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HISTORICAL AND FUTURE TRENDS IN AIRCRAFT PERFORMANCE, COST, AND EMISSIONS

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■ **Abstract** The interdependency of aircraft technological systems, the global reach of the aviation transport industry, and the uncertainty surrounding potential atmospheric effects have made defining the relationship between aviation and environmental impact an arduous task. Air travel continues to experience the fastest growth of all modes of transport, and although the energy intensity of the aviation transport system continues to decline, fuel use and total emissions have steadily risen. This trend, which represents a conflict between growth and environmental impact, has motivated the aircraft manufacturing and airline industries, the scientific community, and governmental bodies to consider what pace of emissions reduction is acceptable. This paper analyzes the historical influence of aircraft performance on cost to examine the potential pace of future efficiency improvements and emissions reduction. Technological and operational influences on aircraft energy intensity are quantified and correlated with direct operating cost and aircraft price using analytical and statistical models built upon historical data for US airlines. The energy intensity reduction potential and economic characteristics of future aircraft are also projected, through extrapolations of historical trends in aircraft technology and operations.

CONTENTS

1. INTRODUCTION

Demand for air transportation closely shadows the rate of increase in wealth, and thus as economies continue to grow, traffic volume burgeons and energy use rises. Increases in aviation emissions parallel increases in energy use. Historically, the alleviation of associated environmental impacts has focused on technological progress toward the mitigation of local air-quality impacts and related health effects. As the geographical footprints of air operations expand, these impacts affect an increasing number of people in a manner that is still essentially regional. However, climate-change impacts associated with aviation emissions have the potential to affect much broader populations. In comparison to the few chemical species currently controlled to preserve local air quality, climate impacts are determined by the atmospheric effects of a larger number of exhaust constituents and are thus intimately related to energy intensity (E_I), a system-wide energy efficiency performance measure. Reducing both climate and local air-quality impacts resulting from aircraft emissions requires consideration of the technological performance of the entire aircraft as well as all operational activities undertaken to fly an aircraft.

The objective of this paper is to characterize the roles of technology and operational practice in determining the emissions performance of the aviation system, concentrating primarily on energy intensity as an aggregate measure of total emissions. A statistical analysis of available data is used to develop descriptions of the historical relationships between technology, operations, and cost. This study focuses on two important areas: the rate of technological and operational change in the context of potential emissions mitigation requirements and the capital costs airlines are willing to endure for energy intensity reductions in commercial aircraft. The historical development of these two figures of merit provides a benchmark from which the impacts of environmental improvements on growth can be assessed and a basis for outlining the technological and operational features that determine the substitution rate of capital for operating costs across the air transport system.

Although regulations have never directly focused on energy use, reducing fuel consumption and increasing passenger load factors (fraction of seats filled) have long been routes to increased profitability, driving energy intensity continually lower. Indeed, manufacturers have provided new technologies that have reduced emissions and achieved the largest reductions in energy intensity of any transportation system (1) at the expense of increased aircraft prices. The costs of further reductions, focused on reducing both local air-quality and climate impacts, have been characterized as obstacles to continued growth. It is within this framework of environmental performance versus growth that both the political and technical questions related to aviation and climate change are currently reconciled.

Pressures for further improvements in the environmental performance of aircraft systems, with respect to both local air-quality concerns and global climate issues, are evident at local, state, and intergovernmental levels. There have been several recent examples of this pressure. Elements of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection, an international regulatory body, have pressed for further stringency in NO_x regulations. Sweden and Switzerland have instituted landing fees based on aircraft NO_x and hydrocarbon (HC) emissions performance at national airports. The proposed PM-2.5 regulations promulgated by the US Environmental Protection Agency (EPA) constitute a potential restriction on aircraft particulate emissions. A recent report issued by the Intergovernmental Panel on Climate Change (IPCC) estimates that the aviation contribution to global warming is 3.5% of the sum of all anthropogenic impacts and projects that this contribution will grow (2). The proposed Kyoto Protocol to the United Nations Framework Convention on Climate Change specifically requests that industrialized countries reduce emissions from aviation bunker fuels.

These pressures are met with varying degrees of optimisim regarding the potential that changes in technology and operations have for making effective progress. Although reducing energy intensity tends to reduce overall emissions, there are barriers inherent to air transportation that can act counter to the realized benefit. Reductions in emissions are hindered by the relatively long lifespan and large capital cost of individual aircraft and the resulting lag in the adoption of new technologies throughout the aviation fleet. In improving the performance of technologies that are adopted, trade-offs are inevitable. For example, increasing the efficiency of new engines may increase NO_x emissions as a result of higher peak engine temperatures. Also, the impact of any efficiency improvement is diminished by fuel wasted in airborne- or ground-travel delays or in flying partially empty aircraft. Furthermore, we do not know the cost of change.

Although this review does not venture to determine what rate of technological change is economically sustainable or environmentally beneficial, it is important to place the historical pace of change in the context of current projections for future emissions growth. The perspective this exercise provides is a crucial element in any dialogue that considers particular levels and timetables for reductions. Our analysis indicates that a continuation of the historical trends in technology, aircraft operations, and air-traffic management (ATM) would result in a future decline in E_I [e.g., megajoules per revenue passenger kilometer (RPK)] of 1.2%–2.2% per year over the next 25 years and a decline of 1.0%–2.0% per year in energy usage [e.g., megajoules per available seat kilometer (ASK)]. In comparison, estimates of future air-traffic growth are variously placed at 4%–6% per year. As a result, expected improvements in aircraft technologies and operational measures alone are not likely to offset more than one third of total emissions growth, and effects on the global atmosphere are expected to increase in the future in the absence of additional measures.

An interpretation of the analysis presented in this review relies on an informed understanding of the context in which the questions addressed by this study have been raised. This is the topic of Section 2, where key elements of the aviation-environment relationship are discussed. Section 3 outlines the analytical and informational bases for the simplified relationships developed in this study that connect the evolution of aircraft technology with the development of improved operational methods. Section 4 reviews historical trends in aircraft performance and cost. Section 5 develops a parametric relationship that reveals the consequences of technological and operational change on the cost of operating an aircraft and the purchase price of new aircraft. Section 6 assesses the fuel burn reduction potential of future aircraft systems. A summary is presented in Section 7.

2. AIR TRANSPORTATION AND THE ENVIRONMENT

Efficient approaches to counteracting increases in emissions rely on a clear understanding of the relationship between air transportation activities and emissions. Section 2.1 discusses trends in the demand for air transportation and Section 2.2 reviews the rationale behind historical and current policy responses to emissions impacts. To the extent that it motivates this study as well as the interests of scientists and policy makers alike, Section 2.3 reviews the current state of knowledge with regard to global aviation impacts, including effects on radiative forcing and upper-atmospheric ozone depletion. The relationship between technology and emissions is described and trends in technology that impact emissions are discussed.

2.1. Demand for Air Transportation

The long-term evolution of transportation systems is characterized by a continuous substitution of transport modes by those that better fit the economic and societal needs at any given time. A common characteristic of this substitution pattern is that the mean door-to-door speed of a new mode will exceed that of a previously dominant mode. In passenger transport, low-speed railways have been replaced by faster buses, and the latter by quicker automobiles. For intercity travel, automobiles are being replaced by high-speed transportation systems, mainly aircraft, which are already the dominant mode of transport for trip distances above 1000 km, a threshold distance that is likely to further decline (3).

Rising demand for mobility per capita is well correlated with growth in gross domestic product (GDP) per capita across a wide variety of economic, social, and geographic settings. One reason for this may be found in the roughly constant shares of income and time people dedicate to transportation (4). A fixed percentage of personal income devoted to mobility (the travel-money budget) leads to an increase in total travel demand per capita [e.g., passenger kilometers (PKM) per capita] in approximate proportion to income. In addition, it is observed that a person spends an average of 1.0–1.5 h a day traveling (the travel-time budget). Travelers shift toward faster modes as their travel demand increases (5) and as a result, continuing growth in world population and income levels can be expected to lead to further demand for air travel, in terms of both market share and PKM.

Figure 1 shows historical trends and a projection of future modal traffic volume for automobiles, buses, railways, and high-speed transport (mainly aircraft) for the world, as an aggregate of 11 regions (5). This projection indicates that compared with the 1990 level, world passenger traffic volume will multiply by more than a factor of 2 in the year 2020 and by a factor of 4 by 2050. Because of the high

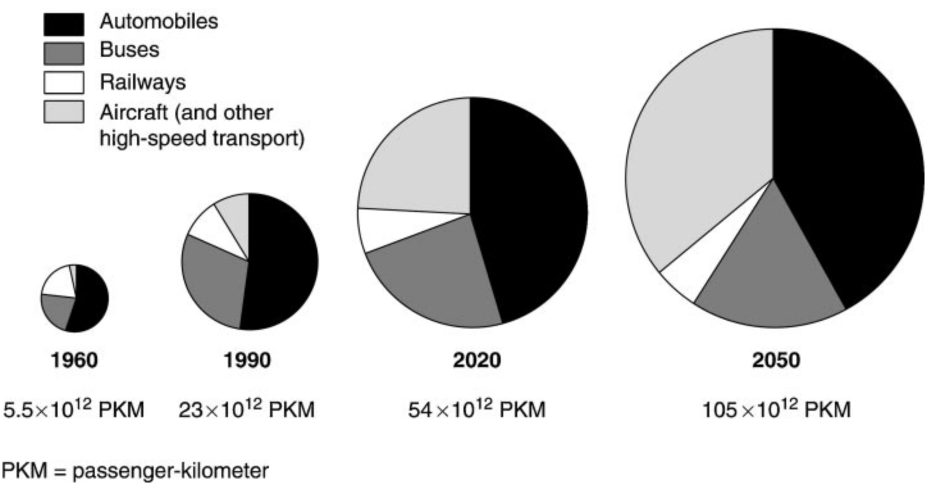

Figure 1 Passenger traffic volume by major mode of transport in 1960 and 1990 and projections for 2020 and 2050. Air travel and other high-speed transport accounted for 2% of world passenger traffic volume in 1960 and for 9% in 1990 and are projected to account for almost 25% in 2020 and 36% in 2050. The underlying gross domestic product growth rates are a hybrid of the Intergovernmental Panel on Climate Change (IPCC) midrange economic growth (IS92a) and high growth (IS92e) projections (7). The average travel-time budget was selected to be 1.1 h/capita/day. [From Schafer & Victor (5).]

per-capita traffic volume in several world regions, which culminates at almost 60,000 PKM/capita per year in North America, high-speed transportation is expected to play an increasingly important role and may account for slightly more than one third of world passenger traffic volume in 2050.

Figure 2 summarizes world economic and air transport sector growth forecasts conducted by major aircraft manufacturers (8, 9), government organizations (2, 7, 10, 11), industry groups (12), and academia (5). As mentioned previously, a higher economic growth rate results in higher air passenger and cargo growth rates. One primary difference between the projections shown in Figure 2 is the relationship between economic and aviation transport growth that is assumed. For example, the IPCC traffic demand forecasts (2) are based on a historical correlation between GDP and aviation transport growth. In contrast, Schafer & Victor (5) employ an aggregate model based on behavioral patterns and constraints resulting from land use and infrastructure turnover rates. Note that demand for freight transportation is expected to grow even faster than passenger travel but will still account for $<10\%$ of aircraft-ton kilometers.

Growth in transportation volume strongly influences potential environmental impact. Although fuel efficiency gains due to technological and operational change can mitigate this influence, demand growth remains the fundamental driver of the total mass of emissions. In 1990, 2.4% of the total fossil fuel used worldwide was burned for air transportation (2). This is approximately 12% of the total fuel used by the transportation sector, second only to road transportation (6, 13). As a whole, transportation accounts for approximately one quarter of the total fossil fuels used worldwide. In comparison to emissions from general aviation and military aircraft, emissions from the commercial air transportation fleet (passenger and cargo) currently constitute over 80% of the total emissions from aircraft worldwide, a figure that is projected to exceed 90% over the next 15 years (2).

To provide estimates of future emissions, methodologies have been developed to merge forecasts of operational and technological change with traffic growth projections in order to estimate future total fuel use and emissions. Previous studies of technological change have employed three methods, or more typically a combination thereof, to determine future trends in aviation system performance. Component efficiencies for an aircraft system, derived from expert or data-driven research and development technology assessments, are used to construct bottom-up engineering estimates of future aircraft efficiency (2, 14, 15, 21; see also 21a).[1] Top-down analyses of historical data, used to formulate best guesses or statistical correlations, provide an aggregate measure of efficiency improvement (2, 16–20)

[1]Additional information for this review has been obtained from unpublished, internal studies conducted by NASA and the Dutch Civil Aviation Department. In particular, we present NASA estimates for future aircraft energy usage as a function of size category provided by the NASA Glenn Research Center Propulsion Systems Analysis Office and the NASA Langley Research Center Systems Analysis Branch, and a Dutch Civil Aviation Department study initiated in 1994 entitled Aviation Emissions and Evaluation of Reduction Options.

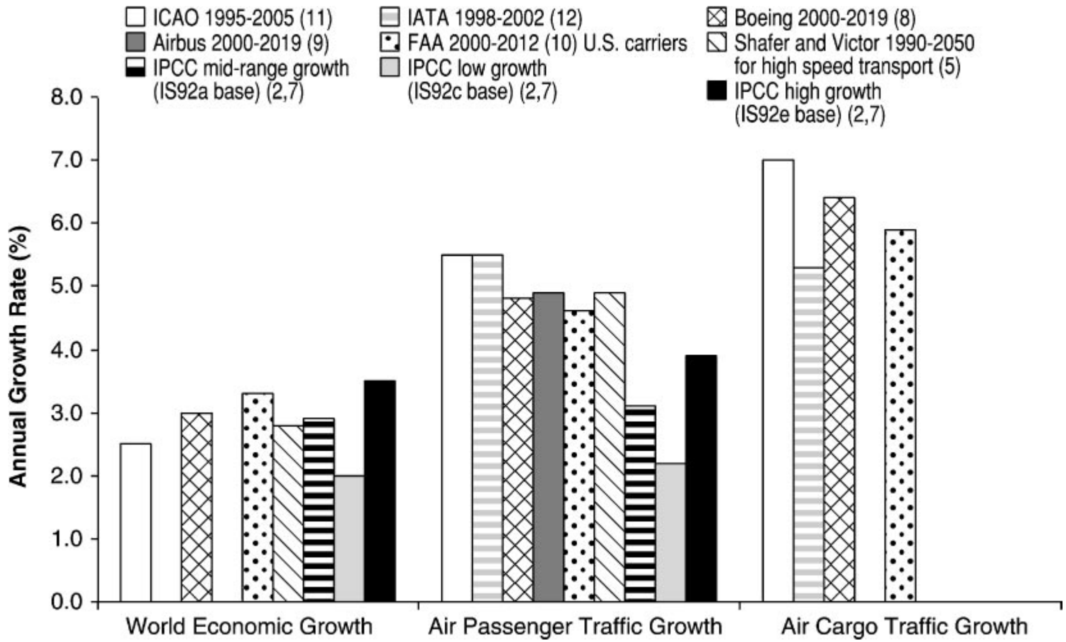

Figure 2 Gross domestic product and air-traffic growth forecasts. ICAO, International Civil Aviation Organization; IATA, International Air Transport Association; FAA, Federal Aviation Administration; IPCC, Intergovernmental Panel on Climate Change.

(see footnote 1). Often, these approaches are supplemented by meta-analyses of the available literature (22).

Long-term projections of emissions from passenger air traffic to the year 2050 as reported elsewhere (2) are summarized in Figure 3, with a comparison to other results (6), which forecast all high-speed transport, both aviation and high-speed rail. Compared with the early 1990s, global aviation fuel consumption and subsequent CO_2 emissions are expected to increase three- to sevenfold by 2050, equivalent to a 1.8%–3.2% annual rate of change. In addition to the different demand growth projections entailed in these forecasts, which account for most of the variability in the projected emissions, some variability also originates from different assumptions about aircraft technology, fleet mix, and operational evolution in ATM and scheduling. Most forecasts reflect a large improvement in NO_x reduction technology, an effort some people believe will slow efficiency gains in the future (2). A comparison of estimates of future efficiency change and historical trends in Section 4 indicates that most assumptions for the rate of E_I reduction are optimistic.

2.2. Decision-Making Mechanisms for Emissions Control

Reduction of fuel costs has traditionally been a driving influence behind the development of more fuel-efficient aircraft. Environmental issues have been less influential, but the confluence of the two issues with respect to climate change has drawn increased attention to the rapid increases in air-travel demand, fuel consumption, and emissions (e.g., see 23, 24). The impetus for establishing US national regulations for aircraft emissions originated not at the federal level but rather through a recognition that the effects of emissions on air quality, addressed initially by local and state actions (25), would be more efficiently addressed uniformly and, thus, federally. Through the 1970 Clean Air Act, Congress provided a foundation for the control of emissions from aircraft engines and erected the institutional structures through which regulations would be established and enforced. Responsibility for setting aircraft emission standards was delegated to the EPA, and enforcement and safety responsibilities were delegated to the US Department of Transportation (DOT) (26). Regulations were promulgated in 1973 (27, 28) for the control of fuel venting, smoke, HC, CO, and NO_x for several classes of subsonic aircraft engines. Controls were (and still are) based on a landing-take-off cycle that extends to an altitude of ~915 m (3000 ft), as represented by specified times in operating modes defined by engine power setting. Emissions above 915 m, where aircraft spend most time in flight, were not (and still are not) controlled. The Federal Aviation Administration (FAA) promulgated certification requirements for aircraft engines in 1974 (29), and in 1990, these certification requirements were codified as federal regulations.

The legal framework provides specific guidance to base regulatory action on the state of technology with regard to safety, developmental capability, and air-quality goals. Pressure for emissions improvement is on manufacturers in the design and retrofit of aircraft engines. To preclude problems with increasingly

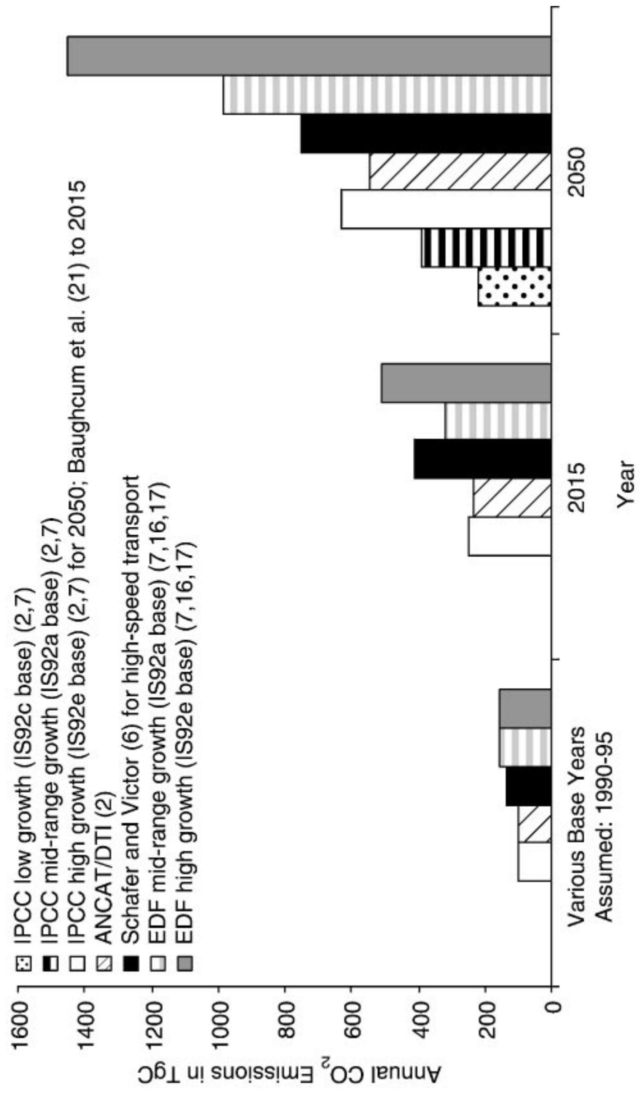

Figure 3 Fleet CO_2 emissions forecasts for passenger air traffic. IPCC, Intergovernmental Panel on Climate Change; ANCAT/DTI, Abatement of Noises Caused by Air Transport/U.K. Department of Trade and Industry; EDF, Environmental Defense Fund.

diverse regulatory systems for emissions among nations, the EPA worked through the ICAO to develop international standards (30), which were instituted in 1981 as Annex 16 to the Convention on International Civil Aviation. ICAO standards are not binding to any signatory to the Convention, but signatories are urged to pursue uniformity in application and to report any differences. However, local actions, such as the emissions-based landing charges instituted in Sweden and Switzerland, still have an impact on emissions decision making. US regulations were brought into agreement with ICAO Annex 16 in 1997 (31; see also 31a). The ICAO Committee on Aviation Environmental Protection, charged with developing emissions regulations, has made it clear that emissions regulations will be made stricter only when the need is recognized, the move is technically feasible, and the impacts economically fair (32).

It is possible that the rules and assumptions employed in current decision-making mechanisms will be perpetuated if climate-related emissions are incorporated into a broader control framework. In this context, understanding the pace of efficiency change and the balance of technology renewal and cost will be paramount. The diverse and sometimes contradictory effects of aircraft emissions, as described below, make reconciling the local air-quality focus of current regulations with the global effects of climate impacts a difficult task. The pace of improvement in E_I, to which reductions in smoke, CO, and HC emissions contribute, are inherently driven by fuel cost considerations within the airline industry and run counter to efforts to control NO_x. Thus, there is a reluctance to add controls or to change the focus of current emissions without adequate understanding of the magnitude and nature of the related atmospheric impacts.

2.3. Aviation and the Global Atmosphere

Because the majority of aircraft emissions are injected into the upper troposphere and lower stratosphere (typically 9–13 km in altitude), the resulting impacts are unique. The fraction of these emissions that is relevant to atmospheric processes extends far beyond the radiative effects of CO_2. In fact, the mixture of exhaust species discharged from aircraft perturbs radiative forcing two to four times more than if the exhaust were CO_2 alone (2). In contrast, the overall radiative forcing from the sum of all anthropogenic activities is estimated to be a factor of 1.5 times CO_2 alone (2). Thus the impact of burning fossil fuels at altitude is approximately double that due to burning the same fuels at ground level. The enhanced forcing due to aircraft compared with ground-based sources is due to different physical (e.g., contrails) and chemical (e.g., ozone formation/destruction) effects resulting from altered concentrations of participating chemical species and changed atmospheric conditions.

Of the exhaust emitted from the engine core, 7%–8% is composed of CO_2 and H_2O, with another 0.5% composed of NO_x, HC, CO, SO_x, other trace chemical species, and carbon-based soot particulates. The balance (91.5%–92.5%) is composed of O_2 and N_2. Emissions of CO_2 and H_2O are products of hydrocarbon fuel combustion and are thus directly related to the aircraft fuel consumption, which in turn is a function of the weight, aerodynamic design, and engine performance of the aircraft. Emissions of NO_x, soot, CO, HC, and SO_x are further related to the manner in which fuel is combusted within the engine and, to some extent, to post-combustion chemical reactions occurring within the engine. These emissions are thus primarily controlled by the engine design, but total emissions can be reduced through improvements in fuel efficiency. Such emissions are therefore typically quoted relative to the total amount of fuel burned as an emission index (e.g., g of NO_x/kg of fuel).

It is important to note that reductions in E_I do not always directly imply lower environmental impact. For example, the prevalence of contrails is enhanced by greater engine efficiency (33, 34). Engine efficiency improvements increase the relative humidity of the exhaust plume because as efficiency increases, reductions in plume temperature are greater than the corresponding reduction in H_2O concentration. As shown below, increases in contrails can, in turn, increase radiative forcing and thus climate impacts. Furthermore, NO_x emissions become increasingly difficult to limit as engine temperatures and pressures are increased—a common method for improving engine efficiency (2).

The mode and scope of impact from an exhaust species are associated with the altitude of deposition and residence time in the atmosphere. Impacts from these species can occur through several mechanisms: direct alterations to the chemical composition of both the troposphere and stratosphere, effects on atmospheric chemistry that can lead to changes in atmospheric chemical composition, changes in particulate and aerosol levels, the creation of contrails in the troposphere (some of which may persist and mutate into cirrus clouds), and changes to existing cirrus cloud cover. Local air-quality concerns, which focus on a subset of the exhaust species (NO_x, HC, CO, SO_x, and particulates), are associated with the direct impact of individual species on human and ecosystem health, the combined effects of exhaust components on local ozone levels, contributions to acid rain, and associated welfare impacts, such as reduced visibility. The processes that contribute to local air-quality changes constitute a subset of the atmospheric processes that lead to regional and global impacts, which are associated with an overlapping set of exhaust species (CO_2, H_2O, NO_y, SO_x, and particulates). Regional and global effects involve changes to the radiative forcing of the atmosphere, which can alter climate, and changes to atmospheric ozone levels, which lead to alterations in the transparency of the atmosphere to ultraviolet-B radiation.

Figure 4 shows recent IPCC (2) estimates of the radiative forcing by various aircraft emissions for 1992 and projections for the year 2050. Radiative forcing is a measure of the change in Earth's radiative balance associated with atmospheric changes. Positive forcing indicates a net warming tendency relative to preindustrial times. The forcing estimates shown in Figure 4 translate to an estimated 3.5% of the total anthropogenic forcing that occurred in 1992 and to an estimated 5% by 2050 for an all-subsonic fleet. As a result, aircraft are expected to account for 0.05 K of the 0.9 K global mean surface temperature rise expected to occur between 1990 and 2050. Associated increases in ozone levels are expected to decrease the amount of ultraviolet radiation at the surface of the earth. The scenarios shown are based on emissions inventories estimated for 1992 (21; see also 21a), with projected traffic

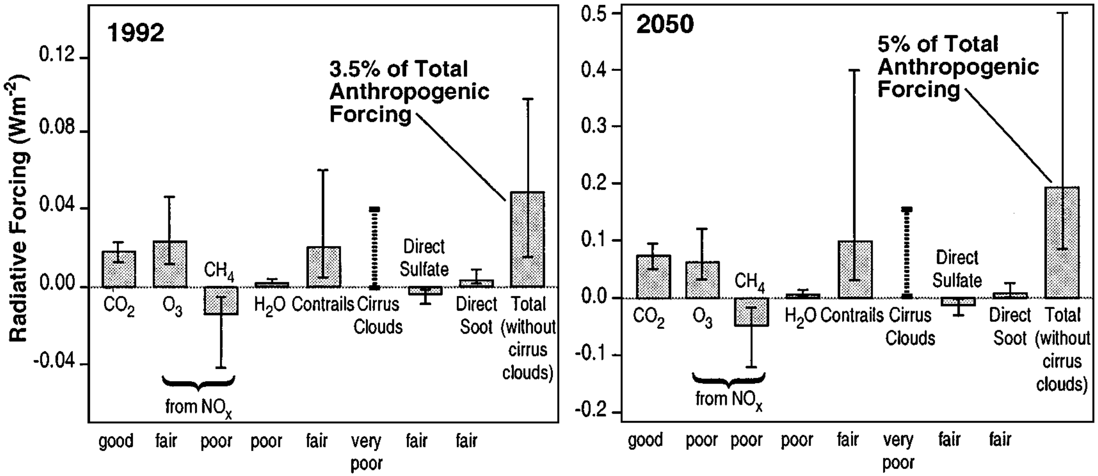

Figure 4 Radiative forcing estimated for 1992 (+0.05 W/m^2 total) and projected to 2050 (+0.19 W/m^2 total). Note differences in scale. Note also that the heavier dashed bar for aviation-induced cirrus cloudiness describes the range of estimates, not the uncertainty. The level of scientific understanding of this potential impact is very poor and no estimate of uncertainty was made. [From Penner et al. (2).]

growth to 2050 based on world GDP growth as projected in a midrange economic growth scenario (IPCC IS92a) (7). For both 1992 and 2050, it is estimated that there is a 67% probability that the value for radiative forcing falls (or will fall) within the range indicated by the error bars. Thus, for 2050 it is likely that the radiative forcing due to aircraft may fall between 2.5% and 13.2% of the total forcing due to man. The notations below the 1992 graph indicate the level of scientific understanding for the impact of each exhaust species. Note that lower or higher demand scenarios would lead to decreases or increases, respectively, in the forcing estimates.

There is concern among aircraft manufacturers and operators that mitigating aircraft emissions may be more costly than equivalent emissions in other economic sectors, partially because of the complexity of the atmospheric effects represented in the estimates shown in Figure 4. The exhaust concentrations of individual species, some of which exist at the level of parts per million or parts per billion, belie their relative importance to atmospheric processes. Sulfur species, for example, are typically emitted in single-digit parts-per-million levels but are believed to influence contrail, direct sulfate, and cirrus cloud impacts. In addition, the impacts of various species are also the synergistic sum of many atmospheric processes. NO_x, for example, leads to a production of ozone in the troposphere and lower stratosphere, which contributes to radiative forcing. However, NO_x depletes ozone at locations higher in the stratosphere. Thus, there is a differentiation between aircraft that fly at high altitude (supersonic aircraft) and those at lower altitude (the current commercial fleet). Also, although NO_x from the current commercial fleet is a contributor to increased tropospheric ozone levels and, thus, increased radiative forcing, it also leads to reductions in atmospheric methane, which acts to reduce radiative forcing. Furthermore, the former impact occurs at a regional level, whereas the latter is felt globally because methane has a much longer characteristic residence time in the atmosphere. Thus the two effects, even though opposite in sign, do not cancel each other.

Despite this complexity, potential for reductions in emissions continues to command attention. From the perspective of air-quality improvement, reductions of emissions from airports are important to the attainment of ozone regulation compliance in many regions of the United States (23). Globally, per-unit reductions in aviation emissions may be relatively more effective in combating climate change than equivalent emissions from ground sources. The rest of this review addresses the particular balance of cost and emissions reduction potential embodied by proposals to improve system energy-use efficiency.

3. ANALYSIS APPROACH AND INDUSTRY DATA

Trends in the technological and operational characteristics of future aircraft are crucial elements in assessing plausible future emissions levels and in determining the potential cost of reductions. In later sections, statistically significant relationships between historical trends in aircraft propulsion, aerodynamic, and structural technologies as well as aircraft direct operating costs (DOC) and prices are derived. In Section 3.1, we give an overview of the methodology used to determine these relationships. Sections 3.2 and 3.3 detail the sources for and important features of the data used in the analysis.

3.1. Analysis Approach

Historical trends in air transportation energy intensity (E_I) depend on the physical determinants of aircraft operation and on consumer demand for air travel. One basic model useful in describing the mechanics of a commercial aircraft in flight is the Breguet range (R) equation.

$$R = \frac{V(L/D)}{g \cdot \mathrm{SFC}} \ln \left[1 + \frac{W_{\mathrm{fuel}}}{W_{\mathrm{payload}} + W_{\mathrm{structure}} + W_{\mathrm{reserve}}} \right]. \qquad 1.$$

In this equation, propulsion, aerodynamic, and structural characteristics are represented by three parameters: specific fuel consumption (SFC), lift-to-drag ratio (L/D), and structural weight ($W_{\mathrm{structure}}$). Given these technological characteristics as well as other operability parameters, including the amount of payload (W_{payload}) and fuel on board (W_{fuel}), the Breguet range equation can be used to determine maximum range for a level, constant speed flight. Because SFC, L/D, and speed (V) are assumed to be constant during the flight, the take-off, climb, and descent portions of flights are not well represented. However, application of the Breguet range equation is a useful predictor of fleet operation.

The Breguet range equation can be reorganized to obtain an equation for aircraft energy usage (E_U) in terms of fuel burn or energy per ASK. In this formulation, the influence of aircraft capacity is explicitly included. With further modification, E_I can be expressed in terms of fuel burn or energy per RPK (E_I) through inclusion of the load factor (fraction of seats filled), a measure of capacity utilization. The E_I can be further modified to include the effects of other inefficiencies in utilization, such as ground and flight delays. When all of these effects are included, E_I can be directly translated into aircraft emissions characteristics and can be used as a rough surrogate for technology maturity and operational efficiency. In Section 5, quantitative relationships between system E_I and both DOC and market price of aircraft are derived through a statistical analysis. Extrapolations of historical trends in technological and operational improvements are then employed to determine the potential DOC and prices of future aircraft systems.

3.2. Aircraft Studied and Technological Data

To provide the system performance inputs required in the construction of the technology-cost relationships, a historical database of aircraft technology, performance, operations, and cost data was assembled. The subject of this study is restricted to aircraft in the US domestic fleet operating both domestic and international flights. Thirty-one commercial passenger aircraft were selected to represent the US fleet (10, 35, 36). These 31 aircraft, introduced between 1959 and 1995, reflect the evolution of technology since the beginning of the commercial jet aircraft era and closely match the evolution of average E_I for the entire fleet. Over 85% of the total sum of these aircraft in the fleet are owned and operated by the 10 major US passenger airlines.[2] The combination of US airlines and associated aircraft types represented by these 31 aircraft cover between 50%–85% of all domestic/international RPK by all aircraft types operated by all US carriers since 1968.

Because technological and economic characteristics vary among different classes of aircraft (e.g., short-range versus long-range), the selected fleet is divided into two groups. An average stage length of 1600 km and a seating capacity of 150 typically divide short-range and long-range aircraft. For in-production aircraft, the dividing range and seating capacity are somewhat larger. The engine/planform configuration also provides a useful guideline for aircraft categorization. In general, two-engine, narrow-body aircraft are short-range jets, whereas three- or four-engine, wide-body aircraft are long-range jets, although several two-engine aircraft (e.g., B767, B777, and A330) are considered long-range.

Cruise SFC data were obtained from published compilations by Gunston (37) and Mattingly (38) and were calculated by interpolating from information on fuel flow as a function of power setting as compiled by ICAO (39, 40). An average SFC value over all available engines for a specific aircraft (e.g., the B777) was used to formulate a value of SFC attributable to each aircraft type. The estimated 95% confidence interval in SFC is $\pm 7\%$, based on the comparison of ICAO (39) and Gunston (37) data. The SFC data were informally checked with industrial sources for veracity, and it was confirmed that all actual SFC values fall within this bound.

Data for L/D were obtained from NASA studies (41) and calculated, when unavailable, using the systems model presented by Hasan (15). Further L/D values were obtained through communication with industrial sources, and it was confirmed that the L/D values used are correct within ± 1, which corresponds roughly to an error of $\pm 18\%$.

The ratio of aircraft operating empty weight (OEW) to maximum take-off weight (MTOW) was used as a measure of structural efficiency. This is a measure of the weight of the aircraft structure relative to the weight it can carry (the structure itself + payload + fuel). Aircraft weight (OEW and MTOW) were obtained from Thomas & Richards (35) and Jane's Information Group (42). The error in specification of $W_{\text{structure}}$ is estimated to be $\pm 5\%$, based on assessments by the authors. Although aircraft structural weights vary for the same type of aircraft depending

[2]The DOT defines major airlines as those with annual operating revenues exceeding $1 billion. As of the end of 1998, the 10 major US passenger airlines were Alaska, America West, American, Continental, Delta, Northwest, Southwest, Trans World, United, and US Airways. Pan American World Airways is added for the years 1968–1989 because it was a large operator of long-range aircraft in that period. Also, the A310, A330, and A340 are used within the United States but are not used by these airlines.

on configuration modifications, a comparison of weight reported by the two sources (35, 42) points to a small error in the specification of structural weight. Reported W_{fuel} and $W_{payload}$ are assumed to be accurate within $\pm 5\%$ (40). Federal air regulations specify that a 30- to 45-min fuel reserve must be loaded onto an aircraft for a flight (43). A 40-min fuel reserve was assumed. Using this value, the error in fuel reserve, $W_{reserve}$ is assumed conservatively to ± 10 min or 25% of the fuel reserve. In the performance of a flight, reserve fuel is an extra weight, as it is typically not used during a flight.

Further variability in the specification of technology parameters derives from changes during a flight. For example, SFC and L/D are not constant during a flight and may deviate from cruise by as much as 50% at take-off. Furthermore, reported parameters are for new aircraft, and usage leads to degradation in engine and aircraft performance (e.g., 44). Variations in weight due to fuel burn are accounted for in the Breguet range equation.

3.3. Traffic and Cost Data

Detailed traffic and cost data for all aircraft operated on domestic and international routes by all US carriers since 1968 was obtained from DOT Form 41 (36). Schedule T-2 reports various traffic statistics, including RPK, ASK, airborne hours, block hours (time from when the blocks are removed from behind the wheels prior to taxiing to when they are replaced after the flight), and fuels issued. Based on this information, further operating statistics, such as load factor and fleet size, were calculated. Explicit values of fuel reserve are not reported apart from total fuels issued. Schedule P-5.2 reports economic data. Cost data in schedule P-5.2 is divided into those categories associated with direct operating costs (DOC) and investment-related costs (I). DOC + I is composed primarily of four major cost categories: crew (~20%), fuel (~20%–25%), maintenance (~15%), and investment or ownership (~25%).[3] 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. The rest of DOC + I is accounted for by other flying operations and maintenance costs, including taxes, aircraft interchange charges, and outside repairs. Figure 5 shows the historical development of DOC + I over the past three decades. Note that DOC + I accounts for roughly 55% of an airline's entire operating budget while the other half of the operating budget consists of indirect operating cost elements, such as ticket commissions, ground operations, various fees, and administrative costs.

Because ownership costs vary significantly from airline to airline, depending on accounting practices and financing rates at the time of purchase, a more transparent measure for the investment portion of DOC + I is the actual market prices airlines

[3]Percentages based on the period 1990–1998. Although crew costs include both pilot and flight attendant salaries, the latter are not classified as part of DOC + I in the Form 41 standard. The subsequent analysis considers only pilot salaries as crew cost.

pay for aircraft. Annual transaction prices of aircraft were taken from Thomas & Richards (35).[4] Reported prices are average market values paid in then-year dollars for new airplanes at the time of purchase. All prices were discounted to 1995 dollars using GDP deflators. DOC data as well as price data are also subject to fluctuations in the economy, and thus, the cost data used in this study represent an aggregated measure of value that may vary from airline to airline. All operating costs were discounted to 1995 dollars using GDP deflators. Variability also exists in Form 41 traffic data. Airlines operate aircraft under different conditions, so performance can be quite dissimilar for the same type of aircraft.

4. HISTORICAL TRENDS IN AIRCRAFT PERFORMANCE AND COST

Historically, air-traffic growth has outpaced both operational and technological improvements in the efficiency of energy use, a common trend seen across many industries. Although as new models are introduced, individual aircraft tend to be more fuel efficient with time, total emissions resulting from flight traffic have increased. The cost of affecting such changes under the constraints of budget priorities generally controls their introduction, even though efficiency improvements can be economically beneficial over the longer term. The following sections review the history of trends in energy intensity (Section 4.1), the technological and operational drivers of efficiency improvements (Section 4.2), and the development of operating costs and aircraft prices (Section 4.3).

4.1. Historical Trends in Energy Intensity

Using E_I as the figure of merit relative to total emissions, the most convenient unit of technology is the system represented by a complete aircraft. Figure 6 shows historical trends in the E_I of the US fleet and for individual aircraft by year of introduction. Aircraft E_I ranges are based on operating data for the period 1991–1998 with the exception of the B707 and B724, which are computed with operational data prior to 1991. Year-to-year variations in E_I for each aircraft type, due to different operating conditions, such as load factor, flight speed, altitude, and routing controlled by different operators, can be $\pm 30\%$, as represented by the vertical extent of the data symbols. A combination of technological and operational improvements has led to a reduction in E_I of the entire US fleet of more than 60% between 1971 and 1998, averaging about 3.3% per year. In contrast, total RPK has grown by 330%, or 5.5% per year over the same period. Figure 6 shows that the average E_I of the part of the fleet composed of the 31 aircraft types used for the analysis is approximately the same as that of the entire US fleet. Long-range

[4]Note that during the period 1972–1985, the prices listed for the 747-200B in Thomas & Richards (35) exceeded catalog prices by as much as 80%. Data (35) for the 747-200B over this time period were replaced with the catalog prices.

aircraft are $\sim$5% more fuel efficient than short-range aircraft because they carry more passengers over a flight spent primarily at the cruise condition.

The economic lifespan of an aircraft in the fleet—the time between when the aircraft is purchased until its eventual retirement—is typically 20–25 years but can extend to 35 years. The lifetime of an aircraft family—a set of aircraft with similar basic designs but differentiated by incremental changes, such as a stretch to include additional seats—is longer. Although the production of many aircraft has been ended, of the aircraft we have studied only the B707 and B720 have been retired from the United States since 1959, and no technological generation has been lost within the commercial aviation fleet. New aircraft models within the same family are introduced every 3–5 years for short-range aircraft and less often for long-range aircraft, with updated features more sporadically introduced in response to operational issues (e.g., new engines, winglets, etc.).

The lag in technology introduction is apparent in Figure 6. It has typically taken 10–15 years for the US fleet to achieve the same fuel efficiency as that of newly introduced aircraft. Apart from in-use aircraft performance improvements, the rate of improvement in the average E_I is determined by the gradual adoption of new, more fuel-efficient aircraft into the existing fleet. This process of technology uptake depends on various cost factors and market signals (10). The limitations on this process imposed by cost factors are considered in following sections. 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. Furthermore, the development programs for new aircraft typically begin 7–10 years before the inaugural aircraft is certified, and basic research required to support the new technology typically precedes the beginning of the development programs by several years. Thus, the time required for ideas to make the transition from basic research to fleet impact can be as much as 25 years.

4.2. Historical Trends in Aircraft Technology and Operability

Technologically, the basic geometry of commercial jet aircraft has remained the same for the past 40+ years, and performance changes over this period have been incremental. Figures 7*a*, 7*b*, and 7*c* show historical trends for SFC, L/D, and OEW/MTOW, averaged for an aircraft type where applicable, by year of introduction. As expressed in the Breguet range equation, efficiency improves with lower SFC, lower weight ratio, and greater L/D. Engine efficiency (Figure 7*a*), as measured by the cruise SFC of newly introduced engines, has improved by approximately 40% over the period 1959–1995, averaging an annual 1.5% improvement. Most of this improvement was realized prior to 1970, with the introduction of high bypass engines. However, as bypass ratios have increased, engine diameters have also become larger, leading to an increase in engine weight and aerodynamic drag. Other routes to engine efficiency improvement include increasing the peak temperature within the engine, which is limited by materials and cooling technology, increasing pressure ratio, and improving engine component efficiencies.

Aerodynamic efficiency (Figure 7*b*) has increased by approximately 15% historically, averaging 0.4% per year for the same period. Better wing design and improved propulsion/airframe integration, enabled by improved computational and experimental design tools, have been the primary drivers (2, 22). Historical improvements in structural efficiency (Figure 7*c*) are less evident. One reason is that over the 35-year period between the introduction of the B707 and the B777, large commercial aircraft have been constructed almost exclusively of aluminum and are currently about 90% metallic by weight. Composites are used for a limited number of components. Another reason is that improvements in aircraft weight have been largely traded for other technological improvements and passenger comfort (22).

Indeed, in viewing these technology trends it is important to note that engine, aerodynamic, and structural efficiencies are interdependent. For example, as much as half of the efficiency improvement associated with higher efficiency engines can be lost on installation on the aircraft because of negative weight and aerodynamic effects (e.g., more-efficient, higher-bypass-ratio engines have higher drag, thus negatively impacting L/D). Furthermore, requirements for noise reduction tend to favor higher-bypass-ratio engines, exacerbating negative effects on aerodynamic and structural efficiencies, sometimes at the expense of overall aircraft efficiency.

Aircraft E_I is also improved through better utilization (e.g., load factor) and greater per-aircraft capacity (e.g., number of seats). Trends in these parameters are shown in Figure 8. Historically, the load factor on domestic and international flights operated by US carriers has climbed 15% between 1959 and 1998, all of which occurred after 1970 at an average of 1.1% per year. Load factor gains have been attributed to deregulation in US and global air travel liberalization, both of which contributed to the advent of hub-and-spoke transportation systems (46). As

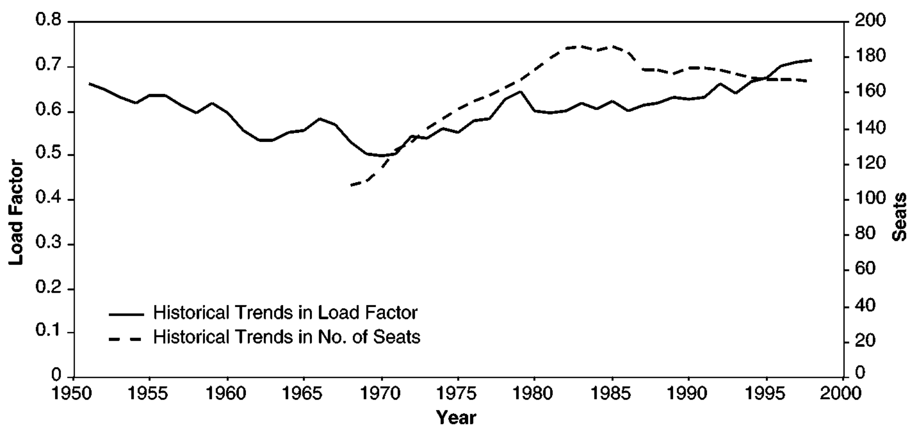

Figure 8 Historical trends in load factor and seating capacity. [From the Air Transport Association load factor database for scheduled US airlines to 1968 and from DOT beginning 1968 (36).]

airlines have sought greater route capacity, the average number of seats has also increased, by 35% between 1968 and 1998, from 108 to 167 seats (an average of 1.4% per year), most of which occurred prior to 1980.

Infrastructure characteristics also impact efficiency. In particular, delays on the ground and in the air can increase E_I. Extra fuel is burned on the ground during various nonflying operations, and hours spent in the air (airborne hours) do not account for more than 0.75–0.9 of the total operational hours of the aircraft (block hours). The ratio of airborne to block hours can be treated as a ground-time efficiency (η_g). Similarly, noncruise portions of the flight, poor routing, and delays in the air constitute inefficiencies related to spending fuel during the flight beyond that which would be required for a great circle trip at constant cruise speed. This inefficiency can be measured by the ratio of minimum flight hours to airborne hours (η_a). Minimum flight hours represents the shortest time required to fly a certain stage length and reveals any extra flight time due to nonideal flight conditions. The multiplication of η_g and η_a gives the flight time efficiency (η_{ft}). Historical trends for η_g, η_a, and η_{ft} presented in Figure 9 show constant air-traffic efficiencies since 1968. One can speculate that these constant trends result from a balance between increasing ATM capabilities and an ever-increasing capacity demand.

4.3. Historical Trends in Direct Operating Cost and Price

E_I influences aircraft operating costs and prices. Profit maximization behavior among airlines has translated into demand for more fuel-efficient aircraft technologies as well as for improvements in the way aircraft are operated. As technology has improved, costs of operating these aircraft (DOC) have been reduced, but

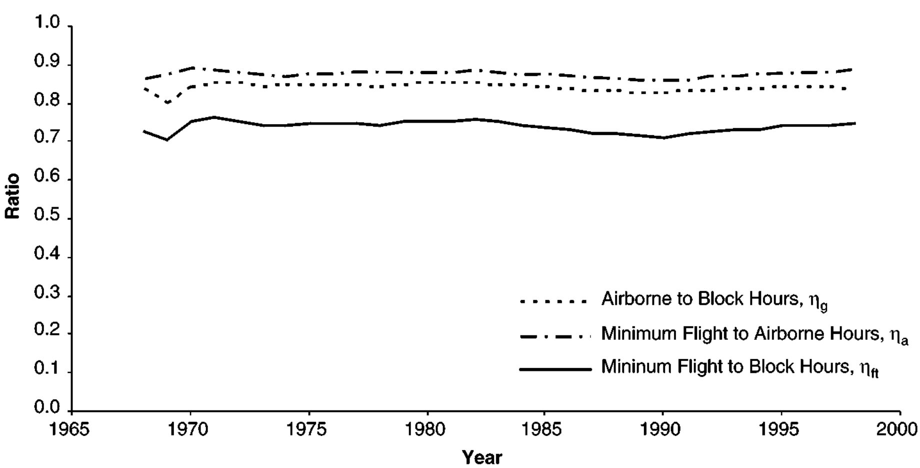

Figure 9 Historical trends in η_g, η_a, and η_{ft}. Data from (36).

purchase prices (I) for aircraft have increased, indicating a willingness on the part of airlines to incur higher capital costs for lower operating costs. Fluctuations in DOC + I are mainly due to variations in fuel price. Historically, fuel costs have ranged from 25% to 65% of DOC + I (or 12.5%–32.5% of total airline costs). Rapid increases in DOC + I resulted from the first and second oil crises in the early and late 1970s. During the second oil crisis, fuel was as much as 65% of total DOC + I, as shown in Figure 5. The rapid increase in DOC + I during the late 1980s was largely stimulated by greater competition, extensive ticket discounting, and route proliferation that occurred as a consequence of deregulation (45).[5] Accordingly, several new aircraft were introduced, including new additions to the B747, B767, A300, and A310 families.

After fuel costs, pilot salaries and maintenance are the largest DOC categories. Figure 10 shows historical trends in DOC/RPK in constant 1995 dollars, computed annually versus year of introduction for short- and long-range aircraft. Aircraft DOC/RPK ranges are based on operational data for 1991–1998 with the exception of the B707 and B727, which are based on available operational data prior to 1991. For Figure 10, to remove the impact of fuel price fluctuations, fuel costs were divided by annual jet fuel price deflated to 1995 dollars and then multiplied by the 1995 jet fuel price. New aircraft models introduced in 1995 were 65% less costly to operate than aircraft introduced in 1959. Three quarters of this reduction is attributable to improvements in maintenance and crew related DOC/RPK. Reduced fuel-related DOC/RPK accounts for the remaining quarter of the reduction. Note that for the operational data employed, load factor and seating capacity do not significantly impact aircraft-to-aircraft trends by year of introduction.

The DOC/RPK of long-range aircraft is about 20%–30% lower than that of short-range aircraft, showing that the marginal cost of flying operations and maintenance per RPK decreases with respect to increasing size and range. Long-range aircraft are, however, more expensive. Figure 11 shows historical trends in prices per seat for short- and long-range aircraft in constant 1995 dollars, computed annually, versus year of introduction. The short-range aircraft price per seat has risen approximately 50%, from $160,000 in 1965 to $240,000 in 1995 while the long-range aircraft price per seat has increased roughly 130%, from $170,000 in 1960 to $390,000 in 1995. An airline purchase decision is based on profitability, and the inherent trade-off between capital investment and lifetime operating expense (46). In order for an airline to recoup this cost, a seat must be utilized beyond a minimum threshold, sometimes stated as a minimum load factor requirement. Historically, for long-range aircraft, DOC and investment cost taken together have stayed approximately the same, as a result of large reductions in operating costs being offset by increasing aircraft prices (9). Long-range aircraft are more expensive because of the higher capital investment required for the generally greater reduction in DOC/RPK.

[5]Note that an increase in DOC does not necessarily reflect a change in DOC/RPK.

Detailed year-by-year trends are illustrated in Figure 12, where the annual prices of each short- and long-range aircraft are plotted versus year of introduction. As newer technologies are introduced, aircraft prices increase, but the price for the same aircraft model can become cheaper with time. A primary factor in the decline of price with time is the gradual obsolescence of technologies by virtue of market competition and replacement by new technologies. Such trends can be altered by exogenous impacts, such as lack of competition and technology leadership. Prices may also be impacted in the manufacturing process, where the cost of producing a unit becomes cheaper as cumulative output increases (47, 48). As a result, aircraft price may be reduced as more aircraft are produced.

5. RELATIONSHIPS BETWEEN TECHNOLOGY, COST, AND PRICE

Having examined trends in aircraft technology, cost, and price, we now seek to relate these trends to each other using physical and statistical models. Sections 5.1 and 5.2 discuss the usefulness of the Breguet range equation as a means to equate E_I to technological and operational parameters. The operational factors inherent in E_I include aircraft usage and size characteristics. These are reflected in RPK (number of passengers multiplied by stage length) and ASK (number of seats multiplied by stage length) data, respectively, as well as in operating hours, which is proportional to stage length, as all large commercial aircraft fly at approximately the same altitude and same Mach number. Influence coefficients reflecting the impact of technological and operational parameters on E_I are also derived. Section 5.3 describes the relationships between E_I, operating cost, and price.

5.1. Range Equation as Predictor of Fleet Operation

The Breguet range equation (Equation 1) is a good predictor of the actual flight operations of aircraft in the commercial fleet. Figure 13 compares stage length, calculated using the range equation, with available technological and operational data (V, SFC, L/D, $W_{structure}$, W_{fuel}, and $W_{payload}$), to the great circle distance reported in Form 41. Because the range equation does not account for takeoff, landing, flight delays, and nondirect routing, the calculated range should be greater than actual distance flown, which is the case shown. Because of limited aerodynamic and structural weight data for some aircraft, only 23 aircraft types operated during the period 1991–1998 are used (excluding the DC9-10, DC9-40, DC9-50, B707, and B720). Calculated stage length is larger than actual stage length flown by about 10%–30% for long-range aircraft, and the deviation gradually increases to 120% for short-range aircraft. Although several factors may be responsible for this trend, the most significant cause is the influence of noncruise, nonideal flight segments in real aircraft operations. That is, all fuel consumed on the ground and during idle, taxiing, take-off, and landing does not contribute to actual stage length. In addition, flight delays both on the ground and in the air also lead to extra fuel burn that does not contribute to actual stage length. Furthermore, the fuel load in this comparison is taken directly from the reported fuels issued. Not all fuels issued may have been consumed, in which case range is overestimated.

An adjustment for fuel burned for nonflying operations and delays on the ground and in-flight can be made by multiplying the range equation by the airborne and ground efficiencies, η_a and η_g, the product of which is the total flight time efficiency, η_{ft}, as described in Section 4.2. To compile these efficiencies, minimum flight hours were calculated with the assumption that all aircraft fly at Mach 0.80 and at altitude of 10.7 km. As shown in Figure 14, η_a and η_g increase with stage length. The lower flight-time inefficiency (η_{ft}) associated with short-range aircraft is related to the more than 40% of block time spent in noncruise flight segments (14, 21; see also 21a). Long-range aircraft operate closer to the ideal as total flight time efficiency approaches 1.0. By multiplying range equation results by η_{ft}, the deviation between calculated and actual range can be corrected as shown in Figure 13. On average, remaining deviations are around 10% over all aircraft types, with a standard deviation of $\pm 6\%$, indicating that most errors associated with the systematic difference between short- and long-range aircraft have been corrected. The remaining differences can be associated with the inaccuracy of fuel reserve amounts, nonreported weight elements, and variability in performance parameters during the flight.

5.2. Energy Intensity

By rearranging the Breguet range equation, aircraft E_I can be modeled as in Equation 2.

$$E_I = \frac{Q \cdot W_f}{\#\mathrm{Seats} \cdot \alpha \cdot \mathrm{SL} \cdot \eta_{ft}} \equiv \frac{1}{\eta_I},$$

$$E_I = \frac{Q \cdot W_f}{(W_p/W_i)} \frac{g \cdot \mathrm{SFC}}{V(L/D)} \cdot \frac{1}{\ln\left(1 + \frac{W_f}{W_p + W_s + W_r}\right) \cdot \eta_{ft}},$$

$$E_U \equiv \alpha E_I \equiv \frac{1}{\eta_u},$$

$$E_U = \frac{Q \cdot W_f}{\mathrm{Seats}} \cdot \frac{g \cdot \mathrm{SFC}}{V(L/D)} \cdot \frac{1}{\ln\left(1 + \frac{W_f}{W_p + W_s + W_r}\right) \cdot \eta_{ft}}, \qquad 2.$$

where E_I is energy intensity (in kg-fuel/RPK or megajoules/RPK), E_U is energy usage (in kg-fuel/ASK or megajoules/ASK), η_I is fuel efficiency (in RPK/kg-fuel or RPK/megajoule), η_U is fuel efficiency (in ASK/kg-fuel or ASK/megajoule), α is passenger load factor (RPK/ASK), Q is lower heating value of jet fuel, SL is stage length as calculated using the range equation, W_f is fuel weight, W_i is weight of a passenger plus baggage (90.7 kg, as specified by Form 41), W_p is payload weight, W_r is reserve fuel weight, and W_s is structural weight.

E_U (megajoules/ASK) captures the efficiency of mechanical performance of aircraft systems as measured by potential utility. E_U is practically independent of load factor. This is because of the weak dependence of range on α due to changes in payload and structural weight. Over the range of load factors typical for current aircraft (0.75–0.9), E_U is constant to within 3% and can thus be considered a reference value.

The 95% confidence interval (2σ) in E_I due to uncertainties in the technology and operability parameters is $\pm 22.3\%$, based on the mean value of all the propagated errors for the 31 aircraft types. SFC and L/D have the largest impacts on the propagated error. Because the 2σ error interval for the calculated E_I is approximately $\pm 30\%$, based on a curve fit to the actual E_I calculated from Form 41 data, the propagated error of the technology and operability parameters account for about 74% of the total variance in the calculated fuel efficiency values.

Utilizing a Taylor series expansion of the E_I equation, technological and operational influences on aircraft fuel burn can be quantified. Overall, a 2.7% reduction in E_I can be achieved by simultaneous improvements in engine, aerodynamic, and structural efficiencies of 1%. Structural efficiency does not have as strong an influence as SFC or L/D. Improvement in E_I due to 1% reduction in structural weight varies between 0.7% for larger aircraft and 0.75% for smaller aircraft. Based on these influence coefficients and the historical constancy of η_{ft} and OEW/MTOW, we estimate that reductions in aircraft E_I since 1959 can be attributed to improvements in SFC (57%) and L/D (22%), as well as to increased load factor (17%) and other changes, including seating capacity (4%). Again, these characteristics are interdependent, and it is important to note that improvements in some categories are achieved at the expense of improvements in others. If less fuel is carried as a reserve, E_I can also be reduced.

All aircraft body-engine combinations have almost the same fuel efficiency improvement potential with respect to technology improvements. This is largely because aircraft of the types we have considered have similar geometric configurations. Thus, for all types of commercial jet aircraft, whether short-range or long-range, the emissions reduction potential due to technology advancement is about the same. However, the ability to reduce aviation emissions is differentiated by the cost aspect of aircraft development and operation, which is further addressed in following sections.

5.3. Impacts on Direct Operating Cost and Price

There is a close relationship between DOC/RPK and fuel efficiency. Figure 15 plots DOC/RPK versus fuel efficiency (here in RPK/kg-fuel) for the 31 selected

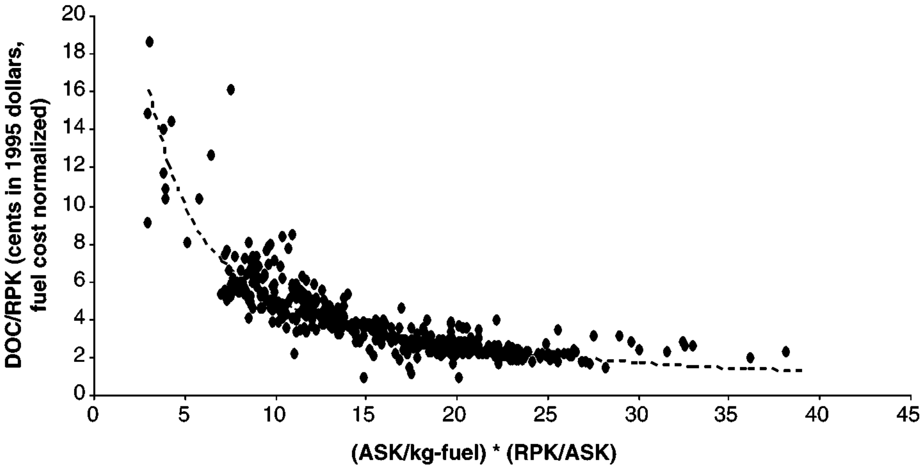

Figure 15 Direct operating cost (DOC)–fuel efficiency relationship. RPK, revenue passenger-kilometer; ASK, available seat kilometer.

aircraft types during the period 1968–1998. By taking a log transformation of both DOC/RPK and fuel efficiency and performing least-squares regression, the log-linear regression model in Equation 3 is obtained. In Equation 3, the fuel efficiency parameter (η_I) is the reciprocal of E_I.

$$\ln\left(\frac{\mathrm{DOC}}{\mathrm{RPK}}\right) = -0.958\ln(\eta_I \cdot \alpha) + 3.83, \qquad 3.$$

where n is 466, the standard error is 0.204, R^2 is 0.788, and t-statistics for coefficients are 41.5 and 60.6, respectively.

The DOC/RPK–fuel efficiency relationship is indicative of the use of technological advances for the purposes of lowering operating costs. However, reductions in future costs are purchased through higher capital and investment costs. That is, airlines are willing to pay higher acquisition cost if they can gain from savings in DOC, mainly through lower fuel and maintenance costs during the lifetime of the aircraft. The plot of aircraft price per seat versus DOC/RPK in Figure 16 shows that aircraft price is inversely proportional to DOC. For example, the DC9-30 costs around 5.6 cents/RPK to operate, and its purchase price was around $160,000 per seat. Comparatively, DOC for the B777 is only 1.4 cents/RPK, whereas its purchase price is around $400,000 per seat. By performing least-squares regression on the log-linear scale, the regression model in Equation 4 was obtained to quantify the relationships in Figure 16.

$$\ln\left(\frac{\mathrm{Price}}{\mathrm{Seat}}\right) = -0.545\ln\left(\frac{\mathrm{DOC}}{\mathrm{RPK}}\right) + 6.06, \qquad 4.$$

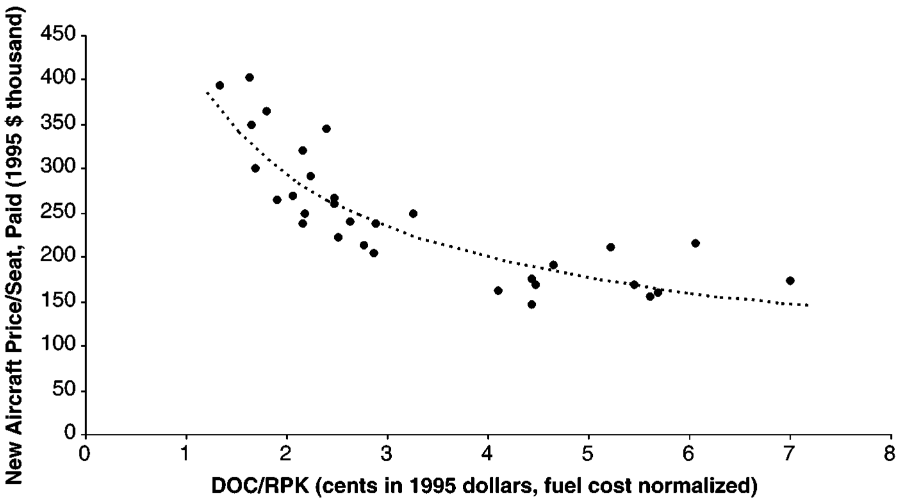

Figure 16 Direct operating cost (DOC)–price relationship. RPK, revenue passenger-kilometer.

where n is 31, the standard error is 0.146, R^2 is 0.754, and t-statistics for coefficients are 9.43 and 88.9, respectively.

The 95% confidence intervals for cost estimates made by the regression models shown in Equations 3 and 4 are approximately $\pm 40\%$ for DOC/RPK and $\pm 30\%$ for price/seat for B777-type aircraft. Because the 2σ-propagated errors of DOC and price models are $\pm 21.6\%$ and $\pm 11.9\%$, respectively, not all the errors are accounted for by the uncertainties in the technology and operability parameters.

Aircraft price is an indicator for advancement in technology, but it is also influenced by many other exogenous factors, such as fuel prices, tax rates, and leasing rates, as well as by airline negotiations with manufacturers and optional specifications. However, although the relatively large variations in aircraft prices show that fuel efficiency or DOC alone cannot fully capture the economic behaviors of aircraft price, the trends are statistically significant. As such, the DOC–fuel efficiency and price-DOC relationships imply a potential constraint for emissions reduction in the aviation sector. If the relative changes in DOC and price with respect to technological improvements occur at historical levels, airlines will continue to adopt newer and more-efficient technologies at a higher price, balanced by the promise of sufficient future revenue. However, it is unclear whether future technologies can be delivered at an acceptable price-to-DOC ratio. If the price is too high, airlines may not choose to pay more, in which case further improvements in environmental performance for the aviation sector may be limited. At the margin, a further 5% reduction in DOC/RPK would be worth ~\$8000 per seat in purchase price and result in a 5% improvement in fuel efficiency.

6. FUTURE TRENDS IN AIRCRAFT PERFORMANCE AND COST

It is both useful and necessary to investigate the potential for future change suggested by historical trends and to understand how such estimates reflect current priorities. This section extrapolates historical trends to evaluate plausible rates of technological and operational change for the next generation aircraft to be introduced by the year 2025. Given the current rates of fleet efficiency lag, it is expected that this best technology will represent the fleet average by around 2050. Because a 2025 horizon is used, we have not considered alternative fuel options. Figure 17 shows projections from this study for a typical future aircraft derived from comparisons between historical trends, technology assessments, and near-term technology introductions for SFC, L/D, structural efficiency, load factor, and η_{ft}, as discussed in Section 6.1. The technology influence coefficients determined previously make it possible to translate technological improvements into an overall reduction in E_{I} or $\mathrm{E_U}$.[6] The B777 is used as the baseline aircraft in Figure 17. For SFC, L/D, and structural efficiency, the annual rates of change are assumed to be 0.5%–1.0%, 0.3%–0.5%, and 0.0%–0.4%, respectively, resulting in a 25%–45% reduction in $\mathrm{E_U}$ by 2025. This is equivalent to a 1.0%–2.0% per year change in E_{U}, 40%–75% of the average rate over the previous 35 years. In terms of E_{I}, the addition of load factor and ATM evolution results in an estimated rate of 1.2%–2.2% per year, or 30%–50% by 2025. For comparison, included in the plot are published projections based on the historical trend of future aircraft E_{I} (18, 22). We use the aircraft typical of new systems in the basis year, the A320-100/200 for 1990–1995 and the B777 for 1995–2000, to place the estimates on the plot. NASA has also projected the fuel efficiency of 100, 150, 225, 300, and 600 passenger aircraft individually for internal studies, the most likely scenarios of which are shown in Figure 17 (see footnote 1). The first two size categories are characteristic of the B737 and A320 families, and the last three are representative of the B757/A300, the B767-777/A340, and the B747/A380, respectively.

Load factor improvements are assumed to be the same for all studies, and thus differences in projections are due to different assumptions about future technology change. In general, trends suggested by some of the other studies shown reflect a more optimistic outlook on technological developments than history would warrant. With the exception of the Dutch Civil Aviation Department study (see footnote 1), which foresees a 1.0% per year reduction in E_{U}, studies variously place the pace of change at an average 2.1%–2.9% over the next 25 years (18, 22) (see footnote 1). One reason for the difference between history and projection may lie in equating research success with technology introduction.

[6]This assumes that the linearity of the Taylor series expansion holds over these ranges. We estimate that within an aircraft type, for example among widebodies or narrowbodies, this method has an uncertainty range of $\pm 10\%$.

Figure 17 focuses on individual aircraft E_U relative to the year of introduction, not the fleet average E_U. The latter is perhaps of greater interest, and the various projections found in the literature typically make estimates for this as well. As shown in Figure 6, over the period 1971–1985, airlines found profitable an average 4.6% per year reduction in fleet average energy intensity (E_I) on an RPK basis, which translates into a slower 2.7% improvement on an ASK basis when the contribution of load factor is removed (E_U). Over the period 1985–1998, however, the rate of change has been slower at approximately 2.2% in E_I and 1.2% per year in E_U. Fleet average projections in the literature include fleet turnover effects and suggest a 1.3%–2.5% annual change in fleet average E_I (2, 16, 17, 21; see also 21a) and a 0.7%–1.3% per year change in E_U (2) (see footnote 1). These studies are consistent with recent historical trends.

Section 6.1 looks at the historical data in more detail and places these comparisons into the context of individual contributors to aviation system efficiency. Section 6.2 evaluates the impact of improvements in E_I on costs.

6.1. Technological and Operational Changes to Reduce Energy Intensity

As discussed previously, aircraft E_I depends on technological efficiencies related to the engine, aerodynamics, and structure of the aircraft and operational efficiencies associated with delays and the utilization of aircraft capacity. Future projections for the technological efficiencies are included along with the historical trends in Figures 7*a–c*. At the recent rate of improvement, roughly 1.0% per year since 1970, SFC is expected to be 20% lower by the year 2025, whereas extrapolation of the average historical trend since 1959 (1.5% per year) suggests a 30% improvement. The fleet average cruise SFC, which reflects technology adoption, has improved by 0.5% per year, primarily because most improvements in engines have been made in application to long-range aircraft, which historically comprise only 55% of the annual passenger miles. The PW8000 engine, a geared turbofan proposed for application to 150- to 180-seat aircraft, reflects a rate of change in SFC intermediate between the recent and complete histories at 0.8% per year (see Figure 7*a*) (48a). Based on projections for engine technology reviewed by Engineering Technical Support Unit (14) and Greene (18, 19), a 10%–20% reduction in SFC is possible with the development of unducted, ultrahigh bypass turbofans, and the use of propfan technology may result in a 20%–30% reduction in SFC. However, noise constraints and passenger acceptance may restrict the introduction of unducted engines. Based on recent historical trends and the projected characteristics of the PW8000 engine, we assume a 0.5%–1.0% annual rate of improvement, equivalent to a 15%–25% reduction in SFC by the year 2025.

The outlook is similarly incremental with respect to both aerodynamic and structural efficiencies. Historically, aerodynamic efficiency has averaged a 0.4% per year improvement, and a continuation of this rate would lead to a 10% increase in L/D by 2025, similar to that proposed by the National Research Council's

Aeronautics and Space Engineering Board (22) (see Figure 7*b*). Technology assessments indicate full chord laminar flow control may lead to fuel savings of up to 25% (14, 18, 22, 49), which, at this rate of change, would not be a characteristic of new aircraft for more than 50 years into the future. Given that this change may be optimistic because of problems with operational implementation (18), we assume a range that reflects the variability associated with aerodynamic technology improvement observed in historical trends, equivalent to a 0.3%–0.5% annual improvement or 10%–15% increase in L/D by the year 2025.

The lack of historical improvement in structural efficiency suggests that weight reductions will be offset by added weight for other purposes (e.g., engines, entertainment, etc.). The A380, a next-generation very large aircraft, appears to continue this trend (see Figure 7*c*) (50). However, if lighter-weight, high-strength materials can be substituted into the predominantly metallic aircraft structures of today, a large reduction in fuel burn can be realized. Assessments envision a 10%–15% weight reduction by 2010 compared with 1990s aircraft, with the potential for 30% savings through the use of composites to the extent they are currently employed for some military applications (14, 18, 22). Again, a major shift in historical trends would be required to accommodate this vision of the future. We assume a range of 0%–10% reduction in aircraft weight by 2025 through use of composite materials, equivalent to a 0.0%–0.4% annual rate of change.

Improved scheduling and equipment commitment can improve load factor (e.g., 49), but congestion and low load factor during early morning/late evening flights may limit improvements to 0.74 by 2019 (9). This represents a continuation of recent historical trends. At this rate of improvement, about 0.2% per year, the worldwide average load factor is expected to reach around 0.77 by 2025. Given the flat historical trends in ground and airborne efficiencies shown in Figure 9, we expect flight time efficiencies to continue at their present levels, 0.90 for η_a, 0.85 for η_g, and 0.75 for η_{ft}. Note that η_{ft} is relative to the upper bound operation of a direct flight at a constant cruise speed with no additional time spent taxiing, climbing, or decending, and it is unlikely that operational improvements can lead to $\eta_{ft} > 0.90$. Although some studies suggest that nonoptimum use of airspace and ground infrastructure will be reduced through congestion control (2), such improvements may only maintain current efficiencies because air-traffic growth remains strong (e.g., 18). Note that for an individual aircraft, increasing the seating capacity for a similar design will also improve E_I. Thus, a seating arrangement that utilizes a small amount of floor space per seat is beneficial to E_I. This trend also applies to the fleet as a whole. It has been estimated that the average number of seats per aircraft will grow by 1.0% annually over the next 20 years (9).

6.2. Economic Characteristics of Future Aircraft

In comparison to projections of technological and operational improvements, relatively little attention has been given to the evolution of future aircraft system economic characteristics in response to technological improvements. We assume that fuel price remains at its 1995 level ($0.14 per liter), DOC categories remain in their current proportions, and the price-DOC relationship is consistent through fluctuations in the economy. Overall, the significance of the cost projections in this section is not so much in the absolute values as in the sensitivity of the projections to technological improvements. DOC decreased by 3.3% annually for the period 1959–1995 while short- and long-range aircraft prices per seat rose approximately 2.3% annually, a ratio of ~1.4. Trends for technology indicate that aircraft DOC and price will change at a slower rate, a reduction of 1.8%–2.6% per year for DOC and an increase of 1.0%–1.4% per year for price. The higher DOC/price ratio of 1.8–1.9 indicates that further decreases in DOC, through technological, ATM, or load factor improvements, come at higher capital costs.

In Figures 10 and 11, projected estimates of DOC and price are shown based on the future technology and operational trends discussed previously. As a baseline for these projections, DOC/RPK and the price/seat for a typical current aircraft is estimated using performance characteristics of the B777 and the correlations among technology, DOC, and price discussed in Section 5 (see Equations 3 and 4). Predictive confidence intervals for these estimates are shown. Cost influences and price premiums placed on the B777 beyond that associated with fuel efficiency are not captured by Equations 3 and 4. In other cases, a price discount may result from features not desirable in operation. Nevertheless, the model-generated price of the B777 serves as a point of comparison for future projections, where the emphasis is given to relative changes in costs with respect to technology advancement. The decreased E_I over the period 1995–2025 is projected to lead to reductions in operating costs of 40%–55% and to increases in aircraft price of 30%–35%.

Variability in fuel prices can mask reductions in E_I. Airlines respond to increases in fuel prices in two ways. In the short term, increases in DOC will likely be borne by passengers through increased ticket fares. Airlines will also, to some extent, alter operational methods to lower the burden of increased fuel costs (46). Depending on the willingness of air travelers to pay, which is largely influenced by individual income, travel-time constraints, and costs of other competitive modes of transport, total air-travel demand adjusts downward. In the long term, however, airlines are expected to lower their operating costs by replacing the older aircraft in their fleets with more fuel-efficient aircraft. Figure 18 shows the historical impact of fuel price change on the relationship between E_I and DOC. The lower curve represents the relationship during the period 1996–1998 when the average fuel price was $0.15 per liter ($0.57 per gallon). The upper curve represents the relationship during the period 1980–1982 when the average fuel price was $0.44 per liter ($1.65 per gallon). Note that fuel cost is not normalized for either case (as it was for Figure 15 and Equations 3 and 4). The large increase in fuel price, $1.08 per gallon, or 190%, raised aircraft DOC by 60%–70%, and the increased fuel price penalized less-fuel-efficient aircraft more severely. In the example of Figure 18, a sustained rise in prices would push airlines to offset the increase in DOC by moving to the right on the upper curve through the adoption of newer, more-efficient technologies as well as through increases in load factor. As a result, the historical trends shown in Figure 18 suggest that the 190% increase in fuel price shown is expected in the long term to drive as much as a 45% improvement in E_I, the difference between the two curves at the same DOC level.

From a regulatory perspective, the elasticity between fuel cost and E_I is an important input. Policy approaches to emissions reductions, as they apply to air-quality concerns, have been marked by requirements for technical feasibility, cost, and safety considerations. Many options for emissions mitigation have been proposed, including higher fuel taxes, emission charges, emission caps or limits, emissions trading, increased stringency of the certification standards, retrofit mandates, voluntary actions, demand management, and the possibility of no action. Although negotiations will settle the form of such policies, they all fundamentally entail considerations of the efficacy of both technological and operational strategies for system efficiency improvement and emissions reduction. We cannot predict the future as it applies to the availability of technologies and their cost, infrastructure and airspace constraints, or the actual growth of air travel. However, the historical record contains some significant relationships between technology, operability, and cost. If the industry is left to progress under the current set of decision-making, technological, and business rules, there is a good possibility that the next several decades will reflect the historical trends.

7. SUMMARY

Aviation emissions are expected to increase and constitute a greater proportion of the total anthropogenic climate impact. It has been estimated that aviation emissions accounted for 3.5% of the total anthropogenic radiative forcing in 1992. Although the composition of aircraft emissions is similar to other modes of transport that use fossil fuels, the influence of aircraft emissions on the atmosphere occurs through different mechanisms, resulting in a comparatively greater effect on the atmosphere per unit mass. In addition, air transportation growth (5.5% per year) has outpaced reductions in E_I (3.3% per year) and will continue to do so through the foreseeable future, perhaps by an increased margin. We have presented a physical model, based on the Breguet range equation and on historically based statistical models, that together compactly explain the relationships between technology, cost, and emissions performance. The analysis suggests that 57% of the reductions in E_I during the period 1959–1995 were due to improvements in engine efficiency, 22% resulted from increases in aerodynamic efficiency, 17% were due to more-efficient use of aircraft capacity, and 4% resulted from other changes, such as increased aircraft size. Combined with an understanding of historical trends, the pace of future changes in technology and operation, as well as the impacts of these changes on operating and capital costs, were estimated. These historically based projections indicate that typical in-use aircraft E_I can be expected to decline at a rate of 1.2%–2.2% per year, a pace of change not sufficient to counter the projected annual 4%–6% growth in demand for air transport. Unless measures are taken to significantly alter the dominant historical rates of change in technology and operations, the impacts of aviation emissions on local air quality and climate will continue to grow.

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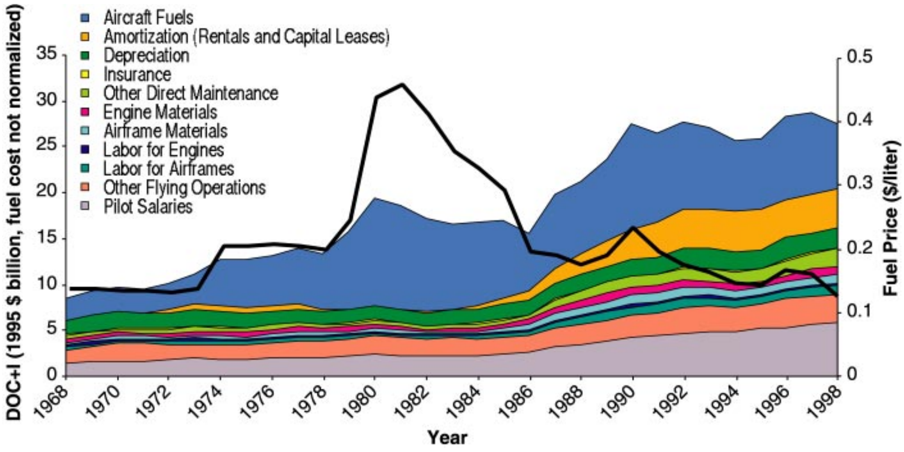

Figure 5 Evolution of investment and direct operating costs (DOC + I) for 10 major US airlines, 1968–1998. [Data from (36).]

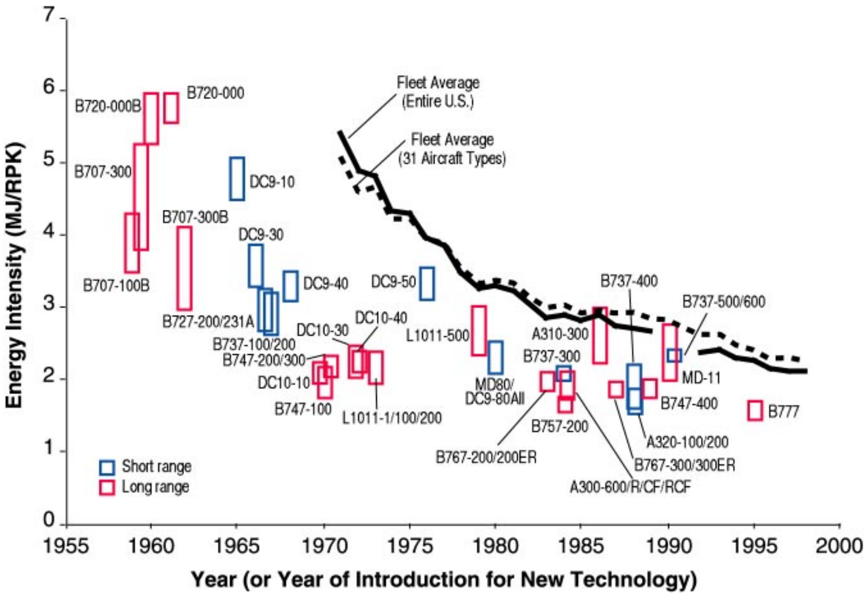

Figure 6 Historical trends in energy intensity of the US fleet. Individual aircraft E_I based on 1991–1998 operational data with the exception of the B707 and B727, which are based on available operational data prior to 1991. Fleet averages were calculated using a revenue passenger-kilometer (RPK) weighting. Data was not available for entire US fleet average during 1990 and 1991. [Data from (36).]

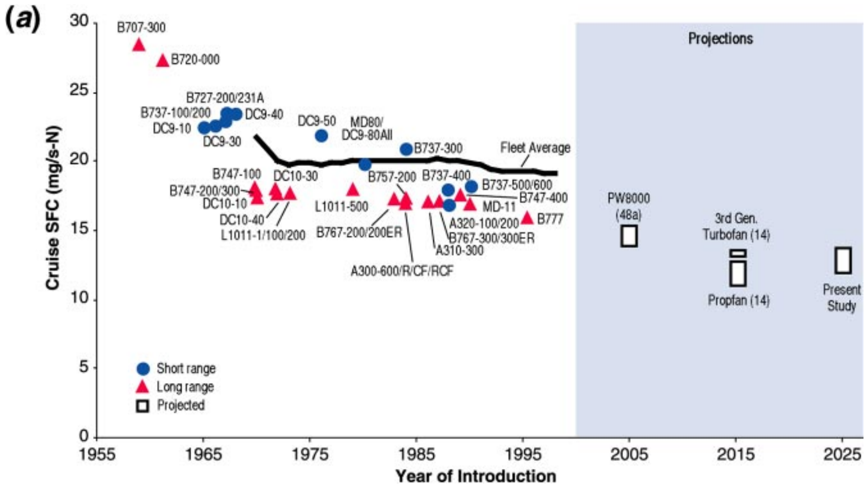

Figure 7 Historical trends in engine, aerodynamic, and structural efficiencies. (*a*) (above) Cruise specific fuel consumption (SFC) data obtained from literature sources (37, 38) or estimated using fits to engine data compiled by the International Civil Aviation Organization (ICAO) (39, 40). The average SFC for all engines available for a given aircraft is shown. A 95% confidence interval of +/−7% is estimated based on a comparison of ICAO and literature sources and discussions with industrial sources. Fleet averages were calculated using a revenue passenger-kilometer weighting. (*b*) (opposite) $M(L/D)_{max}$ [mach number × $\text{lift/drag}_{\text{maximum}}$] obtained from literature sources (41) or estimated using an aircraft systems model (15). Additional $M(L/D)_{max}$ data were obtained from industry sources. Based on verification with these sources, a 95% confidence interval of +/−8% is estimated. Fleet averages were calculated using a revenue passenger-kilometer weighting. (*c*) (opposite) Structural efficiency data obtained from literature sources (35, 42). A 95% confidence interval of +/−5% is estimated by the authors. Fleet averages were calculated using a revenue passenter kilometer weighting. OEW, operating empty weight; MTOW, maximum take-off weight.

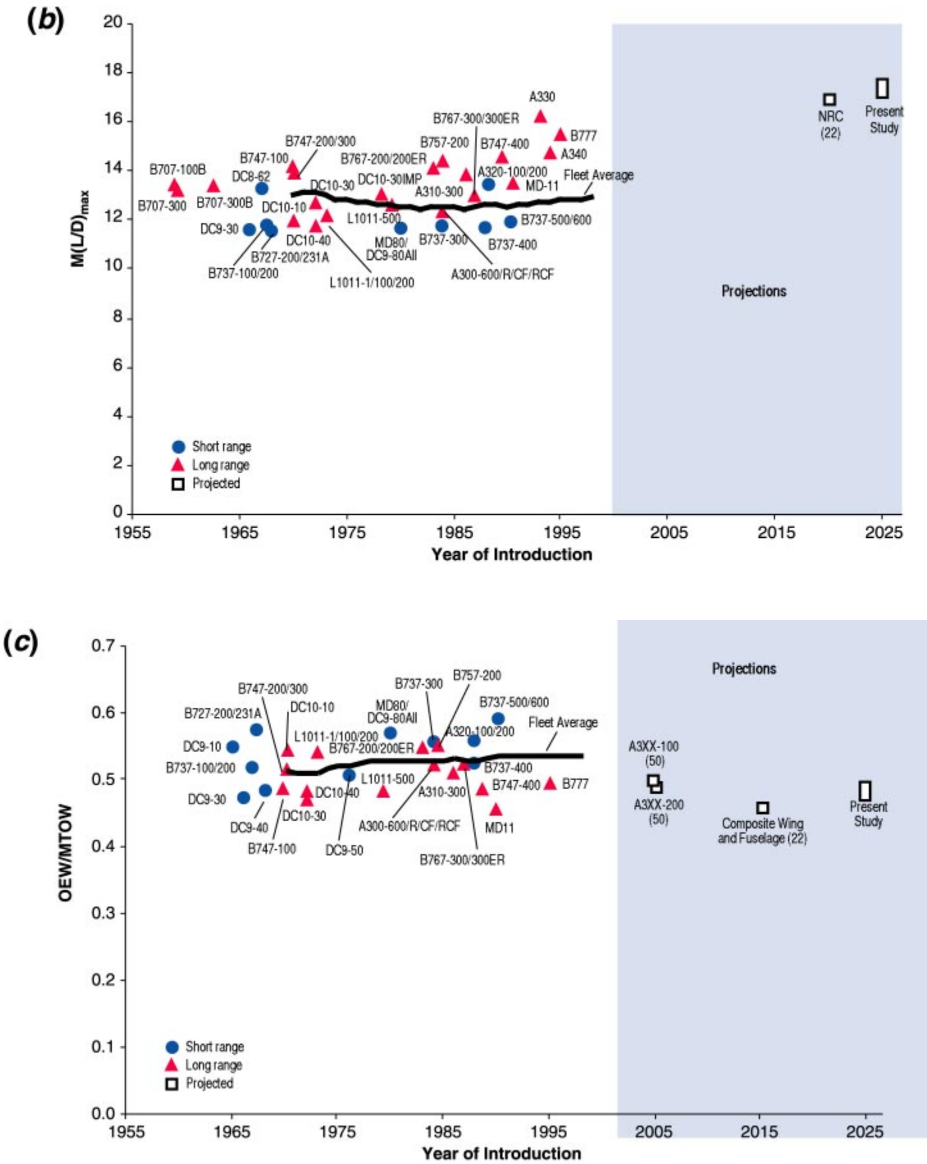

Figure 7 (*Continued*)

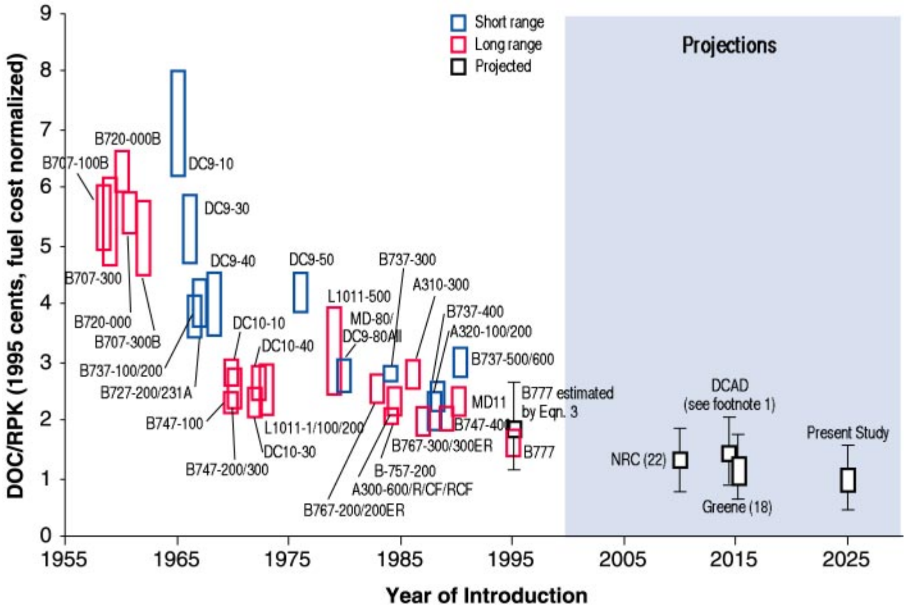

Figure 10 Historical trends in direct operating cost (DOC) per revenue passenger-kilometer (RPK) for short- and long-range aircraft. Individual aircraft DOC/RPK based on 1991–1998 operational data with the exception of the B707 and B727, which are based on available operational data prior to 1991. [Data from (36).]

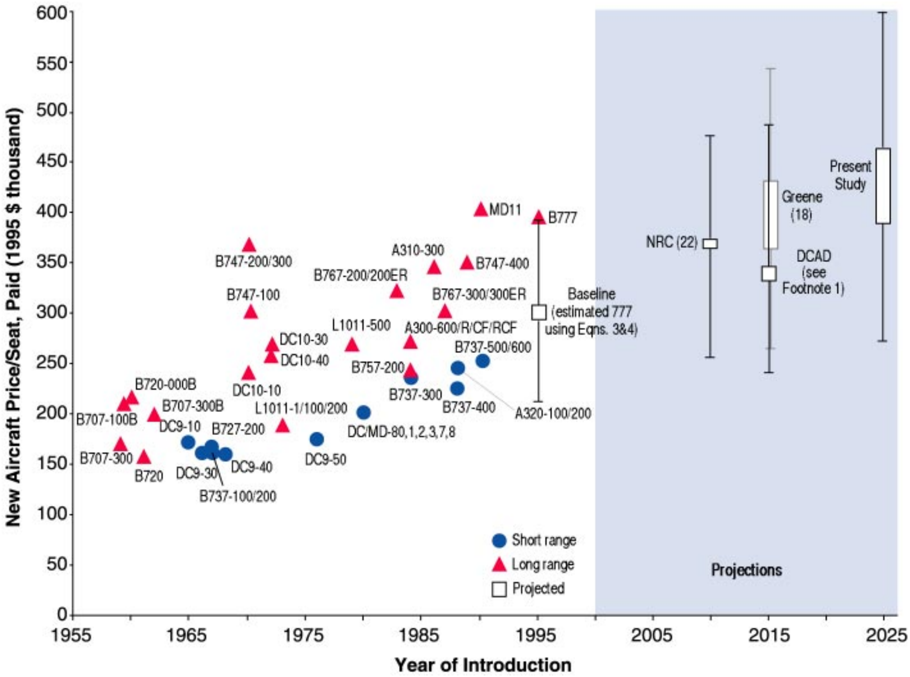

Figure 11 Historical trends in price for short- and long-range aircraft. [Data from (35), unless otherwise noted.] For the period 1972–1985, catalog prices for the B747-200B are used.

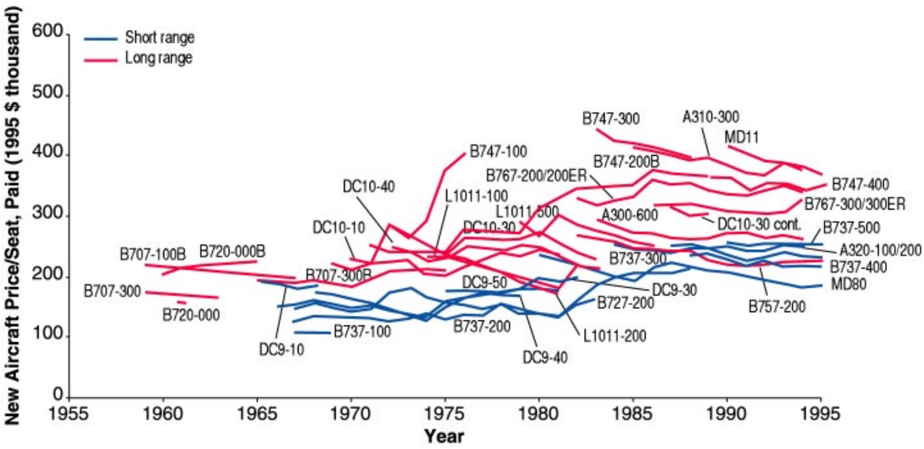

Figure 12 Year-by-year historical trends in price for short- and long-range aircraft. [Data from (35).] For the period 1972–1985, catalog prices for the B747-200B are shown.

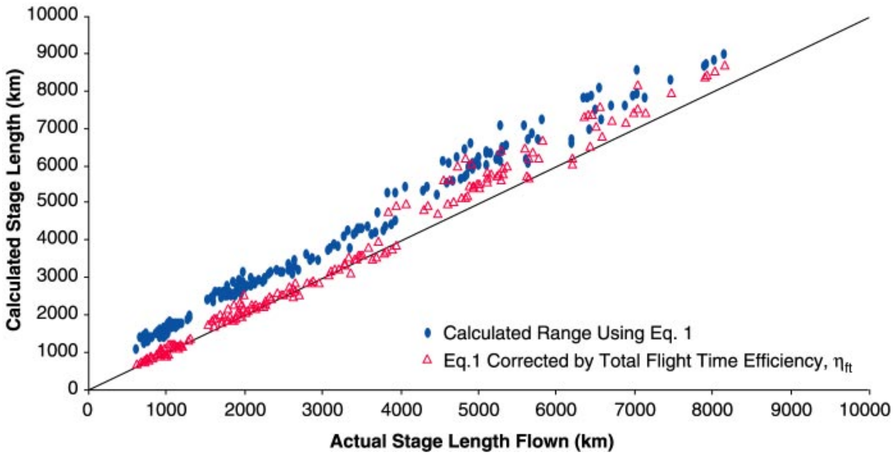

Figure 13 Breguet range equation as a predictor of reported stage length and correction.

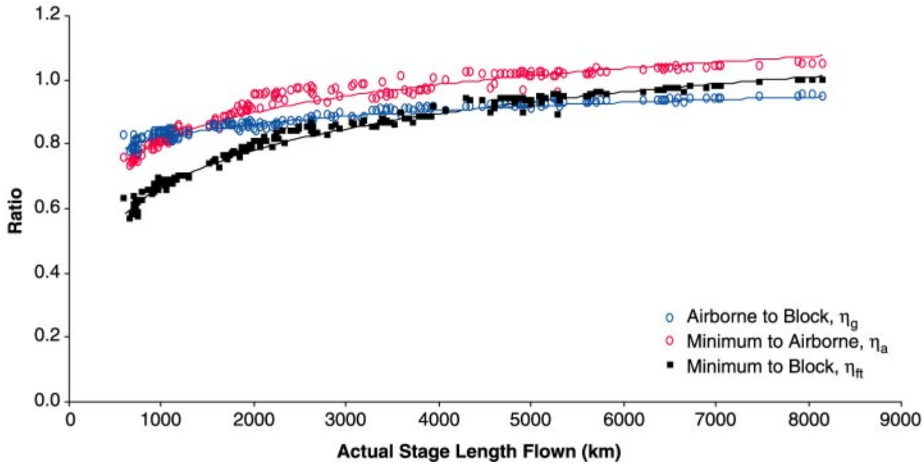

Figure 14 Corrections to Breguet range equation for operational impacts. [Data from (36).]

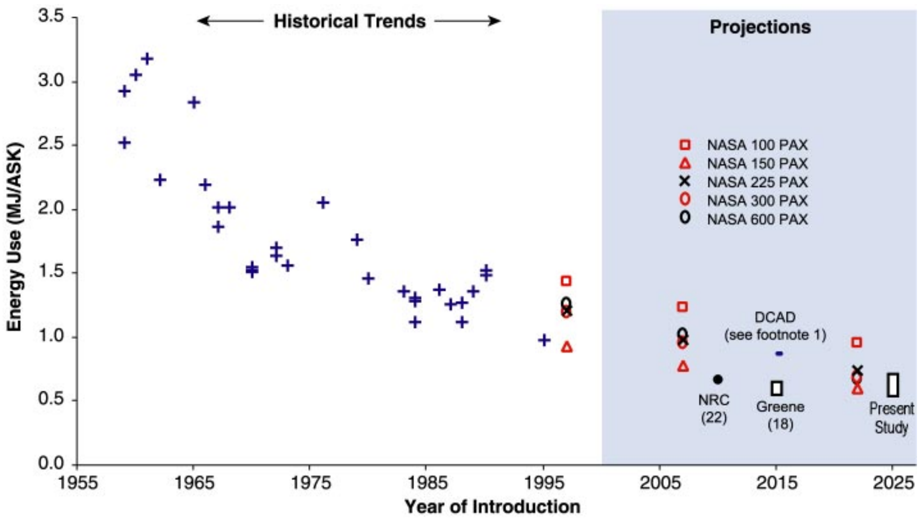

Figure 17 Future aircraft energy usage. [Data from (36), unless otherwise noted.] ASK, available seat kilometer.

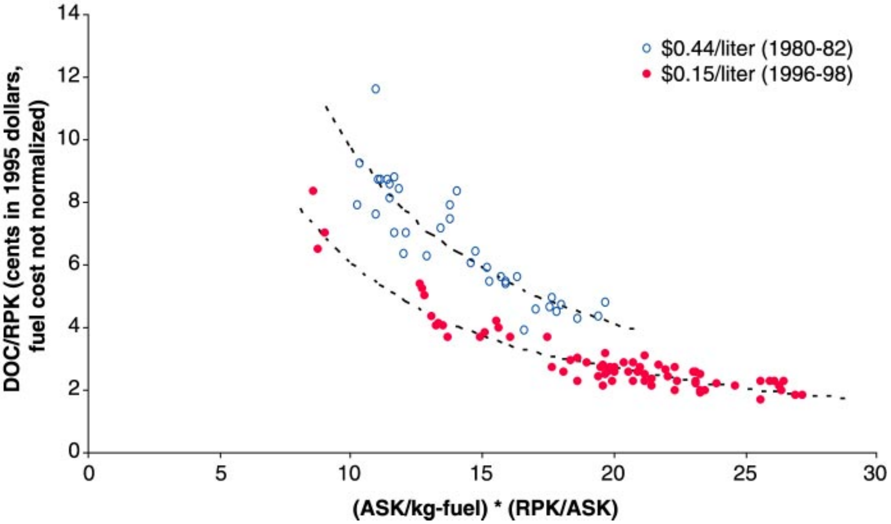

Figure 18 Impact of fuel price on the direct operating cost (DOC)—fuel efficiency relationship. RPK, revenue passenger-kilometer; ASK, available seat kilometer.