An Opportunity for Hydrogen Fueled Supersonic Airliners

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ABSTRACT

This paper takes a new look at the prospects for developing supersonic civil airliners, considering global demographics, climate change issues, fuel prices and technological advances. Dramatic changes have occurred in the demographics, economics, and market intensity of the Eastern Hemisphere since the 1990s. Carbon reduction imperatives provide a major incentive to invest in developing hydrogen-fueled airliners. The "point-to-point" air route architecture has proved viable with long range mid-size airliners. With a cruise Mach number of 1.4, a large number of destinations become viable for overland supersonic flight. A conceptual design process is used to estimate cost per seat mile for a range of hydrocarbon and hydrogen fuel costs. An argument based on the ideal shape for minimal wave drag, estimates the drag penalty from using hydrogen. Viable aircraft geometries are shown to exist, that match the theoretical ideal shape, showing that the drag estimate is achievable. Conservative design arguments and market estimates suggest that hydrogen-fueled airliners can achieve seat-mile costs low enough to open a large worldwide market and justify a viable fleet size.

Keywords: Hydrogen supersonic airliner, wave drag, seat mile cost, demographics

1. INTRODUCTION

The technical and business cases for liquid hydrogen-fueled supersonic transport airliners (LH2 SST) are re-examined in the light of changes that have occurred in demographics, fuel prices and greenhouse gas reduction imperatives. The paper lays out the cases for the existence of a much larger market than was seen for supersonic airliners in the 1950s through 70s, or in recent studies in the 1990s. It then uses conceptual design to explore the fears regarding the high wave drag penalty of using liquid hydrogen. Finally it projects the cost per seat-distance that can be achieved using hydrogen fueled supersonic airliners, to close the loop on the argument about demand.

The Concorde and the Tupolev 144 pioneered supersonic airliner flight in the 1960s, but neither achieved the fleet size needed to be viable in the market. Tu-144 regular passenger service across the Soviet Union was cancelled after only 55 flights, citing safety issues. The Concorde was not allowed to fly overland at supersonic speed because of the perceived destructive effects of sonic boom. Of some 200 initial orders only 14 entered commercial service. The oil crises of the 1970s and 80s, the Cold War and US-Europe competition precluded viability of either the Concorde or the American SST concepts. The cost of supersonic travel stayed beyond the means of most travelers, preventing the market from expanding.

The High Speed Civil Transport (HSCT) project in the USA concluded in 1999 that the technology to develop SSTs existed, and that the environmental problems, including sonic boom and upper atmosphere pollution could be solved sufficiently to meet certification standards, but that the market did not justify development of SSTs. Experts pointed out that the airlines' business model depends on business class and first class travelers to make long-distance routes profitable. An SST would take away these high-paying passengers, and thus cut into the low-risk profitability of the transonic fleet while taking on a huge new risk. This conclusion appeared to be drawn from a market survey that included only US trans-Atlantic and trans-Pacific routes. The very high ticket prices also appear to have forced the assumption that only the very rich, or business and government travelers subject to extreme perks or time pressures, would fly on supersonic airliners. Current industry interest in SSTs, and the accompanying academic studies, appear to be limited to business jets. The political, economic and demographic realities of the pre-1990s made these assessments realistic for that era, but the massive changes since then should induce a careful rethinking of all these assumptions.

In summary, hydrogen-fueled airliners were perceived to be impractical for 4 reasons. The first is the presumed difficulty in handling liquid hydrogen safely. Hydrogen diffuses into oxygen-carrying air quickly, causing explosive fuel-air mixtures to form rapidly. It also has a very high flame propagation speed and short ignition delay, so that flames can start and propagate easier than with the heavier hydrocarbon fuels. The horrifying final spectacle of the Zeppelin "Hindenburg" is often (and incorrectly) mentioned as evidence of the danger of hydrogen, despite the fact that liquid hydrogen fuel has been used on thousands of space missions, in large quantities, for over 50 years with no fatal accidents attributed to hydrogen. There have been numerous crashes of lighter-than-air airships filled with inert gases [1]. There is no denying that handling hydrogen will require good equipment, training and multiple layers of safety in the design. The prospect of tens of thousands of people handling liquid hydrogen systems at thousands of airports, for many flights every day, is a far cry from the few thousand space launches done to-date. However, such precautions, thought and discipline are also required with any other propulsion system that can deliver the power demanded by aircraft engines. The present regulatory and physical infrastructure for hydrocarbon airliner fuel and refueling, is no less exotic when viewed objectively as an alternative, than those needed for handling hydrogen. Perhaps it is due to the two World Wars and other wars fought with and over hydrocarbon fuels that the infrastructure for handling them appears to be so commonplace.

The second difficulty is the high wave drag associated with the presumed large volume of liquid hydrogen. The density of hydrogen at standard temperature and pressure is approximately 1/15 that of air. To carry sufficient quantities for a long flight, the tanks must either be unacceptably large or heavy or both. The most compact form is liquid hydrogen, a cryogenic liquid kept at -253 Celsius (20K) under moderate pressure. Even at this condition, its density is only 68 kilograms per cubic meter, compared to 800 kg/m^3 of Jet-A hydrocarbon jet fuel. Although hydrogen releases roughly 3.8 times as much heat per unit mass as Jet-A, this means that the volume needed for hydrogen would be 3 times that for Jet-A. Unlike at subsonic speeds, the air drag at supersonic speeds includes "wave drag" which strongly depends on the volume of the body moving through the air. So the "wave drag penalty" of carrying hydrogen as fuel at supersonic speeds is believed at first glance to be a compelling argument against hydrogen fuel for SSTs. A simple conceptual design cycle calculation, as shown later in this paper, shows that this fear is groundless, as should be expected from the basic (Tsiolkovsky rocket equation [2]) exponential relationship between liftoff mass and the specific impulse of the propellant of a powered flight vehicle. This is because the total mass of a hydrogen airliner is so much lower than that of a hydrocarbon airliner, for the same payload and distance. Nearly 50% of the mass at takeoff of a long-distance hydrocarbon fueled airliner is fuel mass. The low mass of hydrogen per unit heat release means that much less fuel is needed to carry fuel. Thus to carry the same payload over the same distance, the takeoff mass will be far lower than with hydrocarbon fuel.

The third difficulty is the high cost of producing and storing hydrogen in sufficient quantities. The fourth is the presumed energy inefficiency and carbon footprint of producing hydrogen starting with fossil-driven power plants. These are related. Producing hydrogen, liquefying it, transporting it in volatile liquid form, and storing it at an airport, no doubt pose high energy and equipment costs. Some argue that the energy needed to liquefy hydrogen is greater than that released by hydrogen combustion; however this is not relevant to aviation fuel use, and it is easily defeated by pointing to the cost of exploring, extracting, refining, transporting and storing fossil Jet-A fuel, and to the cost of producing synthetic hydrocarbon fuels that are at best carbon-neutral. However, it remains true that today the cost per unit energy release of liquid hydrogen, is still far above that of liquid Jet-A fuel. One prime reason for the work done in this paper is that this situation may be changing for the better, much faster than we had dared to hope.

Against these objections, there are several newer developments that demand a new look at supersonic hydrogen-fueled airliners. These are explained in the rest of the paper:

1. There may be substantially more demand for supersonic airline travel, than considered before.
2. Security and congestion considerations have advanced the point-to-point airline architecture over the hub-and-spoke architecture.
3. Point-to-point trips now exceed 17 hours using long-range airliners, showing viable demand despite low payload fractions.
4. Reduced time for point-to-point travel would increase trip frequency per aircraft.
5. Going to Mach 1.4 may offer enough reduction in travel time to attract a larger market.
6. With current technology, using atmospheric winds and density layers, sonic boom will be imperceptible on the ground at up to Mach 1.4.
7. The air travel industry's mandate to cut carbon emissions provides a large and unique source of funding, to develop hydrogen-fueled aircraft.
8. In the longer term, hydrogen costs should come down, supply and accessibility being unlimited.

2. SUMMARY OF ISSUES

The problem is distilled to the following questions for the purposes of this paper:

• How have demographics and economic development altered worldwide market projections for supersonic transport? Are there enough viable destinations to justify a large fleet?
• What is the drag implication of using hydrogen, given the lower fuel weight fraction?
• What are the noise implications of the LH2SST?
• What is the impact of global warming concerns and initiatives to reduce atmospheric carbon emission, on the prospects for hydrogen-powered flight?

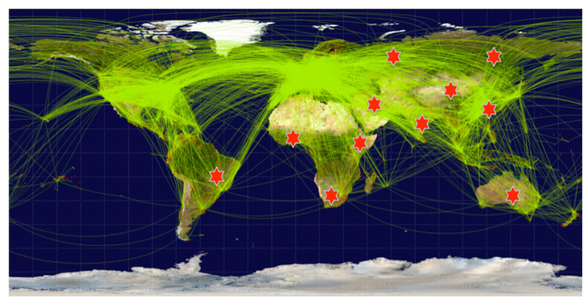

Figure 1: Areas where significant changes have occurred since1990, marked on a world airline route map of 2007. World map courtesy NASA. Airline routes courtesy JPatokal, Wikipedia.

3. GROWTH OF WORLD WIDE AIR TRAVEL

Airline travel has increased by nearly 300% since 1980 [3], reaching 4300 billion passenger-kilometers and 160 billion ton-kilometers by 2008. Deregulation of the US airline industry in 1978 increased the number of air travelers [4]. The world has changed drastically since the early 1990s. Figure 1 attempts to capture some of these changes relevant to supersonic flight, through stars focusing attention on specific areas. The Berlin Wall is down, and the European Union integrated. Russia's arctic airspace opened to many new polar air traffic routes [5]. There has been a dramatic rise in the economies of Asia since the early 1980s, and in the opening of travel inside and to the People's Republic of China. India, viewed by the Concorde designers as primarily a landmass obstacle to supersonic overflight, is a prime supersonic hub of the future with several viable destinations and a large and mobile expatriate, technical and business traveler base. South Africa is an open and booming economy and provides an intermediate stop for long-distance flights connecting Asia and Middle East economies with South America, with South America itself growing in economic activity. The FIFA (soccer) World Cup of 2010 showed how much the world has changed- and how well the younger generation today has adapted to a global view of society. African civil air traffic has seen a 5.7% annual growth in the past 15 years and expects a 7% increase in the coming decade. Australia is also a booming economy with vast natural resources, industrial innovation and a powerful global presence in both business and sports. Viable business destinations and international airports abound now in Central and Southern India, with busy air connections throughout India, the Middle East, Sri Lanka, East Asia and Europe.

The Argument for Speed

According to news stories, when the first Concorde flight landed in New York accompanied by advertisements on the speed of transatlantic business travel, environmental demonstrations caused a delay of several hours on the trip from the airport into the city. Airport transit, security delays and city traffic make the need for supersonic speed very questionable, especially with the advent of global video telecommunications. So it is fair to ask about the relevance of faster flight.

Until recently, rising fuel prices, the small number of international airports equipped with international customs and immigration staff, and the limitations of aircraft designs, drove designers to ever-larger aircraft in order to maximize fuel economy over long distances. Thus airline architectures were optimized for "hub and spoke" operations. Large aircraft would collect and fly large numbers of passengers between a few "hub" airports around the world. Service to other airports required a change of planes at the hub. These hub airports are now stretched to capacity in terms of both ground and air space congestion. At the same time, the payload fraction of medium sized airliners has grown, to the point where they have been shown to be viable for intercontinental flights with only 200 to 250 passengers, rather than the 300 to 500 passengers on the "jumbo jets". The recent competition between the EADS Airbus 380 with its large size aimed at the hub and spoke architecture, and the Boeing B787 with its medium size and "point-to-point" architecture, whatever may be the real drivers of the competition, illustrates the shift. Fortuitously, along with the advent of "point-to-point" architectures, came the sharp increase in concern about the security of airline travel. This brought about the recruitment of security staff and facilities for international document checking and controls, and baggage inspections, to a large number of airports, so that the number of "international airports" has boomed. Along with this security regimen, came the very harsh reality of delays, intrusive procedures and immense stress imposed on travelers, especially aged and infrequent international travelers. The "point-to-point" architecture suddenly looks much more attractive, in avoiding the intermediate stop with all its problems. On the other hand, this also removed the break of a few hours between flight segments. The cost of "point-to-point" is that very long flights of as much as 17 hours are now preferred because the "stopover" has changed from a pleasing prospect to a nightmare. This sets the stage for a large speed increase that will not be cancelled out by long airport transit delays.

The world economy and job market have become "globalized". Along with this comes the desire of aging parents to visit their children and grandchildren working and living in distant parts of the world. A large new middle class has the desire, means and freedom to see the world, but not necessarily the stamina to survive flights of over 8 to 17 hours. Quite simply, changing the flight Mach number from around 0.8 to 1.4, would slash a 9-hour flight down to a bearable 5 hours. The inevitable expansion of supersonic flight to 13,000 kilometers would slash the 17-hour flight down to about 9 or 10 hours. One may well ask why these passengers do not now buy business-class tickets. The answer is that these are people who earned their money the hard way, and will not see the point in paying 3 times the money to sit in slightly more comfort for the same number of hours, but their children may well insist that they fly supersonic if that option were available, to minimize the health risk. Hence the potential market for supersonic travel may be far greater than that envisaged. Asia and the Pacific are at 28% of the market as of 2006. Based upon their rate of growth compared to the rest of the world they will more than likely gain ground on Europe but will not pass them for at least 40 years, assuming current growth rates[4].

The "broken third leg" of the 3-legged stool of market demand that NASA cited in closing the HSCT project in 1999, is no longer broken when viewed in today's changed realities. The commercial air travel market is also expected to maintain a 4-5% a year increase globally, by conservative estimates, for the next 10 to 15 years. This would result in the market for air travel doubling over this period. The assumption that most supersonic travel will be "business" or "boutique" is also flawed. Of course, the market size also depends on the prices at which tickets must be sold to make cost-conscious, sensible travelers buy them. The point made from the above argument is that we can safely assume a fairly large sized fleet and many destinations, thus greatly reducing the unit cost and the cost of operation of these airliners.

4. FUEL PRICES AND THE HYDROGEN ECONOMY

The Hubbert Peak Oil theory [6] holds that fossil fuel prices will rise very sharply as the rate of increase in demand surpasses the rate of increase in supplies [7]. Many experts feel that this may be an imminent event [8], or may occur by 2018 [9] or 2030 [10]. It is less well-known that the prices that airlines typically pay per liter of jet fuel is much less than what people pay for a liter of lower-octane, automobile fuel. This is partly because jet fuel is a form of kerosene, a derivative along the way to refining automobile fuel. Prices of these derivatives are kept lower to keep industrial costs, and the costs of basic necessities to the poorest people, down, at the expense of the "richer" automobile owner. One fear is that as automobile gasoline demand drops due to the advent of hybrids, fuel cell engines and electric cars, and as ground transportation of all kinds moves away from fossil fuel, this price subsidy for airline fuels will disappear, causing jet fuel prices to spike up much faster.

Currently the airline industry is very reliant on fossil fuels. The industry is under increasing pressure to reduce emissions of carbon dioxide, from its levels of around 300 million tonnes per year [11]. In 2009, the International Air Transport Association (IATA) announced sharp cuts in emissions. In the short term, this can only come from buying carbon credits on the market or funding "clean development" projects around the world, to offset the emissions. Given a nominal price of $20 per ton of CO_2 per year this means buying credits worth over $2B per year, into the indefinite future. Most hydrogen produced today comes from steam reformation of fossil fuel. Shifting to renewable solar, wind or biomass sources and improving the efficiency of high-temperature electrolysis in new nuclear reactors will enable hydrogen to be produced at viable costs without generating greenhouse gases [9].

5. SONIC BOOM CONSIDERATIONS

Supersonic flight causes a sharp, loud and damaging pressure signature in the shape of an "N" wave on the surface below. However, if the speed of sound at the ground is higher than the aircraft's speed then the boom is not an issue on the ground. This "threshold Mach number" is around 1.20 for many US cities [12]. When atmospheric thermal layers and winds are considered, the flight Mach number can be substantially higher than the threshold without the boom exceeding permissible noise levels [13]. The best flight altitude may thus be substantially lower than those previously considered for supersonic flight.

Sonic boom intensity is considered by many designers to scale with the gross weight of the aircraft. This comes out of assuming that the wing loading (weight per unit area of the wings) is optimized at some constant value. In fact, the hydrogen SST will probably be optimized at a lower wing loading, and will have much less weight than a hydrocarbon SST for the same payload, as seen later. In other words, we should expect the boom intensity to be substantially lower with a hydrogen SST. It may well go below the perceptible limits.

Two other advances should be considered. In 2003, Northrop-Grumman Corporation [14] and NASA researchers demonstrated that a modification of the nose shape of an F-5 aircraft reduced the leading shock overpressure of the sonic boom on the ground from 1.2 pounds per square foot to 0.8 pounds per square foot, as the aircraft flew at Mach 1.36 at 32,000 feet altitude. This strategy of achieving a "flat-top" sonic boom can thus reduce the boom overpressure significantly while in fact increasing the volume of the aircraft (and slightly increasing the wave drag). This flight demonstration validated the theoretical basis for such boom modification, showing that the modification would remain effective through a real atmosphere. There are also related efforts to modify the boom so that the intensity felt directly beneath the aircraft is reduced, while redirecting some of the energy into parts of the shock waves emanating in other directions. The cumulative effects of such design innovations can be expected to reduce the sonic boom problem to the point where it is not an issue preventing overland supersonic flight for a hydrogen SST at Mach 1.4.

6. PRELIMINARY SIZING AND PERFORMANCE

In the following section, our aim is to show by an elementary conceptual study process, the comparison in possible performance between hydrocarbon-fueled and liquid hydrogen-fueled supersonic airliners, for the same choice of payload and range. This conceptual design study incorporates the general requirements of flying supersonic, the fuel storage issue, and the performance parameters of supersonic cruise. A range of 8,000 kilometers (5,000 statute miles) was specified. Supersonic cruise at 45,000 ft altitude in the international standard atmosphere was chosen. The first step was to validate the overall procedure by comparing the results obtained to the actual performance of the Concorde aircraft. This routine step is not shown in this paper. In general terms the Concorde carried 80 to 100 passengers at Mach 2, flying at 56,000 to 60,000 feet, over a range of 4,500 nautical miles (7,250 km). To accomplish this, it required a fuel fraction of 52% at takeoff. The payload was only 7.23% of takeoff weight.

Following general design guidance [15], the SST here was sized for 200 passengers and 6 crew. Parameters were calculated for an airliner fueled by liquid hydrogen, compared with one fueled with Jet-A hydrocarbon jet fuel. An iterative process used the following constraints:

- The minimum structure fraction needed to build the aircraft was set at 27%. Composite structures demonstrated with the Boeing 787 allow this.
- Engine technology was assumed at the level of the F-35 Joint Strike Fighter, reputed to have an engine thrust-to-weight ratio over 11. It is reasonably predicted that such technology will be made available for a civilian SST, given that over a decade will have elapsed between the introduction of the F-35 and the SST.
- Thrust-specific fuel consumption (TSFC) was assumed to be 1.1 per hour, at the level assumed in the NASA HSCT project, at Mach 1.6 cruise. This is highly conservative, because the engine technology demonstrated for the F-35, and advances in engine bypass ratio, allow lower TSFC than this value. In addition, it does not credit the lower TSFC possible because of the higher overall thermodynamic efficiency with hydrogen combustion.
- The length was limited to 67 m (220 feet).
- The comfort level of modern airline business class seats was assumed.

Figures are presented with British units for the convenience of American readers outside engineering, especially as related to cost metrics.

7. SUPERSONIC DRAG ARGUMENT

The argument in this section is as follows. Well-designed supersonic airliners (and no other kind will fly) will have minimal occurrence and strength of shocks and boundary layer separation. Every effort may be expected from the best developers and aircraft builders in the world, to obtain the absolute minimum possible drag. Thus it is fair to calculate the theoretical minimum of supersonic wave drag, and a reasonable estimate of skin friction drag, with some allowances added for other sources of drag, as the benchmark for total aircraft drag. Lift-induced drag will depend on the choice of wing parameters, which may be driven by other considerations. What we calculate from this process will not be the optimal configuration, but a reasonable approximation. There will be some inefficiencies because the theoretical best cannot be achieved, but also some gains in efficiency from optimization, and from doing better than the conservative estimates that we have made in some respect. Aircraft designers estimate that the "Figure of Merit" (actual efficiency divided by the theoretical efficiency) for transonic airliners has reached well over 90%, but that for supersonic designs it may only be in the 80% range. Keeping this in mind, we have made conservative estimates for engine thrust-specific fuel consumption and some other parameters. The net result of all this is that the real final aircraft should have a performance that is not very far below our estimate.

The volume needed to accommodate the payload, fuel and engines, was obtained, with wings of reasonable thickness, for both the Jet-A and LH2 cases. The theoretical ideal supersonic wave drag for an area distribution (an aircraft shape) that is closed at both ends, is given by the well-known Sears-Haack body shape of supersonic aerodynamics. The corresponding Sears-Haack shape was computed for each configuration. Once the shape was determined, a sanity check of the layout confirmed that the payload, cockpit and fuel could be accommodated. The skin friction drag was estimated using compressible boundary layer estimates used in the industry for high Reynolds numbers such as those on an airliner.

Figure 2 shows a preliminary conventional wing-body shape used for demonstration. Figure 3 shows that this configuration can come to within 5% root-mean-square error of the Sears-Haack without much trouble. It is comfortably assumed that actual aircraft designers will be able to smoothen the sharp features.

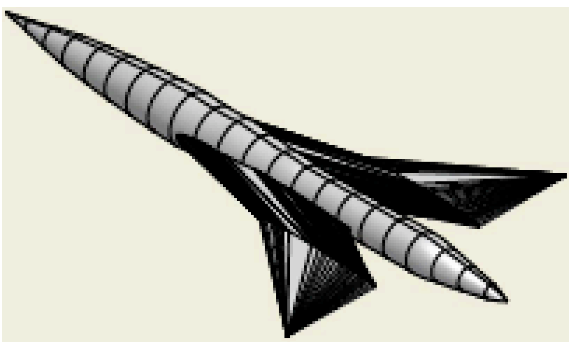

Figure 2: Generic wing-body SST configuration used for conceptual design

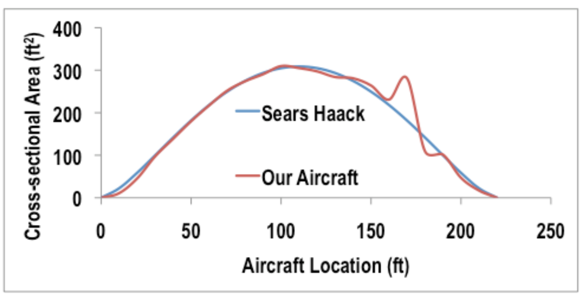

Figure 3: Cross-section area distribution of the conventional LH2 configuration, compared to the Sears-Haack minimum wave drag area distribution.

In supersonic area ruling [16], the area intersected by conical surfaces with the Mach angle (45.6 degrees for the Mach 1.4 cruise case) is plotted. The shape must then be adjusted to approach the Sears-Haack shape. This distribution is shown in Figure 4 before adjustment. It differs by a root mean square error of over 57% from the Sears-Haack, suggesting substantial modification of the wings and redistribution of the fuel into the fuselage. Figure 5 shows a seat layout and the fuel storage space (above the passengers for some of the fuel) that satisfies the requirements for the number of passengers, and the fuel volume.

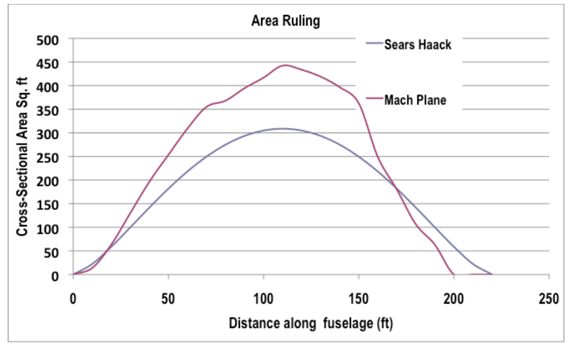

Figure 4: Mach 1.4 conical surface area distribution vs. Sears Haack cross section distribution

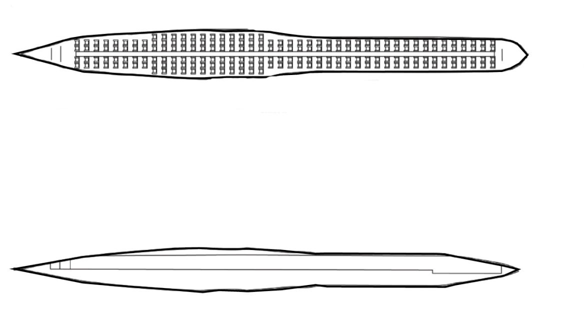

Figure 5: Seating layout (above) and elevation showing fuel storage space above passenger compartment (below)

Some corrections to the above should be considered. The inevitable shock from the nose will cause the relevant Mach number for the fuselage area ruling to be lower than Mach 1.4, thus causing an increase in the Mach cone angle to be used. This would drive the ideal area distribution closer to the Sears-Haack distribution of Figure 3. Nickolic and Jumper (Ref. 16) discuss the issues in comparing the results of different predictions with experimental results, and indicate substantial uncertainties, even in the zero-lift wave drag analysis. Determining the configuration for lowest achievable drag at Mach 1.4 is a matter to be left to more detailed aerodynamic analysis. The point of the above exercise is to show that a liquid hydrogen-fueled SST can be designed for the 200-passenger, 8000km requirements to conform to the Sears-Haack area distribution. This allows us to predict the highest wave drag that should be allowed. Issues and solutions in using liquid hydrogen [17] have been considered elsewhere.

Skin friction drag is calculated from the Boeing flat plate correlation for turbulent compressible flow [18]. Returning to the conceptual design parameter table (Table 2), we see that reasonable choices of wing loading and spans, give a moderate aspect ratio. With the Jet-A SST, to keep the structure weight fraction above 0.27, the payload fraction was reduced to 9.2%. The range of 8000 km is greater than that of the Concorde. In contrast, the LH2 SST achieves a payload fraction of 27.5%, even with the structure fraction increased to 30%. Hydrogen generates about 3.8 times as much heat as Jet-A fuel does, even before accounting for the higher thermal efficiency of a hydrogen jet engine due to higher operating temperatures.

8. HYDROGEN DRAG PENALTY

The choice of a 4.66m (15.3ft) diameter fuselage is conservative, and provides substantial volume for hydrogen storage above. The additional fuel storage volume for hydrogen beyond that required on the Jet-A craft was found by iteration. The wave drag penalty of including this excess volume brought the total drag coefficient to 0.0429 for the LH2 SST versus 0.034 for the Jet-A SST. Thus the upper bound on the "hydrogen penalty" in drag is a 26% jump in total drag coefficient. However, being substantially lighter, for the same payload and wing loading, the total drag of the hydrogen SST is only 60% of that of the Jet-A. So there is no "hydrogen drag penalty". Other designs were considered, including a Blended Wing-Body and an Oblique Wing. These posed difficult challenges to the Sears-Haack based approach for determining a benchmark calculation. An actual SST design will likely use Blended Wing Body concepts to reduce interference drag and engine noise. Table 2 vindicates the critics of the SST in that a conventional Jet-A fueled 8000km (5000mile) SST is not viable with today's fuel prices, regardless of noise issues.

9. SEAT-MILE FUEL COSTS

Airline annual reports circa 2003 indicated that fuel was roughly 20% of total costs (and therefore of averaged cost per ticket). With a sharp increase in jet fuel costs, and cost reductions in other areas, we assume that fuel costs are now between 30 and 40% of total costs. Below, we estimate only the fuel costs, and the carbon costs attributable to the fuel. Figure 6 considers what happens as the cost of hydrogen fuel varies. This cost is expected to come down with improving technology, infrastructure and market acceptance, because hydrogen supplies are unlimited. It is left as the independent variable.

The use of seat-miles and cost per gallon rather than their metric counterparts in Figure 6 is intended to make it easier for the reader used to these common economic parameters. The seat-mile fuel cost of the LH2 SST is the slanting line. The short horizontal lines mark various levels. In the days of the Concorde, the cost of Jet-A used to be below $0.3/gallon. This point is not shown on the figure. The lowest cost today is the seat-mile cost for a long-haul transonic airliner of the Boeing 767 class, with 250 passengers carried for 8000 miles (12,800km), at the current Jet-A price of $2.36 per US gallon [19] as of November 2010. This is $0.0329 per seat mile, which the LH2 SST can match only at a hydrogen price of $0.4 per lb ($0.88 / kg).

The next level up is the seat-mile fuel cost of $0.072 (4.5 cents per seat-kilometer), of the reference SST using Jet-A fuel, at the price level of $1/gallon that existed a few years ago. One could argue that hydrocarbon synthetic biofuels might be able to reach this price in future. At $0.8/lb ($1.76/kg) of hydrogen, the LH2 SST would do better. At a Jet-A price of $2.36 per gallon, existing in November 2010, the Jet-A SST fuel cost per seat-mile is 17 cents, bettered by the LH2 airliner at $1.8/lb (3.96 per kg) of hydrogen. The final level shown is for a Jet-A cost of $3 per gallon, where hydrogen can cost $5.06 per kg and still come out better.

The cost of hydrogen manufactured by the steam reforming process starting with fossil hydrocarbons, liquefied and transported to the point of use, is estimated [20] to be $1.66 per lb ($5.85/kg) as of November 24, 2010. However, only $0.38 /lb is attributed to production and refining. The remaining $1.28 is compression, liquefaction and transportation to the point of use, assuming that this step requires transportation to retail pumps located all over the country. We can safely assume that cost at airport fuel depots can be substantially lower, assuming that there is enough demand to justify production plants nearby. Further, we can project that other manufacturing techniques and renewable resources will compete. Airports typically have plenty of open land around them, that could be used for solar power extraction, though it remains to be seen

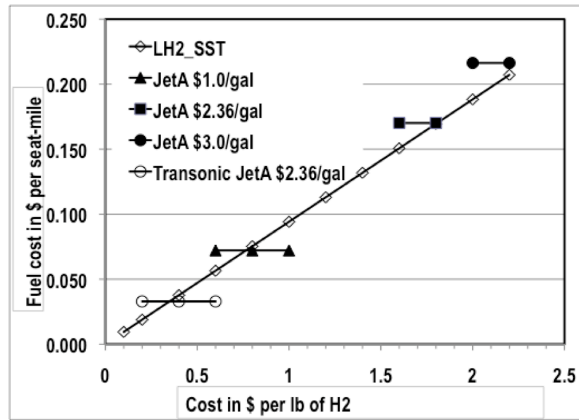

Figure 6: Fuel cost per seat mile as a function of the price of hydrogen

how much is needed as demand for hydrogen at the airport rises. Given these prospects, the best we can do today is to point out that even at the cited current cost of retail delivered hydrogen, the hydrogen SST is able to compete on fuel costs with hydrocarbon SSTs.

The calculation below uses the example of a transonic long-distance route to arrive at a reasonable comparison of ticket prices. The long route with its unique technology demands, low payload fraction and international issues, is best suited to capture both the true cost to the airline and the effect of marginal fuel costs, compared to the busy US-Europe routes where pricing may depend on many other factors. Assuming that seat-mile fuel cost is 40 percent of total airline cost (the upper bound as indicated above), the seat-mile ticket cost (excluding profit) for an "average" transonic airliner seat on the longest flights comes out to be around 6.60 cents. This works out to about $1060 for a round trip ticket for a 25,600 km (16,000 mile) round trip, a reasonable result given that the Atlanta-Dubai nonstop round trip ticket advance-purchase internet ticket price was around $1100 in December 2009 (though it rose to over $1500 in December 2010 with the airlines now happily profitable). Thus to bring the SST ticket price to $2500, the cost of liquid hydrogen at the airport would have to come down to around $0.75/lb ($1.65/kg). The airline might be able to mark this ticket up to $3000 with economy-class service (with food and toilet access, please!) but business-class seat room. It is our claim that this ticket price is well within the acceptable range for many who value the comfort and the reduction in flight time. While it would be great to be able to fly supersonic the entire 12,800km (8000mile) distance non-stop, the paucity of such routes means that aircraft design for this application will probably await the success of the 8000km (5000mile) LH2 SST fleet.

Who will pay $2B to develop a liquid hydrogen SST?

Although the long-term seat-mile cost question is answered in the above, the shorter-term question of development cost remains. Here we could consider the carbon cost. At $20 per ton of CO_2, the transonic airliner adds a carbon cost of $0.00267 per seat-mile. A fleet of 500 LH2 200-seat airliners operating three 8000 km flights per week would save $208 million per year. Looking ahead a decade, over $2B of carbon savings can be reasonably projected, as a source of development funding for the SST. This could be paid directly as the carbon reduction program of the aviation industry, instead of having to go to build other "clean development" projects. Whether $2B is enough to develop such a breakthrough, remains to be seen. However, it is safe to assume as well that the military in Europe, the USA, Japan, Russia and the People's Republic of China will all wish to have large supersonic hydrogen-fueled transports as well, so government funding, quite beyond any civilian funding priorities, will surely pay for a large part of such development. Experience from engine and fuel system technologies and operations already done in the space programs will surely be used.

Table 2: Parameters and results of the 3 conceptual designs compared

Concept	Jet-A SST	LH2 SST	Transonic Jet-A
Range, km	8000	8000	12800
Passengers	200	200	250
Cargo, tons	10	10	10
Payload fraction	9.2%	29%	22%
Gross weight, MT	358	114	175
Wing Loading, N/m^2	4978	4978	5505
Aspect Ratio	6.24	9.33	6.02
Lift Coefficient CL	0.25	0.25	0.74
Engine Thrust/Weight	11	11	11
Aircraft Lift/Drag	9.16	5.4	15.27
Fuel Fraction	61%	37.7%	48%
Structure Fraction	27%	30.6%	27.2%

10. CONCLUSIONS

This paper argues for a new look at hydrogen-fueled supersonic airliners. Dramatic changes in demographics, globalization of trade markets and employment, the development of expatriate communities, and the opening of the Communist Bloc nations and South Africa, all imply significant changes in the market for supersonic transport. A technical approach using the Sears-Haack body for minimum transonic wave drag is used to obtain a conservative comparison of the performance achievable using hydrocarbon (Jet-A) and hydrogen-fueled supersonic airliners. Five main points are shown in this paper:

1. Hydrocarbon-fueled SSTs are not likely to be viable for an 8000 km range needed to reach an adequate number of busy non-stop destinations.
2. The aerodynamics of LH2 SSTs can be designed to be quite effective for 8000 km range.
3. The "hydrogen drag penalty" of carrying a large quantity of liquid hydrogen for intercontinental flights, is non-existent, as the higher drag coefficient is more than compensated by the fact that the LH2 SSST has much lower weight and hence less drag than comparable Jet-A SSTs for the same payload and range.
4. At today's costs of Jet-A and hydrogen, the LH2 SST is already more cost-effective than the Jet-A SST when carbon costs are included.
5. As hydrogen costs come down, it is reasonable to expect that LH2 SST ticket prices will come down to the level of today's transonic business class airliner tickets.
6. The carbon savings of a fleet of 500 LH2 SSTs would provide over $2B in a decade, as a justification of investment in LH2 SSTs. Unlike carbon credits obtained by annual investments in other clean development projects, going towards hydrogen-fueled aircraft is a permanent way to essentially eliminate carbon emissions by the aviation industry.

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