SHORT-HAUL CTOL AIRCRAFT RESEARCH

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SUMMARY

This summary paper reviews the results of the reduced energy for commercial air transportation (RECAT) studies on air transportation energy efficiency improvement alternatives, reviews subsequent design studies of advanced turboprop powered transport aircraft, and discusses the application of this research to short-haul air transportation. Although much has already been published on the RECAT studies, the results of these studies are far from obsolete, and it is important to briefly review these results because of their importance to the ongoing ACEE program. Although most of the ACEE program technology will be applicable to advanced short-haul transport aircraft to some degree, the advanced turboprop is particularly attractive. This will be demonstrated by reviewing the results of several recent turboprop aircraft design studies. The potential fuel savings and cost savings for advanced turboprop aircraft appear substantial, particularly at shorter ranges.

INTRODUCTION

Currently, civil air transportaion consumes about 38 billion liters (ten billion gallons) of fuel annually. While this amounts to less than 2 percent of the total U.S. energy consumption and only 4 percent of the total U.S. petroleum consumption (ref. 1), air transportation is currently 100 percent dependent on petroleum fuels and strongly influenced by the availability and cost of these fuels. Maintaining a healthy air transportation system is important. At present, for any trip greater than a few hundred kilometers, there is no other transportation alternative that can compare in terms of speed, passenger comfort, and reliability. Until such a substitute can be found, we must examine ways to improve air transportation's energy efficiency. Even when alternative fuels are developed, they will undoubtedly be high priced and energy efficiency will still be very important.

Increasing aircraft energy efficiency is not a new objective. It has always been important in terms of performance and operating cost, even at pre-embargo prices. The energy efficiency of the newer, stretched narrow-body jet aircraft is better than the initial smaller jet aircraft and the newest wide-body aircraft are the most energy efficient (fig. 1). From 1965 to 1975, these more efficient aircraft have been added to the airline fleet and the older turbojet aircraft have been replaced (fig. 2). As a result, the average energy efficiency, measured in seat-kilometers per liter (seat-miles per gallon), of the U.S. trunk airlines has increased by 33 percent (fig. 3) over this ten-year period.

An examination of the current U.S. scheduled air carrier fuel usage by stage length and equipment type (fig. 4; refs. 2 and 3) reveals the dominance of the short/medium range operations by the Boeing 727 aircraft. Because of the large number of B727's in service, this single aircraft type currently accounts for 35 percent of the total airline fuel usage (fig. 5). It is also important to note that 53 percent of the airline fuel is used for stage lengths of less than 1600 kilometers (1000 miles) and over 30 percent is used for stage lengths of less than 800 kilometers (500 miles).

While fuel efficiency was important when these aircraft were designed in the 1960's, it has now become one of the major design goals. Until the middle of 1973, the price that the airlines were paying for jet fuel had remained constant for many years. However, since that time, these fuel prices have tripled (fig. 6). Even though labor costs have also increased substantially over this period, these fuel price increases have resulted in fuel cost accounting for a much larger fraction of direct operating cost. In 1973, fuel cost amounted to 25 percent of the direct operating cost for average operation of a Boeing 727; by 1975 it had risen to 38 percent. At the current level of U.S. airline fuel use of 38 billion liters (10 billion gallons) per year, each 0.3-cent per liter (one-cent per gallon) increase in the price of fuel costs the airlines 100 million dollars. Even ignoring the desire to increase airline energy efficiency from a conservation viewpoint, these price increases provide considerable incentive.

RECAT STUDY

From 1974 to 1976 a study examining the "Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System," referred to as RECAT, was conducted under NASA sponsorship. This study involved the coordinated efforts of the Douglas Aircraft Company (ref. 4), Lockheed-California Company (ref. 5), United Air Lines, Inc. (ref. 6), and United Technologies Research Center (ref. 7). The purpose of this study was to examine, on a common basis, many of the alternatives for increasing the energy efficiency of air transportation in order to identify the most promising areas for research and technology emphasis. The alternatives considered included operational procedures (higher density seating, higher load factors, and flight procedures), aircraft modifications, derivatives of current production types, and new aircraft exploiting advanced technology in aerodynamics, composite structure, active control, and advanced propulsion.

Aircraft Operation

One of the quickest methods of increasing aircraft energy efficiency, as measured on a seat-kilometer per liter (seat-mile per gallon) basis, is to increase the number of seats on the aircraft. This can be done by eliminating lounges and garment bag storage areas, reducing the first class/coach seating ratio, increasing the number of seats abreast, and by reducing the seat pitch. Since 1973, the airlines (as indicated by data from United Air Lines) have increased the seating density considerably by these methods. To serve as a basis of comparison in the RECAT studies, a baseline increased density seating configuration was specified. This seating configuration represents a 10 percent first class/90 percent coach arrangement with 965-mm (38 in.) first class/864-mm (34 in.) coach seat pitch and seats in place of garment bag storage on the Boeing 727 and 737 aircraft. These seating density increases result in aircraft energy efficiency increases ranging from 5 to 22 percent relative to 1973 (fig. 7).

While these increases in seating density look very favorable in terms of energy efficiency measured in seat-kilometers per liter (seat-miles per gallon), they really represent a ficticious improvement unless the number of passengers per flight increases also. The increase in passengers per flight can be obtained by increasing the seating density and holding the passenger load factor constant or just increasing the load factor. An increase in load factor from 50 to 60 percent is equivalent (in terms of passengers carried) to a 20 percent increase in seating density with a constant load factor of 50 percent. When frequency of service, load factor, and seating density are considered, the most efficient aircraft for transporting passengers over a given route network is not necessarily the aircraft with the highest energy efficiency in seat-kilometers per liter (seat-miles per gallon). For example, over a 1000 n. mi. stage length (fig. 8), even though a Boeing 737 (17 seat-kilometers per liter (39 seat-miles per gallon)) is some 26 percent less energy efficient in seat-kilometers per liter (seat-miles per gallon) than a DC10 (23 seat-kilometers per liter (53 seat-miles per gallon)), the B737 is the most energy efficient aircraft in terms of passenger-kilometers per liter (passenger-miles per gallon) for carrying less than 97 passengers.

In addition to passenger capacity, another factor which must be considered when comparing aircraft energy efficiency is the aircraft's range capability. For example (fig. 9), at short stage lengths the Boeing 737-200 is more energy efficient in seat-kilometers per liter (seat-miles per gallon) than the Boeing 727-200 or Douglas DC8-61. However, at medium stage lengths, the B727-200 is more energy efficient than the B737-200 or DC8-61. And at longer stage lengths, beyond the capability of the B737-200, the DC8-61 is more energy efficient than the B727-200. In order to provide the long range capability of the DC8-62 or the B747-100, some penalty in shorter range energy efficiency is incurred. In order to maximize aircraft energy efficiency, it is very important to critically examine the desire for extra range capability for scheduling flexibility against the actual range required for the stage lengths on which the aircraft will be flown.

Although the energy efficiency improvements possible with increased seating density and higher load factors are large initially, they are limited in extent and are obtained at the expense of passenger comfort and convenience. Another means of increasing aircraft energy efficiency is with fuel conservative flight procedures and increased aircraft maintenance. In the RECAT studies these operational alternatives were grouped into those that could be implemented within the current air traffic control (ATC) system and those that could be obtained with ATC advances (fig. 10). Within the current ATC system small percentage improvements in energy efficiency can be obtained by reducing cruise speed to long range cruise (maximum n.mi. per kg of fuel) levels, reducing the current step climb increment from 1.2 to 0.6 km (4000 to 2000 ft) to allow closer adherence to optimum cruise altitudes, loading the aircraft closer to the aft c.g. to reduce trim drag, increasing airframe maintenance to reduce excrescence drag, reducing the operating empty weight slightly by removing any accumulated unnecessary equipment, and increasing engine maintenance to reduce the engine specific fuel consumption deterioration with time. Additional operational energy efficiency improvements that require ATC system advances include cruise climb to maintain the optimum cruise altitude, reducing holding delays by an average of one minute, and reducing terminal area delays by an average of four minutes. While the individual fuel savings that are obtainable with improved flight procedures and increased aircraft maintenance attention are small, the summation is significant and worthy of attention.

Aircraft Modification

Another means of improving aircraft energy efficiency, without sacrificing passenger comfort and convenience, is by modification of the current aircraft types. In the RECAT study, the modifications that were examined ranged from adding improved aerodynamic fairings to retrofitting with new engines (fig. 11). The effect of the most promising modifications on the respective aircraft energy efficiency ranged from 4 to 39 percent. The largest aircraft energy efficiency increase was obtained by replacing the existing turbojet engines on the DC8-20 with new refan JT8D engines. However, this modification was estimated to cost about $5 million per aircraft and appeared economically unattractive unless required for some other reason, such as noise abatement. While the aerodynamic modifications offered smaller percentage improvements on the order of 4 to 8 percent, the estimated modification costs were also considerably smaller and appeared economically reasonable. This was particularly true for those aircraft that are expected to remain in service for many years.

Derivatives and New Turbofan Powered Aircraft

Some of the more extensive design modifications are only feasible for new production versions or derivatives of the current aircraft. Derivatives are of interest because they allow the manufacturer and the airlines to capitalize on the experience that has been obtained on that aircraft type and to minimize the development expense that is required. In the past, the most common derivatives have involved a fuselage stretch to increase the aircraft capacity in response to increasing passenger demand. Now, in addition to this desire and with much higher fuel costs, these derivatives must also be designed to operate more efficiently. The effect of increased fuel price on aircraft design is reflected, of course, in increased emphasis on aerodynamics, structures, and propulsion efficiency. Externally, this is most evident in the wing design. At yesterday's fuel prices, the optimum aircraft for minimum direct operating cost (DOC) was designed to cruise at Mach 0.85 and had a wing aspect ratio of about 8 and a wing sweep of about 35°. At a fuel price of 16¢/liter (60¢/gallon), the optimum turbofan powered aircraft for minimum DOC would cruise at Mach 0.78 and have a wing aspect ratio of about 11 and a wing sweep of 28°. If the aircraft was designed for minimum fuel usage, regardless of the economics, the optimum cruise speed drops to Mach 0.7 with a straight wing and a wing aspect ratio over 15.

New Turboprop Powered Aircraft

In the 1950's, the seemingly unlimited supplies of cheap jet fuel coupled with the speed and altitude advantages of the turbojet resulted in its being favored over the 1950's turboprop. Today's environment of higher fuel prices and energy conservation have necessitated a re-examination of the turboprop-- not the 1950's version, but a new, highly loaded, multibladed turboprop using advanced blade structure and aerodynamics technology for efficient, high-speed operation. Because this concept lies between the conventional turboprop and an unshrouded, high bypass ratio turbofan, the Hamilton-Standard Division of United Technologies refers to it as the propfan. Based on analysis and wind-tunnel tests (ref. 8), the propulsive efficiency of the advanced turboprop or propfan is about 20 percent better at Mach 0.8 than a high bypass ratio turbofan (fig. 12). This efficiency advantage is even greater at lower speeds, increasing to 35 to 40 percent at Mach 0.7. In order to evaluate the overall impact on complete configurations and to identify the critical technology areas, three design studies of propfan powered aircraft have been completed to date.

Because of different study ground rules and assumptions, the propfan aircraft fuel savings identified in these three studies ranged from 8 to 28 percent in comparison with their turbofan counterparts for a 1000 n.mi. stage length (fig. 13). In all cases, the efficiency advantages of the propfan compared to the turbofan are greater at lower altitudes and speeds, and this results in larger fuel savings at shorter stage lengths. This is one reason why the propfan looks particularly attractive for the short- and medium-haul markets currently being served by the short-medium range DC9, B737, and B727 aircraft.

The largest fuel savings identified in these studies were for a propfan derivative DC9-30 investigated by the Douglas Aircraft Company. For this comparison, the derivative was not resized to the same design range as the baseline DC9-30. Instead, the gross takeoff weight and payload were held constant. The takeoff, approach, and cruise performance of the propfan derivative were chosen to match the baseline DC9-30 performance and the propfan was sized for Mach 0.8 cruise at 9-km (30 000 ft) altitude. Two levels of porpfan performance were examined. One propfan design was based on performance levels corresponding to an eight-blade propfan with a rotational tip speed restricted to 67 meters/sec (720 fps), corresponding to the Lockheed Electra Propeller, and current technology turboshaft engine performance. This resulted in a propeller efficiency of 0.73 and an installed cruise thrust specific fuel consumption (TSFC) of 0.066 kg/hr/N (0.65 lb/hr/lb). The other propfan design was based on an eight-bladed propfan with a 74-meters/sec (800 fps) tip speed and turboshaft engine performance corresponding to JT10D/CFM56 turbofan core engine technology. This resulted in a propeller efficiency of 0.80 and an installed TSFC of 0.054 kg/hr/N (0.53 lb/hr/lb). Depending on the assumed propulsion system efficiency, the derivative propfan would use from 27 to

33 percent less fuel than the current DC9-30 at its average operational stage length of 290 n.mi. For the same takeoff gross weight with a passenger load factor of 58 percent, this fuel savings would also translate into a maximum range capability improvement of 41 to 73 percent, depending on the propulsion system efficiency assumed.

The fuel savings shown for the DC9 propfan derivative are larger because the comparison is with an older technology, low bypass ratio, JT8D turbofan rather than a comparable technology turbofan. However, the DC9 propfan derivative does not include the application of any of the other advanced aerodynamics, structures, or active controls technologies that could improve the efficiency still further. Also, the low bypass ratio JT8D engines are the ones that are currently in service and being sold in large quantities on this airplane type.

Another advanced turboprop design study was conducted with the Boeing Commercial Airplane Company (ref. 9). In this study, two propfan powered configurations were compared with an equivalent technology level advanced turbofan powered aircraft. These aircraft were designed to carry 180 passengers in equal comfort for a maximum range of 1800 n.mi. at a cruise speed of Mach 0.8. All three configurations were twin-engine, wide-body aircraft using 1976 design airframe technology and engine technology corresponding to 1980-1985 certification. One propfan design had the engines mounted on the wings, the other had the engines mounted on struts attached to the fuselage aft body. The fuel savings identified in this study were more modest, amounting to 13.5 percent for the wing-mounted propfan configuration at a 500 n.mi. stage length and 13 percent for the aft-mounted configuration. These smaller fuel savings reflect the Boeing study assumptions of a propfan noise level in cruise 10 db higher than the Hamilton-Standard noise goal, resulting in a larger acoustic treatment weight penalty, and an increase in drag due to the effect of the propeller slipstream on the wing aerodynamics. These are two of the critical technology areas that are currently being investigated experimentally.

The most recent advanced turboprop design study was a follow-on to the Lockheed-California Company RECAT study (ref. 10). In the original RECAT study, Lockheed examined a four-engine propfan powered aircraft in comparison with an equivalent technology level advanced turbofan (JT10D) powered aircraft. These aircraft were both designed to carry 200 passengers in equal comfort for a maximum range of 1500 n.mi. at Mach 0.8 cruise speed. The technology levels reflect 1985 service introduction and include a supercritical airfoil, aspect ratio 10 wing, active controls for longitudinal stability augmentation, and composite secondary structure. The most recent Lockheed-California study also used these design groundrules for the baseline turbofan and propfan aircraft but expanded the original study to include a comparison at Mach 0.75 cruise speed, 2000 n.mi. design range, and an investigation of alternative advanced engines. The data shown on figure 13 reflects the latest study results for the 1500 n.mi. design range and the propfan powered by a Pratt & Whitney study turboshaft engine (STS 476) based on the JT10D engine core. The resulting fuel saving for the Mach 0.8 cruise speed propfan aircraft compared to a JT10D technology turbofan at Mach 0.8 cruise speed was 19.6 percent for a typical in-service stage length of 475 n.mi. and a 58 percent passenger load factor. This fuel saving increased to 22.9 percent when the cruise speed was reduced to Mach 0.75 for both of these aircraft.

These fuel savings translate into the DOC savings shown in figure 14. These cost savings are for the average in-service stage length assumed for the three studies and are shown as a function of fuel price. The largest savings in operating cost are indicated for the Lockheed propfan aircraft at a cruise speed of Mach 0.75.

Fuel Savings Potential

The RECAT study examined many alternatives for increasing air transportation energy efficiency. In comparing the energy efficiency of current aircraft, modified versions of these aircraft, new near-term aircraft using current technology, and the 0.8 M Lockheed propfan aircraft (CL-1320), the improvement potential is very encouraging (fig. 15). Compared with the DC8-61 for a 1000 n.mi. stage length, a short-body DC10 derivative could save 26 percent in fuel and provide an energy efficiency improvement of 35 percent in seat-kilometers per liter (seat-miles per gallon); a new near-term aircraft using current technology but designed for minimum DOC with 16¢/liter (60¢/gallon) fuel could save 39 percent in fuel and provide a 64 percent improvement in seat-kilometers per liter (seat-miles per gallon); a new advanced technology propfan aircraft could save 52 percent in fuel and provide a 108 percent improvement in seat-kilometers per liter (seat-miles per gallon).

The relative attractiveness of these alternatives is a question of timing and economics. The potential improvement over time is very high (fig. 16). In the near term, extending from 1972 to 1980, energy efficiency improvements will require strenuous attention to the individually small improvements possible with increased load factor, increased seating density, fuel conservative flight procedures, and the gradual replacement of older aircraft with current production types. The airlines have already accomplished a lot in this direction (ref. 11). As a result, the energy efficiency of the U.S. scheduled airlines has risen from 7.4 passenger-kilometers per liter (17.5 passenger-miles per gallon) in 1973 to 8.8 (20.7) in 1976. The airlines actually used 3 billion liters (800 million gallons) less fuel in 1976 than in 1973, while carrying 21 million more passengers. From 1980 to 1985, the introduction of modifications and derivatives of current aircraft can provide continuing increases in efficiency. And, beyond 1985, sufficient advanced technology should be available to justify the development costs of completely new aircraft. By the end of the century, the energy efficiency of air transportation may be twice what it is today. Regardless of whether petroleum derived fuels are still being used, the fuel will undoubtedly be high priced and precious, and these efficiency improvements will be required.

SHORT-HAUL CTOL RESEARCH

As evidenced by the fact that over half of the fuel used by air transportation is used on stage lengths of less than 1600 kilometers (1000 miles), increasing the energy efficiency of short-haul CTOL transports is extremely important. It appears that most of the research in the ACEE program is equally as applicable to the large short-haul CTOL aircraft as it is to long-haul

CTOL aircraft (with the possible exception of laminar flow control). The problem is just more difficult. The aircraft total operating costs per seat-kilometer are higher at the shorter stage lengths and the IOC's become more important. The aircraft spends a larger fraction of its time at the gate loading and unloading passengers and cargo, taxiing in and out, waiting in line for takeoff, climbing and descending, and being routed around in the terminal area. Because this emphasis on performance in the terminal area was recognized many years ago, NASA embarked on research programs oriented toward short-haul powered lift transports for high density markets. Example programs are the Quiet Short-Haul Research Aircraft (QSRA) and the Quiet Clean Short-Haul Experimental Engine (QCSEE). In addition, NASA will conduct flight experiments with the prototype aircraft developed in the Air Force AMST program (YC14 and YC15). These are technology programs oriented toward a thorough understanding of powered lift aerodynamics combined with high bypass turbofan propulsion technology for transport aircraft with short field length capability. Because the advanced turboprop offers efficiency advantages over the turbofan, particularly at the lower altitudes and speeds encountered more frequently on short-haul flights, it looks particularly attractive for advanced short-haul RTOL and CTOL transport aircraft. In support of advanced turboprop research, Ames Research Center has research underway emphasizing advanced turboprop engine-airframe integration technology. The tradeoffs on aircraft design to improve the efficiency and economics for advanced large short-haul CTOL transport aircraft will continue to be examined as the ACEE program research proceeds.

More recently, a modest program has been initiated which is oriented toward the small short-haul CTOL transport aircraft used by the local service and commuter carriers. This is the area where the lack of modern aircraft technology is most apparent. There are many aircraft used today in short-haul air transportation which represent relatively "old" technology, and there are many others which are being operated very inefficiently at short stage lengths. Development of the appropriate technologies for a new, small short-haul aircraft can only come from a better understanding of the diverse nature of the short-haul market and a clear definition of aircraft requirements both in terms of aircraft characteristics (size, speed, etc.) and possible technology improvements. For civil systems, this can only be done through a continuing interchange of ideas with the aircraft-manufacturing and airline industries and an understanding of possible government regulatory and policy actions. As part of this process, the NASA Ames Research Center sponsored a two-day symposium in November 1977, on small community air service, with emphasis on interregional service. The objective of the symposium was to provide a forum for the discussion of the markets for short-haul air transports, aircraft definition, and technology status and future requirements. Because of the diverse market requirements it is obvious that no one aircraft can be defined in terms of size, cruise speed, and field length to satisfy all short-haul markets in an optimum way. However, it is apparent that the potential exists for advanced technology specifically designed for short haul that will have a positive effect on any new aircraft that is developed.

The appropriate research program for small CTOL transport aircraft is still in the early stages of definition. However, the emphasis to date is being placed on modern wing technology for cruise at Mach 0.7 to 0.75 with improved aerodynamics, on the application of new materials and structural design techniques for reduced weight and cost, on the development of advanced aircraft systems, on advanced turboprop propulsion systems, on low cost avionic systems, and on improved high-lift devices. With emphasis on potential near-term developments, reduced aircraft initial and operating cost becomes a major criterion for all aspects of this program.

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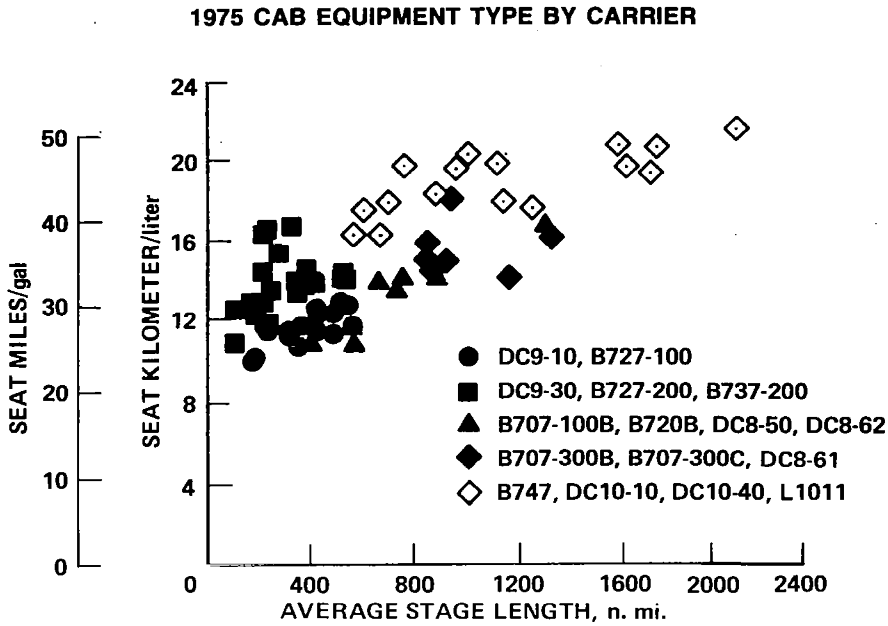


Figure 1.- Airline aircraft energy efficiency.

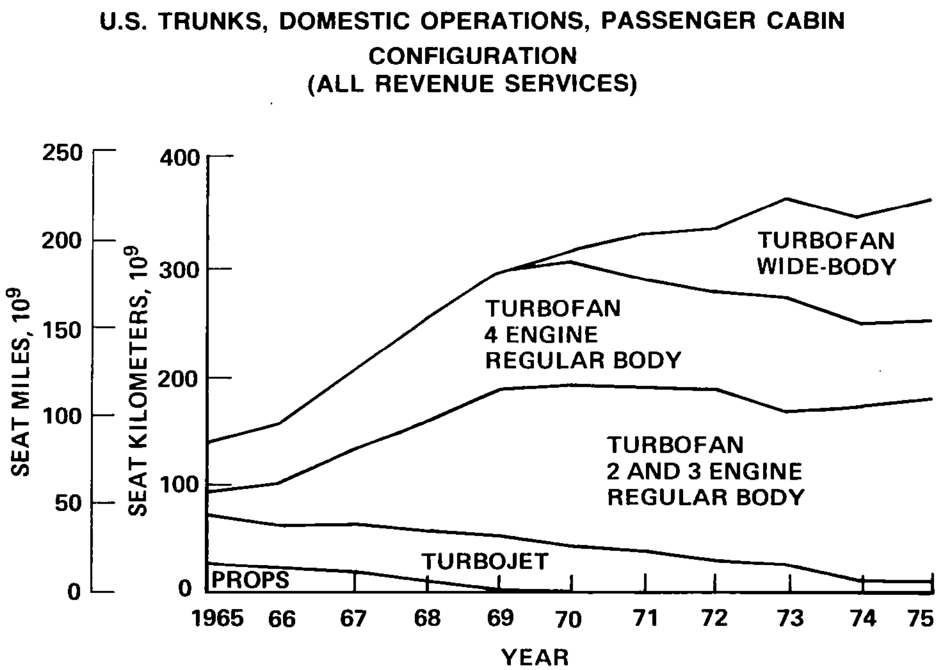


Figure 2.- Airline capacity by equipment group.

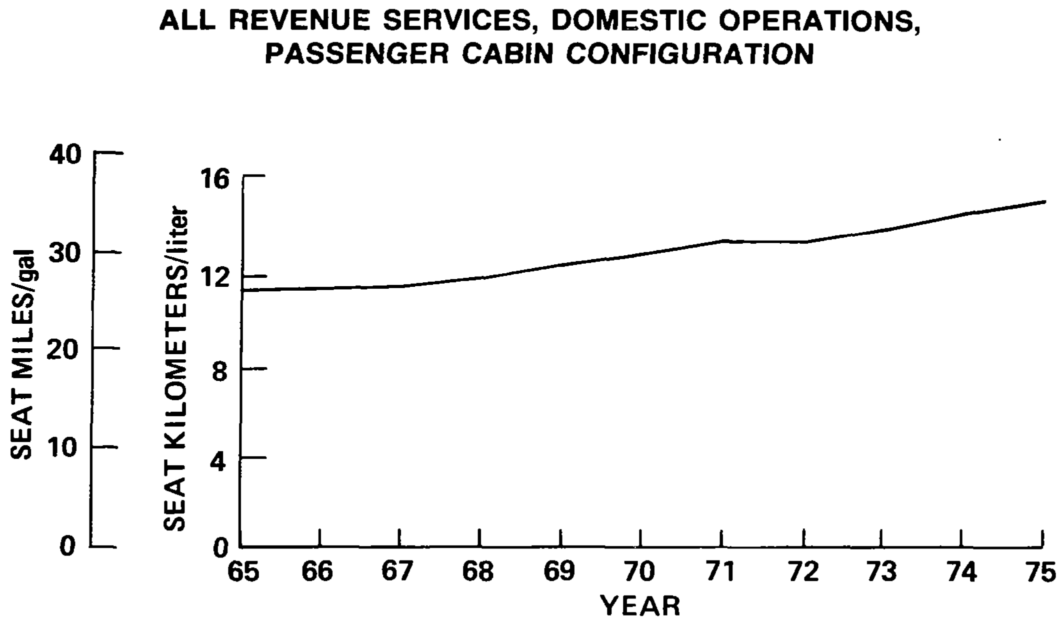


Figure 3.- Average U.S. trunk airline energy efficiency.

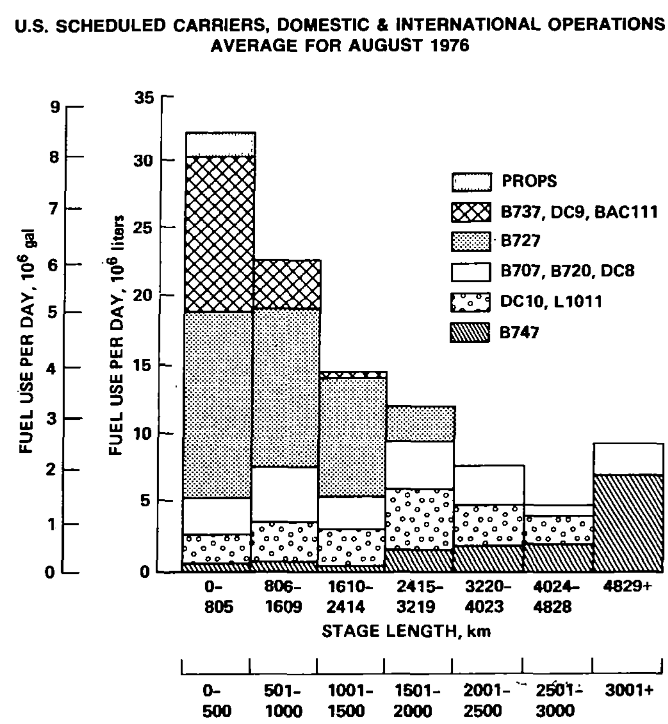


Figure 4.- Aircraft fuel usage.

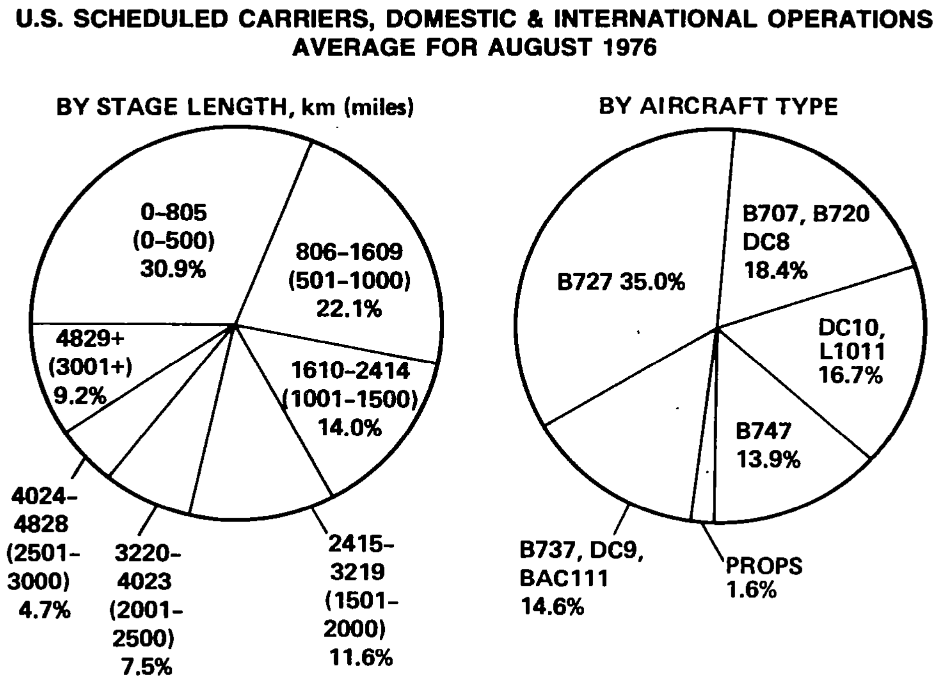


Figure 5.- Aircraft fuel use distribution.

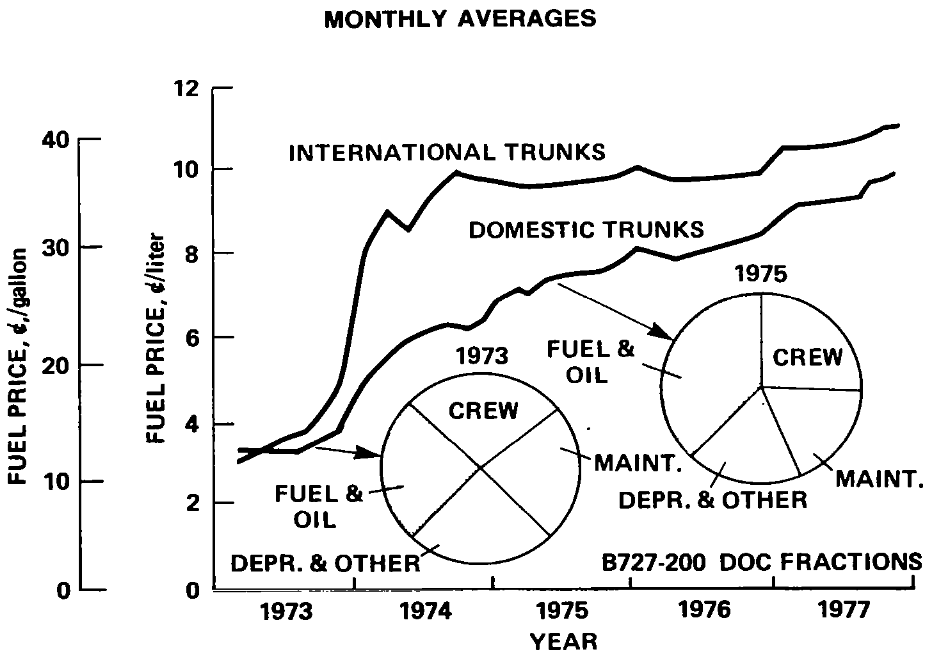


Figure 6.- U.S. airline jet fuel price.

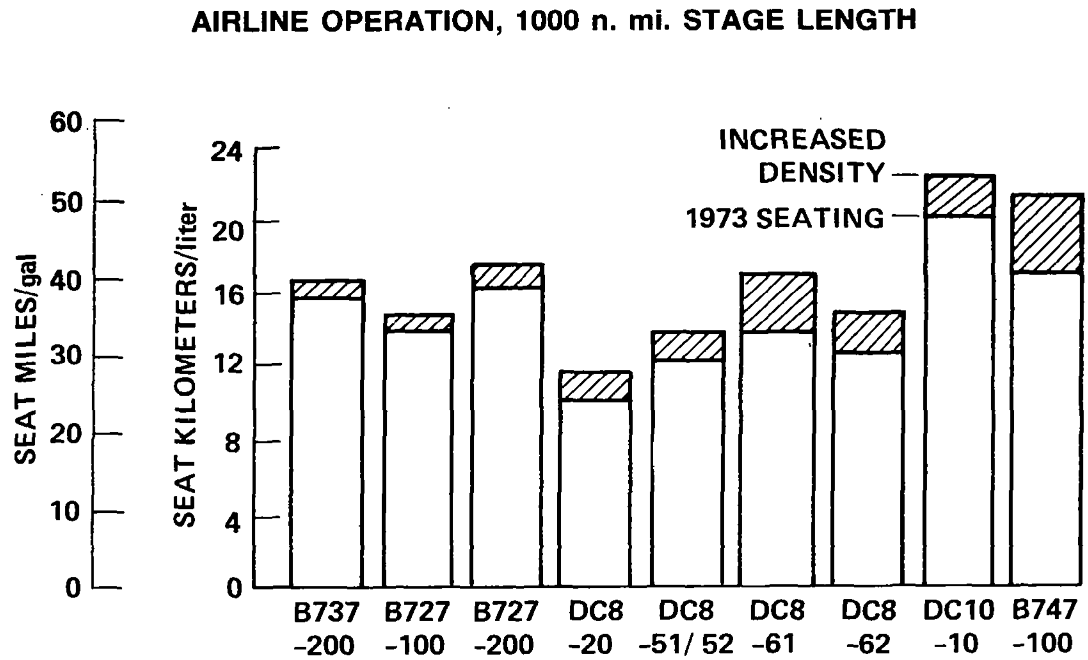
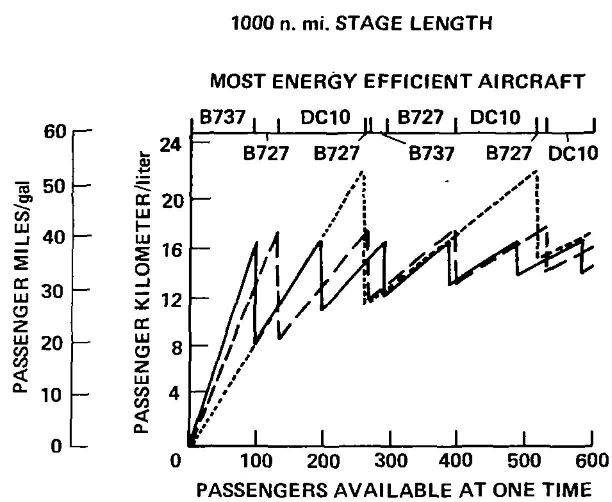


Figure 7.- Effect of seating density on aircraft energy efficiency.



	AIRCRAFT	SEATS	SEAT KILOMETER / liter	(SEAT MILES / gal)
———	B737-200	97	16.5	(38.8)
----------	B727-200	132	17.7	(41.6)
— — —	DC 10-10	258	22.4	(52.7)

Figure 8.- Aircraft energy efficiency versus passengers carried.

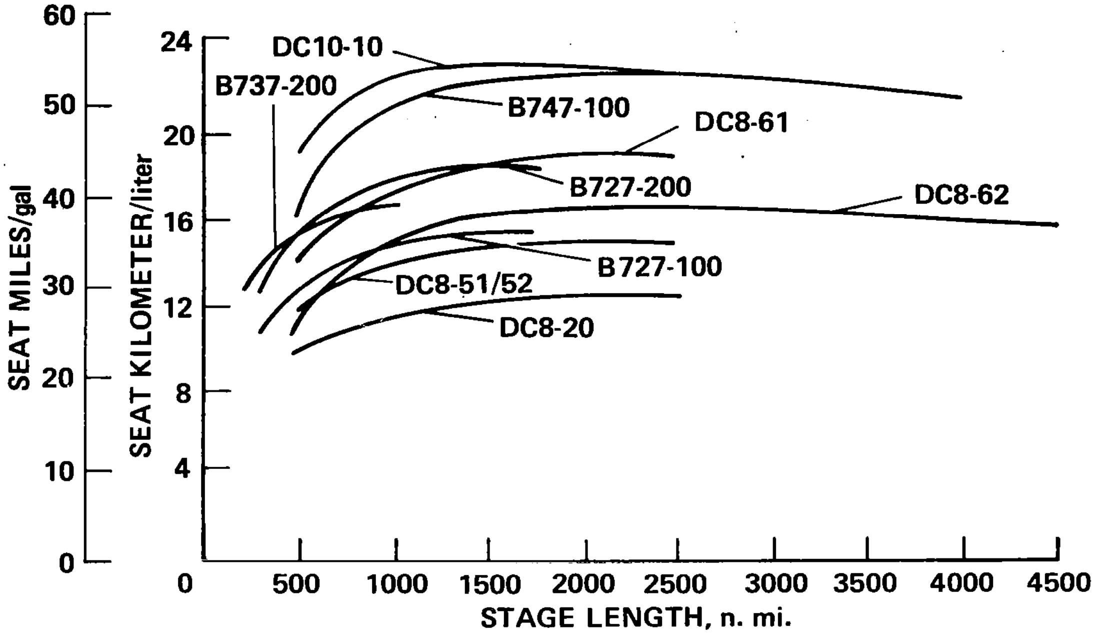


Figure 9.- Aircraft energy efficiency versus stage length for airline operation with increased density seating.

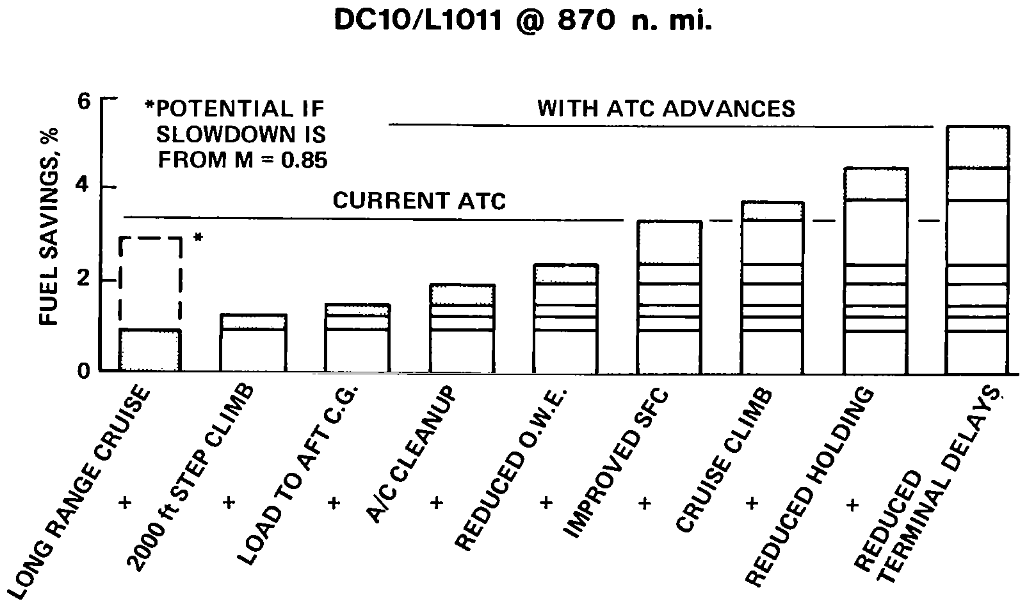


Figure 10.- Effect of flight procedures and aircraft maintenance.

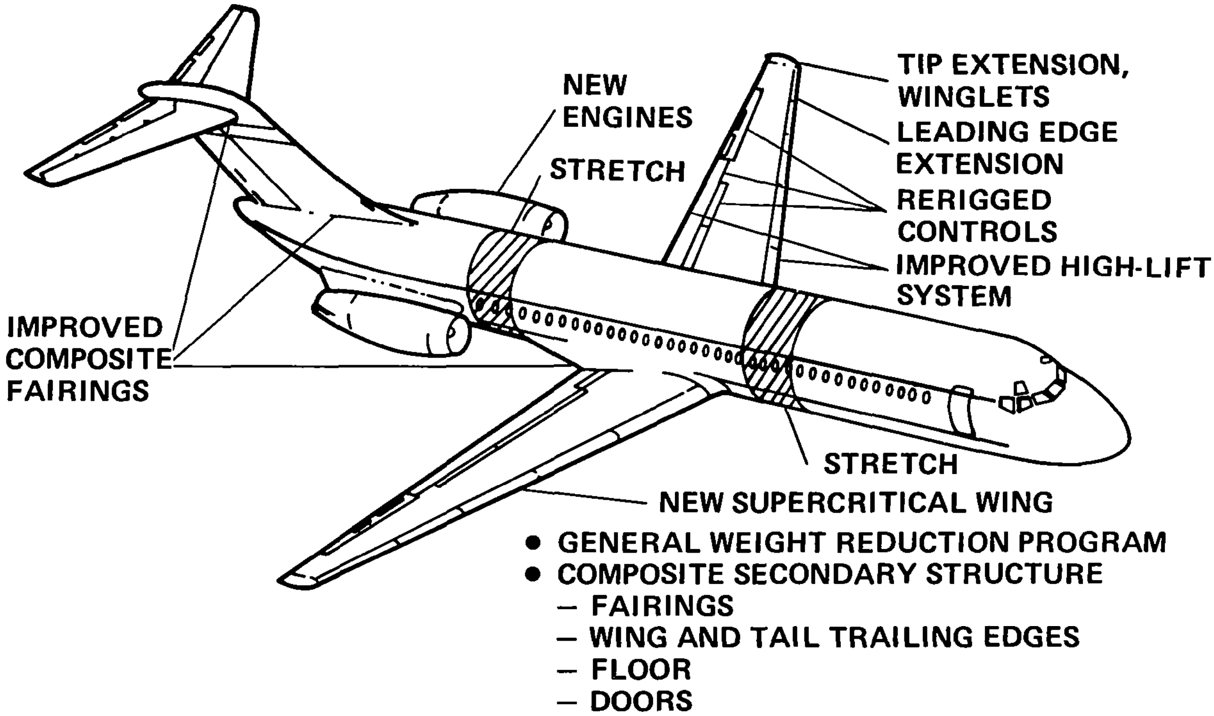


Figure 11.- DC-9 modification and derivative considerations.

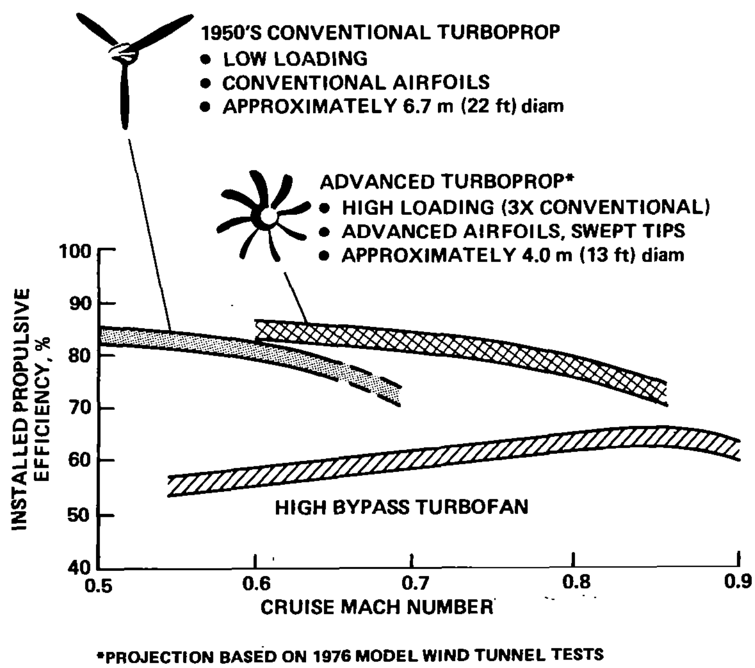


Figure 12.- Propulsive efficiency.

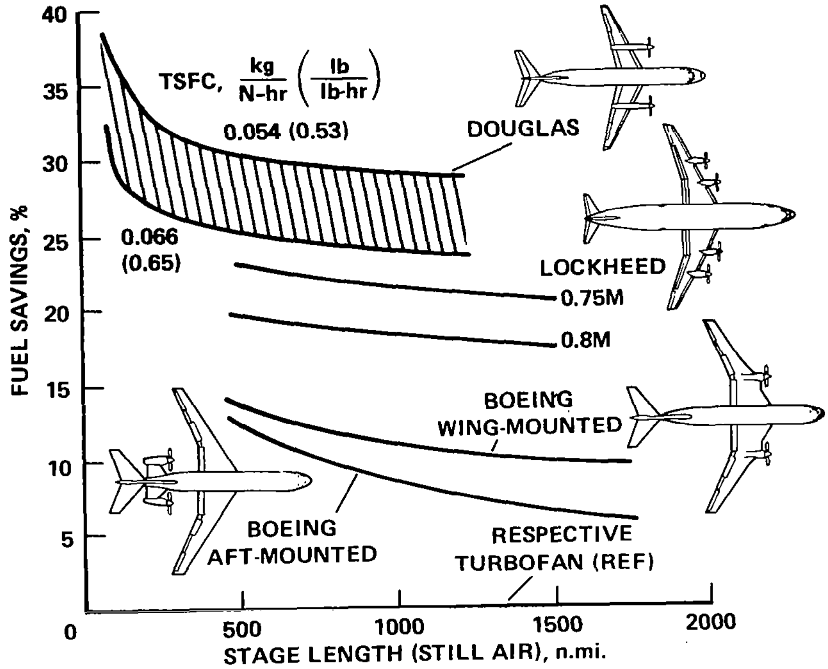


Figure 13.- Propfan aircraft fuel savings.

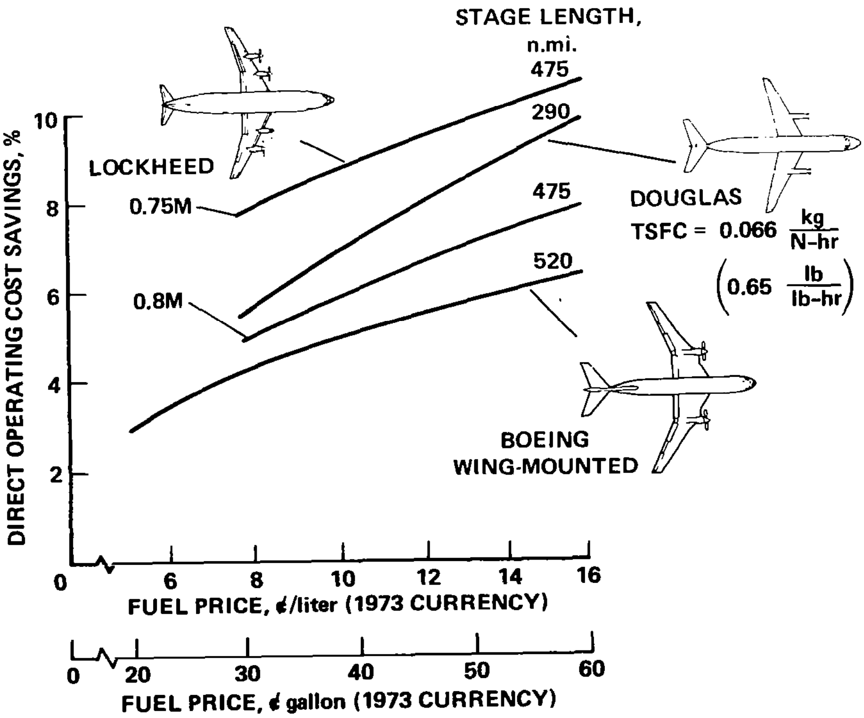


Figure 14.- Propfan aircraft cost savings.

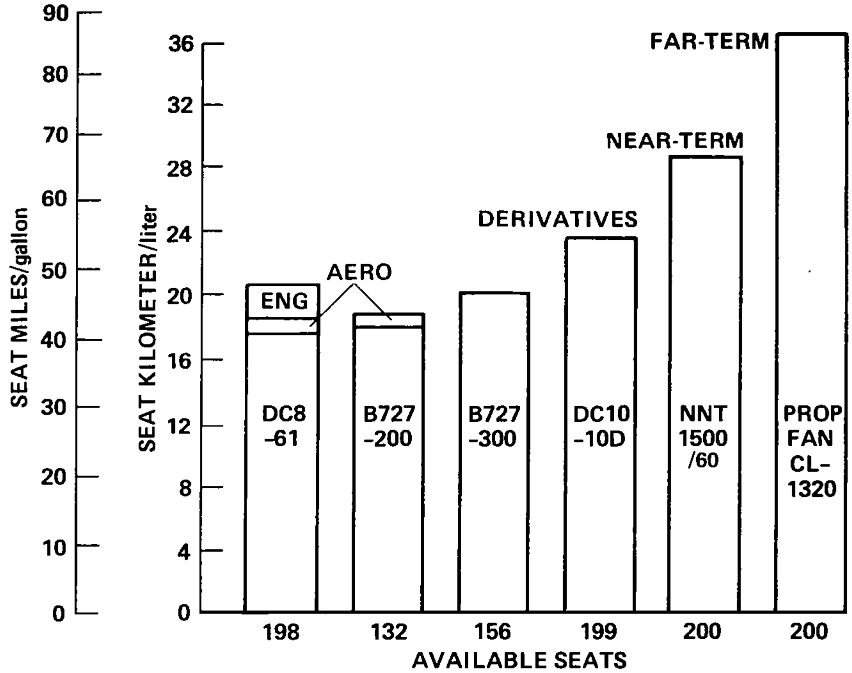


Figure 15.- Aircraft energy efficiency — modifications, derivatives, and new aircraft for airline operation over 1000 n.mi. stage length.

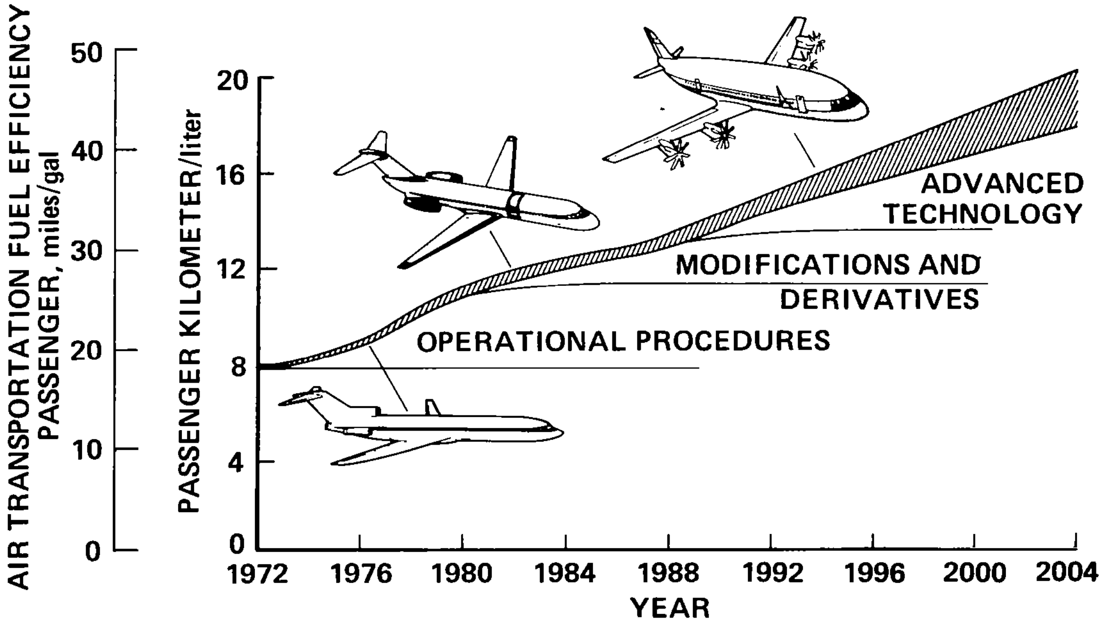


Figure 16.- Air transportation energy efficiency.