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AIRPLANE ENERGY USE and CONSERVATION STRATEGIES

David A. Pilati

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AIRPLANE ENERGY USE AND CONSERVATION STRATEGIES

DAVID A. PILATI

MAY 1974

ORNL-NSF Environmental Program

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ABSTRACT

Domestic commercial airplane fuel use is examined as a function of stage length. A fuel use model is developed using eight of the most popular airplanes. Short flights are very fuel inefficient — a 100-mile flight consumes 2.5 times as much fuel per passenger-mile than a 1,000-mile flight. There are more inefficient short flights than one might expect — half of the flights are for distances under 260 miles.

Fuel consumption for purposes other than flying directly between airports is examined. Over 10% of the total fuel use is for those portions of the flight in which no enroute distance is achieved. Delays account for at least 4.2% of the fuel consumption and auxiliary power units use over 1%. Fuel requirements for attempting to recover lost time and for fuel ferrying are also discussed.

Airplane fuel efficiency can be increased in the short term by operational changes. Increased load factor offers the greatest potential for reducing airplane energy intensiveness. A load factor increase from 50 to 60% would reduce airplane fuel use by 16% for the same traffic. Other fuel-conserving options include reducing cruise speeds, increasing cruise altitudes, and changing ground operations. Each of these strategies offer savings of 1-3%. As fuel prices increase, these options become economically attractive.

Total transportation energy use can be reduced by shifting air passengers to ground modes. Such a shift may be desirable for the inefficient short-stage traffic. The net energy savings for diverting half the flights under 200 miles to buses or trains is equivalent to 6% of the fleet fuel use.

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I. INTRODUCTION

Transportation uses 24% of the total U.S. energy budget. In 1970 the National Petroleum Council[1] predicted that by 1985 transportation's relative energy share would decrease slightly but its absolute energy use would increase by 74%. The Department of the Interior[2] projected that transportation energy consumption would increase by a factor of 2.5 between 1971 and the end of the century.[2]

In 1971, 95% of the propulsion energy requirements for transportation were derived from petroleum. Transportation is the major user of petroleum, accounting for 53% of the total.[2]

Energy use invariably leads to environmental impacts. Although transportation's energy share is only 24%, this use generates 51% (by weight) of the total air pollutants. Over 77% of carbon monoxide generation can be attributed to the movement of goods and people. Transportation is also the most significant source of noise pollution.[3]

Airplanes are the most energy-intensive transport mode. Previous studies[4] showed that each ton-mile (TM) of freight moved by air requires 15 times the energy required for movement by truck and over 60 times that required by train. More than five times the energy per passenger-mile (PM) is required by airplanes as compared with buses.

Both freight movement and personal travel by air are increasing more rapidly than any other mode. Domestic passenger-miles traveled by air increased an average of 14% per year from 1960 to 1970. During this same period, freight movement by air increased nearly 15% per year.[5] In the 10-year span from 1970 to 1980, an average annual growth rate in domestic

air passenger travel of 9% has been predicted, while freight's growth rate may increase slightly (ref. 6 for 4.3% GNP growth rate).

This rapid growth of airplane use will increase the relative energy use by this mode: predicted annual growth rate of jet fuel production from 1970 to 1985 is 8.4% — more than twice the estimated petroleum demand growth rate.[1] By 1985, jet fuel use will be nearly 10% of total petroleum demand compared with less than 5% in 1970. This demand will have strong competition from household heating requirements, central power station use, petrochemical needs, and other transport modes.

A goal of this report is to provide better understanding of how fuel* is used by the domestic fleet of airplanes. Aggregated information concerning airplane fuel consumption and transport service from a number of sources has been used in several studies[4,8] that sought to obtain the average energy intensiveness (Btu/PM or Btu/TM) of the domestic fleet. But this fleet consists of many different airplanes that differ in size, weight, engine type, and use. Therefore, a more detailed analysis has been used in this study.

Another goal is to assess the possible fuel savings for several energy-conservation strategies. The knowledge gained and techniques employed in the fuel-use portion of this report are extended to obtain these assessments. Mutch[9] evaluated several airplane fuel-conservation strategies using approximate fuel-consumption equations. He also obtained the energy intensiveness of the U.S. fleet as a function of trip distance. Although his approach differs considerably from this

---

*Only propulsion energy requirements are considered here. This direct energy use accounts for about 75% of the total energy requirements for commercial airline services.[7]

report, the results and conclusions are quite similar. Where possible, comparisons with this work are included.

A fuel-use model of the domestic passenger/cargo (P/C) airplane* fleet is developed in Section II. The fleet model is obtained from information on eight of the most popular airplanes.

Section III describes how the fleet consumes fuel. The fleet model is employed to obtain the energy intensiveness (EI) of airplane flights as a function of stage length.** Several fuel uses not explicitly obtainable from the model are discussed and evaluated where possible. These uses include consumption of fuel by auxiliary power units, because of delay, and for fuel ferrying.

Section IV evaluates the fuel savings for various energy-conservation strategies. The fleet model is again employed for several of these evaluations. These fuel-saving strategies include increasing load factors, altering modal mix for stages under 200 miles, reducing cruise speeds, cruising at more optimum altitudes, and using alternative ground operations. Possible means of implementing several of these strategies are discussed.

The appendix discusses the various data and assumptions used in the calculations.

The petroleum supply situation changed drastically concurrently with this work. The Middle East oil embargo has particularly affected transportation. Therefore, past fuel-use projections may not be realistic due to severe supply shortages.

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*A passenger/cargo airplane is one that is used primarily for passengers with some cargo space available.

**Stage length is the distance between airports for a single airplane hop. One trip might consist of several stages.

Fuel shortages have already impacted airline operations. Many of the energy-conserving recommendations in this study have been implemented. Most notable of these are capacity cutbacks, cruise speed reductions, and minimization of engine use on the ground. The Federal Aviation Administration (FAA) and the airlines are making a concerted effort to fly airplanes near their optimum altitudes and to decrease delay times.

II. FLEET MODEL

A. 1971 Domestic Commercial Aircraft Fleet

The domestic* fleet consists of many types of aircraft designed for particular tasks. Some airplanes carry only cargo, others carry passengers and cargo (P/C), and still others can be converted to cargo or P/C. Several characteristics of the domestic cargo-only and P/C airplanes are given in Table 1.** Compared with P/C aircraft, cargo-only airplanes fly nearer capacity, fly longer stage lengths, and are more energy efficient. The higher EI of P/C airplanes can be attributed to lower load factors, shorter stage lengths, reduced carrying capacity and a different distribution of aircraft. Because P/C aircraft consumed over 95% of the total fuel consumption (1971) for the domestic fleet, cargo-only planes will not be considered further.

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*Domestic as used here refers to flights within the 50 states and the District of Columbia by a U.S. air carrier.

**All quantitative information in this subsection was obtained using data in ref. 10.

Table 1. Several characteristics of the cargo-only and P/C domestic fleet (1971)

	Overall load factor (%)	Average stage length (miles)	EI (Btu/TM)[a]
Cargo-only	47	990	32,600
Passenger/cargo	41	425	79,200

[a]Numbers in this report are rounded to three significant figures.

Source: ref. 10.

To understand more clearly the fleet fuel use, the P/C airplanes have been disaggregated into several groups. Figure 1 displays PM, average EI, and number of flights for 15 groups of aircraft for 1971. Only fixed-wing aircraft have been included since helicopters carry only a very small fraction of the total air traffic (0.007% of the TM and 0.02% of the fuel use in 1971).*

Turbojet airplanes are more energy intensive than turbofans. Three of the four turbojet groups (Fig. 1) have EI's which are greater than or equal to the EI for all other jet-powered airplanes. The only wide-bodied jet in 1971, the Boeing 747, is the least energy intensive. Turboprops and piston aircraft are somewhat energy inefficient, on the average, because they are used extensively for short hops.

B. Model Description

The fleet fuel-use model is a synthesis of airplane manufacturers' performance data, Civil Aeronautics Board (CAB) data for airplane payloads

*Helicopters are the most energy-intensive type of aircraft — in 1971 their EI was 253,000 Btu/TM.

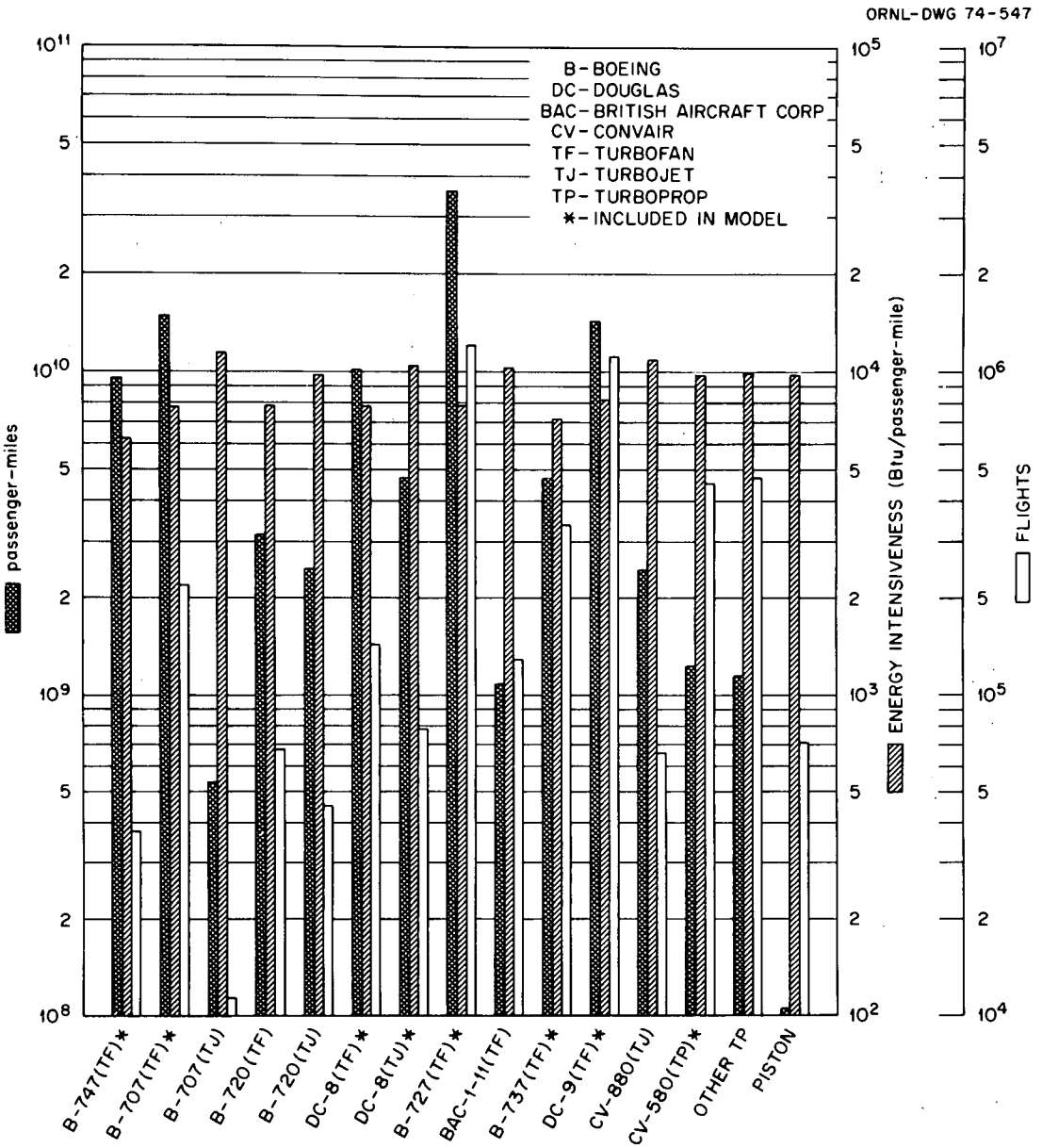

Fig. 1. PM, EI, and number of flights for each group of P/C airplanes in 1971. (Source: ref. 10)

Note: See appendix for discussion on EI calculation.

and stage-length flight frequencies, and information obtained from airline personnel. The airplane groups used in the model are designated in Fig. 1. Included are the top seven passenger-mile generators, the six airplanes with the greatest number of flights, and the most popular turbojet and turboprop airplanes. Performance data for a representative aircraft in each group were obtained from the manufacturer. This information provided a means of calculating each airplane's fuel use.

Each airplane was assumed to carry its 1971 average payload tonnage plus reserve and contingency fuel requirements. Airline flight personnel were contacted to obtain typical flight profiles (see appendix) for each airplane in the model. Each airplane's fuel use as a function of stage length was calculated by the method described in ref. 11 with several small modifications. Each aircraft's flight distribution by stage length was obtained for 1972 from the CAB (these data were not available for 1971). A fuel-consumption model for the entire domestic P/C fleet was constructed from this and other information. For more details, consult the appendix.

To test its accuracy, the model was used to predict the fleet's total 1971 fuel consumption. Table 2 compares predictions with CAB data (comparisons of individual airplanes are in the appendix). Initially the predicted fuel consumption was 93.4% of the actual amount. This discrepancy was resolved by adjusting the EI so that the model predicted the correct total fuel use for 1971. See the appendix for details.

Table 2 also compares average stage lengths, number of flights, and average tonnage. The small differences result from use of 1972 flight distribution data and the fact that only eight airplanes are incorporated in the model.

Table 2. Comparison of fleet model with 1971 CAB data[10] for domestic P/C aircraft (all revenue service)

	CAB data[a]	Fleet model[b]
Average stage length (miles)	432	439 (101.7)[c]
Number of flights (millions)	4.47	4.25 (95.2)
Average payload (tons/flight)	6.36	6.56 (103.2)
Revenue ton-miles (billions)	12.3	12.3 (100.0)
Fuel consumed (billion gallons)	7.19	6.71 (93.4)
Average EI (Btu/TM)	79,100	73,900 (93.4)

[a]Helicopters are not included here. They were included in Table 1.

[b]Normalized to equivalent revenue ton-miles but not corrected for 100% of CAB fuel consumption.

[c]Percent of CAB data in parentheses.

The results indicate that the fleet model is an adequate tool to use in describing the fleet fuel use. Its application in the following section allows calculation of fleet EI, fuel use, and traffic as a function of stage length.

III. AIRPLANE FUEL USE

This section describes how the domestic fleet consumes fuel. The EI of several airplanes and the fleet aggregate are presented as a function of stage length. The fleet model's calculations of cumulative fuel use and traffic are presented as functions of stage length. Several fuel uses, not explicitly obtainable from the model, are estimated or discussed.

A. Fleet Model Results

Airplane EI depends on both airplane type and stage length. (EI also depends on other factors which were fixed in the original fleet model.) This fact is shown in Fig. 2a where the EI* variation with stage length is given for several of the airplanes in the model. EI decreases rapidly as stage length increases. For example, a DC-9 requires nearly three times the energy per mile for a 50-mile stage as it does for a 500-mile stage. This characteristic EI variation is due to the fact that airplanes consume substantial fuel on the ground, in climbing and descending, and for in-flight maneuvering. Since these contributions are not very stage-length dependent, EI decreases for longer stages.

The only turbojet plane considered in the fleet model is the DC-8-20. In Fig. 2a its EI is consistently the highest. This agrees with the CAB data shown in Fig. 1. The DC-8 (TJ)'s average stage length (980 miles in 1971) is much greater than the fleet average, and therefore in Fig. 1 the differences in average EI are not as great as Fig. 2a might imply.

The model results for the fleet-aggregated EI variation with stage length are presented in Fig. 2b. EI variation is qualitatively similar to that of the individual airplanes: EI for short flights is much greater than that for long flights. For example, the average 100-mile flight consumes 2.5 times as much fuel as is required per PM for the average 1,000-mile flight.

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*The passenger EI (Btu/PM) is assumed to equal one-tenth the total tonnage EI (Btu/TM). See the appendix for a discussion of this assumption.

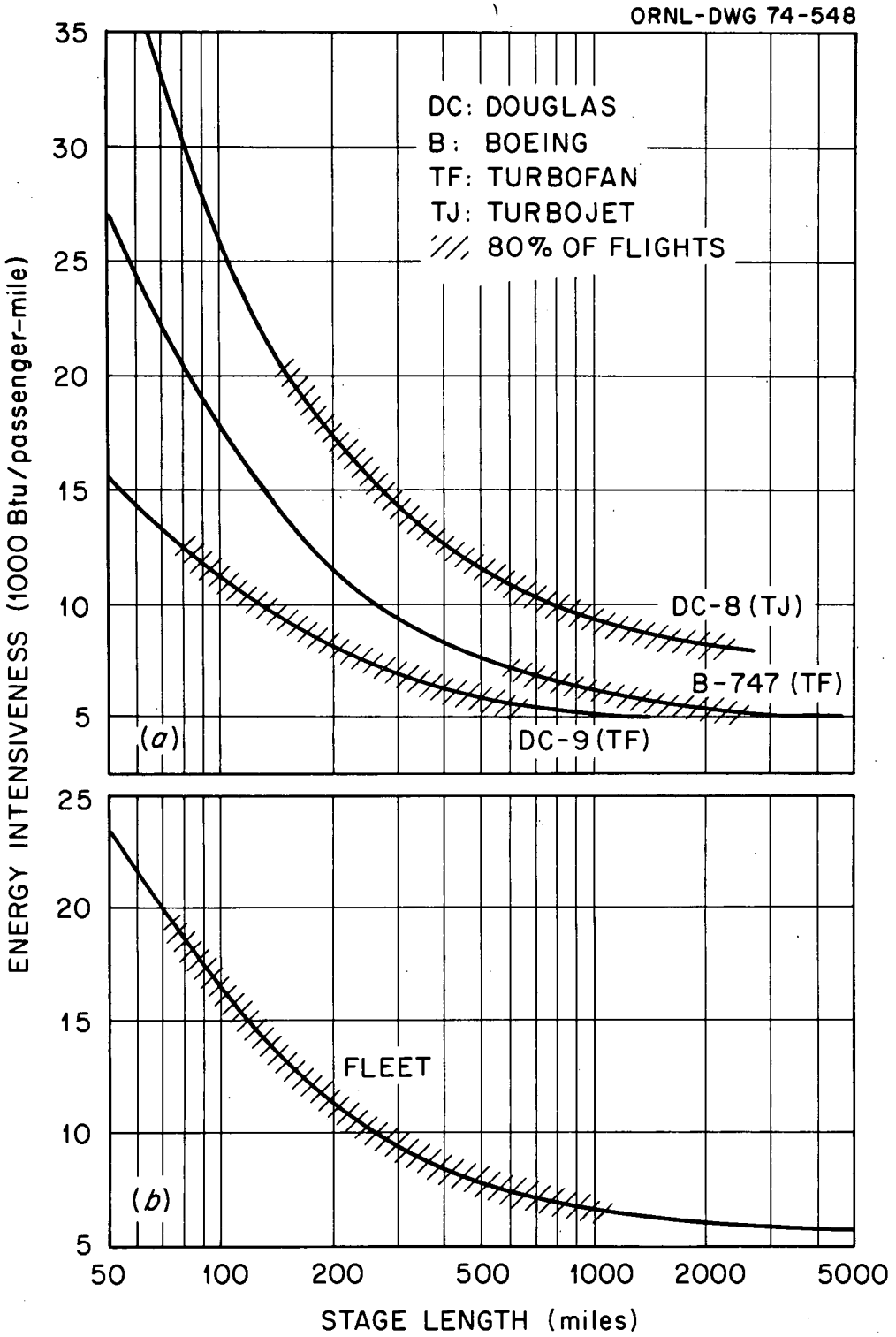

Fig. 2. EI as a function of stage length.

The results presented in Fig. 2 are a function of stage length — not trip length. That is, a trip from A to B may consist of several intermediate stops. This results in considerably greater fuel consumption than if the flight had been non-stop. For example, a 300-mile trip consisting of two evenly spaced intermediate stops consumes 85% more energy than the non-stop alternative. Therefore, airplane EI as a function of trip length is, on the average, greater than that for the equivalent stage length. Figure 2 can be used to obtain trip EI if the various stage lengths are known.

The model results for cumulative flights, fuel consumed, and ton-miles as a function of stage length are presented in Fig. 3. There are more short stages than one might expect. The median trip length for the model's flight distribution is about 260 miles compared with a mean distance flown of 439 miles. Flights with stages of less than 100 miles consumed 4.0% of the fuel but provided less than 1.6% of the ton mileage.

Airplanes consume fuel for other reasons than flying directly between two points. The distance flown is always greater than the straight-line distance between airports because of in-flight maneuvers, takeoff and approach flight pattern requirements, traffic congestion, and travel to and from the FAA airway used for the flight. These considerations were incorporated in the fleet model as described in ref. 11. About 10.5% of the total domestic fleet P/C fuel consumption, as predicted by the fleet model, is attributable to those portions of the flight in which no enroute distance is achieved.

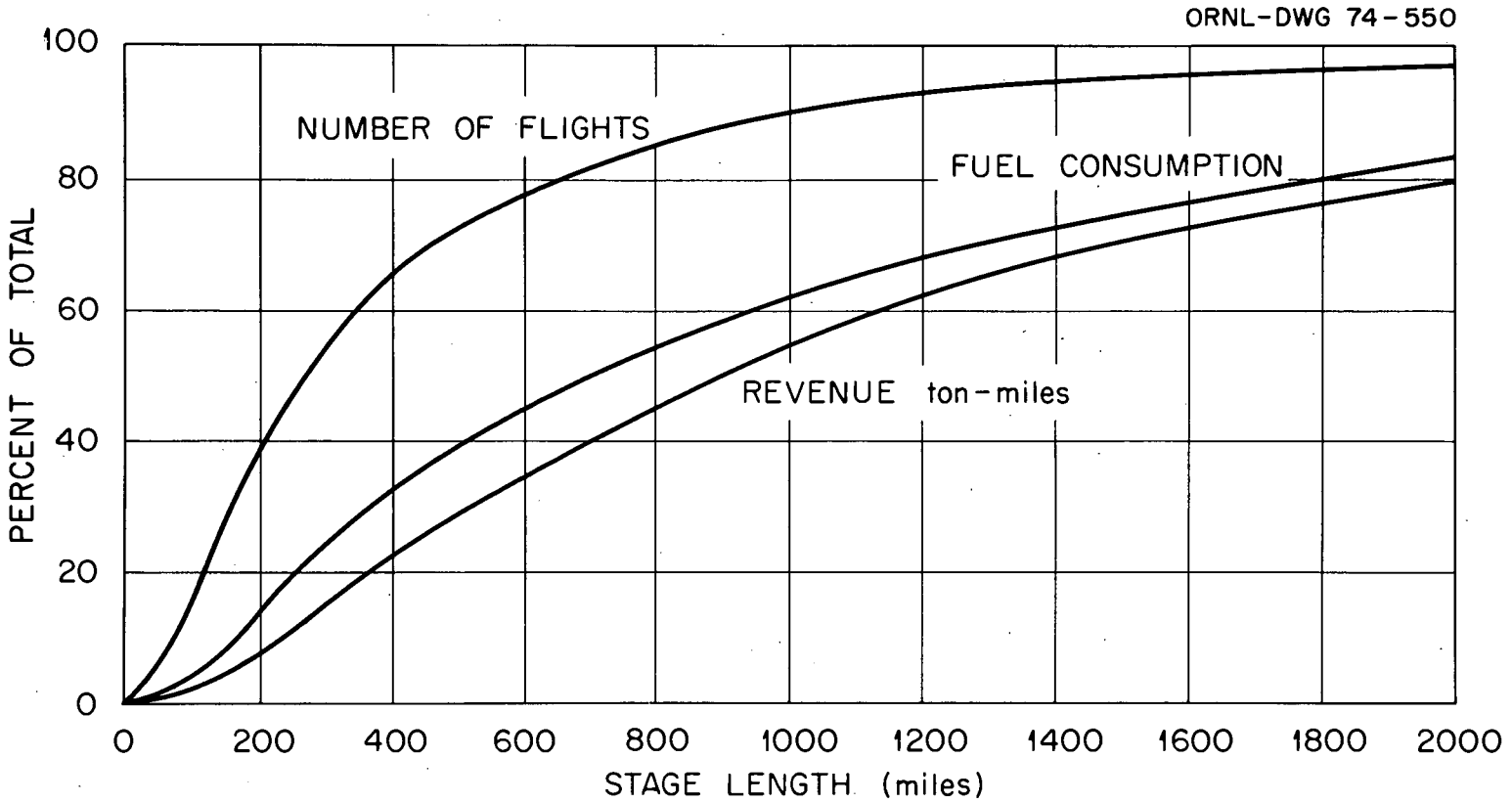

Fig. 3. Fleet cumulative distributions of flights, fuel consumption, and revenue ton-miles by stage length.

B. Delays

Delay, both on the ground and in the air, uses fuel. Air traffic control and airport-related problems cause most delays. Only about 15% of delay time is attributable to weather.[12]

The fleet model does not explicitly account for delay. In-flight delay was implicitly included in the maneuver requirements that resulted in over 10% of the fuel use. In the model, taxi fuel consumption was based on the 1971 average taxi time for each airplane and therefore included ground delay times.

An estimated 4.2% of the domestic P/C fuel consumption in 1971 was associated with delays (see appendix for details). In-flight delays accounted for 3.2%, while the remaining 1.0% was consumed on the ground. Nearly 24% of total taxi time was due to delays.

Reference 9 reports a total delay fuel use of 3.6% for the certificated air carriers* — 2.5% in the air and 1.1% on the ground.

Delays result in an indirect fuel use that was not included in the above estimation. Some airlines attempt to meet schedules after being initially delayed. Such a policy reduces passenger inconvenience — especially the possibility of missing a connecting flight. By flying faster than normal, such flights are more energy intensive than the average.

For example, one airline allows up to 45 gallons of additional fuel to recover each minute of lost schedule time for medium-sized airplanes.

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*U.S. scheduled airlines flying domestic or international flights.

A Boeing 737 flying a 600-mile stage attempting to recover five minutes of lost time could increase its EI for this flight by 17% with such a policy.

C. Auxiliary Power Units

Most modern turbojet and turbofan airplanes have auxiliary power units (APUs) to provide power when the main engines are shut off: to provide cabin air conditioning, engine starting power, and other power requirements while the airplane is loading and unloading passengers. They are also used during some maintenance periods and sometimes while the aircraft is flying.

APUs are gas turbines and use the same fuel as the main engines. Their fuel use is therefore included in the CAB data. The fleet model does not consider APU fuel use per se. APUs are (conservatively) estimated to consume 1% of total fleet fuel use. They may be responsible for up to 3% of the total fuel use (see appendix).

D. Fuel Ferrying

Airplanes ferry fuel from one location to another because of fuel price differences and supply uncertainties. The extra weight carried for fuel ferrying results in greater fuel usage. For this reason, ferrying occurs only for short stages — this may not be true in the future. As the supply problem worsens, increased fuel ferrying will occur resulting in less efficient operations. The increase in EI due to greater fuel ferrying will not be great. For example, a 1.7% increase increase in EI occurs if a Boeing 727 ferries 10,000 pounds of fuel on a 250-mile stage.

Fuel ferrying on long flights presents a potentially greater problem. EI is increased only 0.9% for a Boeing 727 carrying an additional 10,000 pounds on a 1,500-mile hop. However, the additional fuel requirements amount to consuming nearly 10% of ferried fuel.

IV. ENERGY CONSERVATION STRATEGIES

This section evaluates fuel savings that would occur if specific energy-conservation strategies were adopted by the domestic fleet. The strategies assessed include increasing load factors, altering modal mix, reducing cruise speeds, increasing cruise altitudes, and changing taxi operations.

A. Increased Load Factors

The greatest potential for decreasing airplane EI is to increase the amount of passengers and cargo carried per flight. Increasing load factors (ratio of tonnage transported to capacity) would reduce fleet EI and therefore reduce fuel use if traffic (TM) remained the same. For the past several years, overall load factors have been below 50%.

On P/C airplanes the passenger load factor dominates the overall load factor. Figure 4 shows the passenger load factor for the major domestic carriers from 1950 through mid-1973. Since the cargo load factor is about 20% (1971)[10] on P/C aircraft, the overall load factor is somewhat less than that shown in Fig. 4.

Passenger load factors have decreased almost steadily for the last 20 years. In the early 1950's, passenger load factor was nearly 70% (Fig. 4). For the last several years passenger load factor has been about 50%, resulting in overall load factors of less than 50%.

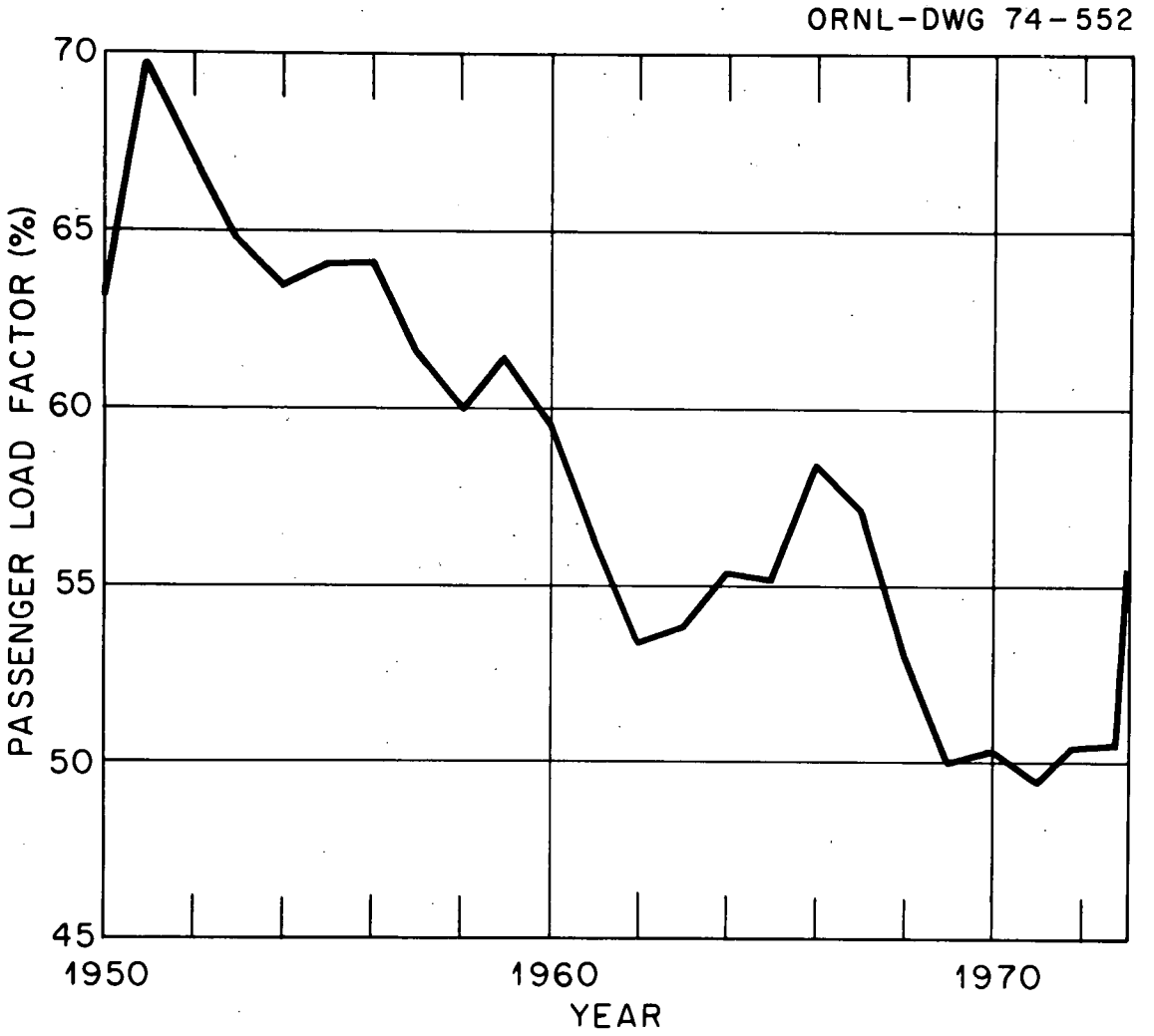

Fig. 4. Passenger load factors for the major domestic carriers. (Source: ref. 5 and several 1972-73 issues of *Aviation Week and Space Technology*)

Most of the energy expended in a flight is for lifting weight other than the payload. For example, the empty weight of a Boeing 727 is 100,000 pounds; its payload averaged only 13,600 pounds in 1971. Therefore, the additional fuel required for greater load is small.

The fleet model was used to evaluate the additional fuel required for a load factor increase. If the fleet increased its load factor by 20% (e.g., from 50% to 60%) with the same number and stage-length distribution of flights, the fuel requirement would be increased only 0.7%. This 20% increase in load factor results in a 16% decrease in EI. (Although based on a different fleet mix and methodology, ref. 9 results are similar.)

The very slight variation of fuel consumption with changing load factor results in EI being (nearly) inversely proportional to load factor. That is, for a 1% increase in load factor, the fleet fuel consumption will be reduced about 1% for the same total traffic. Therefore, airplane EI has the ultimate (but probably not realistic) potential of being nearly halved if all airplanes operate fully loaded.

Load factors can be increased by decreasing the number of flights (capacity) or by increasing the payload at the present capacity. Reduction in capacity is probably the most effective means of increasing load factors, and it would result in decreased fuel use. Present excess capacity may be due, in part, to optimistic projections of airline traffic in the past. Airline competition for routes and nearly unrestrained CAB route approval are also responsible for present load factors. Since the CAB's mandate is to develop an air transportation system to satisfy present and future commerce needs, demands for expanded service are difficult to refuse.

Increasing passenger load factors by reducing capacity presents several problems. Capacity must be reduced nearly 17% for a 20% load factor increase (for the same traffic). Some airline personnel will therefore become unemployed or have to reduce working hours. A 17% reduction in flight personnel and crews for the U.S. scheduled airlines

would result in about 12,000 unemployed persons. (This is a 4% reduction in total airline employment.) Other areas of airline employment would be affected to a much smaller degree.

A long-term problem resulting from capacity reductions would be traveller inconvenience. This negative consequence could be reduced by optimum scheduling and airplane utilization. As shown in ref. 9, an increase in passenger load factor from 50 to 60% would not present a serious problem in passenger inconvenience. As load factor increases, the probability of a passenger being rejected from a flight increases. Mutch[9] found that domestic passenger load factors could be increased to 70.2% before the rejection probability becomes 0.001. That is, if the average passenger load factor were 70%, there would be only one chance in 1000 that a passenger would be rejected from a flight. (?) TIME OF FLIGHT LEAVING ETC WILL INFLUENCE THIS

Raising load factors by increasing traffic would increase airplane energy use but the fuel would be used more efficiently than at present. Because cargo load factor on P/C airplanes is only 20%, attempts might be made to increase it. This might be accomplished by providing "space-available" air freight rates that are less than the current rates.

Reducing P/C airplane EI by increasing the cargo carried may actually increase total transportation energy requirements, because such a change would reduce the cargo carried by other modes which are more efficient. For example, the incremental EI (additional fuel/additional tonnage) for carrying additional tonnage by air is 2,810 Btu/TM. This is equivalent to the average EI of trucks.[4] Since trucking EI is only surpassed by airplanes, freight shifted from ground modes to airplanes could cause an increase in total transportation energy use.

B. Alternative Modal Mix

Airplane and total transportation fuel use could be reduced by shifting traffic from airplanes to more fuel-efficient modes. The possibilities for implementing such a shift are greatest in the short-haul* markets. Short flights are, in general, much more costly (per PM) to an airline than long flights.

Nearly half of all airline passenger trips are for distances less than 500 miles — 26% are for less than 300 miles.[13] The fleet model results show that half of all domestic airplane hops are under 260 miles.

Short-haul traffic is great between large hub cities. For example, the top 10 city pairs accounted for more than one-fourth of the short-haul passenger trips in 1968 — the three densest markets accounted for 17% of the short-haul traffic.[13]

Short stages are particularly energy intensive (see Fig. 2). If the frequency of short-haul trips were reduced, airplanes would increase their energy efficiency. For example, if there were no stages for distances under 500 miles, EI would be decreased 14%.

Many of the social debits of airports, such as noise, air pollution, and traffic congestion, can be attributed to short-haul markets. For example, two-thirds of the passengers landing at or departing from Washington, D.C., in 1968 were on trips of less than 500 miles.[13]

While everyone recognizes the time savings afforded by airplane travel for long flights, short trips may not be as time saving as many persons believe. Figure 5 illustrates the total time required to travel

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*Stages of less than 500 miles.

from one central business district (CBD) to another for various modes. Airplanes (non-stop) provide time savings for trips over 100 miles when compared with other common modes. The Metroliner offers better times for trips up to 140 miles. For a 200-mile trip, an airplane saves only about 40 minutes when compared with the Metroliner.

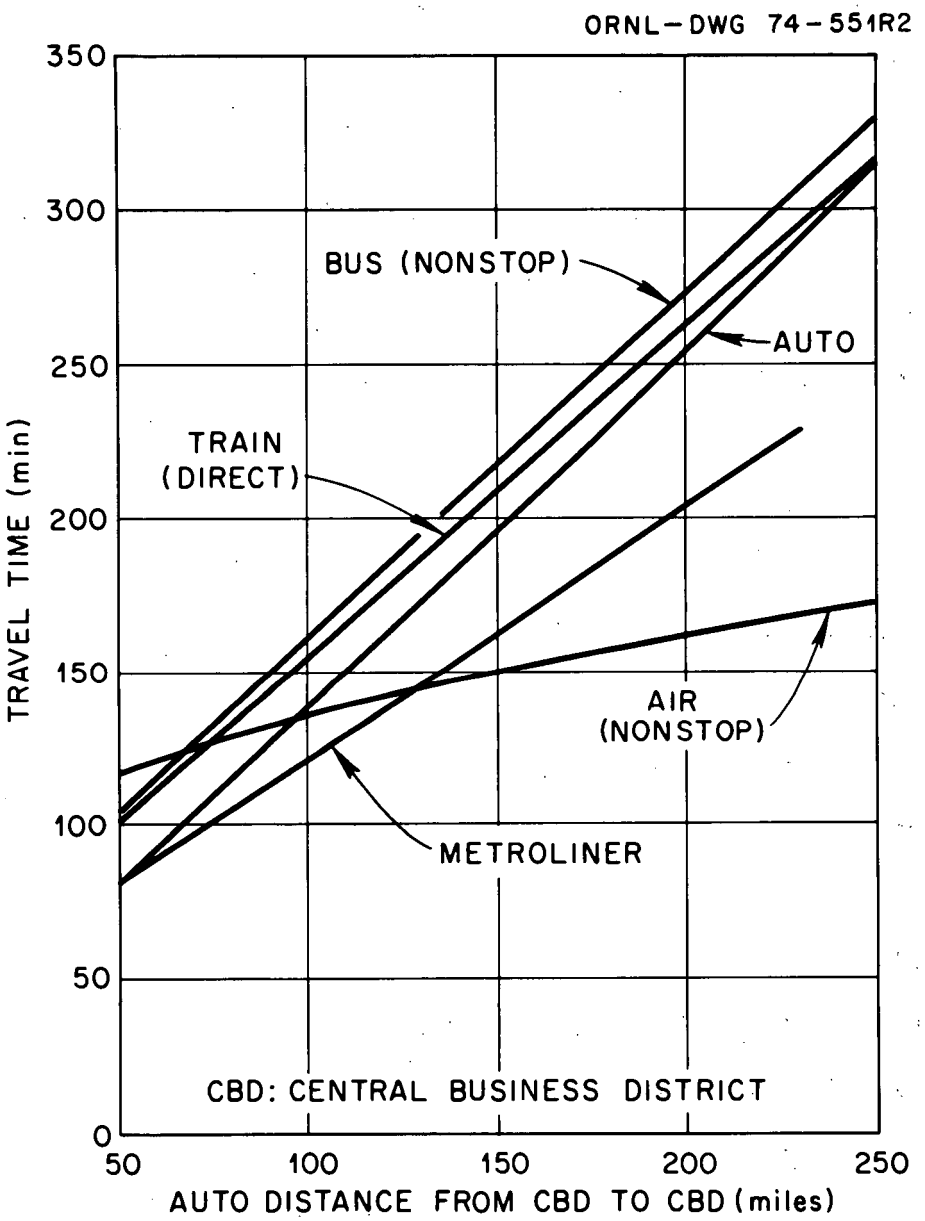

Fig. 5. Travel times for several modes from one central business district to another. (Source: ref. 14)

The problems associated with air travel may cause a shift to other modes for short trips. Short airplane stages are expensive and are inconveniencing the more profitable long-haul operations (e.g., delays, ground traffic, and parking). Airport-associated noise and air pollution would be greatly reduced if short-stage traffic were shifted away from airplanes. Fuel resources would be conserved because airplanes are the most energy intensive mode and because short stages are very energy intensive.

There is evidence that if an alternative mode of travel providing good service is available, it can compete with airplanes in some short-haul markets. The Metroliner seems to offer such an alternative. For example, in 1972, rail passenger traffic between New York and Washington, D.C. grew by 18.6% while air-passenger traffic growth for this market was only 3.0%.[15]

Because the concentration of short-haul passenger traffic is great between large hub cities, the potential for shifting traffic to a rail-type vehicle exists. Other traffic could be shifted to buses and automobiles.

The energy-conserving impact of shifting half the airplane hops of less than 200 miles to other modes was examined. The fuel savings for such a shift in 1971 to trains, buses or automobiles are given in Table 3. A shift from airplanes to buses would result in the greatest savings. However, the differences in potential fuel savings between each of the other possible modes are not great.

A modal shift for stages under 200 miles would provide other benefits than fuel savings. Since 42% of all airplane hops are flown for distances under 200 miles, such a shift would substantially reduce the number of airline operations. Besides the direct fuel savings, secondary effects

Table 3. Net energy savings for various modal shifts for half of the stages under 200 miles[a]

Mode	Percent of airplane fuel[b] saved	Fuel savings (trillion Btu)
Auto	5.3	51
Train	5.7	55
Bus	6.1	59

[a]Modal EIs from ref. 4 based on the ratio of total fuel use to total traffic: auto — 3,400 Btu/PM, rail freight — 670 Btu/TM, rail passengers — 2,900 Btu/PM, and bus — 1,600 Btu/PM.

[b]Domestic P/C fleet.

such as decreased delay time and air-maneuver requirements would result in additional energy reductions.

In 1971, one-fourth of all domestic airline operations were subsidized by the CAB. Only local carriers are eligible for subsidies, and therefore only short flights are affected. For example, 65% of the flights under 100 miles and 40% of those between 100 and 200 miles were federally subsidized in 1971. These subsidized operations should be reexamined in light of their inefficient fuel use. Removal of the CAB subsidy program would cause shifts in the intercity modal mix and result in energy savings.

Many short hops by the major carriers are subsidized by their longer flights. This cross-subsidization results in short-flight passengers paying less than actual operating costs. If the short-hop fare were increased to reflect the true costs, short-stage travelers would tend to travel by competing modes.*

Providing an adequate alternative passenger mode between hub cities would stimulate shifts from airplanes. The traffic concentration between

*According to The Washington Post (March 19, 1974), CAB is restructuring air fares to set them closer to actual costs — short-hop rates will increase and long-hop rates will decrease.

Providing an adequate alternative passenger mode between hub cities would stimulate shifts from airplanes. The Metroliner experience implies that the potential for a substantial shift in short-haul transport exists.

Another possibility for shifting traffic is to investigate specific routes that combine a short hop with a long one. An example is a Miami-Ft. Lauderdale-New York flight. The short leg is not only fuel inefficient, it inconveniences passengers who board in Miami. Because the majority of passengers arriving in New York are probably those that were delayed by the Ft. Lauderdale stopover, providing bus service for the Ft. Lauderdale passengers to travel to the Miami airport may be more efficient (total costs — crew time, fuel, passenger time, etc.).

Shifting airplane passengers to other modes will not be an easy task. Desirable alternatives such as the Metroliner are scarce. Many short-hop passengers are continuing on other flights. With the present transportation system, mixed-mode travel is difficult. A unified transportation system would alleviate many of these problems. For example, convenient bus scheduling and service between short-stage airports (in addition to the downtown bus terminal) is currently rare. Such service coupled with airline short-stage capacity reductions could provide better, less expensive, and more energy-efficient transportation.

C. Reduced Cruise Speed

Airplanes can decrease EI by cruising at slower speeds. Present airline practice is to fix cruise Mach number for each type of aircraft. The Mach number chosen is the one the airline believes will result in minimum costs (not minimum fuel use).

The fleet model discussed earlier was used to estimate fuel savings for a 0.02 Mach-number reduction in cruise and for a slowdown to the minimum practical speed (see appendix).

If the domestic P/C fleet reduced cruise speeds by 0.02 Mach, the fuel saved would equal 1.3% of its total fuel consumption. This savings is less than one might anticipate since the usual assumption is that fuel consumption should be proportional to the square of the speed. But in the present situation a 2.5% reduction only results in a 1.3% savings, because airplanes are not always cruising. In fact, very little cruising occurs in short flights because so much distance is covered during the climb and descent. The time increase due to such a slowdown is dependent upon the stage length and flight altitude. A 1,000-mile hop at reduced speed would result in about two minutes of additional flight time.

Most airplanes could reduce cruise speeds by more than 0.02 Mach number and further decrease fuel consumption. A slowdown to "long-range" operation was also investigated. In general, this cruise speed is that at which the airplane flies at 99% of its maximum specific range (miles/gallon). Such a decrease in cruise speed would result in a 3.0% fuel savings — more than twice the savings of the 0.02-Mach slowdown. A fuel savings of 4.3% was estimated in ref. 9 for slowing down to maximum specific range.

This substantial fuel savings would have considerably greater time cost than the example above. The increased flight time for such a slowdown is airplane dependent. Large aircraft presently fly nearer the long-range cruise speed than do small airplanes. For example, a 0.02-Mach slowdown for the Boeing 747 places its operation very near long range, but a DC-9

would have to slow down by 0.09 Mach to achieve long-range operation. On a 1,000-mile flight, DC-9 passengers would incur a nine-minute time cost contrasted to a two-minute cost for Boeing 747 passengers.

There has been speculation that if the airlines were to reduce cruise speeds their operating costs would increase. The direct operating costs — crew, fuel, and maintenance — are not particularly dependent on cruise speed over some range of Mach numbers. This fact is illustrated in Fig. 6, where the variation in direct operating cost (in cruise) as a function of Mach number is illustrated for the DC-8-61 (see appendix for details). The cost curve is much flatter at lower altitude cruise than at higher altitudes. It should be expected that airplanes are flown at the highest possible speeds (without incurring a severe cost penalty) to provide better service.

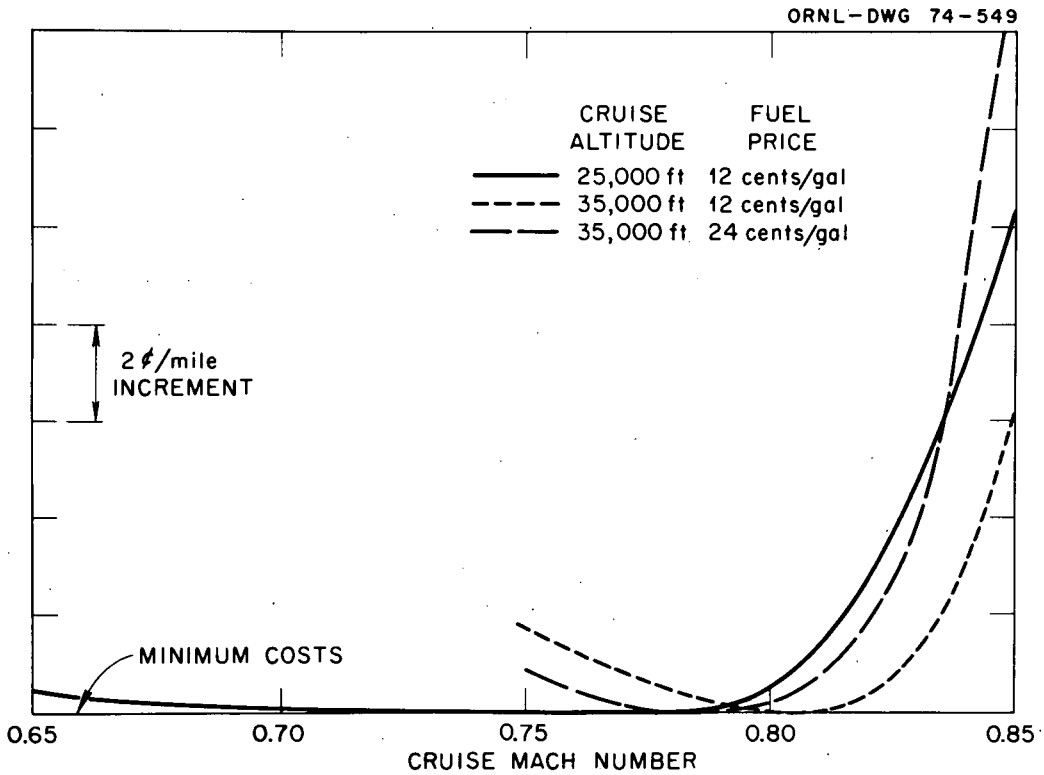

Fig. 6. DC-8-61 direct operating costs during cruise as a function of Mach number. (Costs are relative — absolute minimum costs differ for each example.)

If fuel prices were increased, airlines would tend to slow down out of economic considerations. Figure 6 suggests that if fuel prices were doubled (over 1971 prices), the DC-8-61 might be flown 0.02 Mach slower.

The time cost to passengers is not included in the direct operating cost calculations. The additional costs incurred for increased flight time may be greater than the savings from using less fuel. For example, consider a DC-8-61 flying a 1,500-mile stage at 35,000 feet. If fuel prices were 24¢ per gallon (see Fig. 6), an airline could save about $19.00 per flight by slowing down from 0.82 to 0.80 Mach. This slowdown would result in an increased flight time of about 3.5 minutes. Assuming the 1971 value of time for air travel to be $8.80/hour (see appendix) and 80 passengers per flight, the additional time cost to passengers attributable to slowing down is $41.00. Therefore, for this example, the time costs outweigh the monetary savings from reducing fuel consumption.

D. Increased Cruise Altitude

In general, fuel consumption can be reduced by flying at higher altitudes. There is an optimum altitude (for minimum fuel use) for each airplane's cruise weight and speed. Apparently, airplanes tend to be flown at altitudes below this optimum primarily because of FAA altitude restriction regulations, which are briefly discussed below.

The fuel savings that could be effected for a 2,000-foot increase in cruise altitude (if the increased altitude cruise decreased fuel consumption) was estimated using the fleet model. The savings for such an altitude increase was equivalent to that for a 0.02 Mach-slowdown — 1.3% of the fleet fuel.

As with slowing down, this strategy does not affect shorter flights. Flying higher (at the same Mach number) results in an increased flight time that is less than that for slowing down by 0.02 Mach number. For example, flying 2,000 feet higher on a 1,000-mile stage increases flight time by 1.0 minute compared with 2.0 minutes for cruising slower.

Flight altitudes are assigned by flight controllers according to FAA regulations. Above 3,000 feet and below 29,000 feet, aircraft can only be flown at 1,000-foot increments. Easterly flights can only be flown at the odd cardinal altitudes, for example, 11,000 and 13,000 feet. At 29,000 feet and above, these margins are doubled.

These regulations inhibit altitude selections and cause aircraft, in general, to fly below their optimum altitude. For example, an easterly traveling pilot may request 33,000 feet for cruise, but the request may be refused due to the presence of other aircraft at this altitude. The aircraft may be unable to initially climb to 37,000 feet and will therefore be flown at 29,000 feet or below.

These altitude restrictions are for reasons of safety and were based, in part, on altimetry technology. Improved technology should allow less-restricted altitude regulations. By mid-1974, commercial aircraft will be equipped with an improved altimetry system. This may allow a relaxation of the FAA regulations and, if so, result in reduced fuel consumption.

Relaxed altitude restrictions could result in fuel savings greater than the 1.3% for the 2,000-foot altitude increase. More flexible restrictions would allow aircraft to alter their cruise altitude throughout their flight. This practice is not used extensively at present. As the

aircraft burns fuel and decreases in weight, the optimum altitude increases. By properly increasing cruise altitude during a flight, fuel use is less than at fixed altitude cruise. Again, these fuel savings primarily occur for longer flights.

E. Alternative Ground Operations

Airplanes consume a substantial amount of fuel while on the ground. In 1971 nearly 4.2% of the domestic P/C fleet fuel consumption was for taxiing or idling at airports. Both the Environmental Protection Agency (EPA) and FAA are considering alternative ground operations that would result in decreased ground fuel usage.

The EPA has proposed[16] that turbine-powered aircraft reduce the number of engines while on the ground. The remaining turbines would then operate at higher, more efficient, power settings. This scheme is feasible for turbines because they require essentially no warm-up time.

The EPA has proposed that such a program be adopted at airports with over 1,000,000 enplaned passengers in 1970. If all airplanes (including cargo and international flights) using these airports had reduced their ground engine use, over 4×10^7 gallons (equivalent to 0.55% of the domestic P/C fuel use) of fuel would have been saved in 1971.* The fuel savings would have been 6.1×10^7 gallons if the program was extended to all airports in the 50 states. At 14¢ per gallon, this represents a possible $8.5 million savings to the airline industry.

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*Data actually for year ending June 30, 1971. See appendix for details.

The FAA has funded a feasibility study[17] to investigate towing airplanes on the ground. Towed airplanes would reduce airport noise and air pollution as well as effect substantial fuel savings. In fact, preliminary results show that the fuel savings alone could provide the capital and operating costs for the tow vehicles. If such vehicles were available in 1971 at the larger hubs (as defined in the EPA program above), the total savings (including cargo and international flights) would have been 1.4×10^8 gallons of fuel — 3.5 times the amount saved by the EPA proposal. Although the fuel savings are much greater, tow vehicles are not presently available.

The EPA ground operations proposal is currently being assessed by the FAA. Questions concerning the safety of increased jet blasts and problems associated with the starting of engines after leaving the gate are being addressed. The difficulties associated with this proposal have been found to be both airport and aircraft related. But at least one airline has begun reducing the number of operating engines while on the ground.[18]

Several possible difficulties with the FAA proposal will have to be addressed. Will the tow vehicles increase airport ground congestion and will airports have to be partially redesigned? Total flight times may be increased if aircraft are towed since the taxi time will be longer. At some point one must assess the increased time cost to passengers for such a system. These problems may be minor, and the use of tow vehicles would result in fuel savings in the future.

V. SUMMARY AND CONCLUSIONS

Airplane EI is both aircraft-type and stage-length dependent (for fixed speed, altitude, and payload). Turbojet aircraft use fuel inefficiently while the newer wide-bodied jets are the most efficient. Short hops are much more energy intensive than long ones.

Fuel is consumed for reasons other than flying directly between two airports. Over 10% of the fuel used by airplanes is for various in-flight maneuvers. At least 4.2% of the fuel consumed is directly attributable to delays. Auxiliary power units use over 1% of the fuel in providing power when the main engines are off.

Energy can be used more efficiently by airplanes without major technical innovations. The following changes in airplane use would increase their fuel efficiency: increase load factors, reduce cruise speeds, increase cruise altitudes, and reduce the number of engines while on the ground or tow the airplane while on the ground. Because airplanes are the most energy-intensive mode of transportation, shifts to other modes would reduce total transportation energy use. These shifts would most likely occur for short stages, resulting in decreasing airplane EI. Table 4 summarizes the fuel savings that could be expected if these energy-conservation strategies were invoked by the domestic P/C fleet.

As shown in Table 4, the greatest potential for decreasing airplane EI is to increase airplane load factor. A 20% increase in load factor (e.g., increase from 50 to 60%) for the same traffic would result in a 16% reduction in airplane fuel use. Reducing capacity is probably the most effective scheme for increasing load factors.

Table 4. Potential energy savings[a] for several energy-conservation strategies

Conservation Strategy	Airplane fuel conserved (%)	Energy saved in 1973 (trillion Btu)[b]
Increase load factors 20%	15.9	163
Shift one-half of all airplane hops under 200 miles to buses	6.1	63
Reduce cruise speeds by 0.02 Mach number	1.3	14
Reduce cruise speeds to long-range operation	3.0	31
Increase cruise altitude by 2,000 feet	1.3	13
Reduce number of engines in operation on the ground[c]	0.8	8
Tow airplanes on the ground[c]	2.7	28

[a]Net fuel savings are given. In general, total savings for implementing several strategies are not additive.

[b]Savings for the domestic P/C fleet using estimated 1973 fuel use from refs. 10 and 19.

[c]Assessment is for domestic P/C fleet at all airports.

Airplanes fly many fuel inefficient short hops — half of all domestic flights are for distances under 260 miles. Both total transportation energy use and airplane EI could be reduced if airplane short-stage traffic could be shifted to other modes. If half of all flights under 200 miles were shifted to buses, a net energy savings equivalent to 6.1% of the fleet's consumption would be effected. Such a cutback by the airlines would reduce their number of flights by 21% but only reduce their total traffic (TM) by 4.1%.

There exist several operational strategies that would decrease airplane fuel consumption. The fuel savings for flying slower, flying higher, reducing the number of engines on the ground and towing aircraft while on the ground are each on the order of 1 to 3% (Table 4) of total domestic P/C airplane fuel consumption.

Because over 10% of total fuel consumption is attributable to in-flight maneuvering, energy savings could be effected by changes in FAA regulations and improved air traffic control. This in-flight maneuvering is due to delay, air congestion, approach and departure patterns, and travel to and from FAA airways.

Fuel costs for ground (1.0%) and air (3.2%) delay amount to 4.2% of the total fuel use. Delays are responsible for nearly one-fourth of the total ground operations time. More efficient control of aircraft could reduce airplane fuel use as well as airport-related noise and air pollution.

Additional fuel (and probably money) savings could be realized by the airlines if optimum flight-profile calculations were made for each flight. The present practice of constraining the cruise Mach number for each aircraft-type should be investigated. One airline claims a 4.5% savings in fuel consumption by optimizing each flight segment on a seasonal basis.[20] The value of the fuel savings should be compared with the computational costs to insure its economic feasibility.

Increased fuel prices would cause airlines to use fuel more efficiently. This is demonstrated in Fig. 6 where direct operating costs were given as a function of cruise speed and fuel price. As for slowing down, other fuel-conserving strategies will become attractive if fuel prices increase.

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VIII. APPENDIX

The appendix provides details (including assumptions and approximations) on the methods used to obtain the fleet model, fuel-use calculations, and conservation-strategy assessments found in the main text. An initial section discusses EI disaggregation by traffic type.

Energy Intensiveness

For EI calculations, traffic can be based on passenger-miles or ton-miles. The present study combines passengers (200 pounds/person including baggage) and cargo to achieve an EI that is ton-mileage (total payload) based. Previous studies[4,8] have approached this problem in a different manner.

Mooz[8] considered the total ton-mileage as freight. This method suffers from the fact that P/C airplanes carry additional weight (seat, galleys, cabin crew) not associated with the cargo and therefore penalizes the EI.

Hirst[4] disaggregated fuel associated with passengers and cargo. His scheme compared some of the cargo-only airplanes (cargo-only carriers) to P/C ones and assumed that fuel use was directly proportional to the load factor. This allowed a fuel charge for the cargo on P/C planes, and separate EIs were obtained for passengers and freight. This method suffers from not considering all of the cargo-only airplanes and neglects the facts that cargo-only airplanes fly longer stage lengths and that the airplane mixes for cargo and P/C airplanes are not the same.

A completely satisfactory scheme for separating the cargo and passenger fuel uses on P/C aircraft could not be devised. The total ton mileage

approach has been used. An estimate of the EI based on passenger miles is obtained by assuming the cargo carried was actually additional passengers (200 pounds/passenger) and then charging all of the fuel to the passengers. Because P/C airplanes are primarily for passengers, this assumption is equivalent to having an average of six extra passengers per flight.

Essentially the same result is obtained if the cargo-only airplanes are compared to their P/C equivalents and if fuel charges to cargo are based on an airplane's capacity to carry cargo.

All energy calculations (135,000 Btu/gallon) neglect the energy content of the oil consumed by the aircraft. In 1970 the energy content of the oil used by the domestic P/C fleet was less than 0.02% of the fuel's energy content.[5]

Fleet Model

Fuel use as a function of stage length (for each of the airplanes in the model) was obtained from various performance reports[21-28] using typical flight profiles and a block fuel requirement similar to ref. 11. Zero wind velocity and standard atmosphere were assumed. Airplanes were assumed to always carry their 1971 average tonnage.[10] They were also assumed to carry the reserve fuel required by FAR 121.639 for a 200-nautical-mile alternate landing point and a contingency amount of fuel equivalent to about 80% of the minimum reserve requirement. The operator's empty weight (includes such items as seats, galleys, and flight and cabin crew) was used as the base weight of the airplane. The block fuel requirement[11] was modified so that the assumed taxi time for each

airplane was the same as that obtained from ref. 10 for 1971. The taxi and takeoff fuel rates were obtained from ref. 29 and a one-minute takeoff thrust was assumed. The assumed flight profiles are given in Table 5. The distribution of flights by stage length for each airplane was obtained from the CAB's Service Segment Block Time Data for 1972.

Table 5. Assumed flight profiles for fleet model

Airplane	Stage length (miles)	Cruise altitude (feet)	Cruise speed
Boeing 747-100	0-1000	29,000	0.84 Mach
	>1000	37,000	0.84 Mach
Boeing 707-300C	0-600	24,000	350 knots
	600-1500	29,000	0.82 Mach
	>1500	35,000	0.82 Mach
Douglas DC-8-61	0-1200	30,000	0.82 Mach
	>1200	Step change	0.82 Mach
Douglas DC-8-20	0-1200	30,000	0.81 Mach
	>1200	35,000	0.81 Mach
Boeing 727-200	0-300	15,000	400 knots
	300-1500	29,000	0.82 Mach
	>1500	33,000	0.82 Mach
Boeing 737-200	0-500	25,000	0.78 Mach
	>500	31,000	0.78 Mach
Douglas DC-9-30	0-500	25,000	340 knots
	>500	30,000	0.80 Mach
Convair 580	0-100	6,000	Cruise at 847°C
	100-200	12,000	turbine-inlet
	200-300	15,000	temperature —
	300-400	18,000	speeds vary
	>400	20,000	

For five of the eight groups one airplane model does not represent the total generic class. The results for a particular model were weighted to achieve predictions for the total group assuming that each group's flight distribution and EI were the same as the model representing it.

The results for the individual models used are compared with the 1971 CAB data in Table 6. In general, the predicted fuel use is less than actual. This is due (at least) to not accounting for APUs, not choosing the precise in-flight profiles, not accounting for fuel ferrying, and the calculational assumptions involved. The fact that, in general, the average stage length for the CAB data was greater should result in the opposite being the case. Over-predicting the Convair-580's EI is believed due to fact that the maneuver requirements of ref. 11 are probably excessive for this airplane.

Table 6. Comparison of various airplane predictions with 1971 CAB data[10]

Airplane	Average EI (Btu/TM)		Average stage length	
	CAB	Predicted	CAB	Predicted
Boeing 747-100	61,800	54,600 (88.3)	1986	1770 (89.1)
Boeing 707-300C	80,300	74,700 (93.0)	1014	956 (94.3)
Douglas DC-8-61	71,500	67,200 (94.0)	1129	913 (80.9)
Douglas DC-8-20	104,000	92,200 (88.4)	1064	980 (92.1)
Boeing 727-200	76,300	78,200(102.5)	515	495 (96.1)
Boeing 737-200	71,600	69,900 (97.7)	276	284(102.9)
Douglas DC-9-30	78,000	69,600 (89.3)	293	292 (99.7)
Convair 580	97,200	116,000(119.5)	119	120(100.8)

[a]Percent of CAB data in parentheses.

The ton mileage generated by the model's eight groups provided 86.6% of the 1971 total. The fleet model predictions for the 1971 total ton mileage were compared with the 1971 statistical data in Table 2. Predicted fuel use and EI are 93.4% of the CAB values for 1971. This discrepancy

was resolved by increasing the EI by about 3.3% for all stage lengths and evenly distributing the additional 3.3% of the fuel for each flight. These assumptions for the unaccounted fuel are arbitrary but make little difference in the results. The originally unaccounted for fuel-use was assumed to be unaffected by energy conservation strategies.

Airplane Fuel Use

Total delay time for 1971 was estimated from the delay time per flight for 1969[12] and the first five months of 1973.[30] Distribution of air and ground delay times was assumed to be the same as the 1973 data. Each airplane's share of the delay time was assumed proportional to its contribution to the total fleet's taxi time. Air delay fuel consumption rates were obtained assuming the airplane was holding at an altitude of 5,000 feet. Taxi fuel consumption rates were the same as the fleet model's.

The following assumptions were employed for the APU fuel-use calculation: (1) APUs were used on 60% of the flights, (2) the average APU consumes 6.5 pounds of fuel per minute and (3) APUs operated for 0.5 hour per flight. The seemingly excessive operation time per flight results from attempting to account for APU use while in flight and during maintenance. The APU-usage time may be underestimated. Reference 31 states that APU operating time in excess of airplane flight time has been common and their fuel use may be 3 to 5% for APU-equipped aircraft. Using assumption (1) above implies that APUs may actually consume 1.8 to 3.0% of the fleet fuel.

Assessment of Airplane Energy Conservation Strategies

The extra fuel requirements for increasing the load factor were obtained using the fleet model. In general, the additional fuel required for each airplane was obtained from flight planning charts for each airplane landing at an additional weight equivalent to 20% of its normal payload tonnage.

Central business district travel times for Fig. 5 were obtained from ref. 14 for the automobile, non-stop airplane, direct train, and non-stop bus. The airport access and egress times were increased to total 50 minutes, because ref. 14 times seemed too short. Metroliner times were obtained from combining ref. 14 and Amtrak schedule times.

In Table 3, the EI for each mode was obtained from ref. 4. Train fuel use was calculated assuming that the freight and passenger ton mileage for distances under 200 miles was proportioned the same as the total traffic (87% of the total ton mileage produced by the domestic P/C fleet was due to the passengers).[10] The fuel saved for the various modal shifts is the difference between the mode's energy requirement and half of the energy used by the fleet for stages under 200 miles.

The number of subsidized operations for various stage-length increments was obtained from ref. 32 for fiscal year 1971. The total number of flights flown for each stage-length increment was obtained from the CAB's Service Segment Block Time Data for 1972. This information was used to estimate the percentage of subsidized flights in 1971.

The performance reports were employed to estimate the fuel savings from cruising at 0.02 Mach number slower than initially assumed for the fleet model (Table 5). In general, this estimate was obtained by using

specific range (miles/gallon) differences at a typical cruise weight. The fleet model was then used to calculate the total fuel use for the modified cruise speeds. Fuel savings only occur during the cruise portion of the flight. Therefore, on most short flights there is little, if any, savings.

The same procedure was employed for a slowdown to the lowest practical speed. Except for the Convair 580 this speed is defined as the cruise speed at which the specific range is 0.99 of its maximum. Any additional fuel savings require a substantial decrease in speed.

The direct operating costs consist of the fuel, crew, and maintenance cost for flying an airplane. The crew and maintenance costs per airborne hour for the DC-8-61 were obtained from ref. 10 and assumed to be the cost at 0.82 Mach-number cruise. From discussions with airline experts, it was assumed that 75% of the crew costs and 50% of the maintenance costs are really flight-time dependent. The fuel costs for various cruise speeds were obtained from ref. 23 assuming 12 and 24¢ per gallon prices. As the cruise speed increases, flight time decreases, causing crew and maintenance charges to decrease while the fuel component rises. The opposite is true for slowing down.

The 1968 average value of time ($7.54/hr) in air travel from ref. 33 was increased to $8.80 for 1971. The increased value for air travel was assumed the same as the increase in nonagricultural hourly wages for the period of interest.[34]

The performance reports were also used to estimate the fuel savings impact of the fleet cruising 2,000 feet higher. Differences in fuel use were estimated for that range of stage lengths where fuel could be saved.

In most cases these estimates were obtained from flight planning charts. For several airplanes the additional climb and descent fuel-use had to be balanced with the decreased cruise consumption. The modified fuel consumption for flying higher was then used in the fleet model to calculate total fuel use.

Engine fuel consumption-rates for several thrust settings were obtained from ref. 29. Assuming that the total taxi thrust remains constant, a new fuel-consumption rate was obtained for the EPA proposal. The airplanes departing from the airports with more than 1,000,000 enplaned passengers (as found in ref. 16) were obtained from ref. 35 for the year ending June 30, 1971. There are two reasons why the EPA proposal's assessment is probably underpredicting the potential fuel savings: (1) average taxi times were used and the taxi time at the larger hubs is undoubtedly greater and (2) airplanes are probably overthrusting on taxi and total thrust settings could be reduced.

The FAA program's assessment used the same flight data as the EPA assessment. The following assumptions were employed: (1) tow vehicle fuel-consumption rate is 2 pounds/minute for airplanes less than 175,000 pounds gross weight (typical)[36] and 3 pounds/minute for others, (2) time to tow is 40% greater than present taxi time, (3) tow vehicle no-load speed is twice the tow speed, (4) APUs operate while in tow and consume 6.5 pounds/minute, and (5) the tow vehicles operate an additional two minutes per flight for maneuver and idle. These assumptions are similar to those employed in ref. 17.

Summary and Conclusions

In Table 4 the 1973 domestic P/C fuel use was estimated to be 1.03 x 10^{15} Btu. The CAB's (Table 2) fuel use for 1971 was increased by the projected air carrier jet fuel use increase from 1971 to 1973 in ref. 19.