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Conceptual Design of Supersonic Aircraft to Investigate Environmental Impact

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The SENECA ((LTO) noiSe and EmissioNs of supErsoniC Aircraft) project, funded under the EU Horizon 2020 framework, is dedicated to the exploration of future designs for supersonic business jets and supersonic commercial airliners, placing significant emphasis on minimising landing and take-off noise and mitigating emissions. The research outcomes are intended to inform discussions at ICAO level, providing scientific support to enhance the European perspective on regulatory requirements for novel supersonic aircraft. The overall aim of the research is the development of four different supersonic transport aircraft platforms, comprising both airframes and engines design. These aircraft configurations range from supersonic business jets, designed for cruise Mach numbers of 1.4 and 1.6, to large airliners capable of accommodating 100 passengers, with cruise Mach numbers of 1.8 and 2.2. In pursuit of the next generation of environmentally sustainable supersonic civil aircraft, the research employs a multi-disciplinary design optimisation strategy. This strategy primarily focuses on meeting the current noise regulations for subsonic aircraft during landing and take-off and secondly on reducing emissions levels. This paper details the conceptual development of the platforms specifications for the four supersonic aircraft designed within SENECA project. These specifications include geometrical and configuration data, performance characteristics, as well as mission trajectories and profiles.

I. Introduction

The current state of supersonic aircraft technology and its certification are discussed in this section as well as how SENECA ((LTO) noiSe and EmissioNs of supErsoniC Aircraft) activities endeavour to advance technology and methodologies in order to address the current state-of-the-art challenges. The HISAC (High Speed Aircraft) project and the ongoing ICAO (International Civil Aviation Organisation) CAEP (Committee on Aviation Environmental Protection) work primarily represent the basis for the work in the SENECA project. Overture from Boom Supersonic and the X-59 QueSST Aircraft from NASA and Lockheed Martin represent the state of the art in the future supersonic transport aircraft.

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The main goal of HISAC was to determine the technical viability of a small-size supersonic transport aircraft that complied with environmental regulations using a Multidisciplinary Design Optimisation (MDO) approach and targeted technological advancements to provide recommendations for upcoming supersonic regulations. For this purpose, firstly, the identification of aircraft specifications that could meet the prospective requirements was carried out. Three classes of aircraft concept were designed with special emphasis on environmental impact: noise, emissions and sonic boom [1]. The three classes of aircraft platforms studied in HISAC project are: supersonic overland concept for low boom purposes, supersonic overwater concept focused on long range and low noise concept to meet low noise. The following figure illustrates the external shape of a configuration for each class developed during the HISAC project.

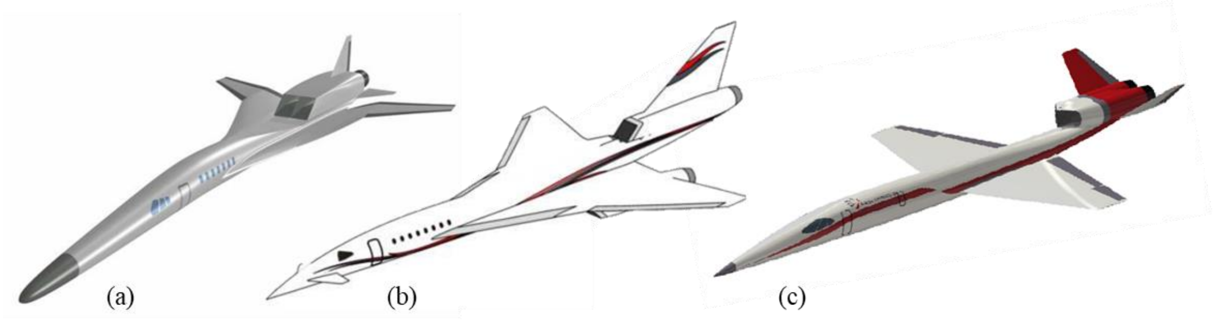


Fig. 1 External shape of low boom (a), low noise (b) and long range (c) HISAC concepts [1].

HISAC project through the definition of these different platforms offered recommendations for upcoming environmental regulations to policymakers as well as provide progress on supersonic aircraft novel technologies maturation and its corresponding design and multidisciplinary optimisation. Finally, the project outcome identified general trade-off in the design of supersonic platforms, this trade-off has two main directions, represented in the picture below, (1) specifications trade-offs and (2) architecture and technology trade-offs [2].

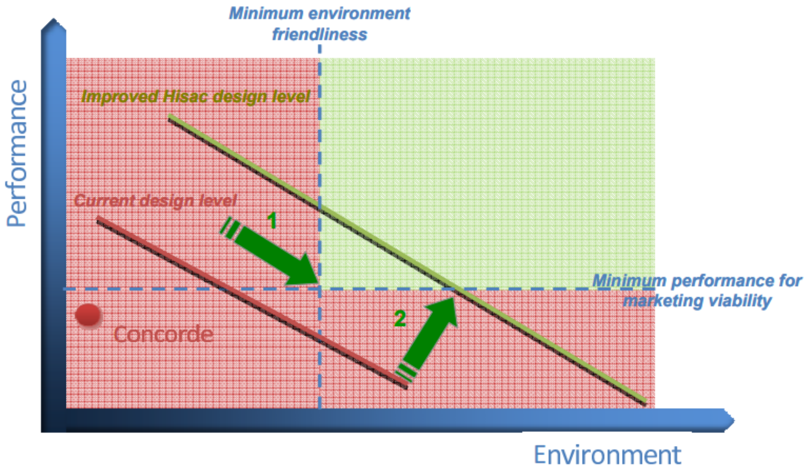


Fig. 2 Performance against environmental impact of HISAC concepts and trade-off studies directions [1].

Regarding the supersonic transport state of the art, Overture by Boom Supersonic is a supersonic commercial aircraft engineered for passenger travel at Mach 1.7 [3]. This aircraft is strategically designed to outperform earlier supersonic designs in terms of fuel efficiency and environmental impact since Boom Supersonic has been working on addressing challenges such as sonic boom, noise reduction, and fuel efficiency in the development of Overture.

In a parallel effort, the X-59 QueSST (Quiet Supersonic Transport) aircraft by NASA and Lockheed Martin, serves as an experimental platform dedicated to studying the effects of sonic boom and pioneering technologies that enhance the quietness and social acceptability of supersonic flight over inhabited areas [4]. This experimental aircraft, equipped with a single engine, is intended to cruise at Mach 1.4 at 55000 ft.

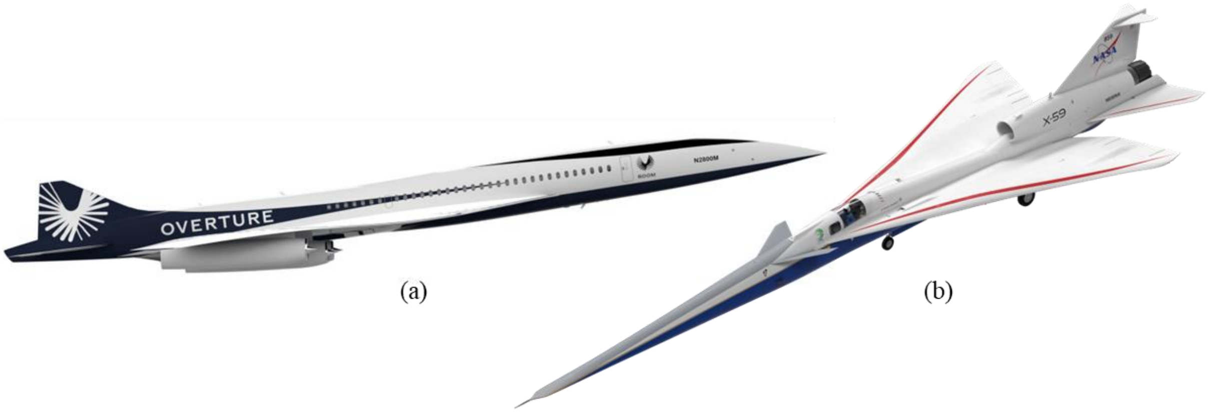


Fig. 3 Overture by Boom Supersonic [3] (a) and X-59 QueSST (Quiet Supersonic Transport) by NASA and Lockheed Martin (b) [5].

As the SENECA project places emphasis on landing and take-off noise investigation associated with supersonic aircraft, it is imperative to delve deeper into the HISAC low noise concept.

The Dassault Aviation low LTO (Landing and Take-Off) noise platform, shown in Fig. 4, was designed to meet the following top level aircraft requirements: cruise Mach number of 1.6, mission range of 4000 nm, three engine configuration and MTOW of 51 tonnes for a cabin size allowing for 8 to 20 passengers. This platform's specific goal was to offer a cumulative margin of 10 EPNdB in comparison to the chapter 4 restriction (equivalent to 3 EPNdB margin vs chapter 14 limit).

During HISAC novel engine designs and LTO noise mitigation techniques were explored. In order to minimise jet noise, two noise reduction approaches were analysed: a mixer-ejector concept and a conventional variable confluence (CVC) concept [6]. The two concepts shared a common goal of diminishing the noise generated by jet engines during take-off, while simultaneously mitigating any adverse effects on the engine or aircraft's other operational parameters, particularly drag during cruising.

Research into advanced take-off procedures revealed that achieving optimal range while meeting noise requirements is only possible through the collaborative optimisation of both aircraft and engine design parameters, as well as effective management of thrust.

Fig. 4 HISAC low LTO noise platform by Dassault [1].

Apart from the technological and design challenges, the first challenge that must be addressed is the lack of supersonic aircraft regulations without which the entry in service of this type of commercial aircraft would not be feasible. Hence, aviation regulatory authorities are working towards a supersonic future, as noise certification requirements are already under development. The certification authorities' approach for the challenges faced as part of the standardisation and rulemaking for supersonic aircraft are explained in the following paragraphs.

The current situation for the international certification rules of supersonic aircraft is as follows: While noise standards (Chapter 14 of ICAO Annex 16 Vol I, [7]) and emissions standards (Chapter 2 of ICAO Annex 16 Vol II- Vol III, [8],[9]) for subsonic aircraft have been updated over time because of the new technologies implemented, for supersonic aircraft there has been no evolution since the Concorde regulations. Existing subsonic aircraft rules present substantial challenges and unsolvable obstacles for any new supersonic transport aircraft (SST) design. Additionally, due to the difference in flying performance of SST in comparison with subsonic transport, alternative speed limits may be required during certification to achieve appropriate noise restrictions. As a result, the FAA have proposed changes to existing subsonic aircraft standards, and numerous research groups are considering them, with a particular focus on departure procedures. ICAO is considering a number of operational rule adjustments to give SST vehicles a realistic chance to comply with the noise certification requirements.

As for the USA proposition, the FAA (Federal Aviation Administration) offered a notice of proposed rulemaking (NPRM) on Noise Certification of Supersonic Airplanes [10] where it is described the noise limitations suggested for each of the three noise references measurement points. The number of engines and the maximum take-off mass of the supersonic aircraft to be certified will determine these limits. The NPRM's regulations apply to business jets with a maximum take-off weight of 150,000 pounds (68,039 kg) and a design speed of Mach 1.8. Furthermore, the proposed standard expressly permits the use of Variable Noise Reduction Systems (VNRS) for propulsion or configuration changes during LTO.

Finally, the European position in supersonic aircraft regulations is based on four major points: the same noise limits requirements for both supersonic and subsonic transports; revision of the current rules in order to include aircraft with innovative available environmental technology; introduce carbon dioxide (CO2) emission regulations; and study the climate impact of supersonic transport considering their operational altitudes.

As for the technological approach, noise reduction technologies alongside performances procedures will be investigated in order to achieve LTO noise certification levels for all aircraft platforms. The ultimate goal is to advance towards environmentally friendly supersonic flight. In order to guarantee that supersonic aviation will uphold the current stringent requirements for noise applied to subsonic aircraft and make suggestions for new emission limits, significant technological advancements must be made.

Only a comprehensive and trustworthy database can serve as the foundation for an informed discussion on the certification of supersonic aircraft. This database ought to demonstrate how key aspects of aircraft and engine design, as well as take-off and landing trajectories, affect the certification levels.

II. Ambition of SENECA

European civil supersonic research on LTO (Landing and Take-Off) noise and emissions has remained dormant since HISAC. Eleven academic and industrial aerospace entities from Europe have come together to address the challenges posed by the European Commission's LC-MG-1-15-2020 call for project proposals named, "Towards global environmental regulation of supersonic aviation". Taking into consideration the potential market entry of this next generation of supersonic aircraft, the project's initial assumptions include that these aircraft will not be able to fly over land at supersonic speeds. Therefore, the design missions for the different platforms through this project are defined to fly at subsonic speeds over land and supersonic speeds over water. As sonic boom analysis and its corresponding mitigation techniques are out of the scope for this project since the upcoming generation of supersonic transport is anticipated to refrain from flying at supersonic speeds over land, the project's primary emphasis centres around the noise and emissions associated with landing and take-off, in addition to the global environmental impact.

The project aims to develop four different supersonic aircraft platforms, from business jets to large airliners, using a MDO approach to meet current noise regulations and reduce emissions while maintaining fuel efficiency. The impact of specific supersonic engine technologies and variable noise reduction systems will be investigated, and fuel burn/CO_2 data and engine emission indices will be provided. The project will also quantify the climate impacts of supersonic aviation and deliver trade-offs between environmental aspects and flight range, disseminating findings to international legislation authorities to develop noise and emissions standards for supersonic aircraft. Throughout the completion of this project, the following areas will be addressed: enhancement of multidisciplinary optimisation of supersonic aircraft, trajectories, and operations to incorporate higher-fidelity environmental models; determination and investigation of physics-based strategies for reducing noise and pollution at airports, on a local and at a worldwide scale while analysing their effects on aero propulsion and trajectory optimisation technologies to further lower noise levels and emissions. The project technical work involves evaluating different combinations of aircraft and engines on relevant example flight missions. Meanwhile, the environmental aspect focuses on assessing the noise and pollution levels at airports as well as the overall impact of supersonic aircraft on the global climate. Figure 5 illustrates that SENECA is divided into six work packages, with four dedicated to technology work (WP2-5), and two focused on project coordination (WP1) and dissemination (WP6).

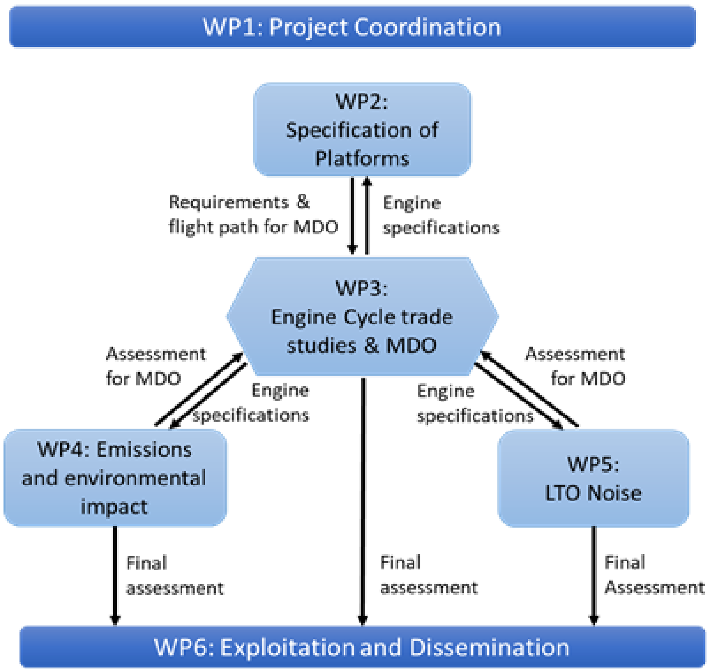


Fig. 5 Pert diagram of SENECA project [11].

WP2 focuses on the development of the airframe design, definition of landing and take-off trajectories and determination of aircraft specifications for engine design and environmental impact assessment. WP3 is responsible for engine development, gathering performance, fuel burn, and geometry data to create engines with the best compromise between environmental impact and flight range. WP4 calculates emission indices and climate impact based on engine specifications, while WP5 predicts noise certification levels and investigates noise reduction technologies for supersonic aircraft. WP6 coordinates the project and disseminates results.

To conclude, the overall ambition of the project is to take the next step in the development of sustainable supersonic transport, while maintaining the current high standards for noise regulations required from subsonic aircraft and provide recommendations for new emissions limitations. In order to have a discussion about the certification of supersonic aircraft, it is crucial to have a comprehensive and reliable database. This database should illustrate how various design parameters of the aircraft and engine, along with landing and take-off trajectories and VNRS, affect the certification levels. SENECA is creating a thorough database by examining the certification levels of different supersonic aircraft models with varying payload and cruise speed. To ensure the reliability of the data, industrial and academic entities will use different tools with varying degrees of fidelity, ranging from empirical methods to scale-resolving numerical simulations which will allow the cross-checking of the results, enhancing the credibility of the findings.

This paper presents the activities and outcome produced by WP2, which entails developing multiple aircraft specifications that will serve as the foundation for conducting further analysis on the potential of these aircraft to enter service, particularly after undergoing rigorous environmental impact assessment. WP2 aims to create platform specifications for supersonic aircraft that are appropriate for evaluating their environmental impact, including emissions and noise. This work will establish specifications for aircraft with a 4000 nm range. This includes two supersonic business jets with capacities ranging from 6 to 10 passengers and cruising Mach numbers of 1.4 and 1.6, as well as two supersonic airliners that can accommodate 100 passengers and cruise at Mach numbers of 1.8 and 2.2. The platforms specifications include geometrical and mass data, performance characteristics, and mission trajectories/profiles. The following figure illustrates the flow of work in the project with the activities from work package 2 in detail.

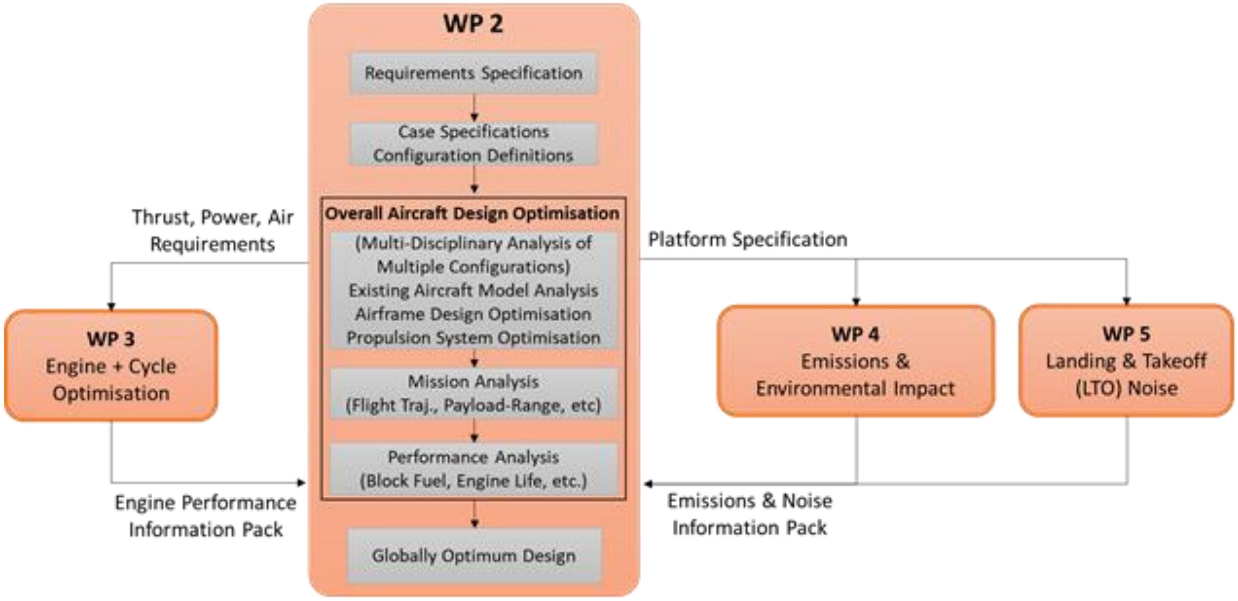


Fig. 6 SENECA project work packages flow of work [12].

In stage 1, the initial specifications of the aircraft, the thrust requirements at relevant operating conditions, geometrical constraints for engine integration as well as noise and emission targets needed in stage 2 for the engine development are generated and exchanged between the work packages. In the following chapter the design approach for these stage 1 results is presented as well as the initial outcome for the overall aircraft design for the four aircraft platforms.

III. Conceptual Design Environment

The SENECA outcome will set the new state of the art for the next generation of supersonic transport aircraft. As for the work package 2 contribution, these results will be highly integrated engine-airframe architectures, designed and optimised from the onset for a specific mission profile and a minimum environmental footprint.

The primary inputs to WP2 are the top-level aircraft requirements (TLARs) which are specified at the beginning of the project by analytical discussion with all the project partners.

Table 1 Top-level aircraft requirements captured for the SENECA supersonic aircraft platforms.

Requirement	Mach 1.4 SSBJ	Mach 1.6 SSBJ	Mach 1.8 SST	Mach 2.2 SST
Range	4000 nm/ 7408 km	4000 nm/ 7408 km	4000 nm/ 7408 km	4000 nm/ 7408 km
Passengers	6-30	8-10	100	100
Mach	1.4	1.6	1.8	2.2
Max Altitude	50000-60000 ft / 15 -18 km	50000-60000 ft / 15 -18 km	50000-60000 ft / 15 -18 km	50000-60000 ft / 15 -18 km
LTO Noise	ICAO Annex 16 Vol I – Chapter 14	ICAO Annex 16 Vol I – Chapter 14	ICAO Annex 16 Vol I – Chapter 14	ICAO Annex 16 Vol I – Chapter 14
Emissions	ICAO Annex 16 Vol II-III	ICAO Annex 16 Vol II-III	ICAO Annex 16 Vol II-III	ICAO Annex 16 Vol II-III

The ongoing work for the aircraft specifications during the initial stage of the project will be based on the extensive collaboration with the engine cycle performance team, data exchange will involve thrust requirements and receiving engine decks in multiple iterations. These engine decks will provide crucial information on both on- and off-design cycle performance as well as geometrical data. This data will then be utilised to refine the platform specifications.

During the later stages of the project, MDO and trade-off studies will be conducted by considering performance, emissions and noise together. This matter falls outside the scope outlined in this paper, as the validated results in question are currently in the developmental phase. The results obtained after performing multidisciplinary design optimisation for the multiple aircraft platforms will be incorporated into a subsequent publication at a later date, closer to the end of the project.

For the definition of the aircraft specifications, mission analysis and performance analysis, a range of multiple Cranfield University in-house and open access tools (AirCADia and NASA FLOPS) have been integrated to establish a computational workflow that achieves low-to-medium fidelity. This workflow incorporates several modules for multidisciplinary analysis, such as structures, aerodynamics, propulsion, mission, and stability.

The design framework employed to develop the initial specifications for the four supersonic designs is mainly based on NASA Flight Optimisation System (FLOPS). The Aeronautics Systems Analysis Branch at NASA Langley Research Center developed this primary aircraft synthesis software which enables rapid conceptual aircraft design and advanced technology impact assessment. This multidisciplinary software includes design modules such as weights estimation, aerodynamics, engine cycle analysis, propulsion data scaling and interpolation, detailed mission performance analysis, take-off and landing performance analysis, noise footprint estimation, and cost analysis [13].

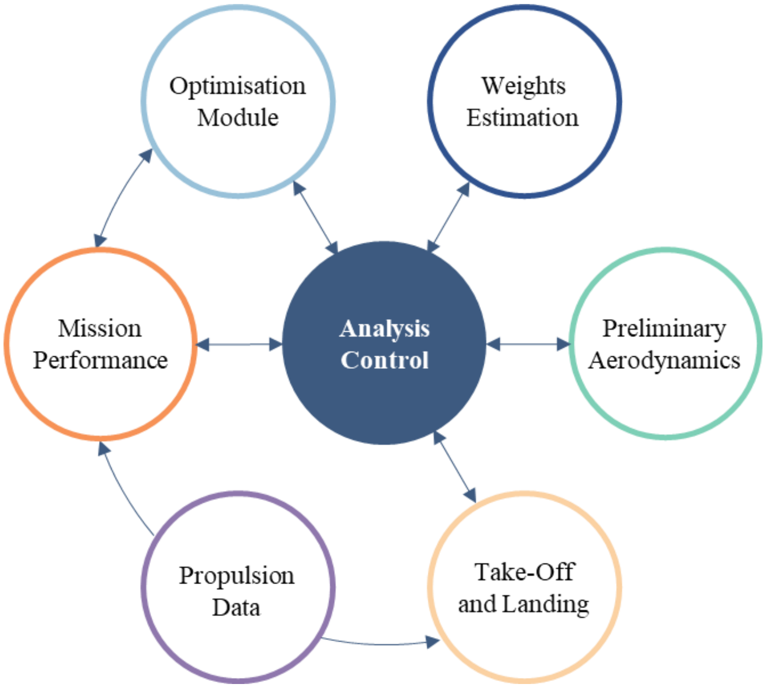


Fig. 7 Modular makeup of the NASA flight optimisation system.

The FLOPS weights module predicts the weight of each element in a group weight statement using statistical and empirical equations. The initial weights estimation module was determined using equations derived from statistical data of existing airplanes through an optimisation process. Each equation was chosen based on its physical sensibility, and all its elements (such as coefficients, exponents, and factors) were optimised using nonlinear programming techniques. The aim was to minimise the squared percentage errors between the estimated and actual weights. Nonlinear programming techniques were preferred over traditional curve fitting methods as they allowed for greater flexibility in determining the equation's form and variables. For combat aircraft, the equations were developed using data from 22 fighter and attack aircraft, while the transport database included civilian aircraft ranging from the T-39 Sabreliner to the Boeing 747 [14].

As for the aerodynamics module, in order to produce drag polars for performance calculations, a modified version of the EDET (Empirical Drag Estimation Technique, [15]) program is implemented. With the modifications included in the program, the drag polars have been smoothed, estimates of the Reynolds number have been made with more accuracy, and skin friction calculations have been performed by employing the Sommer and Short T' method [16]. Alternatively, drag polars may be input and then scaled with variations in wing area and nacelle size [17].

Regarding the engine cycle performance module, it was developed by Karl Geiselhart [18] and is based on the QNEP program [19], a modified version of NEPCOMP and its successors [20]. This module analyses thrust and fuel flow data for various Mach-altitude conditions and for several types of engines, including turbojets, turboprops, mixed flow turbofans, separate flow turbofans, and turbine bypass engines. The engine deck generated from this analysis is inputted into the propulsion data scaling and interpolation module within FLOPS. This module fills in any missing propulsion data and scales the engine data to the desired thrust using linear or nonlinear scaling equations.

The mission performance and take-off and landing modules utilise this propulsion data for their analysis. Mission performance is calculated for all segments using a step integration technique to provide precise values for fuel burned, elapsed time, distance covered, and changes in speed and altitude [17].
The derived weights, aerodynamics, and propulsion system data are used by the mission performance module to determine performance. The climb profiles are optimised depending on the optimisation approach selected, minimum fuel to distance profile in the case of subsonic transports; minimum time to climb in the case of combat aircraft or minimum fuel to climb profile in the case of supersonic transport. Descent may be flown at the optimum lift-drag ratio [21].

The take-off and landing module determines the field lengths for all-engine take-off, balanced take-off with one engine out and aborted take-off, and landing. Once the required data, for the implementation of this analysis, is provided or computed, the module ensures that the design complies with all requirements outlined in FAR Part 25 or MIL-STD-1793. Additionally, the module possesses the ability to produce a comprehensive take-off and climb out profile to aid in determining noise footprints.

IV. Platforms Specifications Definition

A. Platform Specifications for Mach 1.4 Business Jet

The aim of this task is to develop a platform specification for a Mach 1.4 business jet that can carry 6-10 passengers and has a range of 4000 nautical miles. Firstly, an initial M1.4 configuration that complies with the top-level aircraft general requirements, which are defined by the SENECA project consortium, is derived from an existing supersonic business jet aircraft concept, Cranfield University E-5 Neutrino configuration [22]. The primary outputs of this work are the mission trajectory profiles and the required thrust for the different flight phases and conditions, including sea level static thrust, take-off all engines operative, take-off maximum thrust for one engine out condition, transonic acceleration thrust at the initial point and at the final one, top of climb, and mid-cruise. Once the propulsion data is defined by the initial thrust requirements, the engine database will be updated for the complete design mission and the general characteristics of the aircraft will then be calculated in order to meet the global specifications in terms of performance of the aircraft.

The business jet designed for Mach 1.4 is intended to seat six passengers and perform supersonic cruising overwater. It incorporates a cranked delta wing with a low aspect ratio and is powered by two wing-mounted engines. Key characteristics of the aircraft are summarised in Table 2, while Fig. 8 shows a 3D model of the aircraft.

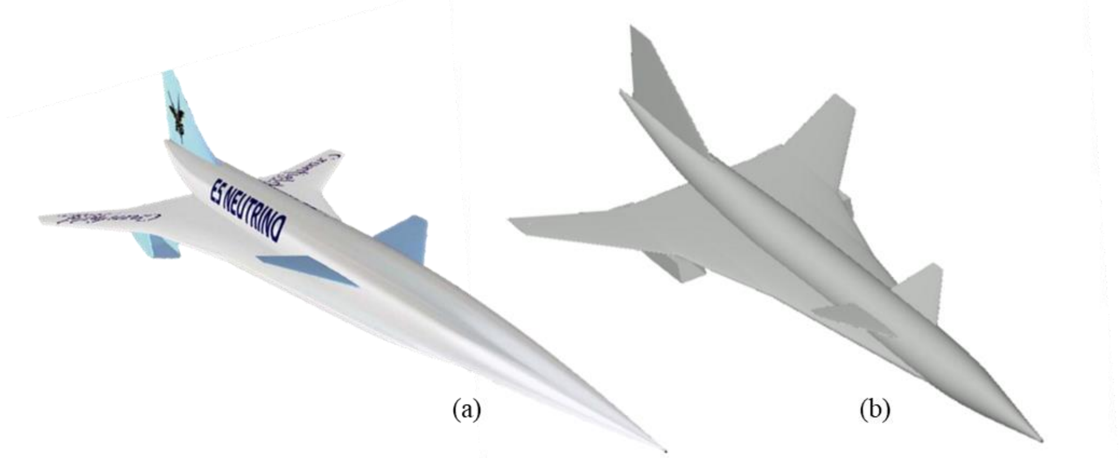


Fig. 8 Surface CAD model of CU E-5 Neutrino (a) and SENECA M1.4 Business Jet (b).

Table 2 Mach 1.4 Business Jet Key Specifications.

Parameter	Value
MTOW	45453.5 kg / 100208 lb
Total Thrust	190001.3 N / 42714 lbf
Thrust per Engine	95000.6 N / 21357 lbf
Wing Area	174.9 m^2 / 1883 ft^2
Wing Loading	259.9 kg/m^2 / 53.2 psf
Thrust to Weight Ratio (T/W)	0.426

In a previous study, an analysis of different wing and fuselage combinations was conducted, leading to the determination that an optimal design for low sonic boom and minimal drag should feature uniform longitudinal volume and lift distributions. The fuselage is expected to be more slender, and a highly swept wing is anticipated to result in a flattened lift distribution. The fuselage is strategically designed to satisfy not only passenger comfort and packaging criteria but also to align with the goals of achieving low sonic boom and minimal drag. The general geometry and main dimensions of the M1.4 business jet are displayed in the following figure.

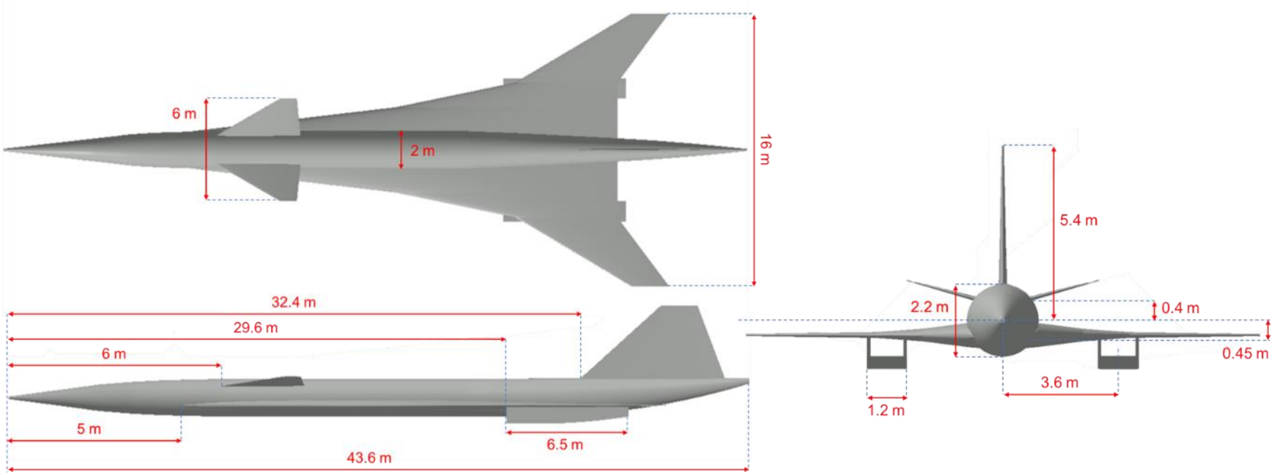


Fig. 9 General geometry of the SENECA M1.4 Business Jet.

The design mission specifies the performance requirements for aircraft's design. The mission requirements for the Mach 1.4 supersonic business jet come from the E-5 design used as baseline, which takes into consideration environmental impacts, technological challenges, and market analysis. Three different studies were conducted for the mission flight path: the first one refers to the original E-5 design mission (M1.8 – 6000 nm), the second one simulates the 6000 nm mission but with a lower design Mach number (M1.4), and the third one is the required SENECA mission (M1.4 – 4000 nm). Table 3 summarises these three studies, while the following section focuses on the details and results of the SENECA mission.

Table 3 Summary of the three mission profile studies conducted on the E-5 design.

Study N°	Mach Number	Range (nm)	Gross Weight (kg)	Fuel Weight (kg)
1	1.8	5976	45454	31795
2	1.4	6844	45454	31795
3	1.4	4346	45454	18144

The assigned mission profile is segmented into various flight phases, encompassing taxiing, take-off, an initial subsonic climb, a segment of constant altitude transonic acceleration at an optimal altitude to transition into the supersonic flight regime, and subsequently, a phase of supersonic climb. The illustration of the design mission for the Mach 1.4 business jet is presented in Fig. 10. During the cruise segment, a climbing cruise is executed for optimal fuel efficiency, maintaining the aircraft's peak performance. As fuel diminishes, the reduced weight alters the balance of lift, prompting increased speed, altitude, or reduced thrust. While higher speed boosts fuel consumption due to heightened drag, lower thrust compromises engine efficiency. Ascending in altitude allows stable engine settings with decreased drag from lower air density. However, cruise climbs may conflict with air traffic services and traffic demands, limiting optimal altitudes for multiple flights. Finally, there is a descent and deceleration phase, culminating in the landing.

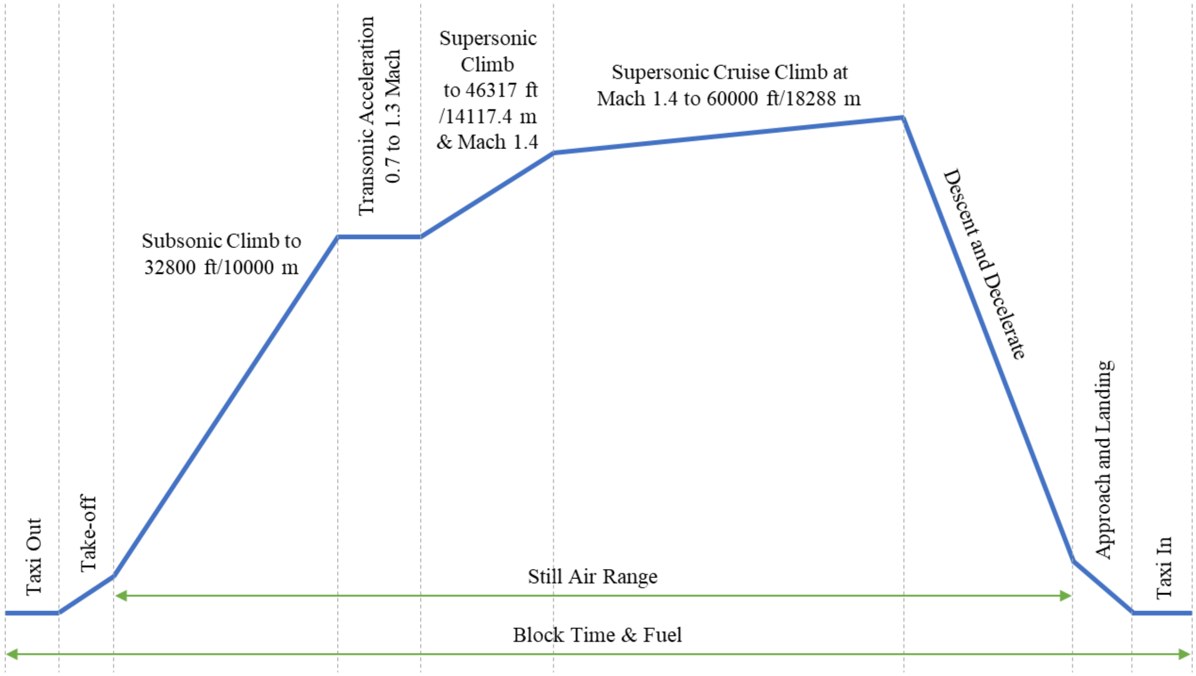


Fig. 10 Design mission for M1.4 Business Jet.

Figure 11 illustrates the complete high-speed drag polar across various Mach numbers at 60000 ft. The methodology employed for calculating this drag polar utilises a low-fidelity empirical drag estimation approach. During the conceptual phase, aerodynamic coefficients play a crucial role in performance estimation. In the case of supersonic aircraft, the primary focus of low-drag optimisations is centred on reducing supersonic wave drag through variations in geometry. At 60000 ft altitude and a Mach of 1.4, the maximum aerodynamic efficiency during cruise is 9.56, achieved with a lift coefficient of 0.129.

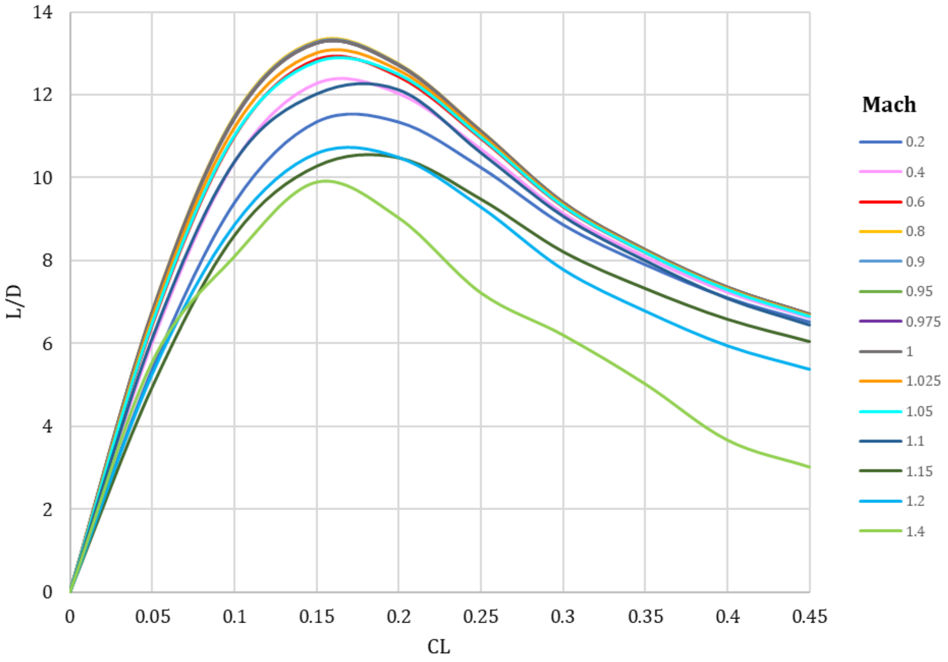


Fig. 11 High speed drag polar (lift over drag ratio vs lift coefficient) for M1.4 business jet.

B. Platform Specifications for Mach 1.6 Business Jet

The platform specifications for the Mach 1.6 business jet are designed to accommodate 8-10 passengers and achieve a range of 4000 nautical miles. The initial step involves reviewing the CU (Cranfield University) E-19 Aeolus [23] configuration with regards to its performance metrics, such as range, take-off and landing distance, approach speed, etc., as well as environmental impact, emissions and noise. Additionally, its physical properties, including geometry and weight, are assessed to generate the M1.6 configuration requirements. Once the initial specifications are defined for this aircraft platform, the task moves on to determining the thrust requirements for the flight domain. This includes calculating the required thrust for critical points in the flight, such as sea level static thrust, take-off all engines operative, take-off maximum thrust for one engine out condition, transonic acceleration thrust at the initial point and at the final one, top of climb, and mid-cruise. In addition, mission trajectory profiles are generated, which will provide critical information about the flight path of the aircraft and its expected performance under different conditions. When the engine database is updated, the overall performance and physical attributes of the aircraft will be determined and modified as needed to meet the global performance specifications. Finally, a database will be created for assessing emissions and LTO noise.

In this design, a horizontal tail is favoured over a canard, as the former contributes to minimising the sonic boom signature in the rear part. It features a cranked delta wing with a low aspect ratio and is equipped with two engines mounted on the wings. Table 4 outlines the main specifications of the aircraft, and a surface model representation can be found in Fig. 12.

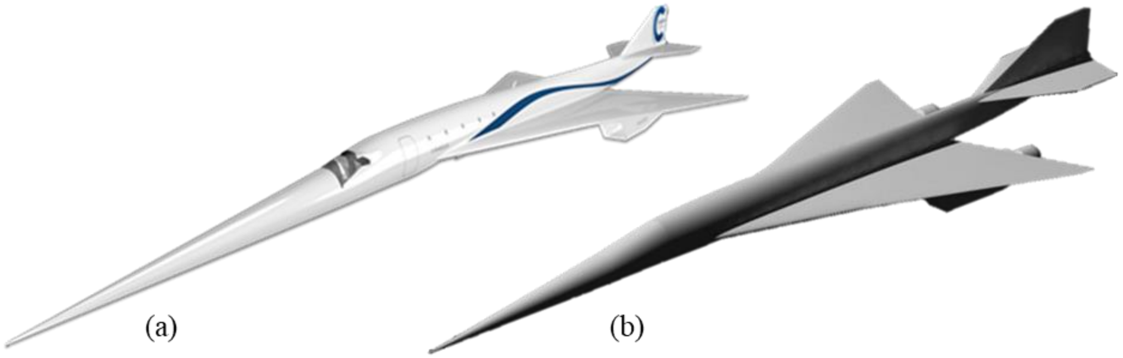


Fig. 12 Surface CAD model of CU E-19 Aeolus (a) and SENECA M1.6 Business Jet (b).

Table 4 Mach 1.6 Business Jet Key Specifications.

Parameter	Value
MTOW	45000 kg / 99208 lb
Total Thrust	248157.4 N / 55788 lbf
Thrust per Engine	124078.7 N / 27894 lbf
Wing Area	151.5 m^2 / 1631.1 ft^2
Wing Loading	297 kg/m^2 / 60.8 psf
Thrust to Weight Ratio (T/W)	0.562

The following figure shows the general geometry and dimensions of the M1.6 business jet.

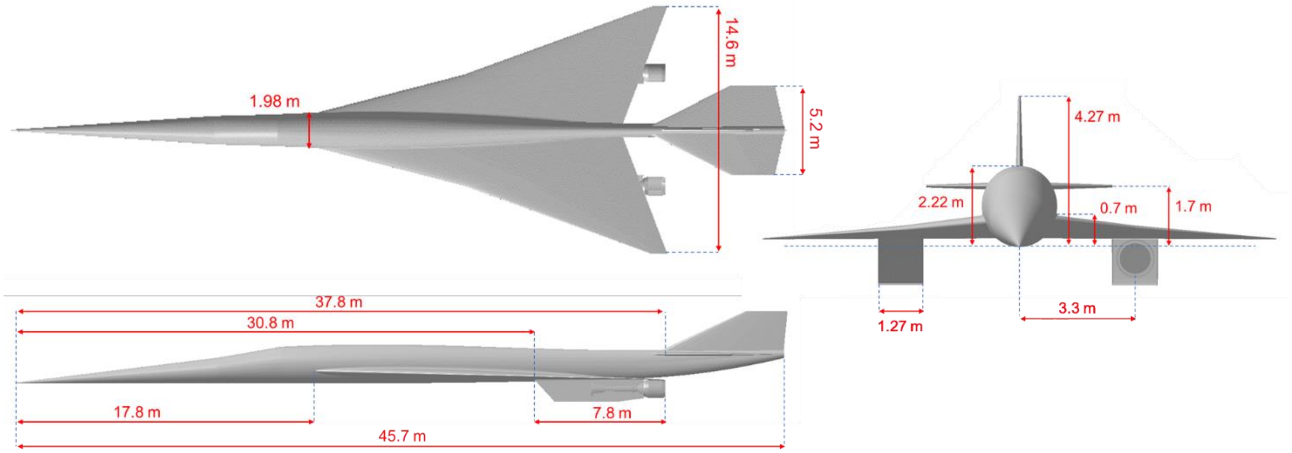


Fig. 13 General geometry of the SENECA M1.6 Business Jet.

The investigation into mission profiles for supersonic business jets reveals three distinct categories based on the conditions at which the transonic acceleration is performed. These different mission definition approaches also exhibit variations in climb and descent schedules, as well as cruise techniques. The first category involves a subsonic climb schedule, where acceleration to supersonic speed occurs once the cruising altitude is attained [24]. The second category features transonic acceleration to supersonic flight during the climb phase, resembling the standard operational procedure of the Concorde [25]. The third category encompasses a level transonic acceleration phase situated between a subsonic and a supersonic climb segment [26], [27], [28], [29], [30].

During the mission profile selection, the primary objective was to find a compromise between timesaving and propulsion performance efficiency. Opting for a subsonic climb schedule does not yield time savings. In addition, when transonic acceleration is integrated into the climb phase, both the required thrust and fuel consumption increase. Therefore, the optimal equilibrium is observed in the level flight acceleration phase. The recommended altitude for this phase is around 33000 ft (10 km), aligning with the altitude at which most commercial aircraft operate at transonic speeds, ensuring a balance between performance, thrust, and drag.

The flight profile of the M1.6 supersonic business jet detailed in Fig. 14, unfolds through distinct phases. Beginning with the take-off phase, next the subsonic climb up to 32800 ft, during this phase the aircraft accelerates from Mach 0.3 to 0.95. The transonic acceleration at 32800 ft makes the aircraft go from a Mach number of 0.95 to 1.3. The selection of these Mach numbers is done taking into account the aerodynamic features of the aircraft and the propulsion capabilities, with the purpose of reducing the thrust required. The subsequent supersonic climb extends from 32800 ft to the project-specified design initial cruise altitude of 50000 ft, involving acceleration from Mach 1.3 to 1.6. The cruise phase employs a constant Mach number of 1.6 and climbing cruise up to 58000 ft. Then descent and approach phase, culminating in the final approach and landing.

For the mission schedule definition (in terms of climb rates, phase time duration, altitude and Mach numbers), the previously referenced documents, highlighting Concorde's performance were taken as guidelines in conjunction with the previous Cranfield Supersonic Business Jet studies for the E-5 and E-19 aircraft designs.

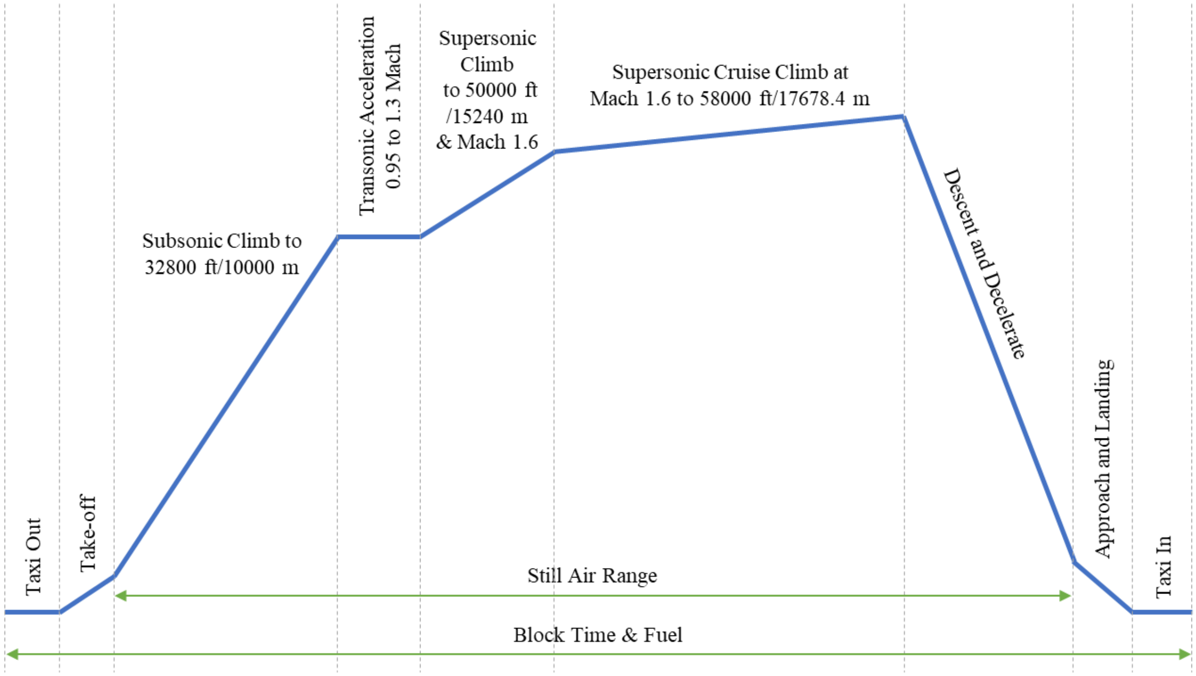


Fig. 14 Design mission for M1.6 Business Jet.

The high-speed drag polar for the Mach 1.6 business jet is displayed in Fig. 15, showcasing different Mach numbers at an altitude of 58000 ft. At an altitude of 58000 ft and a Mach number of 1.6, the maximum aerodynamic efficiency during cruise is 8.98, achieved with a lift coefficient of 0.127.

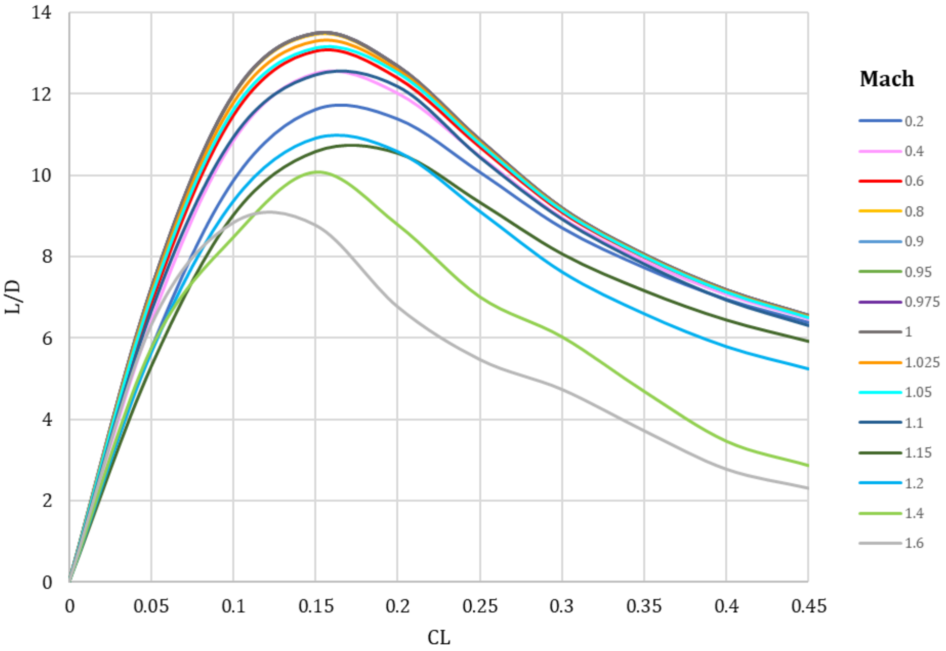


Fig. 15 High speed drag polar (lift over drag ratio vs lift coefficient) for M1.6 business jet.

C. Platform Specifications for Mach 1.8 Airliner

The objective of this task is to create the platform specifications for the Mach 1.8 airliner, which is designed to carry 100 passengers over a range of 4000 nautical miles. The task has been divided into two subtasks for efficient completion. The first iteration involves conducting an analysis of existing NASA STCA (Supersonic Technology Concept Aeroplanes) configurations, which includes both the airframe and powerplant design, to assess its suitability for achieving the desired Mach 1.8 performance level. The primary goal is to establish the platform specifications for the Mach 1.8 airliner relatively early in the project, this will facilitate the commencement of work on engine cycle, emissions, and noise analyses. An analysis study is conducted to select which NASA STCA configuration is used as baseline.

The initial design outcome has been obtained following a comprehensive review of the NASA 765-072B configuration with regards to its performance characteristics such as range, take-off and landing field length, approach velocity, among others, as well as its environmental characteristics including emissions and noise, and physical properties such as geometry and weight. The NASA 765-072B aircraft achieves a trans-Atlantic range of about 4000 nm and meets fuel burn and emissions goals forecast for the 2025 timeframe [31]. This configuration study provides the necessary information to determine the thrust requirements for various stages of the flight, including sea level static thrust, take-off all engines operative, take-off maximum thrust for one engine out condition, transonic acceleration thrust at the initial point and at the final one, top of climb, and mid-cruise as well as the definition of the complete mission profile. It should be noted that the information herein provides a non-optimal, first iteration of the vehicle configuration and mission profile. Any necessary modifications will be made to ensure that the aircraft meets the global performance specifications when the engine cycle database is updated.

It has four engines installed on the wings and a cranked delta wing with a low aspect ratio. The aircraft's key parameters are included in Table 5, and Fig. 16 shows a surface model representation. Figure 17 presents the overall structure and size specifications of the M1.8 supersonic airliner. It must be noted that the nacelles have been sketched only as a reference.

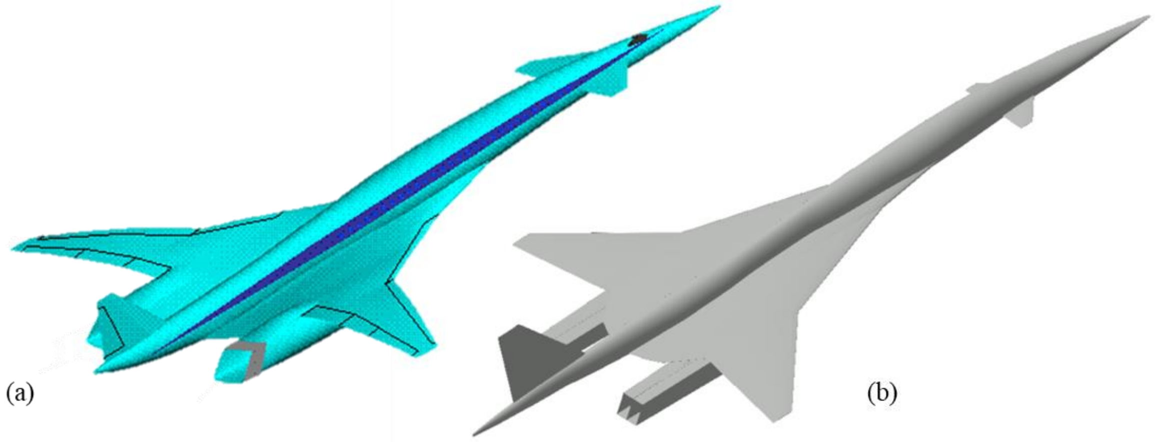


Fig. 16 Surface CAD model of NASA 765-072B STCA (a) and SENECA M1.8 Airliner (b).

Table 5 Mach 1.8 Airliner Key Specifications.

Parameter	Value
MTOW	136077.7 kg / 300000 lb
Total Thrust	636923 N / 143186 lbf
Thrust per Engine	159230.7 N / 35796.5 lbf
Wing Area	427.3 m^2 / 4600 ft^2
Wing Loading	318.4 kg/m^2 / 65.2 psf
Thrust to Weight Ratio (T/W)	0.477

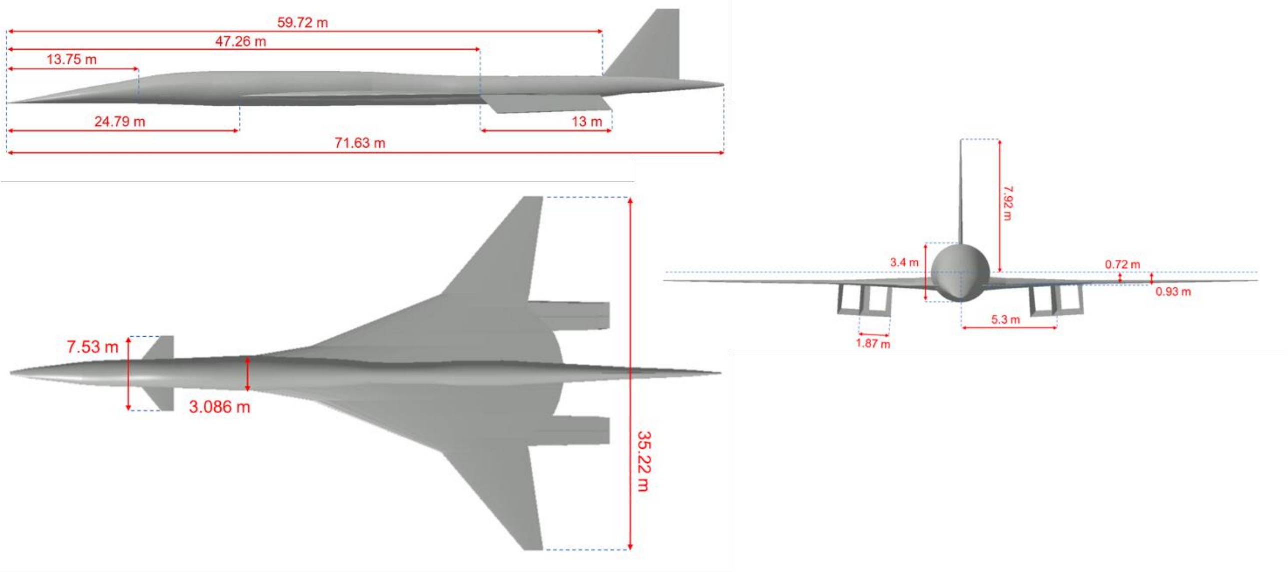
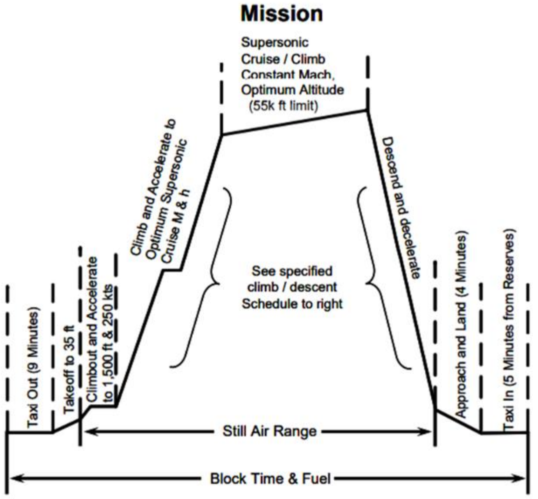
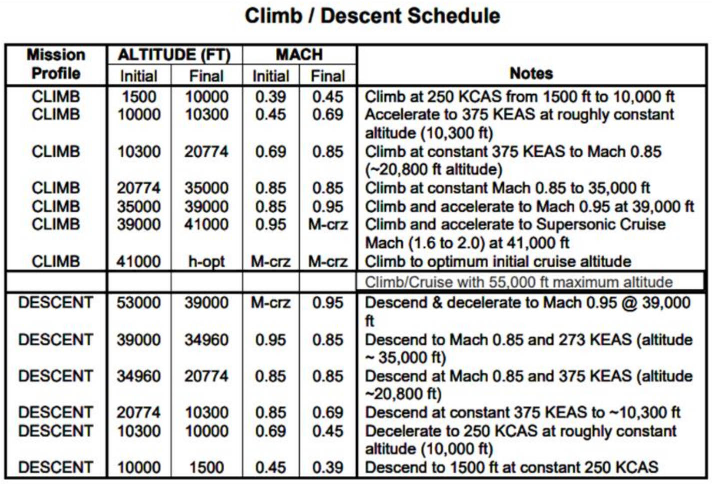


Fig. 17 General geometry of the SENECA M1.8 Supersonic Airliner.

In evaluating various trades, the performance assessment of the NASA concept relied on a supersonic non-stop mission profile. Figure 18 depicts this mission profile, which is parameterised to accommodate changes in both cruise range and Mach number. This profile serves as a foundational reference for evaluating the performance of the SENECA supersonic airliners.





Climb / Descent Schedule

Mission Profile	ALTITUDE (FT)		MACH		Notes
	Initial	Final	Initial	Final	
CLIMB	1500	10000	0.39	0.45	Climb at 250 KCAS from 1500 ft to 10,000 ft
CLIMB	10000	10300	0.45	0.69	Accelerate to 375 KEAS at roughly constant altitude (10,300 ft)
CLIMB	10300	20774	0.69	0.85	Climb at constant 375 KEAS to Mach 0.85 (~20,800 ft altitude)
CLIMB	20774	35000	0.85	0.85	Climb at constant Mach 0.85 to 35,000 ft
CLIMB	35000	39000	0.85	0.95	Climb and accelerate to Mach 0.95 at 39,000 ft
CLIMB	39000	41000	0.95	M-crz	Climb and accelerate to Supersonic Cruise Mach (1.6 to 2.0) at 41,000 ft
CLIMB	41000	h-opt	M-crz	M-crz	Climb to optimum initial cruise altitude
					Climb/Cruise with 55,000 ft maximum altitude
DESCENT	53000	39000	M-crz	0.95	Descend & decelerate to Mach 0.95 @ 39,000 ft
DESCENT	39000	34960	0.95	0.85	Descend to Mach 0.85 and 273 KEAS (altitude ~ 35,000 ft)
DESCENT	34960	20774	0.85	0.85	Descend at Mach 0.85 and 375 KEAS (altitude ~20,800 ft)
DESCENT	20774	10300	0.85	0.69	Descend at constant 375 KEAS to ~10,300 ft
DESCENT	10300	10000	0.69	0.45	Decelerate to 250 KCAS at roughly constant altitude (10,000 ft)
DESCENT	10000	1500	0.45	0.39	Descend to 1500 ft at constant 250 KCAS

Fig. 18 Supersonic Non-Stop Mission Profile Boeing Mission Rules [31].

The design mission for the Mach 1.8 Airliner is illustrated in Fig. 19. This selected mission profile for the M1.8 airliner is segmented into different flight phases, encompassing taxiing, take-off, an initial subsonic climb, which includes a phase of constant altitude subsonic acceleration during mid-climb. Subsequently, there is a segment of constant altitude transonic acceleration at an optimal altitude to enter the supersonic flight regime, succeeded by a phase of supersonic climb. Following this, the aircraft enters the cruise segment, which can take two forms: climbing cruise or cruising at a constant altitude. 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 NOx emissions and cabin decompression limits. Finally, a descent and deceleration phase precede the landing [32].

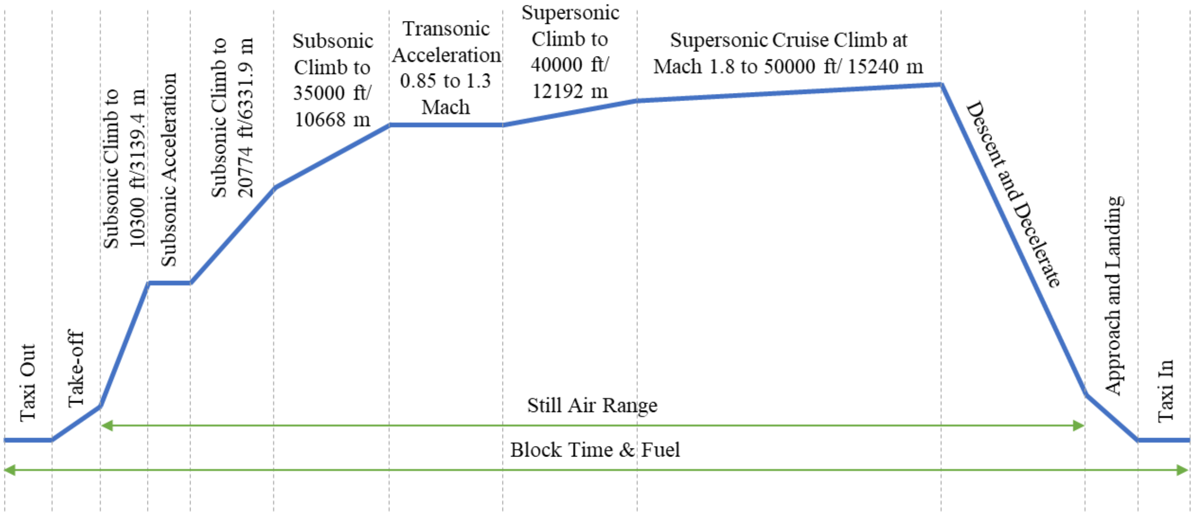


Fig. 19 Design mission for M1.8 Supersonic Airliner.

Figure 20 presents the high-speed drag polar across various Mach numbers, focusing on an altitude of 50000 feet. At this specific altitude and a Mach number of 1.8, the highest aerodynamic efficiency during cruise is 7.43, attained with a lift coefficient of 0.075.

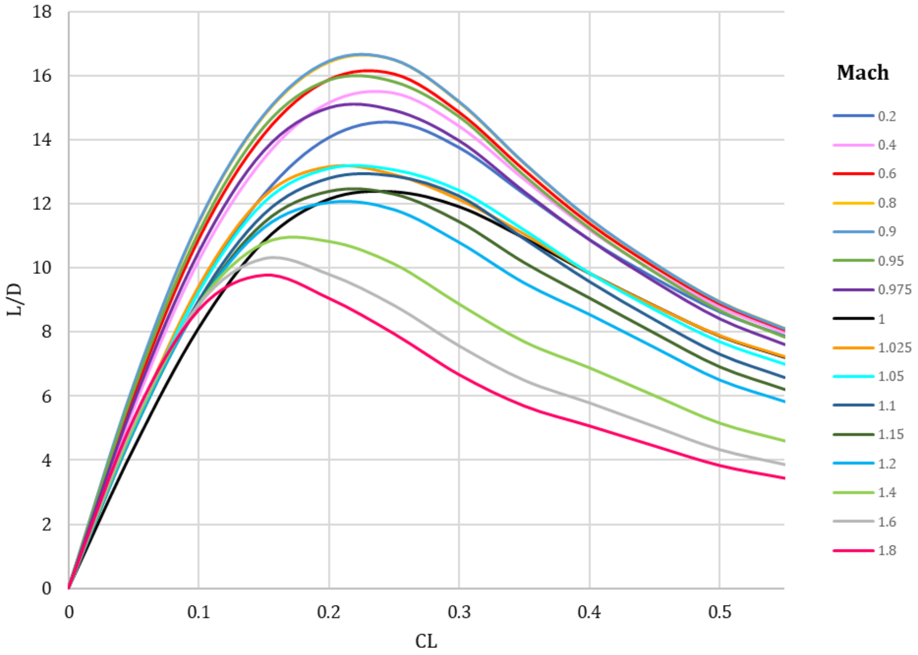


Fig. 20 High speed drag polar (lift over drag ratio vs lift coefficient) for M1.8 Supersonic Airliner.

D. Platform Specifications for Mach 2.2 Airliner

As it has been demonstrated throughout history, designing a practical, commercially and environmentally viable supersonic transport aircraft is a major challenge in the aerospace field. Finding a compromised solution between the different requirements for the next generation of commercial supersonic aircraft and the need for increasingly green designs increases the difficulties to achieve a feasible design. Furthermore, for cruise Mach number greater than 2, the capability of managing and meeting all the requirements becomes even harder. The development of supersonic airliners has led to many unsuccessful attempts such as the Mach 2.7, 250 passenger Boeing 2707 design in the 1960s and the Mach 2.4, 300 passenger HSCT cancelled in 1999.

The initial approach involves establishing the prerequisites and arrangements for the Mach 2.2 airliner. Besides the performance demands, environmental aspects like NOx emissions and flyover/side-line noise will also be taken into account. Once the requirements are identified, several aircraft configurations are simulated with different outer planform wing geometries, empennage types, and powerplant arrangements. For this purpose, a low/medium fidelity computational workflow using FLOPS and AirCADia [33] is set up, with different multidisciplinary analysis modules such as structures, aerodynamics, propulsion, mission, stability, etc. Several design studies are conducted in order to assess the performance of the defined configurations.

Due to the absence of a developed Mach 2.2 supersonic airliner conceptual design which could be used as reference as previously done for the Mach 1.8 airliner, the airframe and the powerplant definition has been carried out from scratch. Both the airframe itself and the engines were designed with the target to reduce the environmental impact with respect to noise and emissions in the vicinity of airports and the global climate impact. The initial outcome of this configuration work has been produced through diverse methodologies and multiple tools, not only FLOPS unlike the initial design results of the other configurations. The design framework developed provides a comprehensive outcome for all the different configurations analysed for the Mach 2.2 airliner design, these results are in terms of performance characteristics, environmental impact assessment results and physical features.

Figure 21 displays a schematic illustration of the design space. The framework was developed by establishing links between external analytical tools and connecting various design modules.

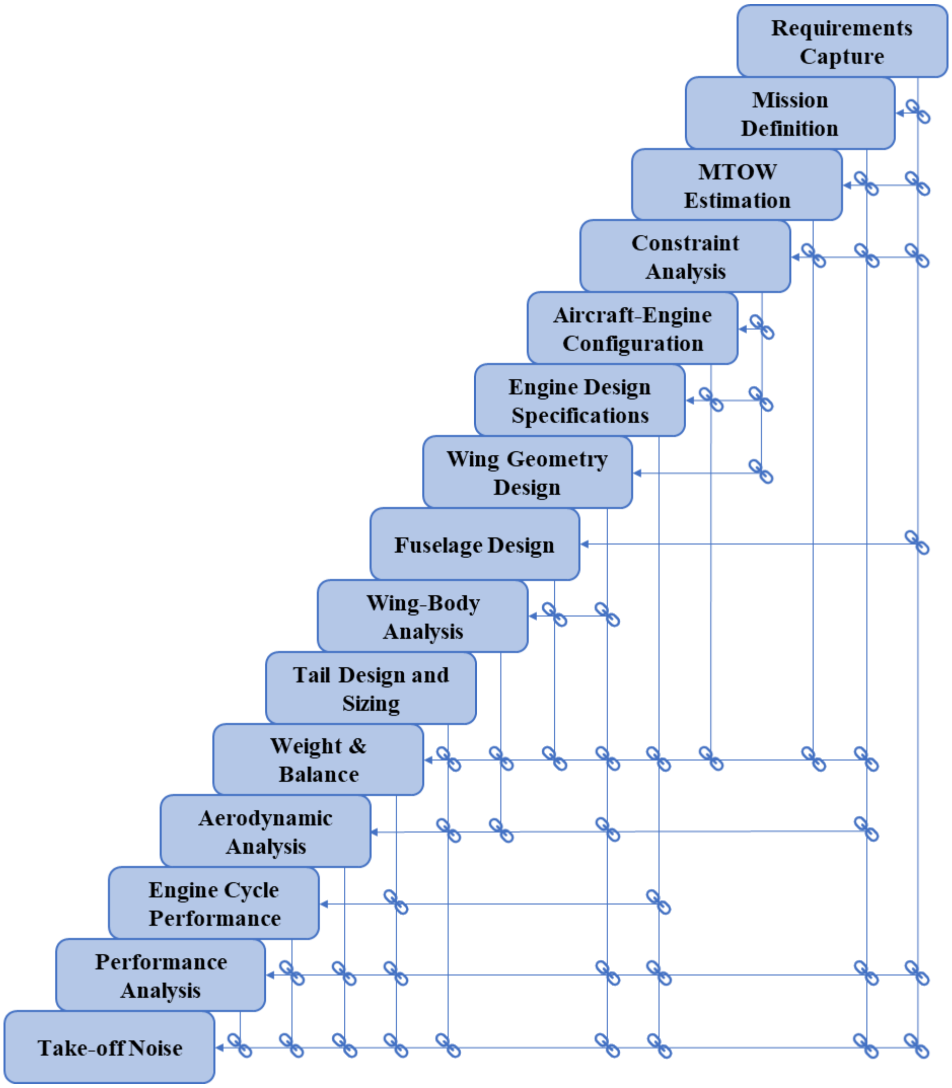


Fig. 21 Supersonic aircraft framework design and data link [34].

In the pursuance of the optimal future supersonic commercial aircraft design, different aircraft configurations, considering different outer planform geometries, empennage types, and powerplant arrangements have been explored for the initial Mach 2.2 supersonic airliner. Among all the feasible configurations, the implementation of only horizontal tail or of horizontal tail and canard has been studied. The aim is to select a baseline layout that represents the best compromise among mission and aerodynamic, performance, weight, emissions, and noise. This supersonic aircraft is designed to carry one hundred passengers and cruise over water at Mach 2.2. A horizontal tail is preferred in this design over a canard because it helps to reduce the sonic boom signature at the back. An aircraft's conceptual design process usually starts with a constraint analysis to make sure all performance requirements will be satisfied. Following the use of empirical methods to compute an initial estimate of the maximum take-off weight, the constraint analysis will yield the wing area and the sea-level static thrust. All airframe-engine combinations use the same design point, and the results are displayed in the following table along with metrics like overall thrust, thrust per engine, thrust to weight ratio, and wing area.

Table 6 Mach 2.2 Airliner Key Specifications.

Parameter	Value
MTOW	156489.4 kg / 345000 lb
Total Thrust	667233.2 N / 150000 lbf
Thrust per Engine (Twinjet)	333616.6 N / 75000 lbf
Thrust per Engine (Trijet)	222411.1 N / 50000 lbf
Thrust per Engine (Quadjet)	166808.3 N / 37500 lbf
Wing Area	267.4 m^2 / 2878 ft^2
Wing Loading	585.3 $\mathrm{kg/m}^2$ / 120 psf
Thrust to Weight Ratio (T/W)	0.435

Findings from the analysis of the twinjet, trijet, and quadjet configurations have been obtained and examined. The twinjet setup raises concerns regarding engine sizing, primarily due to the design mandate of reaching an altitude of 50000 feet at a cruise Mach of 2.2. This requirement necessitates a higher thrust per engine compared to typical transport aircraft, posing challenges in terms of manufacturing and cost efficiency. Consequently, the twinjet configuration is deemed unsuitable for this application. [34]

The following defines the conceptual design of the supersonic airliner platforms for the trijet and quadjet versions using airframe geometrical data. This includes a surface CAD model, Fig. 22, and the main dimensions, Fig. 23.

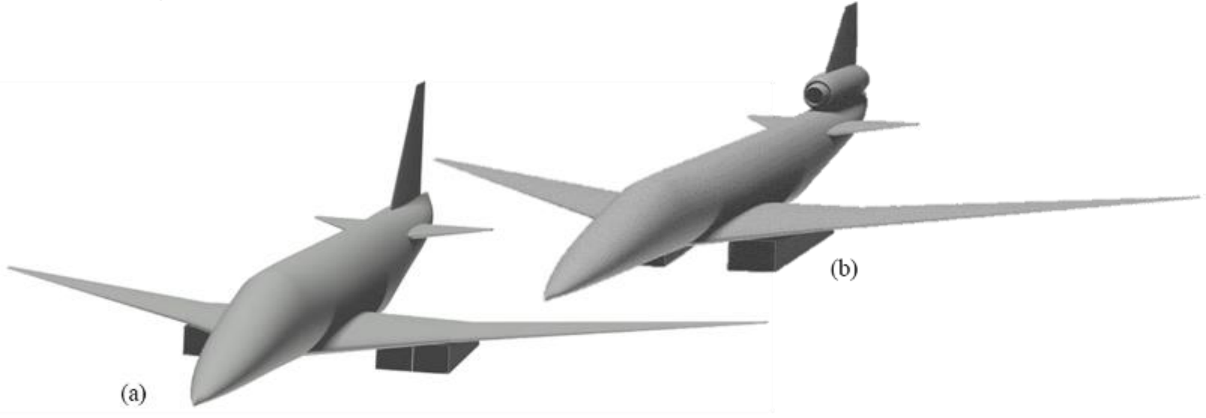


Fig. 22 Surface CAD model of SENECA M2.2 Airliner quadjet (a) and trijet configuration (b).

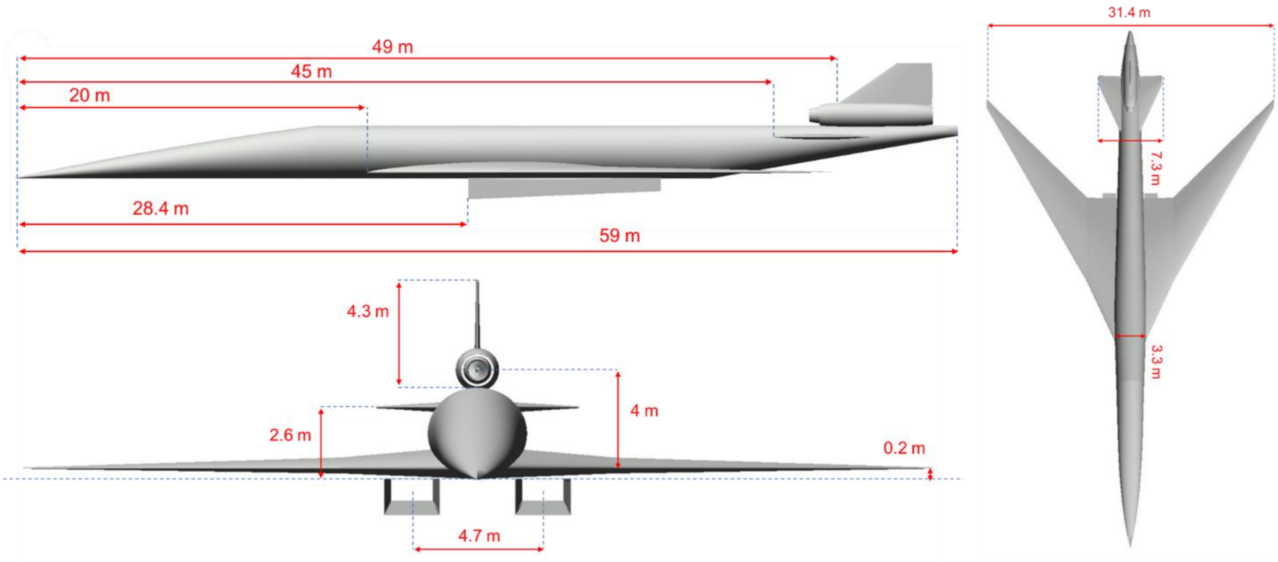


Fig. 23 General geometry of the SENECA M2.2 Supersonic Airliner Trijet Configuration.

Based on the NASA concept assessment and using the same approach as the Mach 1.8 airliner, the Mach 2.2 design mission profile is a supersonic non-stop mission profile for the upcoming iterations. The M2.2 cruises at a constant height, in contrast to the M1.8 SENECA supersonic cruise climb. This variation in cruising approaches aims to assess the effects of such manoeuvres on the demands placed on the propulsion performance and fuel efficiency. A representation of the design mission can be found in Fig. 24.

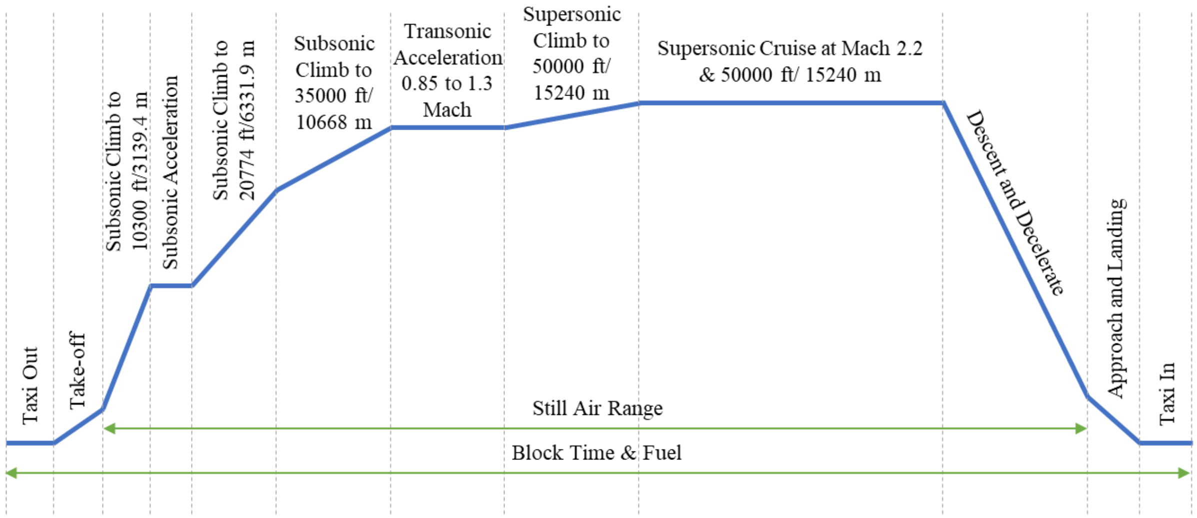
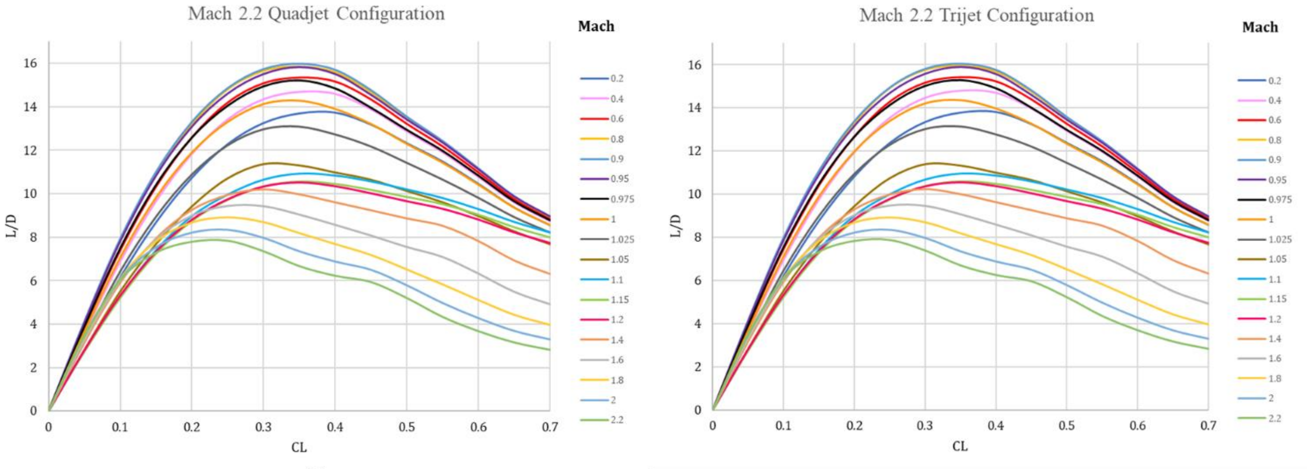


Fig. 24 Design mission for M2.2 Supersonic Airliner.

For an altitude of 50000 ft, Fig. 25 displays the high-speed drag polar for multiple Mach numbers. The aerodynamic outcome for both configurations, trijet and quadjet, indicated that both designs offer comparable performance results as anticipated, given that the differences in drag contribution stem from the distinct engine layouts. For the three-engine configuration, the highest aerodynamic efficiency during cruise at 50,000 feet altitude and Mach 2.2 is 7.04, achieved at a lift coefficient of 0.14. In contrast, for the four-engine design under identical conditions, the maximum lift-to-drag ratio is 6.9, observed at a lift coefficient of 0.135. [34]



(a) (b)

Fig. 25 High speed drag polar (lift over drag ratio vs lift coefficient) for M2.2 supersonic airliner quadjet configuration (a) and for trijet configuration (b).

V. Conclusion

The main objective of the SENECA project is to establish the technical feasibility of an environmentally compliant supersonic transport aircraft by means of trade-off studies and multidisciplinary design optimisation approach and focused on technological improvements to give recommendations for future supersonic regulations. The results of the project will contribute to maintain world-class knowledge and skills in Europe in the field of civil supersonic aviation. To cover the entire range of prospective supersonic aircraft to be expected in the short, mid, and longer terms, SENECA begins with definitions of four different supersonic aircraft platforms. A multidisciplinary optimisation including aircraft, engines and operational procedures will be the final outcome of this project, these results will be included in another publication towards the end of the project since the aim of the work presented here is the conceptual design approach, decisions and initial design results which will define a benchmark for the future of supersonic transport aircraft design. The optimisation process prioritises environmental sustainability, with a particular emphasis on mitigating global and local emissions and noise levels. Currently, there is little knowledge available on the performance of upcoming supersonic business jets and airliners, as well as their sustainability and benefits to the European and global aviation sectors. Significant gaps still exist in knowledge, specifically on how to minimise the environmental footprint (noise, fuel burn, emissions) of supersonic jets and on how to make this sector economically viable. SENECA's primary focus is on expanding and strengthening the evaluation of supersonic business jets and airliners, with the aim of offering a more uniform and comprehensive perspective on the technology. The intended outcome of these efforts is to establish these studies as the standard for any subsequent analysis and future advancements in the field, which will be facilitated through planned dissemination activities.

This paper presents the conceptual design approach of the SENECA project platforms as well as the initial aircraft specifications developed for the two supersonic business jets and the two supersonic airliners which comply with the top-level aircraft requirements expected from the next generation of supersonic transport aircraft.

Acknowledgments

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Conceptual design of supersonic aircraft to investigate environmental impact

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2024-01-04

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