THE FUTURE OF CIVIL SUPERSONIC TRANSPORT IN EUROPE: THE SENECA AND MORE&LESS PROJECTS

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Abstract

The request for a faster and greener civil aviation is urging the worldwide scientific community and aerospace industry to develop a new generation of supersonic aircraft, which are expected to be environmentally sustainable and to guarantee a high-level protection of citizens. Thanks to a considerable number of research activities carried out in the last decades, some innovative supersonic aircraft concepts have now the potential to assure technically viable solutions to fly beyond the speed of sound at higher altitudes with respect to current civil aviation, but no commonly agreed regulations and procedures to support they eventual operations do exist. To pursue this purpose, SENECA[1] ((LTO) noiSe and EmissioNs of supErsoniC Aircraft) and MORE&LESS[2] (MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation), answering to the EC call "Towards global environmental regulation of supersonic aviation" (LC-MG-1-15-2020), aim to support Europe to shape global environmental regulations for future supersonic aviation.

Keywords: supersonic transport, certification, landing and takeoff noise, climate effects.

1. Introduction

Environmental impact of supersonic aircraft – a question of certification

In the past two decades following the Concorde's final passenger flight, there has been a renewed push to develop civil supersonic aircraft, driven by the demand for faster travel times in our interconnected world. The International Civil Aviation Organization (ICAO) needs to define standards for the advent of this new generation of supersonic aviation. Here, the standardization and rule-making can be roughly subdivided into two major challenges: firstly, the sonic boom and its impact on human beings and the environment and secondly, the landing and take-off (LTO) noise and emissions for air quality and climate impact. The EU project SENECA (2021-2024) is specifically dedicated to addressing challenges associated with this new generation of Concorde successors. These challenges include significantly higher fuel consumption compared to subsonic aircraft and the global climate impact of a potential supersonic fleet. Additionally, the project tackles the issue of take-off and landing noise near airports. The EU project MORE&LESS aims at supporting Europe to shape global environmental regulations for future supersonic aviation: recommendations are established on the basis of the outcomes of extensive high-fidelity modelling activities and test campaigns that merge into the multi-disciplinary optimization framework to assess the holistic impact of supersonic aviation onto environment. The project specifically focuses on sonic boom and LTO noise, as well as on chemical emissions of sustainable alternative fuels, i.e. bio-fuels and hydrogen.

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[1] https://seneca-project.eu/
[2] https://cordis.europa.eu/project/id/101006856/de

The datum situation for the certification rules of supersonic aircraft can be described as follows: Whereas the noise standard (actually provided in Chapter 14 of ICAO Annex 16 Vol I [1]) and the emission standard (to be found in Chapter 2 of ICAO Annex 16 Vol II [2]) for subsonic aircraft have evolved over time as technologies have improved, there was hardly any evolvement for supersonic aircraft at all. The noise and emission regulations in Chapter 12 of ICAO Annex 16 Vol I and Chapter 3 of ICAO Annex 16 Vol II, respectively, were originally created for the Concorde airplane and have remained unchanged ever since. Today, the noise standard is no longer valid, as it was limited in time, but the outdated emission standard is still applicable. Already in the CAEP/11(2016-2019) accompanied e.g. by the Horizon 2020 project RUMBLE[3] (2017-2020), progress has been made towards an appropriate noise metric for the sonic boom. Several ongoing research projects (STORMIE [2] and the NASA X-59 test aircraft) have set themselves the goal of reducing the impact of sonic boom through suitable airframe designs, so-called low-boom designs.
When setting the objectives of SENECA project, it was anticipated that the initial generation of these new supersonic aircraft won't entirely overcome the problem of the supersonic boom. This limitation prevents them from flying over land at supersonic speeds. Consequently, the project's primary focus is on missions involving supersonic flights over water and subsonic flights over land, restricting the time advantage of these aircraft to routes primarily over water (see Figure 1).

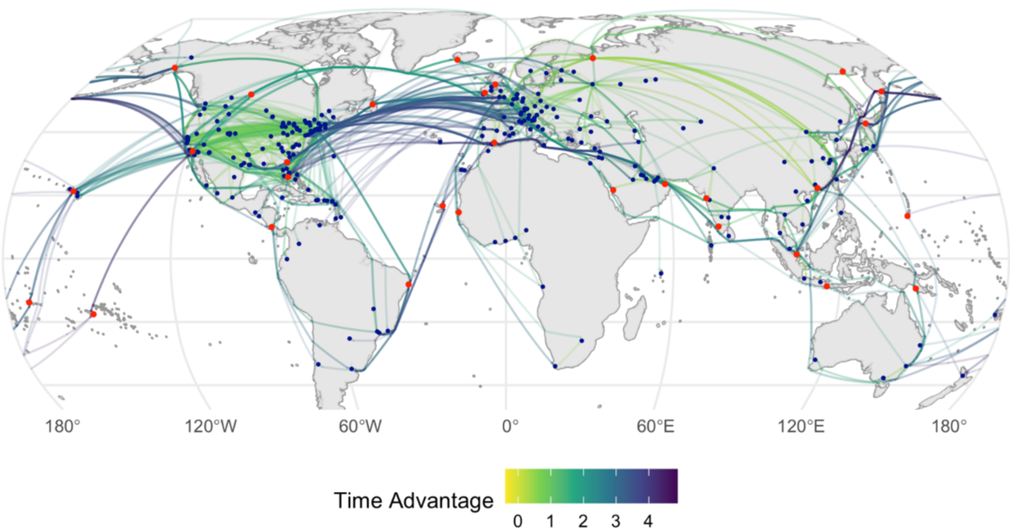

Figure 1: Forecast of the time advantage of a Mach 1.6 business jet on the most frequented long-range

In particular, SENECA aims at supporting the activities of the CAEP/13 cycle (2022-2025) with regard to the regulation of LTO noise and emissions of SST aircraft by providing comprehensive and reliable data on the emissions and noise of supersonic business jets and airliners, along with their global climate impact. Complementary to SENECA, MORE&LESS aims at supporting the activities of the CAEP/13 (and possibly CAEP/14) cycle related to the review of the CO2 Metric Value formulation, thanks to accurate data on supersonic aircraft concepts, as well as to LTO and cruise NOx emissions estimation and sonic boom measurements and estimation.

2. Methodology

SENECA aims to develop an in-depth understanding and detailed modelling of the emissions, LTO noise and global environmental impact of supersonic aircraft. For this purpose, four different SST aircraft platforms of different sizes and flight numbers including the airframe and engines are developed. The development includes a multidisciplinary design optimization (MDO) that aims to firstly at least meet the current noise regulations for subsonic aircraft during take-off and landing and secondly to reduce emission levels. At the same time, the required minimum flight range must be achieved. The level of detail in the modelling of the aircraft platforms is sufficient to allow an adequate prediction of certification levels and aircraft performance. SENECA is contributing its project results to

[3] https://rumble-project.eu/

the ICAO level discussions, in order to scientifically accompany and strengthen the European perspective on the necessary regulations for novel supersonic aircraft. Key milestones of the project dissemination and exploitation plan are aligned to the CAEP work program and agenda.

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) (see Figure 2). WP2 focuses on the development of the airframe designs and the definition of advanced landing and take-off trajectories. In WP3, the respective engines are optimized to achieve the best compromise between environmental impact and flight range. In WP4 chemistry-climate models are applied to identify sensitivities of the atmosphere to supersonic aircraft emissions, evaluating the dependence on altitude and emission index. In particular the impact of emissions at global level, i.e. CO_2, NOx, water vapor and, in turn, their consequences to the ozone and water vapor concentration in the stratosphere are quantified. WP5 predicts noise certification levels and investigates noise reduction technologies for supersonic aircraft.

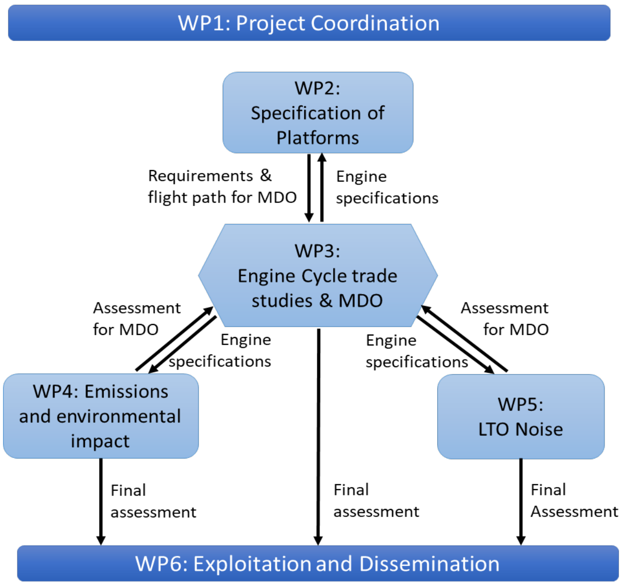

Figure 2: Pert diagram of SENECA project

The concept of MORE&LESS can be summarized in eight main steps, pursuing an incremental path (see Figure 3). The main idea is to move from the definition of supersonic aviation paradigm, up to the support of the regulatory entities to shape the environmental standards, moving through a better understanding of physical phenomena and their innovative mathematical modelling, dedicated test campaigns and the integration of a holistic multidisciplinary framework. All steps deal with the problems stated in a highly multidisciplinary way.

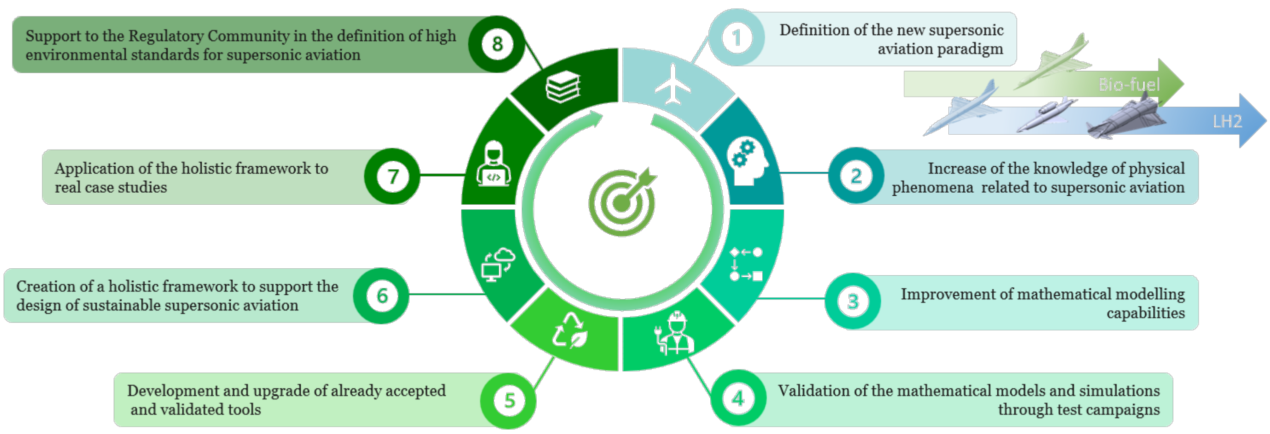

Figure 3. MORE&LESS concept

The eight steps of the MORE&LESS concept are here briefly described:

1. Case studies analysis: assessment of different supersonic aircraft propelled by biofuels or cryogenic hydrogen and designed to operate at Mach 2 or 5.
2. Prediction models: investigations on aerodynamics, aeroacoustics, propulsion, pollutant emissions, air quality, ozone layer, and climate impact aspects.
3. High-fidelity simulations: supplementation of the initial analyses with more accurate results from dedicated software tools (CFD-based tools, ASTOS, EcoSimPro, etc.).
4. Test campaigns: verification of models and simulations against aerodynamic, aeroacoustics and pollutant emissions test campaigns data.
5. Software tools upgrade: Extension of the software tools adopted towards supersonic aircraft domain and development of surrogate models.
6. ESATTO Framework: integration of the updated software tools and routines into a unified multidisciplinary framework for sustainable supersonic aviation.
7. Framework deployment: ESATTO application, including multi-objective optimization process for supersonic aircraft operations and trajectories.
8. Guidelines definition: collection of information derived from ESATTO to formulate guidelines to support the certification of supersonic aircraft.

The specific disciplines tackled within MORE&LESS (see Figure 4) range from pollutant and green-house gases emissions estimation, to LTO noise, sonic boom, aerodynamic and propulsion performance, with dedicated test campaigns on real jet engine, combustion and emissions, sonic boom free flight tests in open field and laboratory tests for LTO noise and aerodynamics.

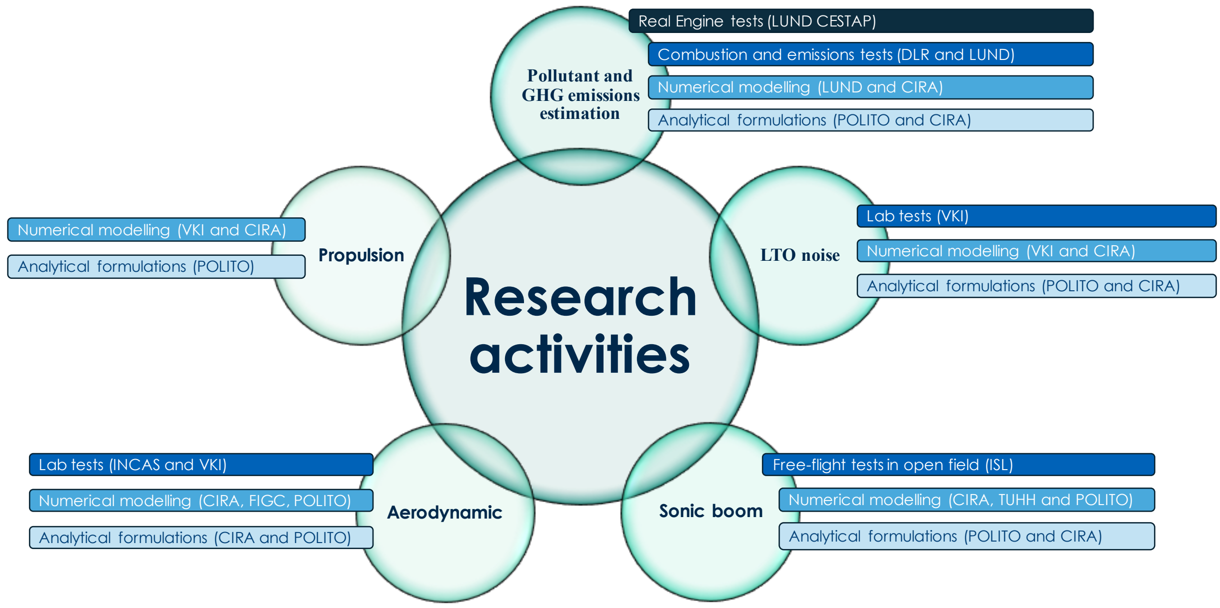

Figure 4. Main research activities in MORE&LESS: multi-fidelity simulations and test campaigns

3. Results

In SENECA four supersonic transport (SST) aircraft platforms have been designed, ranging from business jets for 6 to 10 passengers with cruise Mach numbers of Ma=1.4 and Ma=1.6 to large airliners for 100 passengers with cruise Mach numbers of Ma=1.8 and Ma=2.2 (see Table 1). The targeted flight range is 4000 nm for all platforms. Special attention was paid to the take-off trajectories, which were iteratively optimized with the noise work package. Since the low-Mach aerodynamic properties of the airframes have a major influence on the thrust required during take-off and thus on the noise emission, higher-order numerical methods were used in addition to empirical low-fidelity methods, which further increased the accuracy of the noise prediction (see Figure 5). An overview of the conceptual design of all four platforms, their requirements and mission profiles are given by Villena Munoz [11]. A more recent detailed study of the Ma=1.8 Airliner is presented by Villena Munoz [6].

	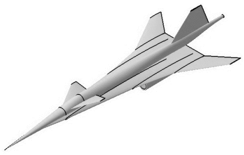		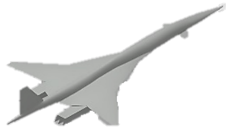	
Cruise Mach	1.4	1.6	1.8	2.2
MTOM	41697 kg	45000 kg	144278 kg	156490 kg
Passengers	6-10	6-10	100	100
Range	4000 nm	4000 nm	4000 nm	4000 nm
Number of Engines	2	2	4	4
Wing area	174.9 m²	151.5 m²	427.3 m²	267.4 m2
Overall length	43.6 m	45.7 m	71.6 m	59.0 m
Span	16.0 m	14.6 m	35.0 m	31.4 m
Wing loading	238.4 kg/m²	297.0 kg/m2	337.7 kg/m²	585.2 kg/m2

Table 1: Figure 2: SENECA supersonic transport platforms

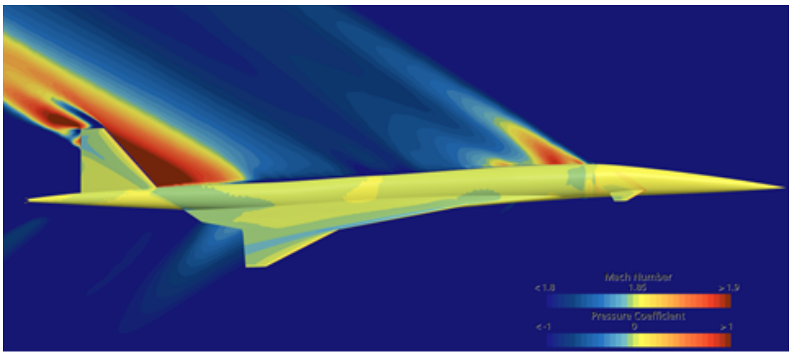

Figure 5: Mach and pressure distribution at 2° AoA for the Ma=1.8 Airliner

In WP3 engine cycles for each aircraft platform have been designed iteratively, considering multiple objectives like engine efficiency, lifetime and installation drag as well as noise and emission performance. In contrast to subsonic engines, where a higher bypass ratio increases both efficiency and noise reduction, supersonic engines must compromise between a subsonic exhaust jet at takeoff with regards to noise emission and low drag losses at supersonic cruise. The engine design is based on high TRL technologies, and the architecture features a two-stage fan, which reduces the load per stage, and a variable area nozzle. Figure 6 illustrates the engine architecture of the Ma=1.8 engine. Final results for the Ma=1.8 Airliner engine are given by Plohr et al. [5] and for the Ma=1.6 BJ by Del Gatto et al. [10].
To estimate the climate impact of a potential supersonic fleet in WP4, the emission indices for NOx, CO, CO2, and SOx were determined based on the respective engine concepts. In addition, numerical simulations have been conducted to predict the mean ice crystal concentration in the contrails (see Figure 7). Simulations of the chemical impacts and associated radiative forcing of NO_x on stratospheric and tropospheric ozone and water vapor have shown that aircraft NO_x emissions can either increase or decrease ozone, depending on the ambient environment that is the resultant of the relative balance of NO_x, HO_x, and halogen radicals in the background atmosphere. More details are given in the joint SENECA WP4 paper by Terrenoire et al. [9].

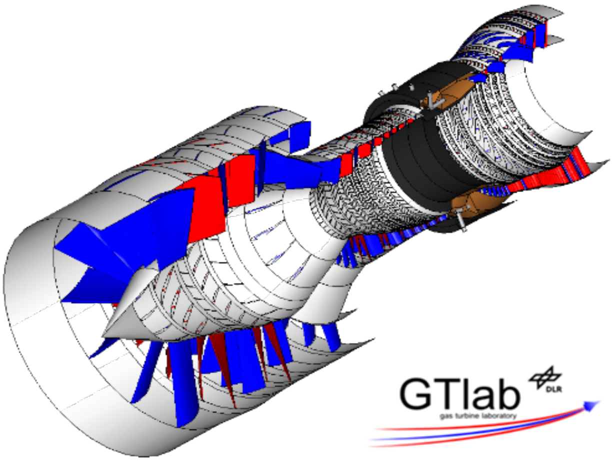

Figure 6: Design of the Ma=1.8 engine

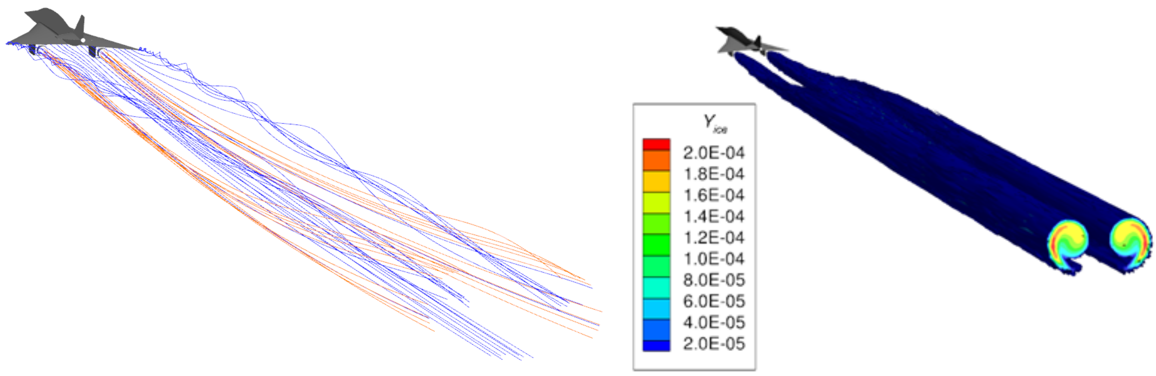

Figure 7: Streamlines behind the aircraft (from the engine in orange and from the wing in blue), and contrail formation

In WP5, advanced takeoff trajectories were investigated that allow for an additional FADEC controlled thrust reduction before cutback, the so-called Programmed Lapse Rate (PLR), and a higher climb-out speed (see Figure 8). In Figure 9 the final noise level estimates for the Ma=1.4 BJ for a selection of take-off trajectories and approach are shown. For the Ma=1.4 BJ and Ma=1.8 Airliner, the optimal PLR thrust reduction was found to be in the range of 20-30% when combined with a higher climb-out speed in the range of V_2+20 kts up to 40 kts for the BJ and the max. allowed speed of 250 kts for the Airliner. In addition, it has been shown that a variable throat nozzle allows much lower jet velocities during takeoff without compromising cruise performance. As a result, takeoff noise can be significantly reduced. It has also been shown that by optimizing the derated take-off thrust prior to take-off and the delayed take-off speed for a targeted climb-out speed and PLR thrust reduction, sideline and cutback levels can be further reduced. Both the Ma=1.4 BJ and Ma=1.8 Airliner aircraft meet the Chapter 14 limits with significant margins.

As the results are disseminated to certification authorities and ICAO CAEP working groups, particular attention was paid to quality and reliability. Since jet noise is the dominant source of takeoff noise, a jet noise prediction benchmark was conducted [7] and additional small-scale experiments were performed to generate additional validation data and to investigate the influence of nozzle and mixer geometry on jet noise [8]. More details can be found in the joint SENECA WP5 paper by Gräbert et al. [4].

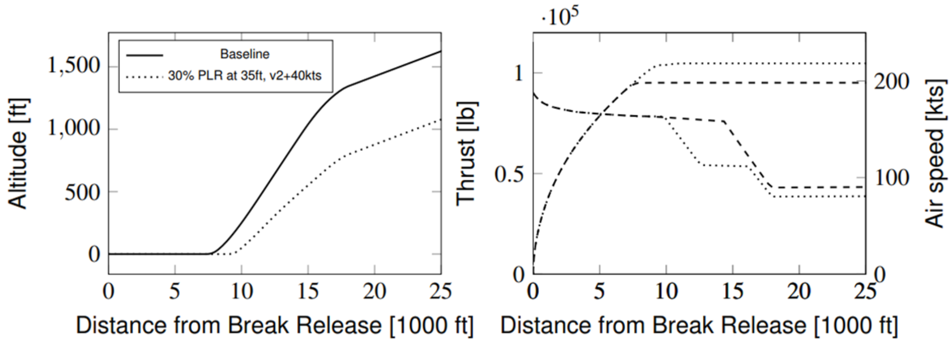

Figure 8: Example of a baseline and an advanced trajectory using PLR and fast climb-out

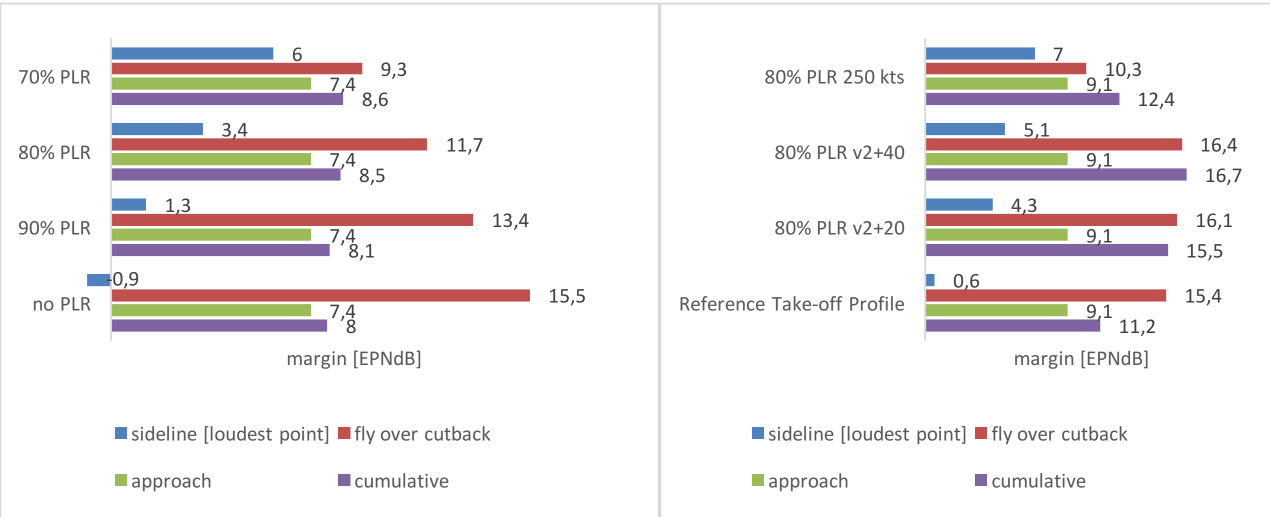

Figure 9: Margin to Chapter 14 noise certification limits for the Ma=1.4 BJ, left: different PLR ratios, right: different climb-out speeds at 80% PLR with derated take-off thrust and delayed take-off speed

In accordance with the main objective of the project, all results were regularly disseminated to ICAO CAEP WG1, WG3 and FESG.

Complementary to SENECA, MORE&LESS investigate higher Mach numbers flights (from Ma = 2 to Ma = 5) and sustainable aviation fuels, including bio-fuels and cryogenic hydrogen. Main case-studies are reported in Figure 10.

To generate reliable emissions inventories of future supersonic and hypersonic civil aircraft using biofuels and hydrogen as propellant, MORE&LESS adopts an integrated multi-fidelity approach (see Figure 11). Results from high-fidelity simulations and test campaigns are used to validate 0D/1D chemical-kinetic mechanisms which, in turn, are used as solid basis for the development of simplified analytical formulations. An integrated multi-fidelity approach has also been pursued to estimate sonic boom and jet noise.

This approach is expected to provide the regulatory community with solid technical basis for the update of existing standards or elements to create new ones.

Final recommendations to Regulatory Entities are established on the basis of the outcomes of extensive multi-fidelity modelling activities and test campaigns that merge into the multi-disciplinary optimization framework (ESATTO framework) to assess the holistic impact of supersonic aviation onto environment.

The ESATTO framework aims to integrate all upgraded and validated software tools, developed within the project or already available to the scientific community (i.e. IMPACT by EuroControl) in a unique holistic framework to assess the environmental impact of supersonic aviation at local, regional and global levels through a multidisciplinary approach, which encompasses different disciplines (aerodynamics, propulsion, aeroacoustics, pollutant emissions and environmental impact) and their mutual relationships, thus allowing to perform a multidisciplinary optimization of supersonic aircraft’ trajectories and operations. A synthetic flow chart of the ESATTO framework is depicted in Figure 12.

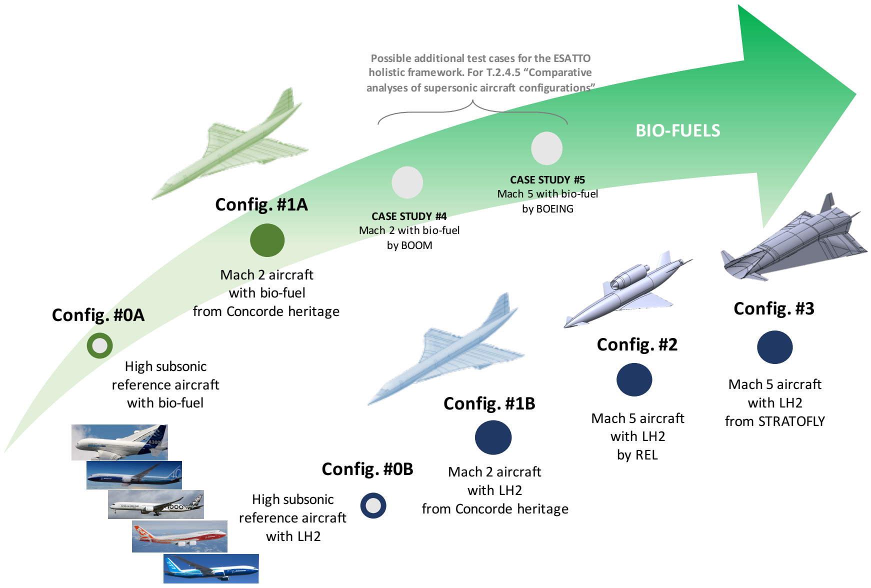

Figure 10. MORE&LESS case-studies with sustainable aviation fuels

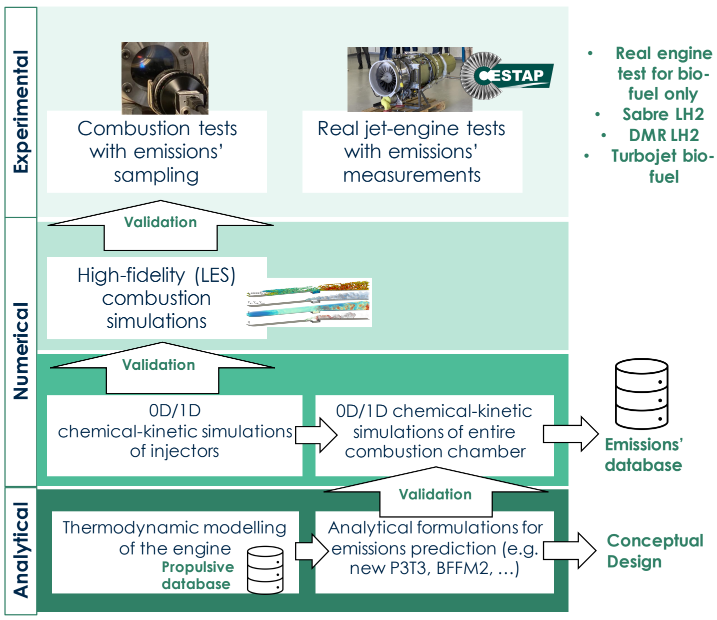

Figure 11. Integrated multi-fidelity approach to estimate chemical emissions

1. Conclusion and Outlook

The EU projects MORE&LESS and SENECA have contributed significantly to the development of design and evaluation capabilities for civil supersonic aircraft systems in Europe.

In SENECA, two supersonic business jets with cruise Mach numbers of 1.4 and 1.6 and two airliners with cruise Mach numbers of 1.8 and 2.2 have been holistically optimized for LTO noise and emissions. To date, the noise studies for the Ma=1.4 and Ma=1.8 aircraft have been completed. By using a variable area throat and an advanced takeoff procedure, both can achieve Chapter 14 noise limits. Great progress has been made in predicting the climate impact of a potential supersonic fleet by estimating the routes and number of flights and the emission indices as well as the crystal ice concentration in the contrails.

By the end of 2024, the end of the SENECA project, the noise results for the Ma=1.6 and Ma=2.2 aircraft will be available. In addition, the climate impact studies will be completed, showing how a potential fleet of civil supersonic aircraft will affect the climate and demonstrating the sensitivity of the atmosphere to emissions from supersonic aircraft as a function of altitude and emission index.

In MORE&LESS two Ma=2 airliners and two Ma=5 civil aircraft have been designed, exploiting sustainable aviation fuels, i.e. bio-fuels and hydrogen. The holistic and integrated multi-fidelity approach has encompassed all enabling technologies and disciplines, to deliver a framework to assess both the impact on climate and on air quality of different technical and operational solutions. Open field sonic boom tests, and jet noise tests, aerodynamic, and combustion laboratory tests have allowed to gather precious and accurate data, to increase physical and chemical phenomena understanding and to validate simulation models.
The next consistent step would be the holistic optimization and investigation of low-boom designs that have a low boom signature as well as low LTO noise levels and pollutant emissions. This would be an excellent opportunity to build on the findings of the EU projects RUMBLE, SENECA and MORE&LESS and to further strengthen and deepen European expertise in the field of civil supersonic aircraft. These research activities would be in line with the next CAEP cycle, which will address en-route noise, secondary boom and focus boom. A European project could make a valuable contribution to collecting reliable data and providing recommendations to certification authorities.

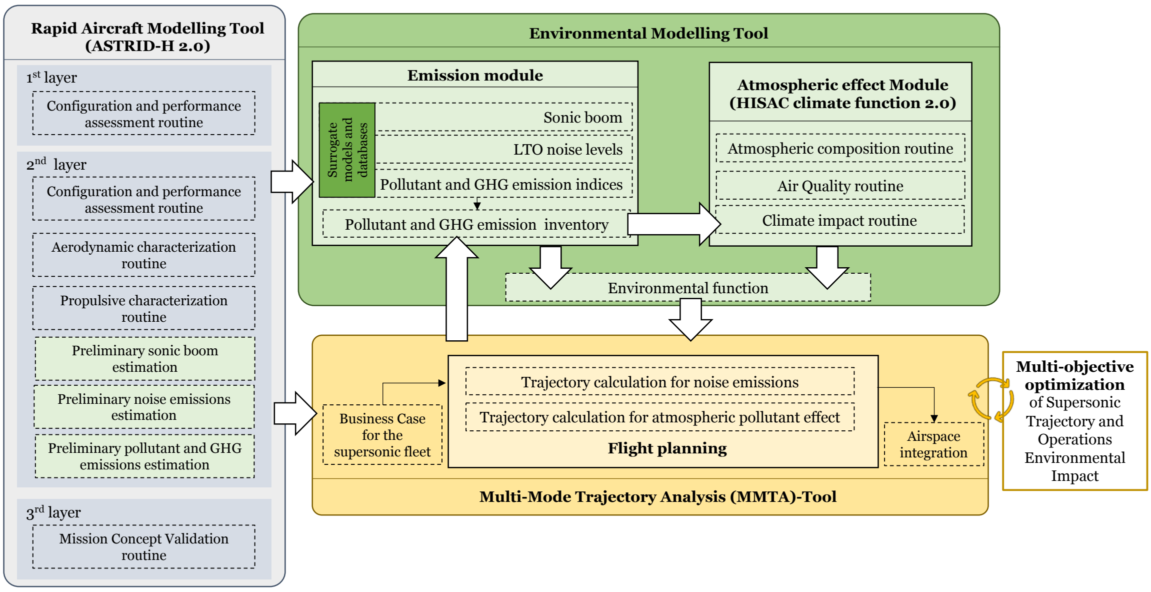

Figure 12. ESATTO framework

2. Acknowledgment

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3. Copyright Statement

References

[1] "Annex 16 to the Convention on International Civil Aviation, Vol. I: Aircraft Noise," International Standards and Recommended Practices – Environmental Protection, 7th ed., International Civil Aviation Organisation, Montreal, July 2014.

[2] "Annex 16 to the Convention on International Civil Aviation, Vol. II: Aircraft Engine Emissions," International Standards and Recommended Practices – Environmental Protection, 3rd ed., International Civil Aviation Organisation, Montreal, July 2008.

[3] Kirz, J. und Bartels, S. und Bertsch, L. und Can, A. G. und Dietl, T. und Ewert, R. und Gräbert, M. und Jaron, R. und Liebhardt, B. und Nöding, M. und Plohr, M. und Schnell, S.: *Predicting Take-Off Noise, Sonic Boom, and Landing Noise of Supersonic Transport Aircraft Concepts.* Chiba, Greater Tokyo, Japn : s.n., 2023. InterNoise 2023.

[4] Gräbert, M., Jaron, R., Plohr, M., Zenkner, S., Richter, C., Stöhr, C., Villena Muñoz, C., Mourouzidis, C. van der Meulen, M.-J., Habing, R., Huet, M., Petrosino, F., Barbarino, M., Fischer, F. and Zaporozhets, O.: *Landing and Takeoff Noise Prediction of Conceptual Supersonic Aircraft*, ICAS 2024, Florence, Italy, 2024

[5] Plohr, M.; Zenkner, S.; Bake, S.; Zeitz, D.: *Thermodynamic Design and Emission Model of a Mach 1.8 Supersonic Airliner Engine*, ICAS 2024, Florence, Italy, 2024

[6] Villena Munoz, C.; Lawson, C.; Riaz, A.; Sharma, A.: *Design of the SENECA M1.8 Supersonic Airliner with Multi-fidelity Aerodynamic Analysis to Enable Noise Optimised Take-off Trajectories*, ICAS 2024, Florence, Italy, 2024

[7] Jaron, R.; Habing, R.; van der Meulen, M.-J.; Huet, M.; LeGriffon, I.; Petrosino, F.; Barbarino, M.; Lefarth, K.; Zaporozhets, O.: *Jet Noise Prediction Benchmark for Landing and Takeoff Noise of Supersonic Aircraft.* InterNoise 2023, Chiba, Greater Tokyo, 2023

[8] Habing, R., van der Meulen, M.-J., Huet, M., Jaron, R., Petrosino, F., Barbarino, M. and Zaporozhets, O.: *Dual-Stream Jet Noise Test with Internal Mixer Design Variations for LTO Noise of Supersonic Aircraft*, ICAS 2024, Florence, Italy, 2024

[9] Terrenoire, E., Muller, M., Ramirez Correra, E., Leyland, P., Synylo, K., Krupko, A., Zaporozhets, O., Lee, D., Owen, B., Lim, L., Skowron, A., Rodriguez De Leon, R., Marsh, D. Matthes, S., Madden, P., Bake, S., Mourouzidis, C.: *SENECA's Aircraft Emissions Evaluation and theirs Environmental Considerations*, ICAS 2024, Florence, Italy, 2024

[10] Del Gatto, D.; Adamidis, S.; Mourouzidis, C., Brown, S.; Pachidis, V.: *Design Space Exploration of Next-Gen Supersonic Business Jet Engine with a Focus on Landing and Takeoff (LTO) Noise*, ICAS 2024, Florence, Italy, 2024

[11] Villena Munoz, C.; Lawson, C.; Riaz, A.; Jaron, R.: *Conceptual Design of Supersonic Aircraft to Investigate Environmental Impact*. AIAA SCITECH 2024, Orlando, Virginia, 2024