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SUPERSONIC BUSINESS JET TECHNOLOGY & MISSION TRADE STUDIES

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Abstract

The effect of the aerodynamic, propulsive and structural efficiencies and specific mission requirements on the performance of a notional supersonic business jet is studied and presented in the form of carpet plots for design. The trade studies are limited to what are considered practical values.

1 Introduction

Significant resources have been invested into the solution of the problems associated with supersonic flight, in particular, for business jets [2]. An area that has recently attracted considerable attention is that of the minimization of sonic booms [1]. For many it constitutes the fundamental obstacle in the realization of a commercially viable supersonic transport because current regulations prohibit flight at speeds greater than Mach 1 in the US airspace [6], and there are similar limitations in other countries. This restriction imposes drastic performance penalties, to the point of making it uneconomical to operate. Hence, if the sonic boom could be reduced to "acceptable" levels, the regulations could be modified, ushering a new era of high speed flight.

Significant progress has been made in this area [1]. There is now a good understanding of sonic booms, how they propagate and interact with the atmosphere, and the theoretical background has been laid down for their minimization, something already successfully proven by flight tests [1]. Because of this, the emphasis on supersonic research has been placed on producing aircraft shapes optimized for sonic boom mitigation. However, all these advances should not detract from the attention given to the important parameters governing aircraft performance if a technically and *economically* viable aircraft is to be achieved. These considerations are fundamental because, in many instances, the low sonic boom design requirements can drive the concept away from efficient performance objectives. For example, in an aircraft solely optimized for low sonic boom, the aerodynamic efficiency, the structural weight and the specific fuel consumption may all be negatively affected to a degree that it could no longer meet its operational requirements.

In this paper, a notional supersonic business jet is sized and used to conduct trade of the main parameters driving the performance such as the mission range, sfc, *L/D*, etc. The values obtained are then compared to the current state of the art.

2 Mission requirements

Current corporate jets have cruise speeds around Mach 0.85 with maximum operating speeds of Mach 0.925. Supersonic speeds would only be beneficial in long distance flights because air traffic control would limit climb and descent to subsonic values and, for short ranges, these segments constitute a larger proportion of the entire mission. Furthermore, time savings at higher speeds only start to be significant for longer distances.

Figure 1 shows the great circle ranges from New York. It can be seen that 3,000 NM is marginally sufficient to connect important city pairs. Therefore, in this study, a range of 4,500 NM will be used as a baseline and trade studies will be conducted around that mission length.

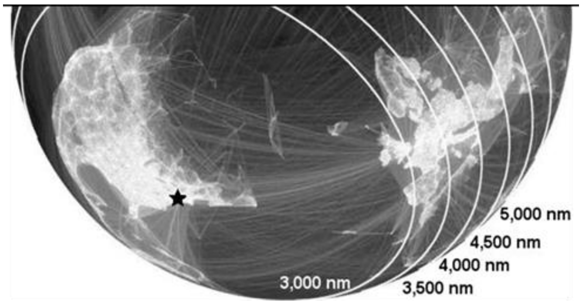

Figure 1. Ranges from New York. Inspection of the map suggests a target range of 4,500 NM for a supersonic business jet (SSBJ).

Cruising at 45,000 ft at Mach 0.85, 4,500 NM takes approximately 9.2 hours. At Mach 2 only 3.9 hr, representing a time reduction of almost 60%. The relative gain between Mach 2 and Mach 1.8 is comparatively small. Therefore, the baseline cruise speed chosen for the present study is Mach 1.8, which saves almost 5 hr (53%) time with respect to Mach 0.85 flight without the aerodynamic heating problems encountered at Mach 2.

For this paper, a typical aircraft capacity of 8 passengers (assumed to weigh 225 lb each), with a two pilot crew and one flight attendant are assumed. The cabin volume used is given by a 74 in. cylindrical cabin, 33 ft long. A cylinder 11 ft long with the same diameter as the cabin is used for the cockpit. These dimensions give typical values for normal comfort standards used by the industry.

An initial 100,000 lb maximum takeoff weight (MTOW) target was selected because the MTOW has a significant influence on many of the performance parameters and also on some other important economic aspects such as landing fees, airport compatibility, noise or emissions criteria and regulations, etc.

3 Preliminary aircraft sizing

A notional SSBJ is sized in this section for the preliminary trades that will follow.

3.1 Determination of MTOW

An initial value for the MTOW is derived from the summation of the fixed weight (here passenger load plus crew), the empty weight and the mission fuel. The latter is calculated using Breguet's range equation for the typical NBAA mission. The empty weight is estimated using historical-statistical data [9].

Figure 2 shows some trends for L/D_{max} for different types of aircraft. It is noticeable the great difference between subsonic and supersonic flight, with significantly lower values for the latter. Furthermore, it is important to note that these maxima and normal flight operations will typically occur at lower *L/D* and that any geometrical modification for sonic boom mitigation can only adversely affect the *L/D*. This point will be explored later.

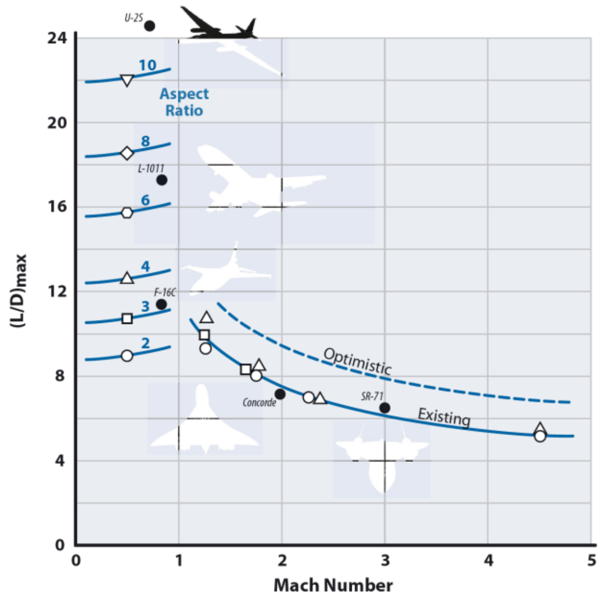

Figure 2. L/D_{max} vs Mach number for typical cruise aircraft [9].

In a similar fashion, generic data for appropriate engines for this type of application are presented on **Error! Reference source not found.**. The sfc presented is for static sea level (SLS) conditions and, at cruise, those values are expected to be higher. Furthermore, the table contains military aircraft engines that are not designed to comply with the civilian noise regulations, something that would have a negative impact on the sfc.

For the estimation of the empty weight, Nicolai [9] has collated data for a large number of aircraft, and has proposed an equation that relates it to MTOW. **Error! Reference source not found.** superimposes over Nicolai's correlation the weights of Concorde, Tupolev Tu-144, Boeing's and Lockheed--Martin's studies for the NASA N+2 and N+3 programs, B-

1B and the European HISAC project (concept studies for supersonic business jets).

Company	Engine	Application	Thrust (Dry) (SLS-lb)	TSFC (Dry) (lb/hr/lb)
GE	F101-102	B-1B	18,473	0.56
	F110-129	F-16	17,595	0.67
	F414-400	F/A-18E/F	14,447	0.82
PW	F100-100	F-15A-D	14,100	0.7
	F100-200	F-16A-D	14,100	0.7

Table 1. Data for selected engines

A new correlation is proposed to more faithfully reflect improvements in structural efficiency, apparent on the HISAC, LM's and Boeing's models, together with the only two data points on the graph that correspond to aircraft that were actually built (Concorde and B-1B). The new correlation proposed here is

$$W_e = 1.6588 \cdot W_0^{0.8939}$$

and is plotted in Fig. 3, showing good agreement with reported data. However, this is still a curve fitting metallic structures. For this reason, here, a technology factor representing a 16% decrease in empty weight to account for the possible use of composites is used.

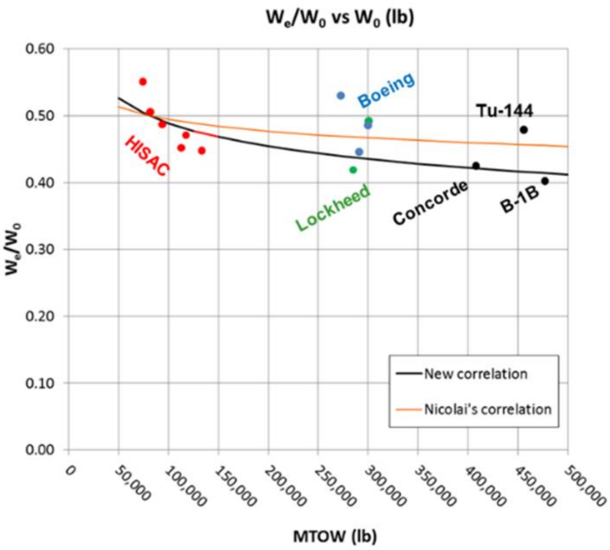

Figure 3. Empty weight fraction vs MTOW with data from Refs. [10 - 12].

Using these preliminary parameters and following standard design methods [9], carpet plots, showing the influence of *L/D* and sfc on the empty weights and, ultimately, on the MTOW, were generated. Every point corresponds to a sized aircraft for a given combination of sfc and *L/D* for the 4,500 NM mission with the specified payload and cruising at Mach 1.8.

Figure 4 shows that if, for example, the *L/D* were 5.6 and the sfc 1.0, not particularly pessimistic values, the MTOW would be a staggering 269,300 lb. Even if this were technically feasible, such weight would be unreasonable for an eight passenger aircraft. Furthermore, such an aircraft would need to carry 167,325 lb of fuel. To put this in perspective, with a cylindrical fuselage fuel tank 6 ft in diameter, that tank would need to be 100 ft long.

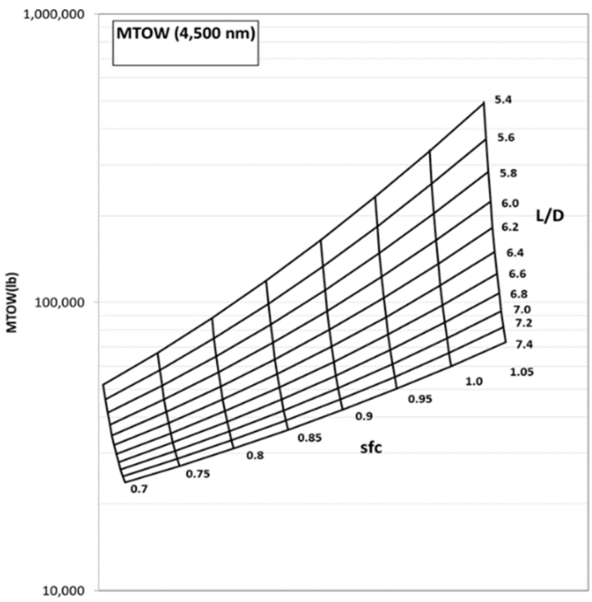

Figure 4. Sized MTOW for given sfc and *L/D* for cruise at Mach 1.8 carrying 8 passengers.

3.2 Mission range trade studies

The effect of the mission length on the MTOW is presented on Fig. 5. The 100,000 lb upper bound is included for convenience. Clearly a shorter range is easier to achieve. Longer missions require higher fuel fractions, e.g., for a 4,500 NM mission with an *L/D* of 5.4 and an sfc of 1.05 the fuel fraction reaches 65%, whereas for the same conditions, but for 3,000 NM, it drops to 58%. This outcome correlates with previous studies regarding the optimum range for

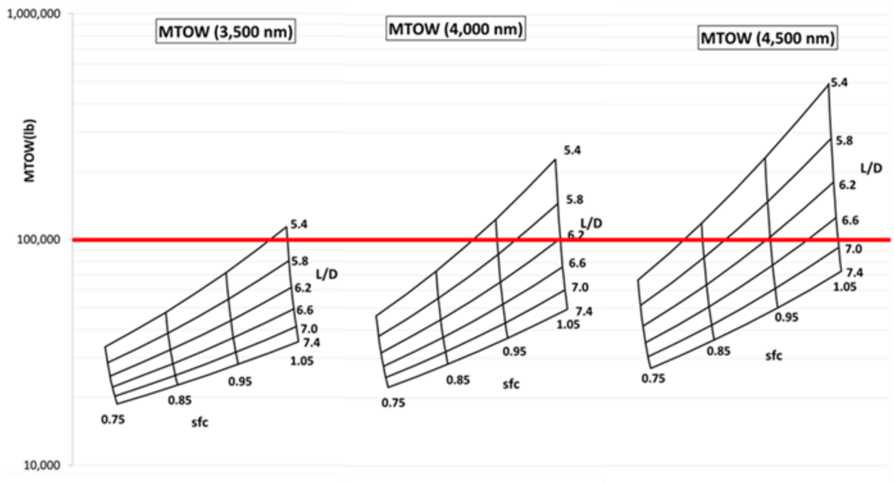

Figure 5. Variation of MTOW with L/D and sfc for aircraft with ranges of 3,500, 4,000 and 4,500 nmi.

commercial aircraft, where the optimum flight distance, within the parameters of that study, was 3,500 NM [13]. Unfortunately, limiting the range of this aircraft would potentially erode most of its commercial attractiveness. Figure 5 presents the minimum performance conditions for a practical SSBJ, i.e., for MTOWs below 100,000 lb. That information is highlighted in Fig. 6.

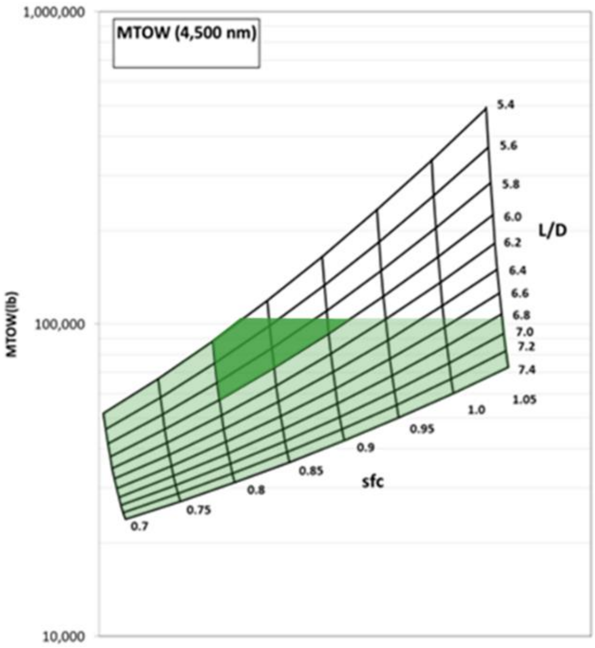

Figure 6. Combinations of sfc and L/D necessary for 4,500 NM mission. Highlighted are the values considered "practical" at the moment.

If the mission cannot be shortened and the Mach 1.8 is maintained and, since suitable engines have sfc's around unity, only aircraft with very high aerodynamic efficiency become feasible. However, currently, for supersonic flight, *L/D* values above 7 can be considered high and difficult to achieve. Figure 6 indicates that for *L/D*'s lower than 6, the sfc cannot exceed 0.9. But noise constraints tend to push sfc values up. Furthermore, low sonic boom flight may require low C_L's, away from the maximum in the *L/D* curve.

With these preliminary calculations it is possible now to present some sensitivities (Fig. 7). It should be obvious that the high gradients at the lower *L/D* and higher sfc values on the graph should be understood more as regions of non-convergence of the calculations (i.e., a non-solution) than as actual sized configurations.

This chart can be used as a first guide in the selection of the design parameters and, consequently, it identifies where the emphasis should be placed for technology development.

Likewise, the sensitivities can be explored as a function of mission distance. The information in Fig. 7 supports the argument that a 4,500 NM mission may be pushing the technology to its present limits. Thus, it should not come as a surprise that the range of Concorde was less than 4,000 NM.

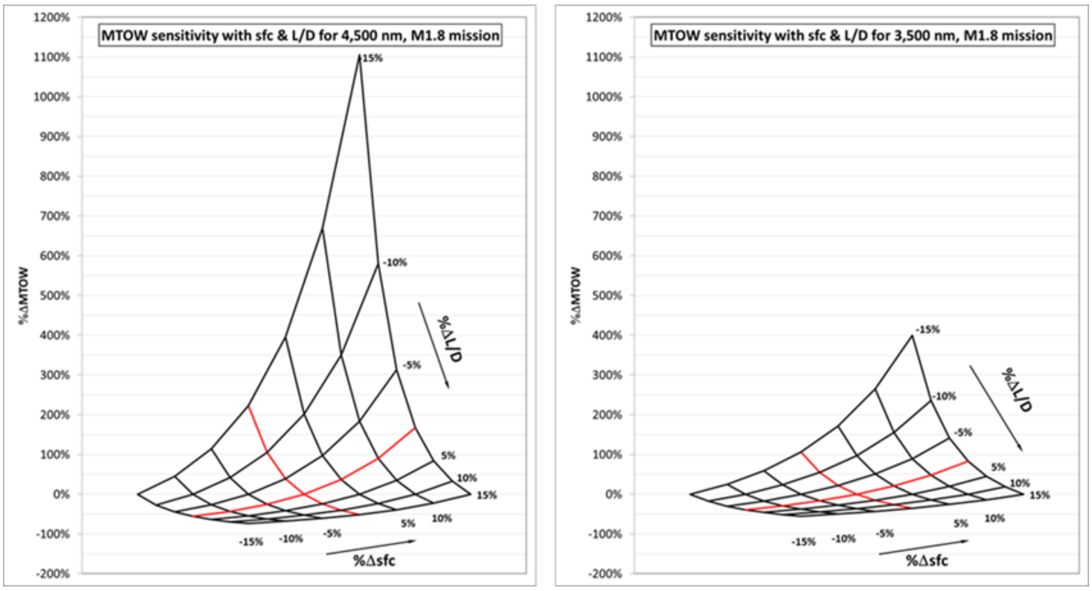

Figure 7. MTOW sensitivity to sfc and *L/D* for 4,500 and 3,500 NM, Mach 1.8 mission. Baseline values are 1 and 6 for sfc and *L/D*, respectively.

3.3 Detailed trade studies around a generic SSBJ

For the following trade studies, a generic SSBJ was sized with the following design parameters: *L/D* of 5.6, sfc of 0.9 lb/hr/lb, which result in an aircraft with a MTOW of 96,550 lb, 39,800 lb empty weight and a fuel weight fraction of 56%.

The aerodynamic data for this aircraft was generated in the following manner:

1. For simplicity a generic NACA 66-206 airfoil was assumed.
2. $C_{L\alpha}$ and the induced drag were calculated using a commercial vortex lattice method (VLM) program, which includes corrections for compressibility and maximum leading edge suction attainable that correlates well with experiment.
3. The zero-lift drag, C_{D0}, was calculated using the component build up method in [9] for both the subsonic and the supersonic cases. However, for the latter, the drag values obtained were considered to be unrealistically pessimistic and, therefore, a target value of 0.0200 was adopted.
4. Because of the low aspect ratio and the high sweep angle, the linear C_L vs. α curves at low speed were corrected to account for vortex lift, following the method in [9].
5. The zero-lift drag in the transonic region was modelled with a hyperbolic tangent function.

The resulting drag polars are given in Figs. 8 and 9, and the difficulty in achieving high *L/D's* at supersonic speeds is evident; also the case for real aircraft data reported in [9].

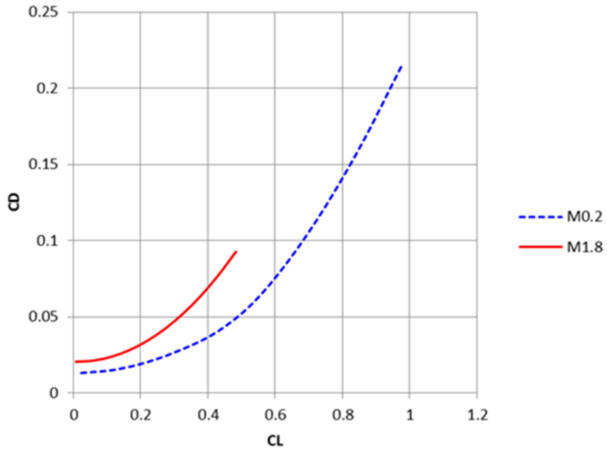

Figure 8. Calculated drag polars for the configuration as sized for Mach 0.2 and Mach 1.8.

3.4 Detailed mission analysis & sizing

In the preceding sections the calculations were performed with simplified handbook methods where some flight segments, such as climb or the transonic acceleration, were approximated using fuel fraction ratios from the literature and from historical data. Furthermore, the *L/D* was assumed constant for the entire mission and independent of the flight speed.

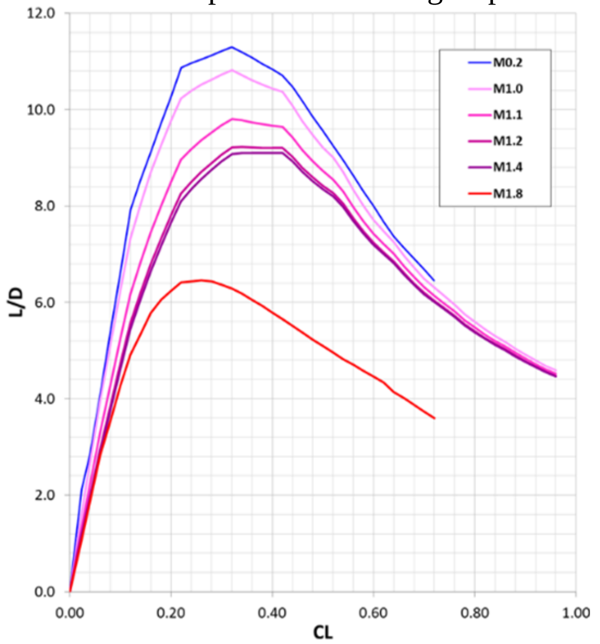

Figure 9. ***L/D*** **curves for different Mach numbers. Note that, for the aircraft in this study,** $\boldsymbol{L/D_{max}}$ **is less than 7.**

Now, the entire mission is calculated by solving the force equilibrium equations, i.e., $L=W$ and $T=D$, at discrete time intervals, using the drag polars derived in the last subsection. A constant value of 0.9 lb/hr/lb for sfc was assumed. The flight profile is based on the NBAA mission, with the following schedule:

- Takeoff and climb at constant 300 kt (EAS) up to crossover altitude for Mach 0.95.
- From 35,500 ft up to the initial cruise altitude of 45,000 ft, climb at a constant Mach 0.95.
- Level acceleration to Mach 1.8 at 45,000 ft, after which the aircraft is allowed to cruise-climb.
- Loiter for 5 min. at 5,000 ft, 250 kt (EAS).
- Cruise to alternate airport at 200 NM at Mach 0.95.
- Finally, loiter at 5,000 ft, 250 kt (EAS) for 30 min.

The results are presented in Fig. 10.

Lacking explicit data for the engine, the model assumed here was that of a turbojet whose thrust is directly proportional to the atmospheric density ratio, i.e.,

$$T_{avail} = T_{max@SL}\frac{\rho}{\rho_{SL}}$$

These mission calculations were ran iteratively to resize the aircraft. With this more refined approach the aircraft weights were updated and are given in Table 2.

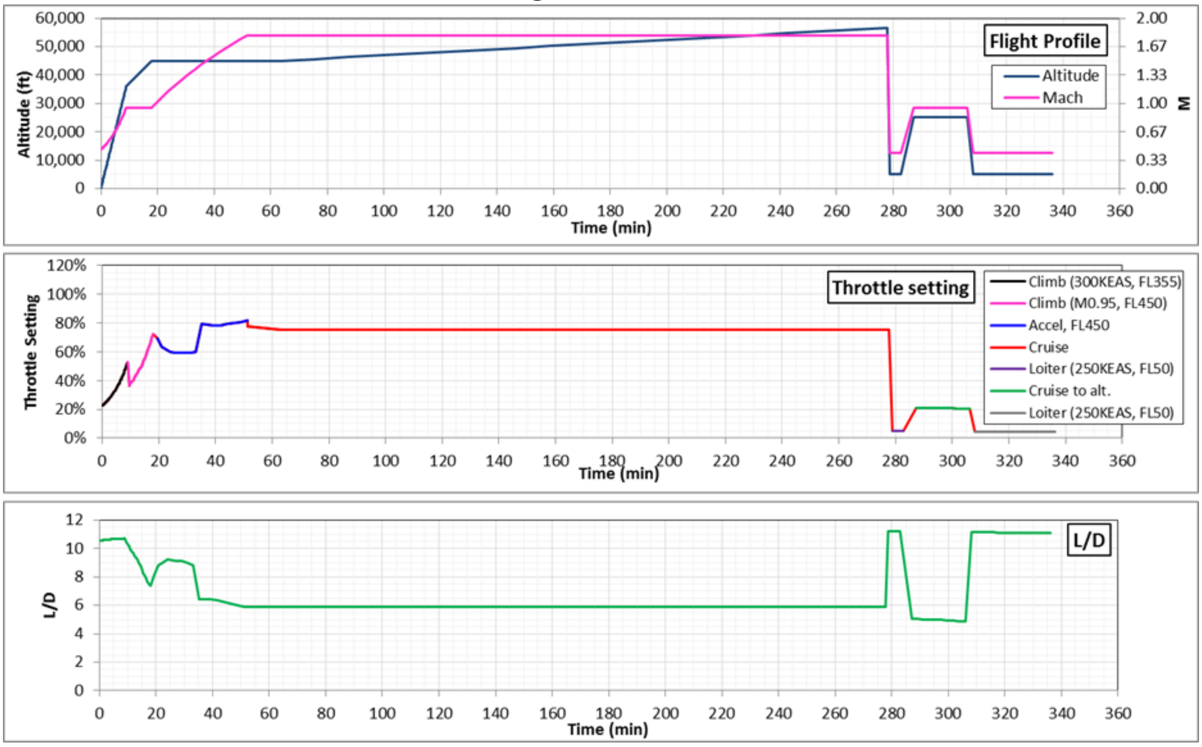

Figure 10. Detailed mission calculation for 4,500 NM at Mach 1.8. (a) shows the altitude and speed, (b) required thrust and (c) flight ***L/D*****.**

Table 2. Design weights resulting from detailed calculation.

MTOW	97,995	lb	
Empty Weight	40,340	lb	41.2%
Fixed Weight	2,400	lb	2.4%
Fuel	55,260	lb	56.4%

Figure 10 plots the "required" thrust (throttle setting) as a percentage of the "available" thrust, calculated for every flight segment with the following constraints:

- The maximum rate of climb was limited to 4,000 ft/min for the initial climb segment.
- This was relaxed to 1,000 ft/min for the climb at Mach 0.95.
- The transonic acceleration was performed with a specific excess power (P_S) of 1,000 ft/min.

Climbing at a constant Mach 0.95 produces the "spike" in thrust at top of climb because the dynamic pressure decreases monotonically, requiring higher C_L's, i.e., non-optimal L/D's. Better results could be obtained using the state energy climb and acceleration optimization but it is unlikely that air traffic control would allow it because of the difficulty in coordinating them with other airspace users.

3.5 Flight Profile Trades

The results presented in the previous section were for 4,000 ft/min rate of climb for the constant EAS segment, 1,000 ft/min for the constant Mach segment and 1,000 ft/min for the acceleration. Those values are now compared to two other cases:

1. all the above segments are all at 1,000 ft/min
2. all at 4,000 ft/min.

Comparison of the results in Figs. 11 and 12 reveals that, with the lower P_S, the time to climb is doubled and the time to reach Mach 1.8 is increased by 30 min; problematic for fitting with other air traffic. Block time is increased by 15 min.

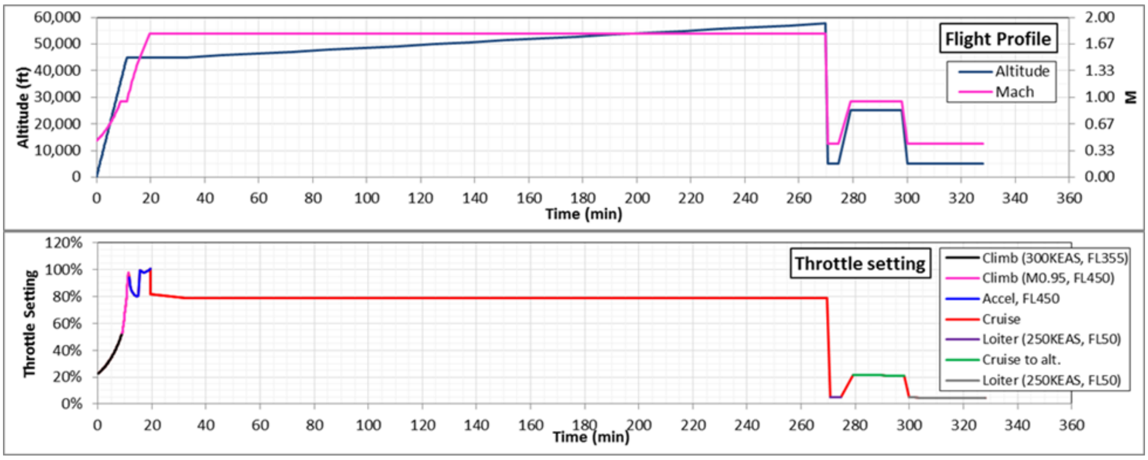

Figure 12. Flight profile and required thrust for the case when the rate of climb and P_S are 4,000 ft/min.

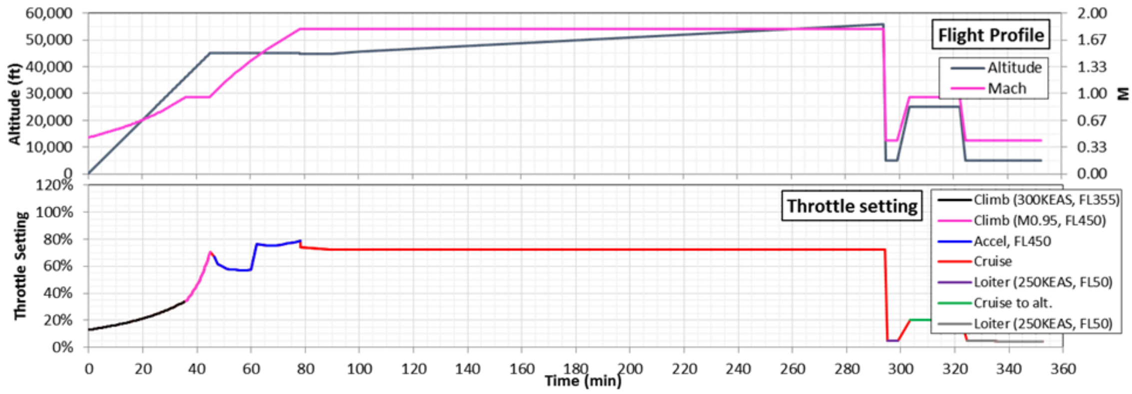

Figure 12. Flight profile and required thrust for the case when the rate of climb and P_S are 1,000 ft/min.

The situation is reversed for the 4,000 ft/min case; the block time is reduced by 10 min and the cruise altitude is reached in only 10 min, promptly leaving below any other traffic. However, the most significant change is in the thrust required. Whereas for the previous two cases the maximum was around the 80% mark, in this case it jumps to 100% during the transonic acceleration.

The change in P_S also has a significant effect on the aircraft weight and fuel burned, as shown in Table **3**. The lowest values occur for the highest P_S. However, it has already been stated the detrimental effects in terms of engine size. The compromise solution appears acceptable but clearly this problem would benefit from a full-fledged optimization.

Table 3. MTOW and fuel burn for different rate of climb and excess power for acceleration

ROC/P_S (ft/min)	MTOW (lb)	%	Fuel Burn (lb)	%Δ Fuel Burn
1,000/1,000/1,000	102,891	5.0	58,357	5.6
4,000/1,000/1,000	97,994	-	55,257	-
4,000/4,000/4,000	94,430	-3.6	53,007	-4.1

3.6 Range Trades

Using the flight profile (4,000/1,000/1,000 ft/min) described above, a trade study on the mission length was conducted; i.e., the aircraft was sized for 3,500 and 4,000 NM ranges. Results are summarized in Table 4

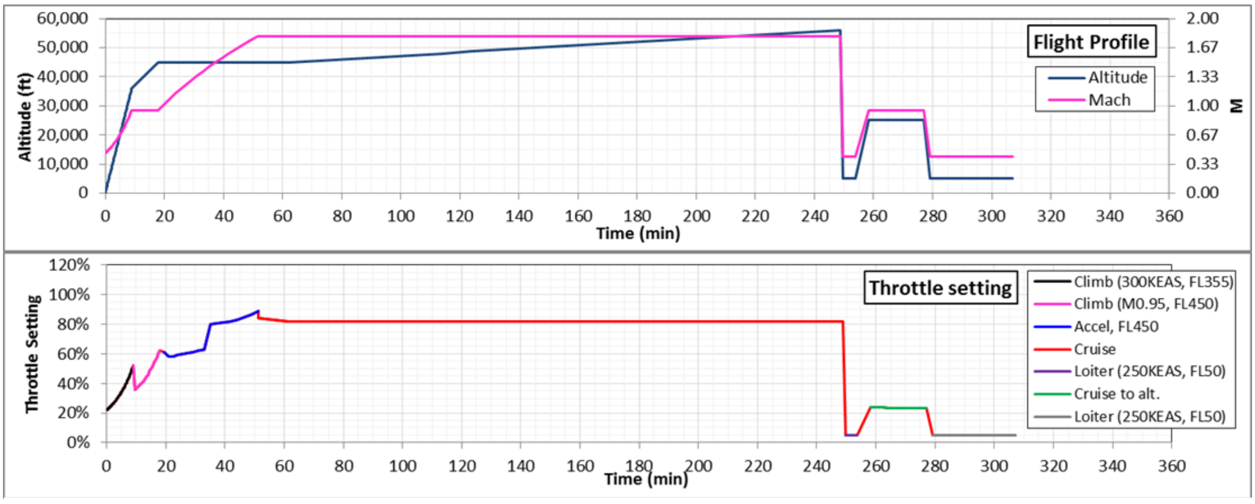

Figure 14. Flight profile and thrust requirement for an aircraft with 4,000 NM range.

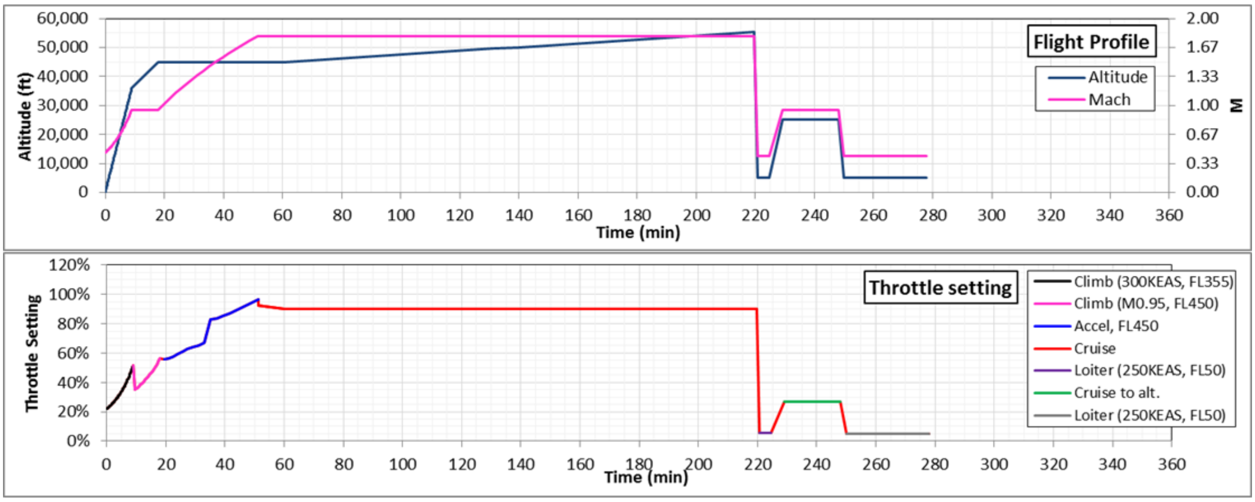

Figure 14. Flight profile and thrust requirement for an aircraft with 3,500 NM range.

Table 4. MTOW and fuel burn variation with range.

Range (NM)	MTOW (lb)	Fuel Burn (lb)	Specific Fuel Burn (NM/gal)
3,500	71,100	38,420	0.61
4,000	83,230	45,970	0.58
4,500	97,994	55,257	0.55

Mission length has a significant impact on the aircraft fuel efficiency. The 3,500 NM mission has 12% better fuel mileage than the nominal 4,500 NM one. The main reason for that is the "snowball" effect on the weight; a shorter range aircraft requires less fuel and, therefore, less structure to carry that fuel, which in turns reduces the fuel needed and, if the aircraft is lighter, then the wings and the engines can be smaller and, consequently, lighter and so on. For this case, the 3,500 NM aircraft has an MTOW almost 30% lower than that of the 4,500 NM counterpart. However, it should not be forgotten that a long range may be critical for this aircraft business case.

4 Implications of Low Boom Configuration

Everything that has been discussed so far are basic principles of aircraft design and performance, without inclusion of any constraints inherent to a low sonic boom aircraft. Quieting the sonic boom requires some configuration and operational features that adversely impact the performance described above. In particular, low sonic boom favors longer fuselages, with smooth cross-sectional variations, or the addition of volume, such as in the lower part of the nose of the NASA/DARPA F-5. All this translates into greater wetted areas and, consequently, higher zero-lift drag.

Furthermore, the strength of the shock waves is directly related to the aircraft weight, i.e., to its lift, hence an interest in keeping low C_L values, which necessarily implies not flying at L/D_{max} which are already low for supersonic conditions and, therefore, the fuel burn would be adversely affected.

Thus, for example, if the airplane sized in the preceding sections were designed with all these constraints, i.e., cruise *L/D* of 4, sfc of 1 lb/hr/lb, MTOW limited to 100,000 lb, the original range of 4,500 NM would not be achieved and, instead, it would be reduced to 2,500 NM

5 Conclusion

The trade studies in this paper showed the interrelations between *L/D*, sfc, structural weight and mission range and their sensitivities. The general conclusions are,

1. Simple (i.e., without sonic boom mitigation), long range, sustained supersonic flight remains a tremendous technological challenge. Specifically, a business jet with a 4,500 NM range, carrying eight passengers, at Mach 1.8 and with an MTOW of less than 100,000 lb is possible with current technology. However, when that aircraft is redesigned to provide *boomless* supersonic flight, the range drops to 2,500 NM. If the mission and payload are not to be decreased, important efforts would be needed to increase the cruise *L/D* and to reduce the sfc.
2. The aircraft performance is highly sensitive to mission length. If the mission range is reduced to 3,500 NM, the fuel mileage is increased by 12% and the MTOW is reduced by 30%.
3. The aircraft requires high *L/D* 's *and* low sfc. However, sonic boom mitigation, may force the cruise *L/D* values to remain low. Therefore, a higher emphasis efforts should be placed into developing engines capable of long distance, sustained, supersonic flight with lower sfc, something particularly challenging if, at the same time, the engine is required to comply with the applicable ICAO regulations regarding noise.
4. Improvements in structural efficiency should be aggressively pursued because, given the "snowballing effect" of empty weight, savings in this regard significantly translate into benefits in all the other areas.

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