ECONOMIC SUPERSONIC TRANSPORT

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Abstract

Recently, it has been explained how supersonic transport aircraft must be designed to be quiet at takeoff. The next question obviously is : can such an aircraft be operated economically ?

Travel cost has several components: Fuel consumption, personnel and catering, depreciation and maintenance, passenger time. Mach 3 travel cost could be up to 40% lower than subsonic.

1 Introduction

Supersonic commercial flights ceased with Concorde withdrawal by British Airways and Air france in 2003. And no supersonic transport has been manufactured for more than 30 years anywhere in the world. And millions passengers continue to accept hard conditions for more than 10 hours on every long-haul flight. It is quite surprising that nothing is in progress to shorten those too long flights. Projects were started in the nineties, in America, Europe and Japan but they were withdrawn rapidly. Precompetitive research actions followed but no design effort has been sustained anymore. The main show stopper was noise. No official specifications have come into force yet but it is usually accepted now that any supersonic tranport will have to comply with the same noise limits as a subsonic with the same weight. In addition, the sonic boom of a big aircraft will not be tolerated over populated areas. In order to bypass those obstacles, it is currently suggested to limit the supersonic perspective to rather light business jets only. This orientation is disappointing for all of those who cannot pay for a luxury jet, but even so for the other few, since the Mach number must be very limited (1.2 – 1.5) to get a chance for a supersonic business jet to be accepted by future noise and sonic boom regulations.

In previous papers [1,2], it has been explained how supersonic transport aircraft must be designed to be quiet at takeoff and landing. The next questions obviously are : can such an aircraft be operated economically and can it be really safe, green and comfortable ?

The basic design of such a quiet supersonic transport aircraft is summarized in Part 2. An economical model is proposed in Part 3. Results of that model are discussed in Part 4. Conclusions and perspectives are given in Part 5.

2 Basic Design of Quiet Supersonic Transport

In order to limit supersonic-transport takeoff noise to the same levels as future subsonic, it is necessary to have an air intake cross section 3 times larger for takeoff than for supersonic Mach 2 cruise, and 4.6 times for a Mach 3 cruiser [1,2]. These large variations of air intake cross section cannot be obtained neither with any variable-cycle engine (practically limited to a 1.5 ratio) nor by any extending ejector (practically limited to 2). Thus it is not possible to use only one type of any engine. Low-BPR (bypass-ratio) turbofans or turbojets are required for economic supersonic cruise. Those engines must be used at a lower power setting for takeoff, and thrust has to be completed by deploying high-BPR turbofans similar to subsonic aircraft engines. Actually, the fuselage cross section is not large enough to accommodate those very big engines and additional retractable coreless fans, powered by the high-BPR turbofans, are needed. This apparent drawback is finally an oportunity as explained now. If one circular fuselage cross section is too small for accomodating the engines with the required mass flow rate, a twin cylinder fuselage with the same total cross section is larger than required. Thus it is possible to keep the high (but not high enough)-BPR turbofans fixed and burried inside the fuselage. Only air intakes and nozzles have to be deployed for takeoff, and retracted for supersonic flight (Fig. 1 and 2).

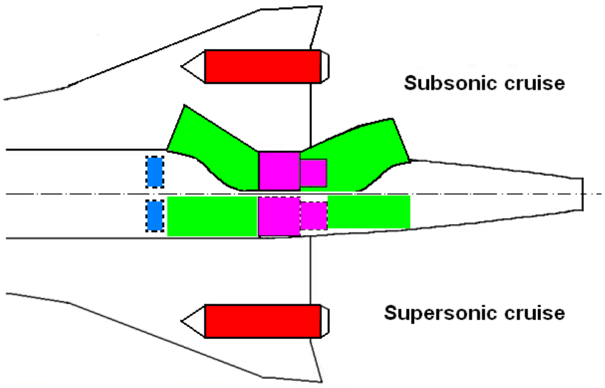

Fig. 1. Underside view of a Mach 2 ultraquiet transport

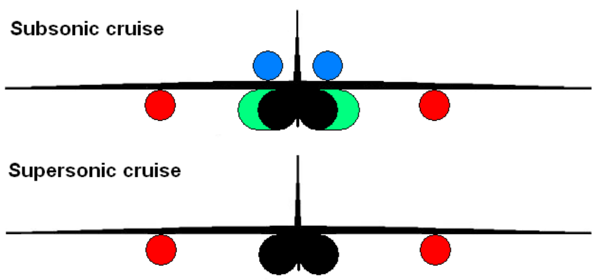

Fig. 2. Front view of a Mach 2 ultraquiet transport

The resulting distorted flow, delivering a decreased thrust must be compensated by a larger diameter of the deploying coreless fans, what is permitted by the space still available in the fuselage. As such a big aircraft will have to be subsonic over populated areas to avoid sonic boom, those flight phases must be competitive with subsonic aircraft, what is permitted by the high-BPR engines. It should be noticed that the twin cylinder geometry has concave shapes in the symmetry plane which can be varied to follow the Whitcomb area rule. Let us choose one exemple of aircraft to show numerals and pictures. In order to have a clear discussion, a 320 tons aircraft designed for transporting about 250 passengers up to 10 000 km at $M = 2$ or 3 is studied (M is the Mach number). The subsonic reference for comparison is a usual commercial aircraft with about the same capacity and range (Airbus A340-200 for instance). The best capability for accomodating big engines is given by a twin cylinder fuselage section as shown in Figure 3.

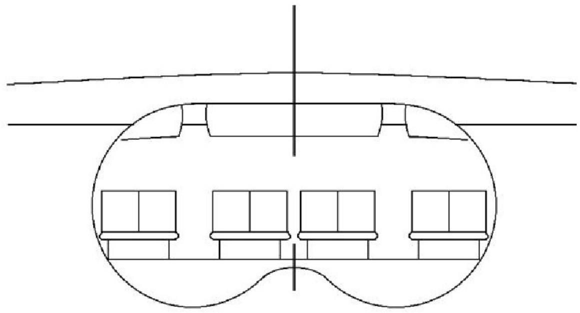

Fig. 3. Cabin section of an ultraquiet supersonic transport

With 3 m in diameter twin cylinders, it is possible to accommodate a twin aisle, 8 abreast, cabin arrangement. There is a nice space for passenger comfort and hand luggage but just a limited bottom volume for fuel. The volume for the baggage hold is to be found elsewhere. With the same cross section, a usual one-cylinder fuselage would be 4.2 m in diameter, typical of a single aisle, 6 abreast configuration for 250 passengers. This 6 abreast configuration with a 1.5 m row separation needs a 63 m cabin length. The 8 abreast seating only needs 48 m. The difference, 15 m, may be used for baggage hold (9 m) and engine hold (6 m) without any length (and weight) extension need with respect to the one-cylinder fuselage. Properties of the propulsion means are proposed in Tables 1 and 2. The figures are those of current commercial engines with similar mass flow rates.

Engine Name	Diameter (m)	Length (m)	Weight (tons)
Low-BPR	2.3		6.6
High-BPR	2.6	< 6	4.8
Coreless Fan and deploying ducts	2.2		2.6
Total			28

Table 1. Dimensions of the propulsion means for a 320 t Mach 2 transport

Engine Name	Diameter (m)	Length (m)	Weight (tons)
Turbojet	1.8		5.0
High-BPR	2.6	< 6	4.8
Coreless Fan and deploying ducts	2.6		3.1
Total			25.8

Table 2. Dimensions of the propulsion means for a 320 t Mach 3 transport

It may be noticed that the weight of the propulsion means is 8 to 9 % the MTOW, instead of a typical 3.9 % for subsonic. The propulsion means may weight up to 2.6 - times the payload instead of 0.4 for subsonic. As fuel consumption is also much larger, the success of supersonic operation depends on engine weight enormously. Only current technology is considered in the present assessment but there is an obvious interest in using titanium for the engines.
The wing is over the fuselage to provide easy access to the propulsion means for maintenance. Another advantage of that configuration is a short landing gear which results in a lower weight and a lower airframe noise.
The aircraft structure is based upon current technology. The reference is similar to an A340-212 aircraft with a 257 ton maximum takeoff weight (MTOW); with a 113 ton engineless empty weight (ELEW), its ELEW/MTOW ratio is 0.440. This same ratio is kept for the supersonic and results in a 140.8 ton ELEW.

The reference subsonic aircraft is supposed to transport 263 passengers and the supersonic 250 or less according to the MTOW. The average passenger weight (with luggage) is assumed to be 96 Kg. With the 263 passengers, the landing weight is m_l = 158,5 tons for the subsonic, with a 10,16 ton fuel reserve.

3 Simple Economical Model

In order to predict and compare the travel costs, a simple model must be setup. The ticket price results from four components:

- taxes,
- fuel consumption,
- plane depreciation, commercial and maintenance costs,
- crew and catering charges.

Taxes are assumed to be the same for all flights: 100 € (The prices may also be read in US $ since the main purpose is comparison between subsonic and supersonic). For subsonic flight, it is assumed that each of the other three lines is one third of the rest of the ticket price, in acceptable agreement with usual airlines budgets. Obviously, it may only be a crude approximation since fuel price has been varying a lot for the last years.
The starting data are the return ticket price for some distance at Mach 0.82. Its fuel fraction determines the ton-of-fuel price which is then used for computing the fuel cost in supersonic for the same distance. Its depreciation and maintenance fraction is kept constant in supersonic for the same distance. And the crew fraction is used to determine work day costs subsequently used for the supersonic assessment (always for the same distance).

3.1 Fuel Consumption

The fuel reserve is assumed to be 0.0544 times the landing weight m_l. The fuel consumption (m_t – m_l), m_t beeing the takeoff weight, results from the usual Breguet equation

$$\boldsymbol{L_n}(m_t/m_l) = cgTD/L, \qquad (1)$$

where c, g, T, D, L are the installed specific fuel consumption (Kg/N hour), the earth acceleration

(9.81 m/s^2), the flight duration (hours), drag and lift, respectively. L/D is chosen to be 19.2, 10.5 and 9 for M = 0.82, 2 and 3 respectively. c is chosen to be 0.065, 0.12 and 0.16 Kg/N hour for M = 0.82, 2 and 3 respectively.

$$T = R / 3.6\, a\, M, \quad (2)$$

R beeing the flight distance (Km) and a the sound speed, chosen as 300 m/s.
For the subsonic aircraft, it has been said that m_l = 158.5 tons (263 passengers) for all of the distances in the study. Thus m_t only depends on T according to Eq. (1) and then the fuel consumption also.
For the supersonic, the landing weight m_l is the sum of the ELEW (140.8 tons), the engine weight (28 tons for Mach 2 or 25.8 tons for Mach 3), the fuel reserve (0.0544 m_l) and the payload (250 X 96 = 24 000 Kg). Then m_t results from Eq. (1). However, if that m_t is larger than the MTOW (320 tons), m_l , thus the number of passengers, has to be reduced consequently.

3.2 Crew and Catering Charges

It is assumed that the work charge only depends on the flight duration T. This assumption is disputable since a supersonic aircraft has some specificity but supersonic flight is operated very peacefully at an altitude without subsonic traffic and the aircraft is exactly like a subsonic when it has to reduce speed for approach and flying over populated areas. Table 3 shows how the number of working days depends on T for a return trip; this number includes 1 rest day for flights longer than 6 hours. Crew is doubled for flights longer than 8 hours. The number of rest nights is also given in Table 3, as well as the number of meals (a light meal is accounted for half a standard).

T (hours)	Work days	Nights	Meals
< 3	1	0	2
3 - 6	2	1	2
6 - 8	3	2	3
> 8	6	4	5

Table 3. Crew and catering charges

Like for the fuel estimate, the starting data are the return ticket price for some distance at Mach 0.82. The crew-and-catering fraction is reduced by the meal fraction (each meal is accounted for 11 €) to get the crew fraction. One half of this crew fraction is shared by the two pilots. The other half is shared by the flight attendants (1 for 50 passengers). A night is accounted for 200 € for a pilot and 150 € for an attendant. For that flight distance, this operation determines the work day costs which are used for the same distance in supersonic. Thus the crew charge in supersonic is that work day cost times the number of days as given by Table 3 according to T.

4 Results

4.1 Payloads and Weights

Aircraft weights are shown in Fig. 4.

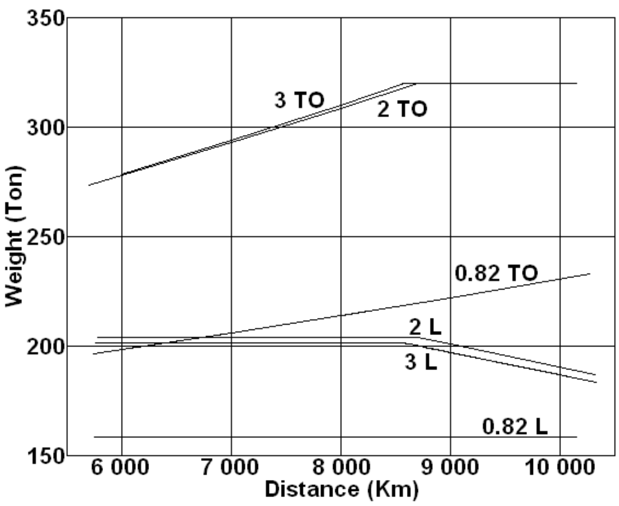

Fig. 4. Takeoff (TO) and landing (L) weight for various Mach numbers

For the Mach 0.82 aircraft, the landing weight with 263 passengers is 158.5 tons. Its takeoff weight increases with distance almost linearly. For the Mach 2 aircraft, the landing weight with 250 passengers is 203.9 tons for distances up to 8 705 Km. For longer distances, the number of passengers must be decreased in order to maintain the takeoff weight not larger than the MTOW (220 passengers for 9 000 Km and 120 for 10 000 Km). For the Mach 3 aircraft, the landing weight with 250 passengers is 201.6 tons for distances up to 8 583 Km. For longer distances, the number of passengers must be decreased (206 passengers for 9 000 Km and 105 for 10 000 Km). It must be noticed that comfort is significantly improved when the number of passengers is reduced so much.

4.2 Fuel Consumption

The fuel consumption is the difference between the takeoff and landing weights. Thus it can be read directly on Fig. 4. For the prurpose of comparison, the fuel consumption per passenger and per Km is shown in Fig. 5.

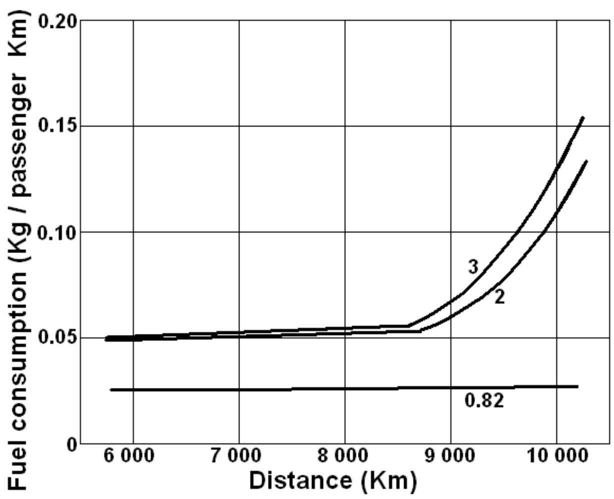

Fig. 5. Fuel consumption per passenger and Km for various Mach numbers

The curves steeply increase when the number of passengers has to be decreased. For the designed number (250 passengers), the specific fuel cosumption, with respect to Mach 0.82, is about twice larger at Mach 2 and three times at Mach 3. But the flight duration is twice shorter at Mach 2 and three times at Mach 3. Thus, there is a balance between a larger specific consumption and a shorter flight duration. Finally the difference is linked with the *L/D* ratio according to Eq. (1): Either at Mach 2 or 3, the fuel consumed per passenger and Km is about twice larger in supersonic than in subsonic.

The flight duration estimate is disputable since it depends on the subsonic fraction (takeoff, climb, populated areas, approach) but it is general and preliminary.

4.3 Crew and Catering Costs

The crew and catering charges are shown on Tables 4 – 6 for various Mach numbers.

Range (Km)	Time (hour)	Pilot (day)	Pilot (night)	Attend. (day)	Attend. (night)	Meals
6 000	6.8	6	4	18	12	3
7 000	7.9	6	4	18	12	3
8 000	9.0	12	8	36	24	5
9 000	10.2	12	8	36	24	5
10 000	11.3	12	8	36	24	5

Table 4. Crew and catering charges for Mach 0.82

Range (Km)	Time (hour)	Pilot (day)	Pilot (night)	Attend. (day)	Attend. (night)	Meals
6 000	2.8	2	0	5	0	2
7 000	3.2	4	2	10	5	2
8 000	3.7	4	2	10	5	2
9 000	4.2	4	2	10	5	2
10 000	4.6	4	2	6	3	2

Table 5. Crew and catering charges for Mach 2

Range (Km)	Time (hour)	Pilot (day)	Pilot (night)	Attend. (day)	Attend. (night)	Meals
6 000	1.9	2	0	5	0	2
7 000	2.2	2	0	5	0	2
8 000	2.5	2	0	5	0	2
9 000	2.8	2	0	5	0	2
10 000	3.1	4	2	6	3	2

Table 6. Crew and catering charges for Mach 3

The resulting crew costs are shown in Fig. 6.

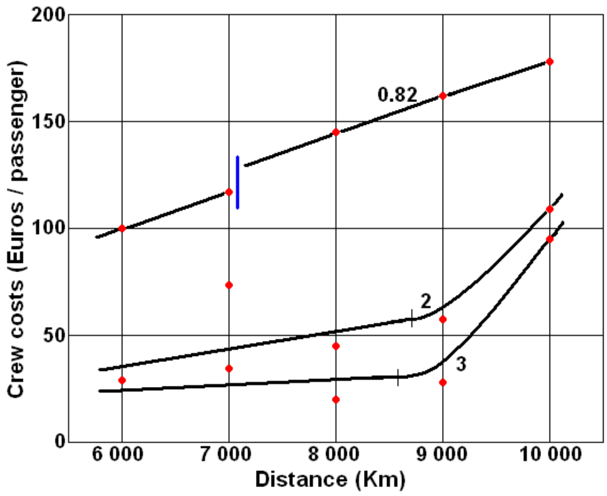

Fig. 6. Crew costs for various Mach numbers

There is a strong discontinuity for M = 0.82 when the crew must be doubled (for more than 7 085 km according to the model). A modest discontinuity is chosen in the total ticket price but the model is left unchanged for clarity. That issue is hardly managed with the simple model and results in artefacts for the supersonic results, especially for 7 000 Km. The model results are shown in red dots but the curves are smoothed for the sake of clarity. For most cases, crew costs in supersonic are less than one half of those in subsonic. This balances the consumption excess.

4.4 Ticket Price

The ticket prices, which are the entry data in subsonic, result from the previous partial results for supersonic operations. They are shown in Fig. 7. The distances for which the number of passengers has to be less than 250 are located with small vertical bars since this is the reason of the steeper price increase. The exact model results are given in red dots but the curves are a little smoothed for clarity.

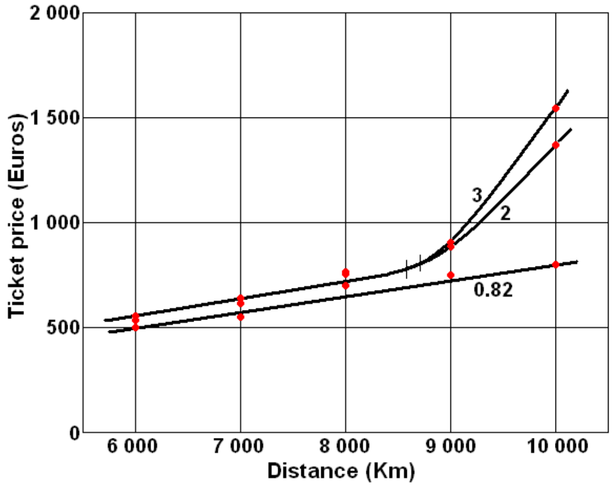

Fig. 7. Ticket price as a function of distance for various Mach numbers

As long as the maximum number of passengers can be embarked, the supersonic ticket is about 10 % more expensive than the subsonic one.

4.5 Travel Cost

The ticket prices are not the final data for economical assessment. An employer has to pay for his employee's time as he sends him to a distant city. Some fraction of the flight time is supposed to be used for working instead of playing with the airplane games or looking at a film but that time is paid anyway. In order to take into account the supposed employee's working capacity, the flight hour cost is modestly estimated to be only 50 Euros. This time cost is added to the ticket price to obtain the travel cost, which is shown in Fig. 8.

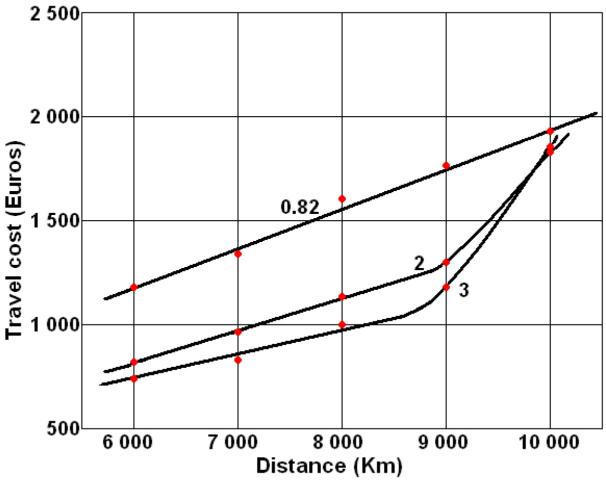

Fig.8. Travel cost as a function of distance for various Mach numbers

Supersonic travel should clearly be cheaper than subsonic and so more pleasant.

5 Conclusions and perspectives

Current technology has been cosidered to assess the specifications of Mach 2 or 3 supersonic transport aircraft. Those planes should be as quiet at takeoff as future subsonic, by design , without any dubious assumptions. Their fuel consumption has been determined and the crew required for their operation has been evaluated. Supersonic and subsonic ticket prices and travel costs have been compared.
It has been assumed for a long time that “supersonic” means “expensive” and the main purpose of the paper was to show that it should be the opposite. The reason of this past erroneous position is a lack of technical and commercial capability. The only available reference is Concorde and it was a luxury solution indeed. Its specific fuel consumption was kept the same for the present Mach 2 estimates since it seems difficult to be improved significantly. But the rest is glorious past of no interest for the future. The main interest of supersonic is to make money with the shorter flight duration. The longer the distance, the stronger its advantage. Concorde's range is the lower limit of the distances considered in this study. Concorde was very noisy whereas the proposed aircraft is as quiet as future subsonic. Concorde had no fuel reserves and needed a priority to be paid for by the passengers, whereas usual reserves were taken into account here. Concorde could not fly economically at a low Mach, whereas it is a requirement for flying over populated areas in the future and the plane equipped with the same engines as subsonic is able to do that competitively. Concorde's cabin was narrow whereas the twin cylinder fuselage can offer a large space for comfort and luggage. And when the number of passengers has to be reduced for large distances, comfort is still improved significantly. Concorde had luxury service and crew was paid more for a shorter time than for a longer on a subsonic flight, whereas the shorter time will permit the companies to pay much less for future supersonic operation. Very short times will turn long haul into short with the possibilities of low-cost operation. The travellers as well as their employers will appreciate economic supersonic transport. Its development does not need any basic research, just design.
Mach 3 operation also has a potential for a better safety since its cruise altitude (22 500 m) is much above dangerous cumulo-nimbus (15 000 m). This altitude also corresponds to the upper fraction of the ozone layer.
The true difficulty is to convince a large airframer to lauch such a programme since the success of that programme will ruin those presently in progress with already important technical and commercial issues. Same situation for the airlines. Thus the supersonic transport needs a formidable request, claimed by the travellers, to be launched.

References

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