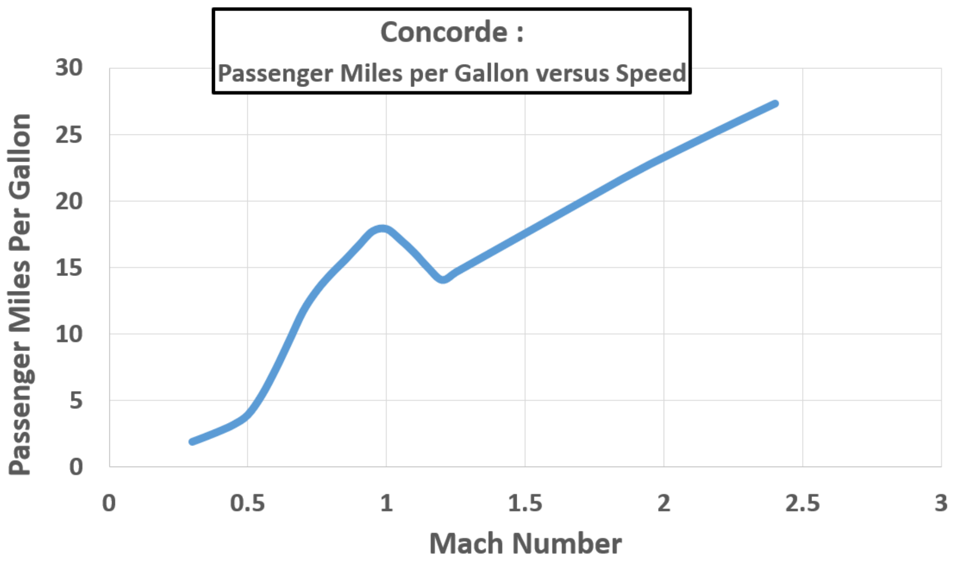
The Supersonic Conundrum

The Faster You Go – The Less Fuel is Used

Dr Fred Starr FIMMM, FIE, MIMechE, C.Eng

In a talk on "Concorde and Its Successors", I gave to the Western Branch of the Newcomen Society in November 2019, the slide that perplexed most people was one which showed that once Concorde has got well past the "Sound Barrier" (Mach1), the passenger miles per gallon (pmg) gets better and better. Giving fuel consumption in this way, might sound a slightly peculiar unit, but it is used by Government and Renewable Energy Organisations to assess the efficacy of various modes of transport. We all have a good idea of what the pmg is for our own cars. For medium range aircraft it is in the 40-60 pmg bracket, depending on the passenger load and other factors. Data quoted in Wikipedia gives a figure of 17 pmg for Concorde, but as the slide showed, the value changes widely with speed.

Focusing on the transonic and supersonic regions, the pmg drops steeply between Mach 0.95, Concorde's subsonic cruising speed, and about Mach 1.2. At this point it is down to 14 pmg, but from then onwards it steadily improves. At Mach 2.05, Concorde's supersonic cruising speed, it up to 23 pmg. If Concorde had ever managed its original target of Mach 2.2, it would have achieved 25 pmg.



For these calculations I assumed that Concorde was at a weight of 350000 lb, a typical value in the early part of the supersonic cruise segment. Passenger numbers were 128, and the fuel consumption of the Olympus engines was set at 1.15 lbs per hour, per pound thrust.

There are not many modes of transport where going faster results in less fuel being expended! The graph shows that Concorde sees this happening both before the sound barrier and then after. It is absolutely dreadful at take off speeds, when a huge amount of power is spent getting Concorde almost nowhere. This is a feature of all jet aircraft, but made worse by Concorde's "narrow delta" wing shape, which is optimised for the supersonic regime.

Essentially, I stand by what I said in the presentation, and what you see above. The aerodynamics of Concorde are covered in some detail in "Aircraft Performance" by W. Austyn Mair and David Birdsall. What they say is based on data supplied by British Aerospace Plc, and the authors used this to calculate the fuel consumption and range of Concorde, among other matters.

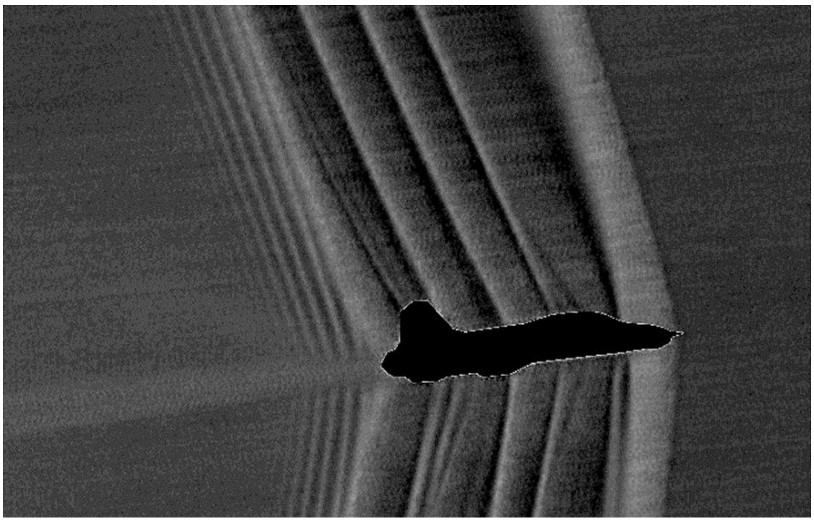
Rather than break up my own somewhat simplistic explanation about why fuel consumption drops with increasing speed, I have left the summary of what Mair and Birdsall wrote towards the end of this piece. You will find that it broadly supports my conclusions.

Wave Drag

The improvement in performance of Concorde all comes down to the peculiarities of a phenomenon known as "wave drag ". It is wave drag why there is such a thing as the sound barrier. People of my age, if they attended an air display in the 1950s, would have hoped to hear a sonic bang. This announced, quite literally, that an aircraft had "crashed through the sound barrier", as journalists loved to write.

The sonic bang is the shock wave associated with supersonic flight, and it is always there at supersonic speeds. It marks an abrupt transition in the flow of air over an aircraft, whereby the pressure and temperature increase across the wave, which, in some respects, is similar to bow wave of a high speed motor boat. Essentially the aircraft is moving so rapidly the air cannot smoothly get out of the way, the wave being no more than a couple of molecules thick. The creation of the shock wave requires, because of the instantaneous changes in air temperature and pressure, energy. This is wave drag. It implies a huge increase in engine thrust.

The picture, taken by NASA shows actual shock waves from an aircraft in flight. It is a Northrop T38 Talon flying at Mach 1.05.

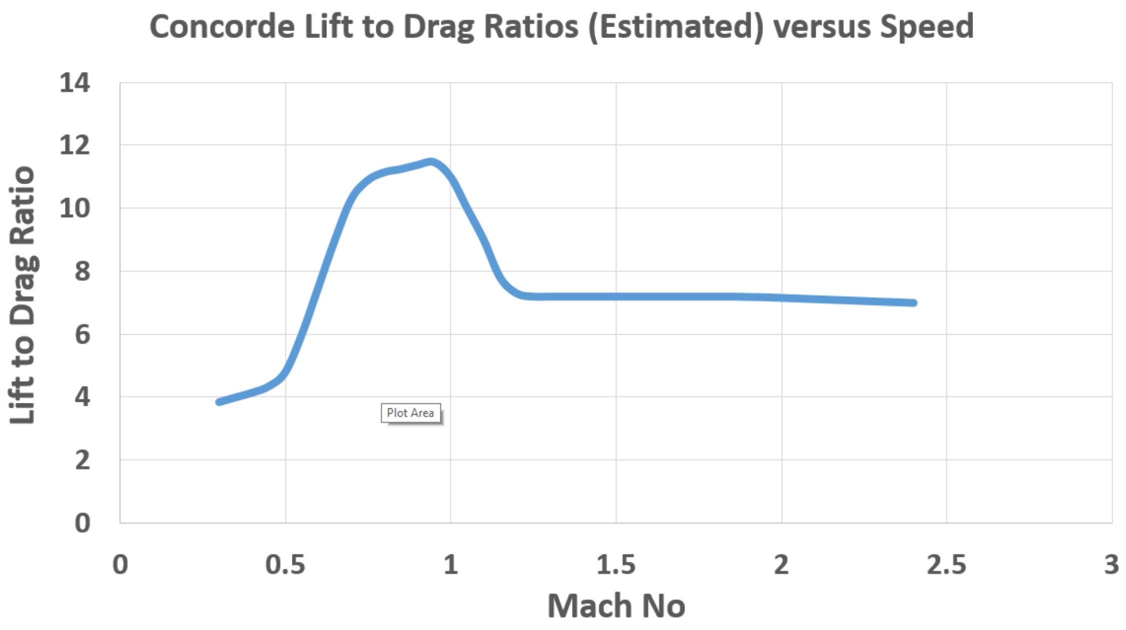


At the speed of sound, Mach 1, the shock wave is at right angles to direction of travel, and its effects on the aircraft and power requirements are at their worst. At Mach 2, the shock waves form a 60° vee, which is why Concorde’s wings have the narrow delta form. They are intended to lie behind the main shock waves.

The Lift to Drag Ratio

The average person might think that the drag on an aircraft simply increases with aircraft speed. Anyone who has had to cycle into a head wind would know that. Aircraft are different, the important factor is the L/D (Lift to Drag) ratio. It translates directly into the thrust needed by an aircraft. Lift is constant, discounting changes in the fuel, and is equal to the aircraft weight. The drag part of the L/D ratio, does change with speed. The cruising speed, in fact, of all aircraft, is close to the point where the drag from the wings (that is lift induced drag) is equal to all the other parts of the aircraft that contribute to drag. That is when the L/D is at a maximum.

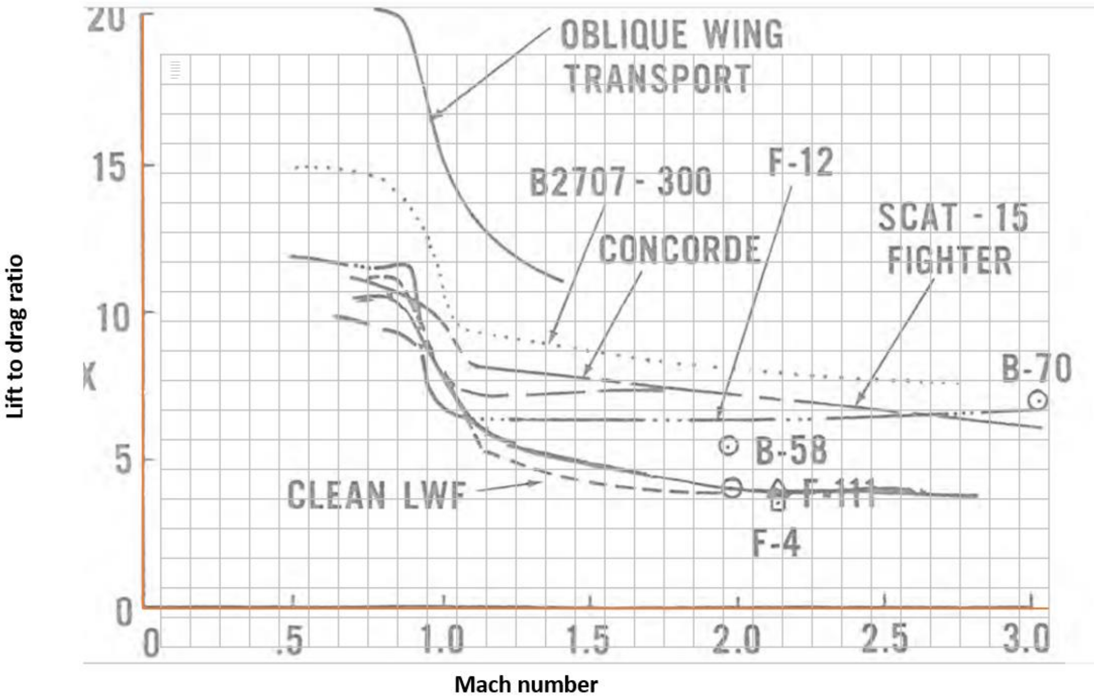
The changes in L/D ratio versus speed or Mach number, for Concorde are shown below*. Note how the ratio changes quite markedly with speed, until above Mach 1.2 it stays more or less the same.



This figure is based on Slide 11 from a presentation entitled “Some Supersonic Aerodynamics” by FK Mason of the Virginia State Polytechnic, which shows the L/D ratios of a number of supersonic aircraft. See below.

All show the same trend, with a drop off in L/D after Mach 1 and then a flattening off to a greater or lesser extent. The original source was a 1976 AIAA paper by Edward Ricconi. His Concorde data only goes up to Mach 1.7 and may be based on the Concorde prototypes, but we do have the actual ratio at Concorde’s cruising speed, which is stated to be 7.14/1.

Pease note that Ricconi's diagram is rather badly labelled. What appears, at first sight to be the Concorde line, actually refers to a "SCAT-15 Fighter". Furthermore, the SCAT-15 programme was a NASA led effort to design a supersonic transport, not a fighter. The Concorde line sits below this.



Concorde's aerodynamics are not exactly brilliant. Even at its best subsonic cruising speed the L/D is less than 11.5/1. The A380 Airbus is 19/1. But note how flat is the curve at the higher speeds. This means that the thrust at Mach 1.2 is essentially the same as at Mach 2.0. It follows that, providing that the performance of Concorde's Olympus engines does not change, **the consumption of fuel, in lbs per hour,** does not change either.

Wave Drag Again

One would expect that as speed increases drag would also increase, Concorde having to fight it way through the air that much harder. Fortunately, the shock waves start to help us. The energy loss weakens, the more bent back the shock waves become at the higher Mach numbers.

There is also an important secondary effect of flying faster. The wing becomes more efficient at generating lift, meeting the air at a shallower angle. That is the "angle of incidence" is reduced, thereby generating weaker shock waves.

This can be seen in the formula for the calculation of the wave drag coefficient

$$\frac{4\alpha^2}{\sqrt{M^2-1}}$$

Here α is angle of attack of the wing and M is the Mach number. For Concorde, at Mach 2, the angle of attack about 3.5°, but at Mach 1.4 it would be about 7°, the wing having to work harder to give lift at the lower speed. At Mach 1.4 the wave drag is 0.062, but for Mach 2 value it falls to 0.00497. In concrete terms the wave drag at Mach 1.4 is more than 12 times what it is Mach 2.

The equation predicts that once an aircraft is through the sound barrier, as the need for thrust falls it would go on flying faster and faster. In practice there are other sources of drag which keep things under control, notably skin friction, and drag from the fuselage and engine nacelles. In consequence, the L/D of most supersonic aircraft tends to fall as Mach number increases. It is to the credit of the designers of Concorde that they kept these other sources of drag under control, so that the L/D curve is so flat. Nevertheless, there would have come a point where wave drag was not the most important factor and the pmg would begin to decline.

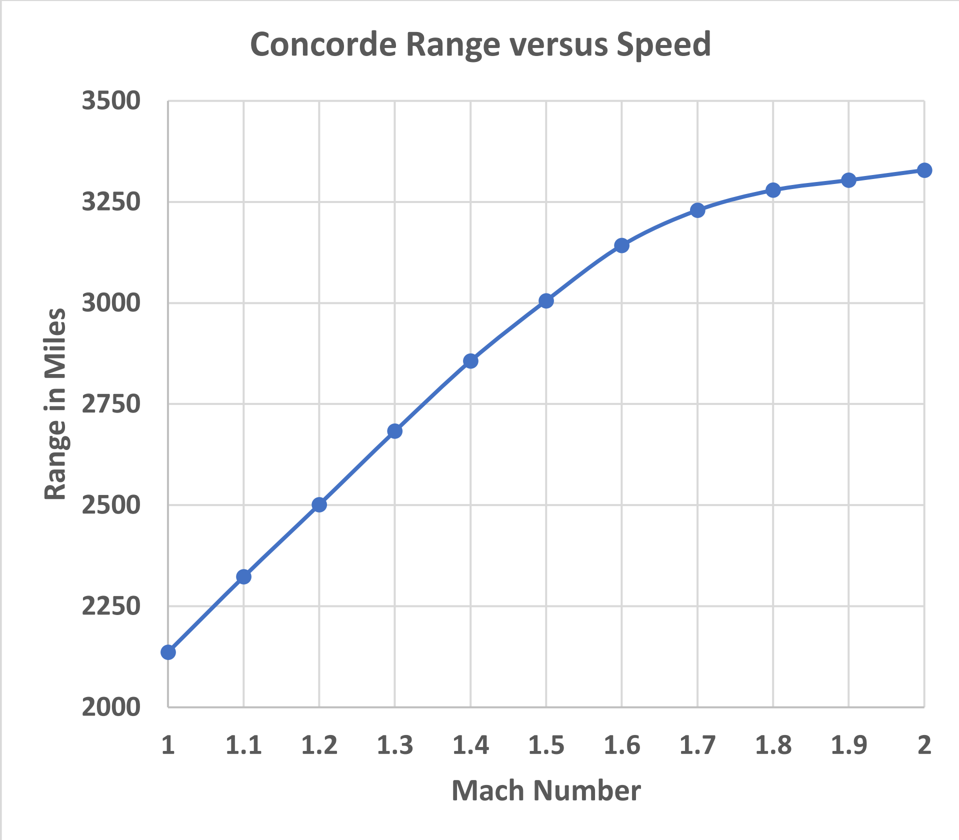
But if only it could have flown at Mach 2.5, it would have been so much better. Pass the blame to the metallurgists. Even today they haven't come up with anything more temperature resistant than RR 58, the aluminium alloy used to make Concorde.

Concorde and its Engines: Mair and Birdsall

As well as being able to use Concorde aerodynamic data, Mair and Birdsall also had access to what was happening to Olympus engines in supersonic flight. Specific fuel consumption, above 40000 ft increased by about 6%, between Mach 1 and Mach 2. At Concorde's cruising speed, the manufacturer's value was 1.165 lb per hour per lb thrust. Very close to my estimate.

What is rather surprising, but not normally mentioned, is that, at a constant height the thrust of the Olympus increases by about 220 % between Mach 1 and Mach 2. This is obviously due to the greater airflow coming into the engine. In the light of this, Mair and Birdsall publish a graph which shows that at 39000 ft, partly because of the deficiency of engine power at around Mach 1, and the high level of drag at this speed and altitude, Concorde would not be able to break the sound barrier on "dry thrust" alone. Dry thrust only begins to exceed drag above Mach 1.2. One begins to see why reheat, in accelerating through the transonic regime, was so vital to Concorde's success.

The calculations done by these two authors are rather complex, but they show that the graph of lift to drag ratios, versus speed is something of an artifact. Each point on the curve refers to the optimum L/D at a given speed and altitude. Concorde would break up if flown at Mach 2 (1520 mph) at sea level! Furthermore, flying at Mach 1 at cruising height, 55000ft, would also be impossible. Its indicated airspeed would be just too low. At 227 mph this would be about Concorde's take off speed. Although Concorde doesn't stall, in the normal sense, it would be "on the back of the drag curve" and requiring well over 60000lbs of thrust. Concorde would be heading back to earth. And, although not out control, one would guess, it would be a hairy time for pilots and passengers.



Mair and Austin have calculated what they refer to as the specific range of Concorde, and the graph above is based on their estimates. The specific range is effectively the miles per lb of fuel, at any given Mach No. Each Mach number corresponds to a given height, for example around 40 thousand feet at Mach 1.2, and 55 thousand feet at Mach 2. The most important part of their calculations entailed working out the best lift to drag ratio for any particular altitude and Mach Number. Their figures equate to 25.6 passenger miles per gallon at Mach 2. Slightly better than my estimate.

The main difference is that the Mair and Austin curve flattens out, indicating that pmg showed not much improvement above Mach 1.8. This mainly due to their estimates of L/D ratio which showed a gradual drop after Mach 1.5. This is in contrast to mine which was much flatter.

But I now realise that my own estimates also incorporated (unknowingly) the fact that each L/D ratio and Mach No are tied to a particular altitude. As an excuse, all I can say is that this type of graph has been around since the early sixties. For speeds of over Mach 2 Concorde would have to be flying at well over 65000 ft. If I were to give this talk again, I would be making this clear.

Materials for Supersonic Transport Aircraft

Finally, as a metallurgist who has got some knowledge of high temperature alloys, it has always been a puzzle as to why for the various supersonic transports, the alloys that were being used were operating at skin temperatures at which there would be a drop off in strength. Quite abruptly, in the case of RR58, the aluminium alloy used for Concorde, or more gradually with the Ti-6Al-4V initially proposed for the American Supersonic Transports.

The skin temperatures, for Concorde at the original Mach 2.2 target were 122°C and 315°C for the American SST. These flight speeds and temperatures were really pushing the chosen alloys. Why not fly just a little slower, and avoid the pain?

The arguments outlined above show why this was not a feasible option. The poor passenger miles per gallon of SSTs would suffer even more by flying more slowly. What Concorde needed, as well as a better engine, was a more resistant aluminium alloy. This was not forthcoming, as the reference below shows. In the American case, there was a better titanium composition in prospect, a complex Beta-Titanium alloy (Ti-13V-11Cr-3Al). Here the fall off in strength was minimal, hence, it could be used in the Mach SR71 Blackbird, capable of Mach 3.3. However, the alloy required a huge amount of development, R&D funding coming from a near unlimited defence budget.

The SR71

Fred Starr : 8th August 2020

I would like to thank Dr Bryan Lawton of the Western Branch of the Newcomen Society for some useful and enjoyable discussions about this piece, which helped unearth quite a few things that are normally taken for granted by Concorde enthusiasts.

Any views expressed here are my own, of course.

References:

Some Supersonic Aerodynamics 10 Virginia Tech / Configuration Aerodynamics Class: WH Mason

www.dept.aoe.vt.edu

Aircraft Performance: W Austyn Mair and David L Birdsall: Cambridge Aerospace Series 5, Cambridge University Press 1992

Jet Propulsion: Nicholas Cumpsty: Cambridge Engine Technology Series 2 : Press Syndicate of the University of Cambridge 1999

Creep Resistant Aluminium Alloys and Their Applications: JS Robinson, RL Cudd and JT Evans : Materials Science and Technology, Feb 2003, Vol 19 pp 143-156