Chapter 1

The Prospects for Commercial Supersonic Transport

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1.1 Introduction

This chapter on the prospects for commercial transport at supersonic speeds must begin by deciding what we will call the generic prospective aircraft. Since the first generation aircraft were called Supersonic Transports, or SSTs for short, this practice is continued here. Today, in the United States, NASA's nomenclature is High Speed Civil Transports or HSCTs, while in Europe and Japan it is Supersonic Commercial Transports or SCTs.

The title of this introductory chapter may seem ill-advised. Commercial transport at supersonic speeds has been a reality since 1976. Indeed, it has been a great technical success. The Concorde fleet has flown over 300,000 hours, most of them at supersonic speeds, and it has done so with over 93% reliability. These aircraft will be in service for many years to come [1]. I can go to my local travel agent and buy a ticket to fly from Kennedy International Airport outside of New York City to Heathrow Airport outside of London on British Airways, or to Charles de Gaulle Airport outside of Paris on Air France, and back. The round-trip fare for the summer season, 1996, was $7,574 for London and $6,516 for Paris. The corresponding first-class, business, and full coach fares are $6,752, $4,496, and $2,274 for London, and $5,700, $3,220 and $2,042 for Paris; the discount coach fares are $586 for London and $838 for Paris. The cost of halving my flight time between New York and London or Paris is, averaging the two trips, about 113% that for first-class, 183% that for business class, 425% that for coach and nearly 10 times that for discount coach. During the previous winter season, the discount coach fares were about 50% less, making Concorde travel over 15 times more expensive than discount coach then. The discount fare to London during the 1996-97 winter season was less than 1/30 of the Concorde's $7995 fare there.

We can probably assume that this fare is covering the direct operating cost of the Concorde, exclusive of the depreciation or amortization of the aircraft itself. At these fares the market for supersonic travel is very limited.

Current scheduled Concorde flights include London - New York, Paris - New York in the summer, and London - Barbados (weekly). Recent reports on the Concorde indicate that the dozen now in service are under-utilized [2], [3]. Excursion flights are a small but growing part of the Concorde operations. While service to and from Dulles Airport to de Gaulle and to Heathrow was provided by both airlines for many years, this (from Dulles to Heathrow) was discontinued in November 1994.

The first SST to fly was the Tupolev-144, with its maiden flight on December 31, 1968, a year before the Concorde's first flight. Tu-144 mail service began on December 26, 1975. Passenger service commenced on November 1, 1977, but was discontinued 7 months later. While this aircraft was not an operational success, the Concorde has been an operational success for the two airlines that operate this small fleet. Commercial transport at supersonic speed is a reality. Does a second generation SST make sense? This chapter reviews the Concorde and U.S. SST programs, and provides the author's own conclusion regarding the prospects for a second generation SST. The readers should develop their own conclusions; this book will help them to do so.

1.2 The Concorde

On November 5, 1956, the British had their first meeting of the Supersonic Transport Aircraft Committee, or STAC. The members had concluded that the U.S. Boeing 707 and Douglas DC-8 would capture so much of the subsonic market for commercial aircraft that the only options available to them were to go above the speed of sound or to give up the market [4]. It may have been better strategy to remain with subsonic aircraft, although the Concorde program did much to bring Britain into the European community.

In March 1959 STAC urged the controller of aircraft in the Ministry of Supply to consider the development of a supersonic transport, estimating a market of 125-175 aircraft. The British then approached the French about a joint program, with one goal being their eventual admission to the European Common Market, then dominated by France. Later there were repeated attempts by Britain to cancel the Concorde. Then President de Gaulle stood by the simple, irrevocable, two page treaty between the United Kingdom and the French Republic, entered into on November 29, 1963 [4], [5].

Commercial flight operations began twenty years ago in January, 1976, with British

Airways (then BOAC) flying between London and Bahrain, and Air France operating between Paris and Rio de Janeiro [6]. In a carefully considered (and in retrospect, enormously wise) decision, Secretary of Transportation William T. Coleman, on February 4, 1976, permitted limited scheduled flights of the Concorde into the United States, initially for a trial period of 16 months [5]. Two flights per day for each carrier were to be allowed into Kennedy, and one flight per day for each carrier was to be allowed into Dulles. Because the FAA operated Dulles, there was no difficulty in obtaining permission to operate there, and commercial service began at Dulles on May 24, 1976. The New York Port Authority banned such flights in March 1976, but this ban was overturned in court and commercial operations began there on November 27, 1977.

To my knowledge there have been no lasting complaints of concern about Concorde operations in selected U.S. airports. But one must presume that for an economically successful SST, the fleet size will not be small, and with this increased SST traffic, it may be necessary to adhere to the latest airport noise level regulations for subsonic aircraft. Perhaps some modest deviations for SSTs will be allowed.

Perhaps the golden age of the Concorde was in 1987 and 1988 when over 60,000 passengers were transported by each airline, more than 40,000 of those in a destination market with load factors just over 60%. In January, 1993, *Air and Cosmos/Aviation Magazine* wrote, “Since 1989-1990 the situation has declined to the point of Air France not even reaching 40,000 total passengers last year. And the results for the first trimester of 1993 do not indicate a substantial increase....” [3].

Important national goals were achieved by the Concorde program. Perhaps the most important was the development of a successful European community aircraft consortium. It is unknown, and not knowable, whether the joint British-French venture to develop the Concorde was the best or the only route to this end. It was achieved, however, and this must be attributed, at least in part, to this joint venture. The French also gained a considerable technological advance in their aircraft. Together, they proved the reliability and safety of public transport at supersonic speeds. The program's cost, through March 1976, was put at between 1.5 and 2.1 billion in 1976 pounds sterling, or between 3.6 and 5.1 billion in 1977 U.S. dollars (yearly weighted exchange rates) [7].

1.3 The U.S. SST Program

The U.S. SST program began in June, 1963 when President Kennedy, in a commencement speech at the Air Force Academy, said, “As a testament to our strong faith in the future of air power.... I am announcing today that the United States will commit itself to an important new program in civil aviation ... a plane that will move ahead at a speed faster than Mach 2, more than twice the speed of sound, to all corners of the globe.” The day before this speech the president of Pan American World Airlines had made the announcement that Pan Am was taking options on six Concordes. Prior to that Air France and British Airways had ordered eight Concordes each.

A few days later President Kennedy followed up his commencement address with a message to Congress in which he said, “In no event will the government investment be permitted to exceed $750 million” [8]. Development costs were then estimated to be approximately $1 billion.

This program soon became one with two competitive aircraft designs, one by Lockheed and the other by Boeing, and two competitive engine designs, one by General Electric and the other by Pratt & Whitney. Boeing and General Electric were the eventual winners of this competition with the Boeing 2707-100, a swing wing, M = 2.7, 200-300 passenger aircraft with a presumed range of 3500 nautical miles, weighing 750,000 pounds, an aircraft that was not then - and perhaps is not now, technically realizable. The swing wing provided both airport noise reductions and improved aerodynamic performance at lower speeds. The weight of the mechanism used to pivot the wings resulted in unacceptably low range, or low payload, or both. The Boeing design evolved to a fixed wing, titanium aircraft, not unlike that proposed by Lockheed. The government's investment in the SST program was to be repaid by royalties on aircraft sales. The government's investments, including interest, would be recovered with the delivery of the 300th aircraft.

The two principal issues of concern with SSTs in the late 1960s were their economic viability because of a likely restriction to subsonic operation over populated areas and airport noise levels upon takeoff. There was limited concern before 1970 about the effects of such aircraft on the stratosphere.

The U.S. program died in the Senate in May 1971, in part from concerns about noise in the airport environs, in part from concerns about its impact on the stratosphere, in part due to politics, and in part because its economic success seemed far less than certain. Today, twenty-five years later, these remain legitimate concerns.

1.4 Air Traffic

The current trends in air traffic are well known [9]. Growth has been positive for most of the past twenty-five years. International travel is growing faster than developed countries’ domestic travel, leisure travel is growing faster than business travel, and Asia-Pacific traffic has the largest regional growth rate. Air travel has become a commodity in the following sense: 40% of the travel is discount coach travel; the remaining 60% of the travel is comprised of 20% coach, 30% business class and 10% first class. One would be wrong to conclude, however, that full-fare passengers comprise 60% of travel; most of this travel is also discounted. Because of frequent flyer upgrades and business and other traveller discounts, less than 30% of the passengers on international routes pay “full” fare. In 1995, 95% of the revenue passenger miles in the U.S.were sold at a discount. In the first seven months of 1996, the discount averaged 68%.

Two airline systems have now developed. One is the airline system that dominates most markets and provides air service to both the economy and business passengers, subsidizing economy travel by higher fares for the business traveller. The other provides a true commodity service: no advanced seat assignments, no meals, and sometimes no baggage connection to other airlines. The latter airlines have enlarged the market for commodity travel. For any new aircraft to succeed in the commercial aircraft market, it must compete either in convenience / comfort, or in fare, or some combination of the two.

In 1968 nearly eight million international passengers arrived at or departed from Kennedy International Airport, with 97 thousand arrivals and departures. In 1982 over eleven million passengers arrived at or departed from Kennedy. Because of the introduction of wide-body aircraft, this travel was accommodated with under 55 thousand arrivals and departures. In 1993 fifteen million international passengers used Kennedy, requiring 92 thousand arrivals and departures. Once again aircraft arrivals and departures there are close to the airport's capacity.

Expected growth in air traffic cannot be accommodated for long with the world's current airports and aircraft. In developed countries there are few airports that can be added. Thus, it is presumed that some of the increased traffic will be accommodated by larger aircraft. One SST configuration, a wing with passengers inside, flying obliquely, must be large and responds to both the SST and the large aircraft market. This Oblique Flying Wing is discussed in two chapters in this book.

1.5 Market

Within a few months of the first flight of the French and the British Concorde prototypes (March 2, and April 9, 1969), the US SST finalist, the Boeing 2707, had booked 122 options from 26 airlines to purchase aircraft; the Concorde had booked 74 options from 16 airlines. Thus, nearly 200 SSTs were "on order." A year later, in 1970, the FAA predicted 500-800 SSTs would be in operation by 1990. It is now 1996.

Twelve Concordes operate today with a limited schedule and at load factors below 50%. These aircraft need only pay their operating costs exclusive of the amortization of their purchase; they were essentially free to the two airlines flying them [10]. What happened? The fares required to pay for their operation deter their use. Maintenance costs are said to be seven times those of a 747 and fuel costs per passenger mile at least three times that of the 747.

Studies by Boeing and by McDonnell Douglas predict a market for 600 to 1500 SSTs [11], [12]. Mizuno of Japan Aircraft Development predicted a market for 600 Mach 2.5 SSTs with a 5500 nautical mile range, and estimated perhaps a 50% increase in this market derived from its stimulation by the travel time saved [13]. Davies, on the other hand, found it to be between 9 and 36 aircraft, depending on how optimistic one is [14]. The enormous differences among these studies stem from what one projects for the fare required to cover the aircraft's total operating costs. It takes a long time to sell one thousand aircraft. The first Boeing 747 began commercial flights in 1970; twenty-four years later one thousand 747s had been delivered.

The challenge is to design, build, certify and operate an SST while providing the airlines a return on investment comparable to a similar investment in subsonic aircraft. This can only be accomplished with marginally increased fares over those for subsonic transport. The marginal increase in fares required, however, depends upon many factors, including aircraft price and operating cost.

Marginally increased fares - what does that mean? Assume such transport effectively saves the traveler some fraction of a day, or at most, a whole day. Whatever that traveler‘s expenses would be for that day, or, correspondingly, whatever his income might be for that day, provides a reliable guide as to what he would be willing to pay to save a fraction of a day of business travel, or have as extra time for his vacation. This intuitive judgment agrees with studies which predict little fall-off in ticket sales for a 10% surcharge [11], [13].

As noted earlier, non-discount passengers comprises 30% of the international market. To secure a significant fraction of this market an SST will need to provide three-class service. Current Boeing studies reflect this, but show an SST with about 9% of the passengers in first class, 19% in business class, and 72% in economy. Can an SST succeed if it fills empty seats with discount coach passengers? Can it succeed if it does not?

A final comment is warranted on the growth of revenue passenger miles accorded air transports. The “information highway” will reduce business travel needs. For a few hundred dollars you can buy the software needed for your group to discuss and share visual information by electronic mail. It is now possible, with more expensive software, to have the real-time image of each member in a working group displayed, hear their voices, and share visual information. A telecommunications vice president recently told me that he spent $23,000 on hardware and software and saved $100,000 in travel costs in the first year. The importance of this change was noted some years ago by Simpson in his remarks to the 1989 European Symposium on Future Supersonic-Hypersonic Transportation [15]. When the information highway becomes an international highway, which it now nearly is, this will reduce the need for international business travel while simultaneously expanding the amount of international business. It seems likely that these two effects will offset one another.

Technology has progressed steadily since the Concorde was conceived. But reduced energy efficiency, the sonic bang, engine emissions, and airport noise, remain deterrents to the economic success and acceptability of an SST. Let me now turn to the environmental barriers facing a future SST.

1.6 Environmental Barriers

As I've noted earlier, the U.S. SST program was canceled in part because of environmental concerns. The Concorde's economics have been greatly affected by being prohibited from supersonic flight over most land areas, and by the cost of fuel. The environmental, and thereby political, barriers to a successful SST are: energy consumption, sonic bang, atmospheric impact, and airport noise.

1.6.1 Energy Consumption

The fuel consumed by SSTs per passenger mile is several times that of subsonic transports. Supersonic flight entails a new penalty, that of wave drag. Lift has to equal, and sometimes exceed, weight if there is to be air travel. Wave drag due to lift is inescapable except for an infinitely long swept wing, best approximated by the way, by an oblique wing. Volume can be moved through the air supersonically with no wave drag, but at considerable expense in skin friction drag from extra surfaces.

Sixty countries have ratified a treaty that commits them to better manage their generation of greenhouse gases [16]. Developed countries are to provide plans by the end of this century that show how they will return to 1990 levels of greenhouse gas generation. Does this argue against an SST? As Secretary of Transportation Coleman said in his decision to let the Concorde operate: "It would border on hypocrisy to choose the Concorde as the place to set an example ... (for energy efficiency) while ignoring the inefficiency of private jets, cabin cruisers, or an assortment of energy profligates of American manufacture" [5].

The Concorde achieves 17 seat miles per gallon and, at 67% load factor, is equivalent to a car with only the driver, achieving 12 miles per gallon. But the Concorde's passengers are going more than twenty times as fast and following nearly a straight line to their destination. A future SST should not be rejected because of energy considerations. However, its economics and thereby its market, are more sensitive to fuel costs than its subsonic counterparts and these are not only variable, but jet fuels may eventually be taxed for their carbon content.

1.6.2 Sonic Bang

Just as wave drag due to lift is inescapable, so is the sonic bang. Adolf Busemann liked to illustrate this by depicting the conical shock wave system and its reflection from the ground as the crow-bar that supported the weight of the aircraft [17]. Ironically, while the weight of the aircraft is to be found in the integral of the pressure signature over the ground, it is not to be found in the first-order pressure field there [18]. In the U.S. we call the sonic "bang" the sonic "boom." The "bang" in the sonic boom derives from the abrupt pressure increases through the two, and sometimes more, shock waves emanating from a supersonic aircraft. We call the integral of the positive phase of the pressure with respect to time the "impulse". The bang is directly related to the outdoor annoyance of animals and humans; the impulse is related to structural damage and, to some degree, to indoor annoyance.

The increasing acoustic impedance (i.e., the product of the density and the sound speed) below the aircraft in a real atmosphere freezes the shape of the pressure signature before it reaches the ground. In the approximation of an isothermal atmosphere this occurs in $\pi/2$ atmospheric scale heights, or about 40,000 feet. This knowledge set me and my colleague Al George to tackle the minimization of various parameters of the sonic boom signature, including its bang and its boom, or any weighted average you might use of the parameters. Indeed, for the cruise characteristics of the Mach 2.7 Boeing 2707 at 60,000 feet lifting 600,000 pounds, an aircraft 527 feet long need not have a sonic bang at all, i.e., the pressure field below the aircraft need not steepen into shock waves [19]. But as we noted then, reducing or eliminating the "bang" in the sonic boom increases the impulse, or total pressure loading, for obvious reasons: the bang part of the boom, that is the shock waves, dissipates the energy in the signature. Consequently, reducing or eliminating the shock waves makes the impulse worse.

Very considerable studies by the NASA over the past decade have explored whether or not such shaping of the sonic boom signature would lead to an acceptable sonic boom. The NASA's conclusion reinforces ours of two decades ago. Unless a supersonic aircraft is very light, but long, its sonic boom cannot be reshaped to be acceptable [20]. Very small supersonic aircraft, such as a corporate supersonic transport, may have an acceptable, indeed nearly inaudible, sonic boom. This stems, in part, from a thickening of the shock waves as their strength is reduced.

SSTs will be constrained to subsonic operation over populated areas, and perhaps to supersonic operation over the oceans alone. The penetration of the pressure field of sonic booms into water, versus their reflection from it, is now well understood [21]. For aircraft traveling less than the speed of sound in sea water, this is simply a travelling source of acoustic radiation. Commercial transport at supersonic speeds over the oceans, and perhaps over unpopulated areas, is likely to continue to be acceptable. Flights over land areas with significant populations of wildlife may not be allowed. Through constraints on aircraft routes we can avoid the problems caused by sonic booms, but in doing so we reduce the market for a second generation SST.

1.6.3 Atmospheric Impact

Whenever we burn hydrocarbon fuels using air, we impact the atmosphere and, in some cases, the local air quality. Whatever fuel we burn using air will produce oxides of nitrogen. A concern during the late 1960s was the effect of water vapor from SST engine exhausts on stratospheric ozone levels. It was soon realized, however, that the oxides of nitrogen were much more important [22]. This led the Department of Transportation, in 1972, to launch the Climatic Impact Assessment Program. This monumental and highly regarded 7200 page study, comprising the work of over 500 individuals, concluded that a limited fleet of supersonic transports, such as the 30 Concordes and TU-144s then envisioned, posed an insignificant threat to the atmosphere. This study also aided the extraordinary discovery of the reduction of atmospheric ozone by CFC refrigerants (Freon 11 and 12), culminating in the Montreal Protocol (1987) which will lead to the eventual elimination of these refrigerants.

The oxides of nitrogen catalytically destroy ozone above about 13 kilometers in mid-latitudes; they catalytically create ozone below this altitude. Aircraft emissions are the major unnatural source of these oxides in the stratosphere. They are also an important source of them in the upper troposphere, at least of mid-latitudes in the northern hemisphere [23]. Thus it appears that SSTs in the stratosphere may reduce our protection from ultra-violet radiation by ozone on the one hand. At altitudes of 12-14 kilometers (13 kilometers = 42,650 feet), the effect of these oxides on ozone is minor. The calculated ozone column change due to the injection at 20 kilometers of the amount of NO_X expected from a full fleet of SSTs was about -12% in 1975. New knowledge changed this to +3% in 1979. Since that time, increasing knowledge provided a result of -10% in 1988, about double the -5% predicted ozone depletion if CFC releases remained at their 1974 rate [24]. Recent results show NO_x to be less significant than was once thought, but raise the issue of the effects of engine emissions on stratospheric aerosol surface area. This could also play a role in depleting stratospheric ozone [25].

1.6.4 Airport Noise

Remarkable advances have been made in propulsion since jet engines were introduced. Over the past 25 years there has been about a 20% reduction in the amount of fuel required to produce a unit of thrust [26]. Because much of this gain has come from higher bypass ratios, take-off noise levels have fallen in some cases below those required by current noise regulations. Current SST engine concepts, without augmented suppression systems, are probably 15-20 decibels (equivalent perceived noise decibels) above these standards. Further noise suppression adds weight and reduces thrust. Low lift-to-drag ratios at takeoff demand considerable thrust, and this, in turn, leads to larger exhaust velocities and more noise. At the moment there are sound ideas, but no tried techniques, on how to accomplish this noise reduction with acceptable weight increases. Unlike the sonic boom, however, we are not up against a fundamental momentum balance. A breakthrough is possible. Given that subsonic transport noise levels continue to fall, and the near certainty that conventional supersonic transports will operate only from selected coastal cities, current noise regulations need to be examined to see what airport noise levels might be acceptable from a small fleet of supersonic aircraft.

1.7 The Prospects

The development of a supersonic transport that can be operated at a profit by the airlines, and sold in sufficient numbers for the airframe and engine manufactures to eventually realize a profit as well, remains a challenge. The U.S. and European supersonic research programs now have very focused, and somewhat different, goals. These programs involve the companies that profit from the sale of their subsonic jets. It would take some bold competitive vision, not unlike that which led to the Concorde, for a supersonic transport production program to emerge from these studies. Such an aircraft faces the real possibility that it, too, will be a technical success, but not an economic one. This book, therefore, focuses much of its attention on the underlying tools for the study of such aircraft, as well as on unconventional configurations.

For unconventional configurations the technical and risk barriers are very high. It appears that an oblique flying wing (see Chapters 19 and 20) could provide a Mach 1.4, or higher, transport that operates with a minimum surcharge over future subsonic transports and that competes with them over land as well. If it is large enough it becomes the “New Large Aircraft” and, in this size, such an aircraft may compete in fare with its subsonic counterparts. But without further research, considerable experimentation, and flight tests, this remains a conjecture. Such an aircraft would also require rethinking of selected aviation regulations and perhaps even some minor reconfiguration of airports. Both were required with the introduction of the Boeing 747.

A conventional configuration, operating at a higher Mach number, benefits from high productivity and substantially reduced travel times. Because of past and current government research programs, including that which led to the Concorde, the needed research is largely done and the technology mature. Consequently, the development costs of such an aircraft appear to be reasonable. Because of its limited subsonic and transonic performance, and its restriction to intercontinental routes, this aircraft’s market is relatively small. As a fleet, its contribution to the acoustic environment in and around selected airports may be small enough to deserve continued regulatory relief.

A small, corporate, supersonic transport appears to have a significant market and, if small enough, might well be certified for supersonic operation over land. Military technology and excess production capacity provide the basis for making such an aircraft affordable.

At a meeting on sonic boom research in 1967, Adolf Busemann, having comprehended the concept of bangless sonic booms, concluded this meant we would have to fly in the troposphere to make the sonic boom acceptable. He stood up, placed his arm over his eyes, and said: “This is terrible; we will have to fly through the wind, the sleet, the rain, and the snow.” Further research showed even this would not be enough. Large transports will not be able to fly at supersonic speeds over populated areas.

It may be a long time before most of us can fly twice current speeds at affordable fares. And we may have to fly obliquely to do so. Before this happens, some will have travelled at Concorde speeds in corporate supersonic transports such as the proposed Sukhoi S-21.

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