Aircraft and Energy Use

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Glossary

bypass ratio The ratio of air passed through the fan system to that passed through the engine core.

contrail The condensation trail that forms when moist, high-temperature air in a jet exhaust, as it mixes with ambient cold air, condenses into particles in the atmosphere and saturation occurs.

drag The aerodynamic force on an aircraft body; acts against the direction of aircraft motion.

energy intensity (E_I) A measure of aircraft fuel economy on a passenger-kilometer basis; denoted by energy used per unit of mobility provided (e.g., fuel consumption per passenger-kilometer)

energy use (E_U) A measure of aircraft fuel economy on a seat-kilometer basis (e.g., fuel consumption per seat-kilometer).

great circle distance The minimum distance between two points on the surface of a sphere.

hub-and-spoke system Feeding smaller capacity flights into a central hub where passengers connect with flights on larger aircraft that then fly to the final destination.

lift-to-drag ratio (L/D) A measure of aerodynamic efficiency; the ratio of lift force generated to drag experienced by the aircraft.

load factor The fraction of passengers per available seats.

radiative forcing 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.

structural efficiency (OEW/MTOW) The ratio of aircraft operating empty weight (OEW) to maximum takeoff weight (MTOW); a measure of the weight of the aircraft structure relative to the weight it can carry (combined weights of structure plus payload plus fuel).

thrust A force that is produced by engines and propels the aircraft.

thrust specific fuel consumption (SFC) A measure of engine efficiency as denoted by the rate of fuel consumption per unit thrust (e.g., kilograms/second/Newton).

turbofan engine The dominant mode of propulsion for commercial aircraft today; a turbofan engine derives its thrust primarily by passing air through a large fan system driven by the engine core.

An aircraft is composed of systems that convert fuel energy to mechanical energy in order to perform work—the movement of people and cargo. This article describes how aircraft technology and operations relate to energy use. Historical trends and future outlook for aircraft performance, energy use, and environmental impacts are discussed. Economic characteristics of aircraft systems as they relate to energy use are also presented.

1. INTRODUCTION

The first powered passenger aircraft were developed at the turn of the 20th century. Since then, there has been rapid growth in aviation as a form of mobility and consequently significant growth in energy use. In 2002, aviation accounted for 3 trillion revenue passenger-kilometers (RPKs), or approximately 10% of world RPKs traveled on all transportation modes and 40% of the value of world freight shipments. Among all modes of transport, demand for air travel has grown fastest. If, as expected, strong growth in air travel demand continues, aviation will become the dominant mode of transportation, perhaps surpassing the mobility provided by automobiles within a century. This evolution of transportation demand also suggests an increase in per-person energy use for transportation. Minimizing energy use has always been a fundamental design goal for commercial aircraft. However, the growth of air transportation renders ever-increasing pressures for improvements in technology and operational efficiency to limit environmental impacts.

In the analysis presented here, trends in aviation transportation demand, energy use, and associated environmental impacts are examined (Sections 2–4). In Sections 5 and 6, aircraft systems from an energy conversion perspective are introduced and key performance parameters of aircraft technology and operation are discussed. A technology and operational outlook for reduced aircraft energy use is presented in Section 7, followed by a summary of industry characteristics and economic impacts that affect energy use of individual aircraft and the fleet as a whole in Section 8.

2. ECONOMIC GROWTH, DEMAND, AND ENERGY USE

On a per capita basis, rising demand for mobility is well correlated with growth in gross domestic product (GDP)—a measure of national economic activity—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. A fixed budget for travel leads to an increase in total travel demand per capita (e.g., RPK per capita) in approximate proportion to income. In addition, a person spends an average of 1.0–1.5 hours/day traveling. One key implication of such invariance is that as demand for movement increases, travelers tend to shift toward faster modes of transportation. Consequently, continuing growth in world population and income levels can be expected to lead to further demand for air travel, both in terms of market share and RPKs. As a result, high-speed transportation, in which aviation is anticipated to be the primary provider, will play an increasingly important role and may account for slightly more than one-third of world passenger traffic volume within the next 50 years. In general, among industry and government predictions, growth in passenger air transportation has been typically projected to be between 3 and 6%/year as an average over future periods of 10–50 years.

Aviation fuel consumption today corresponds to 2–3% of the total fossil fuel use worldwide, more than 80% of which is used by civil aviation operation. Energy use in the production of aircraft is relatively minor in comparison to that consumed in their operation. Although the majority of air transportation demand is supplied by large commercial aircraft, defined as those aircraft with a seating capacity of 100 or more, smaller regional aircraft have emerged as an important component of both demand and energy use within air transportation. For example, in the United States, although regional aircraft currently perform under 4% of domestic RPKs, they account for almost 7% of jet fuel use and for 40–50% of total departures. Future growth in demand for regional aircraft RPKs could be up to double the rate for large commercial aircraft. Cargo operations account for some 10% of total revenue ton-kilometers and fuel use within the aviation sector. Economic activity, as measured by world GDP, is the primary driver for the air cargo industry growth. World air cargo traffic is expected to grow at an average annual rate of over 6% for the next decade.

3. ENERGY USE, EMISSIONS, AND ENVIRONMENTAL IMPACT

The growth in air transportation volume has important global environmental impacts associated with the potential for climate change. On local to regional scales, noise, decreased air quality related primarily to ozone production and particulate levels, and other issues, such as roadway congestion related to airport services and local water quality, are all recognized as important impacts. In this section, the focus is on emissions-related impacts; because of its relative importance, some additional detail on the aviation role in climate change is provided.

The total mass of emissions from an aircraft is directly related to the amount of fuel consumed. Of the exhaust emitted from the engine core, 7–8% is composed of carbon dioxide (CO_2) and water vapor (H_2O); another 0.5% composed of nitrogen oxides (NO_x), unburned hydrocarbons (HC), carbon monoxide (CO), and sulfur oxides (SO_x); there are other trace chemical species that include the hydroxy family (HO_x) and the extended family of nitrogen compounds (NO_y), and soot particulates. Elemental species such as O, H, and N are also formed to an extent governed by the combustion temperature. 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 aircraft weight, aerodynamic design, engine design, and the manner in which the aircraft is operated. Emissions of NO_x, soot, CO, HC, and SO_x are further related to details of the combustor design and, to some extent, to postcombustion 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., grams of NO_x/kilogram of fuel). A host of minor constituents exist in very small, trace amounts.

The climate effects of aviation are perhaps the most important of the environmental impacts, both in terms of economic cost and the extent to which all aspects of the aviation system, operations, and technology determine the impact. Because a majority of aircraft emissions are injected into the upper troposphere and lower stratosphere (typically 9–13 km in altitude), resulting impacts on the global environment are unique among all industrial activities. The fraction of aircraft emissions that is relevant to atmospheric processes extends beyond the radiative forcing effects of CO_2. The mixture of exhaust species discharged from aircraft perturbs radiative forcing two to three times more than if the exhaust was CO_2 alone. 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. 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 from 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. However, many of the chemical and physical processes associated with climate impacts are the same as those that determine air quality in the lower troposphere.

Estimates of the radiative forcing by various aircraft emissions for 1992 offered by the Intergovernmental Panel on Climate Change (IPCC) and the 1999 projections from Penner *et al.* for the year 2050 are shown in Fig. 1. The estimates translate to 3.5% of the total anthropogenic forcing that occurred in 1992 and to an estimated 5% by 2050 for an all-subsonic fleet. Associated increases in ozone levels are expected to decrease the amount of ultraviolet radiation at the surface of the earth. Future fleet composition also impacts the radiative forcing estimate. A supersonic aircraft flying at 17–20 km would have a radiative forcing five times greater than a subsonic equivalent in the 9- to 13-km range. It is important to note that these estimates are of an uncertain nature. Although broadly consistent with

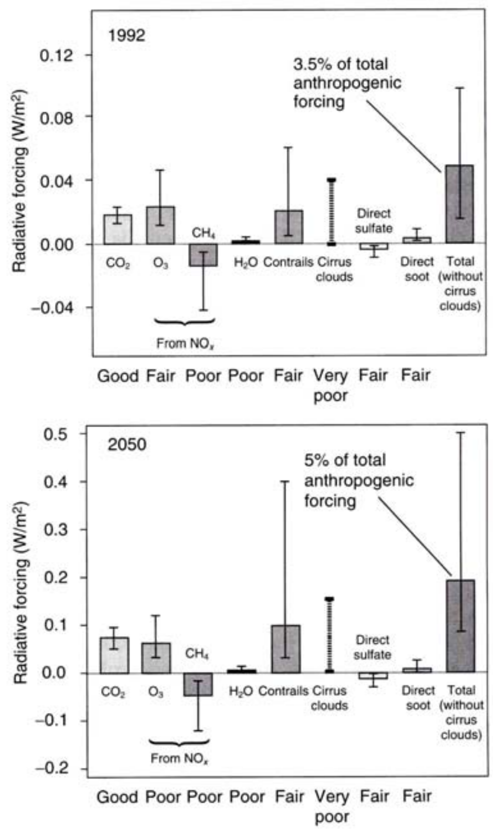

FIGURE 1 Radiative forcing estimated for 1992 (0.05 W/m^2 total) and projected to 2050 (0.19 W/m^2 total). Note differences in scale. Note also that the dashed bars for aviation-induced cirrus cloudiness describe the range of estimates, not the uncertainty. The level of scientific understanding of this potential impact is very poor and no estimate of uncertainty has been made. Cirrus clouds are not included in the total radiative forcing estimate. Reproduced from Penner *et al.* (1999), with permission.

these IPCC projections, subsequent research reviewed by the Royal Commission on Environmental Protection (RCEP) in the United Kingdom has suggested that the IPCC reference value for the climate impact of aviation is likely to be an underestimate. In particular, although the impact of contrails is probably overestimated in Fig. 1, aviation-induced cirrus clouds could be a significant contributor to positive radiative forcing; NO_x-related methane reduction is less than shown in Fig. 1, reducing the associated cooling effect, and growth of aviation in the period 1992–2000 has continued at a rate larger than that used in the IPCC reference scenario.

4. TRENDS IN ENERGY USE

Fuel efficiency gains due to technological and operational change can mitigate the influence of growth on total emissions. Increased demand has historically outpaced these gains, resulting in an overall increase in emissions over the history of commercial aviation. The figure of merit relative to total energy use and emissions in aviation is the energy intensity (E_I). When discussing energy intensity, the most convenient unit of technology is the system represented by a complete aircraft. In this section, trends in energy use and E_I are elaborated. In the following section, the discussion focuses on the relation of E_I to the technological and operational characteristics of an aircraft.

Reviews of trends in technology and aircraft operations undertaken by Lee *et al.* and Babikian *et al.* indicate that continuation of historical precedents would result in a future decline in E_I for the large commercial aircraft fleet of 1.2–2.2%/year when averaged over the next 25 years, and perhaps an increase in E_I for regional aircraft, because regional jets use larger engines and replace turboprops in the regional fleet. When compared with trends in traffic growth, expected improvements in aircraft technologies and operational measures alone are not likely to offset more than one-third of total emissions growth. Therefore, effects on the global atmosphere are expected to increase in the future in the absence of additional measures. Industry and government projections, which are based on more sophisticated technology and operations forecasting, are in general agreement with the historical trend. Compared with the early 1990s, global aviation fuel consumption and subsequent CO_2 emissions could 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 such forecasts, variability in projected emissions also originates from different assumptions about aircraft technology, fleet mix, and operational evolution in air traffic management and scheduling.

Figure 2 shows historical trends in E_I for the U.S. large commercial and regional fleets. 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 (Fig. 2A). For large commercial aircraft, a combination of technological and operational improvements led to a reduction in E_I of the entire U.S. fleet of more than 60% between 1971 and 1998, averaging about 3.3%/year. In contrast, total RPK has grown by 330%, or 5.5%/year over the same period. Long-range aircraft are $\sim 5\%$ more fuel efficient than are short-range aircraft because they carry more passengers over a flight spent primarily at the cruise condition. Regional aircraft are 40–60% less fuel efficient than are their larger narrow- and wide-body counterparts, and regional jets are 10–60% less fuel efficient compared to turboprops. Importantly, fuel efficiency differences between large and regional aircraft can be explained mostly by differences in aircraft operations, not technology.

Reductions in E_I do not always directly imply lower environmental impact. For example, the prevalence of contrails is enhanced by greater engine efficiency. NO_x emissions also become increasingly difficult to limit as engine temperatures and pressures are increased—a common method for improving engine efficiency. These conflicting influences make it difficult to translate the expected changes in overall system performance into air quality impacts. Historical trends suggest that fleet-averaged NO_x emissions per unit thrust during landing and takeoff (LTO) cycles have seen little improvement, and total NO_x emissions have slightly increased. However, HC and CO emissions have been reduced drastically since the 1950s.

5. ENERGY CONSUMPTION IN AN AIRCRAFT SYSTEM

Energy intensity can be related to specific measures of technological and operational efficiency in the air transportation system. The rest of this article takes a more detailed look at trends in these efficiencies and

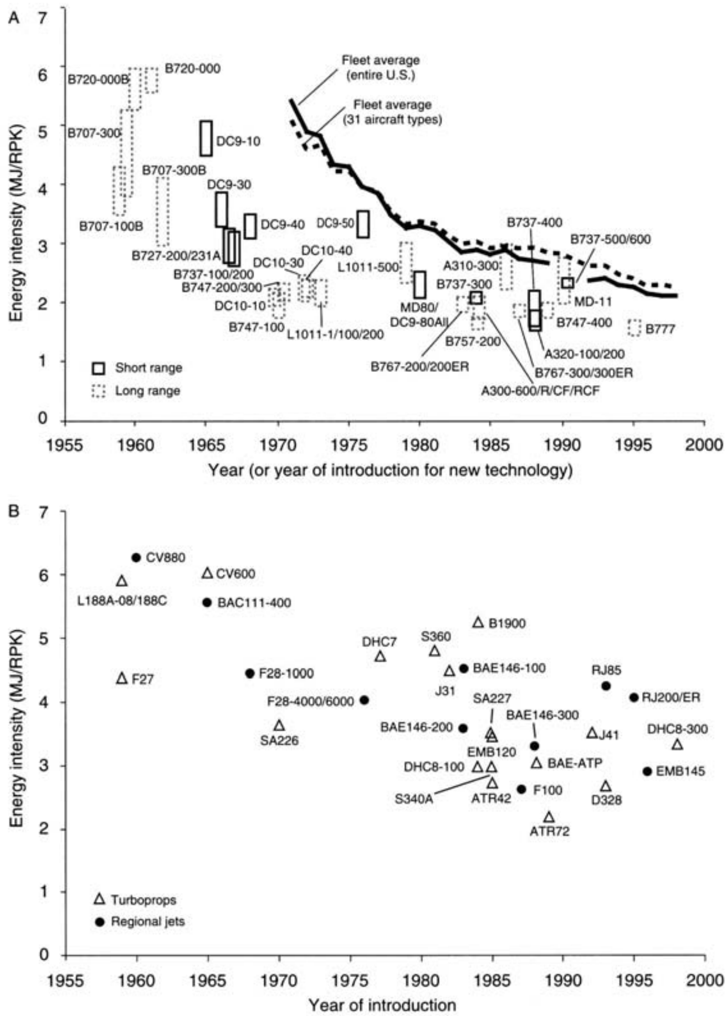

FIGURE 2 (A) Historical trends in energy intensity of the U.S. large commercial fleets. Individual aircraft E_I based on 1991–1998 operational data with the exception of the B707 and B727, which are based on available operational data prior to 1991. Fleet averages were calculated using a revenue passenger-kilometer (RPK) weighting. Data were not available for the entire U.S. fleet average during 1990 and 1991. Reproduced from Lee *et al.* (2001), with permission. (B) Historical trends in energy intensity of the U.S. regional fleets.

options for controlling energy use. The first step is a simplified description of the energy conversion within an aircraft engine. An aircraft engine converts the flow of chemical energy contained in aviation fuel and the air drawn into the engine into power (thrust multiplied by flight speed). Overall engine efficiency is defined by the ratio of power to total fuel energy flow rate. Only one-fourth to one-third of fuel energy is used to overcome drag and thus propel the aircraft. The remaining energy is expelled as waste heat in the engine exhaust. A parameter that is closely related to the overall engine efficiency is the specific fuel consumption (SFC). When judging the efficiency of an aircraft system, however, it is more relevant to consider work in terms of passengers or payload carried per unit distance. Energy intensity is an appropriate measure when comparing efficiency and environmental impact to other modes. E_I consists of two components—energy use, E_U, and load factor, α, as described by Eq. (1). Energy use is energy consumed by the aircraft per seat per unit distance traversed and is determined by aircraft technology parameters, including engine efficiency. E_U observed in actual aircraft operations reflects operational inefficiencies such as ground delays and airborne holding. The fleet average E_U is of interest because it is the fleet fuel efficiency that determines the total energy use. Load factor is a measure of how efficiently aircraft seats are filled and aircraft kilometers are utilized for revenue-generating purposes. Increasing load factor leads to improved fuel consumption on a passenger-kilometer basis.

$$E_I = \frac{\text{MJ}}{\text{RPK}} = \frac{\text{MJ}}{\text{ASK}} \Big/ \frac{\text{RPK}}{\text{ASK}} = \frac{E_U}{\alpha}, \qquad (1)$$

where MJ is megajoules of fuel energy, RPK is revenue passenger-kilometers, ASK is available seat-kilometers, and α is load factor. To show E_I as a function of the engine, aerodynamic, and structural efficiencies of an aircraft system as well as load factor, it is necessary to have a model of aircraft performance. Because a major portion of aircraft operation is spent at cruise, the Breguet range (R) equation, which describes aircraft motion in level, constant-speed flight, is a relevant model. In the Breguet range equation [Eq. (2)], engine thrust is balanced by drag, and lift balances aircraft weight. Propulsion, aerodynamic, and structural characteristics are represented by three parameters: SFC, lift-to-drag ratio (L/D), and structural weight ($W_{\text{structure}}$). 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.

$$R = \frac{V(\text{L/D})}{g \cdot \text{SFC}} \times \ln\left(1 + \frac{W_{\text{fuel}}}{W_{\text{payload}} + W_{\text{structure}} + W_{\text{reserve}}}\right), \qquad (2)$$

where g is the gravitational acceleration constant, W_{reserve} is the reserve fuel, and V is flight speed. By rearranging Eq. (2), a relationship between aircraft energy use and technology parameters can be derived as shown in Eq. (3). As implied by Eq. (3), aircraft system efficiency improves with lower SFC, greater L/D, and lighter structural weight.

$$E_U \equiv \alpha E_I \equiv \frac{1}{\eta_U}$$

$$E_U = \frac{Q W_{\text{fuel}}}{S} \cdot \frac{g \cdot \text{SFC}}{V(\text{L/D})} \times \frac{1}{\ln\left(\frac{W_{\text{fuel}}}{W_{\text{payload}} + W_{\text{structure}} + W_{\text{reserve}}}\right)}, \qquad (3)$$

where η_U is fuel efficiency (e.g., seat-kilometers/kilogram of fuel consumption), Q is the lower heating value of jet fuel, and S is the number of seats.

6. HISTORICAL TRENDS IN TECHNOLOGICAL AND OPERATIONAL PERFORMANCE

6.1 Technological Performance

As shown in Eq. (3), engine, aerodynamic, and structural efficiencies play an important role in determining the energy intensity of an aircraft. Engine efficiency in large commercial aircraft, as measured by the cruise SFC of newly introduced engines, 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 turbofan 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 pressure and temperature within the engine, which is limited by materials and cooling technology, and improving engine component efficiencies. Aerodynamic efficiency in large commercial aircraft has increased by approximately 15% historically, averaging 0.4%/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. Historical improvements in structural efficiency 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 structural efficiency have been largely traded for other technological improvements, such as larger, heavier engines and increased passenger comfort.

6.2 Operational Performance

Infrastructure characteristics also impact efficiency. In particular, delays on the ground and in the air can increase energy intensity. Extra fuel is burned on the ground during various non-flight operations, and hours spent in the air (airborne hours) do not account for more than 75–90% of the total operational hours of the aircraft (block hours). The ratio of airborne to block hours can be treated as ground-time efficiency, η_g. Similarly, non-cruise portions of the flight, poor routing, and delays in the air constitute inefficiencies related to spending fuel during the flight beyond what would be required for a great circle distance 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 are calculated with the assumption that all aircraft fly the entire route at Mach 0.80 and at an altitude of 10.7 km (no climbing, descending, or deviation from the minimum distance, the great circle route). Minimum flight hours represent the shortest time required to fly a certain stage length and reveal any extra flight time due to nonideal flight conditions. The product of η_g and η_a gives the flight time efficiency, η_{ft}. Both η_a and η_g increase with stage length. The lower η_{ft} associated with short-range aircraft is related to the more than 40% of block time spent in non-cruise flight segments. Long-range aircraft operate closer to the ideal as total flight time efficiency approaches 0.9. The impact of operational differences on E_U is evident in Fig. 3, which shows the variation of E_U with stage length for turboprop and jet-powered aircraft (both regional and large jets) introduced during and after 1980. Aircraft flying stage lengths below 1000 km have E_U values between 1.5 and 3 times higher compared to aircraft flying stage lengths above 1000 km. Regional aircraft, compared to large aircraft, fly shorter stage lengths, and therefore spend more time at airports taxiing, idling, and maneuvering into gates, and in general spend a greater fraction of their block time in non-optimum, non-cruise stages of flight. Turboprops show a pattern distinct from that of jets and are, on average, more efficient at similar stage lengths. The energy usage also increases gradually for stage lengths above 2000 km because the increasing amount of fuel required for increasingly long stage lengths leads to a heavier aircraft and a higher rate of fuel burn.

Aircraft E_I is also improved through better utilization (e.g., load factor) and greater per-aircraft capacity (e.g., number of seats). Historically, the load factor on domestic and international flights operated by U.S. carriers climbed 15% between 1959 and 1998, all of which occurred after 1970 at an average of 1.1%/year. Figure 4 shows historical load factor evolution for both U.S. large commercial and regional aircraft. Load factor gains have been attributed to deregulation in the United States and global air travel liberalization, both of which contributed to the advent of hub-and-spoke systems. As airlines have sought greater route capacity, the

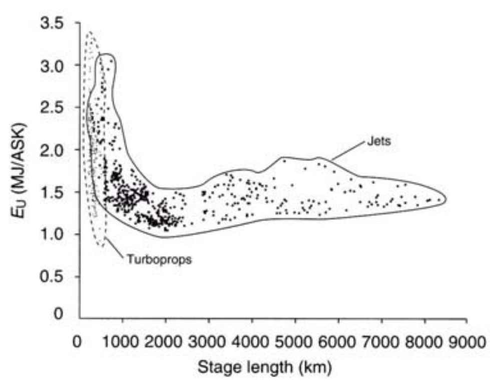

FIGURE 3 Variation of E_U with stage length. ASK, Available seat-kilometers.

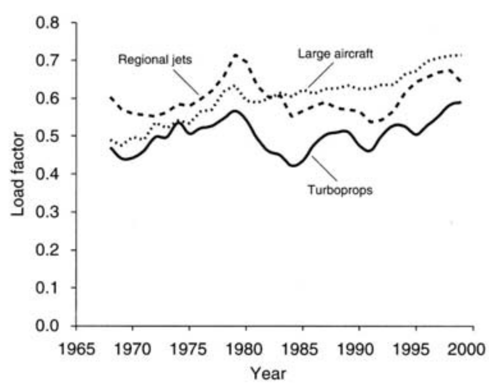

FIGURE 4 Historical trends in load factor for the U.S. large commercial and regional fleets.

average number of seats has also increased, by 35% between 1968 and 1998, or from 108 to 167 seats (an average of 1.4%/year), most of which occurred prior to 1980.

7. TECHNOLOGICAL AND OPERATIONAL OUTLOOK FOR REDUCED ENERGY USE IN LARGE COMMERCIAL AIRCRAFT

The outlook for future reductions in energy use is necessarily based on the potential for increased technological and operational efficiencies. In this section, the outlook for such improvements in large commercial aircraft over the next quarter century is examined.

Engine efficiencies may be improved by between 10 and 30% with further emphasis on moving more mass through engines that operate at higher temperatures and higher pressures. A continuation of the historical trend would lead to a 10% increase in L/D by 2025, and further improvements in the reduction of parasitic drag may extend these savings to perhaps 25%. However, the technologies associated with these improvements have weight and noise constraints that may make their use difficult. For example, 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). However, weight represents an area wherein major improvements may be found without the constraints that may hinder improvement in engine or aerodynamic efficiency. If lighter weight, high-strength materials can be substituted into the predominantly metallic aircraft structures of today, the potential exists for 30% savings through the use of composites to the extent they are currently employed for some military applications.

Although some studies suggest that non-optimum use of airspace and ground infrastructure will be reduced through congestion control, such improvements may only maintain current efficiencies because air traffic growth remains strong. Historical trends for η_g, η_a, and η_{ft} also show constant air traffic efficiencies since 1968. Improved scheduling and equipment commitment can improve load factor, but congestion and low load factor during early morning/late evening flights may limit improvements to the historical rate. This represents a continuation of recent historical trends. At this rate of improvement, about 0.2%/year, the worldwide average load factor is expected to reach around 0.77 by 2025. For an individual aircraft, 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 may grow by 1.0% annually over the next 20 years.

Based on this outlook, a 25–45% reduction in E_U would be possible by 2025. This is equivalent to a change in E_U of 1.0–2.0%/year, i.e., 40–75% of the average rate over the previous 35 years. In terms of E_I, the addition of load factor results in an estimated improvement of 1.2–2.2%/year, or a 30–50% reduction in E_I by 2025. As was shown in Fig. 2, over the period 1971–1985, airlines found profitable an average 4.6%/year reduction in fleet average E_I on an RPK basis, which translates into a slower 2.7% improvement on a seat-kilometer basis when the contribution of load factor is removed (E_U). Over the period 1985–1998, however, the rate of change was slower, at approximately 2.2% in E_I and 1.2%/year in E_U. Fleet average projections in the literature suggest a 1.3–2.5% annual change in fleet average E_I and a 0.7–1.3%/year change in E_U. These studies are consistent with recent historical trends.

Beyond the evolution of the current aircraft platform, hydrogen and ethanol have been proposed as alternative fuels for future low-emission aircraft. Hydrogen-fueled engines generate no CO_2 emissions at the point of use, may reduce NO_x emissions, and greatly diminish emissions of particulate matter. However, hydrogen-fueled engines would replace CO_2 emissions from aircraft with a threefold increase in emissions of water vapor. Considering uncertainties over contrails and cirrus cloud formation, and the radiative impact of water vapor at higher altitudes (Fig. 2), it is not clear whether use of hydrogen would actually reduce the contribution of aircraft to radiative forcing. In addition, several issues must be resolved before a new fuel base is substituted for the existing kerosene infrastructure. The actual usefulness of such alternative fuels requires a balanced consideration of many factors, such as safety, energy density, availability, cost, and indirect impacts through production. Renewable biomass fuels such as ethanol have much lower energy density than does kerosene or even hydrogen, requiring aircraft to carry more fuel. They would again increase water vapor emissions from aircraft in flight. Hence, kerosene is likely to remain the fuel for air travel for the foreseeable future.

8. INDUSTRY CHARACTERISTICS, ECONOMIC IMPACTS, AND BARRIERS TO TECHNOLOGY UPTAKE

Although reducing energy intensity tends to reduce overall emissions, factors inherent to air transportation can act to counter the potential benefits. Reductions in emissions are hindered by the relatively long life span and large capital and operating costs of individual aircraft, and the resulting inherent 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 potentially increase NO_x emissions as a result of higher peak engine temperatures. Further, the impact of any efficiency improvements is diminished by fuel wasted in airborne or ground travel delays or in flying partially empty aircraft. Perhaps most importantly, we do not know the cost of change. In this section, some industry characteristics and the economic impact of introducing energy-saving aircraft technologies are examined.

The lag in technology introduction is apparent in Fig. 2. It has typically taken 15–20 years for the U.S. 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 forces. The models described below consider the limitations on this process imposed by cost factors. In assessing future aviation fuel consumption and emissions, it is important to consider the time delay between technology introduction and its full absorption by the world fleet.

Figure 5 shows the relationship between how much it costs to carry a passenger 1 km, in terms of aircraft operation (direct operating cost/revenue passenger-kilometer) and the fuel efficiency of the aircraft (here in RPK/kilogram) for 31 selected aircraft types during the period 1968–1998. In addition to fuel efficiency, stage length has a strong influence on operating costs of regional (very short stage length) flights. The direct operating cost (DOC)–fuel efficiency relationship is indicative of the use of technological advances for the purposes of lowering operating costs. However, reductions in the future cost stream are purchased through higher capital and investment costs. That is, airlines are willing to pay a higher acquisition cost if they can gain from savings in DOC, mainly through lower fuel and maintenance costs during the lifetime of aircraft. The plot of aircraft price-per-seat versus DOC/RPK in Fig. 6 shows that aircraft price is inversely proportional to DOC.

The DOC–fuel efficiency and price–DOC relationships imply a potential constraint for energy use and emissions reduction in the aviation sector. If the relative changes in DOC and price with respect to technological improvements occur at historically accepted levels, airlines will continue to adopt newer and more efficient technologies at a higher price, balanced by the promise of sufficient future revenue.

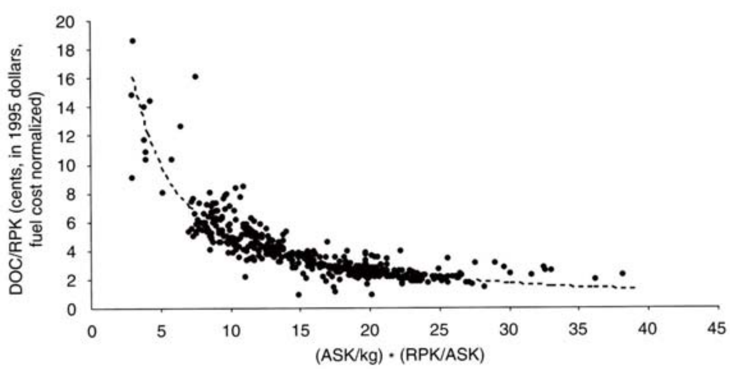

FIGURE 5 Direct operating cost (DOC) and fuel efficiency relationship. The DOC here is composed of crew, fuel, and maintenance costs. RPK, revenue passenger-kilometers; ASK, available seat-kilometers. Reproduced from Lee *et al.* (2001), with permission.

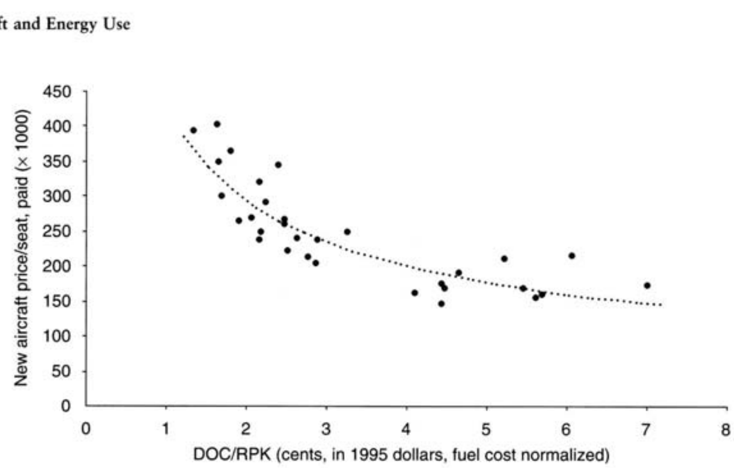

FIGURE 6 Direct operating cost (DOC) and price relationship. Reported prices are average market values paid in then-year (1995) dollars for new airplanes at the time of purchase. All prices were adjusted to 1995 dollars using gross domestic product deflators. RPK, revenue passenger-kilometers. Reproduced from Lee *et al.* (2001), with permission.

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 for energy-saving technologies, in which case further improvements in energy use for the aviation sector may be limited.

SEE ALSO THE FOLLOWING ARTICLES

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