A New Look at 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[1] and the Tupolev 144[2] pioneered supersonic airliner flight in the 1960s, but neither achieved anywhere near the fleet size needed to be viable in the marketplace. 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[3] in 1999 that the market did not justify development of SSTs. Experts pointed out that the airlines' business model depends on business/first class travelers to make long-distance routes viable. An SST would take away these high-paying passengers, and thus cut the low-risk profit 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. Current interest in SSTs appears to be limited to business jets.

Hydrogen-fueled airliners were perceived to be impractical for 4 reasons:

- The presumed difficulty in handling liquid hydrogen safely.
- The high wave drag associated with the presumed large volume of liquid hydrogen.
- The high cost of producing and storing hydrogen in sufficient quantities.
- The presumed energy inefficiency and carbon footprint of producing hydrogen starting with fossil-driven power plants.

Against these objections, there are several newer developments that demand a new look at supersonic hydrogen-fueled airliners:

- There may be substantially more demand for supersonic airline travel, than considered before.

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

2. Summary of Issues

The problem is distilled to the following questions:

- How have demographics and economic development altered worldwide market projections for supersonic transport? What are viable destinations, and what are the flight times, curfew implications and business implications of supersonic flight between these destinations?
- What is the drag implication of using hydrogen, given the lower fuel weight fraction?
- What is the impact of Global Warming/ Carbon emission reduction initiatives on the prospects for hydrogen-powered flight?
- What are the noise implications of the LH2SST?

3. Growth of World Wide Air Travel

Airline travel has increased by nearly 300% since 1980[4], 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[5]. The world has changed drastically since the early 1990s. The Berlin Wall is down, and the European Union integrated. Russia's arctic airspace opened to many new air traffic routes[6]. 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. 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. Most dramatic is the rise in the economies of Asia since the early 1980s, and the opening of travel in and to the People's Republic of China. 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 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. 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 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.

4. Fuel Prices and the Hydrogen Economy

The Hubbert Peak Oil theory[7] holds that fossil fuel prices will rise very sharply as the increase in demand surpasses the increase in supplies[8]. Many experts feel that this may be an imminent event[9], or may occur by 2018[10] or 2030[11]. 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[12]. 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 or wind 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[13]. 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[14]. The best flight altitude may thus be substantially lower than those previously considered for supersonic flight.

6. Preliminary Sizing and Performance

A conceptual design study incorporated the general requirements of flying supersonic, the fuel storage issue, and the performance parameters of supersonic cruise. A range of 5,000 statute miles was specified. Supersonic cruise at 45,000 ft was chosen. Following general design guidance[15] validated against Concorde numbers, the aircraft was sized for 200 passengers and 6 crew. An iterative process used the 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.
- Thrust-specific fuel consumption was assumed to be 1.1 per hour, at the level assumed in the NASA HSCT project, at Mach 1.6 cruise.
- 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 volume needed to accommodate the payload and fuel, with wings of reasonable thickness, was obtained, for both the Jet-A and LH2 cases. The corresponding Sears Haack shape for minimum wave drag was computed. The drag of an actual airliner can be assumed to be close to this ideal. Once the shape was determined, a sanity check of the layout confirmed that the payload, cockpit and fuel could be accommodated.

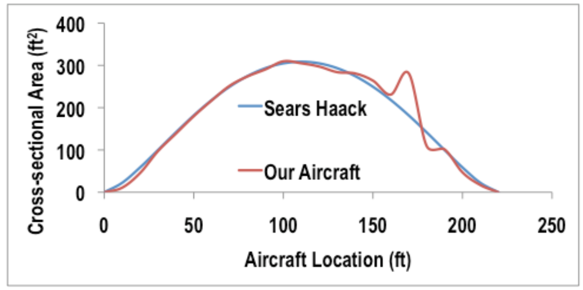

Figure 1: Area distribution of the conventional LH2 configuration, compared to the Sears-Haack minimum wave drag area distribution

Figure 1 shows that a conventional fuselage/ swept wing configuration (shown in Figure 2) 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.

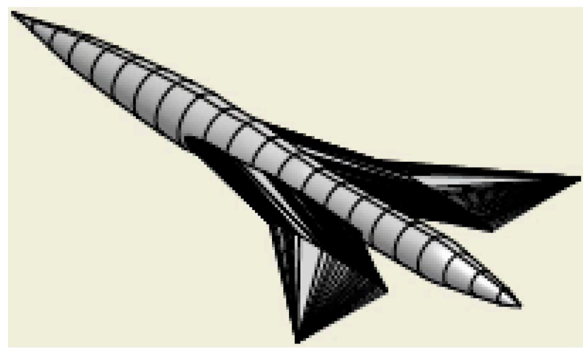

Figure 2: 200-seat Sears-Haack configuration

In supersonic area ruling[16], the area intersected by conical surfaces with the Mach angle (45.6 degrees or higher for the Mach 1.4 cruise case) is used to smooth out discontinuities that would cause shocks. This distribution is shown in Figure 3. 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.

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 further towards the Sears-Haack distribution of Figure 1. 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.

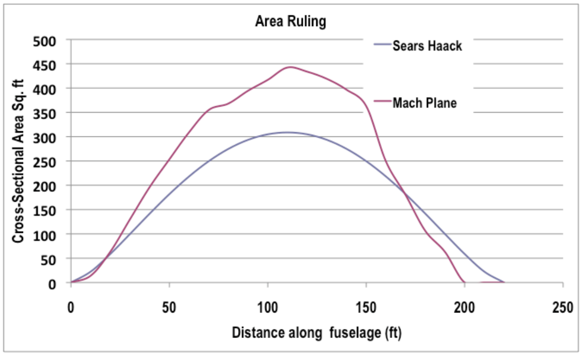

Figure 3: Mach 1.4 conical surface area distribution vs. Sears Haack cross section distribution

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 shape is optimized for transonic conditions, leaving a substantial safety margin because the drag coefficient decreases at supersonic Mach number. 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.

8. Aerodynamics at Supersonic Cruise

Skin friction drag is calculated from the Boeing flat plate correlation for turbulent compressible flow[18]. Reasonable choices of wing loading and spans, give moderate aspect ratio. With the Jet-A SST, to keep the structure weight fraction above 0.27, the payload fraction had to reduced to 9.2%. The range of 8000 km is 20 to 25% greater than that of a 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 temperatures.

9. Hydrogen Drag Penalty

The choice of a 4.66m (15.3ft) diameter fuselage is conservative, and probably provides substantial volume for hydrogen storage above. However, 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 0.0394 for the LH2 SST versus 0.027 for the Jet-A SST. Thus the upper bound on the "hydrogen penalty" in drag is a 50% 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 55% 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 vindicate the critics of the SST in that a conventional Jet-A fueled 8000km (5000mile) SST is not viable, regardless of noise issues.

10. 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-cutting 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 4 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 4 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. The lowest is the seat-mile cost for a long-haul airliner of the Boeing 787 class, with 250 passengers carried for 8000 miles (12,800km), at the current Jet-A price of $2.237 per US gallon[19] ($0.59 per litre) as of April 2010. This is 3.12 cents per seat mile, which the LH2 SST can match only at a hydrogen price of $0.66 per kg.

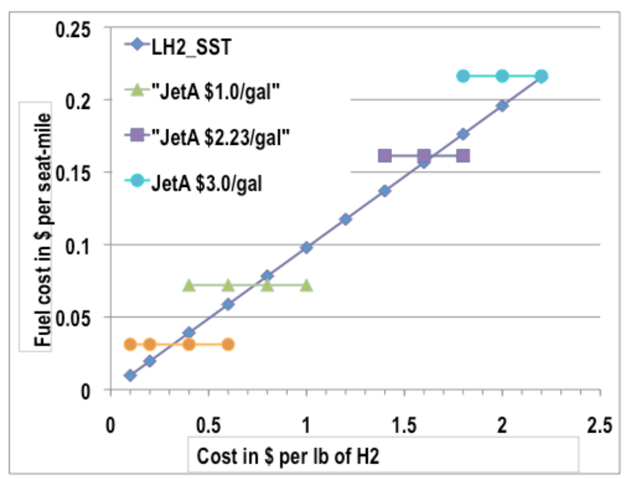

Figure 4: Fuel costs per seat mile.

The next level up is the seat-mile fuel cost of 7.2 cents (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. At $1.65 per kg of hydrogen, the LH2 SST would do better. At today's Jet-A price of $2.237 per gallon, the Jet-A SST fuel cost per seat-mile is 16.1 cents, bettered by the LH2 airliner at $3.52 per kg ($1.60 per lb) of hydrogen. The final level shown is for a Jet-A cost of $3 per gallon, where hydrogen can cost $4.84 per kg and still come out better. Today's hydrogen cost from the steam reforming process, liquefied and transported to the point of use, is estimated[20] to be $3.65 per lb. Thus the LH2 SST is already close to being cheaper than the Jet-A airliner at today's prices.

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 6.24 cents. This works out to about $1000 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. The LH2 SST at today's hydrogen prices would thus cost about 16.5 cents per seat-mile in fuel, and the round trip ticket would cost the airline $2640, marked up to a $3000 ticket price with economy-class service, 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.

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.

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, Metric tons	358	114	175
Wing Loading, N/m^2	4978	4978	5505
Aspect Ratio	6.24	9.33	6.02
CL	0.25	0.25	0.74
Engine T/W	11	11	11
L/D	9.16	5.4	15.27
Fuel Fraction	61%	37.7%	48%
Structure Fraction	27%	30.6%	27.2%

11. Conclusions

This paper argues for a new look at hydrogen-fueled supersonic airliners. Dramatic changes in demographics, globalization of trade markets and employment, and the maturing of expatriate worker communities, and the opening of the Communist Bloc nations and South Africa, all imply large and 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 5000-mile range.
3. The "hydrogen drag penalty" of carrying a large quantity of liquid hydrogen for intercontinental flights, is non-existent, as these aircraft will have much lower drag than comparable Jet-A SSTs.
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. At today's costs of Jet-A and hydrogen, the viable ticket price on LH2 SSTs will be about 3 times that of advance-purchase transonic long-distance tickets. With mass-production efficiencies reducing hydrogen costs, it is realistic to expect LH2 SST ticket prices to come down to the level of today's transonic 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.

12. Acknowledgments

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