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LTO NOISE AND SONIC BOOM PREDICTIONS IN EARLY CONCEPTUAL DESIGN PHASES

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Abstract

This paper discloses a workflow to integrate LTO noise and sonic boom predictions since the beginning of the design of future supersonic civil aircraft. The application of state-of-the-art models to the future high-speed case study is discussed, and solutions to overcome limitations are presented. The workflow is validated against Concorde literature data and then applied to the design of a future sustainable Mach 3 aircraft.

Keywords: supersonic civil aviation, LTO noise predictions, aircraft conceptual design

1. Introduction and background

The aviation industry has transformed dramatically over the past century, forever changing how we live and work by bringing people closer and connecting the world. While travelling thousands of miles in just a few hours is easier than ever before, moving faster than the speed of sound is also in the air. The EU-funded MORE&LESS project is reviewing the environmental impact of supersonic aviation, by applying a multidisciplinary holistic framework to help check how enabling technologies of supersonic aircraft, trajectories, and operations comply with environmental requirements. This project covers the entire supersonic speed regime (from Mach 2 to Mach 5) and the most promising aircraft configurations, propulsive technologies, and alternative fuels (considering biofuels and liquid hydrogen). The findings will inspire the future of environmentally sustainable supersonic aviation. Since the last civil supersonic aircraft took off, growing environmental concerns have tightened new regulations, limiting the development of the next generation of high-speed aircraft. Specifically, the high noise level generated in the vicinity of airports, particularly during take-off, and the sonic boom overpressure achieved flying in a supersonic regime are two of the most important environmental issues that threaten the viability of future supersonic aircraft. For this reason, organizations and research institutes around the world are working to define appropriate standards for low noise and low boom supersonic transport. Meanwhile, many studies have been pursued to integrate the evaluation of these standards within the aircraft design process. However, state-of-the-art models used to obtain accurate estimates may require information that are not available at the conceptual design phase. Consequently, the introduction of methodologies to evaluate the noise impact of high-speed aircraft in the earliest stages of the design process is still an open topic. In line with this recent research effort, this paper focuses on applying state-of-art methodologies to predict noise emissions from the beginning of the design process for future supersonic aircraft. This approach will anticipate the evaluation of the effects of noise emissions constraints on aircraft design and ensure that sustainability requirements are met more effectively. Second, it paves the way toward an increasingly integrated design methodology, coupling LTO and sonic boom noise level estimations. In addition, it will provide a guideline in conceptual design for LTO noise assessment and sonic boom prediction analysis.
Several methodologies aimed at different fidelity levels and objectives can be employed to predict noise generated by the aircraft and/or its components during take-off and landing operations (e.g., fully analytic method, CFD combined with the acoustic analogy, semi-empirical method, or fully numerical method). However, assuming a system-level point of view rather than a more detailed component-level, two main methods categories can be recognized [1]:

- Theoretical (or scientific) methods, which rely on both experimental data (typically from fly-over test campaigns) and physical-based aspects. The total aircraft noise is predicted as an assembly of each individual noise source, modeled through parametrical and semi-empirical relationships.
- Best practice methods, which rely almost exclusively on ground measurements of a specific aircraft. The aircraft emission noise level is determined by the segmentation of the trajectory and then the noise contributions from each of these segments are subsequently summed at the observer position to provide an evaluation of medium to long term average noise levels around airports.

Being these the differences between the two approaches, theoretical methods are more appropriate than other prediction models to perform design trade-off studies and run noise sensitivity analyses. Indeed, those methods can easily handle parametric changes in airframe/engine design and operational settings, enabling a fast evaluation of their impact on noise generation and facilitating the identification of the best low-noise aircraft solution. However, the disadvantages of these methods are the reliability and the fidelity-level of the results, especially when applied to novel aircraft configuration, due to the variety of data required for models' validation. Nevertheless, the integration of semi-empirical aircraft noise prediction within the design process has been widely investigated in the last decades. The National Aeronautics and Space Administration (NASA) initiated research on this topic at Langley Research Center in the early 1970s, starting with the development of the Aircraft NOise Prediction Program (ANOPP) [2], the first computer program with noise prediction capabilities. ANOPP incorporates a design framework that provides all the input required to accomplish the noise analysis. The noise prediction is performed by dedicated modules to account for noise source modelling, noise propagation (spherical spreading, atmospheric attenuation, and ground reflection on the received noise), and calculation of certification noise levels. Advances in the fidelity level and the capability to cover also unconventional designs have been made over the years and included in the latest release ANOPP2 [3]. Currently, many other similar prediction tools can be found in the literature, such as the Parametric Aircraft Noise Analysis Module (PANAM) [4], developed by the German Aerospace Laboratory (DLR), and CARMEN [5], developed by the French aerospace laboratory ONERA. The methodology underlying these programs is almost analogous to what is present in ANOPP, with remaining differences in noise models and individual code implementation. Although, to date, PANAM and CARMEN can be applied only to conventional tube-and-wing aircraft.

As already mentioned, another relevant issue concerning supersonic flight is the sonic boom noise level. All bodies moving faster than the local speed of sound generate a shockwave system. For a supersonic aircraft with a classic configuration, the shockwave system forms a series of shocks that at a great distance usually coalesce into a bow shock and a tail shock to form the N-wave. These waves move at the same Mach number as the vehicle and extend from the aircraft itself to the ground both along the ground track and tens of it, and are also reflected from the ground. Sonic boom minimization techniques have a considerable interest because of the annoyance that the phenomena cause to both the people and structures. Adequate estimation of bow shock overpressure could also be obtained through simplified methodologies. It is known that the factors that influence sonic boom in a major way are due to aircraft design, flight operations, and atmospheric effects. As far as flight operations are concerned, they are related to cruise altitude, Mach number, aircraft weight, and flight path. The first study for shock formation was investigated by Whitham, with correction of the linearized theory by including local variation in the speed of sound. Subsequent development were conducted considering a standard, isothermal atmosphere such as that studied by George and Seebass. The effects of the actual atmosphere were studied first by Hayes and later taken up by Pierce and Maglieri, with the most widely used methodologies described by Plotkin. Along with these methodologies, which are very complex and require high computational cost, simplified methods have been developed that manage to approximate the Whitham F function. The best-known is the one studied by Carlson, in which the Whitham F function is estimated with a constant aircraft shape factor that includes information regarding the geometry of the aircraft and its evolution along the longitudinal coordinate. Another method for estimating sonic boom is the one formulated by Plotkin, which is a method for the estimation of sonic boom for an aircraft maneuvering in a horizontally stratified

and windless atmosphere. This methodology uses ray shape function tables, where the atmosphere is defined and ray tube areas are calculated through tables and algebraic relationships.
Finally, the most used programs for the study of the sonic boom are:

- ARAP which calculates the sonic boom for an aircraft manoeuvring in an arbitrary horizontally stratified atmosphere.
- Thomas[15], developed by NASA that use the waveform parameter method of signature aging.
- TRAPS[16], that use Hayes' formulation with the use of ray distance instead altitude as the independent variable and accepts atmospheric data in standard meteorological format.
- ZEPHYRUS [17], which reformulates Hayes' method by incorporating more physical effects and treats over-the-top booms.
- PCBoom3 [18], represents an evolution of Thomas' code with the addition of a focal zones by application of the Gill–Seebass focus solution and Guiraud's scaling law. It manages to accept initial signature of both F function or can generate simplified Carlson F functions from built in aircrafts.
- MDBOOM [19], similar to PCBoom3 which incorporates area rule F function calculation.

Based on the available literature, the selected methods for estimating aircraft noise levels were the semi-empirical model implemented in the early versions of ANOPP and Carlson's method. Then, they have been adapted to support conceptual studies and drive initial consideration towards low noise and low boom supersonic aircraft. To achieve these multi-faceted goals, the N+2 effort requires Multi-Discipline Analysis and Optimization (MDAO) efforts between airframe and propulsion industries to address system integration. Integrated vehicle design is performed to simultaneously achieve supersonic cruise efficiency, low sonic boom signatures, as well as low take-off noise. Integrated design concerns include:

- Sonic boom reduction
- Airport Noise
- Cruise Efficiency
- Light Weight structure for airframe/propulsion systems
- Aero-Propulso-Servo-Elasticity
- High altitude emissions

This introduction and background on research activities provide an overview of the state of art in aircraft noise models and sonic boom methodologies. The following section will explain how sonic boom and LTO noise are estimated from conceptual design, along with a description of the methods that are used for noise prediction. To assess the results found, the methodologies were applied to known case studies. Moreover, the workflow represented below has been used to study a supersonic conceptual design 20 meters shorter than Concorde that manage to reach Mach 3 in cruise. The results for the following case studies are reported in Section 4, highlighting a comparison with Concorde. Finally, conclusions and possible future improvements to the method are presented.

2. LTO noise and sonic boom prediction in conceptual design

2.1 Proposed Workflow

The primary purpose of conceptual design is to demonstrate the technical feasibility of the configuration to allow for more accurate studies in the detailed design phase. However, performance analyses should be carried out to evaluate the different layout proposed in the early phase of aircraft development. In addition, from the early stages of the design, sustainability must be evaluated as a key goal for the viability of new supersonic transportation. Following the MORE&LESS project objective mentioned in the introduction, an integrated workflow has been developed to support future supersonic aircraft from the conceptual design stages concerning noise requirements as represented in figure 1.

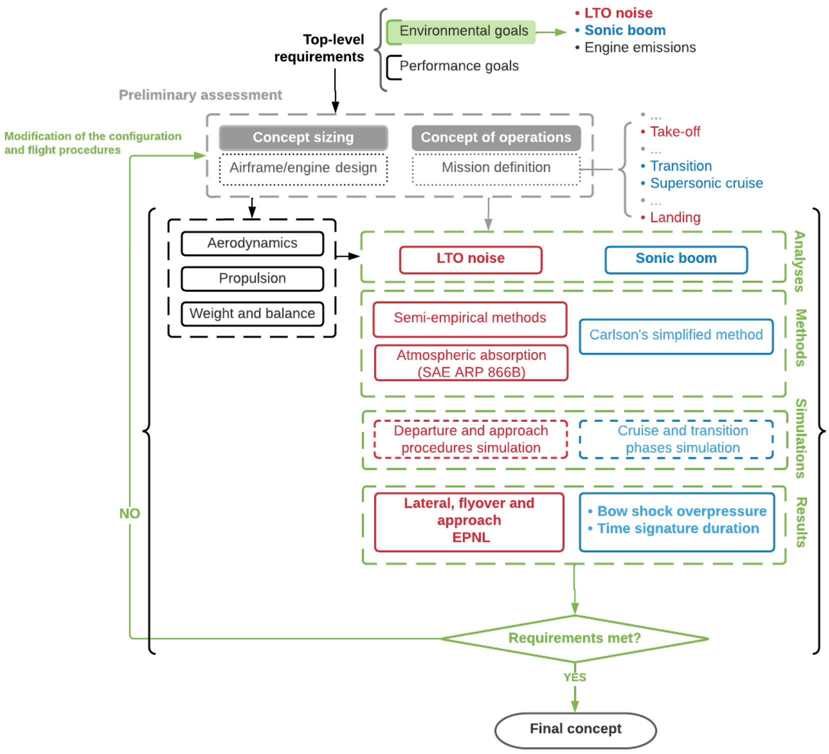

Figure 1 – Integrated conceptual design workflow with noise requirements evaluation.

Integration begins by considering new environmental targets and design constraints, besides classic performance requirements. In particular, the following paper focuses on the maximum allowed noise in terms of LTO and sonic boom for community acceptability. Given the aircraft configuration and its mission profile, the first guess database is available to perform initial analyses. As far as the environmental analysis is concerned, the required input data are derived from aerodynamics, propulsion system, weight distribution, as well as data from the mission profile. Boxes framed with the green dashed line in figure 1 highlights also the methods employed, the simulations performed, and the results obtained in this study, which will be disclosed in detail in the following sections. Finally, verification of current noise standards allows for design modifications and identification of optimal solutions for low-noise supersonic aircraft. Through this workflow, the procedure can be used to evaluate the benefits of new technologies and new designs. The following tables 1 and 2 show the input values necessary to simulate LTO noise and sonic boom; through these tables, it is also possible to evaluate the differences in input values between the two aircraft analyzed.

Input Variable	Unit of Measure	Concorde	GreenHawk3
Mach Number	[ ]	2.0	3.0
Flight altitude	$[m]$	18200	20000
Aircraft Weight (MTOW)	$[kg]$	185066	38256
Flight path angle	$[deg]$	inserted by the user	inserted by the user
Ray path Azimuth Angle	$[deg]$	inserted by the user	inserted by the user
Maximum Thrust (take-off)	$[kN]$	$\approx$ 680	$\approx$ 317
Cruise Thrust	$[kN]$	65.44	23.01
Speed of sound	$[m/s]$	295.07	295.07

Table 1 – Flight condition input data

Input Variable	Unit of Measure	Concorde	GreenHawk3
Aircraft Length	$[m]$	61.66	42.00
Fuselage width	$[m]$	2.87	3.00
Fuselage height	$[m]$	3.32	3.00
Wing surface	$[m^2]$	358.25	131.42
Wingspan	$[m]$	25.60	18.00
Height vertical tail	$[m]$	11.32	4.00
Number of Strut landing gear	[ ]	2	2
Number of wheels landing gear	[ ]	8	8
Number of engines	[ ]	4	2
Local Span of the aircraft	$[m]$	$b(x)$	$b(x)$
Engine diameter	$[m]$	1.212	≈ 1.23
Inlet cross sectional area	$[m^2]$	1.08	1.51
Air mass flow	$[kg/s]$	186	173.73
Rotation Speed	$[Hz]$	108	108

Table 2 – Geometric and performance input data

2.2 LTO noise prediction model

The LTO noise prediction model is described in figure 2. Following well-established methodologies to introduce noise emissions estimation within the aircraft design process, a semi-empirical modelling approach has been selected. The main aircraft noise sources are identified (airframe, jet, and fan). Then, each noise source contribution is further detailed, as specified in figure 2. For this purpose, it is necessary to account for the peculiarities of a supersonic aircraft case study concerning subsonic aircraft, such as the absence of high-lift devices and horizontal stabilizers, the delta wing, and the noise-induced shock cells structure resulting from the high jet exhaust velocity at take-off. Open literature on semi-empirical methods considering these aspects is restricted to NASA research activity to support ANOPP development. Hence, the models applied in this work for each aircraft's main noise source and related sub-components are based on the available early version's methods of ANOPP [20]. All these methods were validated against experimental data, and, even if some limitations or shortcomings exist, these models have been widely used due to their capability to provide a sufficiently reliable and fast noise prediction correlated with the main design and operational parameters.

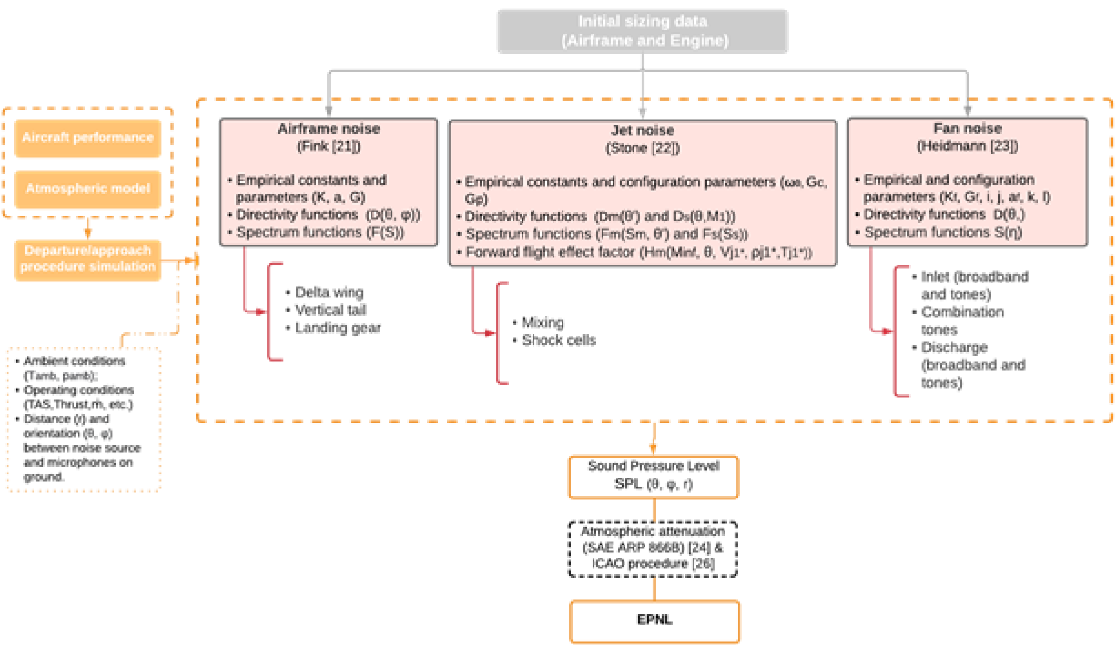

Figure 2 – LTO noise prediction model applied for supersonic aircraft conceptual studies

Precisely, airframe noise is modeled accordingly to Fink's method [21], where noise generated by the clean aerodynamic surfaces is assumed to be caused by the turbulent boundary layer flow over the trailing edges, and noise due to landing gear is fully empirical determined. Jet noise is predicted following the Stone method (generally applicable for both turbojet and turbofan engines) for single stream and coaxial circular jets [22], which includes both jet mixing noise and shock-turbulence interaction noise. Specifically, jet mixing noise is generated by turbulent mixing of the exhaust stream with the external air, which produces noise having acoustic power whose variation depends on jet exhaust speed.In the suggested method, this noise source is independent of the azimuthal directivity angle (between the symmetry plane of the vehicle and the observer on the ground) and is calculated by modifying the mean-square acoustic pressure for a stationary jet at the reference distance with a forward flight effect factor. On the other side, the shock cell noise occurs when the fully expanded jet Mach number is greater than 1, and the intensity of this shock-associated noise is dependent on the degree of mismatch between the design Mach number and the fully expanded jet Mach number. Heidman's method [23] is used to predict fan noise. It applies to turbojet compressors and single-and-two-stage turbofans with and without inlet guide vanes. The total noise levels are obtained by spectrally summing the predicted levels of broadband, discrete-tone, and combination-tone noise components. Specifically, the predicted noise radiation consists of a composite of the noise emitted from the fan or compressor inlet duct (broadband noise, discete-tone noise, combination-tone noise) and the noise emitted from the fan discharge duct (broadband noise, discrete-tone noise).
All these methods allow for predicting the far-field noise radiation, and the mathematical representation of the noise sources relies on empirically-based constants, parameters, and functions. The overall acoustic power is estimated, and then the mean-square acoustic pressure is calculated modulating along with the frequency band this overall acoustic power through the directivity and spectrum functions, accounting also for the Doppler effect and spherical spreading of sound. Thus, the mean-acoustic pressure is expressed as a function of frequency and directivity angles. TThe Sound Pressure Level (SPL) can be easily computed from it. Noise emission is estimated for each aircraft sub-component, and then the mean-square acoustic pressures are assembled to predict the overall contribution. Ultimately, to predict the noise level received on the ground with a sufficient accuracy level, at least the atmospheric attenuation of sound propagating through the atmosphere should be considered, as temperature and humidity significantly affect the sound when the distance between the noise source and the observer increases. To determine the entity of these losses, the mathematical procedure suggested in SAE ARP 866 B has been adopted [24]. Other phenomena influencing the sound received on the ground are neglected, to keep the approach applicable at the conceptual design level. To predict noise levels received at a certain point on the ground, these methods require information about initial geometrical and performance data of the aircraft and the engine, that should be derived from the connection with the other aeronautical disciplines within the design process workflow. Once first-guess estimations derived from initial conceptual studies are available, basic departure and landing procedures should be simulated to provide point-to-point ambient and aircraft operating conditions, together with information about the relative position of the aircraft concerning the microphones on the ground.

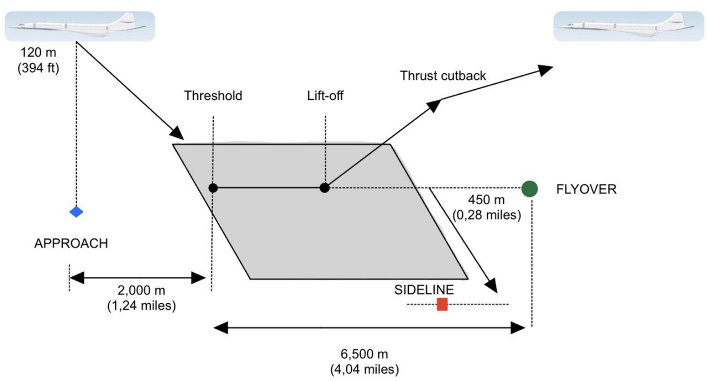

Figure 3 – ICAO noise certification measurement points

Therefore, the selection of an atmospheric model is the first step in predicting aircraft noise along the flight path. Atmospheric properties affect the performance of the aircraft, the noise generated by the aircraft and its engines, and the propagation of this noise through the atmosphere. As the model has to be only representative of the atmosphere below 10 km, the International Standard Atmosphere (ISA) static atmospheric model has been selected. The atmospheric model shares ambient conditions data along the trajectory to update basic modules for flight path simulation and engine performance. Indeed, estimating all the needed parameters to predict aircraft noise (especially for what concerns the engine operating conditions) with simple and low-fidelity models typical of the conceptual design stage and trying to obtain at the same time reliable results is one of the most challenging aspects of the integration of noise prediction methods at the very beginning of the design process, as well as uncertainties in the input data will affect the fidelity of the results. Hence, basic modules for flight path simulation and engine performance have been developed to overcome this issue. Specifically, the flight path is constructed from various standard procedural steps, whereas the engine operating conditions are evaluated through a one-dimensional model of a two-spool turbojet based on Olympus 593 data [25]. At least, the overall SPL received at the three certification points defined by the ICAO, that are sideline (or lateral), flyover, and approach (Figure 3), can be processed following the ICAO procedure [26] get the perceived noise levels and then the Effective Perceived Noise Level (EPNL).

2.3 Sonic Boom prediction model

The methodology used in this paper for the study of sonic boom is "Carlson's simplified method", which allows the evaluation of maximum overpressure and time signature duration from the earliest stages of design without the need to use software that requires high computational cost or flight test. Unlike other methodologies previously reported, it does not require a large amount of data regarding the aerodynamics, the geometry of the aircraft, and wave propagation. It is applicable for all supersonic aircraft operating at a flight altitude less than 76 km in a level condition or with moderate descents or ascents. However, the method has numerous limitations, such as the fact that it is only applicable for N-wave signatures, considers only a standard windless atmosphere, and it only considers the positive portion of the signature. It is also not able to evaluate acceleration phases, but only stationary ones. As for the assumption about the N-wave, it is generally true for supersonic aircraft with a classic configuration wing plus fuselage.

The methodology to simplify the Whitham F function uses a constant called aircraft shape factor which is exclusively a function of the geometry and its evolution along the longitudinal axis and the flight conditions of the aircraft. The shape factor evaluation is the first procedure for calculating the sonic boom properties of the vehicle, knowing the flight conditions such as weight, altitude, Mach number, flight path angle, and ray path azimuth angle. The following steps concern the evaluation of the atmospheric parameters that can be obtained from the effective Mach number and the effective flight altitude. Having them know it is possible to proceed to derive the parameter that is necessary for the estimation of the bow shock overpressure and time signature duration. The last step is the evaluation of these two terms through the following formulations: equation 1 for bow shock overpressure and time signature duration in equation 2.

$$\Delta P_{max} = K_P \cdot K_R \cdot \sqrt{p_v \cdot p_g} \cdot (M^2 - 1)^{\frac{1}{8}} \cdot h_e^{-\frac{3}{4}} \cdot l^{\frac{3}{4}} \cdot K_S \tag{1}$$

Where K_P is the pressure amplification factor, K_R is the reflection factor that is assumed to be 2.0, p_v is the atmospheric pressure at aircraft altitude, p_g is the value of atmospheric pressure at ground level, h_e is the effective altitude K_S is the aircraft shape factor.

$$\Delta t = K_t \cdot \frac{3.42}{a_v} \cdot \frac{M}{(M^2 - 1)^{\frac{3}{8}}} \cdot h_e^{\frac{1}{4}} \cdot l^{\frac{3}{4}} \cdot K_S \tag{2}$$

Where K_t is the signature duration factor, a_v is the speed of sound at aircraft altitude, h_e is the effective altitude and K_S is the aircraft shape factor.

The calculation of the shape factor for vehicles that are not covered by specific charts consists of the evaluation of some parameters. The first one is related to the estimation of the equivalent area due to volume, which considers the evolution of the cross-sectional area normal to the flight path instead of that defined by the Mach cone. If it is known, the area of the flow tube entering the engine inlet must be eliminated.

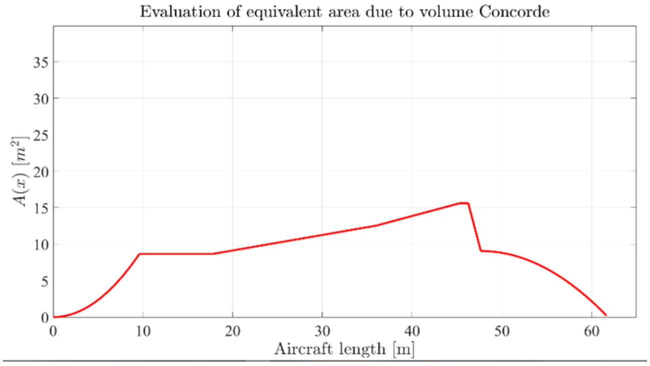

Figure 4 – Equivalent area due to volume, Concorde

The following step is the definition of the equivalent area due to lift, with the simplification that allows to approximate it as the planform area distribution and is defined in equation 3:

$$B(x) = \frac{\sqrt{M^2-1} \cdot W \cdot \cos\gamma \cdot \cos\theta}{1.4 \cdot p_v \cdot M^2 \cdot S} \cdot \int_0^x b(x)dx \tag{3}$$

Where W is the aircraft weight, γ is the flight path angle in deg, θ is the ray-path azimuth angle, p_v is the atmospheric pressure at aircraft altitude, S is the aircraft planform area and $b(x)$ is the local span of aircraft planform at a given value of x coordinate.

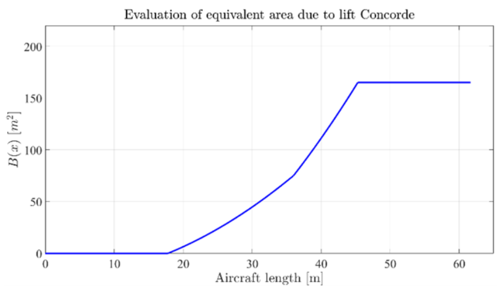

Figure 5 – Equivalent area due to lift (Concorde)

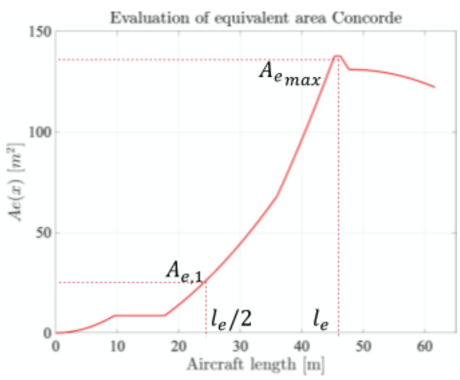

Figure 6 – Effective Area (Concorde)

The next step is to add the two previous contributions to form the total effective area of the aircraft A_e. From the obtained curve, it is possible to determine the value of the maximum effective area $A_{e,max}$, it's position in terms of longitudinal coordinate or effective length l_e of the aircraft and the effective area $A_{e,1}$, that are essential for the calculation of the shape factor parameter. Finally, the last step consists of the evaluation of the value of aircraft shape factor can be directly read from the shape factor parameter curve having known the ratio between the two areas that arises approximating the function $A_e(x) = k_1 \cdot x + k_2 \cdot x^2$ with the selected constants such that the curve passes through those points. The values of the pressure amplification factor, ray path distance factor, and signature duration constants can be obtained having known the effective flight altitude and Mach number. Interpolating functions have been created, that manage to reproduce their behavior when these two parameters vary. The effective Mach number is described as the Mach number that would be given in level flight, which would have the same ray-path angle in the flight-track plane while the effective altitude is the distance perpendicular to the aircraft's flight path. The simplified effective Mach number is defined by equation 4:

$$M_e = \frac{1}{\sin(\gamma + \cot^{-1}(\sqrt{M^2 - 1}))} \tag{4}$$

Where M_e is the effective Mach number and γ is the flight path angle in deg. The component of distance in direction of aircraft ground track is essential for the calculation of the effective distance and it is defined as shown in Equation 5:

$$d_x = K_d \cdot \left(\frac{h}{\sqrt{M_e^2 - 1}} \right) \tag{5}$$

Where K_d is the ray path distance factor, h is the altitude of the aircraft, M_e is the effective Mach number and d_x is the component of distance in the direction of aircraft ground track. And finally the effective altitude is defined by Equation 6:

$$h_e = h \cdot \cos\gamma + d_x \cdot \sin\gamma \tag{6}$$

Where h_e is the effective altitude, h is the altitude of the aircraft and γ is the flight path angle. TThe introduction of these parameters is due to reduce computational calculation. The values of these atmospheric constants were obtained by interpolating remarkable points as a function of the effective Mach number and the effective flight altitude.

A series of polynomial equations has been created to describe the evolution of these coefficients as the two previous parameters vary. The value of the cut-off Mach number was also studied as a function of altitude, for which the sonic boom signal does not reach the ground.

3. Methodology validation with Concorde data

3.1 LTO noise for Concorde

To evaluate the applicability of a simplified methodology to supersonic aircraft with traditional Concorde-like configurations and assess the accuracy level in the prediction, the results of dedicated comparison against Concorde data are presented. The validation has been carried out for flyover trajectories at different altitudes (630 ft - 10,000 ft) , and thrust settings (10,000 lb and 32,000 lb) , and the methodology has been used to predict Noise Power Distance (NPD) data produced at these flight conditions. The aircraft speed is costant to 160 knots (82 m/s), following the reference airspeed used to derive the NPD from experimental measurements, whereas the ambient conditions have been set to the reference conditions suggested in [27] for noise contours modeling around the airports (ambient temperature T_{amb} = 15 °C and the relative humidity HR = 0.7).

To overcome the lack of available experimental data from flight campaigns or thanks to a comparison of the results from an already accepted and validated software, NPD data provided by the Aircraft Noise and Performace (ANP) database [28] (an open-source repository of noise data by Eurocontrol) have been taken as a reference to evaluate the correspondence with the predicted noise levels. Furthermore, as annoyance-based noise levels are more sensitive to the signature and tonal content of noise rather than loudness-based metrics, LAmax and SEL have been estimated to perform the validation. Graphical comparison between experimental and predicted NPDs is reported in Figure 7. The degree of matching between predicted and experimental curves has been quantitative estimated through a numerical indicator for each validation point, respectively defined for LA_{max} and SEL as follows:

$$E_{LA_{max}} = \left| \frac{LA_{max_p} - LA_{max_{ANP}}}{LA_{max_{ANP}}} \right| \tag{7}$$

$$E_{SEL} = \left| \frac{SEL_p - SEL_{ANP}}{SEL_{ANP}} \right| \tag{8}$$

Where LA_{max_p} and SEL_p are the predicted noise level, thus $E_{LA_{max}}$ and E_{SEL} are the correspondent relative errors.

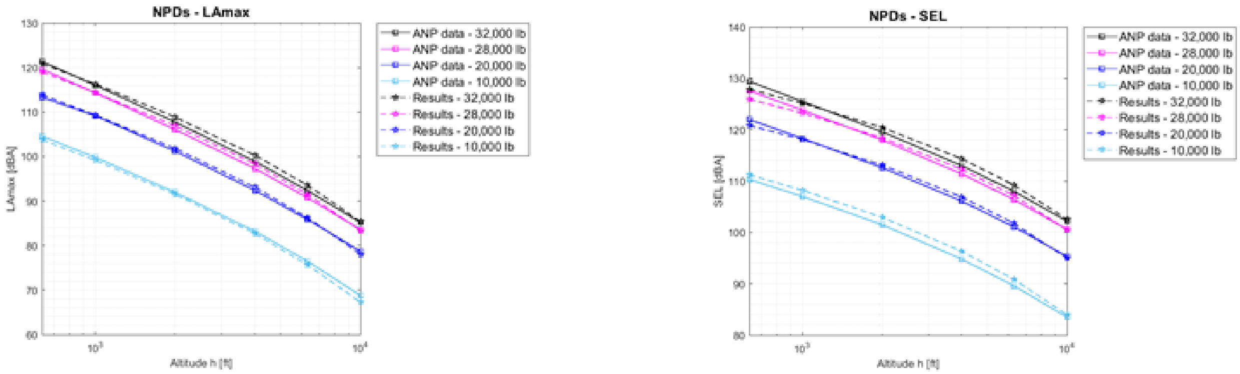

Figure 7 – Matching between experimental and predicted NPD curves for LAmax and SEL (Concorde)

The maximum prediction error is $\pm 2.19\%$ around the experimental value, attaining a good accuracy level for conceptual design applications.

4. Sonic Boom of Concorde

To demonstrate the accuracy of the method for evaluating the sonic boom for a supersonic aircraft, various tests were carried out for the Concorde. The flight conditions of interest and most burdensome are related to the transition phase from subsonic to the supersonic regime and the first phase of the cruise where the aircraft has a weight still close to MTOW and has reached the desired altitude and Mach number. Finally, another relevant analysis concerns the variation of the bow shock overpressure as the flight altitude changes. As for the first analysis of the transition phase from subsonic flight to supersonic flight regime, the simulations were made between the altitude of 11500 and 13000 meters, with a Mach number between 1.2 and 1.5. The second test concerns the influence of weight and was carried out at a fixed altitude of 18000 meters, varying the weight between 165000 and 145000 kg with a variation in the Mach number between 1.4 and 2.0. Finally, regarding the variation with the flight altitude, the analysis was carried out between 17000 and 19000 meters with the variation in Mach number always between 1.4 and 2.0 with a fixed weight of 165000 kg. All simulations were carried out considering the aircraft in horizontal flight, in a standard atmosphere without wind, and in a stationary phase.

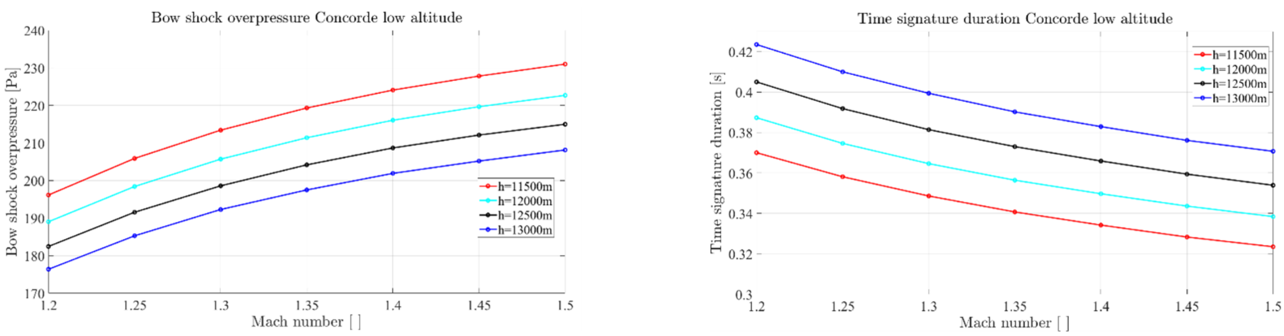

Figure 8 – Case 1: Bow Shock overpressure and time signature duration with Low Mach and low altitude

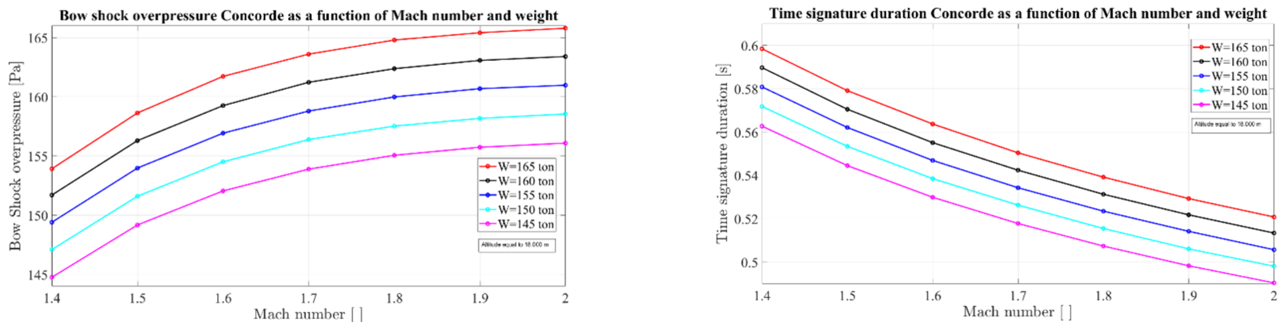

Figure 9 – Case 2: Bow Shock overpressure and time signature duration
ith Mach number and weight variation

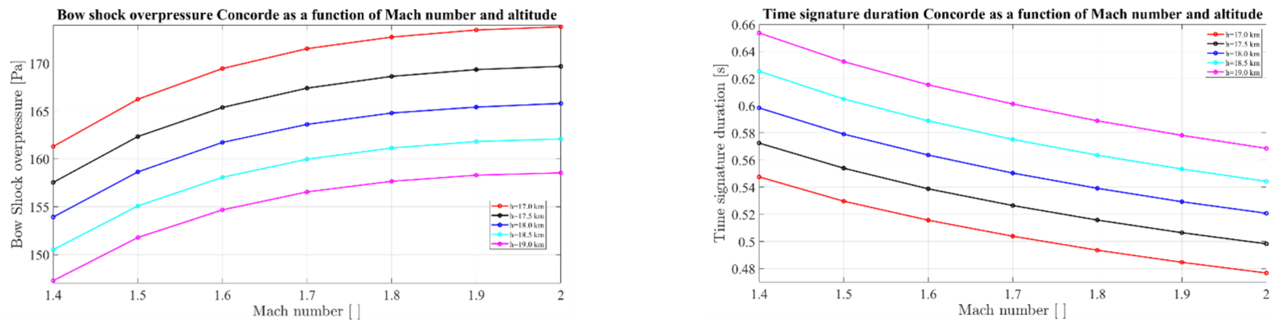

Figure 10 – Case 3: Bow Shock overpressure and time signature duration with altitude and Mach number variation

5. Application to GreenHawk3

5.1 Case study description

Figure 11 – GreenHawk3 Aircraft

The GreenHawk3 aircraft is a concept developed by a group of students from the Politecnico di Torino between 2020 and 2021 to create a future sustainable supersonic business jet. The project aims to develop an aircraft capable of covering intercontinental distances while significantly reducing flight time. To realize the concept, the vehicle had several requirements set, such as the number of passengers being 20, biofuel as fuel, and a cruising Mach number of 3.0. The choice of HEFA as the biofuel is dictated by the fact that it is already on the market and can significantly reduce carbon dioxide emissions. As a drop-in fuel, the aircraft does not need modifications in terms of the structure and type of tanks, as well as the ground facilities. The biofuel selected has physical characteristics that are similar to traditional fuels, especially in density and flashpoint. One of the most representative challenges for this type of aircraft is the propulsion system, which must be able to accelerate the vehicle from a stationary condition up to cruising speed, and then maintain this speed.
Numerous engine combinations could carri out this type of mission, with both turbojet/turbofan, tur-

bines integrated with ramjets, and the integration of air-breathing engines with rocket cycles. Following a trade-off analysis between the turbojet without an afterburner and an engine cycle option, it was noted that the first option was more suitable. Regarding the engine, it was decided to use two prototype engines studied by NASA with a net thrust of 35,667 lb for each one and a thrust-to-weight ratio of 8.04. These engines were designed by NASA for a 250-passenger aircraft that could replace the Concorde in the early 2000s and were capable of flying at Mach 3. The project aimed to build a vehicle that could fly by 2035, so it was assumed that only technologies that already existed would be used, without any financial budget constraints. Using the ASTRID software, it was possible to carry out a preliminary analysis of all the flight subsystems in terms of power and mass budget. Moreover, the matching chart of the aircraft was developed, together with the positioning of the center of gravity. The mission profile was performed using ASTOS software, including a mission from Sydney to Tokyo. The results shows that the aircraft has a maximum flight altitude of about 20000 meters and a Mach number close to 3.0.

As far as the lift to drag ratio is concerned, during supersonic mission phases, the value is close to 6.0, while for the subsonic ones it exceeds the value of 10.5. The final evaluation of the software shows the amount of fuel available at the end of the mission, which is 2200 kg. As far as the tanks are concerned, it was decided to allocate four tanks in each wing plus two in the fuselage to complete the mission safely; furthermore, the evaluation of the center of gravity position following fuel consumption was evaluated to ensure the stability of the aircraft throughout the mission profile. The configuration was then built with SOLIDWORKS, including all the subsystems previously studied with ASTRID. At the end of the project, the overall power and mass budget was evaluated, and the configuration was forty-two meters long with a wingspan of eighteen. Due to the presence of subsonic flight phases, a cranked arrow wingspan was evaluated, using the NASA SC(02)-0404 profile with a root chord of 14474 millimeters with a first sweep angle of 64 degrees and the second of 51. It was decided to use a tailess configuration because of the high thermal load and weight, the vertical surface has an area of approximately 12.50 m^2 and a height of four meters. The wing loading is 326 kg/m^2 and the Thrust to weight ratio is just under 0.4. The total thrust in take-off conditions is approximately 320 kN, which can be obtained through two engines. The total maximum take-off weight is just below 40000 kg, with around 20 tons for the fuel and around 3 tons for the passenger payload.

5.2 LTO noise for GreenHawk3

A comparison between Concorde and GreenHawk3 is shown in this section to verify the sensibility of the proposed simplified methodology in capturing the impact of design and performance variations on noise generation. Indeed, the same standard take-off and landing flight paths specified in the ANP database for Concorde have been simulated for both case studies to focus only on the effect due to aircraft and engine design, and performance rather than flight procedures modification. Distance, altitude and True Air Speed (TAS) data are provided by this set of ANP fixed-point flight procedures, while thrust setting is modified according to the specific engine performance (Figures 12 and 13). Specifically, the take-off path includes the cutback procedure, therefore, after the climb segment, the thrust setting is lowered and, consequently, the climb angle. The Maximum Tone Corrected Perceived Noise Level (PNLTM) at sideline, flyover and approach measurement points is presented respectively in the Figures 14 and 15.

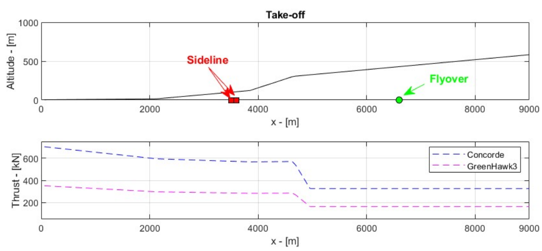

Figure 12 – Take-off procedure.

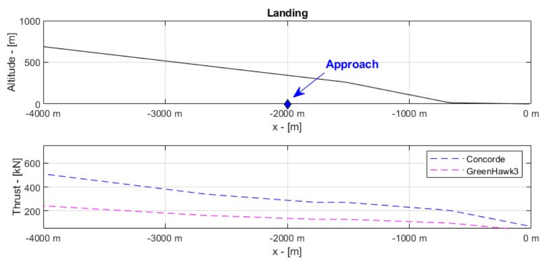

Figure 13 – Landing procedure.

A PNdB reduction between 1 and almost 5 PNdB in single contribution occurs for all the measurement conditions. Looking in detail the take-off condition, the airframe noise level is the one that is lowered the least, while the jet noise is the most. Therefore, the method has proved to capture the beneficial effect due to the absence of the afterburner, the reduced number of engines and the smaller configuration. In contrast, since there was no change in aircraft speed between the two case studies, it could be inferred that weight reduction is not sufficient to reduce the airframe noise component without a change in flight procedure slowing down the speed.

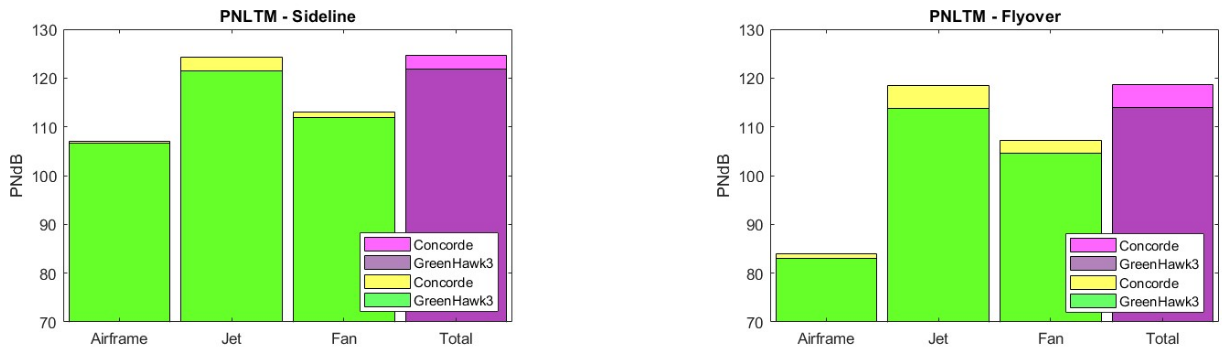

Figure 14 – Comparison between Concorde and GreenHawk3 PNLTM measured during take-off procedure at Sideline noise measurement point (left) and Flyover measurement point (right).

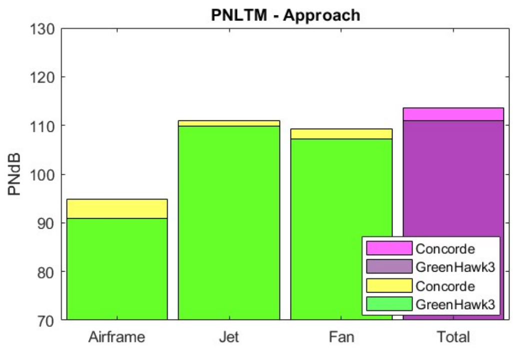

Figure 15 – Comparison between Concorde and GreenHawk3 PNLTM measured during landing procedure at Approach noise measurement point.

The reduction occus also for the landing condition, where differently this time the airframe noise is lowered the most. Therefore, in this case the noise generated is lower due mainly to the smaller configuration of the GreenHawk3 compared to the Concorde. At least, the EPNL at the three certification measurement points are listed the Table 3 and compared with current noise standards defined by ICAO (Annex 16, Volume 1, Chapter 12) for similary sized subsonic aircraft equipped with four jet-powered engines.

Aircraft	Sideline $[EPNdB]$	Flyover $[EPNdB]$	Approach $[EPNdB]$
Concorde	122.22	113.94	111.99
GreenHawk3	117.63	112.52	109.80
Target	**100.15**	**103.60**	**101.86**

Table 3 – EPNL at the three certification measurement points compared to current noise limits.

As it can be seen, a reduction of almost 5 EPNdB could be accomplished for supersonic aircraft since the beginning of the design process. However, more significant changes are needed in design and also in flight procedures to succeed in meeting the current target.

5.3 Sonic Boom for GreenHawk3

A comparison was made between Concorde and the GreenHawk3 to assess how differences in configuration can lead to more or less marked differences in sonic boom parameters. Case 1 was then carried out relating to the transition phase between subsonic to supersonic flight regimes. The flight conditions were the same as previously discussed for Concorde. Case 2 was also analyzed in which there is a simultaneous change in Mach number and aircraft weight. Regarding the weight, following the indications provided by ASTOS, varied between 35000 kg to 25000 kg.

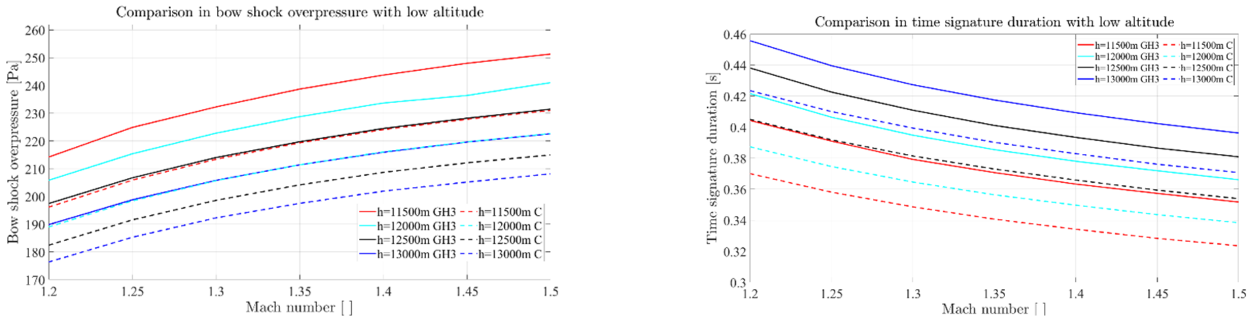

Figure 16 – Case 1: Comparison in bow shock overpressure and time signature duration GH3 and Concorde

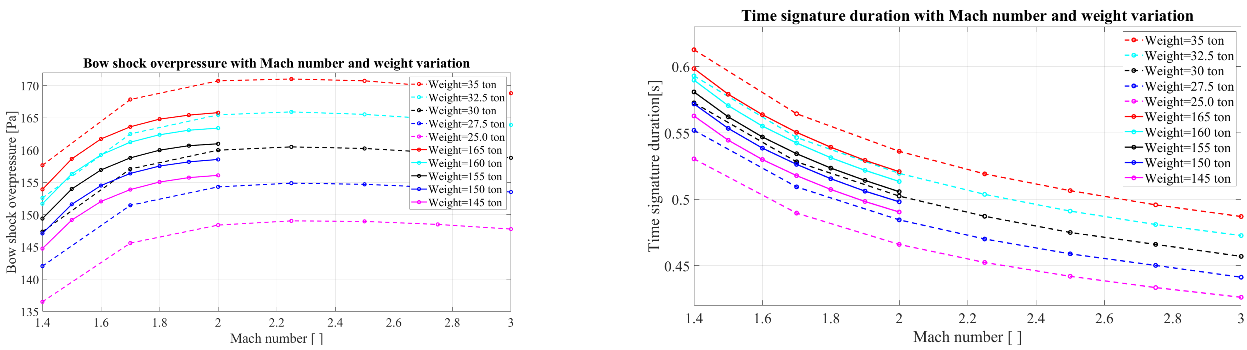

Figure 17 – Case 2: Bow Shock overpressure and time signature duration with Mach number and weight variation

5.4 Comparison between Concorde and GreenHawk3

As could be seen from Figure 16 , at low Mach number and low altitude, the value of both bow shock overpressure and time signature duration for the GreenHawk3 are higher than those from Concorde, and this is due to the shape of the aircraft. Regarding the variation of the two previous parameters when varying weight and Mach number, it is noticeble that the trend is approximately the same. However, as the weight change increases, the GreenHawk3 aircraft has a much higher reduction in overpressure. Analysing the graphs above, and based on the simulations performed, the following results can be written for sonic boom. In table 4 there are the value of the peak overpressure as a function of aircraft weight.

Condition	Weight [kg]	Overpressure [Pa]	Overpressure [psf]	Mach number
Start of Cruise Concorde	$\approx$ 165000	165.80	3.46	2.0
Start of Cruise GH3	$\approx$ 35000	168.81	3.52	3.0
Middle of Cruise Concorde	$\approx$ 155000	160.98	3.36	2.0
Middle of Cruise GH3	$\approx$ 30000	158.80	3.31	3.0
End of Cruise Concorde	$\approx$ 145000	156.09	3.26	2.0
End of Cruise GH3	$\approx$ 25000	147.78	3.08	3.0

Table 4 – Cruise value

As can be seen from table 4, as the weight of the aircraft decreases, the overpressure value drops quite noticeably.
In the case of the GreenHawk3 aircraft, it has a more pronounced variation as the percentage change in weight throughout the mission is much higher. However, its bow shock overpressure value is very high since the design of the aircraft is such that the very backward wing positioning results in a very high aircraft shape factor value.

Aircraft	Altitude$[m]$	Mach number	Overpressure $[Pa]$	Overpressure $[psf]$
Concorde	12500	1.2	182.45	3.81
GreenHawk3	12500	1.2	197.40	4.12

Table 5 – Transition phase from subsonic to supersonic

As can be seen from table 5, the GreenHawk3 aircraft despite its lower weight, due to a less suitable shape has higher overpressure values in the early stages of the mission in the supersonic regime, and then lower in the remaining flight phases.
One of the limitations of Carlson's method is its inability to analyze focus booms, as well as the fact that it is able to simulate just the N-wave because it only considers stationary phases. However, the acceleration phase is represented by a non-stationary condition, and a phenomenon of coalescence of the wave system is present, which leads to the formation of a U-wave, with higher overpressure peaks. Flight tests estimate the factor due to acceleration to be between 3 and 5, while through Carlson's method this factor does not reach 2, certifying the inadequacy of the process for the focus boom.

6. Conclusions and Future works

In line with the current efforts towards an updated design process for future sustainable supersonic aircraft, an integrated design workflow including LTO and sonic boom evaluations since the early stages of the deisgn process was presented in this paper. The selected state of art models for noise prediction have been disclosed and applied to two different case studies, checking their capabilities in noise prediction and comparing the results to define preliminary guidelines for the next generation of supersonic aircraft. The highest criticality lies in obtaining accurate estimates of the parameters required to perform the noise analysis at this design level, and there is, therefore, a need to place it at the end of the iterative process cycle in a design-to-noise configuration. Consequently, there was a need to impose simplifications to keep the approach as simple as possible and capture the preliminary effects of all design components and operational parameters for low-fidelity noise generation.
Despite this, it has been shown that using this methodology it is possible to have an initial assessment of noise requirements at an early stage of the project. In addition, the consideration of reference values has confirmed that radical changes in configuration will be necessary for the future generation of supersonic aircraft to meet the standards for noise acceptability by the community. It has been assessed that the GreenHawk3 aircraft is more suitable than the Concorde for both the LTO cycle and the sonic boom. However, the configuration can be considerably modified and improved to achieve a noticeable reduction in the sonic boom itself. Therefore, future sensitivity and trade-off analyses will be necessary to define the aircraft configuration in order to meet future regulation of public acceptability. The proposed procedure was useful for identifying the main parameters influencing noise generation and assessing their impact in a quantitative manner, in particular it was seen that:

- For LTO noise, the absence of the afterburner is advantageous at sideline measurement point, along with having a reduced configuration for landing condition. With the smaller configuration a reduction of almost 5 EPNdB could be achieved, but the flight procedure modification remains essential to gain an higher reduction in noise generation.
- For sonic boom, the weight of the aircraft is an important factor, so it will be much easier to stay within acceptable limits with a small business jet than rather a large commercial aircraft such as Concorde.

- Also for sonic boom, the flight altitude plays an important role and the influence of the Mach number is much less pronounced. This also results in a reduced overpressure value for the GreenHawk3.

Through these methodologies, it is possible to define guidelines for the future generation of supersonic aircraft, emphasizing their maximum weight and flight altitude, without imposing numerous limitations on Mach number.
At least, the workflow presented in this paper paved the way toward integrated system design methodologies, attempting to couple and unify LTO and sonic boom noise assessments with the traditional design process. Future advances in the procedure implemented in the design flow could also include the assessment of engine emissions, to achieve the most up-to-date design methodology possible for the construction of a new generation of sustainable, supersonic aircraft.

6.1 Evaluation of a new standard of acceptability for Sonic Boom

Although there are still no clear rules regarding future regulations, several past tests suggest some possible overpressure values. The primary evidence relates to tests conducted in Oklahoma City between February and July 1964 and behavioral exams and subjective reactions to low and medium levels of sonic boom conducted in 1974.
In the latter one, the researchers evaluate the response of a certain group of male subjects aged 18-29 years following well-defined overpressure stimuli.[30] Among the studies, the researchers evaluate the percentage of those who gave a startle response regarding eyeblink and arm-hand. They also assessed cardiac response and heart rate variation following these stimuli. Finally, it was asked to compare the annoyance value given by the sonic boom at a certain overpressure with a 130 Db .22 caliber gunshot, setting a scale of 100 for this value.
The test showed that the difference in response with an overpressure level of 30 Pa or 50 is similar, whereas with values of 130 Pa the level of annoyance is much greater. Therefore, in the first instance, considering a value of 50 Pa(about 1 psf) as a reference for the future generation of supersonic aircraft is acceptable.
Another test made in California and Nevada in the 1970s involved training with SR-71 in the western part of the country. Although the purpose of the flights was not to create sonic boom questionnaires but to train pilots, several people were interviewed about six months after the end of flight operations. The tests were related to exposure with values between 0.5 and 1.0 psf for about a week, with the results showing little to moderate annoyance, startle reaction frequently noted and vibrations noted, with little damage caused by the sonic boom. These results, although not focused on sonic boom questionnaires, confirm that the 1.0 psf limit may be considered acceptable in the future for a new category of supersonic aircraft.[31].
As far as the reference value is concerned, we can see that it is much lower than that obtained by both Concorde and GreenHawk3. However, the former aircraft has a very high weight and size, while the latter is not designed to have a design-to-noise, and the wing positioning is such that it has a very high aircraft shape factor. With a different arrangement of the wing surfaces, it would be possible to obtain a configuration such that peak overpressure values would be much lower. The future generation of supersonic aircraft will necessarily have to be small in weight and size to be able to guarantee an overpressure value of less than 50 Pa or 1 psf.

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8. Copyright Statement

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