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Article

Airworthiness and Conceptual Design Optimization Considerations of the Environmental Impact Assessment of a Supersonic Business Jet Aircraft

Ilias Lappas [1,*,+] , Nikolaos Pergamalis [2,+]

[1] Department of Mechanical and Aeronautical Engineering, School of Engineering, University of South Wales, Treforest Campus, Treforest CF37 1DL, UK
[2] State Aircraft Depot, Hellenic Air Force, Elefsis Air Force Base 19200, Elefsis, Greece; nikolaos.pergamalis@haf.gr
* Correspondence: ilias.lappas@southwales.ac.uk; Tel.: +44-01443-482565
† These authors contributed equally to this work.

Abstract: In recent years, the anticipation of sustainable commercial supersonic jet operations has elevated again. Advances in propulsion together with the increased usage of composite materials favour the potential of sustained and cost efficient supersonic commercial operations. However, obstacles remain with regards to the certification of the new supersonic aircraft platforms, while the two main certification bodies EASA and FAA are under pressure to develop certification requirements which will reassure that the supersonic operations are going to have the least possible environmental impact. From a design perspective, past and current research suggests that a trade-off exists between the aircraft performance and the environmental impact, which should be balanced. The current study attempts to balance this trade-off and to conceptually design a SuperSonic Business Jet (SSBJ) by taking into account environmental concerns of the supersonic flight together with design methods that facilitate a sustained supersonic cruise. An environmental impact assessment is undertaken for the SSBJ design and its results are compared to a typical commercial subsonic airliner.

Keywords: supersonic business jet; SSBJ; environmental impact assessment; supersonic flight; airworthiness; aircraft certification; airworthiness.

Acronyms

AR	Aspect Ratio
CFD	Computational Fluid Dynamics
FAA	Federal Aviation Administration
HSR	High Speed Research
ISA	International Standard Atmosphere
MAC	Mean Aerodynamic Chord
MTOW	Maximum Take Off Weight

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MZFW	Maximum Zero Fuel Weight
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
QueSST	Quiet Supersonic Technology
SSBJ	Super Sonic Business Jet

1. Introduction

The prospect for sustained commercial supersonic operations has reached new heights lately. Advances in propulsion and the increasing use of composite materials favour even more the success of the supersonic flight . NASA has already launched research efforts for a low-boom supersonic passenger aircraft under the project Quiet Supersonic Technology (QueSST) . Moreover, the start-up company Boom Technology Inc. has been working on developing a supersonic passenger aircraft, which will fly at a speed of 2.2 Mach, carrying up to 45 passengers [1].

The economic feasibility will be vital for the success of any future supersonic design, but at the same time the environmental concerns of the supersonic flight are significant factors as well and they should be thoroughly anticipated. The overland flight ban due to the sonic boom and the related emissions are major concerns that affect the certification and the desired mission requirements of a particular aircraft design. At the present study, the process of a supersonic passenger aircraft conceptual design is outlined, based on inputs from the current and future market forecast. The conceptual design process and its validation are demonstrated and an environment impact assessment of the design is undertaken.

The ability to fly supersonically for non-military purposes has always been a very challenging endeavour. Following the retirement of Concorde in 2003, the supersonic non-military transportation capability has been halted. It is certain that the technology necessary to design and manufacture a modern supersonic passenger aircraft exists, the financial sustainment though of the concept is still considered a very challenging task [2]. As such, a fast paced turn of the civil transportation to supersonic operations seems to be a very low probability event for at least the next ten to twenty years. At the same time the demand for long-haul flights is anticipated to increase during the upcoming years. Airbus [3] expects a 95% increase of the long-haul operations from 2016 to 2035. This sets rather optimistic expectations for the potential of the commercial supersonic operations, having the competitive advantage of significantly reducing the flight time. Small supersonic passenger aircraft with low development and expenditure risks which will be able to carry from 15 to 25 passengers could facilitate the financial viability of the project, while achieving a promising market share [4]. Potential customers could be government agencies, big corporations and individuals who can already afford the costs of operating business jets. With regards to the overland ban, long-haul overseas route networks can be designed and this mitigates the restrictions of an extreme low-boom design.

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Having reviewed additional studies [5, 6, 7, 8, 9], there is a consensus that the most feasible supersonic passenger aircraft design, considering primarily the economical and not the technical aspects, should be the production of a small supersonic business jet design (SuperSonic Business Jet-SSBJ from now on), that could transport 15 passengers and achieve a range of about 7200 km. A small size supersonic aircraft is considered to be an attractive choice for frequent business travellers and for a significant share of business jet users, which together make a potential 10% market share [10]. The SSBJ will cruise at 1.7 Mach, which is about double of the typical cruise speed of a subsonic passenger jet. Although a higher speed would have been more enticing for the clients, the choice of a moderate supersonic Mach number would have resulted in an aircraft with reduced weight, having a positive effect in fuel burn and noise generation [11]. In general, a combination of lower speeds and cruise altitudes facilitates the mitigation of aviation related global warming [12]. Several studies [12, 13, 14, 15] have attempted to assess the aviation climate impact and how this might influence the aircraft design criteria of typical generic or existing subsonic airliners and the novelty of the present study is that it attempts to perform an environmental assessment comparison and to look at aircraft design criteria implications of a particular SSBJ design.

2. Methodology

The environmental concerns of the supersonic flight together with design methods that facilitate a sustained supersonic cruise are introduced at the following paragraphs. Based on those concerns and design methods, the conceptual design of the SSBJ is going to be undertaken, resulting in a model which will be used to estimate its potential environmental impact.

2.1. Sonic boom

One of the most significant environmental concerns of the SSBJ design is the aerodynamic noise produced by the shock waves [16]. NASA has been conducting research in this subject to create a low boom design. The early sonic boom research has focused to modified linear methods, based on Whitham's approach [17], [18]. The linear theory assumes that the pressure signatures reaching the ground are N-waves, which are typical for aircraft with high W/S. However, more recent research efforts have shown that generation of non-N-waves on the ground was possible [19]. Some important issues have been associated with the linear methods, which made necessary the development of more robust methods and their flight test validation. As a result, the recent efforts have focused on aircraft design concepts that would result in non-N-waveforms at the ground, instead of attempting to mitigate the noise of the N-waves.

Haglund [20] has examined several concepts based on a reference design. The delta baseline wing has been modified to a wing arrow design with similar aerodynamic efficiency. One of the findings was that a bigger wing is beneficial since the lower value of W/S results in reduced pressure levels to sonic boom for the lift contribution. However, this sonic boom loudness reduction will materialize with an associated 12% increase of the Maximum Take Off Weight (MTOW) per passenger. As such, it became evident that the low boom design is associated with a performance penalty. In addition, the high value of the wing sweep, together with a low value for the Aspect Ratio (AR), deteriorates the low speed performance of the aircraft. All the previous observations suggest that there exists a trade-off between the aircraft performance and the sonic boom loudness, which should be balanced [21].

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Moreover, designing for low boom usually contributes to the increase of the wave drag . One of the design features for sonic boom minimization is the blunt nose, which creates a strong detached shock, so that the secondary shocks are weak and do not overtake and enhance the front shock. This way, the produced far field pressure becomes much weaker in comparison to the case of a sharp nose, in which the front detached shock wave coalesces with the stronger secondary shock waves [22]. Hence, the shape of the nose is a trade-off between the loudness of the sonic boom and the magnitude of the wave drag.

Research on low boom concepts for aircraft designs with high payload has shown that it was very challenging to achieve theoretical ground overpressure substantially less than 1 psf [23]. As a consequence, a less heavy and smaller design would be a more suitable candidate to decrease the loudness of the sonic boom . A less heavy platform will demand less lift to sustain a steady and level flight, which is amongst the factors which decrease the intensity of the sonic boom [24]. For shaped pressure signatures, work of Shepherd and Sullivan [25] provides a method to achieve the appropriate level of noise loudness.

The wing shape and area are significant factors to achieve a reduced sonic boom. For a small SSBJ aircraft, a low value for W/S is desired and thus a large wing planform. It is of paramount importance that the wing has a long wing root, which will facilitate the gradual development of the wing area and the lift. At the same time, the span should be kept at an appropriate value to offer acceptable performance for the low-speed segments of the flight. Typically, the wing planform in a low boom design should be placed well aft so that its interference with the aircraft nose shock wave is minimized. By placing the wing so much aft the designer should then be facing a lot of challenges with respect to the stability of the aircraft. The position of the center of gravity of the fuel inside the wing can be at a relatively long distance from the position of the center of gravity of the fuel empty aircraft, which can affect the longitudinal stability characteristics of the aircraft [26]. It is crucial then that as much fuel quantity as possible should be placed in the front portion of the wing, if its increased size and volume, can offer this option. Finally, this will place a constraint on how much thin airfoils should be used to achieve the desired volume for the fuel , which would in turn affect the overall drag.

One of the disadvantages of the SSBJ design is its low fineness ratio, due to the fact that the length of the body is smaller, but the maximum diameter cannot be decreased too much since it will still need to be able to house the passengers and the aircraft systems. This will impose a significant wave drag penalty on the aircraft design. Moreover, the optimal positioning of the propulsion system would be the area behind the wing trailing edge [23]. This wing-nacelle interaction would be avoided and the flow field disturbances of the nacelles would correspond just to the volume and not to the lift contribution effects.

2.2. Enviromental concerns of the supersonic flight

The climate change and the ozone layer depletion are amongst the most important environmental effects of the aviation industry. The two more distinctive operational differences between supersonic and subsonic cruise flight are the higher fuel consumption, which leads to increased combustion products, and the higher cruise altitude of the supersonic aircraft.

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The climate change, which is usually referred in the literature as enhanced greenhouse effect or global warming, is a very significant environmental concern. The uniqueness of the aircraft operations is the emission of pollutants into the higher levels of the atmosphere. The involved gases, which contribute to the greenhouse effect, are the carbon dioxide, the nitrogen oxides and the water vapor. Heat is trapped inside the atmosphere as a consequence of the greenhouse effect and as such, the temperature of the earth increases. By looking at the historical data, the global average earth surface temperature has increased during the 20th century, and a further increase of at least 1.8 ^{0}C is expected for the next century [27]. Other side effects of the global warming on the planet are the appearance of heavier rainfall, floods, tornadoes, thunderstorms. Oceans are also possible to expand, the ice on the poles to melt and the surface of the sea level to rise .

For the time being, the contribution of the aviation industry emissions can be considered as being only a small share of the overall greenhouse gases emissions, but the continuous growth of the industry and subsequently of the air traffic, indicate that the aviation emissions can become a serious parameter of the climate change. European Environmental Agency studies [28] state that the emissions of CO_2 have increased about 80 % between 1990 and 2014 and they will further grow 45 % between 2014 and 2035. No certification requirements exist nowadays with respect to the greenhouse gases for the aircraft engines. If the current trend of the aviation emissions continues, then their influence on the enhanced greenhouse effect should become more critical.

The most problematic emission for the greenhouse effect is considered to be the CO_2, which, among other implications, has also a long life cycle. For the commercial supersonic operations, the H_2O can also be considered an important emission due to the higher operational ceiling of the supersonic passenger aircraft. When operating at such high altitudes in which the temperature is very low, the produced water vapor is converted into persistent contrails, which take long time to evaporate. These contrails are typically very long and form the so-called cirrus cloud fields, which can potentially affect the climate change. The water is produced as a fixed ratio to fuel during the combustion process of the kerosene, like in the case of the CO_2 . In average, the combustion of 1 Kg kerosene produces 3.16 Kg CO_2 and 1.24 Kg H_2O [29].

2.3. Conceptual design of the SSBJ aircraft model.

Having discussed the environmental concerns of the supersonic flight and some of the design methods which facilitate a sustained supersonic cruise, the present section will look at the conceptual design of a commercial solution for a SSBJ model. The aircraft model parameters will be used at the next section to estimate its potential environmental impact.

2.3.1 Initial sizing

The desired requirements for the SSBJ of the study are presented at the Table 1.

Table 1. Summary of the desired SSBJ requirements.

Parameter (unit)	Value
Cruise speed Mach number	1.7
Minimum payload mass (Kg)	1900
Cruise altitude (ft)	49000
Range (Km)	7200

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Loiter time (min)	20
Landing distance (m)	3500
Take off distance at ISA, Sea level (m)	3500
Thrust specific fuel consumption at cruise condition (g/KNs)	26.9
AR	3.2

The payload corresponds to the weight of the pilot and the co-pilot, two crew members and a total of fifteen passengers. A mass of 100 kg is allocated to each person on-board, including the mass of the baggages. A low AR value of 3.2 has been selected for the design, since a long wing would have resulted in a larger contribution of the wave drag component. The weight fractions and the maximum lift-to-drag ratio for the most efficient cruise condition have been calculated assuming the typical mission profile for a passenger aircraft design (Taxi, Warm Up → Take off → Climb → Cruise → Loiter → Descend → Landing and Taxi).

Mariens [30] and Roskam [31] methodologies have been used for the estimation of the fuel required for the baseline mission profile. Those methodologies use the classic Breguet performance theory combined with statistical factors which estimate the fuel weight of each segment of the mission. Table 2 shows the values of the fuel fractions for each segment of a typical mission.

Table 2. Fuel fraction for each segment of a typical flight mission [31] .

Fuel weight fraction (M_{ffi})	**Turbojet aircraft**
Start and warm up	0.990
Taxi	0.990
Take off	0.995
Climb	0.980
Cruise	Calculated
Descent	0.990
Landing, taxi and shutdown	0.992

The fuel weight fraction M_{ffi} is defined as the ratio of the total aircraft weight at the end of the flight segment to the total weight of the aircraft when the segment has begun. Thus, the total fuel weight fraction defines the burned fuel as a ratio of the total aircraft weight at the end of the mission to the total aircraft weight at the beginning of the mission. As such, the total fuel weight fraction can also be expressed analytically as the product of all the fuel weight fractions, as per the equation (1) below:

$$M_{ff} = \prod_{i=1}^{n} M_{ffi} = 1 - \frac{W_{fuel}}{W_{take\,off}} \quad (1)$$

Using empirical relations from Raymer [32], the wing loading W/S and the thrust to weight ratio T/W can be estimated, which allow us to estimate the MTOW and the Maximum Zero Fuel Weight (MZFW), thus the weight of the aircraft at cruise W_{cruise}, can be estimated by the equation (2) below [33]:

$$W_{cruise} = \sqrt{(MTOW)\ x\ (MZFW)} \quad (2)$$

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Table 3 is a summary of the initial sizing analysis results.

Table 3. Summary of initial sizing analysis results

Parameter (unit)	Value
Empty weight fraction	0.472
Fuel weight fraction	0.464
Take off mass (Kg)	29500
Wing loading at take off (N/m^2)	5110
Wing loading at stall (N/m^2)	4539
Maximum thrust to weight ratio	0.585
Take off distance at ISA, Sea level (m)	2283

2.3.2 Wing

A trapezoidal shaped wing with a NACA 64-006 aerofoil and a leading edge wing sweep of 45 degrees has been selected for the SSBJ configuration, which will generate the lift necessary to satisfy the performance requirements with regards to takeoff and landing distance. The swept wing endorses a low value for the taper ratio to maintain the desired elliptical lift contribution, which in turn reduces the lift induced drag. However, one of the side effects of a relatively low taper ratio is a tendency for wing tip stalling. Typical values of taper ratio in supersonic flow for wings with high sweep angles are 0.2 - 0.3 [32], [34]. For practical and structural reasons, the lower value of 0.2 has been chosen, since it allows for a larger chord near the root of the wing. This is a desirable feature for the placement of the engines, as well as because it creates enough internal volume due to increased maximum thickness, facilitating this way the positioning of the landing gear system and the fuel tanks. The wing will have a zero dihedral and a low-wing configuration has been selected, mainly for the practical reason of placing the landing gear. A summary of the basic wing dimensions is presented at the Table 4 below.

Table 4. Summary of wing basic dimensions.

Parameter (unit)	Value
Area (m^2)	63.75
Span (m)	14.28
Root chord (m)	7.44
Tip chord (m)	1.49
Mean Aerodynamic Chord-MAC (m)	5.12
Spanwise location of the MAC (m)	2.78

2.3.3 Tail

The horizontal and vertical tail area are estimated using the tail volume coefficients, which, in general terms, illustrate how the wing compares with the tail. A first estimate for the vertical tail can be made using the equation (3) (from [32]):

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$$S_{VT} = \frac{V_{VT} b_W S_W}{L_{VT}} \quad (3),$$

in which S_{VT} is the vertical tail surface, V_{VT} is the volume coefficient, b_W is the wingspan, S_W is the wing surface and L_{VT} is the moment arm of the vertical tail. It is critical to minimize the horizontal tail volume so as to facilitate an area-ruled design and decrease the wave drag component. The tail arm moment L , which is the distance between the quarter chord position of the wing and the quarter chord position of the tail, has been set to 40% of the fuselage length for both the vertical and horizontal tail arm. The horizontal stabilizer has been modelled as a straight trailing edge tapered wing, with a leading edge sweep angle of 50 degrees, that is 5 degrees larger than the sweep of the wing, so that the tail has a higher critical Mach number value compared to the wing.

The vertical stabilizer has been modelled as a trapezoidal wing with a 60 degrees sweep angle. AR values are 2.5 for the horizontal and 1.3 for the vertical stabilizer, and the taper ratio is 0.15 for the horizontal stabilizer and 0.2 for the vertical stabilizer. The NACA 64-006 aerofoil has been selected for the horizontal stabilizer and the symmetric NACA 64-009 has been selected for the vertical stabilizer. A summary of the basic tail dimensions is presented at the Table 5 below.

Table 5. Summary of tail basic dimensions.

Parameter (unit)	**Horizontal stabilizer value**	**Vertical stabilizer value**
Area (m^2)	12.10	7.59
Span (m)	5.50	3.14
Root chord (m)	3.84	4.03
Tip chord (m)	0.56	0.81
Mean Aerodynamic Chord-MAC (m)	2.61	2.77

2.3.4 Fuselage

Primary considerations for the sizing of the fuselage were the existence of adequate usable volume for the passengers and the conformance to the area rule requirements [35]. Applying the area rule dictates that the fuselage has to be squeezed when meeting the wing, so that a smooth distribution can be achieved for both the volume and the cross-sectional area. Initial estimates for the fuselage length (L_{fus}) can be provided by the equation (4), which is based on statistical data [32].

$$L_{fus} = 0.287\ W_0^{0.43} \quad (4),$$

in which W_0 is the takeoff weight. The length of the fuselage has then been stretched by about 3 m to facilitate the application of the area rule design requirements and to create space for placing mandatory equipment for a passenger jet (lavatory etc.).

Moreover, a typical value for the cabin compartment to overall length ratio for supersonic passenger jets is about 0.55 [34], hence, the stretched fuselage should be offering the space required to accommodate the passengers. When comparing the supersonic passenger jet to a subsonic one, a sharper and longer nose is expected and a typical value for the nose length to diameter ratio will be

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about 4 [32]. This is a very well established design technique which mitigates the formation of strong detached shock waves at the nose of the aircraft, which would have contributed otherwise to a significant increase of the wave drag component. Figure 1 shows the fuselage's top view and Figure 2 shows the fuselage's side view.

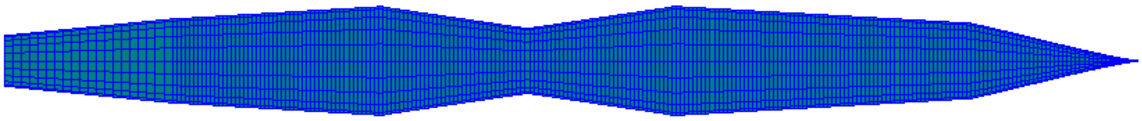

Figure 1. Top view of the fuselage

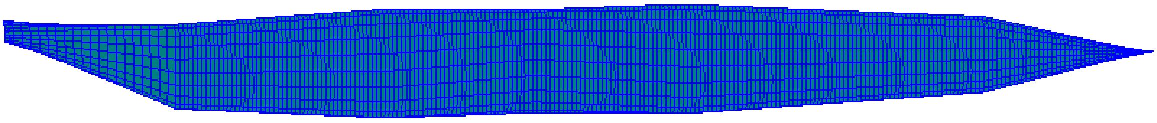

Figure 2. Side view of the fuselage

At Figure 2 it can be observed that the tail component of the fuselage has been intentionally designed to converge towards the higher side. This allows for the empennage to be placed higher up of the wing, minimizing the aerodynamic interactions created by the wing wake. Table 6 is a summary of the basic dimensions of the fuselage. It has been calculated that the total volume of the fuselage is 78.75 m^3.

Table 6. Summary of fuselage basic dimensions.

Parameter (unit)	Value
Nose length (m)	4.00
Nose maximum diameter (m)	1.80
Cylindrical part length (m)	19.00
Cylindrical part maximum diameter (m)	2.60
'Squeezed' part minimum width (m)	1.56
Fuselage tail length (m)	4.00
Fuselage tail maximum diameter (m)	2.00

The design has a low-wing arrangement and the MAC has been positioned 14.07 m behind the nose of the fuselage. The area ruled configuration of the aircraft assembly can be seen in Figures 3 and 4.

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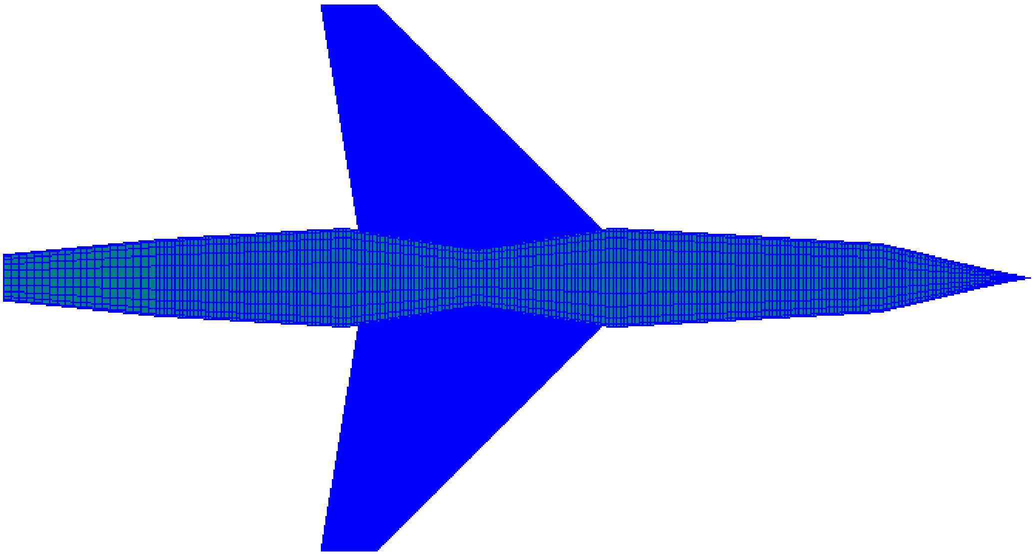

Figure 3. Top view of the fuselage-wing assembly

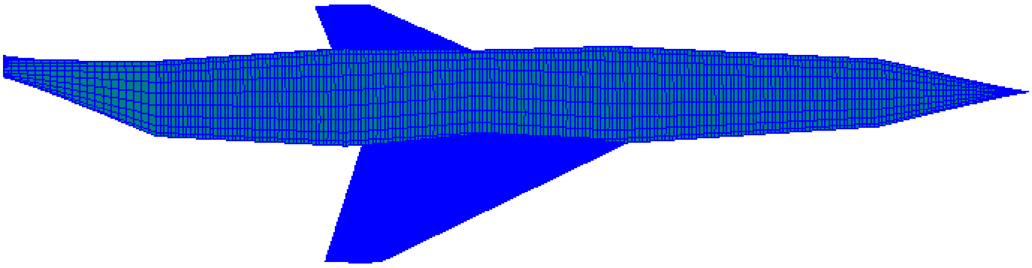

Figure 4. Side view of the fuselage-wing assembly

This configuration favors a high enough value for the tail arm, which has provided flexibility when defining the appropriate tail size.

2.3.5 Air intake

Concerning the propulsion system of the model, each engine has been positioned at the bottom surface of the wing. For supersonic fighter jet configurations, it is common to use fuselage side-mounted inlets. This arrangement enables the design of short ducts and mitigates potential distortions of the air. However, this is not a practical arrangement for a low-wing passenger design, since the engines should be placed outside the fuselage and the wing has at the same time to accommodate the undercarriage. Mounting the engines at the bottom side of the wing offers a quite undisturbed airflow, and eliminates the chance of potential interferences between the two exhaust nozzles. The structural stress on the wing is also decreased due to the effect of the inertial relief. For a proper operation of the compressor of the engine, the free stream flow needs to get slowed down

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to about 0.4 Mach [36]. The intake's efficiency is disproportionately related to the total pressure loss, and the total pressure loss depends to the pattern followed by the generated shock waves.

The type of supersonic inlet that has been used for the SSBJ design is the external compression rectangular ramp inlet. The shock wave pattern of that type of inlet consists of a series of weak oblique shocks generated outside the inlet, which is terminated by a normal shock wave at the cowl lip. The supersonic inlet has been designed to achieve very high efficiency and its shock pattern consists of a combination of three weak oblique shocks, followed by a normal shock wave. Table 7 presents the properties of the shock wave pattern for the inlet design.

Table 7. Properties of the 4-shock external inlet (Free stream Mach number: 1.7).

Wedge angle (deg)	Mach number	Shock angle (deg)	Pressure recovery (%)
5.9	1.59	39	99.96
5.8	1.49	42	99.96
6.1	1.27	50	99.71
-	0.80	90	98.40

As shown above, the total pressure recovery for the designed supersonic inlet will reach 98.40 % while the free stream flow is decreased from 1.7 to about 0.8 Mach. For the off-design operation of the engine at lower speeds, the mass flow demand will be reduced. This reduction in the demand will result in an increase of the static pressure at the inlet of the compressor, which will subsequently cause the air flow to spill outside the compressor. As a consequence of the spill out, the normal shock moves further upstream from the lip cowl, and the so-called spillage drag will increase significantly [37]. A design feature which can be used to mitigate this effect and to preserve the normal shock wave at the cowl lip, is the use of a bypass door at the diffuser. The bypass door will allow the excess air to exit the compressor is reached.

2.3.6 Propulsion system

The propulsion system has been selected to provide the appropriate thrust for the aircraft's performance, while meeting the maximum T/W ratio, having the least possible thrust specific consumption with a low weight and a small size, to minimize the associated drag. A low-bypass ratio turbofan has been incorporated to the design instead of a turbojet, which offers also reduced noise levels. Out of the existing engines which should satisfy the criteria, the turbofan EJ200 has been selected and its specifications are shown in Table 8 [38]. Two EJ200 engines have been used in the proposed design.

Table 8. Propulsion system basic dimensions (from [38]).

Parameter (unit)	Value
Intake length (m)	2.36
Capture area (m^2)	0.416
Throat diameter (m)	0.60
Nacelle length (m)	5.36
Nacelle width (m)	0.78

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The dimensions of the intake, subsequently of the integrated propulsion system can now be estimated for the conceptual SSBJ design. The respective ratio of intake length to engine diameter is 3.19. The two nacelles have been positioned at a distance of 2.9 m from the aircraft body axis. Table 9 shows the specifications of the EJ200 engine.

Table 9. EJ200 engine specifications (from [38]).

Parameter (unit)	Value
Maximum thrust, dry (KN)	60.0
By pass ratio	0.40
Overall pressure ratio	26:1
Specific fuel consumption, dry (g/KNs)	21.0
Air flow rate (Kg/s)	77.0
Maximum diameter (m)	0.74
Length (m)	4.00
Weight (Kg)	1010

The aircraft model top and side views are shown at the Figures 5 and 6 respectively.

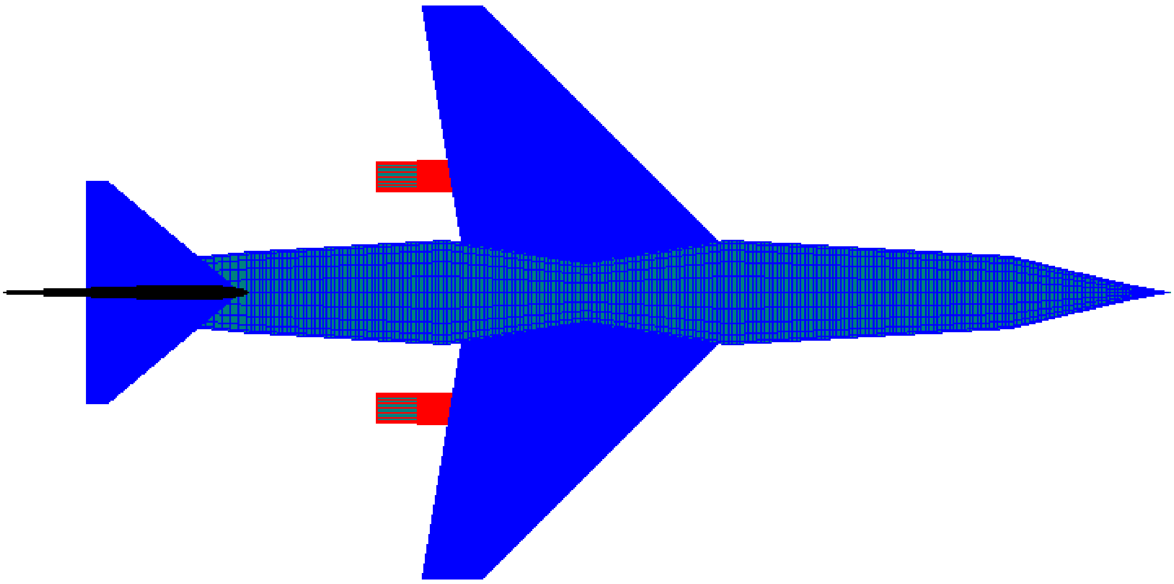

Figure 5. Top view of the aircraft model.

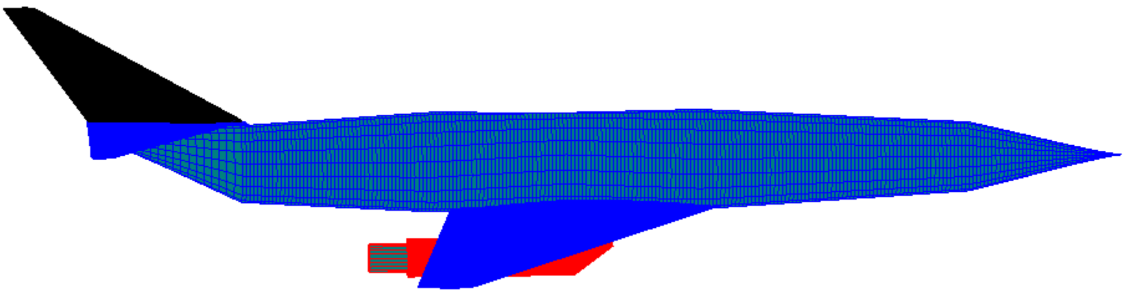

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Figure 6. Side view of the aircraft model

3. Environmental Impact Assessment Results and Discussion

3.1. CO_2 and H_2O emissions

The emissions of CO_2 and H_2O have been calculated by using the method outlined at [29]. Tables 10 and 11 show how the calculated emissions of CO_2 and H_2O of the SSBJ design compare to those of a subsonic passenger jet. The results refer to a 6050 km flight with a 100% passenger load factor. The emissions of the proposed SSBJ aircraft design per Km are lower, which is explained by its lower payload value and thus smaller size. However, the 'per seat' emissions metric provides a different picture, since the emissions of CO_2 and H_2O per Km per seat of the SSBJ are about 5.85 times greater than the subsonic passenger jet. That is explained by the fact that the subsonic passenger jet cruises at a significantly higher lift-to-drag ratio, having a lower value for the thrust specific fuel consumption, which is 16.14 g/KN/s for the RB211-524H engine at cruise conditions[39].

Table 10. Water vapor emissions comparison (6050 Km distance flown).

Aircraft	H_2O (Kg/Km)	H_2O (Kg/Km/seat)
Boeing 747	13.22	0.032
SSBJ	2.79	0.186

Table 11. Carbon dioxide emissions comparison (6050 Km distance flown).

Aircraft	CO_2 (Kg/Km)	CO_2 (Kg/Km/seat)
Boeing 747	33.70	0.081
SSBJ	7.12	0.47

The order of magnitude of the results for the SSBJ suggests that the potential influence of the operations of small supersonic passenger aircraft would not be so problematic with regards to the greenhouse effect. It is certain tough that a rapid growth of the supersonic commercial operations, which will involve large aircraft designs, will definitely affect the total aviation emissions.

3.2. Ozone layer depletion

Supersonic flight operations possess environmental challenges for the ozone layer. Almost 90% of the ozone is present at the stratosphere. Since the SSBJ designs are going to cruise at altitudes from 48,000 to about 57,000 ft, the produced NOx will be emitted directly at the ozone layer. NOx is emitted as well by the subsonic commercial aircraft which operate long haul missions at cruise altitudes of around 35,000 ft, in other words at the low levels of the stratosphere. The NOx emissions at the stratosphere participate in catalytic chemical reactions that lead to the destruction of the ozone. A disruption of the ozone layer may let ultraviolet radiation emitted from the sun to reach the earth, harming the living organisms. NOx is emitted as a consequence of the operation of both subsonic and supersonic aircraft, however, the impact of the SSBJ which operates at higher cruise speeds and at higher altitudes is more prominent, since those are altitudes with higher ozone concentration [8]. As such, relatively long flights of large supersonic passenger jets at cruise velocities higher than Mach 2, cruising at flight levels with high levels of ozone concentration, burning at the same time a lot of fuel, could potentially be the most challenging supersonic passenger jet project when it comes to the issue of the ozone depletion.

The NOx is a product of the combustion process of the kerosene. Work by Lipfert [40] has shown that there exists a simple correlation between the NOx emission index (EI_{NOx}) and the combustor inlet total temperature (T_{tc}). The equation (5), found on [29], is an empirical relation which is used to predict the NOx emissions:

$$EI_{NOx} = 10^{(1+0.0032(T_{tc}-581.25))}\sqrt{\delta} \quad (5),$$

in which δ is the ratio of the static pressure at the cruise altitude to the sea level static pressure. The equation (5) illustrates that for high values of the combustor inlet temperatures and subsequently for high values of engine pressure ratios, the NOx emissions can be significantly increased. The pressure ratio, which determines the total temperature at the exit of the compressor, affects the actual primary zone temperature in the combustion chamber [29] hence, the production of NOx too. The NOx production is also affected by the equivalence ratio Φ, which is a parameter that is used to classify whether a fuel-air mixture is rich, stoichiometric, or lean:

$$\Phi = \frac{(m_f/m)}{(m_f/m)_{stoichiometric}} \quad (6) \text{ [from 29]},$$

in which m_f is the mass of the fuel and m is the mass of the air.

Figure 7, shows the variation of the calculated NOx emissions index as a function of the overall pressure ratio for a subsonic passenger jet and for the SSBJ design. The subsonic passenger jet is the Boeing 747-400, and the cruise conditions are 0.85 Mach at an altitude of 11 *km*. For the SSBJ the cruise speed is 1.7 Mach at an average flight altitude of 16 *km*. The upper limit of the overall pressure ratio of the RB211-524H engine of the Boeing 747-400 is set to 33 [39], while for the EJ200 of the SSBJ design is set to 22. This way the total temperature at the compressor exit will not exceed 900 K, which is a practical operational limit of the materials of the compressor materials [41].

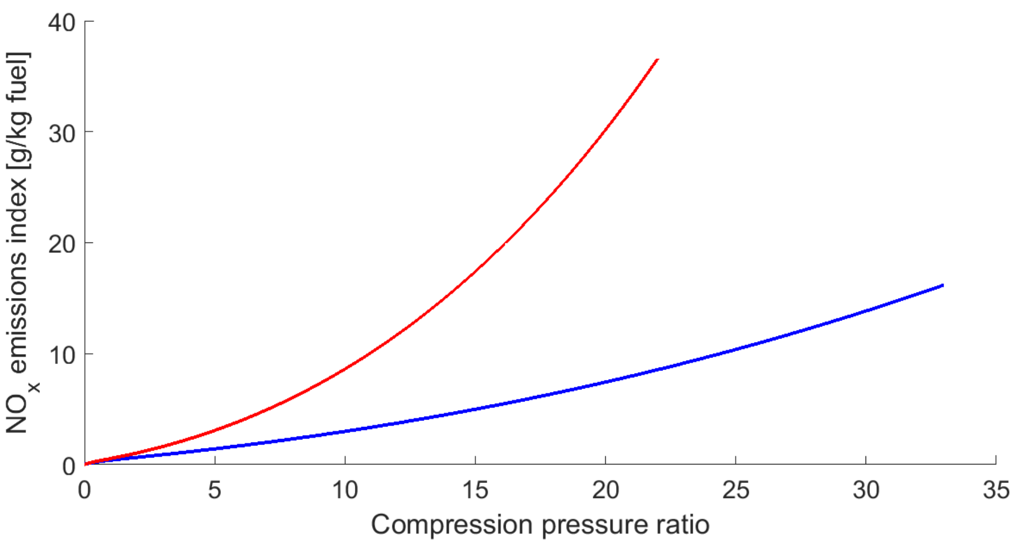

Figure 7. NO_x emissions index for the SSBJ (red) and for the long haul subsonic airline (blue).

For the RB211-524H engine, it has been assumed that the value of the diffuser isentropic efficiency is 0.97, and the value for the intake isentropic efficiency for the SSBJ has been estimated at 0.95. For both engines, a typical value of 0.85 was set for the compression isentropic efficiency. The results of the Figure 5 suggest that the maximum EINOx of the subsonic passenger jet is about 16.2 g/kg fuel at its maximum compression ratio of 33, which is a finding in agreement with the study of Wahner and Geller [42]. For the SSBJ design, the pressure ratio effect on the EINOx is much more evident with a value of 36.58 g/kg fuel at the maximum set pressure ratio of 22. Higher fuel consumption of the SSBJ is also another factor which contributes to even higher NOx emissions and this is something which generates concerns for the environmental sustainability of a robust growth of the commercial supersonic activity in the years to come.

4. Conclusions

Research suggests that the climate effects due to non-CO_2 emissions from supersonic aircraft could be considerably greater than the non-CO_2 effects from subsonic aircraft [43]. Furthermore, no noise neither CO_2 certification requirements exist for supersonic aircraft in Europe [44], while the FAA has recently initiated steps for noise certification and special flight permits to conduct flight testing of supersonic commercial platforms in the USA [45]. Keeping NOx emissions within sustainable limits, will require values of emissions index as low as 5. This is an about 80% reduction of the calculated above values. Achieving such values for NOx emissions, will require new engine concepts to be developed, which will need at the same time to maintain the requirements of low thrust specific fuel consumption, high thrust-to-weight ratio, reliability, and operation at the low emissions region of the equivalence ratio Φ. Novel nozzle integration techniques can be investigated for that purpose [46] and the financial viability of a project to build a new engine suitable for supersonic passenger jets should need to be addressed as well.

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