2035. The efficiencies of these aircraft are then fully realized by the world fleet in 2025 and 2050, respectively.

Analysis estimates show that total aviation fuel consumption will more than double by 2050, and total CO_2 emissions are also expected to grow by the same fold. This result is comparable to the IPCC base scenario projection that the total aviation fuel burn will increase by 2.7 times by 2050 compared to 1990 level (IPCC, 1999). Various other emissions inventory studies project much higher emissions growths (IPCC, 1999). Note, however, that the differences in CO_2 emissions forecast mainly originate from the large differences in projected demand for air transport. That is, the IPCC reference scenario (CAEP/4-FESG Fa) estimates only about a six-fold increase in air travel demand in 2050 while some others including Schafer and Victor projects up to a twenty-fold increase in air travel demand for the same time period over the 1990 level. Analysis also shows that if all the old aircraft were replaced instantly in 2050 with the aircraft that consume 57% less fuel per RPM, both fleet average fuel consumption and DOC would decrease by about 20% while price would increase by 13%.

While much uncertainty exists as to the exact level of future aviation emissions, overall results suggest that the strong air travel demand, which has grown more than 5% per year recently and is expected to continue the same growth, will simply surpass the capability of emissions reduction through improvements in technologies and some operational measures alone at the current rate. As a result, total aviation fuel consumption and CO_2 emissions are expected to continue to grow, and all other aviation emissions including NO_x and H_2O are also expected to increase by a significant amount. Consequently, the effects of aviation emissions on the global atmosphere are likely to increase in the future.

6.5.3.2. Emissions reduction and limiting factors

The emissions forecast analysis also implies that in order to stabilize or even reduce aviation emissions by the mid-century, *i.e.*, 2050, drastic technological improvements are necessary in a very short term. However, no strong incentive exists at present to make any more rapid technological improvements with fuel price remaining at the current low level. For example, during the late 1970's and early 1980's when fuel costs, peaked at $1.37 per gallon in 1981, accounted for more than half of DOC, fuel efficiency was the paramount concern in aircraft purchasing, retrofitting, maintenance, and operation. This greatly motivated technological improvements and penetration through the U.S. fleet. As a result, in-use, fleet average, fuel burn per passenger-mile improved by 40% as previously shown in Figure 3.9. On the other hand, today's fuel price remains in the vicinity of $0.55 per gallon, and it provides a less incentive to buy more expensive technology to save fuel or even modify operations to conserve energy (Greene, 1992).

Various external constraints also limit the emissions reduction potential for the aviation sector. First, the technological and economic uniqueness of aircraft systems must be taken into account. For example, volume and weight considerations and the complexity of aircraft systems significantly constrain available aircraft technologies. Timescales for technology development and product life are of the order of decades, and costs to develop, purchase, and operate aircraft are also high relative to many other forms of transportation. Safety is, of course, one of the most important considerations that cannot be compromised. Therefore, any more rapid, economically feasible technological improvement beyond the historical trends may not be practical.

Airport infrastructure and airspace congestion should also be considered in assessing change in future aviation emissions. Currently, little strategy exists to increase worldwide airport capacity or free airspace to cope with the fast growing air travel demand except some expectations about improved ATM. Thus, efficient aircraft mechanical systems and operations alone cannot guarantee less total aviation emissions.

6.5.3.3. Alternatives to emissions reduction

One possible measure to address growing aviation emissions on top of technological and operational improvements is through stabilizing air travel demand. For example, increasing ticket fares through higher fuel prices may shift air travel passengers to other modes of transport. In order to accommodate this, an equivalent fast mode of transport may have to substitute air travel for short-haul trips. However, no feasible alternative mode is readily available as of today.

Hydrogen and methane have been proposed as alternative fuels for future low emissions aircraft as they have high energy per unit mass. Hydrogen is the most attractive because of its potential for eliminating CO_2. While hydrogen-fueled engines generate no CO_2 emissions, however, they are expected to produce more water vapor. The contrails formed from water vapor emissions may rather increase global warming potential even in absence of CO_2. In addition, the use of hydrogen aircraft requires new aircraft designs and new infrastructure for supply. For example, hydrogen as well as methane has the disadvantage of low energy per unit volume, requiring that both gases be stored as a cryogenic liquid (IPCC, 1999). In general, the overall environmental impacts of the production and use of hydrogen or any other alternative fuels have not been quantified. The actual usefulness of such alternative fuels require a balanced consideration of many factors, such as safety, energy density, availability, cost, and indirect impacts through production. Hence, kerosene is not likely to be replaced by alternative fuels for another several decades (IPCC, 1999).

6.6 Chapter Summary

In this chapter, future trends in aircraft performance, cost, and emissions have been examined. The major contributors to aircraft fuel burn reduction in the future are higher engine and aerodynamic efficiencies, which are expected to improve by 20% each and account for more than 70% of the fuel burn reduction over the next 50 years. Gradual reduction in aircraft structural weight of about 10% through some use of composite materials and changes in operational measures, primarily increased load factor of about 12%, are expected to account for the remaining improvements in fuel burn. Aircraft structural weight has a reduction potential of up to 30% through full implementation of composite materials on the wings and fuselage; however, it is still uncertain when they will become practical for commercial products while they are already in use for military aircraft. Improvements in ATM will also continue. However, they may merely hold airport delays constant given the rapidly growing aircraft fleet size congesting airport alleys and runways and therefore lead to little benefits in fuel burn. As a result of overall improvements in aircraft technology and operations, aircraft fuel burn per passenger-mile is expected to decrease by about 57% by 2050 compared to today's airplanes. This improved fuel efficiency then results in about 50% reduction in direct operating cost while price is expected to increase by about 50%. Note, however, that it is likely to take additional 15 to 20 years for the entire world fleet to reach the same level of these efficiency improvements and cost changes because of the time delay in technology uptake. On the other hand, air travel is expected to continue the strong growth so that the world passenger miles are estimated to increase by more than five-fold by 2050. As a result, the expected improvements in aircraft technologies and operational measures alone are not likely to fully offset growing total aviation emissions, and aviation's effects on the global atmosphere are expected to increase in the future.

Table 6.1: Various Fuel Burn Reduction Projections (numbers shown in %)

Fuel Burn Reductions from Technological Improvements

	1990	1995	2000	2005	2010	2015	2020	2025	2030	2040	2050	Average Annual Improvement
ANCAT	Base					29						1.4
ETSU	Base					51 - 64						2.8 - 4
NRC	Base				40							2.5
ECoA		Base						50 - 62				2.3 - 3.2
AERO	Base					25						1
ADL			Base	13 - 20		20 - 29			33 - 41			1.3 - 4.4
IPCC			Base			20					40 - 50	1.0 - 1.5
NASA			Base								53	1.5
MIT			Base								47	1.3

Total Fuel Burn Reductions with ATM and Operating Measures Included

	1990	1995	2000	2005	2010	2015	2020	2025	2030	2040	2050	Average Annual Improvement
ADL			Base	17 - 25		25 - 37			37 - 47			1.6 - 5.5
IPCC[1]			Base				26 - 32				48 – 58	1.3 - 1.9
MIT			Base								57	1.7

Notes:

1. Forecast years assumed

Table 6.2: Direct Operating Cost and Price Projections for Future Aircraft (in 1995 U.S. dollars)

Aircraft Types	Year of Introduction	ASM/gal	Load Factor	Aviation System Efficiency	DOC/RPM (cents)	Price/Seat ($ thousand)
MIT Model Baseline	2000	67.0	0.72	47.9	3.37	286.8
NRC	2010	105.4	0.73	77.2	2.13	367.9
IPCC 2015	2015	83.7	0.74	62.0	2.63	328.2
ETSU Low	2015	129.0	0.74	95.6	1.74	411.4
ETSU High	2015	175.6	0.74	130.1	1.29	483.2
ANCAT	2015	89.1	0.74	66.0	2.48	339.0
AERO	2015	84.3	0.74	67.5	2.61	329.4
ECoA Low	2025	133.9	0.76	101.5	1.64	424.4
ECoA High	2025	176.2	0.76	133.5	1.26	489.8
ADL Low	2030	99.9	0.77	76.6	2.15	366.4
ADL High	2030	113.5	0.77	87.0	1.90	391.6
IPCC 2050 Low	2050	111.6	0.80	89.3	1.85	397.0
IPCC 2050 High	2050	133.9	0.80	107.2	1.56	436.7
NASA Best Kerosene	2050	141.4	0.80	113.2	1.48	449.2
MIT	2050	126.3	0.80	101.1	1.64	423.6

Notes:

1. Load actor is projected based on 0.17 percentage points increase per year. 1998 base year load factor is 71.2 percent.
2. Baseline aircraft is B-737-400 for ETSU and ANCAT and B-777 for all others.

Table 6.3: Total Aviation Fuel Consumption, CO_2 Emissions, and Associated Economic Characteristics in 2025 and 2050

		1995	2025	2050	2050 Instant Replacement
Total RPMs	(billion miles)	1576	4681	8658	8658
Load Factor		0.673	0.758	0.800	0.800
Fleet Fuel Efficiency	(ASM/gal)	53.6	71.7	101	126
	(RPM/gal)	36.1	54.3	80.6	101
Fuel Consumption	(gal/RPM)	0.0277	0.0184	0.0124	0.00989
Total Fuel Consumption	(billion gallons)	43.7	86.1	107	85.6
CO_2 Emissions	(billion kg)	419	827	1031	822
DOC/RPM	(cents)	4.41	2.98	2.04	1.64
Price/Seat	($ thousand)	247	306	376	424

Notes:

1. 1995 traffic statistics are based on USDOT Form 41.
2. Load factor projections are based on Airbus forecasts.
3. World traffic growth is the CAEP/4-FESG Fa scenario based on IPCC IS92a. (IPCC, 1999)
4. B-777 fuel economy = 0.0207 gal/RPM (2000 baseline aircraft)
5. 2025 fleet fuel economy = 2010 technology = 0.0184 gal/RPM (11% less fuel burn in comparison to B-777)
6. 2050 fleet fuel economy = 2035 technology = 0.0124 gal/RPM (40% less fuel burn in comparison to B-777)
7. 2050 Instant Replacement is where all old aircraft were replaced instantly in 2050 with the aircraft that consumes 57 percent less fuel per RPM.

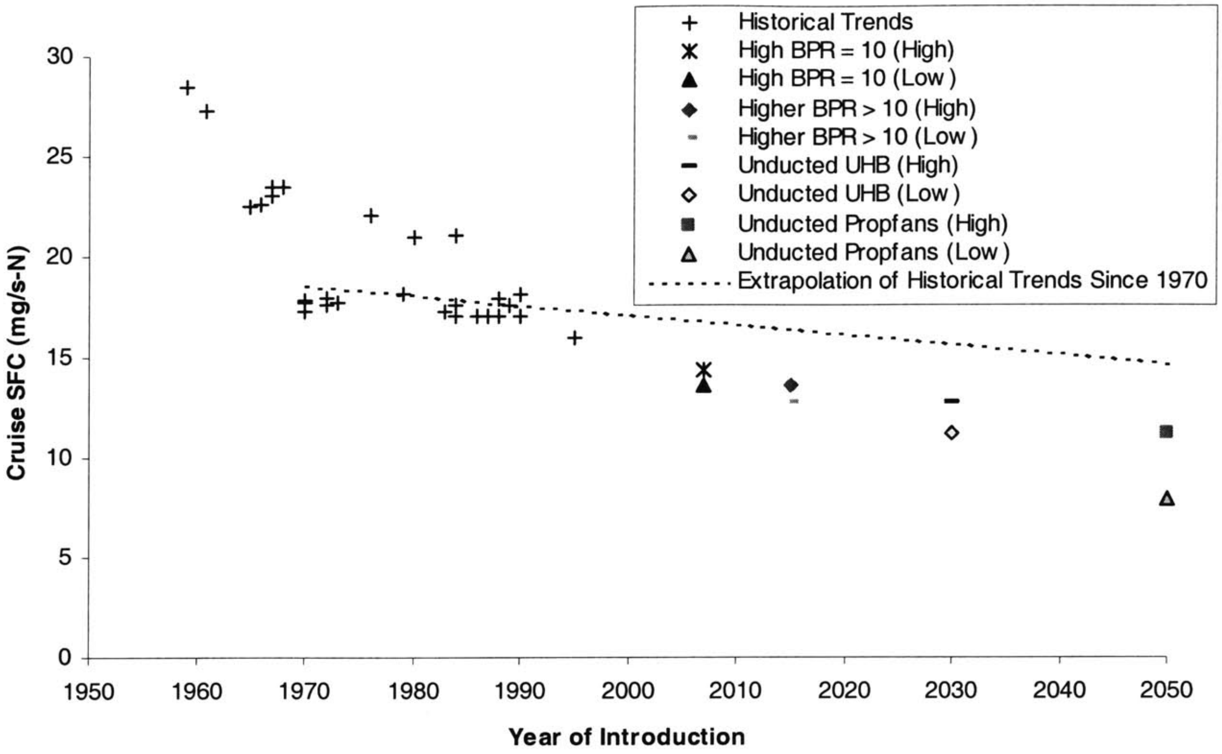

Figure 6.1: Future Trends in Specific Fuel Consumption

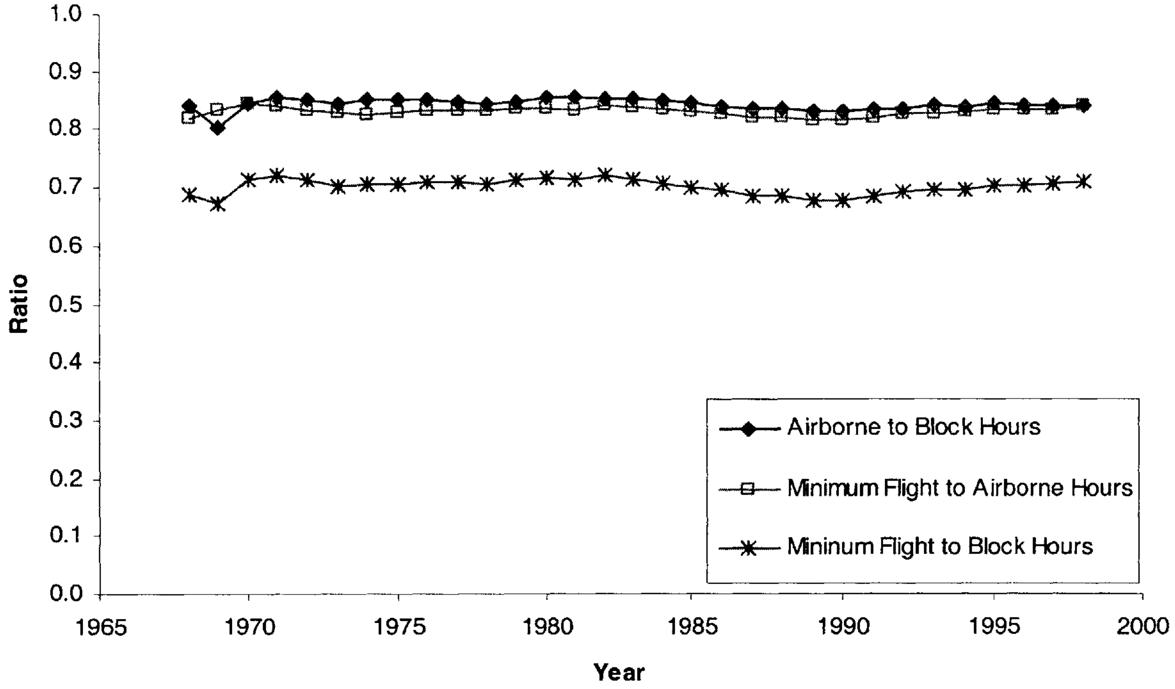

Figure 6.2: Historical Trends in Ground, Airborne, and Total Flight Time Efficiencies

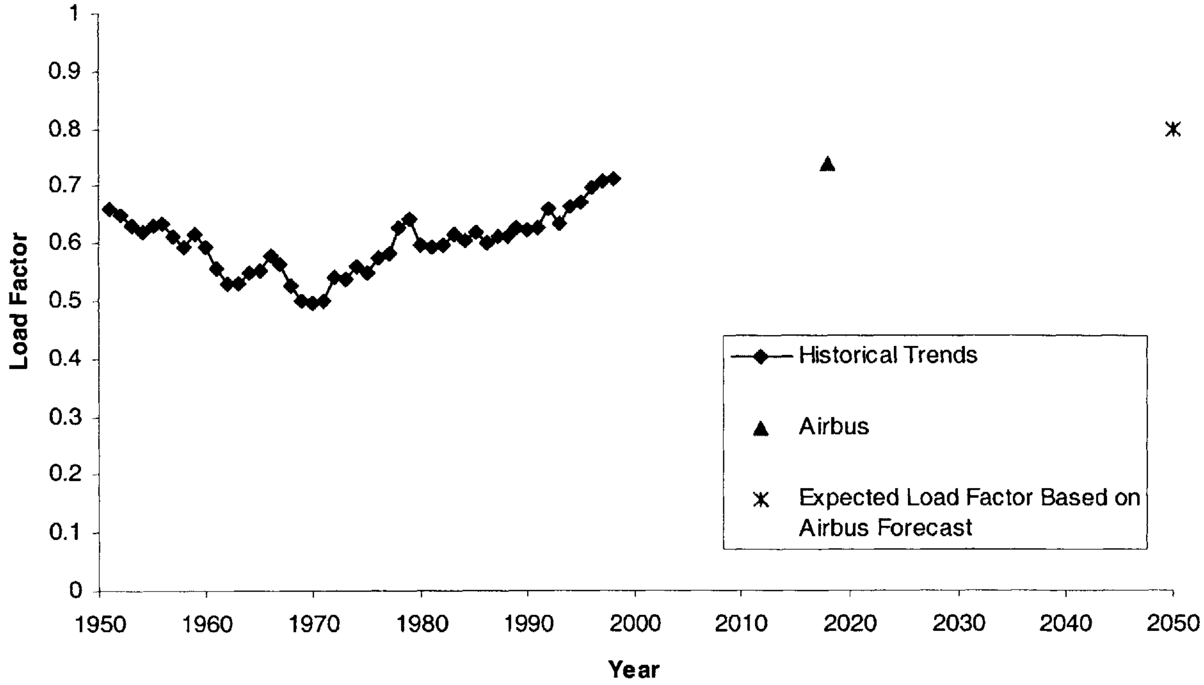

Figure 6.3: Historical and Future Trends in Load Factor (USDOT Form 41, 1968-Present and ATA, 1998b; historical trends based on entire U.S. fleet)

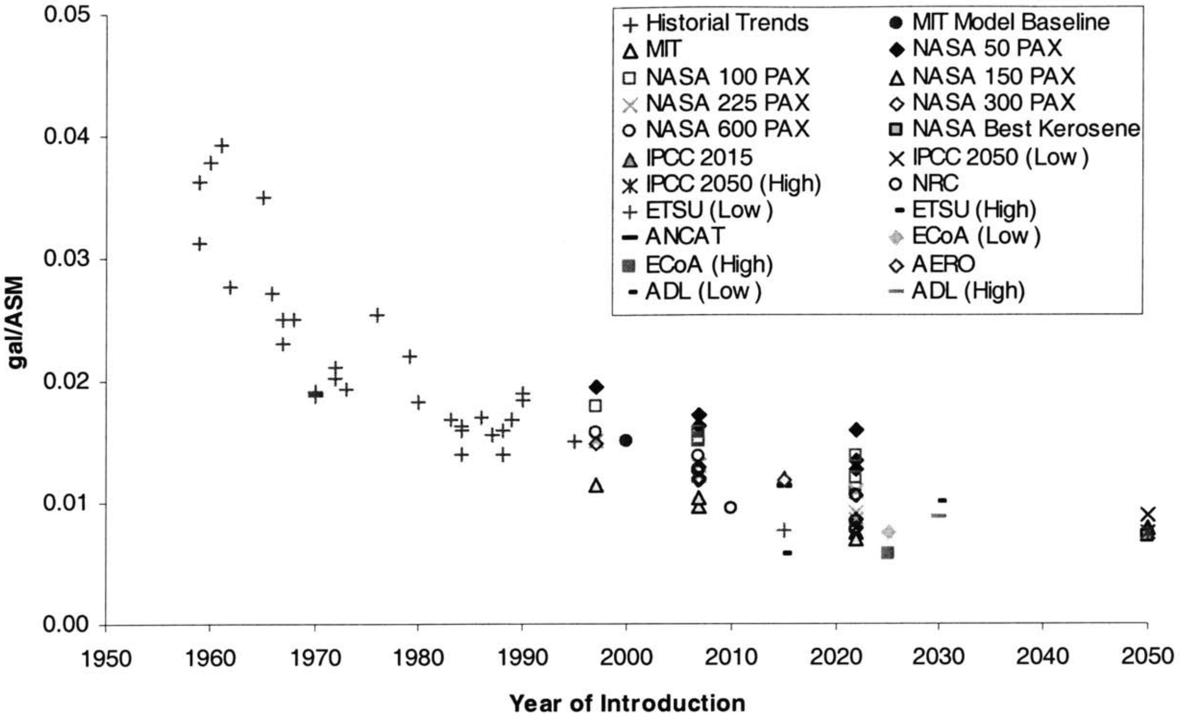

Figure 6.4: Various Fuel Burn Reduction Projections

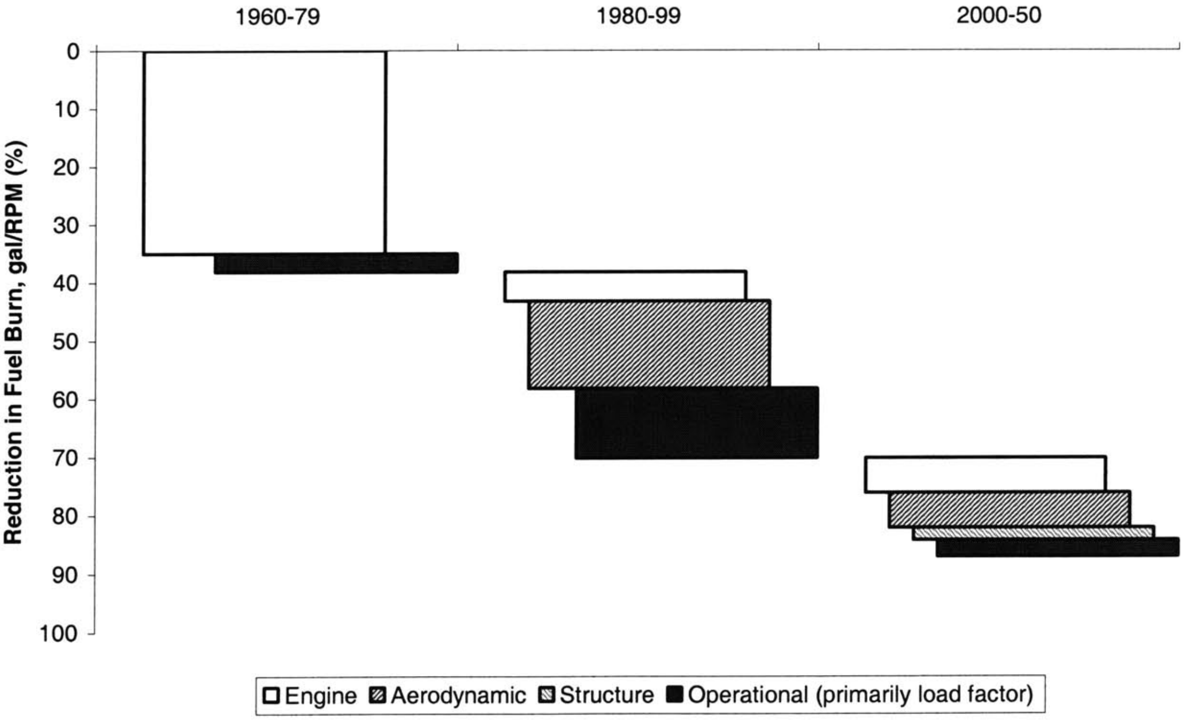

Figure 6.5: Major Contributors for Aircraft Fuel Burn Reduction in the Past and Future

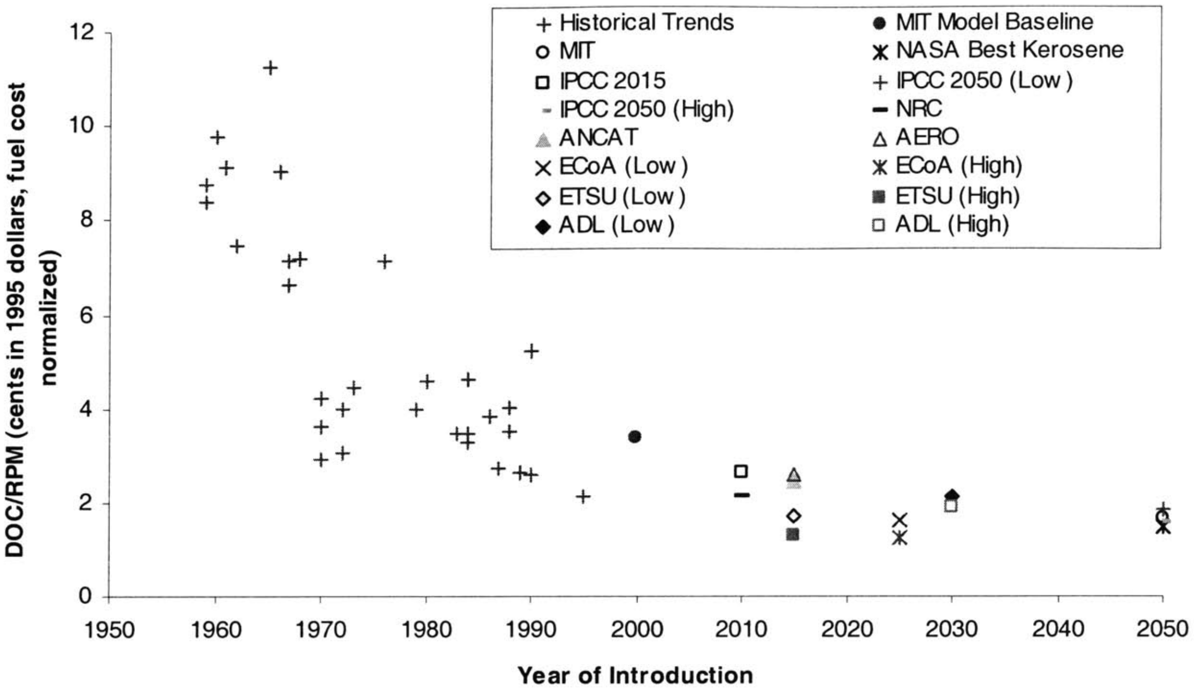

Figure 6.6: Projected Direct Operating Costs for Future Aircraft

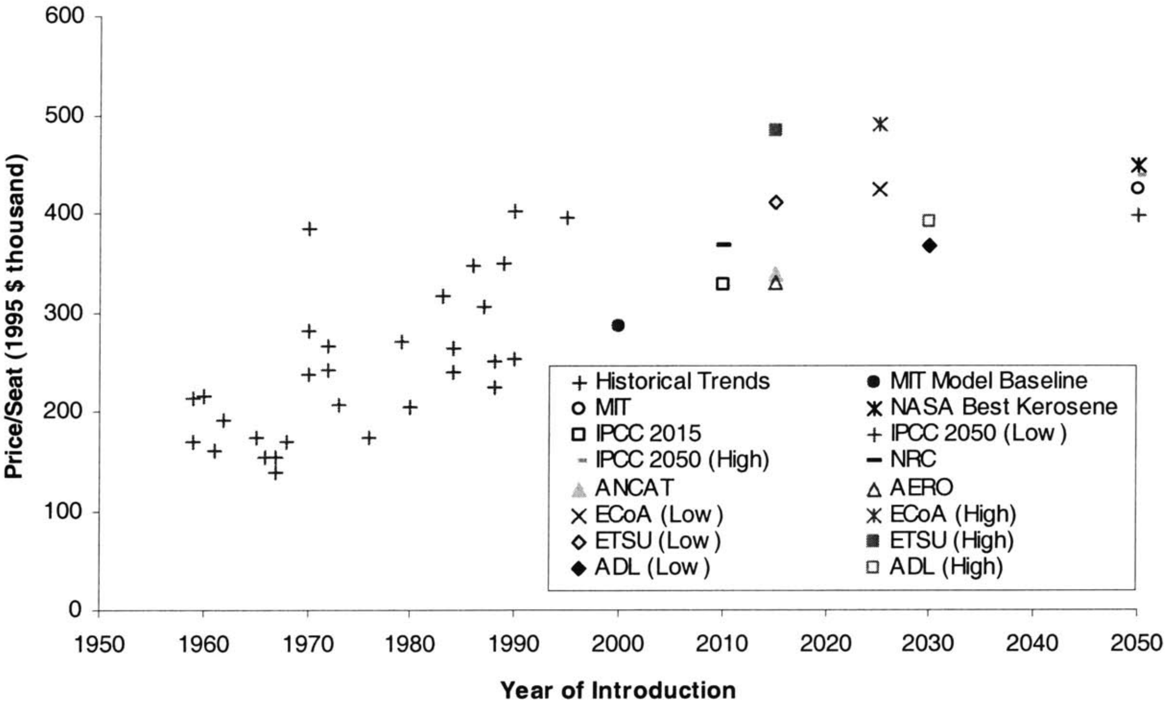

Figure 6.7: Projected Prices for Future Aircraft

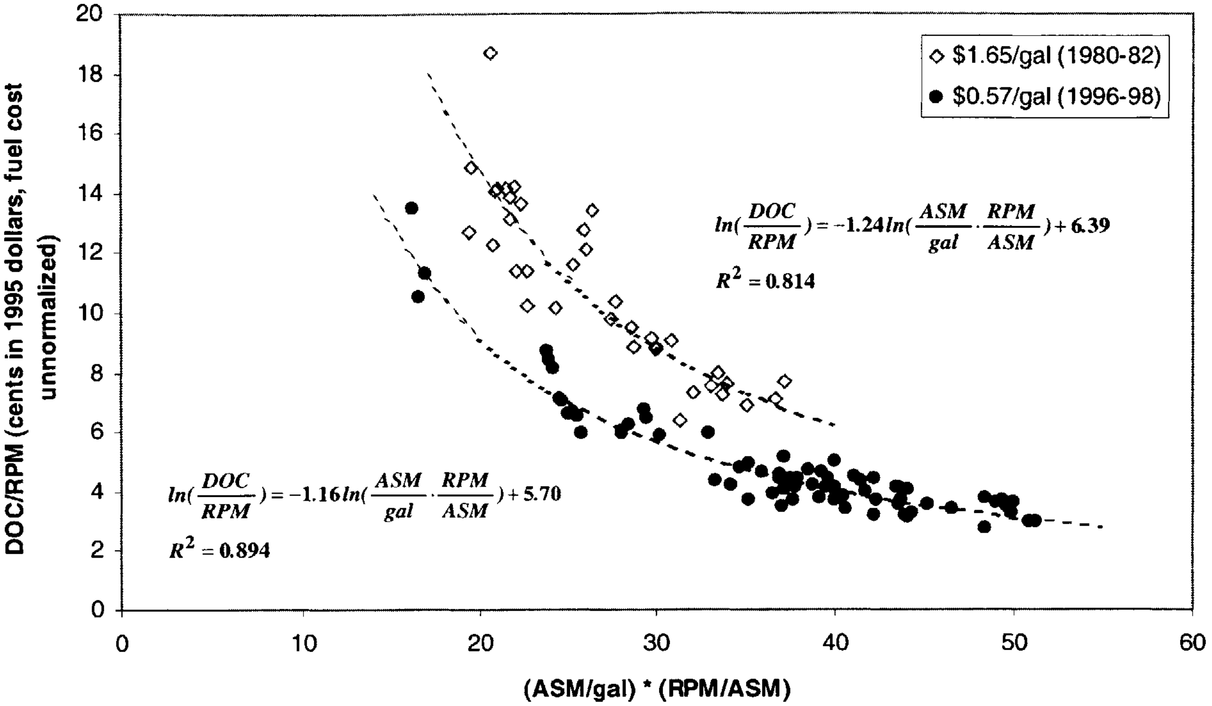

Figure 6.8: Impact of Fuel Price on Direct Operating Cost

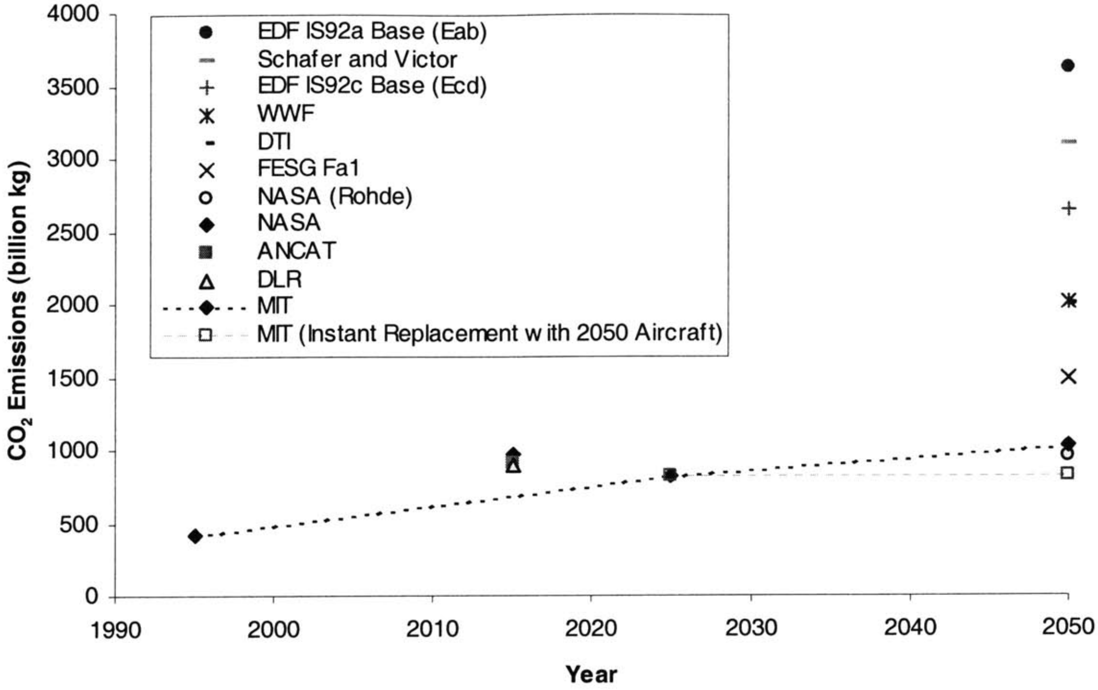

Figure 6.9: Various CO_2 Emissions Growth Forecasts

Chapter 7

Aviation Emissions and Policy Perspective

7.1 Introduction

Since improvements in aircraft engine and airframe technology and in the efficiency of operational measures and air traffic control may not fully offset the strong growth of aviation emissions, a dialog of what policy framework is necessary to further reduce the cumulative effects of aircraft emissions is currently ongoing. This chapter explores various policy options to address growing aviation emissions. By taking into account potential emissions reductions through policy options, a feasible emissions reduction burden for the aviation sector is also discussed.

7.2 Aviation Emissions Policy

7.2.1 Goals

Aviation emissions policy has two goals. One is to encourage the air transport industry to develop new technology and absorb it into the fleet more quickly while the other goal of aviation emissions policy is to manage the growth of air traffic volume.

Under these two goals, most aviation emissions policy options are expected to lead to increased airlines' operating costs and ticket fares (IPCC, 1999). Airlines then gradually switch to more fuel-efficient technologies that consume less energy and save operating costs. At the same time, increased ticket fares result in reduced air travel demand. Consequently, total aviation fuel consumption and subsequent aviation emissions are expected to be reduced when policy options are appropriately implemented.

7.2.2 Policy Options for Emissions Reduction

Currently, specific policy options under consideration include more stringent aircraft engine emissions regulations, market-based options, such as environmental levies (charges and taxes) and emissions trading, removal of subsidies and incentives that have negative environmental consequences, voluntary agreements, research programs, and substitution of aviation by other high-speed modes of transport (IPCC, 1999).

7.2.2.1. Engine certification

In reducing specific aircraft emissions, engine certification is a direct means to regulate emissions for carbon monoxide, hydrocarbons, NO_x, and smoke during LTO cycles. ICAO has also begun to develop similar standards for aircraft emissions at cruise (IPCC, 1999). On the other hand, no engine certification requirement exists for CO_2 emissions. Thus, it may be possible to develop fuel efficiency standards, such as an SFC requirement, in engine certification processes and reduce aircraft specific CO_2 emissions. Note, however, that a careful analysis of technological feasibility, extra cost and time required for certification, implementation plans, and actual benefits must proceed the introduction of such additional standards.

7.2.2.2. Environmental levies

Environmental levies are market-based options which provide an economic incentive to airlines to operate a more fuel-efficient aircraft and also have an effect on stabilizing air traffic demand. Environmental levies take various forms of charges and taxes. For example, Zurich Airport has imposed an emissions surcharge to its landing fee based on engine certification information. An aircraft engine is classified within one of five groups subject to an emission charge in 0 to 40% to the landing fee. This Zurich emission charge intends to provide an incentive to airlines to fly their lowest NO_x emitting aircraft into Zurich and accelerate the use of the best available technology (IPCC, 1999). However, since landing fees are typically less than 2% of DOC according to the 1998 operating cost data reported in USDOT Form 41 (USDOT, 1968-Present), an emission charge of the maximum 40% of the landing fee then corresponds to only 0.8% of DOC at most. Thus, the Zurich emission charge causes almost no change in the ASE-DOC relationship and provides little incentive to improve in terms of aircraft fuel efficiency as shown in Figure 7.1.

In Europe, a \$0.20 per liter CO_2 emission charge, which is equivalent to a 125% increase in fuel price, is expected to lead to as much as a 30% reduction in CO_2 emissions on top of gradual technological improvements in the long term (Dings *et al.*, 1997). This projection is roughly consistent with the ASE-DOC relationship where 125% increase in fuel cost, or about 30 to 40% increase in DOC/RPM indeed leads to about a 25% improvement in aviation system efficiency, or about 20% reduction in fuel consumption as also shown in Figure 7.1.

Environmental levies can also be applied as taxation on passenger distance or aircraft distance (Barret, 1991). Direct increases in airfares through ticket charges also lead to reduced air traffic growth. However, it does not provide an incentive for airlines to improve the environmental efficiency of air transport (Dings *et al.*, 1997). Environmental levies are also claimed to have an effect on optimizing aircraft design beyond improvements in individual components, such as engines and airframes. For example, as fuel price rises and becomes a larger share of total DOC, the aviation industry is expected to react in the long term by designing an aircraft that is optimized for lower speed using higher bypass ratio engines with lower SFC and also has larger wingspans and lower weight (Morrison, 1989; Dings *et al.*, 1997).

7.2.2.3. Emissions trading

Emissions trading is another type of market-based policy option. In emissions trading, each airline could be given an emissions budget for its fleet of aircraft and trade emissions credits with other regulated sources. This way, airlines have the flexibility to reduce their own emissions and sell remaining credits to others or to purchase equivalent reductions from others, if the latter option would be less expensive. Thus, emissions trading provides an economic incentive to be cleaner by adopting newer, more fuel-efficient technologies and reducing emissions below the level any specific technological standard might require. This option has not been tested in aviation (GAO, 2000; IPCC, 1999).

7.2.2.4. Alternative transport modes

Substitution of aviation by rail and coach is also considered as a potential policy option to reduce aviation emissions while the scope for this reduction is limited to high density, short-haul routes that have coach or rail links. According to the IPCC Special Report, up to 10% of European travelers could be transferred from aircraft to high-speed rails. However, a broader-scope analysis including tradeoffs between a wide range of environmental effects, such as noise exposure, local air quality, and atmospheric effects, is necessary to assess the potential benefit of this substitution (IPCC, 1999).

7.3 Aviation Sector's Emissions Reduction Burden

If adopted, the Kyoto Protocol would require industrialized countries to reduce their total national emissions by an average of 5% for the average of the period 2008 to 2012 compared to 1990 levels. If the aviation sector were to be equally responsible to meet the same provision, which would be around 400 to 500 billion kg of CO_2 emissions per year, analysis based on the previous CO_2 emissions forecast in this thesis shows that the fuel burn of the world fleet between 2008 and 2012 must be reduced nearly by 50%, as shown in Table 7.1. This would require that drastic technological and operational improvements be introduced today while it is uncertain whether such measures are available.

Another important constraint for aviation emissions reduction in the Kyoto perspective is the relative aircraft cost changes with respect to technological improvements. Assuming that the required improvements in aircraft fuel consumption could be made today mainly through technological innovations, an analysis based on the technology-cost relationship shows that DOC would be lowered by about 46% while price would increase by 40% as a result of such improvements in technology as shown in Table 7.1. Note that these are the relative changes between technology, DOC, and price that would be accepted by the industry as they have been in the past. In other words, the aviation sector would be willing to pay higher prices for the large improvements in technology if it could balance off through savings in DOC. The question is whether future technologies could be delivered at the same price level that would correspond to the same level of savings in DOC in the historical trends. If the price is too high for expected savings in DOC, the industry may not adopt more efficient, yet too expensive technologies.

A more feasible environmental burden for the aviation sector would be some degree of additional emissions reductions on top of what expected improvements in aircraft technologies and operations could achieve. Policy options for these additional emissions reductions seem to exist; however, their effects and implementation plans have not been fully investigated or tested (IPCC, 1999). In assessing the outcomes of any policy measures including the ones discussed in this chapter, it is also important to consider the response time of the aviation sector until these policy measures become fully effective. In general, the response to a policy measure takes place over a relatively long time period, possibly of the order of several years to decades. For example, ICAO's CAEP established new noise certification standards (Stage 3 aircraft) in 1990. Some states in Europe then started phasing out Stage 2 aircraft, which met the noise certification levels in Annex 16, Volume I, Chapter 2, but not those in Chapter 3 (ICAO, 1996). The full implementation of the Stage 3 aircraft noise restriction is then to be completed by 2002 (ICAO, 1997). In this case, the phase-out of Stage 2 aircraft will have taken 12 years. Thus, the aviation sector may not realize any immediate benefits in emissions reduction even if a new policy measure is implemented in the near term. Furthermore, in order for such policy measures to be effective, they would need to be addressed in an international framework because of the global scope of the issues associated with aviation emissions and climate (IPCC, 1999).

Other greenhouse gases than CO_2 emissions also deserve attention. However, the uncertainties associated with the global warming potential of each of different gases and tradeoff effects between them make it difficult to focus emissions abatement efforts. For example, NO_x reduction technologies may have an adverse net effect on global warming because they could lead to generating more CO_2. Also, higher efficiency engines increase the potential for water contrail formation. Therefore, as of today, the best emissions abatement strategy to mitigate aviation's effects on the global atmosphere seems to be reducing total aviation fuel consumption through improved aircraft fuel efficiency and managed air travel demand.

7.4 Chapter Summary

Various policy options, such as aircraft engine emissions regulations and market-based options including environmental levies and emissions trading, exist to further address growing aviation emissions while most of them would lead to increased airline costs. Before adopting any of these policy measures, however, the discussion of broad policy matters must first rest on the assessment of what must be accomplished next in order to resolve the issues associated with aviation's effects on the global atmosphere. For this, the science community must provide more sophisticated models and definitive answers to the questions regarding the effects of aviation emissions on the global atmosphere. Industry must continue to drive technological innovations. The policymaker's challenge is then to develop mechanisms ensuring consistency in adoption of international standards and uniformity in application, to develop concurrent and cooperative problem-solving approaches that are based on demonstrated environmental needs, and are technically feasible, institutionally flexible, and economically sound, and lastly to develop the means to finance change (Aylesworth, 1996).

Table 7.1: Fuel Efficiency Improvement Required to Meet Kyoto Protocol and Resulting Economic Characteristics

		1995	2008-12	% Change
Total RPMs	(billion miles)	1576	2972	89
Fleet Fuel Efficiency	(RPM/gal)	36.1	69.0	91
Fuel Consumption	(gal/RPM)	0.0277	0.0145	-48
Total Fuel Consumption	(billion gallons)	43.7	43.1	-1.3
CO_2 Emissions	(billion kg)	419	414	-1.3
DOC/RPM	(cents)	4.41	2.37	-46
Price/Seat	($ thousand)	247	347	40

Notes:

1. World traffic growth is the CAEP/4-FESG Fa scenario based on IPCC IS92a. (IPCC, 1999)
2. RPM projection for the period 2008 to 2012 is based on 2010 growth forecast.

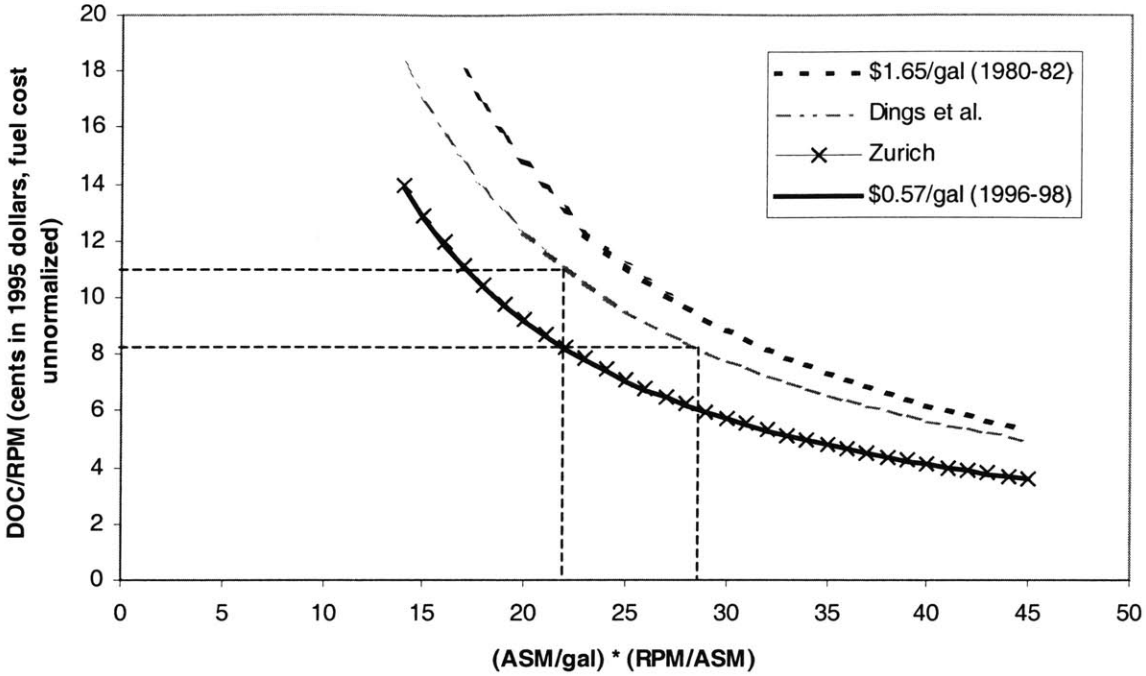

Figure 7.1: Impacts of European Emission Charges

Chapter 8

Summary and Conclusions

Since air travel is continuing to experience the rapid growth at average rates of 5 to 6% per year, interest is increasing among the industry, scientific community, and governments to address the potential impacts of aviation emissions on the global atmosphere. Despite the various efforts to understand and mitigate aviation's emissions impacts, it still remains uncertain which emissions abatement options are feasible ones under the various constraints of the aviation sector. Economic feasibility may be one of the most important limiting factors in aviation emissions abatement efforts because of the narrow profit margin of the air transport industry (NRC, 1992). In this context, this thesis is the first of its kind to analyze the relationship between aircraft performance and cost and assess aviation emissions reduction potential based on analytical and statistical models founded on a database of historical data.

Historical trends in aircraft performance during the period 1959 to 1995 show that the fuel consumption per revenue passenger-mile of the 31 aircraft types has decreased by 70% through continuous improvements in aircraft technology and operations. Based on the database of historical data, the technological and operational influences on aircraft fuel efficiency have been quantified utilizing the Breguet range equation, which describes the physics of aircraft in steady level flight. As a result, it has been shown that the 40% improvement in SFC and the 15% improvement in L/D analytically comprise 55% reduction for the overall 70% reduction in aircraft fuel burn observed in the historical trends. Increase in load factor (15% improvement during the period 1959 to 1995) then accounts for about 12% reduction in fuel burn while other operational improvements including increased seats are to account for the remaining 3% reduction in fuel burn in the past.

In terms of historical trends in aircraft cost, direct operating cost without fuel cost has decreased by about 65%. On the other hand, short- and long-range aircraft prices per seat have risen approximately 70% during 1965 to 1990 and 130% during 1959 to 1995, respectively.

Overall, historical trends in aircraft performance and cost indicate that aircraft price decreases with age of the aircraft model, but a larger investment is required as new, more efficient models with technology advancement are introduced.

In order to understand the relationship between aircraft system performance and cost, an aviation system efficiency parameter was first defined as a product of fuel efficiency, a surrogate measure for technology advancement, and load factor, and then correlated with aircraft direct operating cost through multivariable statistical analysis. The relationship between direct operating cost and price was also determined statistically. Overall, it was shown that the complex technological and economic behaviors of aviation systems can be described by only a few simplified parameters. In particular, the aviation system efficiency parameter was developed as the most suitable environmental performance metric to relate aircraft performance, cost, and emissions.

Based on the comparison of extrapolations of historical trends in aircraft technology and operations and the future projections made by NASA, IPCC, and other major studies, potential improvements in aircraft fuel consumption were estimated for the time period up to 2050. In addition, the direct operating cost and price of future aircraft systems were estimated based on the projected improvements in aircraft fuel consumption through the technology-cost relationship developed in this thesis. While the model results may not be the precise values for the DOC and price of future aircraft systems, they provide meaningful insight into the sensitivity of aircraft cost with respect to improvements in aircraft technology and operations and the economic feasibility of technology introduction.

The major contributors to aircraft fuel burn reduction in the future are higher engine and aerodynamic efficiencies, which are expected to improve by 20% each and account for more than 70% of the fuel burn reduction over the next 50 years. Gradual reduction in aircraft structural weight of about 10% through some use of composite materials and changes in operational measures, primarily increased load factor of about 12%, are expected to account for the remaining improvements in fuel burn. Aircraft structural weight has a reduction potential of up to 30% through full implementation of composite materials on the wings and fuselage;

however, it is still uncertain when they will become practical for commercial products while they are already in use for military aircraft. Improvements in ATM will also continue. However, they may merely hold airport delays constant given the rapidly growing aircraft fleet size congesting airport alleys and runways and therefore lead to little benefits in fuel burn. As a result of overall improvements in aircraft technology and operations, aircraft fuel burn per passenger-mile is expected to decrease by about 57% by 2050 compared to today's airplanes. The improved fuel efficiency then results in about 50% reduction in direct operating cost while price is expected to increase by about 50%. Note, however, that it is likely to take additional 15 to 20 years for the entire world fleet to reach the same level of these efficiency improvements and cost changes because of the time delay in technology uptake.

On the other hand, air travel is expected to continue the strong growth so that the world passenger miles are estimated to increase by at least five-fold (and perhaps as much as twenty-fold) by 2050. As a result, the expected improvements in aircraft technologies and operational measures alone are not likely to fully offset growing total aviation emissions, and aviation's effects on the global atmosphere are expected to increase in the future.

Various policy options, such as aircraft engine emissions regulations and market-based options including environmental levies and emissions trading, exist to further reduce the effects of growing aviation emissions on the global atmosphere as most of them would lead to increased airline costs. By utilizing the technology-cost relationship, it has been shown that a fuel tax, which directly increases DOC, would penalize less efficient aircraft more severely as the percent increase in DOC with respect to the same amount of increase in fuel price grows larger for the aircraft with lower aviation system efficiency. Also, 125% increase in fuel price, which increases airlines' direct operating cost by about 30 to 40%, would drive as much as 25% improvement in aviation system efficiency, or about 20% reduction in aircraft fuel consumption. While it is still uncertain how much additional emissions reductions are possible through these policy measures, a more feasible burden for the aviation sector seems to be some degree of additional emissions reduction on top of what expected improvements in aircraft technologies and operations could achieve.

Today, the uncertainties associated with the global warming potential of each of different aviation emissions species and tradeoff effects between them make it difficult to focus abatement efforts. Thus, the best emissions abatement strategy to mitigate aviation's impacts on the global atmosphere seems to be reducing total aviation fuel consumption through improved aircraft fuel efficiency and managed air travel demand. To this end, the strategy for the sustainable future of aviation must be based on scientifically-based, comprehensive, and long-term solutions.

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Appendix 1

SFC Calibration Procedure

$$\textit{Specific Fuel Consumption (SFC)} = \frac{\textit{Fuel Flow}}{\textit{Thrust}}\left[\frac{kg/s}{N}, \textit{or } \frac{lb_m/hr}{lb_f}\right] \quad \text{(A1.1)}$$

ICAO take-off SFC is first calculated based on the equation (A1.1) and compared with Jane's take-off SFC as shown in Figure A1.1.

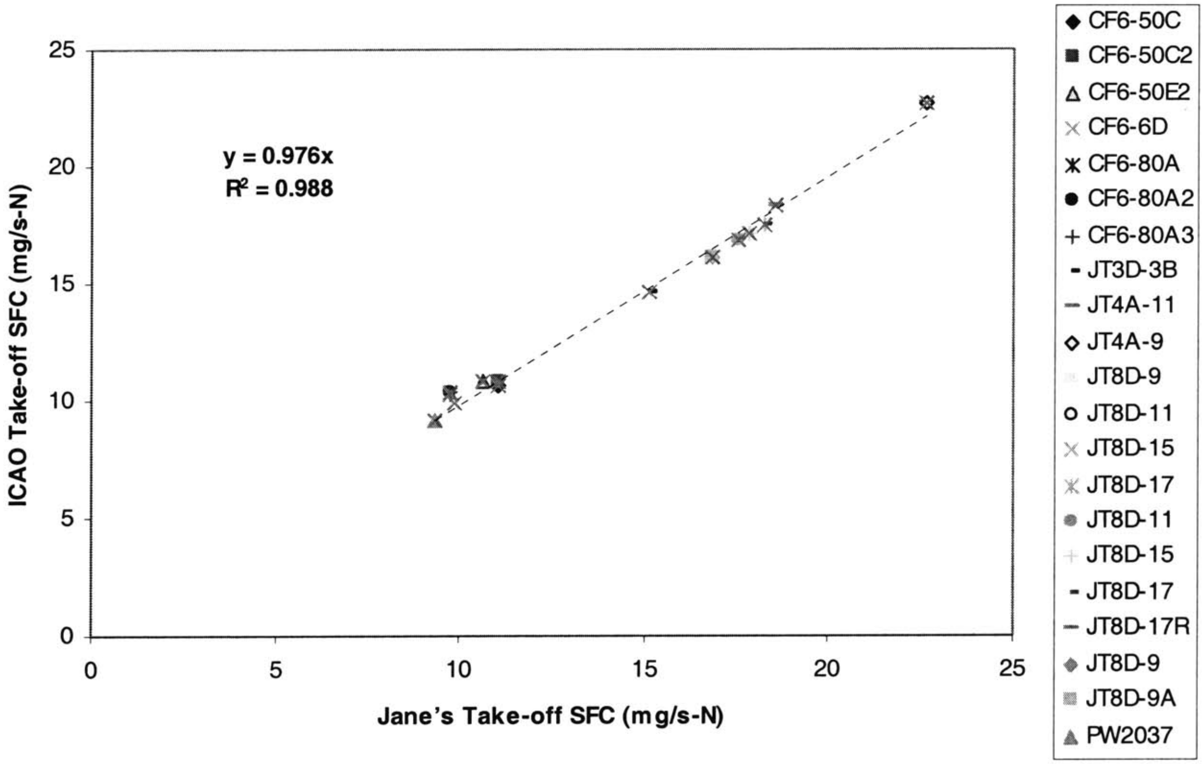

Figure A1.1: ICAO Take-off SFC versus Jane's Take-off SFC

Once the validity of ICAO data is confirmed, cruise SFC at altitude of 35,000 ft is obtained by calibrating take-off SFC from the ICAO engine database to cruise SFC in Jane's Aero-Engines as shown in Figure A1.2. The calibration equation, y = 0.869x + 8.65 is obtained with

$R^2 = 0.878$. Using this calibration equation, all ICAO take-off SFC data are converted to cruise SFC data.

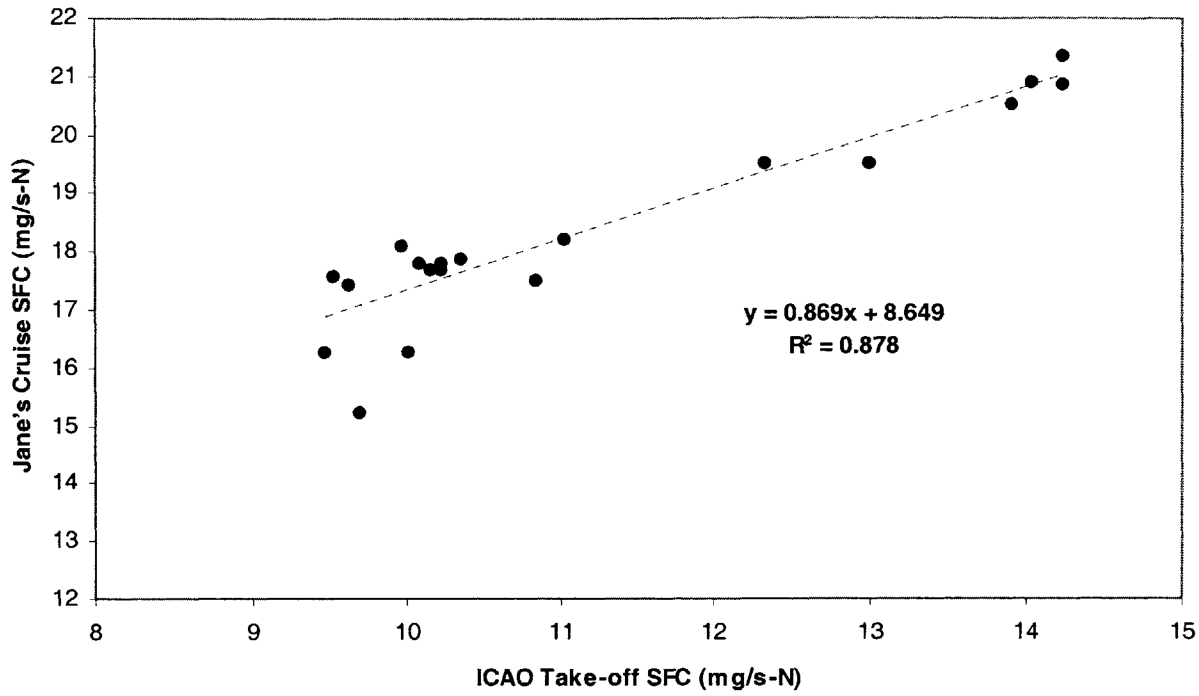

Figure A1.2: Jane's Cruise SFC versus ICAO Take-off SFC

Notes:

1. Standard error of this straight line fit is 0.624. Thus, the estimated error of cruise SFC is approximately ±1.25, or 7% for 2σ confidence.
2. Exceptions of the calibration procedure above are CFM56-3B1, CFM56-3B2, CFM56-3C, CFM56-5A1, CFM56-5A1, CFM56-5A3, and CFM56-5B4. For these engines, cruise SFC values from Jane's Aero-Engines are used.
3. When an aircraft has more than one engine option, the average SFC value of all available engine types for the aircraft is used.
4. SFC of JT3C-6 is used for JT3C-7.
5. SFC of PW4056 is used for all PW405x engine types.
6. SFC of CF6-80C2 is the average value of those of all C2 series.
7. SFC of GE90 is the average value of those of all GE90 series in ICAO database.

8. For DC-9-50 and B-737-300, the SFC values of their engines (JT8D-15 and -17) are substituted by that of JT8D-15A found in Mattingly.
9. SFC of B-767-200ER is assumed to be the same as that of B-767-200.
10. SFC of B-747-100 is assumed to be the same as that of B-747-100B.
11. SFC of B747-200 is assumed to be the same as that of B747-200B.
12. SFC of DC-9-10 is assumed to be the same as that of DC-9-30.
13. SFC of MD-81 is assumed to be the same as that of MD-82.
14. SFC of B-727-200 is the average value of those of B-727-200 Advanced and Stretch.

Appendix 2

Engine/Planform Configurations for Selected Aircraft Types

Planform	Engines
A300-600	CF6-80C2A1
	CF6-80C2A5
	JT9D-7R4H1
	PW4152
	PW4158
A300-600C	PW4158
A300-600F	PW4158
A300-600R	CF6-80C2A5
A310-300	CF6-80A3
	CF6-80C2A2
	CF6-80C2A8
	JT9D-7R4D1
	PW4152
	PW4156A
A320-100	CFM56-5A1
	CFM56-5A3
	CFM56-5B4
	V2500-A1
	V2527-A5
A320-200	CFM56-5A1
	CFM56-5A3
	CFM56-5B4
	V2500-A1
	V2527-A5
B-707-100BH	JT3D-1
	JT3D-3B
B-707-300	JT4
	JT4A-11
	JT4A-12
	JT4A-9
B-707-300BH	JT3D-3B
B-720	JT3C-7
B-720B	JT3D-3B

Planform	Engines
B-727-200 ADVANCED	JT8D-15
	JT8D-17
	JT8D-17R
	JT8D-9A
B-727-200 STRETCH	JT8D-11
	JT8D-15
	JT8D-9
B-737-100	JT8D-7
	JT8D-9
B-737-200	JT8D-15
	JT8D-17
	JT8D-9
B-737-300	JT8D-15
	JT8D-17
B-737-400	CFM56-3B2
	CFM56-3C
B-737-500	CFM56-3B1
B-747-100B	CF6-45A2
	CF6-50E2
	JT9D-7A
	RB211-524D4
B-747-200B	CF6-50E2
	CF6-80C2B1
	JT9D-7Q
	JT9D-7R4G2
	RB211-524C2
	RB211-524D4
	RB211-524D4B
B-747-300	CF6-50E2
	CF6-80C2
	JT9D-7R4G2
	RB211-524D4

Planform	Engines
B-747-400	CF6-80C2
	PW4256
	RB211-524D4
B-757-200	PW2037
	RB211-535C
	RB211-535E4
B-767-200	CF6-80A
	CF6-80A2
	JT9D-7R4D
	JT9D-7R4E
B-767-200ER	CF6-80A
	CF6-80A2
	CF6-80C2B2
	JT9D-7R4E
	PW4050
B-767-300	CF6-80A
	CF6-80A2
	CF6-80C2B4
	JT9D-7R4E
	PW4050
B-767-300ER	CF6-80C2B2
	JT9D-7R4D
	PW4056
	RB211-524D4D
B-777-200 STRETCH	GE90-B1
	GE90-B4
	PW4082
	PW4084
	Trent-882
	Trent-884
B-777-200A	GE90-B2
	GE90-B3
	PW4073
	PW4073A
	Trent 870
	Trent 871
B-777-200B	GE90-B1
	GE90-B4
	PW4082
	PW4084
	Trent-882
	Trent-884

Planform	Engines
DC-10-10	CF6-6D
DC-10-30	CF6-50C
	CF6-50C2
DC-10-40	JT9D-20
	JT9D-59A
DC-9-10	JT8D-1
	JT8D-7
DC-9-30	JT8D-7
	JT8D-9
DC-9-40	JT8D-11
	JT8D-15
DC-9-50	JT8D-15
	JT8D-17
L1011-1	RB211-22B
L1011-100	RB211-22B
L1011-200	RB211-524
	RB211-524B
L1011-500	RB211-524B
MD-11	CF6-80C2
	PW4460
MD-81	JT8D
	JT8D-209
MD-82	JT8D-217
	JT8D-217A
MD-83	JT8D-219
MD-87	JT8D-217C
MD-88	JT8D-219

Appendix 3

Form 41 P52 Financial Database for Direct Operating Cost

Category	Account	Description
Flying Operations	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
Direct Maintenance	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)
Depreciation	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

Amorti-zation	70741	Developmental and Preoperating Costs
	70742	Other Intangibles
	70761	Capital Leases - Flight Equipment
	70762	Capital Leases - Other
Other	52796	Applied Maintenance Burden - Flight Equipment
	70739	Net Obsolescence and Deterioration - Expendable Parts
	70981	Expense Of Interchange Aircraft - Flying Operations
	70982	Expense Of Interchange Aircraft – Maintenance

Notes:

1. Direct operating cost is the sum of flying operations and direct maintenance categories.
2. 52796 Applied Maintenance Burden and 70739 Net Obsolescence and Deterioration are totally excluded in DOC+I plots.

Appendix 4

GDP Deflators Used

Year	GDP Deflator
1957	19.8
1958	20.1
1959	20.6
1960	20.9
1961	21.1
1962	21.5
1963	21.8
1964	22.2
1965	22.7
1966	23.4
1967	24.1
1968	24.0
1969	25.2
1970	26.6
1971	28.0
1972	29.3
1973	31.2
1974	33.9
1975	37.3
1976	39.7
1977	42.3

Year	GDP Deflator
1978	45.6
1979	49.7
1980	54.3
1981	59.7
1982	63.5
1983	66.3
1984	69.4
1985	72.0
1986	74.0
1987	76.2
1988	78.9
1989	82.9
1990	86.8
1991	90.3
1992	92.8
1993	95.2
1994	97.4
1995	100.0
1996	102.3
1997	104.3
1998	107.0

$$1995\, U.S.\$ = \left(\frac{GDP\ Deflator, 1995}{GDP\ Deflator, Year\ i} \right) Year\ i\ U.S.\$ \tag{A4.1}$$

Source: International Financial Statistics 1998 and 1985, International Monetary Fund (IMF, 1998 and 1985)

Notes:

1. Base year is 1995.
2. GDP deflators for 1998 and 1999 are estimated from Consumer Price Index.

Appendix 5

Fuel Reserve Requirements

Federal Aviation Regulation (FAR)

§ 91.151 Fuel requirements for flight in VFR conditions.

(a) No person may begin a flight in an airplane under VFR conditions unless (considering wind and forecast weather conditions) there is enough fuel to fly to the first point of intended landing and, assuming normal cruising speed—

(1) During the day, to fly after that for at least 30 minutes; or

(2) At night, to fly after that for at least 45 minutes.

(b) No person may begin a flight in a rotorcraft under VFR conditions unless (considering wind and forecast weather conditions) there is enough fuel to fly to the first point of intended landing and, assuming normal cruising speed, to fly after that for at least 20 minutes.

Notes:

1. VFR stands for Visual Flight Rules.

Appendix 6

Minimum Flight Hours Calculation

$$T = \frac{T_T}{(1 + \frac{\gamma - 1}{2} M^2)} \tag{A6.1}$$

$$V = \sqrt{\gamma R T}\, M \tag{A6.2}$$

M (cruise speed) = 0.85

T_T = 218.9 K (at 35,000 feet, standard atmosphere)

γ = 1.4

R = 287 J/kg-K

$$Minimum\ Flight\ Hours = \frac{Stage\ Length}{Maximum\ Cruise\ Speed} \tag{A6.3}$$

Maximum cruise speed is calculated from standard atmosphere at 35,000 feet and cruise Mach number of 0.85. Static temperature is first obtained to be 191.3K from equation (A6.1). Maximum cruise speed is computed by the equation (A6.2) to be 235.7 m/s, or 527.2 MPH. Minimum flight hours is then stage length divided by maximum cruise speed as shown in (A6.3).

Appendix 7

Jet Fuel Prices Used

Year	Jet Fuel Price, discounted to 1995 dollars ($/gallon)	Crude Oil Price, discounted to 1995 dollars ($/barrel)
1968	0.52	12.3
1969	0.52	12.3
1970	0.51	12.0
1971	0.51	12.1
1972	0.49	11.6
1973	0.52	12.5
1974	0.77	20.2
1975	0.78	20.5
1976	0.78	20.6
1977	0.77	20.3
1978	0.75	19.7
1979	0.94	25.5
1980	1.66	39.7
1981	1.74	53.2
1982	1.56	44.9
1983	1.34	39.5
1984	1.24	37.3
1985	1.11	33.4
1986	0.74	16.9
1987	0.72	20.2
1988	0.66	15.9
1989	0.72	19.1
1990	0.88	23.1
1991	0.74	18.3
1992	0.67	17.2
1993	0.62	15.0
1994	0.56	13.5
1995	0.54	14.6
1996	0.63	18.1
1997	0.61	16.5
1998	0.47	10.2

$$\textit{Fuel Cost, Normalized }(1995) = \left(\frac{\textit{Fuel Price}, 1995}{\textit{Fuel Price, Year } i} \right) \textit{Fuel Cost, Year } i \qquad \text{(A7.1)}$$

Source: Air Transport Association (ATA, 2000) and Energy Information Administration, U.S. Department of Energy (EIA, 1998)

Notes:

1. For the period 1968 to 1979, jet fuel prices are obtained based on crude oil prices. Figure A7.1 shows the relationship between jet fuel prices and crude oil prices during 1980 to 1998. Its regression equation is then used to convert crude oil prices to jet fuel prices for the period 1968 to 1979.

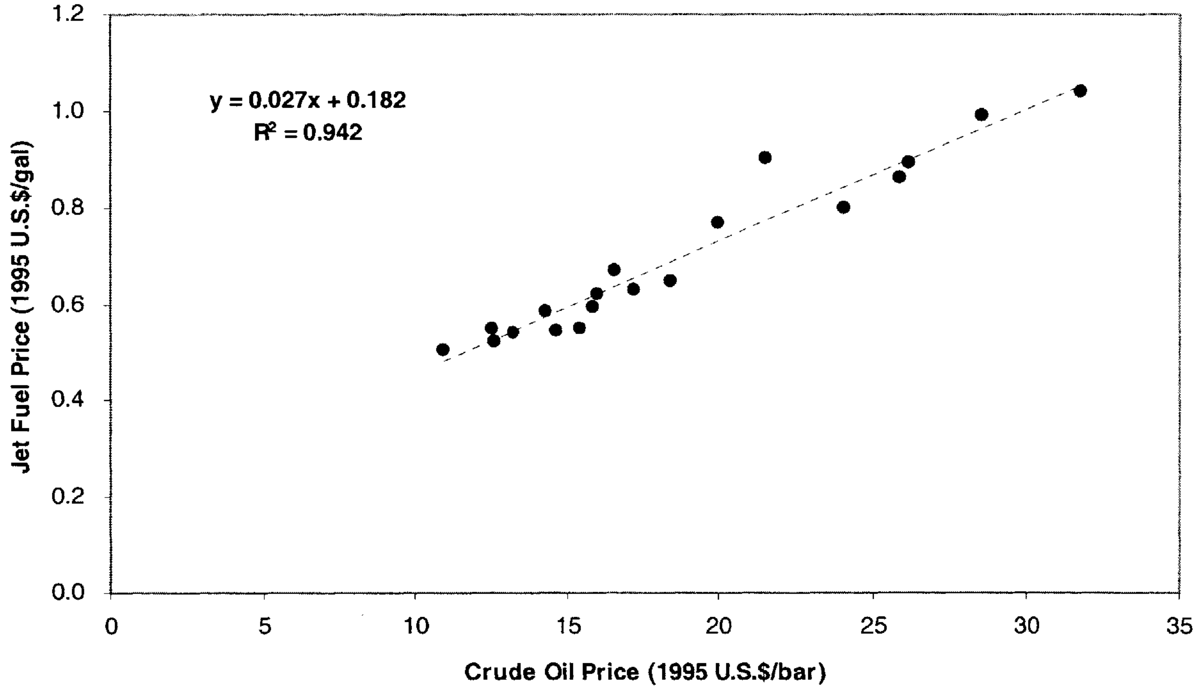

Figure A7.1: Jet Fuel Prices versus Crude Oil Prices during 1980-98

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