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The Future Transport World

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Simultaneous progress in many fields of technology is a prerequisite to each succeeding advanced round of aircraft, including transports. Propulsion technology is usually the key to major forward strides. Indications on which market projections can be based point to a tremendous growth in air transportation, both passenger and cargo, over the next 20 years, a growth so great as to require impractical numbers of aircraft with current capability. Some data are offered to illustrate this statement. At the same time, new engines with significantly improved specific fuel consumption characteristics and ability to produce thrust up to $3\frac{1}{2}$ times current transport thrust levels open enormous vehicle design possibilities. This paper presents some market projection data to illustrate what future requirements might be. It estimates the size of the fleet that would be required to match the projected traffic growth, including in the estimates the effect of higher-capability aircraft in reducing the total number otherwise required. We are rapidly approaching a time of great demand for air vehicles; a time when great vehicles are feasible; a time when great variety in vehicles will be possible; obviously, a time calling for great decisions.

Introduction

A CONSIDERATION of future commercial transports must include a visualization of the transportation world in which aircraft would work. The nature of that work, the magnitude of it, and the time when it must be done are fundamental. A certain skepticism (which we share) about the validity of any effort to predict coming events is, of course, both natural and desirable. However, when one decides to undertake the financing, development, manufacture, and, hopefully, the ultimately profitable sale of major airline equipment, one is indeed dealing in the future. The venture will ultimately become profitable only if the resultant product is good enough in all respects to remain in demand in a time period on the order of 10–20 years following that initial decision.

Historical Growth

Estimates of future growth are, normally, projections of past trends. Fortunately, the history of airline traffic is very well documented. The availability of this mass of information is important in that it does provide the sort of base on which future projections must be made. For our purposes, only the over-all growth is plotted in Fig. 1. This is a significant curve. For example, notice the leveling out around 1961. That was enough to cause great apprehension among the airline industry and its financial supporters. There was much scare talk, with many believing that the only hope for the airlines was to merge. Just imagine the effect overly conservative decisions made during that time period might have had on the ability to meet the growth that has been experienced since!

The passenger mile market has doubled since the introduction of jet transports in 1958. This equals an average annual growth rate of 10.5% per year for the period 1958–1965. The greatest gains in this market have been in coach or economy service, both in passenger miles and passenger revenue.

Projected Growth

In common with those of most economists, our forecasts are predicated to a large degree on the relationship of air transport growth to the general economic health as indicated by the gross national product (GNP). Figure 2 shows projections in GNP by a number of agencies. The average rate of growth in the postwar years 1947–1963 was 3.4%. We have taken the Resources for the Future data as a high at 4.2% and the Committee for Economic Development data as a low at

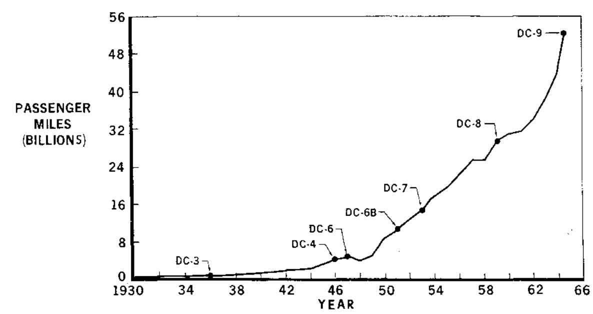

Fig. 1 History of U.S. domestic passenger miles, 1930–1965.

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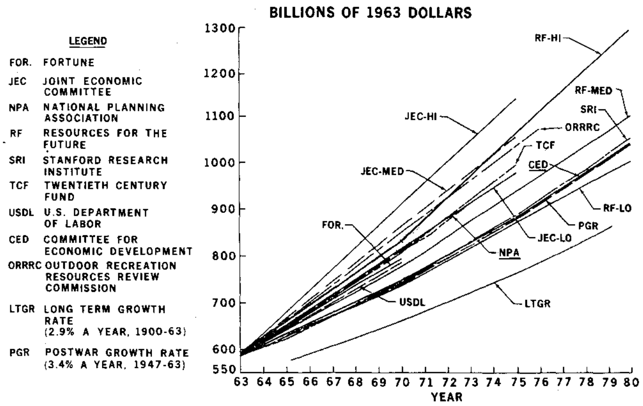

Fig. 2 Principal projections of U.S. gross national product.

3.5%. For our own estimates, we currently use a value between these two of 4.1%. This, in turn, is modified by several other factors such as elasticity of income and price, which will not be discussed in this broad paper.

The importance of the GNP as an intercity traffic indicator is illustrated in Fig. 3, which shows a constant relationship of passenger miles in all forms of intercity transportation to a unit of GNP, from 1929 to the present except for the World War II years. The figure also illustrates the transition from surface to air transportation in the postwar years.

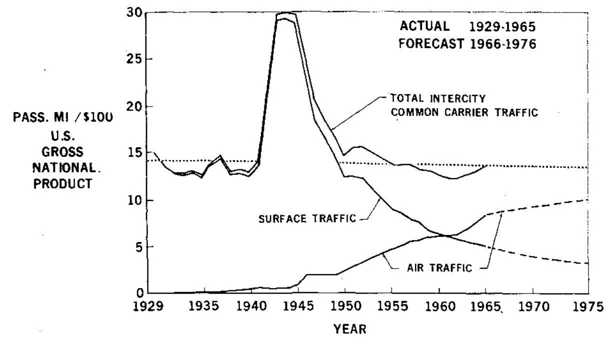

Fig. 3 U.S. domestic intercity common carrier traffic world (passenger travel factors).

Converting the relationship between traffic and GNP to total passenger miles in terms of the expected growth in GNP results in Fig. 4, which, when simplified, leads to Fig. 5. This graph is based upon a continuing high rate of growth through 1970 of 13.5%, and a diminishing rate thereafter. The overall rate of growth is 8.9% for the entire period.

The data, so far, have been in terms of U.S. domestic traffic. For our purposes, we wish to consider international requirements as well. We will refer to the International Civil Aviation Organization (ICAO) countries as comprising, for this paper, what we will call the ICAO world. One important factor in analyzing the entire world market is the declining ratio of air passenger miles in the U.S. vs those of the remaining ICAO world. This declining percentage of the U.S. air travel market is shown by Fig. 6. This estimate is based on the faster economic growth of other areas of the world, especially Europe, which will enable these areas to generate relatively more growth. Combining the relationship between domestic and ICAO world traffic leads to the passenger mile projection shown in Fig. 7.

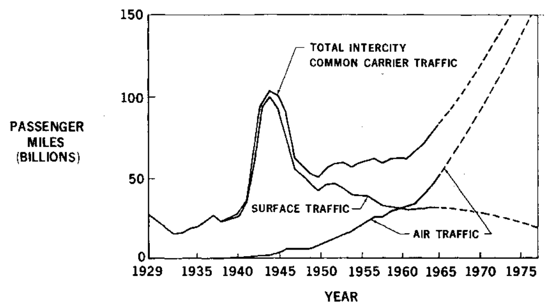

Fig. 4 U.S. domestic intercity common carrier (passenger mile traffic).

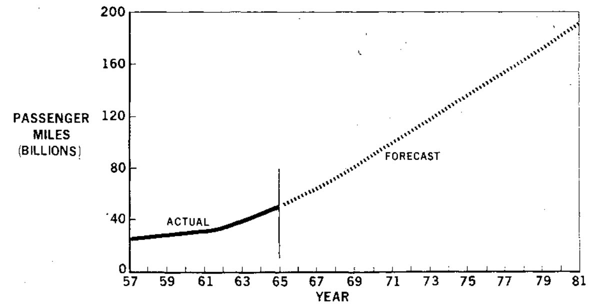

Fig. 5 Forecast of U.S. domestic air passenger miles.

When the projections that have been discussed thus far are plotted in terms of seat miles on the basis of an average load factor of 55% for the total ICAO world, the picture looks like Fig. 8. On this same basis, the seat miles generated by the aircraft on hand and by those on order are also shown.

Thus far, we have been thinking in terms of passenger miles and seat miles (different by the load factor realized).

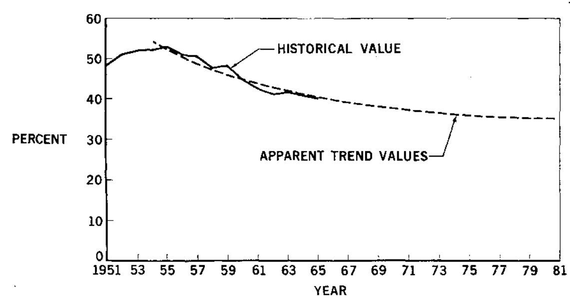

Fig. 6 U.S. domestic air traffic as a proportion of ICAO world total.

To consider what these figures mean in terms of numbers of airplanes, we must consider the productivity of particular aircraft (which we know) and the mix of different aircraft in the total fleet (which we must assume).

Figure 9 illustrates an assumed mix of aircraft types, calculated by the required number of deliveries per year. The number of deliveries per year toward the end of the planning period is lower because the newer types of aircraft will be more productive and because our growth curve of Fig. 5 showed a diminishing rate of growth after 1970.

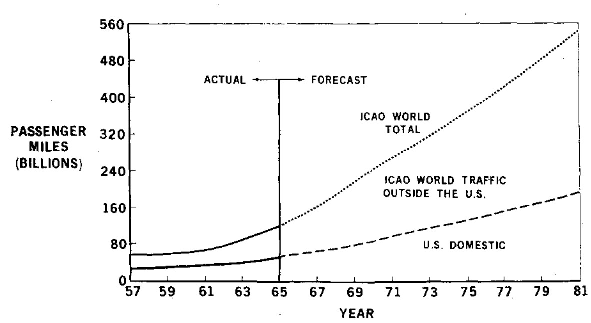

Fig. 7 Forecast of ICAO world passenger mile traffic.

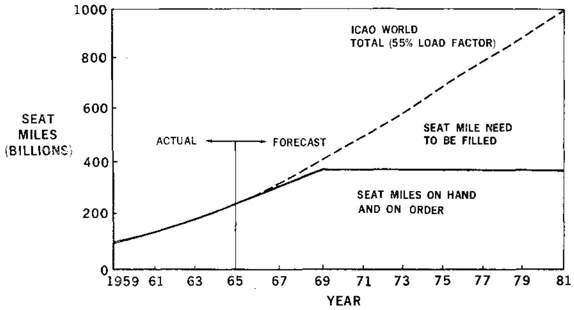

Fig. 8 World seat mile demand and supply (ICAO world 1959–1981).

It is not the intent of the authors to insist on the particular fleet mix shown in this example and in the similar illustrations that follow. This mix, the combined capabilities of which lead to the total fleet size illustrated, was arrived at without the use of any established methodology other than personal judgment and some knowledge of how long it takes to inject significant numbers of new-capability aircraft into the fleet. Aircraft known to be actually on order were included.

To fill the seat-mile need, the projected passenger market will require an average of approximately 340 new jet aircraft of all types per year for the 1967–1976 period. The value of this world passenger aircraft market will average approximately 2.05 billion dollars per year throughout the

Table 1 Distribution of selected air-shippable commodities by distance shipped

Miles	1963 census billion ton-miles (est.)
0–499	243.4
500–1199	22.4
1200 and over	34.2
	300.0
Potential over 500 miles	56.6
Estimated total air potential	80.9

planning period. Fig. 10 is a cumulative curve based on the yearly delivery data presented in Figure 9. Approximately 4800 passenger aircraft are indicated by 1975. Of these, about 3600 will be new jet equipment.

As startling as these projections of passenger traffic may seem, the fact is that air freight has been growing at a much greater rate, particularly since about 1962. The 15-year U.S. air freight history is shown in Fig. 11. The feeling used to be that, although passengers were always in a hurry, fast cargo delivery wasn't really important so long as a steady stream of whatever it was kept on arriving at a reasonable rate. With respect to the very small fraction of the total

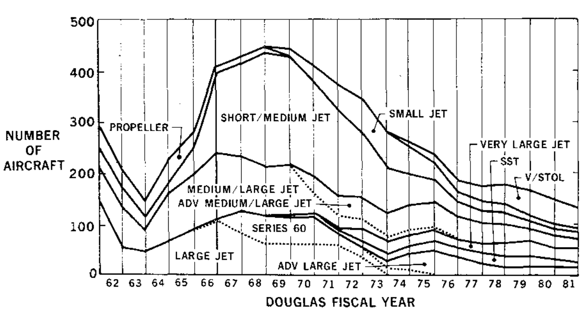

Fig. 9 Passenger aircraft deliveries, scheduled airlines.

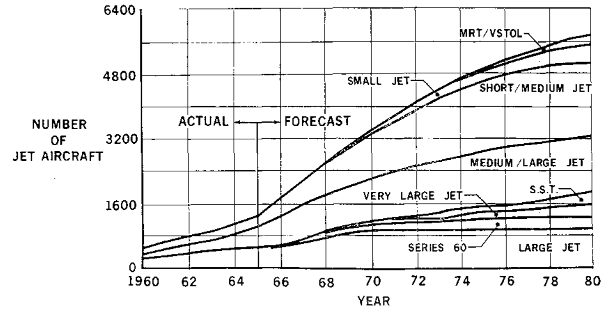

Fig. 10 World passenger aircraft need, cumulative.

cargo that does go by air, this certainly does not seem to be true in the jet age.

Figure 12 graphically illustrates the idea that we are currently in a transition period of rapid expansion. The early phases demonstrate the relatively small role that cargo played in air transportation. The experimentation period was characterized by the use of the DC-3 as the principal cargo carrier, and the early experience phase was boosted by the use of DC-6's and Constellations. However, it wasn't until the advent of jet cargo aircraft, with their greater capacity and speed and improved economy, that the technological development necessary to enter the transition and expansion phase occurred. These aircraft and those envisioned for the near future will permit and foster a rapid increase in total

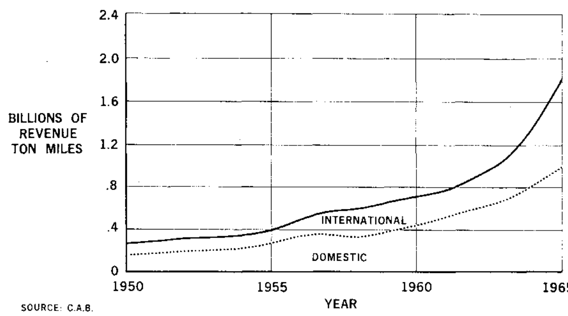

Fig. 11 Total U.S. air freight, scheduled service.

ton-miles. It is anticipated that this high rate of growth will continue for at least the next 15 years. Some time after 1980 it is expected that the high rate of growth will begin to taper off, and the industry will assume the characteristics of a more mature mode of transportation. When the air freight industry reaches maturity, its forecasting will be more closely related to the fluctuations in the national economy than is the case during the current transition and expansion phase.

A study of the nature of the movement of air-shippable commodities within the U.S. was made on the basis of 1963 information. Table 1 shows that about 80% of it was shipped less than 500 miles. Trucks do a good job over such

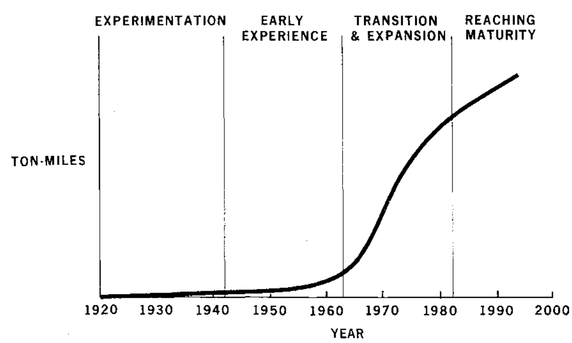

Fig. 12 Air cargo development phases.

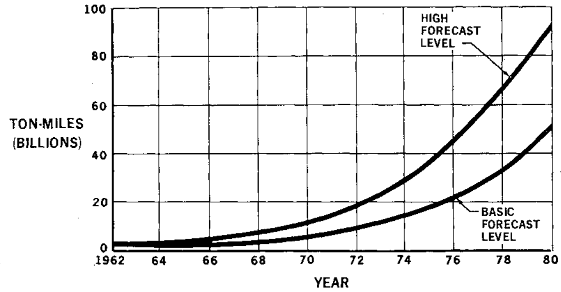

Fig. 13 ICAO world air cargo forecast, Douglas.

ranges and undoubtedly will continue to do so. The air-shippable cargo that was moved 500 miles or more amounted to 56.6 billion ton-miles, of which only 0.7 billion ton-miles was actually carried by air, as indicated previously by Fig. 11.

Two forecasts are presented in Fig. 13. The basic (lower) forecast is predicated on the possibility that although a considerable fleet of jet cargo aircraft will be in operation by 1967, problems relating to tariff reductions may not be resolved until perhaps 1970–1971. In that event, the emphasis for selling air cargo will be strictly on the merits of distribution cost savings and improved service, rather than the effect of a competitive rate structure. The high forecast assumes that

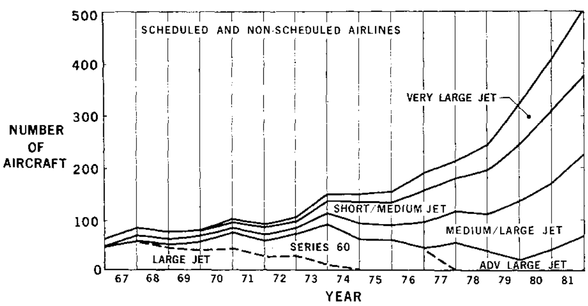

Fig. 14 Cargo aircraft deliveries.

because a sizable fleet of jet cargo aircraft will be in service by 1967, the carriers, operating these aircraft with their tremendous capacity, may reach early tariff agreements that will have the effect of reducing the over-all cargo rate structure.

The ton-mile projections are translated into numbers of aircraft by means of a procedure similar to that used previously for passenger traffic. It is based on the capabilities of the various types of cargo aircraft in a typical mix comprising the total cargo fleet and a 60% load factor. Figure 14 shows the number of aircraft required per year to match the average of the projections set forth in Fig. 13. The cumulative result of such a delivery schedule is shown in Fig. 15.

When the passenger aircraft (Fig. 10) and the cargo aircraft (Fig. 15) are added, the resulting total requirements for

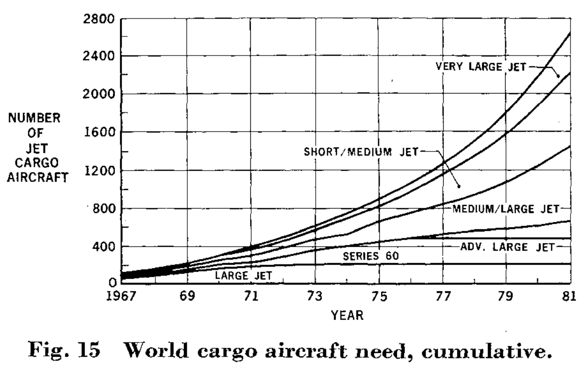

Fig. 15 World cargo aircraft need, cumulative.

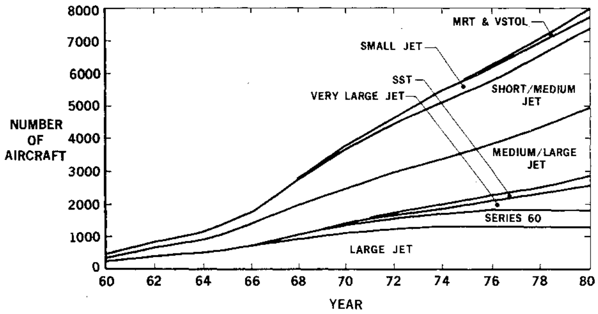

Fig. 16 Total world aircraft need 1966–1980, cumulative.

the ICAO world fleet (Fig. 16) reach about 7000 aircraft in 10 years, even though the productivity of advanced types is here being counted on to help meet the projected volume of business. This is about $2\frac{1}{2}$ times the present fleet in numbers, and far more than $2\frac{1}{2}$ times the present fleet capability.

Advanced Technology

We have thus far examined what the future transport demand might be like. More and better transports are indeed indicated. A transition to greater emphasis on air cargo operations in all phases of the system will probably char-

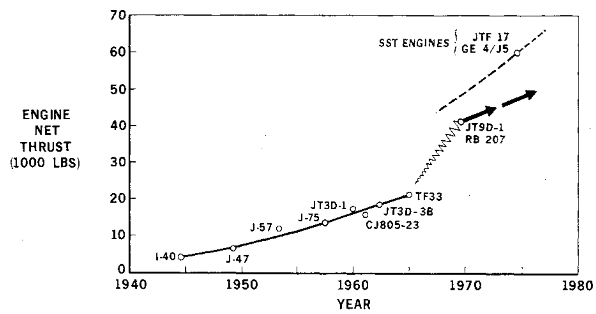

Fig. 17 Turbine engine thrust growth.

acterize the time period we are examining. Let us turn now to examining some of the technical trends that might permit more productive future transports to meet the future requirements. Advances in propulsion, aerodynamic design, structural weight fraction, mechanical sophistication and precision in all phases of instrumentation, navigation, and communication will characterize each new round of vehicles. This paper will not examine all of these elements. It is necessary, however, for our immediate purposes, to place a current sudden jump in propulsion technology in some sort of perspective.

Figure 17 illustrates the increase in available jet engine thrust from 1945 to the present. The majority of the large jets have for several years been powered by relatively low-

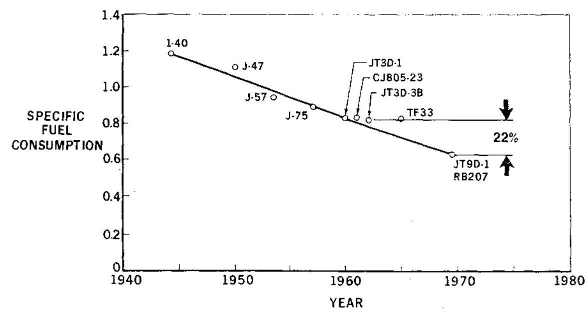

Fig. 18 Turbine engine SFC improvement (subsonic cruise).

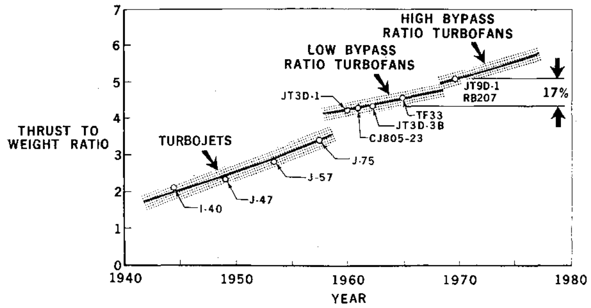

Fig. 19 Turbine engine thrust/weight ratio improvement.

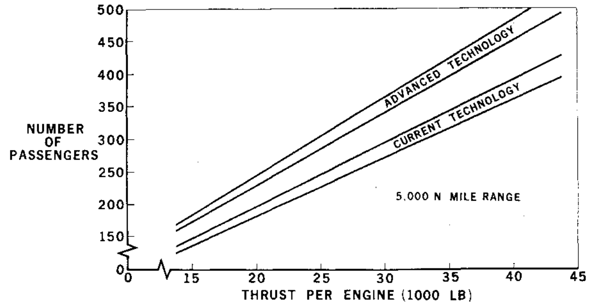

Fig. 21 Payload vs thrust.

bypass-ratio fan engines of 18,000-lb thrust. Thanks to Air Force foresight in setting the requirements for the C-5A program, a whole new order of engine performance has been brought into existence. This new technology is exemplified by several engines, of which the JT9D and the RB207 can be named, centered nominally on 42,000-lb thrust but actually available up to about 50,000 lb if desired. As a result of increased bypass ratio, higher turbine temperatures, and optimized internal aerodynamics, these engines are not only vastly more powerful but also more efficient. As shown by Fig. 18, these engines continue the decrease in specific fuel consumption that has characterized jet engine development thus far. Figure 19 illustrates the steady improvement in thrust-to-weight ratio. These new-technology improvements are so great as to open up a whole new realm of vehicle possibilities with respect to both increased size, if desired, and increased efficiency.

From the standpoint of aerodynamic design efficiency of the vehicle itself, apart from propulsion improvements per se, Fig. 20 shows the improvement in aerodynamic cruise performance (Mach number times lift-to-drag ratio) during the last three decades. We see that the product of Mach number times lift-to-drag (L/D) ratio shows a healthy increase with time. This improvement, it should be noted, is primarily the result of increasing cruise speeds. L/D ratios of subsonic commercial transports have generally remained in the neighborhood of 17–20. To continue the increase in cruise performance, increasing emphasis must be placed on improving L/D ratios. The importance of the cruising L/D to the economics of the SST has been widely recognized. As a result of the expenditure of much engineering effort, the U.S. version of the SST agrees remarkably well with the trend line. Future subsonic transports could benefit from similar intensive effort.

To illustrate the effect of the improvement in propulsion and aerodynamic technology already discussed, Fig. 21 depicts the significant difference in payload capability, expressed in terms of numbers of passengers, between the two levels of technology. For any given range (here taken as 5000 nautical miles), increasing the payload requires a proportionately greater increase in gross weight and thus an increase in engine thrust.

To show what the advanced technology might mean in terms of direct operating costs (DOC), Fig. 22 compares relative direct operating costs at both current and advanced technology levels vs sea level static thrust, again for the 500-nautical-mile-range case. It should be noted that DOC does not decrease simply by increasing thrust, but because the increased thrust means increased passenger capacity. We see that while increasing the thrust (and therefore the payload) results in a worthwhile reduction in DOC, it is the advanced technology that makes possible the major portion of the reduction.

Future Transports

We have, thus far, studied projections that indicate a formidable traffic growth, both passenger and cargo. The indicated traffic volume would appear to require, roughly, a four-time increase in number of transport aircraft by 1980. This assumes the vehicles entering service in the years up to that time period are capable of more and more useful work per unit, as we have shown that the state-of-the-art will permit.

In addition to the supersonic transports that will be entering the fleet during the latter half of this time period, one can readily visualize a whole new spectrum of more advanced subsonic transports that will in fact become the backbone of the civil fleet.

These may range all the way from two-engine aircraft with advanced-technology engines of the order of 25,000 lb of thrust and STOL characteristics up to behemoths with perhaps six new-technology engines of the order of 50,000 lb of thrust or more, permitting operating gross weights well in excess of 1 million lb. The smaller of these must compete with the highly developed versions of the existing subsonic transports, which are not easy to beat for efficiency and economy. The larger versions will be capable of marked reductions in unit costs of producing seat-miles and ton-miles, but need to be injected into the fleet at the right time. We can assume with certainty that increased efficiency will by synonymous with the emergence of the new transports.

Such growth as is illustrated here is contingent not only on the need for the services and the ability to enhance the efficiency of the vehicles that perform the services, but also on simultaneous advances in many important related areas.

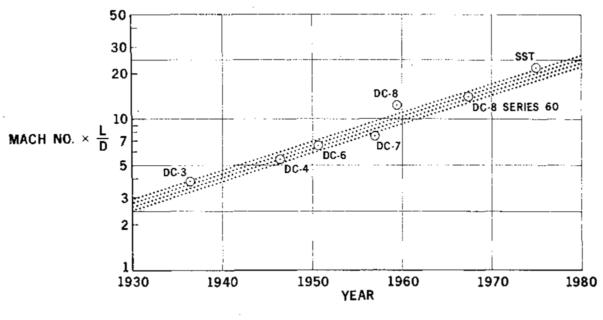

Fig. 20 Aerodynamic efficiency trend.

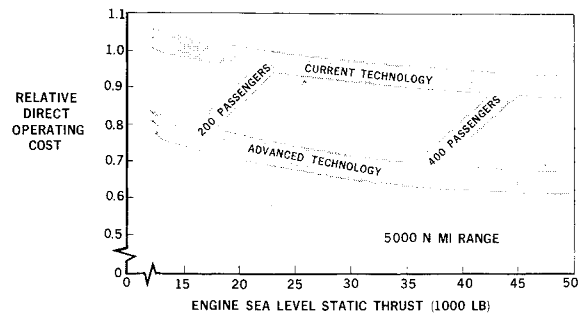

Fig. 22 Effect of engine thrust on direct operating cost.

Such growth simply would lead to chaos if there were not adequate advances in all-weather flying capability, air traffic control, noise abatement, air terminal development and ground transport, or more probably, would not take place at all!

As we said at the outset, reservations about future predictions are proper and in order. Yet, simultaneous progress in all these areas hinges on a profound understanding of what the future might hold. This is an understanding that has to be developed before the fact, developed now, not then.

Since this paper was first presented, there has been much discussion of it. In general, little or no resistance to the size of the projected traffic volume is in evidence. There are, in fact, other equally serious projections predicting greater growth than this study. However, it has been rather difficult for people to accept the large numbers of airplanes associated with such a traffic volume. The fleet size will indeed change as different fleet mixes are assured, but not much, except as much larger inputs of SST's and very large new subsonic transports are assumed. It may seem presumptuous to make predictions for as far ahead as 1980 but, in terms of the number of significantly advanced aircraft that can be injected into the fleet, 1980 isn't very far away.

Conclusions

Even with advanced transport vehicles of much greater productivity than that of current transports included in the fleet, the future growth of the air transportation business will require large numbers of aircraft by comparison with the present total fleet. The technology is at hand to make feasible vehicles of much greater productivity. These more-productive vehicles will operate at significantly reduced operating costs.

A total air transportation system on the scale here projected for the 1980's has implications far beyond the vehicles themselves. Airline operating techniques, regulatory considerations, international agreements, airway and ground facilities, and many other vital elements of the total system will require careful integration to permit this expansion.

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Linear Theory of Superbooms Generated by Refraction

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An analysis is made of the flow past a slender body of revolution, moving at supersonic velocity, in an atmosphere in which the speed of sound decreases linearly with altitude. The problem is treated in the context of linearized theory. The primary interest is directed to the pressure distribution occurring in regions where the signal generated by the body is focussed, because of refraction, in the nonuniform medium. Explicit expressions are derived for this pressure signature, and it is found that the rise in pressure behind the Mach surface in the nonuniform atmosphere at the focal distance is of the order of four times that occurring behind the Mach cone in a uniform atmosphere at similar distances from the moving body.

Nomenclature

a = sound speed gradient
$c(z)$ = speed of sound
c_0,c_g = speed of sound at body and at ground
$_i(z), i = 1,2,3$ = functions expressing envelopes in plane $y = 0$; Eq. (12)
$G_{c1},G_{c2},G_{v1},G_{v2}$ = form functions for pressure signature at cusp level
$H(t)$ = unit step function
K = source strength
L = body length
$m(x)$ = source strength per unit length
$M(z)$ = Mach number: $M(z) = M_0/(1 - \epsilon z)$
M_0 = Mach number at $z = 0$
N = number of roots of Eq. (8)
p = pressure due to single source
P = pressure due to source distribution
$R_0(x)$ = radius of slender body
$S(x)$ = slender body cross-sectional area
t = time
t_i = roots of Eq. (13)
$t_{fi}, i = 1,2$ = roots of Eq. (13) corresponding to envelopes $f_i(z)$
t^* = root of Eq. (13) corresponding to cusp point
t_0 = thickness ratio of slender body
$T_i, i = 1,2,3$ = dimensionless roots of Eq. (13): $T_i = \epsilon c_0 t_i$
V = speed of moving body
x,y,z = coordinates fixed in moving body
α = dimensionless time difference: $\alpha = \epsilon c_0(t_{fi} - \theta)$
β = $\beta^2 = M_0^2 - (1 - \epsilon z)^2$
β_0 = $\beta_0^2 = M_0^2 - 1$
Γ = coefficient in cusp level pressure distributions
$\delta(x_1, \ldots, x_n)$ = Dirac delta function in n dimensions
δ = distance away from Mach envelopes
Δ = dimensionless distance from leading Mach envelope
ϵ = parameter expressing sound speed gradient
$\bar{\epsilon}$ = dimensionless parameter: $\bar{\epsilon} = \epsilon L$
θ = elapsed time after source disturbance
ν = function defining elementary fronts, Eq. (4)
ρ_1,ρ_2 = $\rho_1^2 = \xi^2 + \eta^2 + \zeta^2$, $\rho_2^2 = \rho_1^2 + 4(1 - \epsilon\zeta)/\epsilon^2$
ξ,η,ζ = coordinates fixed in space
$\sigma_i, i = 1,2,3$ = function defined in Eq. (25)
τ = instant of source disturbance

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