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Preliminary design of next generation Mach 1.6 supersonic business jets to investigate landing & take-off (LTO) noise and emissions – SENECA.

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Abstract. With the approach of next generation supersonic transport entry into service, new research activities were initiated to support updates on ICAO regulations and certification processes for supersonic transport vehicles. Within this context, the EU Horizon 2020 SENECA project has been launched to investigate the levels of noise and gaseous emissions in the vicinity of airports as well as the global climate impact of next generation supersonic civil aircraft. This paper introduces some of the preliminary outcomes of this investigation. It presents the preliminary design and performance analysis of a Mach 1.6 business jet, following an integrated aircraft-engine design approach. The preliminary design was performed accounting for the limitations posed by future environmental restrictions on respective subsonic vehicles. The market space and mission route definition exercise assumed only “over-sea” supersonic operations, while for “over-land”, only subsonic operations where allowed. Parametric studies on engine integrated design demonstrated modest core temperatures while cruising and the significant impact of engine installation on performance. At this first design iteration, assuming current state of the art technology, the Mach 1.6 business jet showed good potential to satisfy the predicted mission requirements while respecting the environmental constraints in terms of Landing & Take-Off (LTO) noise and emissions.

1. Introduction

The roots of civil supersonic aviation can be traced back to early 1950s. In the aviation world, the efforts in research and development were limited to military applications and allowed progress to a technology level that foresaw supersonic aircraft for civil applications with travel speeds of Mach 1.8 or higher (1). Three research programmes were launched in the 1960s in the USA, Europe, and the USSR. The beginning of the civil supersonic flight era can be set on the 31st of December of 1968 with the first flight of the Tupolev Tu-144. The Russian aircraft was followed shortly after by the Concorde's beginning of operations on the 2nd of March of 1969.

Although the Tupolev was the first to achieve flight, it operated only for several years, due to issues such as the cabin noise and the economic inefficiency. On the other hand, the Concorde is the most successful Supersonic Transport (SST) so far, operating for more than 27 years, ceasing its operations in 2003 (2). From 1968 to 2003 no new civil supersonic transportation was developed although the industry and academic interest didn't vanish. Among the companies that were directing their efforts towards a new sustainable SST, Boom Supersonic has recently reached an agreement with United Airlines for the purchase of 15 of Boom's Overture airliners with an option to buy 35 more aircraft. Academic entities are also involved in SST design. Several research programs on supersonic aviation were launched across the years. Most notably, NASA led the Supersonic Cruise Research (SCRas well as the N+ programs (3), and the recent Quiet SuperSonic Technology (QueSST) study. The Japanese space agency has put a lot of effort in the NEXST and S3TD projects (4), for the development of a reduced boom supersonic unmanned technology demonstrator obtained via MDO analysis while the European union funded the High-Speed Aircraft (HiSAC) (5), which included Russian partners SUKHOI, ITAM, TSAGI, CIAM.

As the entry into service of the next supersonic aircraft is approaching, new research studies are needed to improve the understanding on the possible scenarios related to supersonic civil aviation and to assist the ICAO in the process of setting new regulations and certification processes, as the only available data so far are from the Concorde era. The EU Horizon 2020 Landing & Take-Off (LTO) Noise and Emissions of Supersonic Aircraft (SENECA) project represents a European effort that was launched for this purpose.

2. EU Horizon 2020 SENECA project

The SENECA consortium involves eleven academic and industrial aerospace entities from all over Europe, considering the forthcoming market entry of a new generation of supersonic aircraft. The project aims to develop detailed models for performance, emissions, and LTO noise to enhance understanding about the global environmental impact of supersonic aircraft. Building on this, the consortium aims at developing beyond state-of-the-art technologies to reduce the environmental impact of supersonic aviation. The results will contribute to the ICAO-level discussions and will strengthen scientifically the European Union approach to the regulatory framework for novel supersonic aircraft.

The key objectives include:

a) Modelling of two SST business jets (1st with 6 passengers, cruising at Mach 1.4, and 2nd with 10 passengers cruising at Mach 1.6) and two SST large airliners (1st with 100 passengers, cruising at Mach 1.8 and 2nd with 100 passengers cruising at Mach 2.2).
b) Quantification of environmental impact in terms of fuel burn, gaseous emissions and LTO noise.
c) Investigation of the feasibility and impact of modern engine technologies on aircraft and engine performance, LTO noise and emissions.
d) Adaptations to certification assessment models and regulatory procedures.

The project workflow is organised in four packages as shown in Figure 2-1, namely WP2 – Specification of aircraft platforms, WP3 – Engine cycle trade studies and multi-disciplinary design optimisation (MDO), WP4 – Emissions & environmental impact assessments, WP5 – LTO noise assessments. The aircraft design iteration begins with the specification of the aircraft platforms in WP2, which set baseline aircraft geometry and top-level mission requirements. This work is carried out in collaboration with the SENECA advisory board for the market target space and mission route definition exercises. With the mission profile selected and the top-level aircraft requirements defined, the engine cycle trade and MDO studies begin in WP3. The resulting engine performance tables and preliminary design dimensions are then passed to WP4 and WP5 for the assessment of the environmental impact in terms of gaseous emissions and LTO noise.

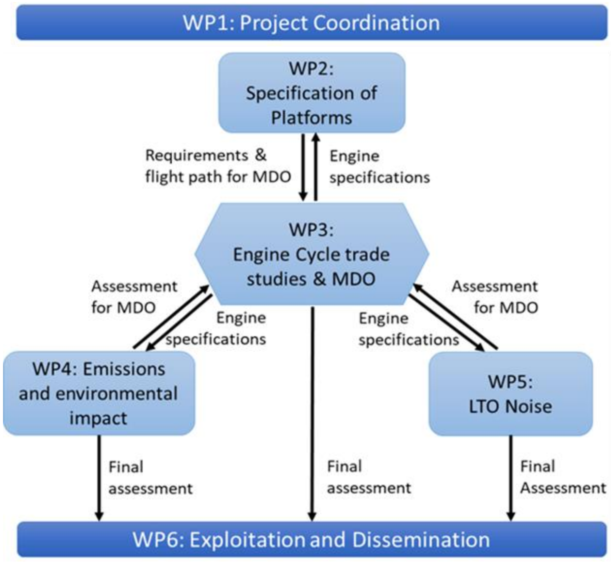

Figure 2-1 SENECA Project workflow

3. Specification of Aircraft Platforms

The E-19 Aeolus is a low-boom low-drag supersonic business jet, developed by Cranfield University in the context of the Aircraft Vehicle Design MSc group design project, in 2020 (see *Figure 3-1*). The baseline aircraft was designed in the Centre of Aeronautics and was presented at the 50th anniversary of the Concorde's first flight (6).

The E-19 was targeted at the 2025-2035 and its design attempts to address critical issues related to the reintroduction of civil supersonic flight, trying to achieve low fuel consumption together with low drag and low emissions and noise, having in mind the economic feasibility of the aircraft itself. The overriding design constraint for this concept, other than the cruise speed and the range, has been in fact to be economically viable and capable of supersonic flight overland. Therefore, the design is performed considering performance and reliability capabilities as well as looking at emissions and sonic boom mitigation strategies.

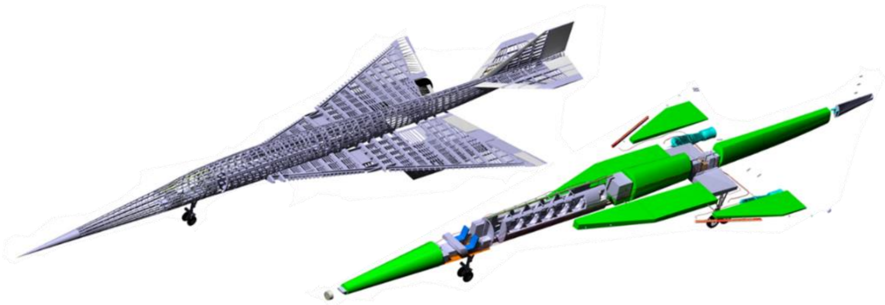

Figure 3-1 Cranfield E-19 Aeolus Aircraft

The present paper presents the current outcomes for the preliminary design of one of the two supersonic business jets researched in SENECA project, namely the SENECA Mach 1.6, which is based on the E-19 Aeolus design. The SENECA Mach 1.6 is a Supersonic Business Jet (SSBJ) concept, shown in *Figure 3-2*, designed to carry 10 passengers for 4000nm of range with a cruise speed of Mach 1.6. Whilst acceptable levels of sonic boom are still being debated, for the conceptual design of the SENECA

Mach 1.6, a maximum ground overpressure of the order of 1 psf has been demanded. In order to achieve this level, it has been necessary to constrain the maximum take-off-mass of the aircraft to 45000 kg and the geometry of both the fuselage and the wing. A conventional wing-tail configuration is preferred rather than a canard as it helps reducing the boom signature in the aft region. As high levels of sweep angles are needed to allow for subsonic flow at the leading edge, the wing is cranked with a leading-edge inboard sweep angle of 76° and a leading-edge outboard sweep angle of 70°. A 3% thickness-to-chord ratio has been chosen for all the aerofoils. Very simple plain flaps have been used for both trailing edge devices and ailerons.

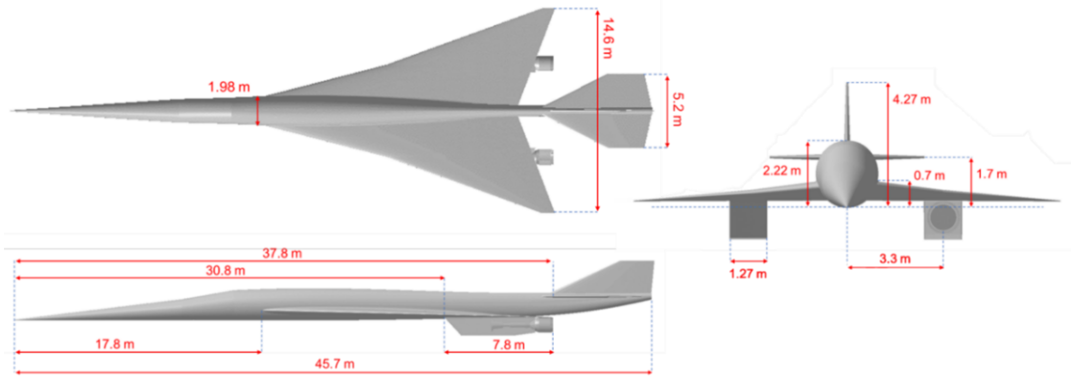

Figure 3-2 SENECA Mach 1.6 general layout

The baseline mission profile divided into the three main flight segments, namely: climb, cruise, and descent. The aircraft performs a rapid initial climb to reach the 10000 m mark avoiding subsonic traffic and then performs a transonic acceleration from Mach 0.95 to 1.3. Subsequently, it climbs supersonically reaching Mach 1.6 and then it climb-cruises with a constant Mach number up until 3950 nmi before starting to descent. In Table 3-1 the total values of fuel burn and time for the achieved range are highlighted. It can be seen that this aircraft can reach 4167 nmi range in 5.1 hours, burning approximately 21.7 tons of fuel. Thus, approximately 2.17 tons of fuel burn corresponds to each passenger for this flight or in other words, on average, more than half a kg of fuel is burned per passenger per nmi travelled.

Table 3-1 SENECA Mach 1.6 overall mission performance

Overall Mission Performance	
Fuel Burn [kg]	21756
Flight Time [hrs]	5.1
Range [nmi]	4167
Specific Air Range [kg/nmi]	5.22
Fuel/PAX/Range [kg/PAX/nmi]	0.522

4. Aircraft-engine integration

The airframe-powerplant integration of a supersonic aircraft is a complex engineering issue of multidisciplinary nature. It is related to aerodynamic, thermodynamic, mechanical and systems designs, operational and control aspects of the installation, which affect its overall design and performance (7). The integrated design replaces the separate development of the powerplant and the airframe with integrated schemes that are used in properly defined powerplant-airframe performance interfaces. Accurate accounting of the airframe-powerplant integration effects early in the design process of a supersonic transport aircraft is a key element for accurate modelling of the performance, affecting crucial design decisions that are made during the conceptual and preliminary design stages. Specifically, integration aspects should include the inlet and the nozzle effects, which in the supersonic aircraft design are major. Consequently, the need for the development of rapid computational tools that participate in the general design optimisation loop is reflected, providing the inlet and nozzle aerodynamic performance and geometry. During the design process and the overall performance evaluation, it is important to establish proper net thrust (FN) accounting and installation-related drags bookkeeping. Following NASA's example, the installation-related drags are included within the engine FN accounting and not within the airframe-related drags. The "uninstalled" FN accounts for the customer bleed, customer power extraction and inlet pressure recovery, however, the "throttle-dependent" drags are not considered. The latter are related with the inlet and exhaust nozzle/afterbody drag production and are affected by the engine airflow. Consequently, the "installed" FN is the subtraction of "throttle-dependent" drags from the "uninstalled" FN, as described in Equation 1 (8),(9),(10).

$$\mathrm{F}_{\mathrm{net,installed}} = \mathrm{F}_{\mathrm{net,uninstalled}} - \mathrm{D}_{\mathrm{inlet}} - \mathrm{D}_{\mathrm{nozzle}} \qquad \text{(Equation 1)}$$

5. Engine integrated design parametric study

The engine preliminary design for supersonic applications is constrained by numerous requirements. It has to meet aircraft requirements in terms of FN, power and air supply at all flight conditions and geometrical constraints imposed by the airframe and the ground clearance, while guarantee gaseous and noise emissions in line with future aviation limits (11), especially during Landing and Take-off (LTO) operations. NOx levels are of particular interest, both in cruise and take-off, as the aviation world is leading towards net-zero environmental impact technologies and cycles (12).

For this study, a "booster-less", mixed-flow turbofan (MFTF) has been considered as the engine architecture, as it offers a good compromise between cost, complexity and performance compared to more exotic engine arrangements. Additionally, at this first iteration, the architecture assumes a fixed geometry nozzle throat area, but a variable nozzle exit area. Subsequent design iterations will include further nozzle geometry variability.

Components efficiency have been selected to represent a 2025-2035 entry-into-service technology, while turbine temperature limits for continuous operations reflect those of nickel-based superalloy blades. Figure 5-1 shows the outcome of the engine cycle design parametric study. It shows the engine Specific Fuel Consumption (SFC) at supersonic mid-cruise (MCR), supersonic top of climb (STOC) as well as the fan diameter and the nozzle exit Mach number at End of Runaway (EOR). The SFC trend shows optimum values for ByPass Ratios (BPR) between 2 - 2.5. Targeting lower EOR jet velocities leads to lower values of Fan Pressure Ratio (FPR) and thus higher BPRs. Higher BPRs lead to a steep increment in SFC to compensate for the increasing engine related drags. Nonetheless, a lower FPR can be delivered with a single stage fan, which is a very desirable feature for this particular engine. A hard limit on EOR jet velocities has been imposed using the nozzle exit Mach number (<0.98). At this stage of the study, unchoked nozzle at EOR is one of the main design constraints for noise, with the subsonic jet velocities lowering the noise produced by the jet plume. Engine cycles with BPRs lower than 3.25 presented chocked nozzle at EOR (Mach $_{\text{Nozzle, Exit}}$ = 1). The red arrow highlights the selected engine cycle design for the first iteration.

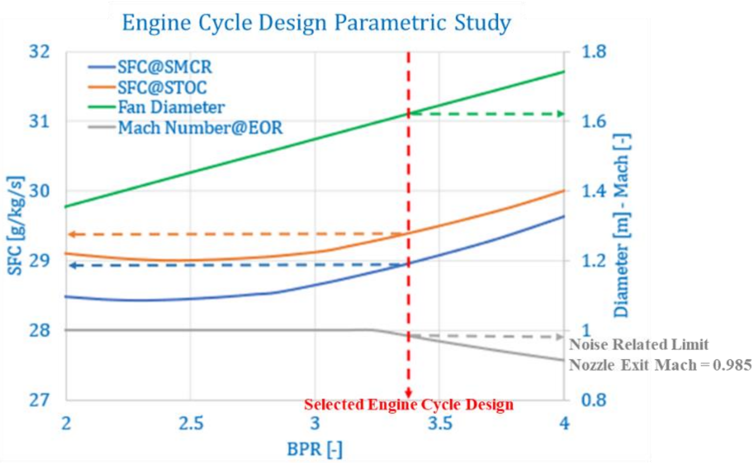

Figure 5-1 SENECA Mach 1.6 Cycle Design Parametric Study and Initial Selection

Figure 5-2 below illustrates key performance parameters for the selected engine cycle design points. The most critical point for turbomachinery is the End of Transonic acceleration (ETR), showing the highest engine FPR and Overall Pressure Ratio (OPR) as well as T40 and T41 (High Pressure Turbine HPT Rotor Inlet). The highest compressor delivery temperature (T30) is at STOC, due to the higher flight Mach number which increase the engine inlet total temperature. Nonetheless, within the flight envelope, the Transonic Pinch point of the transonic acceleration phase is expected to be the most demanding point in terms of core temperatures and thus the cycle design process will include it in the second design iteration instead of the ETR.

The drag bookkeeping for the design points showed that the highest ram drag condition is close to the transonic acceleration phase due to the maximisation of the flow capacity at Mach 1. Moreover, it shows that with the current set of assumptions and the intake and afterbody characteristics used, there is substantial impact of the intake and afterbody drags, which at MCR conditions reduce the FN produced by about 10% and 20% respectively.

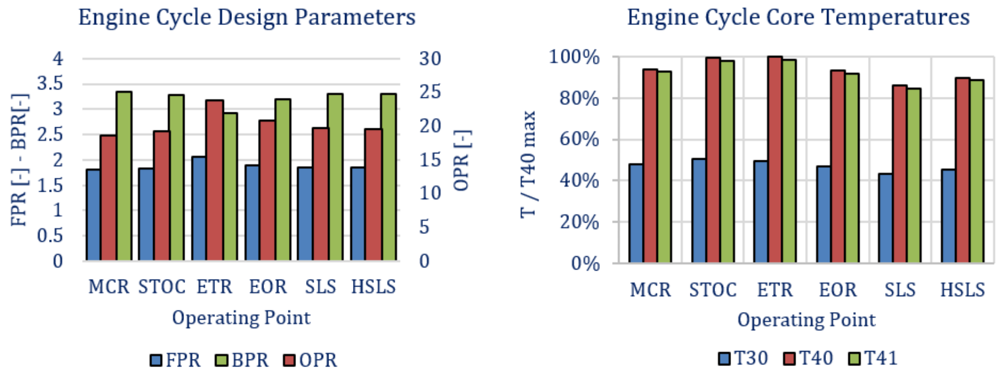

Figure 5-2 SENECA Mach 1.6 Cycle design main parameters: a) FPR, OPR, BPR b) T30, T40, T41

6. Emissions Assessment

An initial preliminary estimation for emissions has been conducted at ICAO based LTO cycle points. Key pollutants CO2, H2O, CO, and NOx have been considered and the emission indices calculated at ICAO points rated at MTO ISA SLS conditions, with thrust ratings of 5, 7, 15, 30, 34, 65, 85 and 100%.

The preliminary results were generated using Chemical Reaction Network models and full kinetic modelling and are shown in Figure 6-1. The Open Source Cantera tool was used for the chemical mechanisms (13). The model has been calibrated on mass flow distribution considering the experimental results available at the ICAO emissions data bank (14). The predicted CO and NOx EIs are within the limits for current ICAO limitations (Annex 16, Vol 2, Part 2, Ch 3) for subsonic engines, showing a promising picture for future supersonic engines. The results for the SENECA Mach 1.6 SSBJ are shown in Figures 6.1 for EICO and EINOx. Average Emission Indexes for CO2 & H2O are estimated as EICO2 [g/kg] = 3100. EIH2O [g/kg] = 1373. EICnHm are underestimated with the present model for low thrust (idle/ground/taxi) conditions and are under investigation.

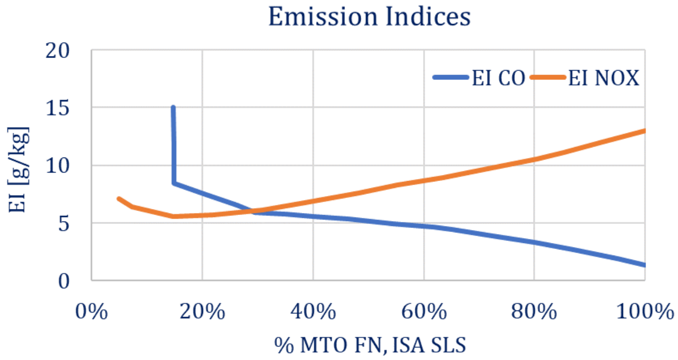

Figure 6-1 Engine emissions estimation for CO, NOx

7. Noise Assessment

An initial nozzle preliminary design has been performed looking for aero-acoustic optimization for low take-off noise. The outcome is a variable area nozzle capable of generating the required thrust at each operating point. The acoustic analysis is performed with the empirical model of Stone et al (15). It is shown for different design variables characterized by the Nozzle Pressure Ratio (NPR). Figure 7-1 presents the Overall Sound Pressure Level (OASPL) for each design, plotted against the cone angle.

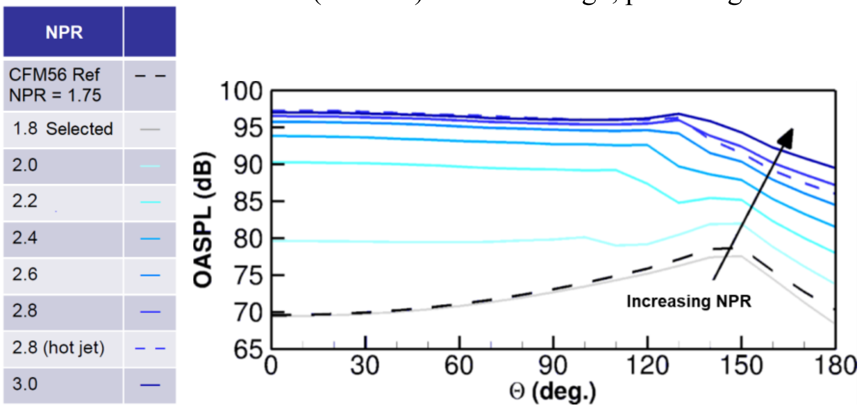

Figure 7-1 Nozzle jet acoustic analysis

A modelled CFM56 (dashed line) is considered as a reference for acceptable noise levels. The selected design (NPR = 1.8) shows OASPL noise levels similar to the reference subsonic engine. An overview of the Effective Perceived Noise levels (EPNdB) at Flyover, Sideline and Approach certifications points of an A320-214 equipped with CFM56-5B4/3 engines is presented in Table 7-1. The cumulative margin is 16.5 EPNdB lower than the ICAO Chapter 3 requirements. The preliminary design of the SENECA Mach 1.6 SSBJ therefore shows satisfactory results, but noise levels need to be consolidated to ensure the aircraft reaches the ICAO Chapter 14 requirements (-17 EPNdB) on cumulative levels, while assuring acceptable emissions and fuel efficiency.

Table 7-1 Flyover, Sideline and Approach measured noise values

EPNdB	Flyover	Sideline	Approach
Ch. 3 Limit Value	91.2	96.6	100.3
Measured Value	82.3	93.8	95.5
Margin	8.9	2.8	4.8
Cumulative measured EPNdB = Limit - 16.5 EPNdB			

8. Route definition and emissions inventory

The Eurocontrol open source *himach* (16) tool was used to identify routes that could be served by the SENECA Mach 1.6, in terms of range and if necessary, refueling stops. This calibration process also produced the route trajectories that the SSBJ may traverse, and at which point they will fly at subsonic speed (over land) and supersonic speed (over water). *himach* finds minimum time, rather than minimum distance routes, under certain constraints (such as limiting circuity), and the SSBJ range.

The forecast for the number of SSBJ flights for a specific airport pair is dependent on the forecast year and scenarios for rates of delivery. The number of in service SSBJ was scaled by ~400 flight hours per aircraft per year (optimistic scenario based on European data). These flight hours were then allocated randomly to the top 3000 airport pairs (for long range, subsonic business jets) from Flightradar24. An example route network is illustrated in Figure 8-1.

The number of SSBJ flights will be combined with a subsonic fleet to generate a range of scenarios that will include factors such as demand growth and SST/subsonic fleet mix. Emission inventories will be constructed for these scenarios based on the SSBJ performance data and emission indices, forming the basis of the climate impact assessments.

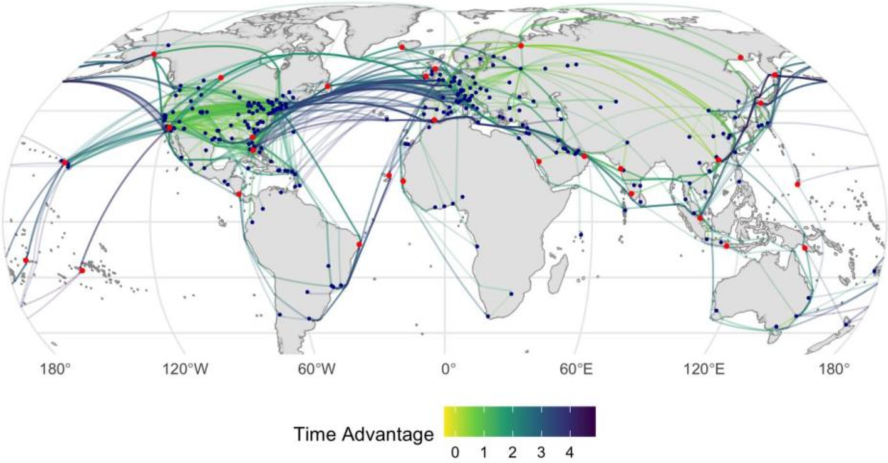

Figure 8-1 Example route network for the SENECA Mach 1.6 SSBJ

9. Conclusions/Summary

The near entry-into-service of the next civil supersonic aircraft urges the introduction of new regulations and certification processes. The SENECA project is actively involved in assisting the ICAO deliberation process. This paper provides an overview of the work undertaken in SENECA, showing the preliminary design of a supersonic business jet capable of cruising at Mach 1.6 along with its mission performance analysis, and the environmental and noise assessments. The engine cycle has been designed considering an initial trade-off between engine efficiency, size and noise during LTO operations. The analysis of the intake and afterbody associated drags has highlighted the importance of the airframe-engine integration early in the design process. A preliminary emissions estimation confirmed that the design is sufficiently satisfactory to meet the ICAO chapter 3 limits for pollutant emissions and current noise limitations, although further refinement is necessary to abide to the ICAO Chapter 14 limitations.

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