Chapter III

VARIABLES AFFECTING A SUPERSONIC TRANSPORT MARKET

Any supersonic transport that is developed will have to be feasible in economic terms and acceptable from an environmental standpoint. Environmental constraints will definitely enter into the total economic picture, but so will fuel costs, ridership, stage lengths, and other factors. This chapter lays out some of the variables that are involved in projecting the future market for new high-speed aircraft, specifically an advanced supersonic transport (AST). It considers especially how the variables affect the economic viability of the AST relative to a future possible advanced subsonic transport (ASUBT).

The criterion of economic feasibility will be the return on the commercial investment required to bring the aircraft and supporting systems into being. As the early history of the automobile and the airplane witnesses, the first embodiment of a new technology frequently fails to pay for itself. A new technological path cannot be followed for long unless there is promise that along the way the economics will become attractive. It is assumed here that a bright promise for an economically sound and environmentally acceptable system is a prerequisite for pursuing either new subsonic or new supersonic aircraft.

As the historical discussion in chapter 11 brought out, considerations other than long-term economic ones often enter into the decision concerning a long-range technological development program. Some of these, such as national pride, are not economic at all, at least in a strict sense. Others, such as the lobbying of a particular industry, are economic, but not essentially long-sighted. Nonetheless, this study assumes that such considerations will not prevail for long if the program at issue does not make long-run economic sense.

THE PATH TO IMPROVED PRODUCTIVITY

An aircraft's product is seat-miles. Aircraft productivity is usually measured in terms of the seat-miles an aircraft can generate per hour of operation. Two primary ways that productivity can be improved are increased size—moving more seats—and increased speed—moving seats at a faster rate. Other variables affecting productivity are discussed later.

Most major transportation improvements have occurred in a sequence of steps. The first trains, the first cars, the first airplanes all represented a jump—or sometimes only the potential for a jump—in productivity and in service that at first cost too much to attract a broader market. As technology improved in a succession of smaller and diverse steps, vehicle and operating costs came down enough that the gain in productivity eventually yielded an actual decrease in costs.

In the early days of aviation, productivity gains that were derived from changes in aircraft design came from successive improvements in size, range, and speed. However, for over 20 years—since the jet replaced the piston engine—nearly all the gains in aircraft productivity have come from size-related improvements (see figure 1, ch. I). Such improvements have been accompanied by some reductions in vehicle cost and technology-related improvements in operating efficiency. Table 3 shows the historical progression of productivity improvements through increases in size and speed. Size multiplied by cruise speed, labeled "cruise speed seat-miles, " is only a rough index of true productivity because it does not account for time lost at airports.

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Table 3.—Progress in Aircraft Productivity

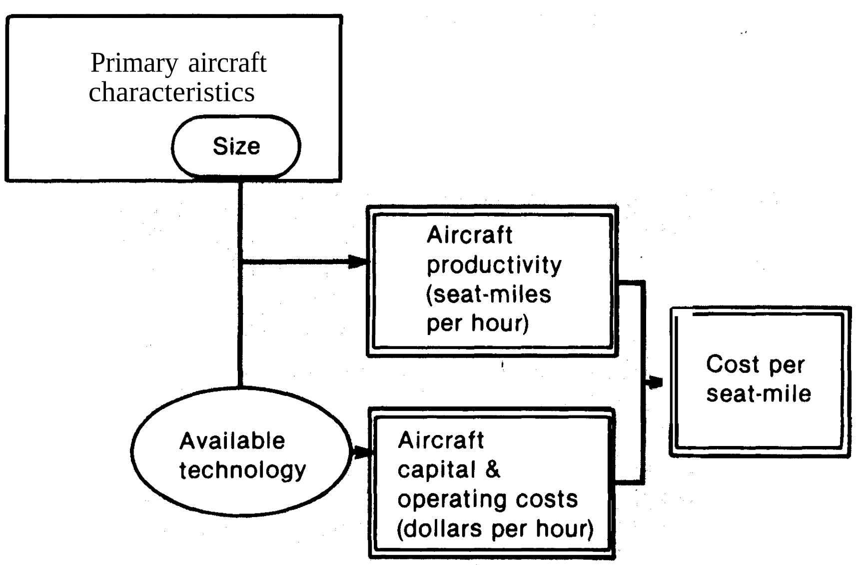
Typical aircraft	Date of introduction	Number of seats	Cruise speed (miles per hour)	Productivity (seat-miles per hour)
Ford Tri-Motor[a]	1926	12	115	1,380
Handley Page[a]	1931	38	127	4,826
Lockheed Orion[a]	1931	6	224	1,344
Douglas DC-2a	1934	14	160	2,240
Douglas DC-3a	1936	21	180	3,780
Convair 240[b]	1948	40	270	10,800
Douglas DC-6....	1948	58	300	17,400
Boeing 707[b]	1958	122	525	64,050
DC-8-61[b]	1967	251	600	150,600
Boeing 747[b]	1970	405	575	232,875
Concorde	1976	90	1,300	117,000
Illustrative AST	?	300	1,600	480,000
Illustrative ASUBT	?	600	575	345,000

SOURCES: [a]Miller & Sawyers, *The Technical Development of Modern Aviation*, Praeger, 1970.
[b]Hazard, *Transportation Management.Econom/cs-Poticy* (Cambridge, Mass: Cornell Maritime press, 1977)

The desirability of an improvement in productility depends both on what it costs and on how it is perceived to improve service. Starting with the cost aspect: if doubling the productivity of an aircraft, say, by doubling its size is accompanied by a doubling of what it costs to buy and operate, no net gain in costs per seat-mile has been made. If, however, the cost of increasing size is proportionately less than the productivity gain, then a net reduction in seat-mile costs has been achieved. Such savings have been the motive behind the development of the B-747, the DC-10, the L-1011, and more recently the A-300 aircraft: the cost of size has been proportionately less than the gain in productivity, so costs per seat-mile have come down. These relationships are arrayed in figure 4.

Size-related productivity improvements are still possible, but have less potential than in the past as a means of savings. The 747 is roughly four times the size of the last piston aircraft.

Figure 4.—The Relationship of Aircraft Productivity and Costs



SOURCE: Office of Technology Assessment.

However, comparable gains do not seem likely in the foreseeable future, even if larger aircraft of 600 to 800 seats do come into being, The market for such very large aircraft appears limited because an enormous number of travelers over a given route would be required to keep such aircraft reasonably full and still necessitate frequent enough departures. Furthermore, their size would make them incompatible with current airport facilities. Therefore, the current objective in designing new ASUBTs is not increased size but improved energy efficiency, reduced environmental impact, and better maintenance and reliability. These areas, along with moderate size increases, provide the opportunity for lower cost aircraft.

Other factors affect seat-mile productivity. One is aircraft utilization, the number of hours per day an aircraft is used. A second is stage length, the distance flown between stops. Because short flights involve a larger proportion of total aircraft time spent on the ground, not generating seat-miles, the productivity of short flights is lower than that of longer flights. Extending aircraft range increases productivity because it decreases the number of intermediate stops and thus the time spent on the ground. Today, long-range aircraft are capable of joining all the major cities of the world and, thus, this avenue of productivity improvement is almost entirely exploited.

The rationale underlying a supersonic aircraft is to take advantage of the last remaining path of major productivity improvement—increased speed. Productivity is proportional not simply to cruise speed, but to average speed, because the time lost in airports and on climbout and letdown as well as the demands of route circuity have to be taken into account. As speeds increase from about the Mach 0.8 of subsonic jets to the Mach 2.0 to 2.4 of supersonics, average speed and therefore productivity roughly doubles.[1] Thus, a 300-seat supersonic aircraft could carry as many passengers per day as two 300-seat subsonic aircraft or one 600-seat subsonic aircraft.

[1] E. Q. Bond, E. A. Carroll, and R. A. Flume, *Study of the Impact of Cruise Speed on Scheduling and Productivity of Commercial Transport Aircraft,* NASA report CR-145189, April 1977.

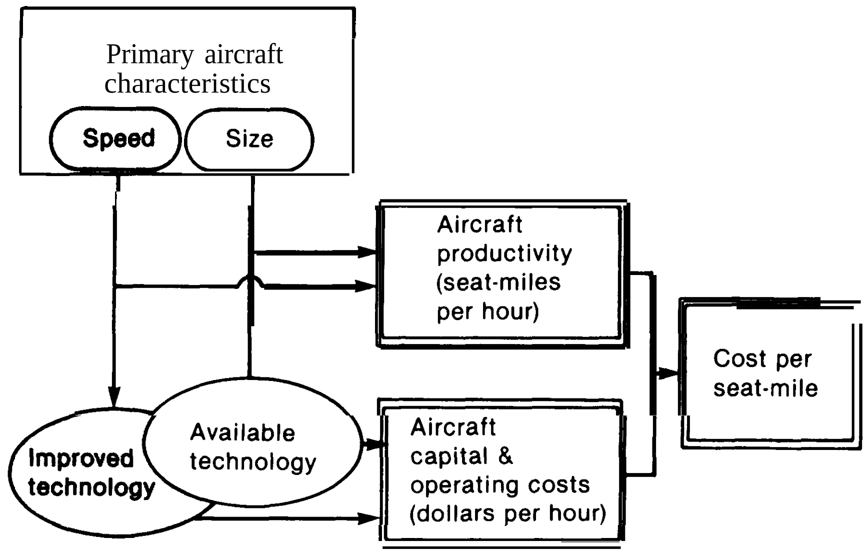
COST OF PRODUCTIVITY FOR SUPERSONIC AIRCRAFT

The uncertainty and controversy over the economics of a supersonic aircraft have never revolved around the issue of its productivity. It is recognized that higher speed will improve productivity, and the degree of improvement is fairly predictable even though it is qualified by other factors such as flight distances and airport turnaround times. The real concern has been the cost associated with obtaining this increased speed. Unlike size increases, which up to a point can usually be achieved with only minor improvements in basic technologies, appreciably higher speeds demand new technological capabilities. Because these capabilities are new, they are expensive and they involve uncertainties.

Figure 5 adds the variable of speed to the relationship arrayed in figure 4. How much the speed costs depends on the state of technology. As the various technologies associated with supersonic cruising flight advance, the cost of building and operating a supersonic transport will come down. As shown in figure 6, the historical experience of subsonic aircraft provides a precedent in this regard.

The first hopes that it might be possible to build a practical supersonic aircraft began to glimmer in the mid-1950's. At the time supersonic flight in military aircraft had been achieved only in dash capability, but anticipated advancements in technology held out the promise of sustained supersonic cruise. The military B-58 achieved limited supersonic cruise capability in the late 1950's. Following an extensive —and, by then current standards, expensive—technical development program, two very high-speed and long-range military supersonic cruise aircraft emerged in the early 1960's: the XB-70 and the SR-71. It is probably safe to conjecture that at this time it would have been technically possible to build a supersonic cruis-

Figure 5.— Influence of Speed on Aircraft Productivity and Costs



SOURCE. Office of Technology Assessment.

ing passenger transport, but at a hopelessly high cost, possibly 5 to 10 times more than the subsonic jets of the day.

During the rest of the decade, technical advancement continued. By 1970, based on the designs produced in the U.S. SST program, the estimated cost of building supersonic aircraft had come down to roughly **3.6** to **4.0** times that of an equivalent subsonic aircraft.[2] Given that the supersonic transport would be roughly twice as productive as the subsonic transport and that indirect operating costs somewhat favored the supersonic, this estimation translated into total operating costs of roughly 1.35 to 1.45 times those of equivalent subsonic aircraft of that period. These higher costs would have implied the need for supersonic fares 1.35 to 1.45 times higher than subsonic fares. Whether these cost estimates were accurate or whether such an aircraft would have been successful in the marketplace is uncertain: there are still strong opinions on both sides of these questions.

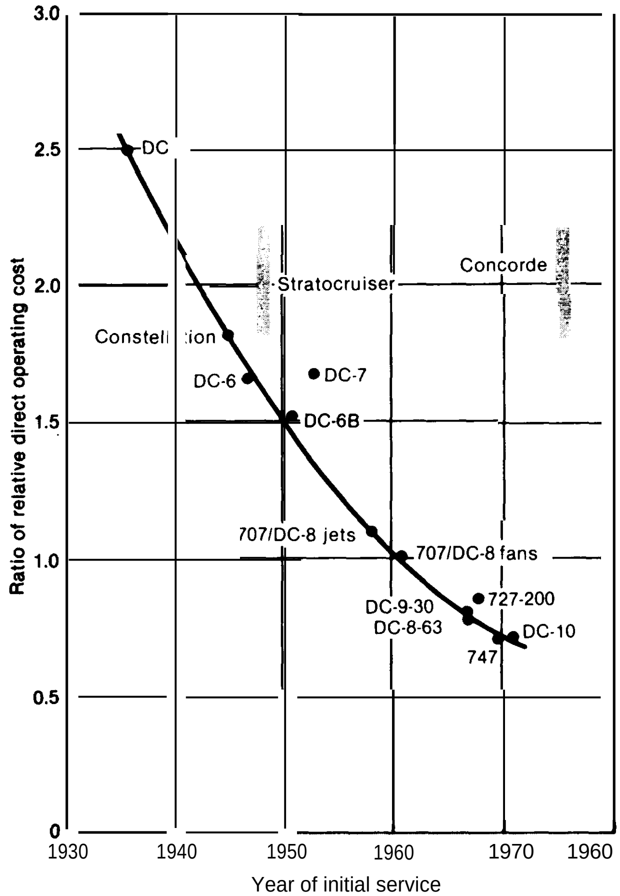
Aerospace industry officials estimate that with reasonably vigorous technology improvement an AST could be built in the late 1980's or early 1990's with the production cost gap narrowed from the 3.6 to 4.0 of the late 1960's to about 2.5 and total operating cost differences from the 1.35 to 1.45 range to perhaps 1.20 to **1.30.**

However, one very important factor stands in the way of further convergence of the costs of the supersonic and subsonic transport. That is the matter of fuel costs. Speed improves the productivity of the capital embodied in the vehicle, the productivity of crew labor, and even the productivity of some of the indirect cost elements such as maintenance labor. But it does not increase the productivity of fuel. It is inevitable that supersonic aircraft will use more fuel per seat-mile than subsonic aircraft. Estimates of the difference vary widely, but a factor of 1.5 to 2 times more fuel per seat-mile for an AST than a present subsonic aircraft seems reasonable. A continuing rise in fuel prices would have a larger impact on supersonic operating costs than on those for a subsonic aircraft (see figure 3, ch. I).

The future availability and price of fuel is an important uncertainty in the future prospects

[2] R. S. Shevell, "Selection of the Fittest: The Evaluation and Future of Transport Aircraft, " *Israel Journal of Technology, vol.* **12, 1974,** pp. **1-22.**

Figure 6.- History of DIrect Operating Costs, 1930-75



SOURCE: R. S. Shevell, "Technological Development of Transport Aircraft—Past and Future," *Journal of Aircraft*, American Institute of Aeronautics and Astronautics, vol. 17, February 1980.

for commercial supersonic aircraft. One can probably expect further convergence in the relative costs of building supersonic and equivalent subsonic aircraft because the less well-advanced state of supersonic technology holds more opportunities for improvement than is likely in subsonic technology. For the same reason, one can expect some further improvement in supersonic fuel efficiency. However, it is likely that supersonic fuel efficiency will continue to be substantially lower than subsonic fuel efficiency. As long as this is true, rising fuel costs will cause this element of total operating costs of the two kinds of aircraft to diverge.

THE IMPACT OF QUANTITY

The costs of technological advancement may be quite high and the price of fuel may prove inflexible. The major variable, bearing on both supersonic and subsonic aircraft, that can mitigate these effects will be the number of aircraft built and sold.

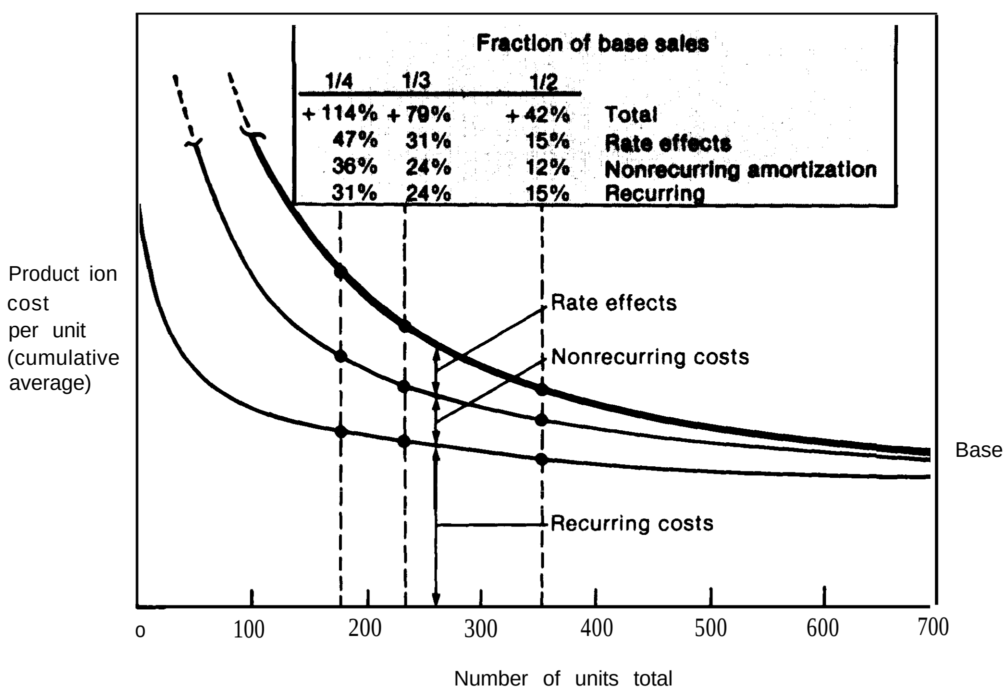
Figure 7 indicates the typical relationship between the cost of an aircraft and the number built. It shows graphically what can happen to costs if an aircraft fails to sell as well as hoped and fewer are built. Such an outcome is a large part of the economic story of the Concorde, production of which halted at 16 aircraft.

Costs decrease with increasing numbers produced for three basic reasons. First, the initial, nonrecurring costs of development, tooling, and facilities are largely independent of the number of aircraft built. These costs are typically absorbed by all the aircraft produced, so the amount allocated to each depends on the number built. Second, there is a learning curve in production, so that recurring production costs come down as more aircraft are built. Third, costs will come down if an optimal production pace is maintained. If aircraft are being built slowly because only a small number are needed and production is extended over a long period of time, the physical facilities and the specialized labor associated with production are not utilized as intensively as they could be and costs rise.

The ultimate cost of an aircraft will depend on the number built, which will depend on the number sold. However, the number sold will depend on their price, which is partially dependent on what they cost. This circular set of relationships is illustrated in figure 8.

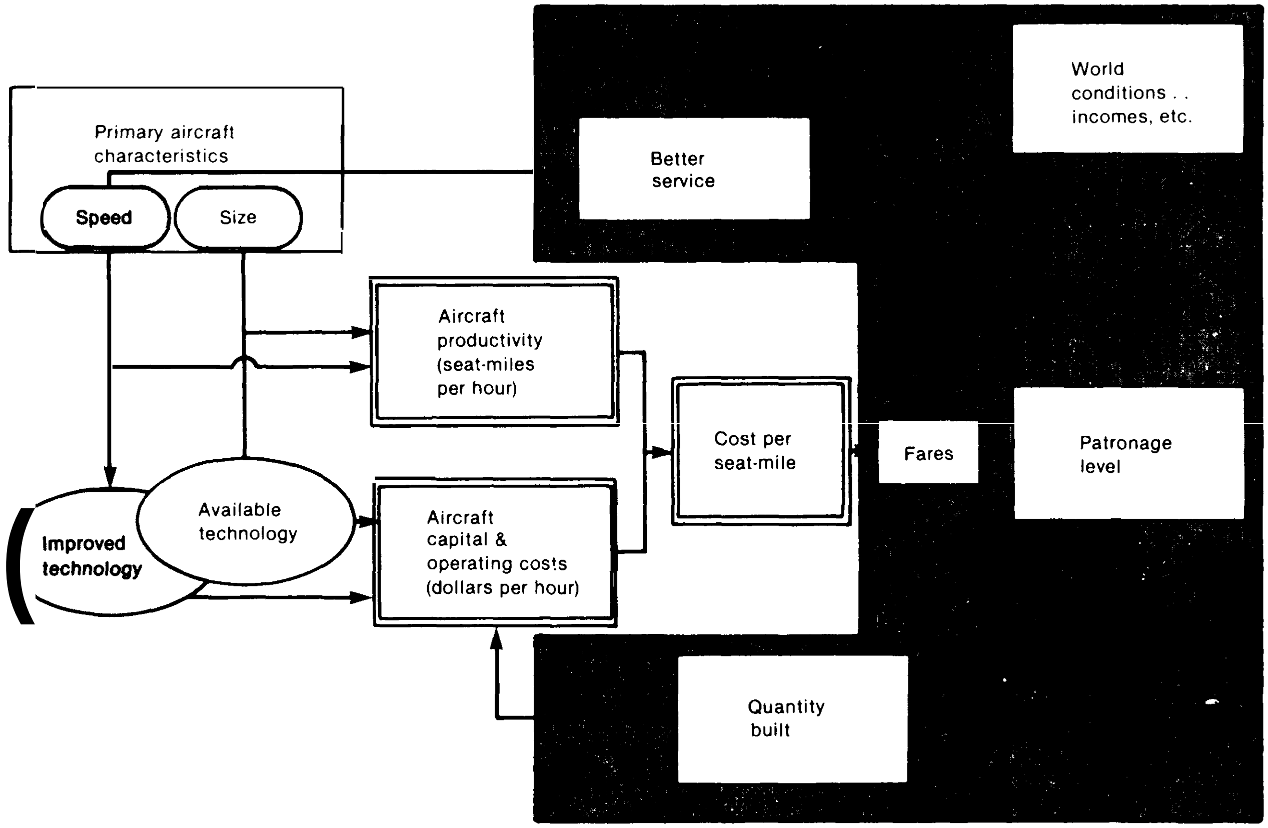
Figure 7.— Influence of Market on Unit Cost

Average unit cost penalties for reduced sales



SOURCE: McDonnell Douglas Corp., Douglas Aircraft Co., Off Ice of Planning,

Figure 8. —Relationship of Aircraft Productivity, Technology, and Costs



SOURCE. Office of Technology Assessment.

THE POTENTIAL MARKET

The number of aircraft built raises the entire issue of the nature and size of the market. Supersonic transportation will thrive only if sufficient patronage can be attracted in competition with alternative subsonic aircraft. The level of patronage is primarily dependent on the fares charged, the incomes of the travelers making the choice, and their perception of the importance of the better service provided by a shorter flight time. Figure 8 illustrates many of these relationships.

Quantifying these relationships so that an estimate can be made of how subsonic and supersonic aircraft will split the market requires hypotheses and assumptions about human behavior. It is assumed here that the choice between subsonic and supersonic service is basically a choice between time and money: supersonic flight will **save** time, but will cost more money. Thus, patronage will depend on how people evaluate the fare difference and the time difference between subsonic and supersonic aircraft. Although there is always a strong motivation to save money, some people will choose the timesaving either because they wish to avoid the discomforts of longer confinement in flight or greater jetlag or because they wish their flight to fit better into the schedule of the business day.

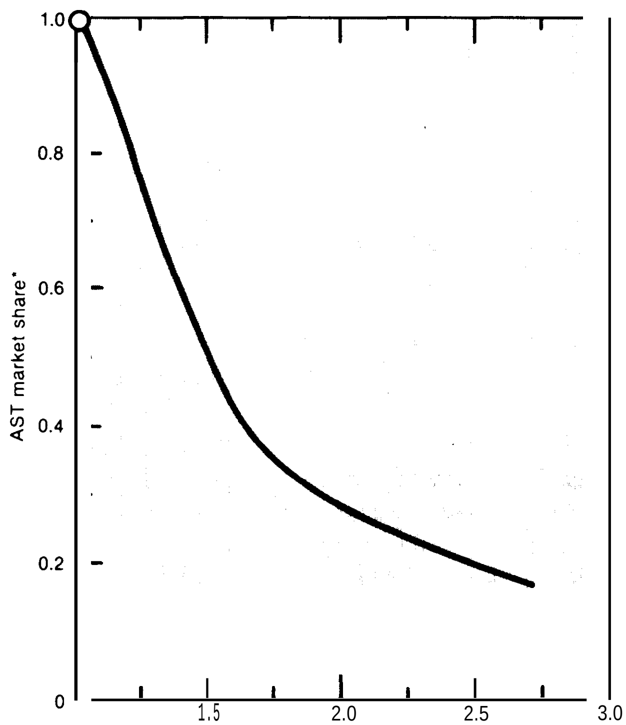
Making quantitative estimates of how many people will choose supersonic service at a given price can be approached in a number of ways. Such estimates may be based on separating potential travelers into different groups based on factors such as income level, purpose of trip, or their typical choice of booking (first-class, full-fare economy, or discount fare). For instance, one approach is to estimate what proportion of first-class, full-fare economy, and discount-fare passengers will choose supersonic service. This approach projects that average revenue per passenger on the AST will be higher than on a subsonic competitor not because different fares are assumed, but because each aircraft carries a different weighted average of the various classes of service.[3]

In order to estimate how future travelers will behave when offered the choice between supersonic or subsonic service, the analyst tries to find past situations where travelers faced dollar-time tradeoffs and deduce from what actually happened how people seem to assign relative value to their time and their money. A common assumption is that an individual's value for time saved varies with income level. This suggests quantifying a traveler's willingness to save time in relation to the traveler's hourly income. A recent analysis[4] used data obtained around 1960 when subsonic jets were still competing with propeller aircraft and from the 1970's on routes where the Concorde competed with subsonic jets to derive the multiple of hourly income that people would pay to save an hour of flight time. This analysis found that, on the average, business travelers would be willing to pay about 2.6 times their hourly income to save one hour of flight time, while nonbusiness travelers would only pay 1.3 times their hourly income.

Such analyses must be interpreted very carefully and recognized as imprecise. Though it may be unsatisfying to use such apparently tenuous reasoning to gauge future markets, such estimates do provide some guides. Their cogency depends on our willingness to assume that the basic logic is correct, that past behavior is a guide to future behavior, that future incomes have been correctly forecast, and that all major variables have been accounted for.

Figure 9 shows the results of an analysis of how a supersonic aircraft could split the market with a subsonic transport for varying fares. The curve applies to the New York-Paris route and to income levels projected for 1995. If we assume real incomes continue to rise, then this curve would shift to the right for points further in the future, i.e., if incomes rise, then for the same relative supersonic-to-subsonic cost ratio, more people would be willing to pay for supersonic. Conversely, such curves for the lower income levels of today would show fewer people selecting supersonic service.

Figure 9.—AST Market Shares, New York-Paris Route in 1995



*Assumes a speed greater than Mach 2.0.

SOURCE: A. Dubin, *Supersonic Transportation Market Penetration Model,* AIAA Conference Paper, Los Angeles, Cal If., August 1978.

[3] R. D. Fitzsimmons, "Testing the Market," *Aeronautics and Astronautics,* July/August 1974.

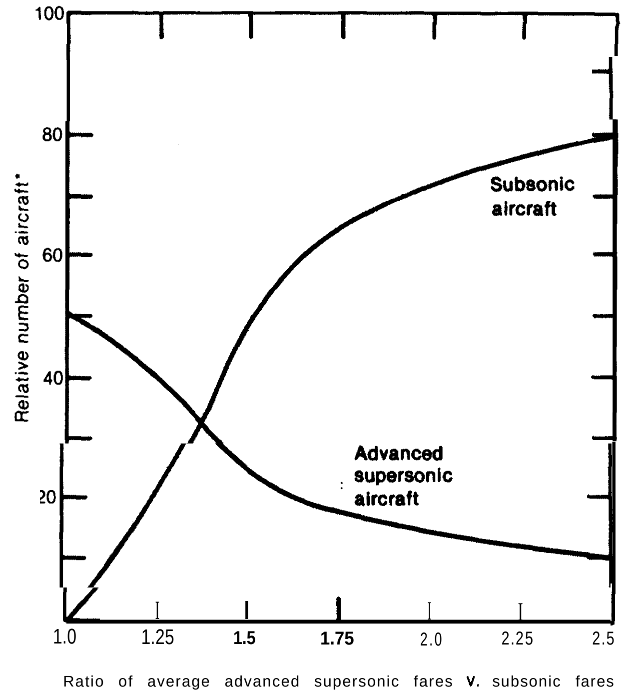
[4] A. Dubin, *Supersonic Transport Market Penetration Model,* presented at the AIAA Conference on Air Transportation: Technical Perspectives and Forecasts, Los Angeles, Calif., August 1978.

While not used in later analyses, this curve, which is drawn simplistically, illustrates how the cost convergence between supersonic and subsonic aircraft will affect patronage. According to figure 9, if the average AST fare were, for example, 75 percent higher than that of a subsonic jet (that is, 1.75 on the curve), then roughly 35 percent of the people would fly the supersonic aircraft and **65** percent would fly the subsonic. This would suggest that, out of 100 total aircraft, 35 would be supersonic and 65 would be subsonic aircraft. However, because an AST would be twice as productive as a subsonic aircraft only half of the 35 ASTs would be required (assuming all the aircraft were the same size). Therefore, only 17 ASTs and 65 subsonic aircraft would be needed to satisfy the given demand. The total of supersonic and subsonic aircraft would be reduced to 82, of which 21 percent would be supersonic. If AST costs could be lowered so that fares were only 25 percent above subsonic (1.25 on the curve), then roughly 80 percent of the travelers would choose the AST: now 66 percent of the aircraft could be supersonic.

By filling in other values, the curves of figure 10 are obtained. These show how the markets for both supersonic and subsonic aircraft change as the net costs (as indicated by fares) of the one aircraft change relative to those of the other. The aircraft are assumed to be otherwise equivalent: the same size and utilization and operating at the same passenger load factor. As AST costs (and therefore fares) approach ASUBT costs, approaching 1.0 on the figure, the shift in the relative AST-ASUBT market accelerates. Because the AST is twice as productive as the ASUBT, one added AST displaces two ASUBT aircraft, so the ASUBT market drops twice as fast as the AST market grows. The number for aircraft in the total fleet also drops correspondingly.

As a final point, the impact of any reduction in the net costs of an AST that might be achievable through improving technology is leveraged by the combined and interacting effects of the expanding market (figures 9 and 10) and the lowering of aircraft purchase costs with increased quantity built (figure 7). For example, if

Figure 10.—Impact of Relative Fares on Fleet Mix, New York-Paris Route in 1995



*Assumes same aircraft size and load factor.

SOURCE: Office of Technology Assessment.

one starts with a 100 AST market at 1.5 times subsonic fares, a reduction of roughly 10 percent of the potential fare brought about by technological advancement can expand the market to roughly 175 aircraft and lower the fares by 17 percent, i.e., to 1.25 times subsonic fare. * This is because of the additional cost reductions derived from the increased quantity built as the market expands. The total cost reduction from R&D (10 percent) and the quantity effect (7 percent) is the 17 percent needed to move from 1.75 to 1.25.

Improving technological capabilities should lower the cost of supersonic flight by a greater percentage than it will lower the cost of sub-

* This calculation is illustrative only and assumes the 30-percent reduction in airplane purchase costs from figure 7 results in a 7-percent reduction in the net costs on which fares are based. This varies with other conditions and costs, but it is a reasonable figure for illustration.

sonic flight. Progressive cost convergency should increasingly expand the supersonic market and shrink the subsonic market. Likewise, a continuation in the rise of incomes would be likely to expand the potential market for supersonic transport. Because prices depend in part on market size, the impact of both technological improvements and rising incomes would tend to allow lower prices and thus a further expansion in the market.

ENERGY UNCERTAINTIES

The major uncertainty and adverse factor for the supersonic market is the cost of fuel, as noted above. Fuel consumption per seat-mile for an AST is estimated to be about twice that of an ASUBT based on current projections and fuel costs are therefore a much larger proportion of total costs for supersonic than for subsonic aircraft. Thus, the general uncertainty about fuel costs in the future is more serious for supersonic aircraft. For example, in one design study comparison, doubling fuel costs over 1976 levels raised the supersonic total operating costs by 33 percent as compared to a 19-percent increase in subsonic costs.

But costs are only part of the question. An aircraft introduced in 1990 would likely be in production in 2005 or 2010, and these aircraft would still be flying in the years between 2025 and 2040. By then, parts of our economy may be based largely on entirely new fuels, say, hydrogen or methane. While the technology—the state of metallurgy, fabrication, aerodynamic knowledge, electronics—to build a supersonic aircraft using hydrogen is not really different from that for a kerosene-fueled aircraft, the specific design is very different. Thus, one of the uncertainties is deciding what fuel should a new supersonic be designed to use. This decision does not have to be made now, but it would have to be before starting a new aircraft program.

STAGE LENGTHS AND ENVIRONMENTAL CONDITIONS

Besides fuel considerations, two other factors are important in evaluating the ultimate potential of the AST and ASUBT markets.

First, stage length—the distance between stops—must be large for the AST to have an advantage over the ASUBT. The productivity of an AST is twice that of an equivalent subsonic aircraft (100-percent advantage) only at ranges beyond about 2,000 nautical miles. As the distance decreases to 1,500 nautical miles, the advantage drops to about 80 percent and, at 1,000 nautical miles, it drops to slightly over 60 percent. The reason subsonic and supersonic productivities converge with decreasing stage length is that the productivity of the higher speed aircraft is penalized more by the time lost in airports and in climbout and letdown. This loss in relative productivity of the AST causes its costs to rise relative to the ASUBT. As the AST's relative advantage in regard to speed decreases, so also does its advantage in regard to service. Thus, it is hard to visualize ASTs competing successfully with less expensive subsonic aircraft on short- or even medium-distance routes (although supersonic planes may sometimes fly these routes as segments of longer trips). As far as can be judged, this portion of the market is secure for subsonic aircraft.

A second constraint on the potential AST market is the sonic boom associated with supersonic flight. It must be assumed that the next supersonic aircraft, like the Concorde today, will be prevented from operating supersonically over inhabited land because of regulations against sonic booms propagated by commercial aircraft over land. This assumption eliminates the AST from contention in the large U.S. coast-to-coast domestic market and equivalent over land markets in other countries and confines its market to international flights over water.

Work has been done indicating the possibility of designing a low-sonic-boom supersonic aircraft at some penalty in operating costs.[5] If an acceptable over land supersonic aircraft could be designed with only a moderate cost penalty, a very much larger market could be realized. For example, the capability of cruising supersonically over land would increase the market potential of an AST and might eventually permit it to replace most long-range subsonic transports. This is another technological "if" that should be researched further and considered in evaluating the long-term potential for supersonic aircraft. Given the potentially large size of this market and the sensitivity of aircraft unit cost to quantity, solving this problem might be of great consequence.

An over land AST would not have the same configuration as the basic over water craft, but it might have many subsystems in common with it. The important point is that the physical phenomena that would permit alleviation of the noise impact of sonic booms have in general been identified and understood, and design principles to exploit them are known and have been partially explored. Further research is needed, although based on what is known today it is not likely such over land derivatives are possible for a next generation of AST.

[5] L. J. Runyon, A. Sigalla, and E. J. Kane, "The Overland Supersonic Transport With Low Sonic Boom—A Feasibility Study," *Acta* Astronautic, vol. 4, 1977, pp. 163-179.

THE COST OF ENVIRONMENTAL ACCEPTABILITY

Noise is now considered to be the principal environmental constraint for either an ASUBT or an AST. Significant upper atmospheric pollution that could decrease the ozone protection against radiation, which was a widely publicized concern a few years ago, is not presently believed to be a problem. Nevertheless, our knowledge is still imperfect, and that issue should remain open.

These and other environmental issues are discussed in chapter VII. However, in this context, it is important to remember that there is a relationship between environmental constraints and economics and therefore the size of the AST market. It now appears that it is possible to build an AST that meets the Federal Aviation Administration's (FAR part 36, stage 2) noise standards for subsonic aircraft at a relatively small penalty in direct operating costs. If noise standards are made much more stringent, however, the costs of meeting them begin to rise much more rapidly unless some better technological approaches to noise suppression are found. The impact of costs on market size has already been illustrated. The direct relationship between the size of the market and the stringency of environmental standards should thus be clear.