



DESIGN OF THE SENECA MACH 1.8 SUPERSONIC AIRLINER WITH MULTI-FIDELITY AERODYNAMIC ANALYSIS FOR NOISE-OPTIMISED TAKE-OFF TRAJECTORIES

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Abstract

SENECA project aims to advance the state-of-the-art in the development of sustainable supersonic civil aircraft. Aimed at meeting current noise regulations for subsonic aircraft during take-off and landing while minimising emission levels, the project also seeks to create concepts for a new generation of environmentally friendly aircraft with optimal fuel efficiency and low drag. The modelling precision of the aircraft platforms is designed to forecast certification noise levels and mission performance accurately. The technical work involves considering various combinations of airframe and engine matching in typical flight missions. The environmental investigation prioritises evaluating local noise and pollution levels at airports, as well as the global climate impact of supersonic aircraft. The methodology employs Multi-Disciplinary Analysis (MDA), integrating airframe, engine, payload, performance and mission parameters. Trade-off studies are conducted implementing methods with different degrees of fidelity. The reliability of the data is enhanced by computing the aerodynamic and performance analysis with tools of different levels of fidelity ranging from empirical methods up to scale-resolving numerical simulation. This allows the cross-checking of the results and hence will increase the credibility of the design outcome. Higher fidelity analysis is accomplished using Computational Fluid Dynamics (CFD) to benchmark achievable cruise performance and explore aerodynamic enhancements. The outcome includes a comprehensive description, analysis results, and geometric definition of the final aircraft platform for an airliner cruising at Mach 1.8, comparing the low/medium fidelity computational workflow results with the higher-fidelity ones.

Keywords: Supersonic aircraft; Multi-Disciplinary Design; Environmental impact, Landing and take-off noise, programmed lapse rate, SENECA project.

1. Introduction

As the aviation industry strives to push the boundaries of speed and efficiency, understanding the complexities and advancements in these key areas is crucial. The pursuit of supersonic travel has witnessed renewed interest and innovation in recent years. Researchers have extensively examined the aerodynamics and propulsion systems required to achieve and sustain supersonic speeds. The challenges inherent in supersonic flight are varied, including aerodynamic, structural, and propulsion considerations. The design of an efficient engine for a supersonic airplane can be a significant challenge; this efficient design is crucial for reducing fuel consumption and adverse environmental impacts in terms of emissions and noise pollution. [1]

The noise produced by high-speed aircraft has drawn more attention in the past few years since it will significantly disturb human beings when the second generation of civil supersonic aircraft enters service. The noise issue can be considered in two categories; the sonic boom produced during supersonic cruise, and that experienced by those near the airport during take-off and landing (LTO). This work is concerned with the latter challenge and the design work herein is to enable landing and take-off noise assessment in subsequent research.

The primary source of noise generated by aircraft during LTO is acknowledged to be the engine, specifically jet noise. Conversely, when high-altitude jet aircraft are in subsonic flight, the noise levels experienced at ground level are comparatively lower than the ambient noise in a city. It is noteworthy that the noise generated by a single high-speed aircraft flying at low altitude generally surpasses that produced by a substantial formation of high-speed aircraft at high altitude, even though the latter scenario results in a prolonged duration of noise exposure. A supersonic aircraft engine will be noisier during take-off than its subsonic counterpart due to the higher thrust requirements for supersonic cruise and supersonic climb. [2]

The first issue that needs to be addressed, in addition to the technological and design ones, is the absence of supersonic aircraft regulations, which are necessary for that kind of commercial aircraft to be able to enter service. The certification regulators impose noise standards that require compliance with specified noise criteria at three distinct three reference measurement points. The two noise reference points during take-off are flyover and lateral full power while during landing, the noise measurement location is the approach reference noise measurement point. Additionally, there is a cumulative volume standard for these three points. The highest noise thresholds for the three certification points can be computed using the formulas outlined in ICAO Annex 16 Chapter 3 [3]. It is essential to account for the additional stringency enhancements introduced in Chapter 4 and Chapter 14, reflecting advancements in noise reduction technologies integrated into both engine and airframe design. These advancements have resulted in incremental improvements in the overall noise performance of the aircraft. The noise reduction requirements specified by these regulations are illustrated in Figure 1, which shows the noise margin of different commercial subsonic aircraft upon entering service. The regulations also impose constraints on the cumulative noise level from the three noise certification points. Consequently, the actual noise reduction for each individual noise measurement location is significantly less than the cumulative noise margin value.

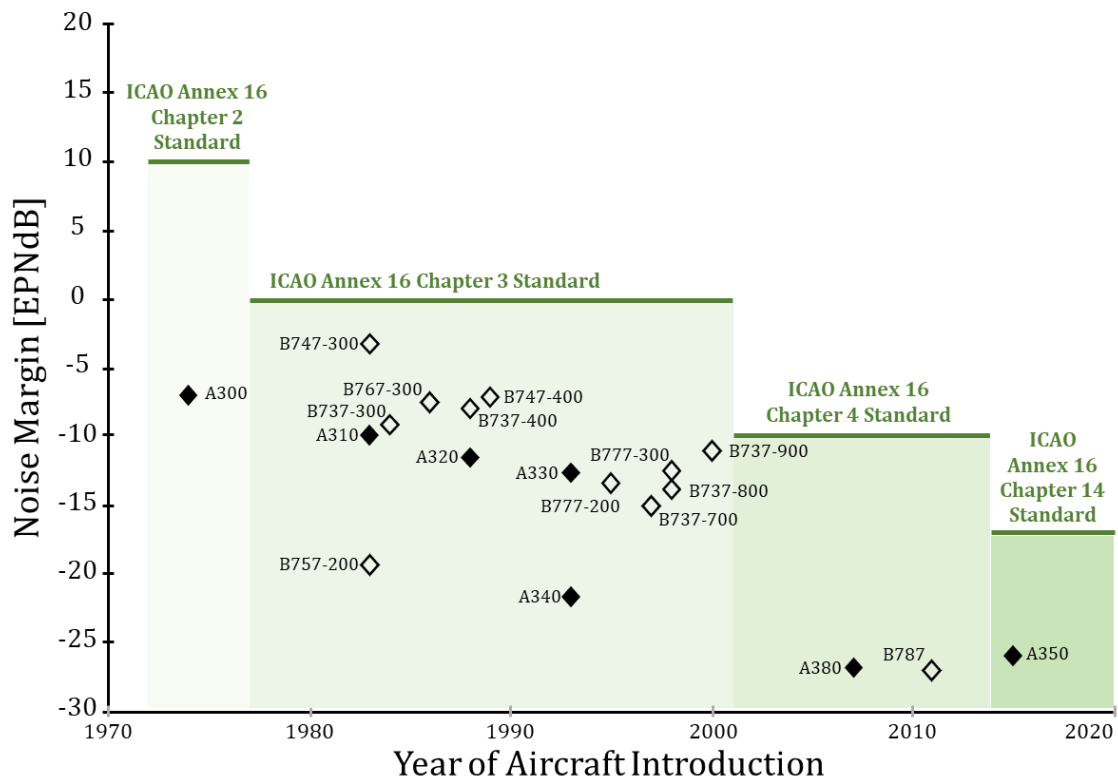


Figure 1 - Noise Reduction Trend Diagram. [4] [5]

ICAO								
MTOM**	0	20.2	28.6	35	48.1	280	385	400
Lateral			94		80.87 + 8.51 log M			103
Flyover	≤ 2*	89			66.65 + 13.29 log M			101
	3*	89		69.65 + 13.29 log M			104	
	≥ 4*	89	71.65 + 13.29 log M				106	
Approach			98		86.03 + 7.75 log M		105	

*Number of engines
**MTOM in 1000 kg

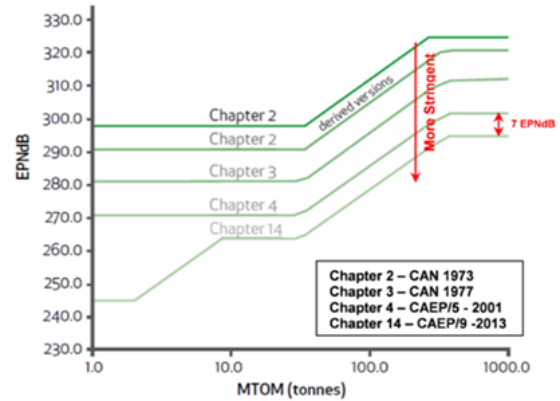


Figure 2 - Maximum noise levels ICAO Annex 16 Chapter 3, 4 and 14. [3]

Presently, the regulations governing civil aircraft's LTO noise are formulated for subsonic aircraft. Notably, there are currently no existing regulations pertaining to supersonic aircraft. The civil aircraft regulation bodies have clarified that the noise regulations specified are not applicable to supersonic aircraft and are actively developing rules for the noise certification of supersonic civil aircraft [6] [7]. The future supersonic aircraft noise standards will also discuss the role of effective reduction of take-off noise through new operating strategies, in order to comply with the current stringent noise limitations. ICAO foresees that the development of new certification regulations for supersonic aircraft may extend until 2025. Currently, the available data on emissions and noise from supersonic aircraft is largely confined to the Concorde, and commercial and research prototypes and studies like the European FP6 Integrated Project HISAC (Environmentally friendly high speed aircraft) [8] and NASA's supersonic flight program. Consequently, comprehensive examinations of the environmental impact of supersonic aircraft, encompassing emissions and noise near airports as well as the global environmental footprint, are imperative. These studies are crucial to inform the decision-making processes of European and international regulatory bodies during the ICAO Committee on Aviation Environmental Protection CAEP/12 and CAEP/13 cycles.

With the purpose of strengthening the European viewpoint on the necessary regulations for novel supersonic aircraft, the EU-funded SENECA project will contribute to the ICAO level discussions with its project results. The entire project plan is structured to work towards the major project dissemination and exploitation plan milestones, which are in line with the CAEP work programme and agenda. The primary objective of the research is to pioneer the development of innovative, medium-range supersonic civil jets that adhere to low drag, low emissions, and current LTO noise certification requirements. The project involves the creation of four distinct supersonic transport aircraft platforms, encompassing airframes and engines. These platforms range from supersonic business jets with cruise Mach numbers of 1.4 and 1.6 to large airliners designed for 100 passengers with cruise Mach numbers of 1.8 and 2.2. The development process incorporates multidisciplinary design, prioritizing compliance with current noise regulations for subsonic aircraft during take-off and landing and addressing the reduction of emission levels and low drag. The goal is to ensure the new generation of sustainable aircraft achieves the necessary flight range while demonstrating fuel efficiency through modern engine and airframe designs. The modelling detail of the aircraft platforms is designed to facilitate accurate forecasting of noise certification levels and overall aircraft performance [9].

SENECA aims to collect comprehensive and reliable data for the formulation of noise and emission regulations for civil supersonic aircraft requested by regulation authorities at national, European, and international levels. This involves examining a spectrum of supersonic aircraft. Both airframes and engines undergo optimisation to minimise environmental impact, considering noise and emissions near airports as well as the global climate impact. Data reliability is bolstered through the use of methods with varying fidelities, ranging from empirical correlations to scale-resolving numerical simulations.

The multidisciplinary design carried out for the different platforms involves constructing models that represent various disciplines within a design process and then integrating these models with an design iterative process [10]. The study presents case studies and methodologies that showcase the effectiveness in addressing in the early staged of the design, the intricate interdependencies between propulsion and acoustics in supersonic aircraft design [11]. Trade-off studies implementing methods of different levels of fidelity to compute environmental impact and aerodynamics will demonstrate the impact on the results as well as the efficiency of the process. NASA's research [12] explains the difference for a low and high fidelity method for multi-disciplinary design and describes that the computational time required for a high-fidelity analysis with CFD/CA is inefficient, suggesting the use of adjoint-based procedure implementing tightly coupled methodologies.

This paper provides a comprehensive overview of the current state of civil supersonic flight, emphasizing the challenges faced by aircraft designers and the advancements made in mitigating these challenges. By exploring the intricacies of supersonic noise and advocating for a multidisciplinary approach, the paper contributes to the ongoing discourse on the sustainable development of supersonic aircraft. While current certification criteria can be potentially met by making modifications to existing aircraft, a more systematic evaluation of these limits is necessary for considerable reductions in noise and emissions. By establishing environmental performance as an explicit design constraint rather than a post-design concern, this technique allows for the examination of both novel and improved aircraft configurations that may result in significant reductions in environmental impact. A range of aircraft can be studied depending on the desired environmental performance by assessing the trade-off between performance and environmental acceptability [13]. The design space is based on a set of procedures that are used to calculate various disciplines of aircraft performance and design. These procedures are integrated into a multidisciplinary design framework.

An application of the design process is detailed here for the SENECA Mach 1.8 airliner which evaluates the trade-off studies covering different configurations and the selection of the final aircraft design in order to meet low drag, low LTO noise and minimal emissions.

2. Multidisciplinary Analysis Framework

In the pursuit of designing innovative and sustainable aircraft platforms, a complex procedure integrating various analytical disciplines, including aerodynamics, structures, performance, and propulsion is required. The aircraft design process unfolds in three major phases: conceptual, preliminary, and detailed, with the conceptual design phase playing a major role in achieving a representative outcome. To initiate the conceptual design, requirements for mission capabilities are established. Subsequently, this initial design undergoes analytical calculations, and the results obtained guide the iterative process of the model in future studies where constraints are established for the multiple objectives to be accomplished by the final design. This iterative process results in a continuous modification of the design, ultimately aiding in the identification of optimal design layouts and nominal operating conditions. The conceptual design studies of innovative aircraft configurations rely on multidisciplinary design analysis. It is necessary to evaluate diverse aircraft configurations using consistent methodologies to measure the actual distinctions and potential advantages that each configuration may provide. To create the baseline configuration for an integrated design exploration of a Mach 1.8 airframe-engine, a series of steps has been undertaken, incorporating various tools for the design process.

This research specifically focuses on developing a conceptual design methodology for modelling the next generation of supersonic transport aircraft. This section details the methodologies and software integrated into the design framework. Below is a schematic representation of the design space in Figure 2. The framework was developed through the interconnection of distinct design modules and the creation of interfaces with external analysis software.

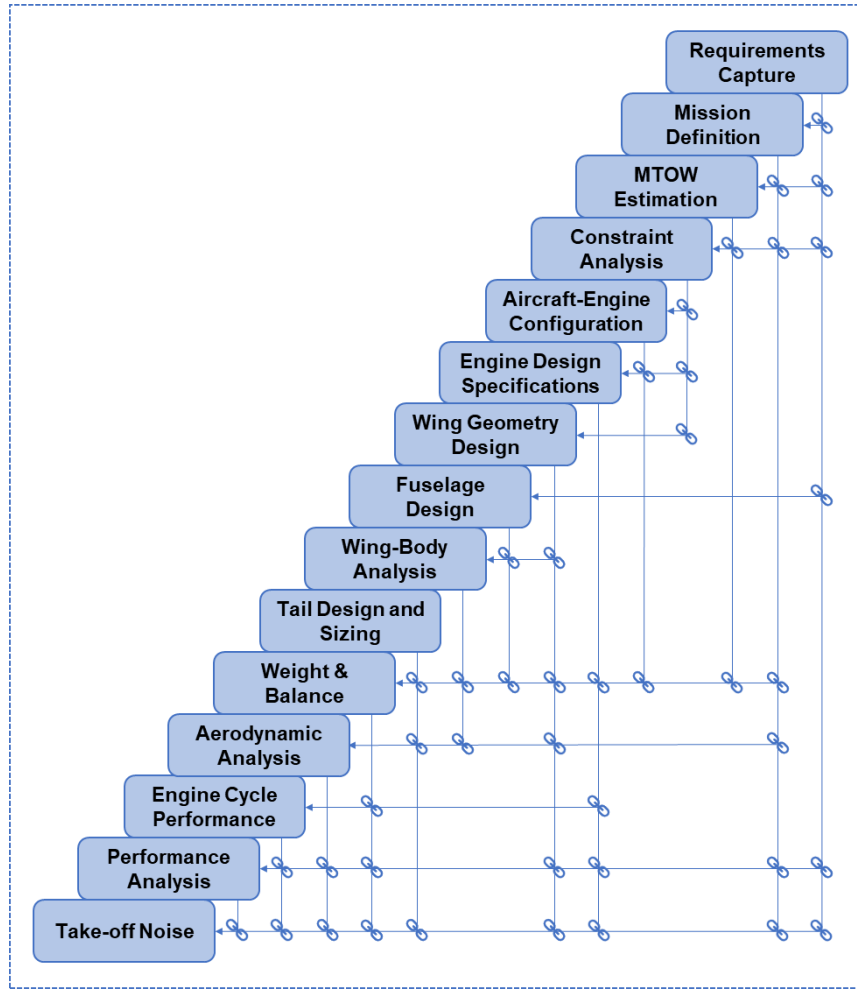


Figure 3 - Framework of multidisciplinary analysis. [14]

2.1. Trade Space Studies Using Different Fidelity Levels

To conduct a comprehensive analysis and build confidence in progressing the SENECA Mach 1.8 airliner platform design, various levels of fidelity analysis must be performed. To capture interactions among different analysis disciplines, a multidisciplinary analysis model was employed. For trade-off studies, the approach involved conducting system-level analyses taking into account environmental impact, aerodynamic performance, mission profile, and engine cycle. The top-level aircraft requirements—such as the number of passengers, cruise Mach, and range—were initially defined in the design. After establishing constraints related to drag studies, mission profile performance, and limitations on noise and emissions, the model recalculates aerodynamics and its impact on performance, stability, and fuel efficiency as well as weights. Adjusting the reference thrust scales the engine size, leading to changes in thrust and fuel flow tables. A shift in engine size also affects the nacelle, necessitating a recalculation of aerodynamics.

This work predominantly concentrates on the aerodynamic analysis, it explores how the constraints of minimising drag and performance influence the final optimal configuration of the Mach 1.8 airliner. Three levels of fidelity were employed in the analysis.

Firstly, in the low fidelity aerodynamics module, a modified adaptation of the EDET (Empirical Drag Estimation Technique, [15]) program is integrated into the FLOPS (Flight Optimization System) software [16]. The program modifications enhance the smoothness of the drag polars, refine the accuracy of Reynolds number estimates, and incorporate skin friction calculations using the Sommer and Short T' method [17]. Alternatively, the drag polars can be inputted and subsequently adjusted, considering variations in wing area and nacelle size [18] [19]. In addition, the lift-curve slope in subsonic flow and in supersonic flow has been calculated using the ESDU 70011 [20] and ESDU 70012 [21] models.

As for the medium fidelity methods, Vortex Lattice Method (VLM) is employed with VSPAero [22]. VLM models lifting surfaces but does not account for the effects of thickness and viscosity. It assumes flows are incompressible, inviscid, and irrotational. However, small-disturbance subsonic compressible flow can be modeled using the Prandtl-Glauert transformation. VSPAero extends VLM to linearized supersonic flow, which remains an inviscid method, with only simple models for viscous drag and stall. It can calculate induced, parasitic, and wave drags. In addition, Flight Stream [23] utilises the Vorticity Transport Model (VTM), which provides a direct computational solution to the incompressible Navier-Stokes equations in vorticity velocity form. This method effectively captures the wake structure without significant spatial smearing, allowing for a detailed representation of wake dynamics.

Finally, for the high fidelity approach, The Reynolds-Averaged Navier-Stokes (RANS) method employs semi-empirical turbulence models to represent the time-averaged effects of momentum and energy transport due to small-scale motions within the turbulent region. For external aerodynamics, Menter's K- ω shear stress transport turbulence model [24] is used. This hybrid model utilizes the k- ω formulation near the wall regions and switches to the k- ϵ model in fully turbulent regions away from the wall, leveraging the latter's insensitivity to boundary conditions. The transition between these models is managed through a blending function applied to the model coefficients. The modifications to the k- ω model enhance its ability to predict flows with strong adverse pressure gradients and flow separation.

3. Design of the Mach 1.8 Supersonic Airliner

Developing a practical, economically viable, and environmentally sustainable supersonic transport aircraft poses a substantial challenge in the aerospace industry, as historical records indicate. The complexity intensifies when seeking a balance among diverse criteria for the next generation of commercial supersonic aircraft while addressing the increasing call for more eco-friendly designs. First, the top-level aircraft requirements (TLARs) for the Mach 1.8 airliner are determined by analytical discussion with all project partners at the beginning of the project [9]. Environmental factors including NOx emissions and flyover/side-line noise are considered in addition to performance requirements. Following the identification of the criteria, a number of aircraft configurations with various outer planform wing geometry, empennage types, and engine configurations are simulated.

Table 1 - Top-level aircraft requirements captured for the SENECA Mach 1.8 airliner.

Requirement	Mach 1.8 SST
Range	4000 nm/ 7408 km
Passengers	100
Mach	1.8
Max Altitude	50000-60000 ft / 15 -18 km
LTO Noise	ICAO Annex 16 Vol I – Chapter 14
Emissions	ICAO Annex 16 Vol II-III

The pursuit of an optimal design for future supersonic commercial aircraft involves exploring various aircraft layouts. The airliner designed for Mach 1.8 is intended to seat 100 passengers and perform supersonic cruising over water. It features a cranked delta wing with a low aspect ratio and is powered by four engines mounted under the wings. The initial configuration, based on NASA's 765-072B [25] concept, adheres to the top-level aircraft general requirements defined by the SENECA project consortium. Key outputs of this analysis include mission trajectory profiles and the required thrust for various flight phases and conditions: sea level static thrust, take-off with all engines operative, take-off with maximum thrust for one engine out, initial and final transonic acceleration, top of climb, and mid-cruise. An iterative process was conducted to match the aircraft with the engines, improving mission efficiency and reducing LTO noise. The M1.8 airliner design has been refined through this iterative process to align the aircraft design with the engine cycle design.

Utilising airframe geometry data, the conceptual design of supersonic airliner platform is outlined below as a surface CAD model.

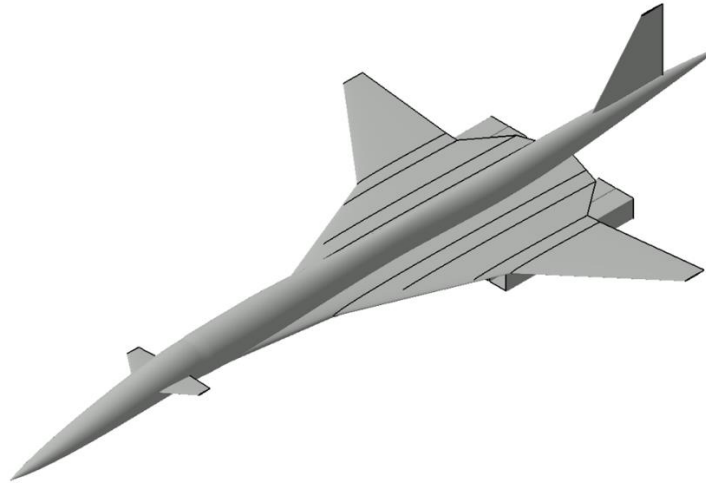


Figure 4 - Surface CAD model of SENECA M1.8 Airliner.

3.1. Aerodynamic Analysis

Initially, the higher speed drag polar for different Mach numbers was computed using the low fidelity methods based on NASA FLOPS and ESDU models. The following figure presents the high-speed drag polar across various Mach numbers, focusing on an altitude of 50000 feet which was the initial cruising altitude in the first mission design iterations. At this specific altitude and a Mach number of 1.8, the highest aerodynamic efficiency during cruise is 7.43, achieved with a lift coefficient of 0.075.

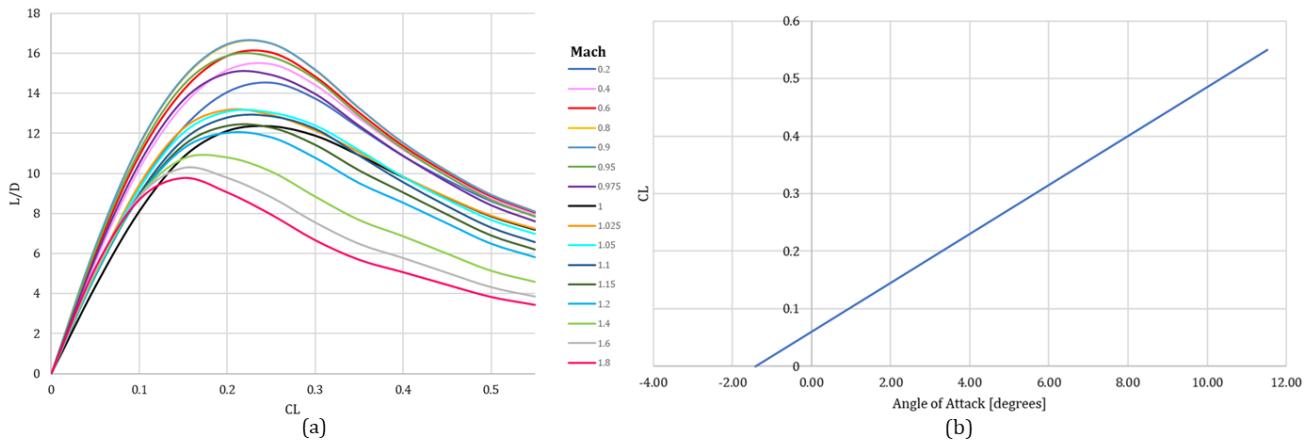


Figure 5 - High speed drag polar (lift over drag ratio vs lift coefficient) for M1.8 supersonic airliner using low-fidelity models (a) and lift coefficient vs angle of attack using ESDU models (b).

Next, the explanation for the CFD analysis and the definition of preprocessing conditions are presented as follows.

CAD geometries were also generated in OpenVSP and imported into the CFD solver as STEP files. The trailing edges were maintained sharp, which is generally not ideal for CFD analysis but is preferred for VLM codes. At the end of this section, the medium-fidelity aerodynamic results obtained using VLM methods are compared with the CFD results. The purpose of the CFD analysis was to validate the accuracy of lower fidelity methods in applicable regions and to generate results where these methods are unsuitable, such as during transonic acceleration. The CFD simulations included only the clean airframe geometry, excluding the engine nacelles.

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Initially, the sizing of the domain is established to achieve an optimal volume necessary for capturing flow characteristics without imposing excessive computational time. Key parameters include the length upstream and downstream of the wing, as well as the far field extent of the domain. The width of the domain is deemed crucial due to the creation of wingtip vortices. Computational analysis involves determining lift (C_L) and drag (C_D) coefficients across various lengths of the far field, inlet, and outlet. Comparing with the smallest domain size, changes in lift and drag coefficients remain below 10%. A cylindrical domain, as determined by the domain sizing study, is employed with dimensions measured from specific points: the inlet's origin is set at approximately two fuselage lengths away, the outlet is positioned at a distance of eleven fuselage lengths from the trailing edge's end, and the far field extends to a radius equivalent to ten half spans.

The simulation of flow takes place within a 3D modelling space, assuming steady flow conditions and disregarding phenomena such as buffeting (which involves high-frequency instability due to airflow separation or shock wave oscillations occurring at specific sections of the wing) and flutter.

The model accounts for fully turbulent flow, incorporating coupled equations for flow and energy in high-speed compressible scenarios. These equations, encompassing continuity, momentum, and energy, are solved in vector form, particularly suitable for situations where density, energy, and momentum exhibit strong interdependence. Density variations adhere to the ideal gas law. To ensure enhanced wall treatment (EWT), it is essential that the centroid of each cell adjacent to the wall resides within the viscous sublayer.

The following figure shows the different meshing densities and sizes across the domain. The total cell count is 38.81 million for SENECA 1.8 configuration at an altitude of 55000 ft for Mach 1.8.

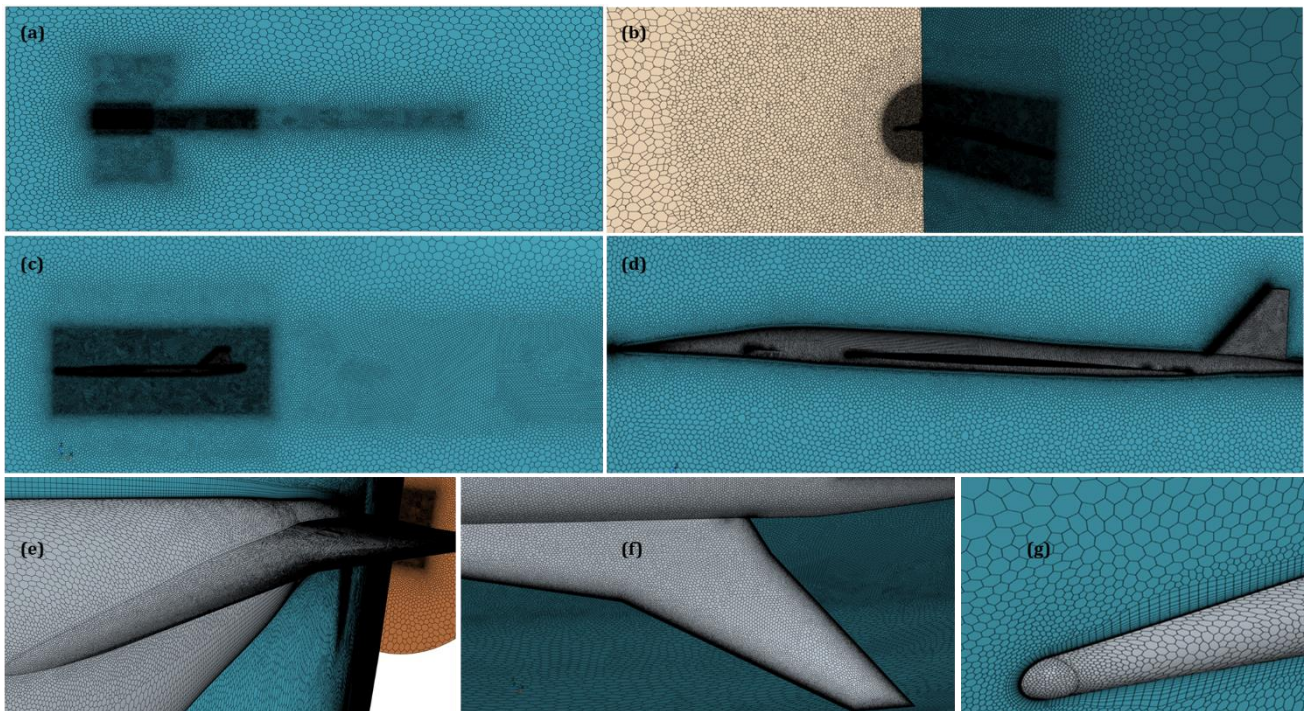


Figure 6 - Full domain mesh (a), 3D domain mesh (b), near body mesh (c), aircraft mesh (d), meshing around fuselage and canard (e), meshing around wing leading and trailing edge (f) and fuselage nose mesh (g).

Regarding boundary conditions, the domain was defined by a constant velocity inlet boundary condition as free stream. At the outlet, an atmospheric pressure boundary condition was imposed, while the outer surface was subjected to a symmetric boundary condition. Along the surfaces of the aircraft, viscous wall (no-slip) boundary conditions were specified. The symmetry plane boundaries were defined with an inviscid wall condition, enabling the use of a half model to reduce computational time. Flow conditions were established based on altitude and Mach number corresponding to a specific mission scenario. Turbulence characteristics were also configured, typically through empirical constants in the turbulence model, aligning with the known flow conditions. Normal turbulent intensities typically fall within the range of 1% to 5%.

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Following the domain sizing, the next step involved determining the mesh size. Due to the intricate geometry from interfaces such as wing-fuselage, tail-fuselage, and canard-fuselage, the strategy entailed creating prism layers over the aircraft body to accurately resolve the boundary layer. Particular attention was paid to areas in the flow field where complex flow physics are expected. Critical regions identified included the wing and canard surfaces, their leading and trailing edges, the wingtip area, the wake behind the wingtips, and the nose of the fuselage. Consequently, special mesh density zones were designated within the flow domain.

The convergence threshold for the supersonic case was achieved with the residuals below $10E-5$ indicating that continuity and energy have converged., meeting.

The figure below illustrates the Mach number distribution along the fuselage, with the pressure coefficient depicted on the aircraft surface. The freestream is set at Mach 1.8, and the figures demonstrate how the flow evolves along the fuselage with varying angles of attack. A shockwave develops around the top front part of the fuselage and the vertical tail. As the angle of attack increases, these shock structures expand rapidly. Initially, two shockwaves are present at the front of the fuselage, which merge into a stronger shock with increased angles of attack. At 0 degrees, the aft fuselage region does not present any shock wave, but at 2 degrees, a shock emerges and grows stronger, expanding toward the front as the angle increases. The fuselage tail also generates a shock that becomes visible only after 4 degrees, rapidly growing towards the trailing edge of the wing.

The pressure distributions over the body indicate where most lift is generated. At 0 degrees, there is minimal lift, but as the angle of attack increases, the flow accelerates over the top of the lifting surface, reducing pressure and creating a pressure difference that generates lift. In this scenario, the inboard wing starts producing lift before the outboard wing. It must be also noted that due to the high sweep, the fuselage experiences a higher Mach number compared to the wings.

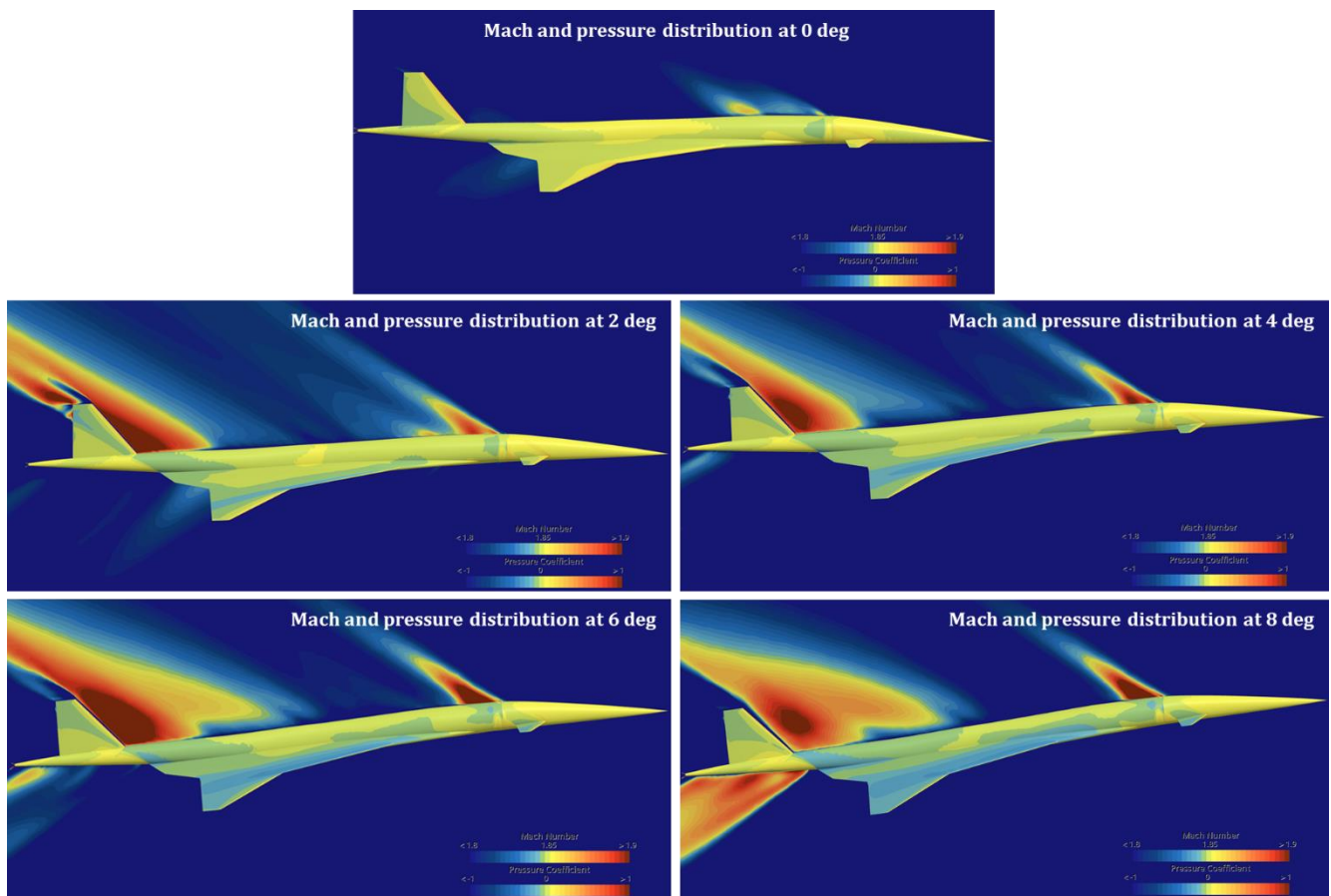


Figure 7 - Mach and pressure distribution at different angles of attack.

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The results from different multi-fidelity aerodynamic solvers, as discussed earlier, are presented in Tables 2 and 3. The RANS results align closely with OpenVSP for lift coefficients, with an error margin of less than 5%. However, for drag, RANS predicts higher values beyond a 2-degree angle of attack, while OpenVSP and FlightStream show similar drag values for the corresponding lift coefficients. The supersonic codes do not account for thickness and are limited in addressing compressibility (Prandtl-Glauert transformation) and turbulence. These codes also do not model flow separation and use wetted surfaces to calculate parasitic drag, relying on empirical equations for wave drag estimation.

Table 2 - Lift coefficient with respect to angle of attack.

LIFT COEFFICIENT			
Angle of Attack	VSPAero (VLM)	Flight stream	RANS
0	0.000925	0.0055	0.00320
2	0.073584	0.0553	0.08087
4	0.147056	0.1105	0.15252
6	0.219152	0.1825	0.22650
8	0.291909	0.2583	0.29391
10	0.364121	0.3344	0.36800

Table 3 - Drag coefficient with respect to angle of attack.

DRAG COEFFICIENT			
Angle of Attack	VSPAero (VLM)	Flight stream	RANS
0	0.0089336	0.0072	0.00305
2	0.0115596	0.0086	0.01163
4	0.0191996	0.0145	0.02034
6	0.0319515	0.0259	0.04076
8	0.0499293	0.0431	0.05855
10	0.0761215	0.0659	0.08140

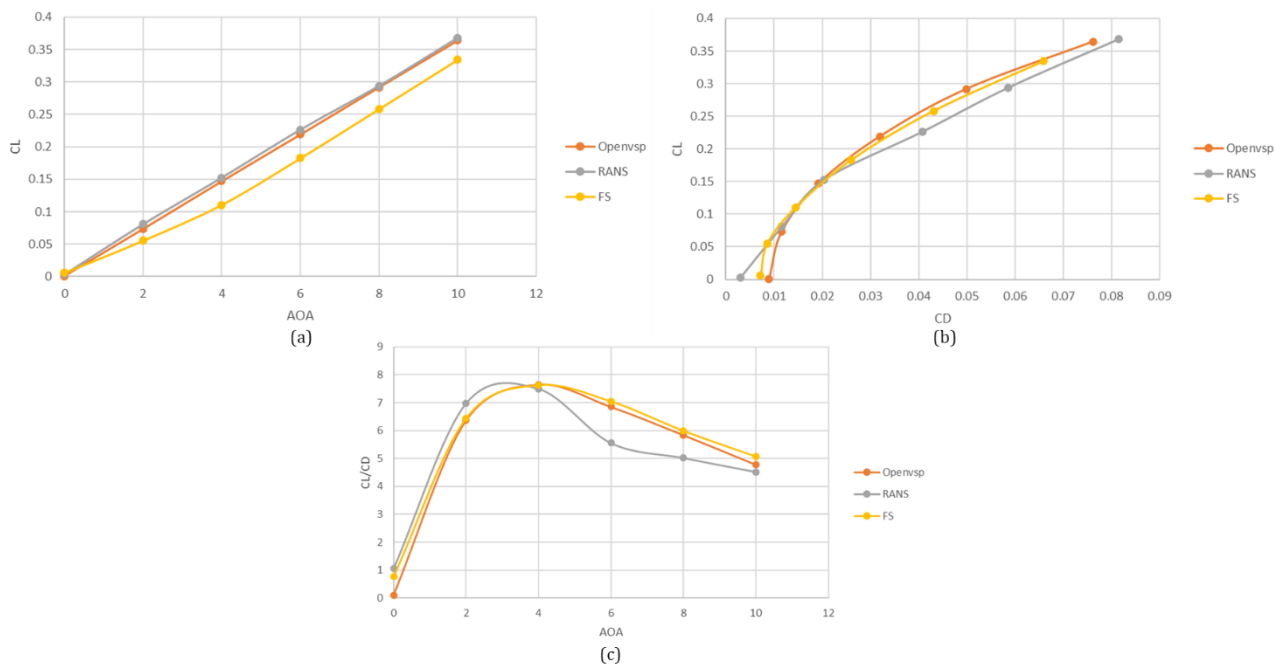


Figure 8 - Comparison of methods predicting aerodynamic efficiency: lift coefficient vs angle of attack (a), lift coefficient vs drag coefficient (b) and aerodynamic efficiency vs angle of attack (c).

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For the nacelle drag, its parasitic drag contribution was computed using VSPAERO. This software calculates parasitic drag by combining form drag, friction drag, and interference drag, which occur in any body moving through a fluid. The combined aerodynamics of the airframe and nacelle were then input into NASA FLOPS to calculate mission profiles. The aerodynamic efficiency of the combined geometry as a function of the lift coefficient is shown in Figure 9.

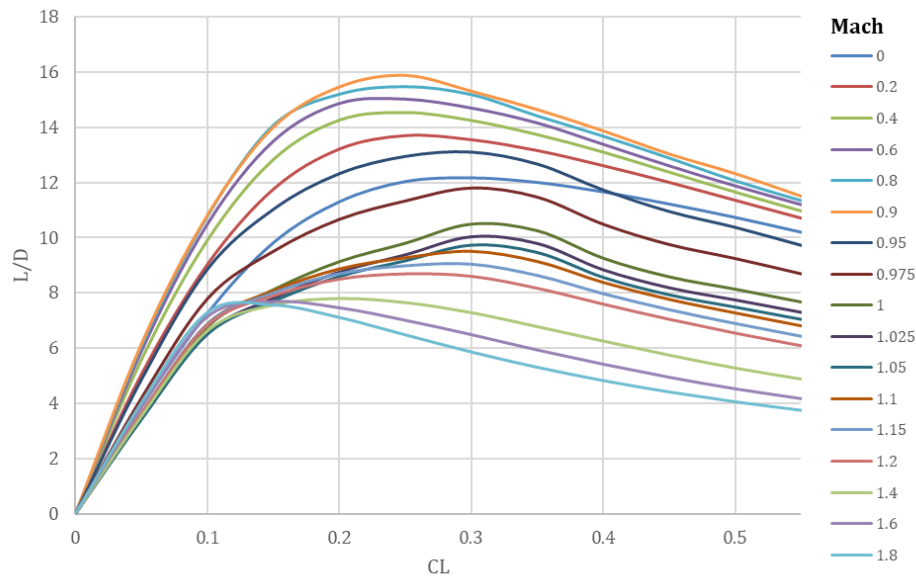


Figure 9 - High speed drag polar (lift over drag ratio vs lift coefficient) with high fidelity results.

3.2. Mission Profile Definition

The study of mission profiles for supersonic airliners identifies three distinct categories based on the conditions under which transonic acceleration occurs. These varied mission definitions also show differences in climb and descent schedules, as well as cruising methods. The first category follows a subsonic climb schedule, with acceleration to supersonic speed taking place after reaching cruising altitude. The second category involves transonic acceleration to supersonic speeds during the climb phase, similar to the standard procedure of the Concorde. The third category includes a level transonic acceleration phase positioned between subsonic and supersonic climb segments.

The supersonic airliner concept's performance evaluation was based on a supersonic non-stop mission profile that was derived from research conducted by Boeing and NASA. This baseline mission profile, which is parameterized to account for variations in both climb and cruise conditions, is shown in Figure 10. This profile is the starting point for assessing the SENECA Mach 1.8 supersonic airliner's performance.

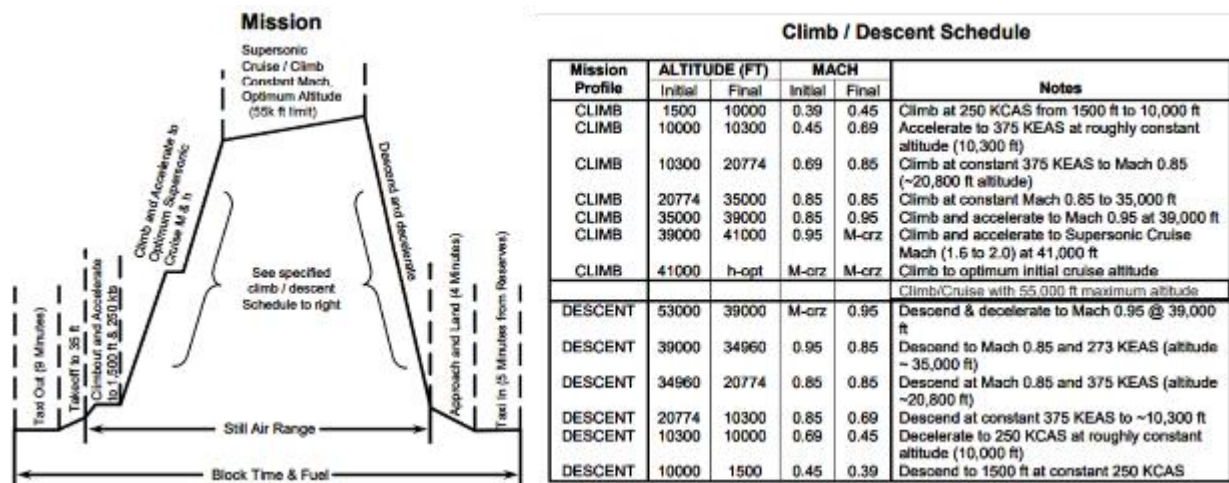


Figure 10 - Supersonic Non-Stop Mission Profile Boeing Mission Rules. [25]

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During the selection of mission profiles, the main goal was to balance time savings with propulsion efficiency. A subsonic climb schedule does not offer time savings, and integrating transonic acceleration into the climb phase results in higher thrust requirements and increased fuel consumption. The most optimal balance is achieved with a level flight acceleration phase, recommended at altitudes between 33000 ft and 40000 ft, to maintain a balance between performance, thrust, and drag.

The flight profile of the M1.8 supersonic airliner, as detailed in Figure 31, progresses through several distinct phases. It begins with the take-off phase, followed by a subsonic climb to 10300 ft, where the aircraft accelerates from Mach 0.45 to 0.69. Next, two consecutive subsonic climb segments occur: first climbing to 20774 ft and accelerating from Mach 0.69 to Mach 0.85, then a second climb to 35000 ft at a constant Mach 0.85. At 35000 ft, the aircraft undergoes transonic acceleration from Mach 0.85 to 1.3. These Mach numbers are selected based on the aircraft's aerodynamic characteristics and propulsion capabilities, minimizing the required thrust where drag increases the most. The final phase is a supersonic climb from 35000 ft to the design top-of-climb altitude of 47378 ft, during which the aircraft accelerates from Mach 1.3 to 1.8. Following this, the aircraft enters the cruise segment, which can take two forms: climbing cruise or cruising at a constant altitude and Mach number. Opting for a cruise climb represents the most fuel-efficient cruising strategy, wherein the aircraft consistently operates at its optimal performance levels. In a climbing cruise, the aircraft maintains a constant cruise Mach number while ascending to the predetermined maximum cruise altitude, constrained by NO_x emissions and cabin decompression limits. The cruise phase is performed at constant Mach number of 1.8 and climbing cruise up to 54652 ft. Finally, a descent and deceleration precede the landing.

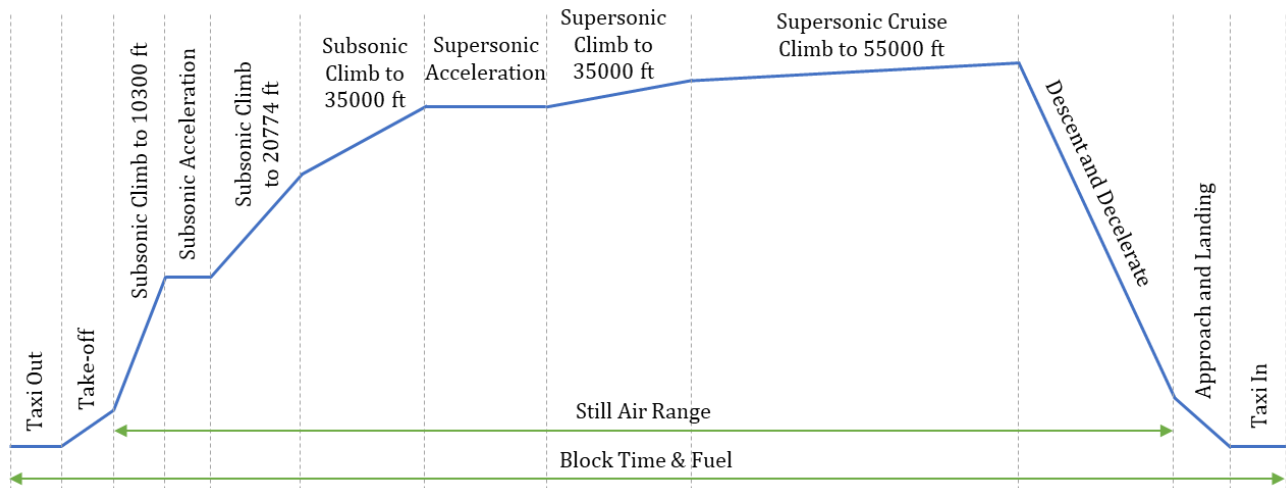


Figure 11 - Design mission for the SENECA Mach 1.8 airliner.

In order to perform the emissions assessment, a variety of mission profiles have been compiled, encompassing varying ranges and cruise speeds. Specifically, two mission profiles spanning 4000 nautical miles have been generated, each featuring cruising speeds of 1.8 Mach and 0.85 Mach. Furthermore, two additional mission profiles spanning 2000 nautical miles have been provided, each with cruising speeds set at 1.8 Mach and 0.85 Mach.

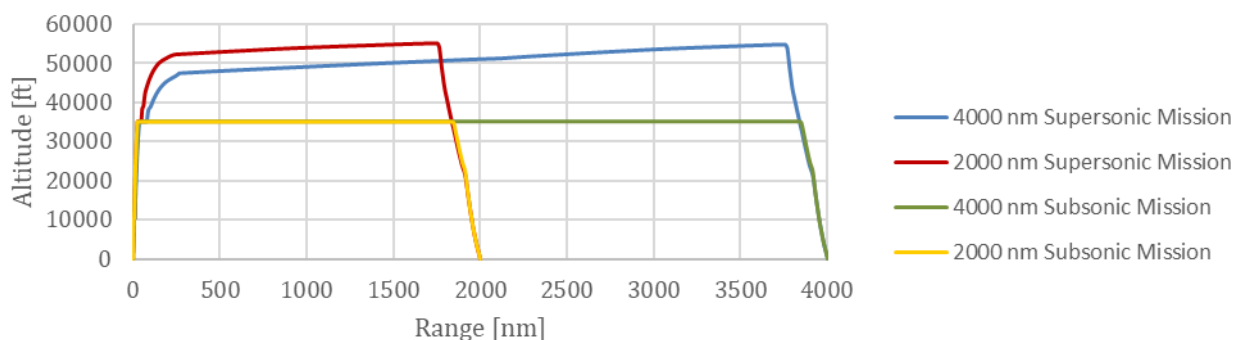


Figure 12 - Different supersonic and subsonic missions for the SENECA Mach 1.8 airliner.

3.3. Programmed Lapse Rate Take-Off Profiles

Every civil aircraft must be capable of flying safely in the event of a complete engine failure, referred to as the engine-out condition. An especially crucial requirement is that the aircraft should be able to execute a take-off, climb, and land safely even if an engine fails at the most critical moment—right as the aircraft is about to leave the ground. While a comprehensive analysis of engine-out operation would determine the optimum condition for the remaining engines, valuable insights can be gained by examining the engine-out behaviour with the remaining engines maintained at the same non-dimensional condition as before the loss of an engine. If an engine were to fail just as the aircraft takes off, it is imperative for the remaining engines to generate sufficient thrust for the aircraft to continue climbing and accelerating. The minimum thrust required for take-off can be calculated following the procedure in [26]. The supersonic cruise and supersonic climb thrust requirements for the propulsion system design results in an abundance of thrust available during take-off for supersonic aircraft. Therefore, the next generation of supersonic civil aircraft aims to take off with minimal thrust while adhering to certification performance requirements during departure procedures. Implementing minimum take-off thrust will imply minimal noise impact.

For the take-off noise assessment, different take-off profiles have been simulated by implementing a variable noise reduction system that utilises a programmed lapse rate (PLR) to minimise airport noise levels. Once the minimum thrust to take-off is determined while complying with performance requirements in the event of an engine failure, the take-off profile is defined as follows.

The minimum required thrust is upheld until reaching the altitude of 35 feet for obstacle clearance. Beyond this point, the PLR can be initiated at any altitude prior to the conventional pilot-activated thrust cutback. Implementing the PLR at lower altitudes is more advantageous for minimising sideline noise. To address flyover noise mitigation, specific performance requirements must be satisfied. The flyover thrust cutback level is determined by the thrust needed to maintain a climb gradient of 4%. Moreover, in the event of a single engine failure, the thrust level must equal or exceed that required to sustain a 3-percent climb gradient up to an altitude of 400 feet. Another consideration is the horizontal distance at which the thrust reduction for the cutback should be applied. The thrust reduction needs to be carried out before reaching the flyover reference measurement point, which is positioned at 6500 meters (21000 feet) from the start of the roll. This reduction should occur about 3000 feet before the monitoring location. A representation of the noise certification points is shown below.

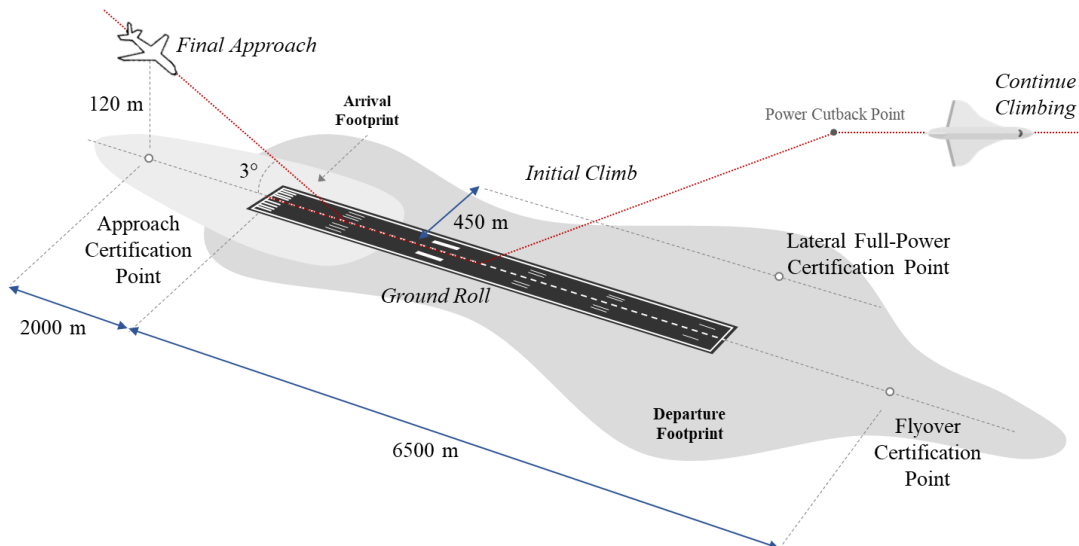


Figure 13 - Reference noise measurement points for landing and take-off noise certification. [27]

There are also requirements regarding the calibrated airspeed during take-off, determined in relation to the V_2 , the designated safe take-off speed for each aircraft platform. In brief, right after take-off, the aircraft must attain a speed of at least $V_2 + 10$ knots, with the speed not exceeding $V_2 + 20$ knots throughout the entire take-off profile. This V_2 constraint for supersonic transport, has been relaxed in the PLR investigation and only a maximum airspeed of 250 knots is mandated in order to enable a rapid climb.

Five different parameters have been considered: derated take-off thrust, rotation speed, PLR activation altitude, PLR thrust level and climb out speed. These different parameters have the following constraints in order to comply with performance requirements. Lower boundaries are established as feasible minimums, such as the obstacle clearance altitude of 35 feet, marking the earliest altitude for activating the PLR procedure. Specific limits are imposed on certain combinations of variable noise reduction system design parameters to prevent scenarios where these variables might yield illogical outcomes and result in failure.

Table 4 - Variable noise reduction system design variables and constraint ranges.

Parameter	Values
Derated Take-Off Thrust	Cumpsty Min=45% of max thrust, 50% of max thrust and 60% of max thrust
PLR Activation Altitude	35 ft; 200 ft
PLR Thrust Level	100% 90% 80% 70%
Climb Out Speed	V_2+20 kts, V_2+40 kts, V_2+55 kts, 250 kts
Rotation Speed	Minimum & Optimal for specific climb-out speed

For the derated take-off thrust, the minimum thrust allowed to take-off safely while complying with all the take-off engine failure certification requirements calculated following Cumpsty method [26], which is 44.85% of the maximum take-off thrust for the SENECA Mach 1.8 airliner. Further analysis has been performed for 50% of the maximum take-off thrust and 60% of the maximum take-off thrust.

For the PLR activation altitude, 35 ft and 200 ft have been analysed, based on noise assessments requirements. As for the PLR thrust level, 90%, 80% and 70% have been analysed. In addition, the 100% case has been included for comparative purposes in order to determine from the noise assessment the impact of following PLR procedures.

For the climb out speed, V_2+20 kts, V_2+40 kts, V_2+55 kts and 250 kts have been analysed. The climb out speed is reached as soon as the aircraft performance allows after passing 35 ft. Rotation speed and the climb out speed are correlated therefore for each specific climb out speed $V_2 + X$ kts, there is an optimal delayed rotation speed. Two cases for each climb out speed have been simulated, the minimum rotation speed and the optimal delayed rotation speed. The delayed rotation speed also comes constrained from having a maximum take-off field length of 10000 ft for this aircraft. The PLR take-off procedure followed in SENECA is shown below in the diagram.

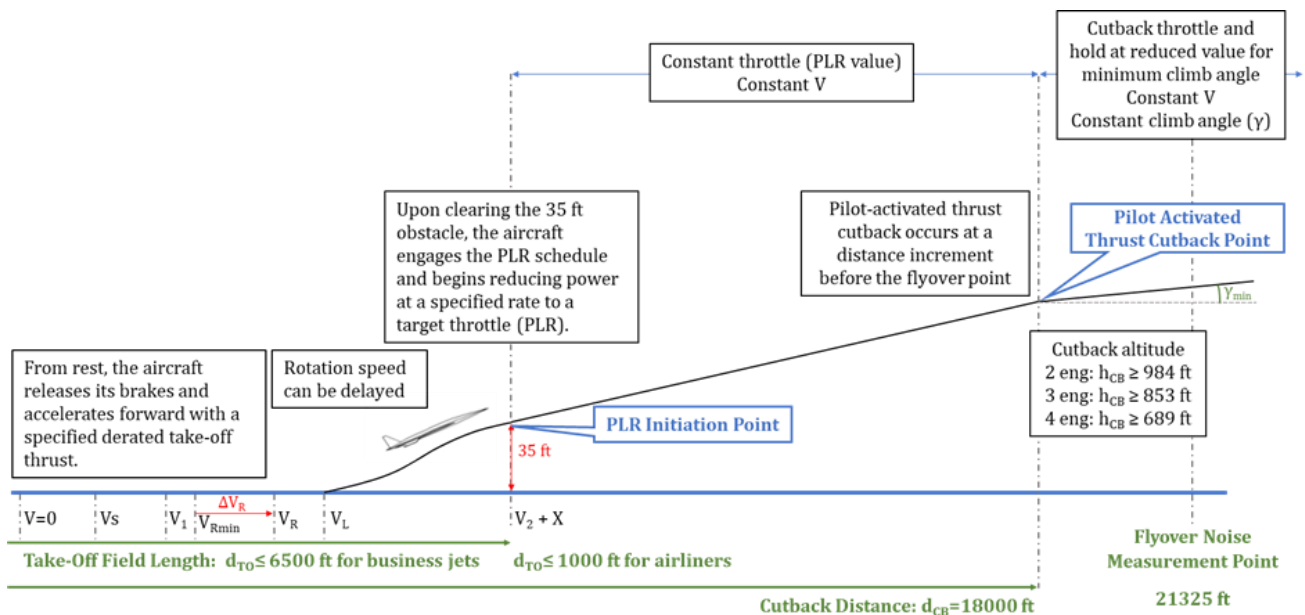


Figure 14 - Programmed Lapse Rate procedure definition. [27]

Figure 15 illustrates different examples of the take-off thrust profiles, taking into account minimum take-off thrust, a PLR initiation altitude of 35 feet, 80% PLR thrust level and different climb out speeds. The graph displays the total thrust against horizontal distance, indicating the points where PLR initiation occurs and where the standard pilot activated thrust cutback is implemented.

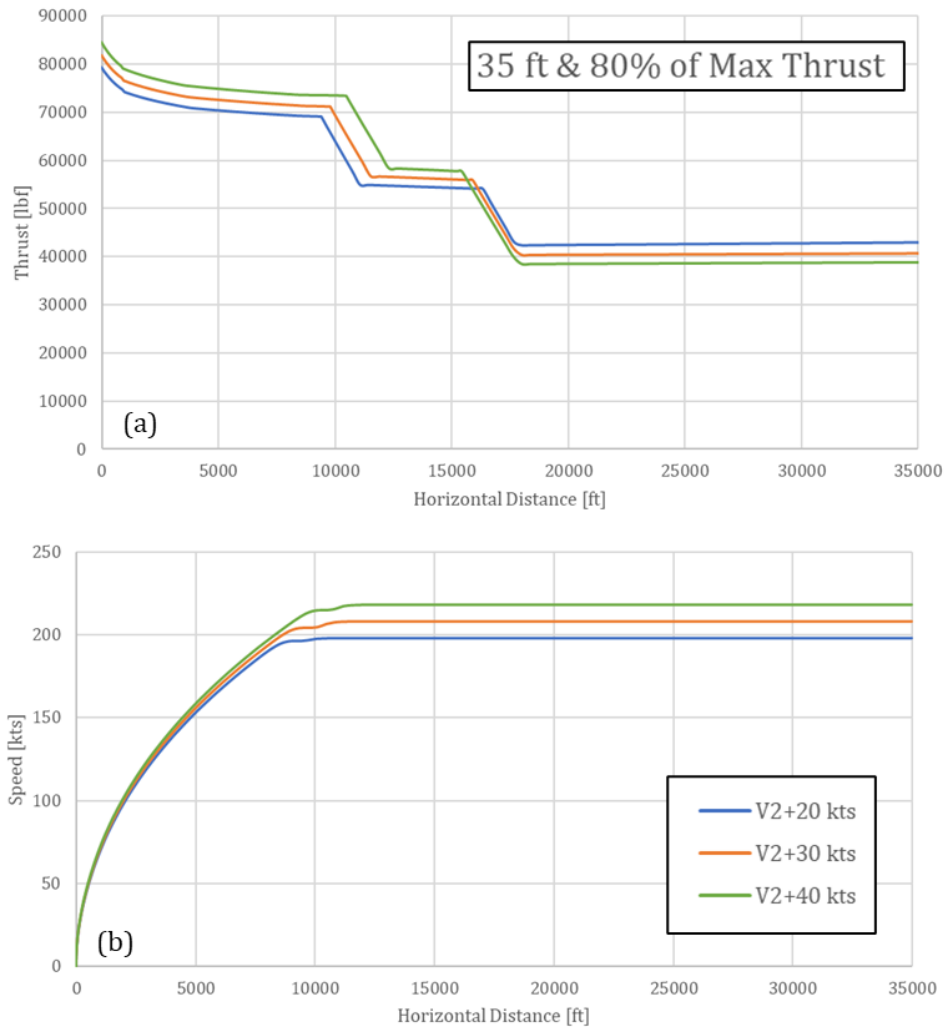


Figure 15 - Programmed Lapse Rate take-off profile for minimum take-off thrust, a PLR initiation altitude of 35 ft and a PLR thrust level of 80%: total thrust vs horizontal distance (a) and speed vs horizontal distance (b).

4. Conclusions

The aircraft design process has been performed to produce a concept for a supersonic airliner with a cruise Mach number of 1.8. Utilising multidisciplinary analysis in the conceptual design of aircraft, specifically considering environmental constraints, enables the identification of designs with minimised environmental impact.

The design of the M1.8 airliner has been refined through iterative processes that match the aircraft with its engine to achieve acceptable levels of take-off noise and mission efficiency. This iterative refinement process has ensured that the aircraft meets stringent noise regulations while maintaining the desired aerodynamic and propulsive efficiency during its missions.

The analysis phase of the project has been comprehensive, incorporating high-fidelity aerodynamic modelling to enhance the robustness of the design and the accuracy of the performance results. This high-fidelity modelling has provided a detailed understanding of the aerodynamic characteristics of the airliner, ensuring that the design meets all performance expectations. Additionally, medium-fidelity aerodynamic modelling using the Vortex Lattice Method (VLM) has been shown to be adequate for initial design assessments. This approach balances the need for detailed analysis with practical considerations of computational efficiency.

Mission profiles have been developed for both supersonic and subsonic missions, providing a clear understanding of the aircraft's performance across different operational scenarios for emissions assessment purposes. These profiles are essential for planning and optimizing the aircraft's routes and operational strategies. Additionally, strategies for mitigating LTO (Landing and Take-Off) noise have been investigated using PLR take-off profiles. This investigation is a critical step towards developing optimal noise mitigation strategies, ensuring that the aircraft can operate within acceptable noise levels in the airport environment.

The findings and data from this work are intended to be used for emissions and LTO noise assessment. The high-fidelity aerodynamic data, mission profiles, and noise mitigation strategies will provide a solid foundation for further research and development in these areas.

In conclusion, the iterative design process, comprehensive aerodynamic modelling, and detailed mission have concluded the M1.8 airliner's development. The work done has laid a foundation for future civil supersonic aircraft design and optimisation.

Establishing the boundaries for reducing the environmental impact of supersonic aircraft designs and exploring the potential of unconventional configurations, trajectories, and propulsion concepts will further enhance the environmental acceptability of supersonic travel. Moving forward, additional aircraft design work should focus on the initial layout of the landing gear, which is crucial for both the structural integrity and operational functionality of the airliner. Furthermore, the conceptual design phase should explore alternative engine mounting positions, specifically above on the rear fuselage, to optimise aerodynamics and structural performance.

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